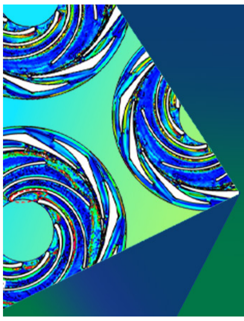
Physics of Plasmas

RESEARCH ARTICLE | DECEMBER 07 2023

Physics and applications of dusty plasmas: The Perspectives 2023

J. Beckers ; J. Berndt ; D. Block ; M. Bonitz ; P. J. Bruggeman ; L. Couëdel ;
G. L. Delzanno ; Y. Feng ; R. Gopalakrishnan ; F. Greiner ; P. Hartmann ; M. Horányi ;
H. Kersten ; C. A. Knapek ; U. Konopka ; U. Kortshagen ; E. G. Kostadinova ; E. Kovačević ;
S. I. Krasheninnikov ; I. Mann ; D. Mariotti ; L. S. Matthews ; A. Melzer ; M. Mikikian ;
V. Nosenko ; M. Y. Pustylnik ; S. Ratynskaia ; R. M. Sankaran ; V. Schneider ; E. J. Thimsen ;
E. Thomas ; H. M. Thomas ; P. Tolias ; M. van de Kerkhof

Phys. Plasmas 30, 120601 (2023)
https://doi.org/10.1063/5.0168088



Physics of Plasmas PERSPECTIVE pubs.aip.org/aip/pop

Physics and applications of dusty plasmas: The Perspectives 2023

Cite as: Phys. Plasmas **30**, 120601 (2023); doi: 10.1063/5.0168088
Submitted: 17 July 2023 · Accepted: 27 October 2023 ·
Published Online: 7 December 2023

View Online Export Citation CrossMark

J. Beckers,[1,a)] J. Berndt,[2] D. Block,[3] M. Bonitz,[4] P. J. Bruggeman,[5] L. Couëdel,[6,7] G. L. Delzanno,[8] Y. Feng,[9] R. Gopalakrishnan,[10] F. Greiner,[3,11] P. Hartmann,[12] M. Horányi,[13] H. Kersten,[3] C. A. Knapek,[14] U. Konopka,[15] U. Kortshagen,[5] E. G. Kostadinova,[15] E. Kovačević,[2] S. I. Krasheninnikov,[16] I. Mann,[17] D. Mariotti,[18] L. S. Matthews,[19] A. Melzer,[14] M. Mikikian,[2] V. Nosenko,[19,20] M. Y. Pustylnik,[20] S. Ratynskaia,[21] R. M. Sankaran,[22] V. Schneider,[3] E. J. Thimsen,[23] E. Thomas,[15] H. M. Thomas,[20] P. Tolias,[21] and M. van de Kerkhof[1,24]

AFFILIATIONS

[1]Department of Applied Physics, Eindhoven University of Technology, P.O. Box 513, Eindhoven 5600 MB, The Netherlands
[2]GREMI UMR 7344 CNRS and Université d'Orléans, 14 Rue d'Issoudun, 45067 Orleans Cedex 2, France
[3]Institute of Experimental and Applied Physics, University of Kiel, Leibnizstr. 19, Kiel 24098, Germany
[4]Institute for Theoretical Physics and Astrophysics, Kiel University, Leibnizstrasse 15, Kiel 24098, Germany
[5]Department of Mechanical Engineering, University of Minnesota–Twin Cities, Minneapolis, Minnesota 55455, USA
[6]Physics and Engineering Physics Department, University of Saskatchewan, Saskatoon, Saskatchewan S7N 5E2, Canada
[7]CNRS, Aix-Marseille University, PIIM UMR 7345, Marseille 13397, France
[8]T-5 Applied Mathematics and Plasma Physics, Los Alamos National Laboratory, Mail stop: K717, Los Alamos, New Mexico 87545, USA
[9]Institute of Plasma Physics and Technology, School of Physical Science and Technology, Soochow University, Suzhou 215006, China
[10]Department of Mechanical Engineering, The University of Memphis, Memphis, Tennessee 38152, USA
[11]Kiel Nano, Surface and Interface Science KiNSIS, University of Kiel, Leibnizstr. 19, Kiel 24098, Germany
[12]Institute for Solid State Physics and Optics, Wigner Research Centre for Physics, 49, Budapest H-1525, Hungary
[13]Department of Physics, and Laboratory for Atmospheric and Space Physics, University of Colorado, Boulder, Colorado 80303, USA
[14]Institute of Physics, University of Greifswald, Felix-Hausdorff-Straße 6, Greifswald 17489, Germany
[15]Physics Department, Auburn University, Auburn, Alabama 36849, USA
[16]Mechanical and Aerospace Engineering Department, University of California San Diego, La Jolla, California 92093, USA
[17]Department of Physics and Technology, UiT the Arctic University of Norway, P.O. Box 6050 Langnes, Tromsù N-9037, Norway
[18]School of Engineering, Ulster University, BC-04-303, 2-24 York Street, Belfast, United Kingdom
[19]Center for Astrophysics, Space Physics, and Engineering Research, Baylor University, Waco, Texas 76798-7310, USA
[20]Institut für Materialphysik im Weltraum, Deutsches Zentrum für Luft- und Raumfahrt (DLR), Cologne D-51147, Germany
[21]Space and Plasma Physics, KTH Royal Institute of Technology, Stockholm SE-100 44, Sweden
[22]Department of Nuclear, Plasma, and Radiological Engineering, University of Illinois Urbana-Champaign, Urbana, Illinois 61801, USA
[23]Department of Energy, Environmental and Chemical Engineering Institute for Materials Science and Engineering, Washington University in Saint Louis, Saint Louis, Missouri 63130, USA
[24]ASML Netherlands B.V., Veldhoven 5504 DR, The Netherlands

[a)]**Author to whom correspondence should be addressed:** j.beckers@tue.nl

ABSTRACT

Dusty plasmas are electrically quasi-neutral media that, along with electrons, ions, neutral gas, radiation, and electric and/or magnetic fields, also contain solid or liquid particles with sizes ranging from a few nanometers to a few micrometers. These media can be found in many natural environments as well as in various laboratory setups and industrial applications. As a separate branch of plasma physics, the field of dusty plasma physics was born in the beginning of 1990s at the intersection of the interests of the communities investigating astrophysical and technological plasmas. An additional boost to the development of the field was given by the discovery of plasma crystals leading to a series of microgravity experiments of which the purpose was to investigate generic phenomena in condensed matter physics using strongly coupled complex (dusty) plasmas as model systems. Finally, the field has gained an increasing amount of attention due to its inevitable connection to the development of novel applications ranging from the synthesis of functional nanoparticles to nuclear fusion and from particle sensing and diagnostics to nano-contamination control. The purpose of the present perspectives paper is to identify promising new developments and research directions for the field. As such, dusty plasmas are considered in their entire variety: from classical low-pressure noble-gas dusty discharges to atmospheric pressure plasmas with aerosols and from rarefied astrophysical plasmas to dense plasmas in nuclear fusion devices. Both fundamental and application aspects are covered.

 https://doi.org/10.1063/5.0168088

I. INTRODUCTION (J. BECKERS AND M. Y. PUSTYLNIK)

With this Perspectives paper, the dusty plasma community for the first time identifies promising future directions for its development. It was prepared by 34 leading experts in the field, representing ten countries. The intention of this paper is to highlight the current state-of-the-art and challenges in the field of dusty plasma physics and its technological applications, thereby serving as a guideline to colleagues in the field and fields connected to it. Moreover, the Perspectives discussed may give a direction to policymakers and (inter-)national funding agencies in terms of allocating resources. The paper consists of 14 topical sections. Each of them is coauthored by two to three experts who present their personal views on the state-of-the-art of the topic as well as on its perspectives. The authors are listed in alphabetic order.

Dusty plasmas are electrically quasi-neutral media that, along with electrons, ions, neutral gas, radiation, and electric and/or magnetic fields, also contain solid or liquid particles with sizes ranging from a few nanometers to a few micrometers. Once immersed in an ionized medium, dust particles unavoidably get charged due to incoming fluxes of electrons and ions on their surfaces. Therefore, the charge (as well as the surface temperature) of the dust is self-consistently coupled not only to electron and ion temperatures and densities but also to parameters, such as collisionality, magnetization, dust density, dust shape, and surface conditions.

Under laboratory and microgravity conditions, dusty plasmas are usually investigated in low-pressure gas discharges in which the dust particles are either grown by chemical reactions or externally injected. The presence of dust in a plasma leads not only to quantitative changes of plasma parameters but also to the appearance of new dust-induced phenomena like void formation and low-frequency instabilities. In general, the modeling of dusty gas discharges is considerably more complicated with respect to the modeling of dust-free discharges due to the very slow dynamics of dust compared to that of electrons and ions present in the plasma. Also, classical plasma diagnostic techniques need to be modified to take into account the presence of dust. Moreover, new diagnostic methods have been developed in recent years in order to measure typical dust parameters, such as temporal and spatial distributions of dust size and/or number density and the charge that dust particles obtain in the plasma.

Micrometer-sized dust particles arrange themselves toward typical inter-particle distances of the order of fractions of millimeters in low-pressure discharges. This makes their suspensions accessible for observation at the level of single dust particles. In addition to that, the strong coupling of the dust particles due to their Coulomb interaction often leads to the crystallization of their sub-system. This makes dusty plasmas interesting model systems for studying generic condensed matter phenomena at the level of atomistic dynamics, such as phase transitions, lattice formation, and density waves. Two-dimensional systems can be created, for instance, in the sheath of a radio frequency (RF) discharge. Three-dimensional systems are studied in different discharge configurations and under microgravity conditions.

As mentioned above, dust particles can grow in low-pressure reactive discharges. Controlling this process allows one to grow semiconductor particles of nm-size (i.e., so-called quantum dots), which have many applications in biological labeling or sensing. At the moment, they are mainly produced in wet chemistry processes, which have certain disadvantages compared to plasma synthesis. Similarly, there are attempts to grow semiconductor nanoparticles in atmospheric pressure microdischarges either from gas phase or from aerosol precursors.

In spite of certain similarites between atmospheric pressure plasmas (APPs) containing aerosols and dusty plasmas, both areas of research have mainly been developing separately from each other. Nevertheless, following the suggestion expressed in the dusty plasma section of the recent low-temperature plasma roadmap,[1] it was decided to bring the two fields together in this Perspectives paper in order to promote possible collaborative efforts. Atmospheric pressure plasmas containing aerosols are important not only for the synthesis of functional nanoparticles but also as reactive media for nitrogen fixation or, e.g., for deactivation of pathogens in bio-aerosols.

The oldest topic associated with the applications of dusty plasmas, dust contamination control of plasma processes, has recently got a new impulse due to the emergence of extreme ultraviolet lithography and other high-tech ultra-clean industrial processes. In such processes, the possible presence of pulsed plasma (either induced by inherent photoionization or by remote plasma sources) may provide charges on the particles and electric fields transporting them to (optical) elements, which are highly vulnerable to contamination.

Recently, several dusty plasma setups with magnetic field in the Tesla range have been introduced. These setups allow us to study basic processes in dusty plasmas of different degrees of magnetization. Those investigations are of importance in the scope of magnetic confinement fusion research where dust, emerging in the plasma volume due to different mechanisms, has long been recognized as a considerable problem.

Ionospheric and space dusty plasmas also represent a traditional branch of dusty plasma research. Many of the current, as well as planned, space missions have investigation of dust in different regions of the Solar system as one of their major goals. The scope of this space dusty plasma research has been considerably broadened to, e.g., the heliosphere, space-debris-related problems, or planetary debris disks of stars.

In spite of the diversity of the topics, the dusty plasma community will definitely benefit from more intense collaborations between experts performing experimental gas-discharge-based laboratory and large-scale-facility research (fusion, long-term microgravity laboratories, space missions, etc.), theory, and modeling. Also, collaborations between groups conducting basic and application-oriented research should allow the former to better streamline their efforts and the latter to better understand the physical mechanisms underlying their applications. Establishing such frameworks would enable the community to tackle more efficiently the scientific and societal challenges ahead.

Throughout this Perspectives paper, we will use the terminology similar to that of Ref. 2. Namely, in cases when the dust component of the plasma consists of industrially manufactured particles of regular shape and definite chemical composition, we will term the dust component as "microparticles." In vast majority of other cases, we will apply the terms "dust," "dust grains," or "dust particles" to the dust component. We will also apply the most general term "dusty plasmas" to all plasmas containing dust. Only in cases when the system of microparticles in plasmas is specifically designed for the purpose of modeling the generic phenomena of condensed matter, we will apply a more specific term "complex plasmas." Established physical terms like, e.g., "dust component" or "dust acoustic wave" will be used irrespective of the source and nature of dust immersed in plasmas. Some sections use specific terminology. For example, in Sec. IV, the term "nanodusty plasma" is used to emphasize the nanometer size of dust particles. In the fusion community (see Sec. VIII), the terms dust and "powder" are used equivalently. Section XI introduces the terminology associated with atmospheric plasmas with aerosols. Terms applied to astro- or geophysical media (e.g., "meteoric smoke" or "noctilucent clouds") imply the presence of dusty plasmas (Sec. XIII).

II. THEORY OF BASIC PROCESSES: CHARGING, HEATING, AND FORCES (G. L. DELZANNO AND P. TOLIAS)

Dust charging dictates single grain dynamics and collective effects.[3,4] The relevant spatial scales are the dust size $r_{\rm d}$, Debye length $\lambda_{\rm D}$, plasma gyroradii ρ_α, collision mean free paths $\lambda_{c\alpha}$, and mean intergrain distance d. For isolated spherical dust, the orbital motion (OM) theory applies in the non-emissive, collisionless, unmagnetized limit, i.e., $r_{\rm d}, \lambda_{\rm D} \ll \rho_\alpha, \lambda_{c\alpha}$.[5–8] It is based on energy and angular momentum conservation, expressed in a non-linear Poisson equation supplemented by the floating potential condition. The orbital motion limited (OML) approach is an OM approximation that neglects effective potential barriers to plasma collection.[9] Remarkably, in OML, the dust potential relative to the plasma potential is determined only by the floating potential condition, thus circumventing Poisson's equation fully. The dust charge is computed without plasma screening, with a vacuum capacitance, limiting OML validity to $r_{\rm d} \ll \lambda_{\rm D}$. Unparalleled simplicity is the reason behind OML's wide utility. The effect of ion–neutral collisions was addressed early.[10–13] Semi-empirical formulas exist in the full ion collisionality range,[14–16] tested against experiments.[17–19] In discharge plasmas, the contribution of ion–neutral collisions to charging becomes significant already for $\lambda_{\rm n,i} \sim 10\lambda_{\rm D}$.[14]

Plasma screening of the dust charge dictates the dust–dust interaction potential: the key quantity for the description of collective effects in dusty plasmas within the one-component assumption. Even for isotropic plasmas, the Debye–Hückel (Yukawa) form[20] is valid for weak ion–grain coupling as well as in the absence of collisions with neutrals and plasma sources/sinks.[21] In the collisionless case, exact potential profiles can be obtained by solving the non-linear Poisson equation with the charge density derived from the stationary Vlasov equation.[22,23] The Yukawa form persists at short-to-intermediate distances provided that an effective screening length is utilized that depends on the ion non-linearity parameter.[24–26] In the collisional case, an asymptotic theory[5,27,28] together with the linearization of a BGK-type ion kinetic equation with point-sinks[29,30] or the drift-diffusion approximation[31,32] have quantified non-Yukawa aspects. In the presence of electron emission[8,33] or source/sink competition,[34–37] the formation of attractive potential wells has been reported.

The ion drag force, due to scattering of drifting ions, has been known to drive dust dynamics in discharges, tokamaks, and space. In collisionless subthermal flowing plasmas, the binary collision approach of classical scattering theory has been employed for Yukawa interactions and arbitrary ion–grain coupling with shifted Maxwellian or more accurate ion distribution functions.[38–41] For ion–neutral collisions and arbitrary Mach numbers, the linear response approach has been employed with self-consistent ion distributions within the weak coupling limit.[42,43] The complementarity of these approaches was exploited in a more general hybrid approach.[44] Particle-in-cell (PIC) simulations provided invaluable benchmark data, bridged the gap between the formalisms, and yielded accurate analytical correction factors at arbitrary collisionality and non-linearity in the practical Mach number range.[45–47]

A. Current status

A problem has been pointed out in the original formulation of OML that did not allow incorporation of plasma screening due to an error in the ion density.[23,48] A revised OML theory has been formulated.[22,23] A comparison with PIC simulations revealed that accuracy is retained up to $r_{\rm d} \sim \lambda_{\rm D}$ and that screening effects on the dust charge can be significant.[49] The extension to positively charged dust has also been reported.[50]

Recent studies have been driven by tokamak dust,[51–55] where effects beyond OML can become important. First-principles simulations have revealed that OML can become very inaccurate in the emission-dominated space-charge-limited regime due to a potential well formed by the slow emitted electrons being attracted back to the positively-charged dust.[8,33,56] The potential well can alter the plasma electron collection and substantially decrease electron heating.[56] A correction to the OML has been proposed, dubbed as OML$^+$, shown to be in good agreement with simulations. Other OML modifications have been proposed[57,58] for direct use in transport codes. Initial work combining electron emission and electron magnetization[59] identified how the emitted electron flux can be reduced by prompt redeposition via gyro-motion, strongly affecting charging. However, more sophisticated charging/heating models[60] accounting for the collisional magnetized presheath suggest a weaker heat flux dependence on the dust charge than in OML, rendering a very accurate description of electron emission less important.

Much attention has been paid to dust charge screening in the presence of ion flows. The shifted Maxwellian ion distribution used in early studies[61,62] has been proven to grossly misrepresent the exact state of affairs.[63] In fact, self-consistent distributions that include neutral collisions and electric field acceleration are asymmetric and much broader. Exact Monte Carlo (MC) results have been compared with kinetic theory for constant cross sections or constant collision frequencies (BGK).[63] Self-consistent distributions were employed for the calculation of the potential profile with a linear response theory.[64,65] PIC simulations of dust pairs helped to elucidate non-linear wake aspects, shadowing in the absorption-induced ion drag force, downstream grain decharging, the importance of ion drag perturbation, and the downstream grain electric force approximation based on the potential structure of the upstream grain alone.[66–69] Experimental studies of wake formation should also be mentioned.[70–72]

The non-reciprocity of dust–dust interactions in flowing plasmas, known from early works,[73,74] has also received scrutiny.[75] Action–reaction symmetry is broken, since interactions are mediated by a non-equilibrium medium. Failure to comply with Newton's third law has some important statistical mechanics consequences. Simple idealized models that decompose the interaction to reciprocal and non-reciprocal parts can capture the main physics and have been employed in simulation studies.[76,77] Non-reciprocal effective forces have been directly measured.[78]

B. Perspectives

1. Dust in magnetized plasmas

There is an imperative need for semi-empirical analytical expressions that accurately describe the collected plasma fluxes, ion drag force, and dust interaction potential. Indicative of the difficulties are the (doubly) broken spherical symmetry, the addition of the plasma gyroradii to the characteristic length scales, the complexity of the magnetized plasma susceptibilities, and the extended collisional pre-sheath including a cross-field transport mechanism for depleted flux tube replenishment. Linear response theory calculations,[79–81] molecular dynamics (MD) simulations,[82,83] MC simulations with *ad hoc* screened potentials,[84] and self-consistent PIC simulations[85–88] have been reported. Interpolation between analytical limits is advisable. Many lessons can be learnt from the tokamak probe theory.[60,89]

2. Simultaneous OML violations

In some scenarios, more than one OML applicability condition can be violated. For dust in fusion devices, thin sheath effects are important for ion collection and electron collection can be magnetized, $\rho_e, \lambda_D \ll r_d \lesssim \rho_i$.[60] Moreover, when considering hot dust embedded in magnetized plasmas, thermionic emission is strongly suppressed by prompt return to the surface in the course of the first Larmor gyration.[59,90,91] Furthermore, multiple electron emission mechanisms can be simultaneously active, such as thermionic and potential ion-induced emission or photoelectric and secondary electron emission. A general theory of particle collection is certainly hard, but many quantitative characteristics can be understood by examining the large size limit, for which respective studies are typically available.[92–95]

3. Effect of closely packed grains

High dust densities have been known to reduce the dust charge.[96,97] Charge cannibalism is mainly not only due to global electron depletion, which can be accounted for via the quasi-neutrality condition, but also due to the sharing of particle fluxes when the mean interparticle distances are smaller than the plasma Debye length.[98–100] Even in the absence of plasma flows, the latter close packing effects on the dust–dust interaction potential have only been studied in an overly simplifying manner.[101,102] In the presence of ionic flows, PIC simulations of multiple grains have confirmed the decharging of downstream grains due to ion focusing and revealed the dependence of the charge on the specific arrangement.[103] Close packing effects should become severe in two frontier topics:[104] magnetized dusty plasmas due to elongated collection areas for the magnetized species and binary dusty plasmas due to pure geometrical considerations.

4. Sheath-within-a-sheath

Theory and simulation efforts to study charge and momentum exchange between isolated grains and flowing plasmas generally assume a homogeneous plasma background. However, in nature or in laboratories, dust is often confined in strongly inhomogeneous plasma regions formed near electrodes, containing walls or large objects. Strong modifications are expected when the plasma inhomogeneity length(s) is comparable to the dust shielding length. This has been confirmed in a work that combined an electrostatic sheath theory with a linear response theory in the point charge approximation.[105] Self-consistent PIC modeling of dust charging and potential screening, including finite size effects, is highly desirable for many sheath-within-a-sheath scenarios, such as dust levitation in rf discharge sheaths,[106,107] dust dynamics in lunar photoelectron dominated sheaths,[108–110] dust release in the magnetized sheaths of tokamaks,[111,112] and dust measurements by spacecraft.[113,114] It is worth to emphasize the particular problem of the detachment of dust residing on the surface of plasma-wetted objects, see, for instance, dust remobilization in tokamaks[115,116] or electrostatic dust lofting on the moon[117] (see Secs. VIII and XIII, respectively), where the large intervening surface prohibits the electrostatic lensing of plasma particles (with strong consequences on the potential profile and ion drag force) and where adhesive forces are important (typically weakened van der Waals interactions due to the unavoidable surface roughness).[118–122]

5. Plasma–dust interface microphysics

A standard dusty plasma idealization concerns the dust interface acting as a perfect absorber. In reality, bound electrons are constantly emitted after electron impact (secondary electron emission),[123] ion/neutral impact (kinetic emission),[124] or ion neutralization (potential emission),[125] while plasma electrons can be inelastically backscattered from the bulk or quasi-elastically reflected from the surface barrier.[123] Moreover, plasma ions are continuously backscattered after recombining,[126] and the material is chemically or physically sputtered as neutrals.[127] Plasma simulation tools model microphysical processes via electron emission or sputtering yields as well as energy/angular distributions of the emitted species.[54,128–130] Parameters are externally adopted from reliable experiments or dedicated MC simulations of particle transport in matter.[131,132] Such plasma–dust simulations are not truly coupled, since they do not consider the effect of plasma on the dust internal structure with the yields adopted from ultrahigh vacuum experiments or modeling *in vacuo*. However, particle induced emission is known to be extremely sensitive to surface conditions[133] and the plasma-induced dust surface charge layers can modify the yields. Progress in the modeling of electron reflection with the invariant embedding approach has confirmed such expectations.[134–136] Energy exchange aspects should be even more sensitive to interface descriptions.[137] The future use of semi-classical (MD, MC), quantum Boltzmann, and *ab initio* (density functional theory, non-equilibrium Green functions) approaches for interface simulations has been discussed,[138] but concrete applications are scarce.[139] Fully integrated plasma–interface–dust modeling remains an ambition.

6. Non-spherical shape and magneto-dielectric properties

Non-spherical dust studies have been reported.[140–144] Non-sphericity gives access to rotational degrees of freedom, which have been argued to be important in various scenarios.[145–149] PIC codes able to conform to objects of arbitrary shape can be used for self-consistent modeling.[150,151] The impact of electric[152] and magnetic moments[153] also remains poorly understood.

III. MODELING OF DUSTY GAS DISCHARGES (L. S. MATTHEWS AND P. HARTMANN)

Modeling dusty discharges is challenging because of the wide range of space and time scales that must be resolved. Given the ratio of the masses of the electrons and a typical 1 μm diameter dust grain, the difference in time scales is about seven orders of magnitude, covering the dynamics of electrons on the nanosecond timescale to the dust particle dynamics on the millisecond timescale. The charging and interactions of dust grains require the resolution of spatial scales as small as the grain radius on the micrometer or nanometer scale and as large as the size of a centimeter-scale gas discharge. The difference in spatial scales ranges over four to five orders of magnitude. Current methods are being developed to bridge these time and length scales.

A. Current status

Laboratory dusty plasma experiments are often conducted at low pressure conditions in direct current (DC) or radio frequency (RF) discharges, where electron transport is generally non-local in nature. Kinetic plasma modeling, e.g., by solving the Boltzmann equation in a continuum model or tracing individual particle trajectories and collisions with particle-in-cell simulations combined with Monte Carlo treatment of collisions (PIC/MCC), is required to achieve physical accuracy.

DC discharges consist of two spatial regimes. Electrons and ions are accelerated in the large sheath electric field near the cathode, resulting in gas-phase ionization and ion-induced secondary electron emission, driving plasma generation. In the positive column regime, a relatively small electric field drives just enough ionization to compensate for recombination losses occurring at the discharge tube walls. The non-local transport in the cathode region can be modeled using a Monte Carlo simulation of the electrons coupled to a fluid-type model for the ions and combined with the electrostatic field solver[154,155] or by solving the two-term Boltzmann equation.[156]

As the positive column increases in length, it is likely that instabilities (ionization waves and striations) will develop.[157] Hybrid simulations are able to reproduce the experimental observations,[158] even in the presence of dust.[159,160] The PIC/MCC method[161] has been successfully used in more recent studies[162] to self-consistently model the whole DC discharge, even in the case of complex gas mixtures.[163]

Low-pressure RF discharge plasma or capacitively coupled plasmas (CCPs) drive the ionization of the background gas by the alternating cycles of collapse and expansion of the RF sheaths at both electrodes; the sheath motion periodically accelerates electrons toward the plasma bulk. At high RF power (>100 W) and high driving frequencies (>100 MHz), electromagnetic effects, such as standing waves and the skin effect, can significantly influence the plasma distribution, but in typical dusty plasma experimental systems (13.56 MHz, 1–100 W), the electrostatic approximation is well justified.

Low-pressure CCPs are self-consistently described by advanced fluid models,[164–166] solutions of the Boltzmann equation for electron kinetics,[167] hybrid schemes,[168] and PIC/MCC simulations.[169–171] The limitations and the optimization of the PIC/MCC method have also been discussed.[172–174]

The charging currents to the dust surface are usually calculated through an orbit motion limited (OML) theory.[175,176] The currents are a function of the grain surface potential and plasma parameters, including plasma density and temperature. In regions of a plasma where electric fields are present, the net flow (drift) of ions due to electric fields not only changes the ion current to the grain surface[177] but also increases the ion density in a region downstream of the grain. The *ion wake* is a positive space-charge region that can exert an attractive force on downstream particles,[178–180] contributing to the stability of dust structures.[181–183] PIC codes have been used to determine the structure of the ion wakefield downstream of a dust grain and to compute the resulting non-linear grain–grain interactions.[67,68,184,185] The characteristics of the ion wakefield behind charged dust grains have also been studied using molecular dynamics (MD) simulations of the ions in the plasma flow, treating the electrons as a Boltzmann fluid.[82,178,179,183,186] A simplification of the wake structure is to represent the ion wakefield as a point-like region of positive space charge (the wakefield focus) located a fixed distance downstream of the grain.[187–189]

Sub-micrometer particles may have a charge of only tens or hundreds of electrons, and the charge fluctuations due to the discrete additions of charge can be a significant fraction of the equilibrium charge.[190] The characteristic time scale for these charge fluctuations can be comparable to those of the dynamic processes affecting the dust,[191,192] with an asymmetry in the charging and discharging times since electrons (which charge a grain) move on shorter timescales than ions (which discharge a grain).[191,193,194]

Non-spherical grains have a varying surface potential, complicating the calculation of the equilibrium grain charge and affecting dust dynamics. The distribution of charge over the surface can be modeled by dividing the surface into discrete patches.[195–197] Charge collects at the extremities of the surface and aggregate grains tends to collect more charge than a spherical grain due to their increased surface area.[196] The non-symmetric charge arrangement can be modeled in dynamics simulations as a monopole plus dipole or more accurately by treating the charge distribution as a set of point charges.[198]

B. Perspectives

To date, no single numerical scheme has been implemented that covers all relevant time and distance scales. Currently, three different regimes are treated by models: resolving electron and ion dynamics to model the gas discharge plasma on timescales up to a microsecond with picosecond resolution; resolving ion and dust motion to model the charging and ion wake on timescales up to a few seconds; and modeling the evolution of an ensemble of dust grains in the plasma on timescales of tens to hundreds of seconds. In the strongly coupled regime, long time scales are needed to capture the dynamics of collective phenomena, such as wave propagation, phase transitions, and instabilities. The loop must be closed to calculate the back reaction of the dust on the plasma. To some extent, this can be done by treating the dust as a fluid,[199] although in this case the interaction with ion wakes is not included and the information on self-assembled dust structures is lost. Until now, some kind of simplified approach has been necessary, focusing on a specific phenomenon while being approximate at other scales. Consequently, we identify here three main directions of development in the near future. These are (i) the improvement of gas discharge modeling by implementing realistic gas phase and surface processes and geometries, (ii) the realization of self-consistent multi-scale models by including feedback loops between the individual modules, and (iii) the use of modern techniques, such as machine learning (ML) algorithms and massively parallel computing architectures.

Recent modeling efforts have used a hybrid approach in which the global plasma properties are modeled using a PIC/MCC approach, and the results are used to provide boundary conditions for an MD simulation of particles within a small region of the discharge where dust resides.[72,183,200] Extending such models to the timescales necessary to resolve the dust motion remains a challenge, especially for cases where the plasma exhibits instabilities or fluctuations.

Models of low-temperature discharges can be improved by including additional chemical and physical processes. The influence of long-lived (metastable) excited states (in the case of noble gas discharges) and reactive radicals (in molecular gases) on the gas-phase ionization and electron emission at the surfaces is known to be significant, but a self-consistent implementation of the interaction between numerous excited states in discharge simulations is computationally demanding. Collisional-radiative models require the density of ground state species and electrons and the electron energy distribution function as input parameters to compute the distribution of excited states and the transition rates between them.[195,201]

Models that focus on dust and ion dynamics, treating the electrons as a Boltzmann fluid, can be adapted for discharge conditions with both hot electrons and Maxwellian cold electrons. The presence of hot electrons has a major effect on the dust charge.[202,203] However, treating electrons as a Boltzmann fluid misses the important back-reaction of the dust on the electrons. Dust clouds in Plasmakristall-4 (PK-4) facility[204] (see also Sec. IX) are dense enough that the electron density can be reduced by a factor of two.[160] This electron density reduction becomes very important in understanding the nature of instabilities in the plasma or rapidly changing plasma conditions, such as ionization waves. Dynamic charging and ion wakes are particularly important for studying the waves and instabilities present in a complex plasma.[205,206]

In laboratory discharges, there are several effects that require modification of the OML currents, such as ion–neutral collisions, ion flow, discrete charging, and irregular grains (see Sec. II). The dust charge can vary significantly depending on where the dust is located in the discharge, whether it is due to variations of the plasma in space (such as the bulk or sheath region),[207] or in time (afterglow).[208,209]

The most fundamental property governing the dynamics of dust in plasma is the dynamical screening of the negative dust grains by the positive ions in the plasma. The ion flow causes the shielding length to vary with position, and in most cases the ion wake is not well represented by a point charge. A goal of current research is to develop a simplified model of the interaction potential between dust grains that accounts for the position-dependent ion wake, which changes in both magnitude and direction as the grains interact with each other (Fig. 1). Both the dust charge and the ion flux, which together determine the wake structure, are functions of plasma parameters, such as neutral gas pressure, electron temperature, and degree of ionization. The gas pressure plays a more important role in determining the dust charge and wake characteristics than the power delivered to the discharge.[210] The shape of the grain also influences the wake characteristics.[211]

More complex models require more efficient algorithms and full utilization of computing resources. Over the past decade, the evolution of computer architectures has shifted from accelerating sequential code to implementing parallel execution capabilities. Modern CPUs provide tens of independent execution units, while graphics processors (GPUs) provide thousands of cores for general-purpose computing. Recent efforts in dusty plasma modeling have taken advantage of GPU-accelerated computing to create MD models that can be easily adapted to a range of boundary conditions and plasma states (MAD-BORIS, SARKAS, DRIAD, and OpenDust).[82,178,212,213] By covering a large parameter space, the results can be analyzed using ML techniques to develop heuristic models of the detailed microphysics that can be incorporated into the simulation of macroscopic systems.

The application of ML techniques, mostly based on neural network models, is in its infant stage in relation to gas discharge and dusty

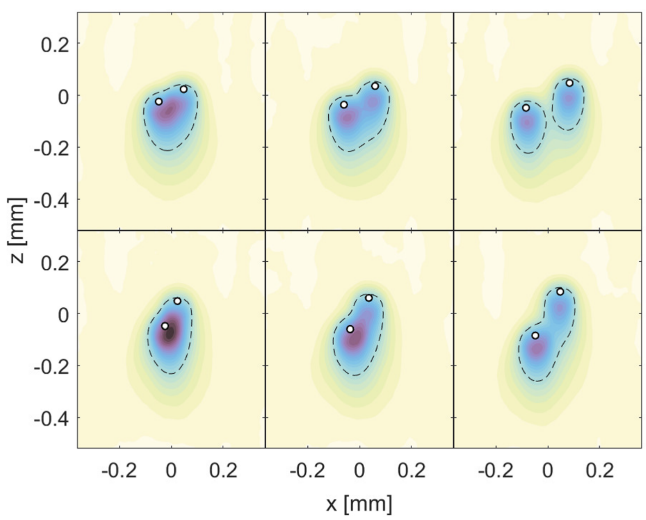


FIG. 1. Changing ion wake structure in the vicinity of two charged dust grains (white circles). Darker shades indicate higher ion density. The dashed lines mark the contours where the ion density n_i is 1.4 times greater than the background ion density n_{i0}. Figure produced using the DRIAD code.[178]

plasma modeling. Current studies include the non-linear response analysis for dust particles to determine the equation of motion and, thus, the effective grain–grain interaction,[214] and the improvement of dust particle detection in noisy environments.[215] Certainly, with the rapid advancement of this technique, it bears a great potential for the prediction of various plasma properties.

IV. DIAGNOSTICS OF DUSTY GAS DISCHARGES (J. BERNDT AND F. GREINER)

Before turning to the topic addressed in the title, it is necessary to clarify its meaning since the term "diagnostics of dusty gas discharge" may be understood in different ways.

The first meaning of diagnostics of dusty gas discharges relates to the measurement of parameters, such as, e.g., electron density or electron temperature in plasmas containing nanoparticles. In this context, the question arises to what extent the presence of nanoparticles affects the performance or interpretation of standard diagnostics, such as Langmuir probes[216,217] or laser absorption spectrometry (LAS).[218] Such methods will probably work the common way as long as the dust concentration in the plasma is low. The Havnes parameter[219] P is an appropriate order parameter for this decision. $P \leq 1$ describes a "dust in plasma" situation where the dust component has almost no global impact on the plasma, whereas $P > 1$ is a dusty plasma situation, where a strong electron depletion ($n_e < n_i$) is in effect (see Ref. 220 for details).

The second meaning of diagnostics of dusty gas discharges concerns the use or development of diagnostic methods that can be used in plasmas in general, but which are of particular interest for the understanding or the control of phenomena occurring in particle-containing plasmas. One example here is the measurement of negative ions, which are believed to play an important role in the formation of nanoparticles in discharges operated with organic monomers.[221,222] As most of the dusty plasmas which have technological relevancy are nanodusty plasmas, which contain particles from 100 nm down to a few nanometers, the particle properties (as size, refractive index, crystalinity, etc.) are *a priori* not known since the particles are produced inside of the plasma.

This leads us to the third meaning of diagnostics of dusty gas discharges. It refers to the diagnostics of the particles themselves, as the detailed knowledge of the particle size, shape, and density are the key parameters for the diagnostic of dusty plasmas. The characterization of the particles will be the focus of this paper. In this context, the term diagnostics covers a variety of different techniques and methods, each of which is used to investigate different particle properties. One further remark that should be briefly made concerns the fact that the diagnostics that will be mentioned here will mostly be *in situ* diagnostics applied to particles that are inside the plasma.

A. Current status

In principle, different particle diagnostics can be—for the sake of simplicity—divided into two main categories: indirect and direct diagnostics.

1. Indirect measurements

The indirect detection methods are based on the fact that the presence of dust particles in a plasma induces changes in the plasma characteristics. This response of the plasma to the formation of particles can be used as a simple and sensitive kind of global diagnostic that delivers information about the existence of particles in the discharge. Several effects can be used here for diagnostic purpose: the change in light emitted by the discharge, the reduction in electron density caused by the attachment of electrons to the particles, and the change in ion currents. Other examples concern the change in "electrical properties" that occur in some RF discharges, such as the DC bias voltage,[223,224] the phase angle between voltage and current, or the anharmonicity of the wave-forms of RF current and voltage.[225]

2. Direct measurements

Most of the direct measurements are based on the interaction of nanoparticles with electromagnetic radiation where the latter can range from the x-ray region to the (far) infrared. Depending on the particle properties to be investigated, there are different types of diagnostics, e.g.,

Laser scattering imaging:[226] The video analysis of dust ensembles is the working horse of dusty plasma physics with micrometer sized dust particles. The basis of this technique is a 2d laser stripe which enables the video analysis of 2d cross sections of 3D dust clouds.

- *Computed tomography:*[227,228] The 3D dust distribution of arbitrarily shaped dust clouds is determined by a combination of 2d extinction measurements and computed tomography.

Information about the particle size (and depending on the method, also about the refraction index of the particles) can be obtained by

- *Light extinction spectrometry*[229]
- *White light scattering*[230]
- *Kinetic Mie polarimetry without*[231,232] *and with imaging properties*[233]
- *Laser-induced incandescence (LII).*[234]

Information about the elemental composition of particles, respectively, their bonding situation can be acquired by

- *Laser induced particle explosive evaporation*[235]
- *Infrared absorption spectroscopy*[236–238]
- *X-ray scattering techniques.*[239]

Information about particle charge can be gained by

- *Infrared phonon resonance shift (IRPRS)*[240]
- *Laser-induced electron detachment.*[241]

Absolute densities of precursor molecules inside of the nanodusty plasma are measured with

- *Frequency modulation spectroscopy.*[242,243]

Again, this list including the cited literature is not exhaustive, and it must be emphasized that these diagnostic methods (in contrast to the aforementioned indirect techniques) were not developed specifically for the study of dusty plasmas, but are more general tools often used in fields, such as aerosol research. (In the literature cited here, we limit ourselves to cases in which these diagnostics were used in the study of dusty plasmas.) There are some important *in situ* diagnostics that are not based on the interaction of light with nanoparticles:

- *Mass spectrometry*[244]
- *Multi-mode microwave cavity resonance spectroscopy*[245]
- *Dust density wave diagnostic (DDW-D).*[220,246]

Of course, the current knowledge about the physics of dusty plasmas relies on the interplay of experimental investigation, modeling, and simulation. Simulations are challenging, however, because the dust has a highly variable charge. Even for particles with a radius of 100 nm, the charge can vary from zero to more than 1000 elementary charges at a given time within the same discharge system. Simulations and consequently the diagnostic of such plasmas[247,248] have to take into account the coupled physics of the plasma discharge, the plasma chemistry,[249] the "aerosol" physics of the charged dust, and the plasma related details of particle growth processes.[180]

B. Perspectives

The question of which diagnostics should be developed further or deserve more attention depends heavily on the intended applications or the specific research one is aiming for. In the field of complex plasma research, particles with known properties are very often injected into the discharge and it is studied, for example, how individual particles or collections of particles form certain time-dependent structures. In this area of research, there is obviously no need for diagnostics that provide information about the properties of the particles. Instead, tomographic methods are needed that provide precise, time-resolved information about the locations of a large number of individual particles.

In research areas dealing with the formation of particles, which are particularly important for applications, the situation is quite different. The diagnostic challenges are clear from Fig. 2, which provides a simple illustration of nanoparticle formation in (reactive) plasmas. The figure shows the different phases of the particle growth chain from molecular precursors to micrometer-sized particles and the transitions between the different phases. Regardless of the exact details of this process, which may vary depending on the precursors used (e.g., acetylene, methane, silane, HMDSO, and other gases or vapors), the simple schematic illustrates the need for diagnostics that can detect different types of species: from molecules to macromolecules to clusters (charged and neutral) and finally to particles at the nanometer or micrometer scale.

In addition to these requirements, the diagnostics used to monitor particle formation must be able to detect processes that can involve time scales ranging from less than a millisecond to several hours. The need for time-resolved diagnostics arises not only from the different time scales inherent in the process but also from the large technological potential of pulsed discharges,[253] which automatically involve new and often small time scales. In addition, information about the spatial distribution of particles is of great importance, especially for technical processes where, for example, the contamination of certain components must be avoided. This underscores the need to develop imaging techniques that can directly provide such detailed spatial information.

It is unlikely that any single diagnostic will be able to fulfill this task. The future task, therefore, is rather to employ several different (*in situ*) diagnostics in such a way that their combination can help to provide a more complete picture of the entire process. One of the biggest challenges (and one of the biggest needs) here is certainly the spatially and temporally resolved detection of clusters in the sub-nanometer to the nanometer range. Therefore, adapting existing techniques, such as coherent Rayleigh–Brillouin scattering,[254] to technically relevant plasma environments is a high priority for the future.

Another important parameter that has to be addressed in more detail in the future is time dependent surface temperature of growing nanoparticles (see also Sec. VII). In particular, for processes, such as, e.g., the deposition of ultra-thin films or the fabrication of nano-composite materials, it is also highly desirable to obtain information on the surfaces exposed to the species flows emerging from the plasma. Especially the contribution of large (potentially charged) macromolecules or clusters to

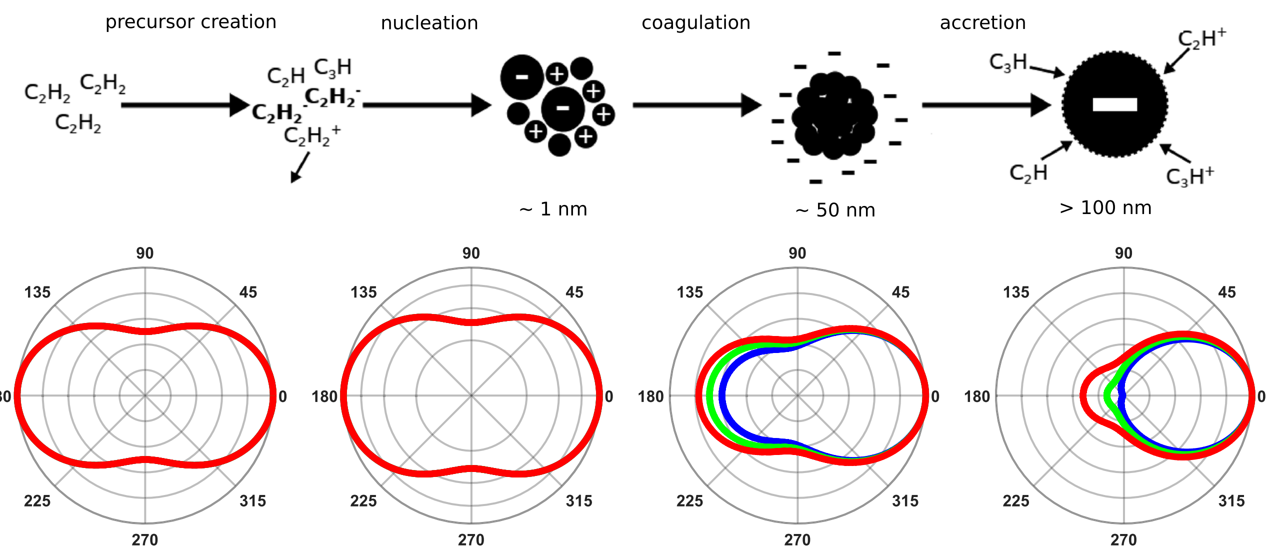


FIG. 2. Growth chain of nanoparticles in a low-pressure discharge in argon with acetylene admixture. The different phases of particle growth are strongly related to the specific conditions of the plasma and its interaction with the precursors, clusters, and nanoparticles (based on Ref. 250). The lower graph shows the angle-dependent light scattering of red, green, and blue light of a spherical particle with a refractive index of $N = 1.84 + 0.07i$ (typical refractive index of a:C–H particles) at radii of 0.17, 1, 50, and 100 nm. The intensity for each radius is normalized to its maximum intensity. The Mie-code from Bohren and Huffman[251] in Mätzlers implementation[252] was used.

the growth of such systems is of great interest in this context. Only the combination of *in situ* (surface) diagnostics such as GISAX[255] and TEM, plasma diagnostics such as mass spectrometry (that measures the flux of species), and diagnostics that provide information on the growth of clusters in the plasma volume will provide sufficient information to understand the whole process. However, the simultaneous use of different types of diagnostics is extremely time-consuming and both labor- and cost-intensive. Therefore, it is of great importance in the future to offer simpler alternatives, especially for mere users of dusty plasmas. These alternatives may not be able to draw a complete picture of the entire process but allow easy process control and optimization.

The aforementioned indirect diagnostics may offer such an alternative since they are easy to employ and relatively cheap. However, they initially provide only quite limited information about the complicated processes in dusty plasmas. The combination of sophisticated diagnostics and new modeling efforts may resolve this dilemma. Such an effort could lead to new insight that would allow a better interpretation of the signals resulting from indirect measurements. This is, in particular, important for the control of particle growth in reactive plasmas. Simultaneous time-resolved measurements of multiple quantities, such as (total) light emission or DC self-bias, could help to monitor the different phases of particle growth (see Fig. 2) with relatively simple diagnostic tools and greater accuracy. The use of diagnostics that provide (time resolved) signals with a high signal-to-noise ratio would facilitate the extraction of useful information from the acquired data.

However, the collection of large amounts of data associated with such measurements presents new challenges and opportunities. A concerted effort of experimental and theoretical investigations in combination with new techniques such as ML may help to understand, control, and especially predict the basic processes of the dust growth across all phases shown in Fig. 1. This is important for processes where the formation of particles needs to be suppressed as well as for processes where one wants to "harvest" nanoparticles or nanoclusters with a certain size.

V. VOIDS AND INSTABILITIES IN DUSTY GAS DISCHARGES (M. Y. PUSTYLNIK AND M. MIKIKIAN)

Dust immersed in gas-discharge plasmas or grown in gas-discharge plasmas modifies the plasma properties.[2] This modification is the result of four different physical mechanisms: Dust particles (i) absorb the fluxes of plasma species on their surfaces; (ii) non-negligibly contribute to the formation of electric fields; (iii) are sensitive to fluxes and temperature gradients in charged as well as neutral components of the plasma; and (iv) due to their low charge-to-mass ratio, exhibit significantly slower dynamics compared to those of other plasma components. Presence of dust, therefore, leads, in many cases, to the appearance of "new" dust-induced phenomena that do not exist in dust-free plasmas and, moreover, disturb its calmness and uniformity which is desired for technological applications and microgravity experiments. In the following, we will present the current status of understanding of these phenomena and highlight the possible future directions of their investigation and control.

A. Current status

Dust acoustic wave (DAW) or dust-density wave instability revealing itself as a compressional wave pattern propagating along the local electric field is one of the most ubiquitous instabilities in dusty plasmas. It was observed in practically all types of discharges, dc,[256,257] inductively coupled rf,[258,259] and capacitively coupled rf,[260] under laboratory[261] and microgravity[262,263] conditions, with injected microparticles[264] and grown dust.[265] Lots of works are devoted to the details of its theory.[258,260,266–274] This instability is understood as a streaming instability, caused by ions drifting through the dust suspension confined in a plasma. It was shown to cause coagulation of dust particles.[275,276] It is also used for diagnostics of electric field and dust charge in nanodusty plasmas.[246,277]

Different instabilities were observed during growth of dust particles in reactive rf discharges of different chemistry. For example, when growing dust by sputtering graphite[278,279] or plastic microspheres lying on the bottom electrode of the discharge,[280–283] the electrical and optical characteristics of the discharge started to exhibit instabilities which stopped only when dust particle size reached fractions of a micrometer. During the first dust growth in silane chemistry,[284,285] the instability was associated with the agglomeration of the very first nanoclusters. However, in the further dust growth cycles with uninterrupted silane supply,[286] the instability became continuous as in the case of sputtering experiments. Other plasma instabilities triggered by the growth of dust particles cause the appearance of numerous regions of bright plasma emission of spheroidal shape (of mm sizes) which appear in the close vicinity of the electrodes[287] and sometimes rotate[288] as in the carousel instability.[289] In fully developed instabilities, these spheroids are also present in the bulk plasma where they can merge or split.[290] The nature of these spheroids is not clear but they could be small dust-free regions where an enhanced emission takes place.

Operation of PK-4 facility on the International Space Station[204] (see also Sec. IX) revealed three specific dust-induced instabilities in the dc discharge: "dust-induced stratification,"[2,160] "transverse instability,"[291] and "partitioning of the dust suspension."[2,292] The last two instabilities observed in the polarity-switched discharge (which represents the main working regime of PK-4) significantly limited the parameter range in which calm and uniform dust suspensions could exist. No reliable explanation proven by systematic experiments exists for both instabilities.

The problem of void, usually an eye-shaped (sometimes more complicated shapes are observed[293–295]) dust-free region in the center of a discharge,[278,296,297] seemed to be closed for rf plasmas since the microgravity experiments on void closure in PK-3 Plus laboratory[298] and numerous simulations.[299–304] The void was supposed to occur due to the mechanical balance of ion drag force (due to the outward drift of ions) and electrostatic force exerted by the ambipolar electric field confining the dust in the plasma. However, comparison of experimental and simulated plasma emission patterns and dust distributions[305] as well as very recent discovery of dim and bright void regimes[306] (Fig. 3) have questioned the universality of that simple and widely accepted concept. Earlier observations of void size increase on the increase in dust particle size in reactive plasmas[307] also suggest dim-to-bright-void transition during dust growth.

Closely related to the void problem is the problem of the so-called "heartbeat" instability.[308–316] It appears in dusty rf discharges as periodic contraction of the void with (sometimes very) low frequency. A bright flash of plasma emission precedes the contraction of the void.[312] Careful investigations[313] have shown that the heartbeat instability is a mixed-mode oscillation in which rare catastrophic void

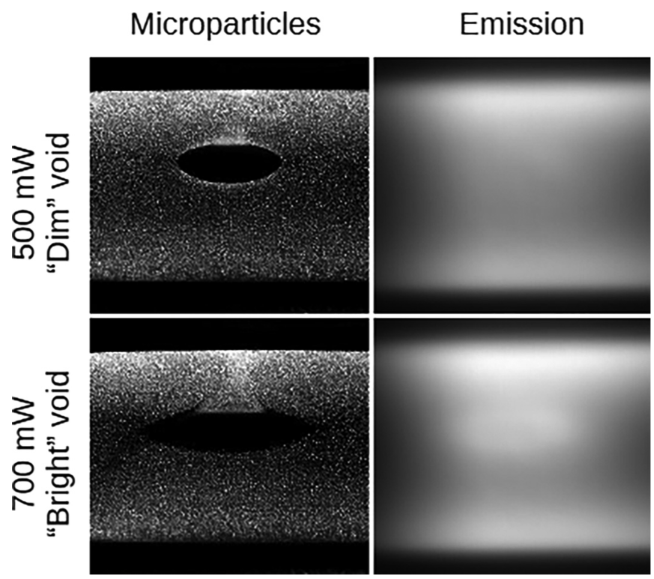


FIG. 3. Dim-to-bright void transition on the increase in the RF discharge power. Reproduced with permission from Pikalev *et al.*, Plasma Sources Sci. Technol. **30**, 035014 (2021). Copyright 2021 IOP Publishing Ltd.

contractions are mixed with small breathing oscillations of the void boundary.[316] Not only dust component, but the entire plasma exhibits this mixed-mode behavior. At a fixed amount of dust in the discharge, the instability was shown to occur in a certain range of discharge power and neutral gas pressures.[315] Discovery of dim and bright void regimes led to the hypothesis that the heartbeat instability is nothing but a self-excited oscillation between these two regimes. This hypothesis, however, still leaves many open questions on the mechanisms that could lead to such an oscillation.

B. Perspectives

Dust-induced phenomena in gas discharges are rarely so local that they can be explained by local effects of dust only.[2] Usually, the entire discharge including its optical and electrical characteristics is modified by presence of dust. Therefore, progress in understanding the dust-induced phenomena in gas discharges can only be achieved with the improvement of basic understanding of the physics of dusty gas discharges.

Generalization of scattered experimental and simulation results led to the formulation of a heuristic concept of the formation of dusty discharges which connects mechanical balance of dust particles with the ionization balance in the plasma. According to this concept, in the presence of only ion drag and electrostatic forces acting on dust particles, there are two principles according to which the dusty discharges form: (i) At relatively low discharge powers, the ion densities are so small that the mechanical balance can only be achieved if local ambipolar electric field vanishes; the ionization balance then localizes due to the absorption of plasma species on the surface of dust particles; (ii) at relatively high discharge powers, the mechanical balance of dust particles can be achieved at a finite value of the ambipolar electric field, and the ionization balance then stays non-local as in a dust-free discharge.

Systematic theoretical and simulation work is required not only to give this concept more solid grounds but rather to understand how the transition between the two formation principles occurs. Nowadays, dim and bright void regimes as well as the heartbeat instability are supposed to represent manifestations of these two principles and of a dynamic transition between them, respectively.[2,306,316] More detailed understanding of the connection between the mechanical and ionization balance in dusty plasmas could lead to further progress in understanding of other dust-induced phenomena.[317–320] In addition to this, on the experimental side, improvement of plasma diagnostics is required. In particular, optical measurements of electric fields in the range of $0.1 - 1\,\mathrm{V\ cm^{-1}}$ would make the observation of the above mentioned transition possible. Such measurements are usually performed at low neutral gas pressures (~ 0.1 Pa) using laser-induced fluorescence (LIF) technique[321,322] on ions. Extension of this technique to higher neutral gas pressures could help to improve the understanding of the connection between mechanical balance of dust particles and ionization balance.

Very recently, experiments in the PK-4 facility revealed an abnormally fast compressional wave mode in dusty plasmas.[323] This mode was treated as an ionization wave in dusty plasmas where the ionization balance is localized due to absorption of plasma species on the surfaces of dust particles.[323,324] Although, it is still unclear whether the ionization effects play a role in this particular case,[325,326] their role in the propagation of compressional waves in dusty plasmas should be clarified.

First-principles simulations of dusty gas discharges represent a difficult problem due to the enormously large difference in the charge-to-mass ratio between electrons and dust particles (see Sec. III). New approaches have to be sought to either speed-up the calculations or to simplify the models while keeping all the essential physics inside. For complicated phenomena (like, e.g., heartbeat instability), development of phenomenological mathematical models or adaptation of such models from other fields would already represent a large step forward.[313]

Real-time diagnostics capable of measuring temporal evolution of dust particle density and size at a nanometer scale[233] (see Sec. IV) have to be further developed in order to describe the coupling between dust particle properties and the plasma behavior. This improvement would lead to progress in understanding the particle-growth instabilities.

It would be also very interesting to implement the feedback control of the instabilities in dusty plasmas in analogy to what is done for, e.g., instabilities in electronegative plasmas.[327] It is a promising method for limiting the impact of instabilities on plasma processing or basic plasma experiments requiring calm conditions.

Apart from purely academic importance, the issues described above are vital for the improvement of the design of (quite expensive) microgravity complex plasma experiments as well as for the improvement of the quality of interpretation of their results. Knowledge gained about the dust-induced phenomena in gas discharges should be used to design the experimental hardware in such a way that the dust suspensions remain uniform and calm in the widest possible parameter range. This is especially important for project COMPACT[328] (Sec. IX) which is at the moment in the feasibility study phase.

VI. (COMPLEX) DUSTY PLASMAS AS MODEL SYSTEMS (R. GOPALAKRISHNAN, L. COUËDEL, AND M. BONITZ)

A. Current status

Laboratory complex plasmas containing injected well-characterized spherical micro-particles amenable for optical tracking are an ideal experimental test system to analyze correlation effects in macroscopic or mesoscopic many-particle systems.[329–331] The attractive feature of complex plasmas is the mesoscopic size of the suspended dust grains and the comparatively large inter-particle distances (of the order of $\sim 100\,\mu$m), which enables direct optical imaging of crystal or fluid-like states of grain collective behavior. In addition, the dynamical time scales associated with the dust grains, of the order of tens of milliseconds, allow the accurate resolution of the dynamics of a system of particles with the use of fairly unsophisticated high speed video cameras. Direct visual tracking is not possible in other strongly correlated systems, such as electrons in solids or nuclear matter. Complex plasmas are complementary to other experimental model systems used in soft matter physics, such as colloids and granular media.[332]

Complex plasmas are an ideal test bed for understanding strong coupling phenomena. Indeed, complex plasma experiments allow the detailed kinematic resolution of elementary collision processes at mesoscopic ($r \sim 10\,\mu$m to mm) length scales that mimic the *atomic* level of ordinary matter in a purely classical context. With nominal dust particle charge magnitudes in the range $Z_p \sim 10^2 e, \ldots, 10^4 e$, where e is the elementary charge, the Coulombic interaction between highly charged microparticles decaying as r^{-1} ensures a strong coupling (as measured by the coupling parameter $\Gamma \approx Z_p^2 e^2/(4\pi\epsilon_0 n_p^{-1/3} m_p v_p^2/2)$ at experimentally easily attainable dust grain concentrations ($n_p \sim 10^4, \ldots, 10^6\,\text{cm}^{-3}$) and nominal mean microparticle kinetic energies $(m_p v_p^2/2)/k_B \sim 10^2, \ldots, 10^3$ K. This is a major advantage compared to other strongly coupled systems, such as ion or electron one-component plasmas (OCPs), which attain strong coupling behavior only at extremely high number densities (in that case, $Z_p = 1$, and densities exceeding solid state density) or ultracold temperatures (~ 1 mK, $\ldots$, 10 K).[330] Thus, complex plasmas are ideal model systems to analyze strong coupling effects in classical OCPs. However, unlike ion/electron OCPs, microparticle motion in a strongly coupled complex plasma is under-damped due to dissipative dust–neutral collisions.[333,334] Collisions can also non-trivially modify the microparticle charge.[14,17,25,335–337] Flows of ions can also induce an ion drag force on the microparticles.[25,38,45,46,260] Finally, due to the presence of the background plasma, interactions are not purely Coulomb but, in a first approximation, follow a screened-Coulomb (Yukawa) interaction with a typical screening length given by the plasma Debye length.[338–340] Other forces can also act on the microparticles depending on specific experiments (thermophoresis, laser forces, etc.).[340] In a microparticle suspension trapped in a gas discharge, the microparticles gain kinetic energy through electrostatic interactions. This energy is dissipated by the neutral gas medium, effectively *cooling down* the microparticle suspension and allowing for strong coupling between the particles.[341,342] The gas pressure is, therefore, an important control parameter in complex plasma experiments for studying strongly coupled system behavior in under-damped regimes with particle level kinematic resolution.

A phase diagram of complex plasma states of matter in two dimensions[343] and three dimensions[344] allowed to identify the coupling regime of the different phases resolved experimentally on the single-particle level: the Coulombic gas ($\Gamma \ll 1$), liquid complex plasma ($1 < \Gamma < \Gamma_m, \Gamma_m$ is the melting/freezing point in Γ-space; Γ^{-1} being a measure of grain kinetic temperature), and solid phases ($\Gamma > \Gamma_m$). Strongly coupled systems of microparticles have allowed the study of collective phenomena, such as waves,[259,345–348] phase transitions,[342,349–351] energy transport,[349] viscous[352] and visco-elastic[353] dissipation, and crystal lattices,[347,354–357] behaving as *classical* analogues of real matter. Complex plasmas also offer the possibility of studying pseudo-attractive interaction of like-charged microparticles. When the microparticles are located in regions of ion flow in the plasma, ion wakes are formed downstream of each particle,[358–360] leading to non-reciprocal attractive forces between dust particles. In two-dimensional complex plasma crystals, these ion wakes, under specific conditions, can trigger the mode coupling instability during which energy is transferred from the ion flow to the microparticle monolayer.[181,206,361] Such systems can be used as model system to study flame propagation in 2D solids[362] and impulsive spot heating in ordinary reactive matter.[363]

Laboratory studies of complex plasmas can also be used to study the action of very strong magnetic fields on charged particles,[364–366] which is particularly important to understand the dynamics of dust particles, for example, in nuclear fusion devices[367] (Sec. VIII) and astrophysical environments[368] (Sec. XIII). A key question relevant to both, the dusty/complex plasma and the fusion plasma communities, is the effect of magnetic field on the dynamics of the plasma and the dust. However, the sensitivity of charged particles to magnetic fields is low due to the very low charge-to-mass ratio of dust particles. While electrons and ions are considered to be magnetized for relatively low magnetic fields ($\gtrsim 5$ and $\gtrsim 100$ mT, respectively), very strong magnetic fields (>1 T) are needed to magnetize the dust particles. However, at high magnetic fields, the gas discharge plasma in which the experiments are performed (typically capacitively coupled radio frequency discharges) can become inhomogeneous (due to phenomena such as filamentation[364,369]) consequently destroying the dust particle cloud homogeneity as well or even imposing circulation patterns.[370] The plasma filamentation phenomenon is generally observed at low pressures (≤ 20 Pa), such as studies of propagating waves. In addition, in most reported experiments, to date, the applied magnetic field was not large enough to magnetize the dust component but only the background ions and electrons.[366] These experiments have, nevertheless, allowed one to improve our understanding of the dust charging process,[371,372] ion wake formation,[373,374] dust density waves, etc.[375,376] However, even if experiments with real magnetic fields are limited to a few Tesla,[364–366] a quasi-magnetic field can be produced by setting a microparticle suspension in a plasma in rotation and using the formal equivalence of the Coriolis force to the Lorentz force as proposed by Kählert *et al.*[377,378] It allows one to reach effective magnetic fields of up to 3000 T for the microparticles (whereas electrons and ions are almost unaffected) and successfully demonstrated to accurately reproduce the collective modes[379] and transport properties, such as diffusion coefficient in magnetized plasmas[380] otherwise inaccessible in standard experiments using real magnetic fields.

B. Perspectives

Complex plasmas offer opportunities for foundational discoveries both at the level of a single microparticle (particle level) and at the length scale of the microparticles as a population (particle phase level).

1. Particle level transport processes

A complex plasma can be viewed as a collection of microparticles that are exchanging mass, momentum, energy, and in some cases, chemical species with the plasma that consists of ions, electrons, neutral gas molecules, photons, and electric fields. Coupled transport processes that take place on the surface of a single microparticle, such as charging, ion drag, heating, aggregation, or radiation (see Sec. II), are of interest to the fusion community in understanding plasma–wall interactions.[55] The same processes are also of interest to the materials synthesis and processing communities[381] (see Sec. VII). Especially, the contribution of dust to the overall energy balance in fusion reactors is important to understand and ensure that it does not significantly hinder energy production. For instance, a reliable technique to infer the particle's surface temperature is not available at the moment (see Sec. IV) even though many studies have discovered that the particle temperature can far exceed that of the background gas,[382] being still well below the electron temperature. On the other hand, particles can also be used as probes to understand the local plasma conditions. Their dynamics, a result of the charge and net force exerted by the local environment, can be used as a diagnostic.[186] Further work is necessary in this area to develop reliable diagnostic tools of microparticle parameters, such as surface temperature, charge, and surface reaction rates, to name a few to understand local plasma conditions. Finally, light scattering can also be used to infer local discharge properties.[383–386] Scattering by both single microparticles and their suspensions can be done by varying the wavelength of the incident light to extract structure factors that contain information about the particle's local geometry that scatters light. Finally, superconducting grains levitating in superfluid helium can be used as a sensitive probe for collective quantum effects in and out of equilibrium.[387]

2. Particle phase level behavior

The ability to resolve single particle dynamics when combined with advanced machine learning and deep learning algorithms[388] can potentially unravel the interactions between microparticles that have remained an open question for long due to difficulties in completely characterizing the gas discharge conditions using probe as well as non-invasive measurements. Specifically, the effect of ion wakes, ion flows, and the effect of externally applied magnetic fields can be holistically approached by taking advantage of the particle-level resolution offered by complex plasmas. The key challenge is that the recorded microparticle trajectories are the result of physics intrinsic to the plasma itself as well as the physics that one is trying to understand by deliberately introduced perturbations. While the kinetic resolution of particle motion is certainly exciting, it becomes expensive to obtain large system sizes (number of microparticles) that can realistically mimic the behavior of continuous media. Recent developments that use large electrodes (for instance, 85 cm diameter electrodes as part of the large diameter RF complex plasma device at DLR[389]) and the ability to engineer dust–dust and dust–ion potential interactions by adjusting the gas discharge parameters are some of the approaches taken to use complex plasmas for studying important condensed matter effects. The most challenging aspect is the isolation of specific plasma effects from the collective phenomenon being studied. Wherever that is not trivial, modeling must be used to deconvolute the two efforts to draw inferences about strong coupling phenomena.

VII. GROWTH OF FUNCTIONAL NANOPARTICLES (U. KORTSHAGEN, E. KOVAČEVIĆ, AND E. J. THIMSEN)

Chemically reactive non-thermal plasmas have a propensity to nucleate and grow nanoparticles. While this was first identified as a contamination problem in semiconductor processing by Selwyn and co-workers,[390,391] more recently non-thermal dusty plasmas have gained significant attention for the growth of functional nanoparticles.[381] For nanoparticle synthesis, several attributes uniquely differentiate dusty plasmas from other synthetic routes, such as colloidal solutions or flames.

Nanoparticle charge. As in other dusty plasma situations, nanoparticles in plasmas are generally negatively charged, even though their charge may fluctuate and particles may temporarily become neutral for very small particles with only a few nanometers in diameter.[392] Due to their unipolar negative charge, nanoparticles mutually repel each other, which strongly suppresses or eliminates particle agglomeration,[393] that is, a problem for other gas phase syntheses.

Nanoparticle heating. Nanoparticles in plasmas experience intense exothermic surface reactions, such as electron–ion recombination, reaction with chemical radicals, or recombination of hydrogen atoms and other species. These reactions can release large amounts of energy that, on a per atom basis, significantly exceed the atomic kinetic energy at the gas temperature. Accordingly, nanoparticles in plasmas can temporarily reach temperatures that exceed the gas temperature by several hundreds of Kelvin, which explains the capability of non-thermal dusty plasmas to create crystalline nanoparticles of materials with very high melting points, such as silicon,[394] titanium nitride,[395] graphite/graphene, and alumina.[396]

Size control. Non-thermal dusty plasmas offer excellent size control for the nanoparticles grown. In most cases, the nanoparticle size is linearly correlated with the residence time of particles in the plasma.

Green chemistry. Non-thermal plasmas, already considered a green technology in some countries when operated with renewable electricity, can be a fully carbon-free synthesis that does not require solvents or wet chemical processes, thus potentially reducing toxicity and waste.

A. Current status

Interest in the use of non-thermal dusty plasmas for the synthesis of functional nanocrystals initially focused on silicon for use in novel electronic and optical devices.[397,398] Effective dusty plasma synthesis techniques were developed both at low pressure[394] and atmospheric pressure.[399] In subsequent years, dusty plasma synthesis of nanoparticles was extended to a wide range of materials, including carbon based materials, metal oxides, sulfides, nitrides, and elemental metals as well as alloys. The state of the art until about 2016 has been summarized in several review papers.[381,400]

Since then, important progress has been made in multiple areas. Doping of semiconductor nanocrystals had long been a challenge.[401] Hence, the successful synthesis of doped silicon nanocrystals demonstrated this exciting capability of dusty plasmas[402,403] and opened the door to new device applications, such as thermoelectric materials. It is believed that the non-equilibrium nature of a dusty plasma may favor kinetic control of nanoparticle growth and may enable structures that deviate from thermodynamic equilibrium. For example, hyperdoping of silicon beyond the thermodynamic solid solubility limit was demonstrated with dusty plasma synthesis.[404] These hyperdoped nanocrystals exhibited exciting new properties, such as near-infrared plasmomic resonances.[405] Moreover, co-doping with both boron acceptors and phosphorous donors enabled near-infrared emission.[406]

Nanoparticles in non-equilibrium plasmas can vaporize despite the low background gas temperature. This phenomenon is the basis for a synthesis aerotaxy, in which at least one of the precursor streams is comprised of an aerosol. To date, vaporization has been observed with relatively soft elements, such as Bi,[407] Ga,[408] In,[409] Sb,[410] and Zn. Vaporization can result in interesting physical modifications of the nanoparticle population, such as size focusing.[407] Furthermore, the vapor can chemically react in the plasma to synthesize condensed phase compounds, including the III–V semiconductors GaN,[408] GaSb,[410] and InN.[409]

B. Perspectives

Particle trapping in dusty plasmas containing micrometer or sub micrometer particles has been known for a long time[390,391,411] and been associated with the periodical growth behavior observed in some dusty plasmas.[412] However, in the synthesis of sub-10 nm particles in widely used laminar flow reactors, Fig. 4(a), the possibility of particle trapping had long been ignored, because sub-10 nm particles can be neutral for a large fraction of time and the particle size was found to be linearly related to the gas residence time in the reactor, suggesting a continuous transit of particles through the reaction [Fig. 4(b)]. Only recently, researchers realized the importance of particle trapping in laminar flow reactors. Xiong *et al.*[413] demonstrated that temporary electrostatic trapping of nanoparticles during their growth, typically close to the RF electrodes, leads to size filtering that enables very monodisperse size distributions [Fig. 4(c)]: small particles are electrostatically trapped and continue to grow until they reach a threshold size at which the gas drag force will overcome the electrostatic trapping force, leading to very monodispersed particles. The improved understanding of particle trapping was exploited in the synthesis of highly monodisperse silicon optically Mie-resonant particles with diameters between 60 and 220 nm, with standard deviations of the size distribution of less than 5% of the average size.[414] A better understanding of temporary particle trapping during the synthesis of functional nanomaterials is required and will lead to increased control of the process as well as the ability to synthesize entirely new classes of materials, such as core–shell nanoparticles. To fully harness, the benefits of temporary particle trapping will require a better understanding of particle charging and its dependence on nanoparticle materials properties. Nanoparticle trapping may be further augmented by pulsed power operation. By intermittently turning off the plasma, particles may be released from the trap, only to be pulled back into it when the plasma is reignited. This may be utilized to creatively affect the size distribution of nanoparticles as they grow.[415,416] Pulsing was also successfully used to either induce or suppress dust particle formation and growth,[253,393] leading to the introduction of a critical frequency dependent on precursor presence. Control of nanoparticle growth via pulsing is still a new field with significant need to explore the relevant

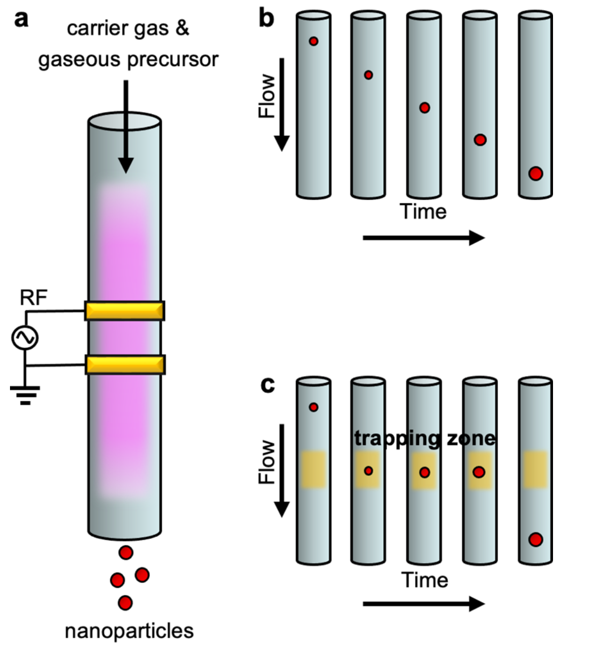


FIG. 4. Schematic of temporary particle trapping in laminar flow reactor (a). (b) Traditional view: plug flow reactor. (c) Temporary trapping until particles grow to critical size. Adapted with permission from Xiong *et al.*, J. Phys. D: Appl. Phys. **55**, 235202 (2022). Copyright 2022 IOP Publishing Ltd.

mechanisms in terms of the typical timescales for gas flow, particle charging, and trapping.

The heating of nanoparticles in plasmas remains another topic that requires further investigation. Estimates of nanoparticle temperature in non-equilibrium plasmas have been primarily made by model calculations. Some experiments have been performed wherein these calculations were related to crystallization temperatures for materials.[396,417] Unfortunately, crystallization temperatures are not well-defined quantities. Furthermore, whether nanoparticle heating can explain the observed vaporization in aerotaxy, or not, depends on the selection of a heating model and choice of the empirical accommodation coefficients. This results in significant uncertainty in the magnitude of the excess temperature, which is the main obstacle to understanding the aerotaxy mechanism. Widely applicable direct measurements of nanoparticle temperature in non-equilibrium dusty plasmas would be a significant breakthrough. Fluorescence decay thermometry may be a viable route to measure nanoparticle temperatures in dusty plasmas. Recently, there has been great success using fluorescence decay thermometry to characterize background gas temperatures in non-equilibrium plasmas.[418–420] The probe, which was inserted into the plasma, consisted of a photoluminescent crystal that has a temperature-dependent emission lifetime. The photoluminescence lifetime is on the millisecond timescale, which allows for relatively straightforward measurements. For example, Cr^{3+}-doped Al_2O_3 (ruby) exhibits a sharp emission line at 695 nm that has a temperature-dependent lifetime in the range of 0.01–10 ms for the temperature range of 900–300 K.[421,422] In the future, this technique could be translated to nanocrystals comprised of Cr^{3+}-doped Al_2O_3 (i.e., nanorubies) that would be aerosolized and introduced to the plasma, wherein their

PL lifetime could be measured and related to the particle temperature in the plasma. Compared to the early work,[423] this technique could be adapted to flow-through reactors, much higher particle temperatures, and sub-10 nm particles.

Carbon materials, including carbon nanotubes, graphene, nanodiamonds, carbon-based quantum dots, and even the polymer nanoparticles, are a continued area of interest. Dusty plasmas can obviate the need of catalysts that exists for other synthesis methods. One interesting example is the non-catalytic growth of graphene nanoflakes by Tatarova *et al.*[424] Especially in biomedical applications, such as theranostics,[425] it is crucial to endow the surfaces of these materials (such as nanoparticles or flakes) with specific chemical functionalities. The negative charging of nanoparticles in plasmas causes these units not coagulate into larger units. Combining plasma synthesis with subsequent plasma-assisted functionalization could provide a path toward large-scale production of nanomaterials with tailored surface functions. Aside from one step functionalization based on comixing of precursors with gases, such as NH_3 or N_2,[425,426] possible ways include the introduction of functional groups by evaporation of liquid precursors. Liquid precursor introduction also enables the production and surface functionalization of plasma polymer nanoparticles, such as polyaniline[427] as a conductive polymer, important, for example, as absorber for microwaves or for molecular electronics. Other intriguing areas include dusty plasmas that contain or generate carbon or oxides as well as multimaterial particles, such as Janus particles, metal-organic frameworks (MOFs), MoS_2/carbon, and similar materials, which are crucial for applications in renewable energy, including batteries, fuel cells, hydrogen production, and storage. Additionally, nanoparticle deposition onto surfaces may contribute to the development of biomimetic surfaces, improved adhesion, electronic materials, and quantum dots for diagnostics tools. For example, Marvi *et al.*[428] used photoluminescent semiconductor quantum dots as a plasma–surface diagnostic for nanoparticle charging. Carbon nanoparticles also play a significant role in astrophysics where laboratory dusty plasmas may serve to produce "astroanalogs." Laboratory-produced materials, such as hydrocarbons, ice particles, and non-spherical dust particles, provide a testing ground for simulating astrophysical processes. They may be utilized to study particle cooling and heating, the role of dust particle surfaces as sites for the formation of new molecules, unidentified optical and radio frequency emission, and absorption lines, the birth and destruction of dust on planetesimals.[429,430]

VIII. DUST IN FUSION DEVICES (S. RATYNSKAIA AND S. I KRASHENINNIKOV)

Dust in fusion devices concerns both *in situ* produced particulates as well as deliberately injected populations. The former is unavoidable and constitutes a safety problem for future reactors with possible consequences for diagnostic equipment and even plasma operation. Due to this fact, studies of *in situ* produced dust are guided by safety and operational needs. On the other hand, investigations of the interaction of injected populations with fusion plasmas are motivated by the possibility to control plasma confinement and stability. Dust–plasma and dust–vessel interactions in fusion machines are governed not only by plasma physics but also by various aspects of surface physics, atomic physics, contact mechanics, impact mechanics, electrochemistry and computational fluid dynamics. In the following, we discuss issues of intrinsic dust in fusion reactors as well as novel applications of powder injection.

A. Current status

Due to the problem of fuel retention in plasma-facing components (PFCs), the decision was taken to move away from graphite-based to full-metal machines.[431,432] The main in-vessel materials of interest are tungsten and beryllium, as expected in ITER.[433–435] The vessel composition is naturally reflected in the composition of collected dust.[436–446] Experimental evidence in tokamaks typically stem from dust collection activities and *in situ* camera observations, though innovative diagnostics have been proposed.[54,367,447–451] To mimic the edge plasmas of future reactors but with better diagnostic access, linear plasma devices, capable of producing relevant heat fluxes, are utilized that provide detailed measurements not viable in tokamaks.[111,452–457]

Reactors must comply with safety limits that are imposed on the in-vessel dust inventory.[458,459] The processes involved in the dust inventory evolution concern dust formation and remobilization, dust–plasma interactions, and dust–vessel mechanical collisions, as outlined in Fig. 5. The physical processes of dust impacts, dust remobilization, and dust adhesion have been successfully described within the framework of impact mechanics,[111,460–462] the framework of contact mechanics,[115,463] and the Lifshitz theory of van der Waals forces,[120,121,464] respectively. The effects of nanometer scale surface roughness, diffusion bonding after prolonged thermal treatments, and plasma exposure on dust adhesion have been experimentally studied.[119,465–468]

Deposit delamination, PFC cracking, unipolar arcs, and unstable molten pools in the course of high energy transients constitute the primary mechanisms of dust production in contemporary and future full metal tokamaks.[55,469] Deposit flaking and PFC cracking are well-documented mechanisms of solid irregular dust production,[470–472] which strongly depend on the local plasma loading pre-history. Unipolar arcing can be accompanied by the formation of micrometer-sized droplets released with speeds of several tens of m/s.[446,473–476]

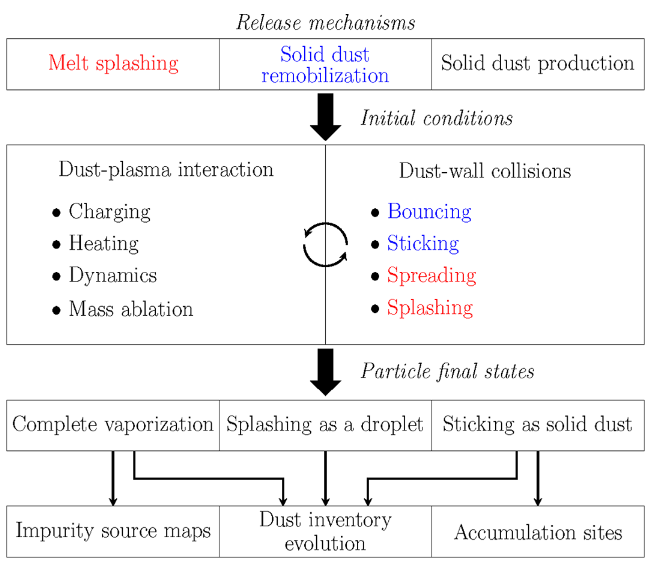


FIG. 5. The processes involved in dust inventory evolution, in-vessel accumulation sites, and impurity production in fusion devices. Fluid dynamics and contact mechanics problems are highlighted in red and blue, respectively. Reproduced with permission from Ratynskaia, Vignitchouk, and Tolias, Plasma Phys. Controlled Fusion **64**, 044004 (2022). Copyright 2022 Authors, licensed under a Creative Commons Attribution (CC BY) license.

Modeling has focused on cathode spots, where axisymmetric plasma heat fluxes and pressure gradients lead to local melting, push the melt outwards forming a crater, and produce metallic jets that breakup into droplets.[477–479] The possible (shear, buoyancy, and geometry-driven) instabilities of melt layers, which are formed during off-normal events and can lead to droplet ejection, have been discussed from a theoretical perspective.[55,469] Fully self-consistent calculations are computationally costly due to the scale separation between the melt extent and most unstable wavelengths. An efficient modeling strategy combines macroscopic melt simulations that estimate large-scale motion[480–483] with local simulations that focus on free surface dynamics.[484] Ejected droplets constitute a source of large, $> 10 - 100\,\mu$m, spherical dust.[55,469,484]

The distinct feature of dust–fusion plasma interactions lies in the importance of incident heat fluxes that are responsible for dust mass loss and strong thermionic emission in the case of tungsten. The surrounding clouds of vaporized material as well as the complex dust shape and composition can alter plasma–grain interaction and hence dust dynamics.[367,485,486] Several dust codes have been developed[128,487–492] to describe dust transport and survival in hot and dense fusion plasmas. Due to the low dust densities, they simulate isolated dust injected into a prescribed plasma background with given initial conditions. The coupled set of equations for the evolution of linear velocity, angular velocity, mass, enthalpy, and electric potential is solved, with the principal differences between codes lying in the physical models of the source terms (forces, heat fluxes, and collected currents).[469] Rotational dynamics can also affect dust and droplet lifetime.[55,149,367,469,493,494]

B. Perspectives

Splashing of unstable molten metallic pools formed on PFCs is a major component of the dust inventory, especially in terms of the mass given the large droplet radii.[469] Such pools are formed when PFCs receive high plasma heat fluxes in the course of edge-localized modes, vertical displacements events, and major disruptions. With ion and electron energies in the kiloelectronvolt range, melting is caused by surface heating and extended thin melt layers are formed, whose physics have been well understood and whose efficient modeling no longer poses a problem.[480,482,484,495] However, there is the possibility of electrons with relativistic energies, which concerns runaway electrons (RE) formed in major disruptions. REs lead to volumetric heating and their energy deposition is characterized by non-monotonic profiles that can induce explosive material detachment.[496–498] Today, no computational tools are available for the reliable modeling of the complex process of RE-PFC interaction that is associated with compressive flows and thermal shocks. Nevertheless, simulations of solid–fluid and solid–solid interactions are necessary for the prediction of the solid ejecta sizes and speeds. It is worth noting that the solid dust kinetic energy lies in the range capable of causing further wall damage upon subsequent impacts.[496] Thus, in addition to the main wall damage by RE beams, there is secondary non-localized damage spread over the vessel.

An unexplored route of metallic dust formation concerns the *in situ* growth of nanodust during the extended pulses of DEMO type fusion reactors. Divertor operation in the semi-detached or detached regime with the use of high-Z seeding will provide more uniform plasma loading on the PFCs without compromising confinement but will also generate divertor conditions that favor dust survivability, wall sputtering, and atomic clustering. The use of heterogeneous nucleation theory,[499] together with aerosol dynamics models,[500–502] is envisaged for the investigation of the growth of the nanoscale particles. In these scenarios, one has to rely solely on modeling, since conventional tokamak dust diagnostics cannot detect such small sizes.

Dust transport and dust survivability models, which lie at the core of predictive inventory studies, must be able to account for the strong background magnetic field and various plasma–surface interaction processes.[55,469,487,493] A peculiarity of fusion plasmas is vapor shielding; the heat flux attenuation due to the interaction of the cloud of vaporized dust material, which surrounds the grain, with the background plasma. The plume of ionized ablated material expands mainly along the magnetic field lines. The situation becomes even more complex for the case of the powder injection (see below), where plumes from different grains can overlap causing strong modification of local plasma parameters. The question of whether vapor shield can cancel out the effect of irregular dust shapes on dynamics[54,144] has not been addressed yet. Available theoretical models are still rather qualitative[485,486] and poorly benchmarked against experimental data.

Moreover, considering the large dust sizes and moderate initial speeds, metallic dust motion (especially for tungsten) is characterized by a strong inertial component, which makes accurate initial conditions of crucial importance for reliable predictions. In this aspect, benchmarking of modeling results against available (though often limited) data from present tokamaks and fusion-relevant devices is the most effective and promising route to constrain the expected dust sizes and release velocities. Since (re-occurring) remobilization of survived dust is an essential component of dust inventory evolution,[116] the plasma-induced remobilization velocities also constitute crucial input for modeling. Despite multiple controlled remobilization experiments,[112,115,463,503–506] nearly no empirical input is available concerning the release speeds due to technical limitations.[115,463]

Limited attention has been paid to ferromagnetic and strongly paramagnetic dust that can be lifted by the magnetic moment force and interfere with plasma startup.[51,507] This was first observed in DIII-D[508] and confirmed in recent studies.[153,509,510] A magnetic dust population can be formed due to the change in iron crystalline phase from austenitic to ferritic during re-solidification of stainless steel droplets.[509,510] We note that stainless steel use is anticipated in ITER[433] and DEMO[511] with significant stainless steel dust production expected in ITER.

Another distinct feature of tokamak dust concerns fuel retention.[512] Oxidized tritiated tungsten dust may behave like dielectrics and sustain charge due to β-decay.[444,513–516] The impact of tritiated dust on tokamak safety is a topic of on-going research.[514] Detailed simulations of electrostatic self-charging have been initiated only recently.[515]

Let us also mention possible advances in the science of powder injection for fusion applications. The wall is often covered with a thin layer of a low-Z material—the so-called wall "conditioning," to prevent the penetration of high-Z impurities into the core plasma and to reduce plasma recycling. In recent years, powder droppers have been used on virtually all major devices for *in situ* wall conditioning.[517–526]

Being injected into hot fusion plasmas, powder particles (B, BN, and Li) ablate and the material is deposited on the wall. An unexpected consequence of powder injection has been reported; it appears that in many cases it eliminates violent bursts of unstable plasma, which are responsible for the strong erosion of divertor targets. The physics behind this effect is not clear yet. It is plausible that the 3D nature of powder injection leads to the modification of plasma equilibrium conditions and exhibits the stabilizing effect. Further understanding would require coupling of 3D plasma turbulence codes with dust dynamics codes to enable simultaneous modeling of powder particles transport and ablation and, thus, spatiotemporal evolution of the source of neutrals. Finally, the injection of powder could promote the plasma detachment regime, which is characterized by a very low power loading on divertor targets and, thus, of a primary interest for future reactors.[527] However, this idea is still waiting for its thorough investigation.

IX. MICROGRAVITY COMPLEX PLASMA RESEARCH (H. M. THOMAS, U. KONOPKA, AND C. A. KNAPEK)

In dusty plasmas, the solid particle sizes can cover a range from nanometers to centimeters. Starting with diameters larger than about 1 μm, the particles become individually observable using basic illumination techniques. Then, the particle positions and velocities and, thus, their full dynamics can be deduced from optical imaging. Studies of dusty plasmas utilizing this technique represent the basis of experimental complex plasma research. While these particle systems are optically resolvable down to their individual particle dynamics, they are also subject to particle weight effects. With increasing particle size, the gravity induced acceleration becomes more and more important. Sedimentation effects start altering or even dominating studied phenomena especially for microparticle systems embedded in a low-pressure plasma environment. The latter is the reason why microgravity research is a complementary and mandatory pillar in the research on complex plasmas allowing one to access unique conditions to investigate large three-dimensional, homogeneous systems in the absence of weight-induced effects. Microgravity experiments have been successfully performed utilizing parabolic flights,[528–539] sounding rockets,[297] and three sequentially established and operated facilities aboard the International Space Station (ISS). The ISS based complex plasma experiment facility series consists until now of PKE-Nefedov, PK-3 Plus, and PK-4.[204,540,541] These experimental setups have dominated the study of complex plasmas under low-gravity conditions without any major gap since the year 2001.

A. Current status

The research under weightlessness (microgravity) conditions has proven to be of major importance for the utilization of complex plasmas as a classical condensed matter model system (see Sec. VI). Microgravity has shown to be even mandatory to utilize the complete plasma bulk volume for particle confinement and, as a result, to create complex plasma system of statistically relevant size, in contrast to ground-based experiments. Phenomena that have been studied cover crystallization and melting processes, wave and shock wave propagation, lane formation, transition from laminar to turbulent flow, and driven shear flows. In most cases, the particle behavior could be resolved down to the dynamics of individual particles. The research also included studies of particle decharging in the plasma afterglow as well as particle sputtering and growth through polymerization from the gas phase. Even experiments in a plasma free background have been performed, investigating effects, such as fast agglomeration due to oppositely charged particles, an interdisciplinary study that has the potential to trigger alterations of planet formation models.[542–554]

Recent results were achieved by using the facility PK-4 in the Columbus Module on the ISS for long-term and parabolic flights where short-term investigations were sufficient. One of the highlights from the parabolic flights concern the investigation of the demixing of binary complex plasmas (containing two different particle sizes) where it was found that the demixing process is mainly driven by the plasma forces on the different sized particles in contrast to first theoretical considerations where a spinodal decomposition was considered as a dominant process.[555–557]

Conversely, PK-4 on the ISS allowed the detailed long-term investigation of the formation of strings in electrorheological plasmas formed in AC electric fields and could resolve their 3D structure and formation process and their influence on wave propagation.[72,558–560] The strings are forming due to the interaction of the negative charged particles with positive ion wake regions. The latter are formed downstream of the microparticles due to the flow of ions in the AC electric field and their interaction with the negative charged microparticle, which act like an attractor/collimator for the ions. The question whether the arising attraction in the microparticle–plasma system is of short-range or long-range order could be resolved as short-range by careful comparison of experimental results and molecular dynamics simulations.[561]

The research under reduced gravity is not only important for investigations on complex plasmas as a model system for classical condensed matter formed in the bulk of a plasma device but also for solving fundamental questions regarding the charging and screening of individual particles or the interaction with ions leading to ion drag and ion wakes. It helps also to observe strong coupling effects producing waves and shock waves in the dust component[263,561–564] and the influence of the dust component on the background plasma in general. This all is important in understanding natural dusty plasmas and dusty plasmas in plasma processing (see Fig. 6).

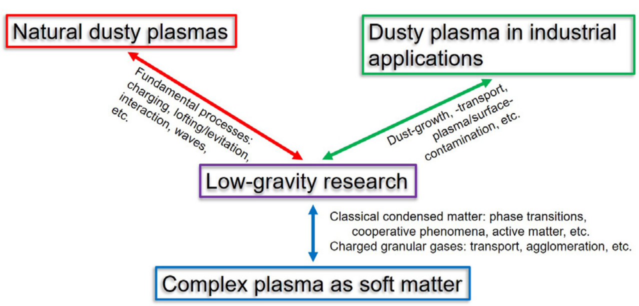


FIG. 6. Low-gravity complex (dusty) plasma research in the context of soft matter research, natural dusty plasmas, and dust in industrial plasma applications.

B. Perspectives

Complex plasmas are useful tools to test models of statistical physics, plasma physics, and soft-condensed matter through the study and reconstruction of the full distribution function. Since the latter is experimentally accessible, the simultaneous investigation of single-particle and collective scales is possible. This kind of potential studies is unique, especially since complex plasma allow one to obtain this insight over a wide range of system dynamics from over-damped to quasi-undamped system as well as over a wide coupling range, from loosely coupled (gaseous) to strongly coupled (crystalline) phases. As such especially the microgravity complex plasma research that opens the possibility to study full 3D systems has a wide potential in the coming research endeavor. The perspectives of low-gravity research in complex and dusty plasmas have been published recently in a white paper.[565] They can be differentiated between the research as a model system of classical condensed matter physics (complex plasma) and natural dusty plasmas.

Examples of open research questions are the experimental determination of the equation of state that describes the state of matter via the relation of thermodynamical quantities,[566,567] the investigation of transport properties, such as viscosity,[568] heat conductivity,[349] or diffusion,[569] and anisotropic and non-reciprocal interactions that emerge in the presence of inhomogeneities in the system.[570]

Additionally, the measurement of crystal dynamics on the atomic scale during phase transitions in solids can give new insight on the temporal development of crystal structures and the structural complexity on the surface.[571] This knowledge is relevant for applications, such as materials design, through the influence of the structure on general properties of the macroscopic materials.

The supercooled state and the system behavior close to or even beyond the glass transition point are another topic of future research and can be studied by quenching the liquid system below the melting point, yielding new insight into the microscopic foundation of supercooled liquids[572,573] and the elementary mechanisms which determine the stability of supercooled fluids against crystallization.

The investigation of fluid dynamics at the discrete level, especially of non-linear phenomena, such as non-linear waves[545,574–576] and turbulence,[577] can yield valuable insights into the underlying microscopic processes and their connection to large-scale hydrodynamic motion, e.g., how microscopic interactions lead to the development of large-scale non-linear (turbulent) motion.

Active matter consists of particles that take energy from their surroundings and convert it into non-thermal motion. The emerging motion is usually far from equilibrium and exhibits phenomena, such as swarming, aligning, clustering, self-crowding (jamming), active microrheology, active turbulence, active baths, and many more. These can be studied in complex plasmas by inserting active particles, e.g., Janus particles[351,578] or anisotropic particles[579] into the discharge. Introducing active particles into the plasma opens up a new research direction covering many aspects of active matter, such as the structure and ordering in an active particle system, or how the collective behavior of self-propelled particles connects to the energy input on the single-particle level.

Natural dusty plasmas are numerous in astrophysical environments, such as the Moon, asteroids, planetary rings, cometary tails, interplanetary and interstellar clouds, and Earth's mesosphere[117,197,580–583] (see Sec. XIII). Many of those are low-gravity environments. Especially on planetary bodies close to Earth, dust and dusty plasma pose challenges for human exploration by its hazardous effect on technical equipment or humans. A better understanding of the physical processes of dust formation, charging, lofting, or levitation, their movement and dynamics will not only give insight into the fundamental physics but can help to improve methods of dust mitigation that will be essential for future exploration missions, especially for the Artemis program to the moon.[110,584]

Finally, utilizing dust particles as probes in the bulk plasma, the investigation of the trajectories can yield information on the plasma itself.[186,585,586]

Future research activities can be realized with the multi-user, multi-purpose facility COMPACT[587] planned for the ISS as a follow-up lab to PK-4, by parabolic flights performed, e.g., with lunar-g characteristics ($1/6\,g$)[588] or directly by dusty plasma experiments *in situ* on the Moon.[110] To complement the research under low-gravity, it is mandatory to perform advanced theoretical modeling and numerical simulations—from molecular dynamics to particle-in-cell methods—in parallel to dedicated experiments under gravity conditions using plasma and particle diagnostics not available, e.g., in COMPACT due to their size/mass and complexity.

X. TWO-DIMENSIONAL COMPLEX PLASMAS (V. NOSENKO AND Y. FENG)

Two-dimensional (2D) complex plasmas are single-layer suspensions of micrometer-size solid particles in the plasma sheath of a gas discharge, see Fig. 7. They have a special place in the field of complex plasmas. For one thing, the discovery of 2D plasma crystals[589–592] in 1994 gave a major boost to the whole field. For another, 2D complex

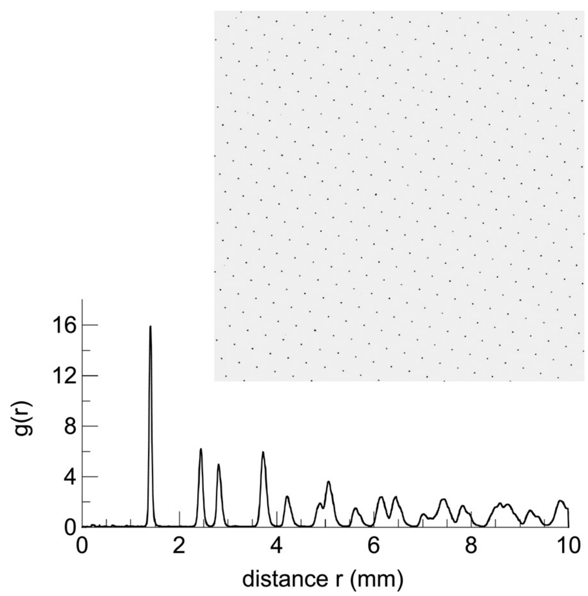


FIG. 7. (Upper panel) Snapshot of a 2D complex plasma crystal showing about 400 particles and (lower panel) the corresponding pair correlation function $g(r)$ for particles. The image is inverted and its brightness is adjusted for better viewing. Reproduced with permission from Nosenko *et al.*, "New radio frequency setup for studying large 2D complex plasma crystals," AIP Adv. **8**, 125303 (2018). Copyright 2018 AIP Publishing.

plasmas possess a number of unique features which make them attractive objects to study in laboratory experiments and computer simulations. First, they are relatively easy to prepare and observe, 100% of their constituent particles can normally be imaged by video cameras throughout the experiment. Second, in-plane interparticle interaction potential is approximated well by the (purely repulsive) Yukawa potential,[20] which means simpler analysis, general interest, and the relevance to generic 2D phenomena (phase transitions, transport phenomena, waves, etc.). Third, unlike in 3D suspensions of particles in bulk plasmas, in 2D systems the particles levitate in the plasma sheath where the electric field is strong, therefore, the system description can be based on the linearization around finite values, not zero as in bulk plasmas. This makes 2D complex plasmas well-defined systems open to analysis and computer simulations.

A. Current status

In our opinion, the most interesting and significant recent advances in 2D complex plasma research took place in the following areas.

1. 2D complex plasmas as model systems for plasma-specific and generic 2D phenomena

- Thermodynamics and statistical mechanics. Entropy was measured in 2D complex plasmas.[567] In 2D complex plasma experiments with shear flows, the fluctuation theorem was obeyed,[593,594] leading to the temporal convergence of the fluctuation theorem,[593] which was then attributed to the viscoelasticity of complex plasma.[594]
- Equation of state (EOS) and phase transitions. Using computer simulations, the EOS for 2D complex plasma liquids was obtained,[595–598] from which their various physical properties were analytically derived.[599–601] Shear[602,603] and bulk moduli[604] of 2D complex plasma solids were also obtained from simulations. For both 2D and 3D complex plasmas, it was found that the supercritical transition between the liquid-like to gas-like phases always occurs at 20 times of the corresponding melting point from various Frenkel lines,[605] just corresponding to the transition between strong and weak couplings of complex plasmas. Slow dynamics of the glassy state was discovered in a 2D complex plasma experiment[606] and the corresponding simulation.[607]
- Transport mechanisms. Ratchet rectification and its reversal were experimentally demonstrated by adjusting plasma conditions using naturally persistent flows of one particle chain inside asymmetric sawteeth of gears on the electrode.[608] Shear viscosity was determined from the fluctuations of shear stress in shear flows.[609] A Stokes layer was experimentally observed by applying a sinusoidal shear using the laser manipulation method,[610] then the frequency-dependent complex viscosity was also obtained in this system.[611] From various scaling laws of viscosity and the time of the atomic topological structure change, the origin of viscosity at individual particle level was discovered.[612]
- Dislocation dynamics. From dislocation dynamics in 2D complex plasma experiments with shear flows, the Orowan equation introduced in 1940s was first demonstrated to accurately determine the plastic strain rate.[613] Shear softening and hardening effects of 2D dusty plasma solids in different orientations were also discovered.[614]
- Compressional shock and soliton dynamics. Thermodynamic properties after the shock propagation were analytically derived.[615–617] Shock induced melting[618,619] and elastic-to-plastic transition[620] were both systematically investigated. Fast particles overtaking the shock front[621] and the dispersive shock wave around the shock front[622] were both investigated systematically. It was found that rarefaction waves are generated simultaneously when the compression is suddenly stopped.[623] Compressional shocks were also performed in 2D complex plasma experiments with a well-controlled exciter to determine the resulting shock speed and width,[576,624,625] so that quantitative comparisons with simulations were made. The propagation of a dissipative soliton was experimentally studied in a 2D binary complex plasma in amorphous and crystalline states.[626]
- Substrate dynamics. A substrate, or a force field with potential wells, was introduced into 2D complex plasma simulations to generate new dynamics, which can be experimentally realized using a stripped electrode, or interference of powerful laser beams. Under the modulation of 1D periodic substrates, the new phonon spectra,[627] the sub-diffusion, and the reentrant melting transition,[628] as well as the oscillation-like diffusion,[629] were all discovered. During the depinning procedure, three dynamical phases of pinned, disordered plastic flow, and moving ordered states[630,631] were found. Asymmetric 1D periodic substrates induced bidirectional flows with unbiased external excitations were also found.[632] It was also found that, under 2D periodic substrates, the resulting phonon spectra[633] exhibit more complicated coupling. In the depinning procedure of the system modulated by 2D periodic substrates, the direction locking effect,[634] the dynamical commensuration effect,[635] and the superlubric-pinned transition[636] were all discovered.
- Plasma-specific phenomena. Plasma wakes downstream of the ion flow past negatively charged particles modify the interparticle interactions making them non-reciprocal (in quasi-2D complex plasmas). This leads to rich dynamics, including the mode-coupling instability,[206,363,637] coupling of non-crossing wave modes,[638] and thermoacoustic instability.[639]

2. Extending the scope of 2D complex plasmas

- The most common structure of a crystallized 2D complex plasma is a triangular lattice with hexagonal symmetry. Recently, the square lattice was experimentally observed under appropriate conditions in (1) binary quasi-2D complex plasma[640] and (2) monodisperse quasi-2D complex plasma.[641]
- Apart from traditional particle tracking velocimetry (PTV) and particle image velocimetry (PIV) image analysis methods, new methods based on machine learning are emerging. A supervised machine learning method was used to study a phase transition in a 2D complex plasma.[388]
- Larger 2D complex plasmas, up to 27 cm in diameter (previously 5–6 cm) consisting of up to 34 000 particles (previously 5000–15 000 particles), were recently observed.[389,638]
- The scope of complex plasmas as model systems was recently extended to include active matter systems. Active matter is a collection of active particles, each of which can extract energy from their environment and convert it into directed motion, thereby driving the whole system far from equilibrium. Single active

Janus particles as well as 2D complex plasmas with their inclusion were recently studied.[578,642,643]

B. Perspectives

In our opinion, 2D complex plasmas will continue to be in the focus of intense research. The following topics will likely receive increased attention.

- Due to their unique characteristics as model systems, 2D complex plasmas will be used to study plasma-specific and generic 2D phenomena. This will be facilitated by recent and expected hardware developments, such as the emergence of new-generation plasma chambers,[328] higher-resolution and faster video cameras, 3D imaging techniques using stereoscopy and plenoptic cameras. Therefore, more sophisticated experiments and more accurate data are expected leading to the possibility of studying more subtle effects in thermodynamics, non-equilibrium statistical mechanics, physics of transport phenomena, glassy state, phase transitions, and dislocation dynamics.
- Some plasma wake-mediated effects predicted theoretically still await experimental verification, for example, emerging activity in bilayered dispersions of particles.[644] The relationship between the discharge parameters and ion wake characteristics is not well understood. A molecular dynamics simulation of ion dynamics and particle charging was performed to self-consistently determine the particle charge and ion wake characteristics for different synthetic experimental conditions.[210] Direct experimental measurement of the plasma wakes, e.g., using laser-induced fluorescence would be a much-welcome breakthrough.
- System-size dependence of complex plasma properties is a long-standing problem. In particular, the dependence of transport coefficients on the system size is of interest. In fact, the very existence of valid transport coefficients in 2D systems is debated.[645] Therefore, experiments with larger 2D systems will be necessary to address these questions.
- Following the recent experimental discovery of square lattice,[640,641] other more complicated structures predicted theoretically[77] are expected to be observed in dedicated experiments.
- Ensembles of active Janus particles suspended in a plasma are promising model systems to study active Brownian (Langevin) motion, where the particle damping and propulsion can be tuned.[578,642,643] Since Janus particles can be considered an extreme case of particles with inhomogeneities, they can be used as a study model for the so-called "abnormal" particles with irregular trajectories,[646] possibly helping to develop a method of controlling them in experiments with complex plasmas.

XI. ATMOSPHERIC PRESSURE PLASMAS WITH AEROSOLS (P. J. BRUGGEMAN, D. MARIOTTI, AND R. M. SANKARAN)

Aerosols are introduced or produced, intentionally or unintentionally, in non-thermal atmospheric-pressure plasmas (APPs) for both fundamental research and current or emerging technologies.[647–651] Understanding the interactions between particles and plasmas is critically important to engineer nanoparticles[648,652] and thin films with specific properties[649,652,653] and is also more broadly relevant to atmospheric science and water treatment, as well as catalysis, environmental science, medical applications, and other fields.[654,655]

A. Current status

Compared with more traditional low-pressure dusty plasmas, APPs containing aerosols offer the possibility of working with a much wider range of materials, from liquids to high melting point compounds. Aerosol particles in APPs can be maintained at room temperature (e.g., with minimal evaporation for liquids)[656,657] or heated to melting temperatures for solid particles.[658,659] Particle charging is a common feature for both low-pressure as well as APPs, however, due to a collisional sheath (for both electrons and ions) particle charging can be different compared to low pressure dusty plasmas. For droplets, charge could for example, penetrate into the droplet and the large dielectric constant of water can lead to asymmetric charging and sheaths around droplets.[660,661] A key advantage of plasma processes, both at low-pressure and at atmospheric pressure, is the possibility of controlling the separation between the background gas temperature and the energy of electrons, a condition that creates novel pathways for particle growth and interfacial chemistry. However, because of the atmospheric pressure operation, these characteristics allow for APPs to be compared more directly with colloidal or aerosol routes, also operated at atmospheric pressure, but where such pathways driven by energetic electrons are inaccessible. These characteristics place APPs containing aerosols in a related, but separate research space from that of both low-pressure dusty plasmas and colloidal chemistry.

Research progress on APPs containing aerosols has been characterized by many reactor configurations and in particular, microplasmas[648,662] or small-scale plasma reactors (compared to larger traditional low-pressure plasmas).[663] Furthermore, at atmospheric pressure, drag forces are large and particles are more readily carried by the gas flow; hence, APPs are often operated in a flow-through mode (e.g., plasma jets or flow-through reactors[664–666]) as depicted in Fig. 8. In these cases, particles evolve as they travel through the plasma where phenomena, such as nucleation, growth, chemical/phase transformation, evaporation, coagulation, condensation, fragmentation, deposition, and charging, can take place.[667] When particles reach the edge of the plasma, they enter downstream the so-called spatial afterglow, through a space charge region with large electron, gas temperature, and species densities gradients.[648,668] The spatial afterglow likely transforms particle properties and can have both beneficial and detrimental impact depending on the targeted application.[666,668,669]

Solid particles within APPs have been widely investigated in the context of nanoparticle synthesis[648,670] (see also Sec. VII). In these cases, atomic or molecular precursors are injected in flowing plasmas, where conditions for particle formation are deliberately created. Hence, the plasma evolves spatially, to include initially the formation of clusters, and subsequently the growth of larger particles. The transit of such particles through the afterglow, downstream of the plasma, is an important stage of the synthesis as it impacts the phase, surface states, and charge on the particles.[668] These approaches have been used not only to collect nanoparticles but also to deposit films on substrates;[649,652,653] however, the literature rarely assesses or even makes the distinction if particles form within the plasma prior to deposition or if the role of the plasma is purely to activate precursors. While material synthesis has shown a high degree of success, fundamental understanding of the processes is lacking with few exceptions.[654,659,660,668,671–673] Other work with solid particles can have applications for material recycling, repurposing, or waste remediation. APPs interacting with liquid droplets leverage the ability to generate

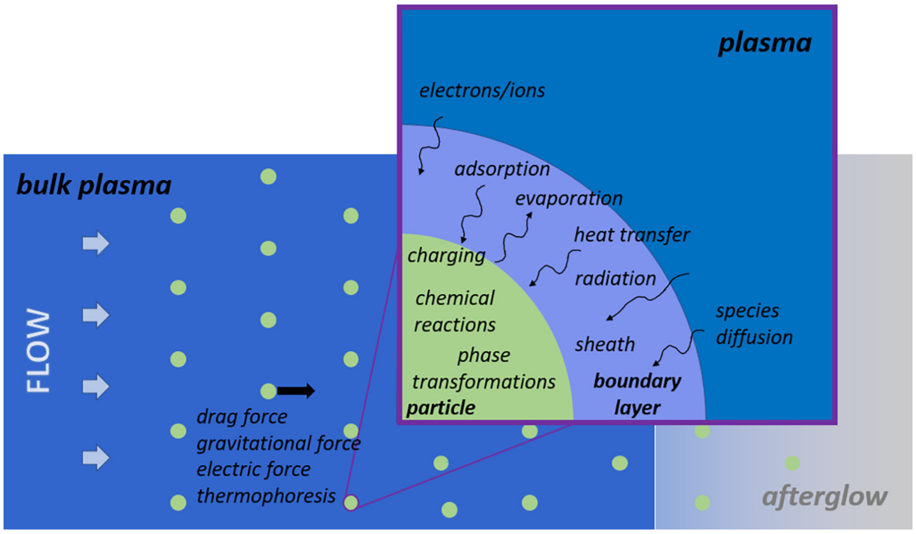


FIG. 8. Schematic representation of a flow through, atmospheric-pressure plasma containing an aerosol indicating key processes that embody plasma–aerosol particle interactions.

chemically reactive species in gas-phase plasmas to produce chemical reactions and reactive species in the liquid phase. Droplets with a large surface-to-volume ratio interspersed in the plasma are a strategy to reduce transport limitations in plasma activation of solutions.[651,674] Recently, the use of liquid precursors and, therefore, the injection of liquid micrometer-droplets in APPs has been increasingly investigated for materials synthesis.[675–677] This is often motivated by the absence of suitable precursors with appreciable vapor pressure. In addition, some vapor precursors may be difficult to handle or contain undesirable components (e.g., organics). Alternatively, precursors could be introduced as a liquid droplet by, for example, dissolving in an appropriate solvent and evaporating the solution in the plasma. Such an approach could be considered as an extension of the work that has been done in synthesizing nanoparticles in liquid solutions by interfacing a plasma either at the surface or inside.[678,679]

The droplet can be also seen as a liquid phase micro-reactor for a variety of other applications, including nitrogen fixation,[680,681] production of reactive species enabling decontamination of pathogens,[682,683] and water treatment.[684] While plasma-induced chemistry can be highly complex,[685] several studies show that the chemistry in droplets can, for certain conditions, be dominated by short-lived species.[684–687] In many cases, the flux of short-lived reactive species in the plasma is large and the transport is limited by diffusion of the chemical compounds from the bulk droplet to the plasma–droplet interface.[686] Furthermore, the complexity of plasma–droplet interactions is significantly enhanced by the strong mutual interaction of the plasma and droplet leading to enhanced evaporation and the introduction of vapor in the plasma with potentially large impacts on the plasma properties surrounding the droplet[684,685] and even the overall plasma chemistry.[688,689]

Plasma–bioaerosols interactions are another unique example with specific relevance for APPs. While such interactions have received increased attention with the COVID-19 pandemic,[683] the ability of a plasma to inactivate aerosolized viruses, bacteria, and fungi was already well established before the pandemic.[690–694] Inactivation of bioaerosols in APPs can occur with contact times on the order of 10 ms, which is orders of magnitude faster than typical plasma-enabled inactivation of pathogens on substrates or in bulk liquids.

B. Perspectives

Plasma–aerosol interactions offer the possibility of opening up new pathways for chemical reactions in aerosol synthesis and processing. While a significant volume of literature is emerging showing the effectiveness of APPs in aerosol-based processes, the key design and operational principles that control the system performance and a thorough understanding of the underpinning fundamental mechanisms are still lacking. The inherently non-equilibrium, non-linear, and complex plasma–aerosol interactions have an excessive number of degrees of freedom that are not always holistically accessible and there is an urgent need for an enhanced understanding and predictive capabilities.

Current needs include a better understanding and control of the nucleation process as a critical step in the formation of solid nanoparticles. The impact of the afterglow on particle properties and dynamics also needs to be better understood, which in view of the large gradients at atmospheric pressure might have a more profound, but to date unquantified impact on aerosol processing. While recent studies focusing on the interaction of a plasma with single droplets has increased our understanding of plasma–droplet interactions, a quantitative understanding of (1) the ultrafast synthesis of monodispersed nanoparticles enabled by plasma–droplet interactions, (2) the plasma-induced liquid phase reactions in droplets in general, and (3) plasma interactions with bioaerosols remains lacking. Recent work on microdroplet chemistry, without a plasma, has shown uniquely different outcomes compared to bulk liquid chemistry,[695,696] which suggest that APPs containing aerosols may also alter reaction mechanisms compared with APPs interacting with bulk liquids. We highlight several proposed areas of focus below.

1. Interfacial processes

The plasma–particle interface presents distinct and challenging characteristics which are of wider scientific interest. For example, electron emission processes, and the likely important role of ionic and metastable species recombination at the interface, remain poorly understood particularly for liquids. The band structure of the particles, and therefore, their composition and phase, are not only highly relevant for many applications but are also an integral part of more advanced models of interfacial processes which need to be developed.[138] Furthermore, the volatile nature of many aerosol particles can lead to significant changes in the local plasma environment surrounding the particle, increasing the complexity as well as directly impacting droplet charging and reactive species fluxes.[684,697]

2. Spatial afterglow

The properties of the afterglow have already been found to enable quenching of nanoparticles exiting the plasma. Nonetheless, the impact of strong gradients on particles, for example, due to space charge boundary layers at atmospheric pressure, and the transition from bipolar charging to a more dominant role of ions in particle charging in the afterglow, is to date not fully understood. Spatial afterglows have some similarities with temporal afterglows in plasmas formed at reduced pressure,[208,698] and the knowledge gained from these studies may be drawn upon to advance our understanding of APP spatial afterglows.[699]

3. Diagnostics

Tackling some of the above-mentioned key research questions will require the implementation of *in situ* diagnostics that could measure (often fast) temporal changes in aerosol properties during plasma exposure and quantify the impact on the local plasma properties surrounding aerosol particles. For droplets, the recent development of on-demand-droplet dispensing technologies may provide opportunities for such *in situ* measurements.[685,687] The ability to trap droplets would allow a detailed *in situ* characterization of droplets using approaches applied by the aerosol community over the last two decades.[700,701]

4. Modeling

Plasma–aerosol interactions are inherently three-dimensional phenomena,[698] nonetheless most modeling studies have been focused on lower-dimensional models. There is an urgent need for the development of 3D models to capture the interactions occurring within plasmas containing multiple aerosol particles. A major emphasis should be on the incorporation of more detailed interfacial interaction mechanisms and on the development of simplified reactor geometries with easy access for diagnostics, which are more amenable to modeling and experimental model validation.

A better understanding of the processes underpinning plasma–aerosol interactions will not only contribute to plasma science but enable the continued impact of this area on technologies and society.

XII. MAGNETIZED DUSTY PLASMAS (E. THOMAS, A. MELZER, AND E. G. KOSTADINOVA)

The interaction between magnetic fields and dusty plasmas plays a key role across Earth, space, and astrophysical phenomena. In Earth's magnetosphere, the interaction of the solar wind and the influx of meteors lead to a number of dusty plasma effects, such as noctilucent clouds and polar mesospheric summer echoes.[702] On the moon, the levitation of charged dust particles in lunar swirls has been shown to map the topology of crustal magnetic fields.[703] The alignment of dust particles in magnetized plasmas at the center of the Milky Way has allowed us to observe its magnetic fingerprints.[704] While the scale and strength of magnetic fields in the universe varies, modern-day magnetized dusty plasma experiments reproduce some key normalized parameters of these environments and serve as dedicated research platforms to study these phenomena (Fig. 9).

Here, a charged particle (electron, ion, or dust particle) is considered "magnetized" when its dynamics is substantially influenced by the magnetic force, $\mathbf{F} = q\mathbf{v} \times \mathbf{B}$, where q and $\mathbf{v}$ are the particle charge and velocity, and $\mathbf{B}$ is the magnetic field. The magnetic force should be comparable in magnitude to the other forces that influence its dynamics. This condition can be quantified by the Hall parameter, $H_\alpha = \omega_{c\alpha}/\nu_{\alpha n} \propto q_\alpha B/(m_\alpha P)$, the ratio of the gyrofrequency $\omega_{c\alpha}$ to the species-neutral collision frequency $\nu_{\alpha n}$. Here, α represents the charged particle species [electrons (e), ions (i), and dust (d)], P is the neutral pressure, and m_α and q_α are their mass and charge, respectively. As the Hall parameter increases with the increasing charge-to-mass ratio (q_α/m_α), the electrons are most easily magnetized, then the ions, then the charged dust particles. Thus, to understand a system that has magnetized dust particles, we must also consider the dynamics of the magnetized plasma electrons and ions.

A. Current status

Weak magnetic fields of $B < 0.1$ T were used to provide confinement of the electrons ($H_e \geq 1$) and weak confinement of the ions ($H_i \leq 1$), but there is effectively no direct impact of a magnetic force on the dust particles. The influence of the magnetic field is largely restricted to modifying the background plasma, which leads a larger trapping volume for the dust particles. In experiments by Merlino *et al.*, an axial magnetic field was used to expand the anode glow region near a biased electrode.[345,705] Other studies focus on modifications of ion instabilities and shocks in these weakly magnetized plasmas.[706–708]

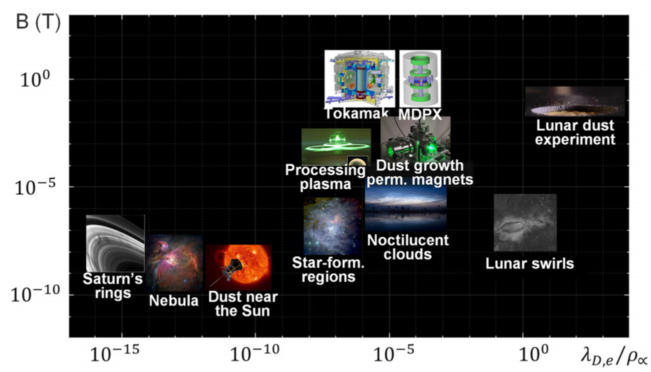


FIG. 9. Representative magnetized dusty plasma regimes in terms of magnetic field (B) vs ratio of electron Debye length to dust gyroradius: Saturn's rings (from NASA/JPL[761]), Orion's Nebula (from NASA/ESA/Robberto[762]), dust near the sun (from NASA/Johns Hopkins APL/Steve Gribben[763]), star-forming region (from ESO, McCaughrean[764]), Noctilucent clouds (Adapted from Ref. 765), processing plasma [Adapted with permission from Merlino and Goree, "Dusty plasmas in the laboratory, industry, and space," Phys. Today **57**(7), 32–38 (2004). Copyright 2004 AIP Publishing.], low temperature plasma chamber for nanoparticle growth with permanent magnets (courtesy of Edward Thomas, Jr., and Saikat Chakraborty Thakur), MDPX (courtesy of Edward Thomas, Jr.), tokamak (Copyright ITER Organization[766]), lunar dust experiment (from NASA[767]), lunar swirls (NASA/GSFC/Arizona State University[768]), and GEC reference cell (from Ref. 769).

In inhomogeneous magnetic fields, there is a modification of the potential structure of the plasma that can lead to rotation of the both two-dimensional and three-dimensional dusty plasma structures.[709–715] Additionally, the formation of dusty plasma tori, i.e., a "ring" of dust that rotates in the plane perpendicular to the magnetic field, were observed to form as a result of a delicate balance between electric, neutral drag, and ion drag forces on the dust grains, where the ion drag is modified by the presence of the magnetic field.[82,716–719]

Dusty plasmas with magnetized electrons and ions, typically characterized by $H_i \geq 1$ and consequently $H_e \gg 1$, usually require substantial magnetic fields of the order of $B > 100$ mT or even $B > 1$ T. Under such conditions, the dynamics of the electrons and ions are greatly influenced by the magnetic field provoking a reaction of the dust component to these altered plasma dynamics.

Laboratory experiments generally employ discharges between electrodes that tend to form filaments at elevated magnetic fields.[364,370,374,720–722] These filamentary structures are elongated along the field, but restricted perpendicular to the field, and feature increased light emission and, presumably, elevated plasma density. The filaments are suggested to be a result of non-ambipolar diffusion due to restricted ion diffusion perpendicular to the field.[723,724] In dense dust clouds with sub-micrometer dust particles filamentation is found to be suppressed.[725] The directed magnetic field also maps features of the plasma boundaries as potential structures into the plasma.[721,726–728]

The presence of electric fields E in bounded discharges give rise to $E \times B$ rotations of the ions (and ion–neutral collision driven neutral gas rotation[713]). The ion (neutral gas) rotation drives rotations of the dust component where the rotation speed generally increases with magnetic field strength,[729,730] eventually leading to a sheared rotation of the different parts of the dust cloud.[729,731–734]

Experiments on the dust charge trapped in the sheath of the discharge reveal only little variation of the dust charge with magnetic field strength, even for fields larger than 1 T.[366,372,373] This is backed by simulations of the dust charging processes with flowing magnetized ions.[82,83,88,735,736] While electron and ion currents to the dust are influenced by the magnetic field, they change in a similar manner so that the net change in the dust charge is small.

In a flowing plasma, a region of enhanced positive space charge (ion focus) is created in the wake of the dust particle due to ions that are scattered into the region downstream of the dust particle.[737–740] Analytical and linear response theory calculations find that the positive space charge potential reduces with magnetic field strength.[79,80,741–743] PIC and MD simulations of the ion focus support this finding.[80,82,83,88,744] MD calculations show that at very high field strengths of the order of 10 T the ion focus turns into an ion "shadow" with a reduction in the positive space charge because the ions follow the magnetic field lines and cannot be scattered into the region downstream of the dust particle anymore.[82,83] All this is accompanied by a reduction in the ion drag force on the dust particle with magnetic field.[84]

Dust-density waves[268,745–747] are excited by an ion flow past the dust particles and feature strong modulations of the dust density at frequencies of the order of the dust plasma frequency.[748] Since the ion flow is affected by the magnetic field, also the dust-density wave dispersion is modified in a magnetic field.[277,749,750] However, the relevant dust cyclotron frequency is still much smaller than the dust plasma frequency for micrometer-sized dust particles even at magnetic field strengths of the order of a Tesla. Moreover, the dust-density wave dispersion remains unaffected when the ion flow is along the magnetic field. One or both of these limitations are met in the experimental situations so far;[277,375,376] hence, a direct influence of the magnetic field on the wave dispersion is not expected. However, the dust-density waves are found to feature stronger wave-damping at higher magnetic fields.[375,376]

In fusion devices with magnetic fields of the order of a few Tesla, dust particles are produced from melting of wall material or from arching and exfoliation[52,54,367,751,752] (see also Sec. VIII). In fusion devices, the plasma production is electrodeless and the plasma densities are much higher than in the situations described above. The main forces on the dust are the ion drag force and "rocket forces" due to non-uniformities in the particle material and the associated different reflection coefficients of plasma particles as well as forces due to dust material ablation. However, also in these conditions, the direct influence of the magnetic field on the dust trajectories is considered negligible.[54,367,752]

A true magnetized dusty plasma, in which the dynamics of all charged particles are dominated by the magnetic field still remains to be fully realized in a controlled experiment. For astrophysical systems[753,754] as well as next-generation fusion experiments,[59,437,755] the role played by magnetized dust particles may have considerable influence on the evolution of the plasma. There are many theoretical models that seek to understand both single particle and collective particle dynamics in a magnetized dusty plasma.[246,277,743,756–760] However, a key challenge of many of these models is fully incorporating the modification in the plasma dynamics and particle charging that occurs as the magnetic field dominates the electron and ion dynamics.

B. Perspectives

The future exploration of magnetized dusty plasmas remains rich with opportunities. Many of the motivating questions in space and astrophysical plasmas about the magnetization of the dust grains still remain unanswered.[770,771] Recent observations of dust in the solar wind from Parker Solar Probe[772–774] and investigations of dusty structures near strongly magnetized black holes[775,776] show that there are still exciting questions.

The ultimate goal to achieve a direct magnetization of the dust component in experiments with $H_d \geq 1$ will probably require magnetic fields exceeding 1 T and sub-micrometer-sized dust particles. When dust cyclotron waves with typical wavelengths of the order of 10 cm are exploited as evidence of dust magnetization, the dust clouds have to be quite large.[366] However, imaging of individual particles (a unique feature of dusty plasmas) will become difficult or even impossible. Experiments would require a control or mitigation of filament formation demanding for a deep understanding of bounded plasma discharges under strong magnetic fields. In this context, questions of particle charging,[82,83,88,735,736] the generation or modification of plasma flows,[80,82,83,88,744] or growth processes in reactive gases[722,777] have to be newly addressed.

The development of advanced analytical models and numerical simulations is crucial to fully bridge laboratory results and space observations. Analytical theory and numerical simulations of magnetized dusty plasma have been developed to investigate the formation of Mach cones (relevant to Saturn's dusty rings),[778] hydromagnetic waves and shocks (planetary ring systems),[779–781] low frequency ion waves (solar atmosphere and pulsar magnetosphere),[782,783] dust acoustic waves (Earth's magnetosphere and auroral regions),[784] and magnetized sheaths (plasma processing and probe theory).[785]

When modeling such systems, apart from a Lorentz force term, it is necessary to account for additional electrostatic fields, plasma inhomogeneities, and anisotropic interactions. The difference in charge-to-mass ratio of the different species in magnetized plasmas leads to charge separation resulting in additional electrostatic fields. This process is believed to cause the formation of lunar swirls.[786,787] Another possible phenomenon is the plasma filamentation at strong magnetic fields.[370,721] Depending on the strength and topology of the external magnetic field, symmetry in the particle shielding may be broken, resulting in anisotropic interaction potentials that affect many dynamical features of the dust structures in magnetized plasmas. Thus, developing self-consistent analytical models to describe these processes and incorporating these effects in numerical simulations of magnetized dusty plasmas still present one of the greatest challenges in the field.

XIII. SPACE DUSTY PLASMAS (M. HORANYI AND I. MANN)

Dusty plasma phenomena in space physics often offer possible explanations for unusual observations. The term dust is used to identify macroscopic charge carriers with a wide range of sizes, from large macro-molecules (nm radii) to pebbles (mm radii). Exposed to UV radiation and/or immersed in plasma, dust particles can exhibit unusual dynamics and can change the properties of their environment. The spatial scale of dusty-plasma-related observations in space also spans many orders of magnitudes, including the small-scale (cm) structures on the lunar surface and the propagation of interstellar dust particles through the entire solar system (hundreds of AU). The atmospheres of the Earth[4] and Mercury,[788] the surface of the Moon,[789] asteroids,[790] comets,[791] and planetary rings,[792] for example, all offer rich laboratories to study the fundamentals of dust charging, transport, and the possible emergence of dusty plasma collective behavior.[219,793]

Challenges, in general, for dusty plasma studies in space are due to the fact that we do not know the composition of the dust, we usually deal with a wide size distribution, and the dust charge remains poorly known because it depends on the dust density itself and a number of processes driven by the radiation and plasma environment. In addition, the very presence of the dust can alter the properties of their environment, acting as sinks and/or sources of the plasma, changing the energy distributions of electrons and ions, and even the composition.

We focus here on dusty plasmas that can be studied with space missions through *in situ* measurements. In the ionosphere of the Earth, dusty plasmas influence the charge balance and are often noticed in an observed lack of electrons in comparison to positive ions (Fig. 10). Some dust plasma collective effects are observed *in situ* with rocket-born instruments and also with ground-based radar. Furthermore, dedicated instruments onboard space missions can detect the mass, charge speed, and composition of dust particles, simultaneously characterizing their radiation and plasma environment, enabling the identification of phenomena that are shaped by dusty plasma processes.

A. Current status

Dusty plasma in the ionosphere of the Earth recently became the focus of studies because it occurs at altitudes where the ionosphere–mesosphere coupling is important. This region overlaps with the zone

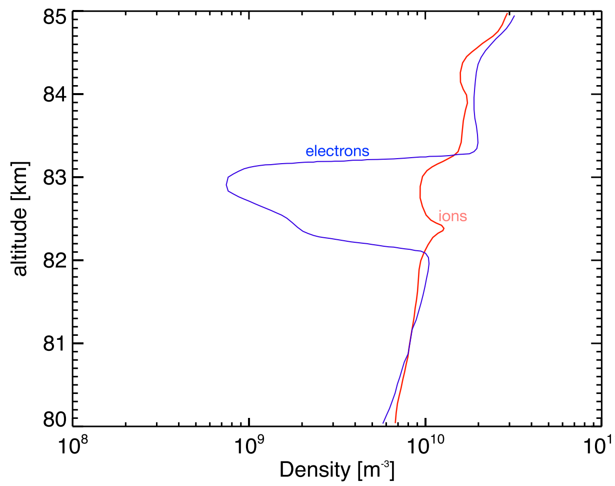


FIG. 10. An electron bite-out measured by a DC probe aboard the rocket ECOMA-6. The difference between the density of positive ions and electrons cannot be due to negative ions, and it is likely due to the charging of macrosopic aerosol particles.[794] Similar electron depletion has been observed by the Cassini spacecraft at Saturn while crossing the plumes emerging from the geologically active south polar regions of the moon Enceladus.[795] Adapted with permission from Friedrich *et al.*, J. Atmos. Sol. Terr. Phys. **73**, 2201–2211 (2011). Copyright 2011 Elsevier.

of meteor ablation.[796] Cosmic dust material that is ablated in the meteor process remains in the upper atmosphere, it forms small dust particles, called meteoric smoke, and it takes part in the ion chemistry and in the growth of ice particles observed in Noctilucent clouds.[797] Noctilucent clouds were among the earliest examples of dusty plasma in space.[4] These are layers of ice particles at about 82 km altitude observed during summer months above mid and high latitudes. The clouds are located above the normal cloud layers at altitudes of the ionospheric D region. They become visible to observers on the ground after sunset, when the upper layers of the atmosphere are still illuminated by the sun and sunlight is scattered by the ice particles. More recently, Noctilucent clouds are observed by backscattering of laser light with lidar, from the extinction of sunlight that they cause in the atmosphere, observed from satellite,[798] and with imaging from balloons.[799] All these methods are independent of dust charge and are biased to particles with sizes of several times 10 nm and larger. It is discussed that the formation of ice is more effective because of the existence of smaller meteoric smoke particles that form through the meteoric dust flux as the extinction measurements suggest that meteoric smoke is mixed with the ice.[800] Also, rocket observations support the hypothesis that ice particles include smaller meteoric dust.[801]

Charge interactions play a role in the formation process.[802] While *in situ* measurements with sounding rockets confirm the existence of charged dust and the *in situ* detections are often correlated with the radar echoes and optical signals,[801,803] the size distribution, charge, and composition of the particles remain mainly unexplored. Smaller particles can under certain conditions be traced with observations of mesospheric radar echoes that form as a result of neutral turbulence and in some cases by the interactions with the solid particles through their surface charging.[804] While the participation of ice particles is confirmed for the formation of the mesospheric echoes in summer, called polar mesospheric summer echoes (PMSE), these echoes depend on a number of parameters which makes it difficult to pin down the dust/ice component and its charged interactions with the ionosphere.[805] The charged dust also participates but is only rarely observed in the incoherent scattering process and a semi-empirical model to describe the incoherent scattering in the presence of charged dust was recently extended including dust with a size distribution.[806]

Electrostatic dust lifting on the lunar surface is a fundamental physical process that has been suggested to explain unresolved observations for more than five decades. For example, the so-called lunar horizon glow is believed to be sunlight scattered off a cloud of $\sim 10\,\mu$m charged dust particles lofted or levitated ~ 30 cm above the surface near the terminator, where enhanced electric fields are created due to differential charging between the sunlit and shadowed regions.[108,807] Similarly, the observations by the Apollo 17 LEAM experiment of dust movement across lit-dark boundaries[808] or the high-altitude nanometer-sized dust lofted up to tens of kilometers height indicated by visual observations of the Apollo astronauts[809] have been suggested to be the results of dust charging and mobilization. Recent theoretical and laboratory studies show promising results to understand the dynamics of electrostatic dust lofting and levitation on the lunar surface.

A new patched charge model has been developed based on laboratory experiments, providing a breakthrough in addressing this question.[197] The model shows that the emission and re-absorption of photoelectrons due to UV radiation and/or secondary electrons due to electron/ion impacts within subsurface microcavities generate large negative charges on the surrounding particles and intense interparticle repulsive forces to lift off dust particles. Following this discovery, more laboratory experiments and modeling work have provided new insight into the dust charging and lofting properties, including the initial charge and launch velocities, lofting rates, and size distributions.[810–812]

B. Perspectives

Several opportunities are coming up for the observations of dusty plasmas in the ionosphere. Ongoing Earth observations, the dedicated studies with the MATS satellite[813] and the new balloon observations[799] provide a basic understanding of the atmospheric structure at NLC and PMSE altitude that will help to investigate dusty plasma at these altitudes. The upcoming EISCAT3D radar with advanced capabilities for incoherent scatter observations[814] will improve chances to measure the influence of dust on the incoherent scatter signal and its tri-static configuration improves the diagnostic of the PMSE formation.[815]

The rapidly increasing number of satellites in low-earth and geosynchronous orbits already generates a difficult-to-solve problem of accumulating space debris. Possible dusty plasma effects can alter the lifetimes of debris[816] and could offer a novel way to mitigate this hazard.[817]

The interest in lunar exploration is going through an unprecedented growth period as several countries are currently engaged in or planning for near future missions to the Moon.[818–822] Many of these carry experiments addressing dust and dusty plasma issues on the lunar surface that are now recognized to be of high importance for both scientific and engineering application.

Dusty plasma studies in planetary magnetosphere will have ample opportunity to collect new observations by ESA's Juice mission, launched in April 2023,[823] and NASA's Europa Clipper mission, to be launched at the end of 2024,[824] both to Jupiter. In addition, NASA long-term plans for the exploration of outer planets include a flagship mission to orbit Uranus.[825] In magnetospheres, the dynamics of small charged particles can be shaped, if not dominated, by electromagnetic forces acting simultaneously with gravity, drag, and radiation pressure. Dust particles traversing various regimes adjust their electrostatic charges as dictated by the changing plasma conditions and respond to electric and magnetic forces. Dusty plasma effects can lead to unexpected effects, including transport,[826,827] ejection,[828,829] and capture[830] of small charged grains.[807]

The heliosphere includes the solar system dust cloud where dust particles form through collisions of larger objects, and also are emitted from comets. New space observations in the vicinity of the Sun motivated studies of charged dust trajectories in the vicinity of the Sun or other stars. The trajectories of nanometer-sized dust that was released from larger particles were investigated using numerical simulations and theoretical models considering the effect of plasma corotation close to the Sun/star. As in previous studies, it was found that nanodust in the vicinity of the Sun or other stars and the effect of plasma corotation is strong for the high rotation rates and/or a low stellar wind speed.[831] Trapping conditions are variable and, for instance, large fractions of trapped particles can escape during coronal mass ejections.[832]

The charged dust trajectories were also investigated for the inner planetary debris disks around Vega and Fomalhaut because both stars display a thermal emission brightness that could possibly arise from hot dust near the stars.[833,834] It was found that, in comparison to the Sun, the trapping conditions would occur closer to the stars because their faster rotation leads to a more closely wound-up magnetic field spiral.[835]

Another example of dust being influenced by plasma is the modulation of the interstellar flux into the heliosphere with the solar cycle. While this modulation is qualitatively understood our models do not satisfactorily explain the variability and direction of the interstellar dust flux.[836–838] NASA's upcoming interstellar mapping and acceleration probe (IMAP), as well as JAXA's Destiny^{+} missions[839,840] to be launched in 2025, will carry dust instruments to monitor the flow of interstellar dust through the inner heliosphere, and observe its variability modulated by the solar cycles, however, superimposed with the solar system dust fluxes. The Parker Solar Probe and the Solar Orbiter at present explore the near solar inner heliosphere and carry antenna instruments that also measure dust impacts. From analyses so far, many of the results can be explained with the orbits of dust that are influenced of gravity force and radiation pressure.[772,841] Charged dust trajectories can become particularly important in the perihelion passages, and parker solar probe can encounter particles that are in trapped orbits since the trapping can for instance occur for 30–75 nm particles that were created inward from 0.16 AU from the Sun.[774]

In addition to naturally occurring phenomena, dusty plasma effects can offer a uniquely efficient approach to cleaning optical surfaces, exposed mechanical devices, thermal radiators, and astronaut's suits, all essential to mitigate dust hazards and enable the planned long-term presence of humans on the lunar surface and eventually on Mars. Dusty surfaces exposed to electron beams with optimized fluxes, energy distributions, and directions can be efficiently cleaned, removing even the smallest nm-sized dust particles.[842–844]

Future space missions and ground-based observations of the near-Earth environment, lunar surface, near solar/stellar regions, comets, asteroids, planetary rings embedded in magnetospheres, our entire heliosphere, and beyond, will have to address dusty plasma issues, including dust charging, mobilization, transport, and yet to be identified, collective effects, in designing, analyzing, and interpreting new observations.

XIV. NANO-CONTAMINATION CONTROL (J. BECKERS AND M. VAN DE KERKHOF)

Dust particles immersed in an environment of ionized gas are known to get (mostly negatively) charged by the collection of plasma species. This feature—together with the typical characteristics of plasma and possibly with the assistance of mechanical vibrations, gas flows, electric fields, and/or photon or electron beam irradiation, may exert additional forces on the particles releasing them from surfaces or altering their location and trajectories (see Fig. 11). Hence, this charging enables opportunities to control and mitigate particle contamination issues in a multitude of scientific endeavors and applications. In the current section, we elaborate on the current status regarding (nano)particle contamination control related research and highlight some perspectives on possible high-potential future research directions. In this contribution, we mainly focus on surface release and gas phase steering of contaminating particles and less on their deposition on secondary surfaces.

A. Current status

It was back in 1989 that Selwyn *et al.* discovered for the first time the presence of plasma-generated dust particles in an IBM plasma processing reactor.[390] The fact that in those experiments the micrometer-sized particles—made visible by *in situ* laser light scattering—appeared to remain levitated in the plasma above the surface, already indicated that plasma can affect the location and movement of such contaminants. Essentially, this was the first encounter of the most fundamental plasma-assisted contamination control mechanism, i.e., the plasma self-induced electric fields E at the plasma's borders (sheaths) interacted with the plasma-deposited surface charge Q on the particles, and generated an electric force $F_E = Q \cdot E$ affecting the particles' positions and trajectories.

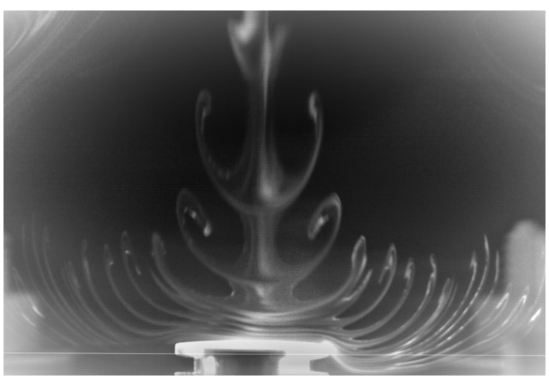


FIG. 11. Example of dust ejected by an atmospheric pressure Ar/HMDSO flow-through plasma and interacting with a witness sample for contamination control research (courtesy of T. J. A. Staps and T. J. M. Donders, CIMlabs, Eindhoven University of Technology, The Netherlands).

Ever since, particle contamination issues in (or due to) plasma environments have appeared in many scientific, instrumental, and industrial areas. For instance, extraterrestrial exploration (e.g., of the Moon, Mars, or other outer-space objects) can be (negatively) impacted by the accumulation of surface-released dust particles on diagnostic instruments[845–847] and solar panels[848] (see Sec. XIII). Often these particles are charged by ultraviolet light irradiation[108,849–851] and by the solar wind plasma.[807,852] In extreme ultraviolet (EUV) lithography scanners, contamination of critical imaging surfaces with particles as small as 50 nm significantly impacts the overall performance and yield of the systems and, therefore, needs to be controlled.[853–855] The particles in such scanners may be embedded in and/or irradiated by a photon-induced plasma and ionizing radiation.[856–860] In plasma material processing tools, surfaces to be processed may suffer from (and be dysfunctionalized by) contamination with particulates that are either released from the environment and reactor walls or that are *in situ* plasma-synthesized from the precursor gas and/or components that are sputtered and etched from surfaces. Especially in the 1990s, significant research efforts have been made to study particle formation, electrical charging, transport, and trapping of particles in (afterglow) plasma processes.[390,861–875] In contrast to most examples, where plasma is inevitably present, sometimes plasma is generated intentionally for contamination control purpose. For instance, an *in situ* plasma-assisted particle seal was proposed for application in robotic feedthroughs in ultra-clean vacuum systems such as those used in semi-conductor processing equipment, EUV lithography scanners, and electron microscopes.[876–879] Finally, in nuclear fusion devices, dust particles may be produced by energetic plasma–surface interactions.[52,55,115] In addition to possibly having a detrimental effect on the plasma operation itself, these contaminants may be radioactive and toxic and, hence, may impact public health in the case of a large-scale accident. This topic is discussed extensively in Sec. VIII of this Perspective paper. The rapid developments of the above-mentioned areas in which dust particle contamination plays a crucial role have boosted both fundamental research endeavors and the development of new technologies to control and mitigate contamination by small particles either on (or from) surfaces or airborne.

With respect to the cleaning of surfaces from particles, be it for application in extraterrestrial missions or in (semi-)industrial processes, many proposed processes use plasma as a basis. Here, plasma-charging of the governing surfaces and contaminants in combination with plasma-self-induced electric fields in the sheath region near the surface is used to generate an electric force on the contaminants that is strong enough to overcome the adhesion force and, hence, to release the particles from the surface. Often, the stochastic nature of charge collection from the plasma by the particles and/or triboelectric charging triggers random/poorly predictable particle release.[880–883] Depending on the specific environment conditions, different types of plasma have been applied. Examples include studies of contaminated surface interactions with highly transient EUV-induced plasmas,[854,855] electron cyclotron resonance plasma sources in hydrogen (to mimic EUV scanner conditions),[884,885] laser-induced plasma shock waves,[886] plasma jets generated between two co-axial electrodes,[887] and many more. Also, other procedures have been developed, which can be possibly combined with (the generation of) plasma, to influence surface contamination and promote the release of particles from surfaces. One successful method appeared the additional irradiation of particle-laden surfaces with (beams of) electrons,[844,881,888–894] which has resulted in the development of the so-called "patched charge model" suggesting that highly localized electric fields in microcavities between particles mutually or between the particles and the surface are responsible for the particles' mobilization. The charge and mobilization of particles on surfaces were also found to be impacted (even in vacuum conditions) by irradiation with ultraviolet (UV) light through the photoelectric effect (e.g., explaining dust levitation from the lunar surface),[108,849,850,895,896] electrostatic traveling waves,[848] work function-matching coatings,[845] high-speed gas jets,[897,898] and surface vibrations.[899,900]

With respect to the mitigation of airborne particles, using plasma has advantages over methods using filters in the sense that plasma-assisted particle removal devices do not obstruct the gas flow. The most basic example for airborne particle removal is the concept of the electrostatic precipitator—invented by Hohlfeld back in 1824 (Ref. 901)—in which particles are electrostatically charged and steered by an electric field toward collector plates. This way of particle filtering has been widely applied in, for instance, coal burning energy plants,[902] diesel engines,[903] and indoor air cleaners.[904] For application in these atmospheric conditions, often corona-like discharges are used.[669] Applications in low pressure (roughly below 100 Pa) high-tech environments usually require (capacitively or inductively coupled) plasmas with much more complex geometries. As in these cases, the plasmas, used to charge the particles, also tend to shield the electric fields applied to deflect them, and pulsed plasma operation is usually considered most effective. For these technologies to be developed, in-depth understanding of particle charging and interaction with afterglow plasmas is crucial. Not only targeting this application but also other applications and fundamental curiosity, many experimental and numerical works have been carried out on particle dynamics in temporal,[209,905–910] spatial,[911,912] and spatiotemporal[208,913,914] afterglow plasmas. Particle and aerosol interaction in atmospheric (flow-through) pressure plasmas has been investigated extensively more recently as well[652,667,670,915–919] (see Sec. XI). Also, considerable research efforts have been undertaken when it comes to the understanding of the growth of contaminating particles inside chemically reactive gases[253,920–929] and the suppression of them in processing plasma applications, i.e., by using sine wave[930] or square-wave modulation of the (usually radio frequency) plasma driving signal.[931]

B. Perspectives

In general, using plasma as a key ingredient for novel contamination, control strategies have high potential. Nevertheless, from a physics point of view, the ecosystems in such applications—especially those in high-tech industries—are rather complex, combining complex-structured and highly sensitive surfaces, (ionizing) photons, electrostatic fields, gas flows, and additional irradiation with charge carriers. Also, plasma may have undesirable side-effects and must be properly managed and confined. Before applications can be developed to their full potential, much more understanding and investigation are needed. For applications where plasma is intentionally applied for contamination control purpose, the challenge is to correctly use and steer the complex interplay between the key plasma parameters, such as electron temperature and density, decay rates in the afterglow phases, etc. (which are to a certain extent controllable), the resulting particle charge (which may vary in time and can even become positive) and the consequent surface-release, deflection, and collection methods. The complexity of the interplay lays in the fact that most processes and parameters are mutually interdependent. Possibly even more challenging is the development of contamination strategies for applications in which plasma is inevitably present, e.g., in space exploration applications, materials processing, and EUV lithography applications, as earlier discussed. In those areas, plasma configurations and key parameters are dictated externally and, hence, the right implementation of plasma-facing surfaces, external electric fields, flow conditions, and irradiation with charged particles and/or photons is essential.

In order to drive the general fundamental understanding regarding plasma-enabled (nano)particle contamination control, the following aspects are considered most important:

Plasma-induced chemistry—i.e., unraveling the influence of plasma-induced chemistry on particle morphology change and (the impact thereof on) the release of contamination from surfaces, especially in atmospheres including gases of which the induced plasma may be depositing, oxidizing, or reducing. In this context, the adsorbed layer surrounding a particle should be taken into account explicitly.[932] This influence should be connected to an overall theoretical framework regarding particle release from surfaces including effects of e-beam and UV irradiation, plasma-induced and externally applied electric fields, electron and ion impact, particle and surface (de-)charging, and particle migration over the surface.

Spatially decaying and highly transient plasmas—i.e., revealing a detailed description regarding dynamics of spatially decaying and highly transient plasmas and their impact on charging of airborne particles. The stochastic particle charging nature might become dominant even for micrometer sized particles when the electron temperature approaches the ion temperature and the plasma density becomes rather low in the late afterglow phase. Although relatively much research on stochastic charging of particles has been conducted,[191,880–883] more detailed understanding remains needed, especially in afterglow conditions.

Nanometer length scales—i.e., obtaining in-depth knowledge on plasma-charging dynamics of nanometer sized particles. The interesting issue of the dominance of stochastic charging processes (see the previous point) especially holds for nanoscale particles. Recent development regarding visualizing of charge on or adjacent to quantum dots may enable such advanced studies in the near future.[428,933,934]

XV. NON-ELECTRIC MANIPULATION OF PARTICLES (H. KERSTEN, V. SCHNEIDER, AND D. BLOCK)

To manipulate highly charged particles, utilization of electric fields is the most obvious solution.[935,936] However, this approach bears a number of difficulties. First of all, a plasma is quasi-neutral and shields very efficient externally applied fields. Thus, electrostatic manipulation is limited to the plasma sheath region or requires to insert additional electrodes[937,938] for manipulation purpose into the plasma. Furthermore, the applied voltages will result in currents and this can alter the discharge properties or at least change the local plasma conditions notably. However, for using particles for diagnostic purpose, the plasma should not be altered. Thus, the manipulation of dust particles by means of forces that do not affect the plasma itself is an important issue. Such forces are gravity, neutral drag, thermophoresis, and interaction with intense electromagnetic radiation, i.e., lasers. The following paragraphs will summarize these approaches and their current status and give an outlook on future perspectives of non-electric manipulation for dusty plasma research.

A. Current status

Although gravity itself is not a variable quantity on Earth, it is possible to use rotating systems to utilize centrifugal forces to act as if hyper-gravity conditions would apply. For this purpose, a fully functioning low pressure dusty plasma setup was mounted at TU Eindhoven on the working stage of a centrifuge, capable of inducing up to ten times the Earth's gravitational acceleration.[939] With this setup, the "weight" of micro-particles can be increased while the general plasma parameters are left unchanged. In addition, the angle of the resulting apparent gravity vector can be changed due to a rotational degree of freedom of the facilitating vacuum vessel suspension. This ability, in combination with the magnitude control of the apparent gravity, allows manipulation of the horizontal and vertical particle equilibrium positions in the plasma sheath. First experiments[939,940] demonstrated that the electric field and the particle charge as a function of levitation height can be probed in the plasma sheath.

A similar approach using centrifugal forces can be applied to dust clusters via rotating electrodes. Here, the centrifugal force is perpendicular to gravity. The rotating electrode can drive a neutral gas flow which (due to viscosity in the background gas and neutral gas drag of the dust particles) gives rise to a solid body rotation of 2D dust clusters.[713] In principle, these experiments are similar to those of Nosenko *et al.*[941,942] where alternating electric fields similar to a Paul trap[943] were applied to horizontal boundaries. While Nosenkos approach drives an ion flow and, thus, affects the plasma, the pure neutral gas drive does not. Interestingly, the circularly moving dust particles are not only subject to centrifugal forces but also to Coriolis forces as well. While the first allows us to measure the screening length via a force balance, the latter allows us (due to a mathematical equivalence of Lorenz and Coriolis force) to study (pseudo) magnetized dust systems[377,944] (see Sec. VI).

Another option for additional non-electric forces acting on the dust are thermal gradients. The thermophoretic force is well known for rarefied gases[945] and the physics are identical in a weakly ionized plasma system. Hence, with heated and/or cooled electrodes, moderate temperature gradients of about $10\,\mathrm{K\,cm^{-1}}$ are sufficient to compete with gravity for micro-particles. For example, Rothermel *et al.*[946] used a vertical temperature gradient to counter act gravity and produce 3D microparticle suspensions, which have a similar void structure as those observed under microgravity.

Finally, lasers are a powerful tool for manipulation of particles without changing the plasma conditions. Laser excitations of single microparticles were used for charge determination,[947,948] to excite waves,[949] to study dynamical properties (shear flows, viscosity, and heat transport), and to increase the average dust kinetic temperature.[950–955] The advantage of lasers is that they provide precise control on location and motion of particles in the interaction region and, thus, allow us to address individual particles as well as complete particle systems. The origin of the force is twofold: First, the photons are scattered by the dust particles and, thus, transfer momentum.[956,957] Second, a part of the light is absorbed and heats the particle up. If this heating is non-isotropic (e.g., due to the sophisticated intensity pattern of Mie-scattering[251]), the interaction with the neutral gas causes a so-called photophoretic force.[647,958]

Optical tweezers[959] use strong intensity gradients to trap transparent microparticles. Ito *et al.*[960] succeeded in trapping and etching poly(methyl methacrylate) (PMMA) particles in vertical orientation against gravity. With a modified setup, structural and dynamical properties of a dust cluster have been manipulated.[82,961,962] That even a vertical controlled motion of particles in the plasma sheath is possible was shown by Schneider and Kersten using two counter-propagating laser beams.[963]

However, it has to be noted that intense lasers yield a heating of the particle which can cause reversible surface modifications[567] or even damage the particle and lead to strong accelerations.[964]

B. Perspectives

As listed above, there are a number of powerful and established non-electric methods which allow us to manipulate particles. Such experiments can be used to gain insight into the physics of the dust component. Furthermore, manipulated individual probe particles can deliver information about the surrounding plasma or sheath properties.

For example, thermophoresis was successfully used to (partially) compensate gravity and may complement the hyper-gravity experiments making the regime up to zero-gravity conditions accessible in the lab[946,965] (see Secs. VI and IX). If gravity is only partly compensated and an additional radial confinement (glass box) is used, finite 3D dust clusters can be created.[966,967] The experiments and simulations on these so-called Yukawa-balls allowed us to explore structural and dynamical properties of finite 3D strongly coupled systems for the first time.[330] This shows that thermophoresis is a powerful tool to alter trapping conditions. Its rather simple technical realization will certainly make it a first choice in future if specific trapping conditions are needed to study structural and dynamical processes in dusty plasmas. In addition to this common thermophoresis, especially thermal creep flows[968–970] might play a role for dust particle growth.[971]

So far, laser manipulation has established as a standard tool to trigger or control dynamical processes in complex plasmas. Lasers are used to control the kinetic temperature of the dust component as well as to trigger collective particle motion or instabilities and the exploration of dynamical processes in complex plasmas is still ongoing. Certainly, laser manipulation will remain one of the working horses in experimental complex plasma research. A few examples for recent and future activities are studies of cold fluids and their viscoelastic properties[972–976] and the excitation of selective modes.[961] Furthermore, it might be possible to generalize the optical tweezers approach and generate optical lattices in order to tailor the structural properties of particle arrangements. These lattices would allow us to tailor the local confinement geometry and strength, for a systematic variation of kappa, which is so far not possible.

A peculiarity of laser manipulation of particles is that two forces are involved: radiation pressure and photophoresis. While the first only depends on the intensity of the radiation, the latter increases with neutral gas pressure and its magnitude and direction depends on the optical properties of the particles. Hence, two particle species of different material within the same plasma volume and being illuminated by the same light source will not experience the same net-force. For example, for binary systems,[977] an increase in kinetic temperature of the particles via a laser heating system[952] will result in a binary system, where the individual particle species have different kinetic temperatures.[567] This can be utilized to study basic thermodynamics in the system, e.g., to measure entropy directly[567] according to its basic statistic definition of Boltzmann and Gibbs. This example shows that the specific properties of radiation pressure and photophoresis can be tailored and utilized to explore fundamental properties of complex plasmas. Additionally, photophoresis plays and important role in configuring optical tweezers. The development of the next generation of such devices for complex plasmas will strongly benefit from being able to quantify radiation pressure and photophoresis.

On the other hand, the particles can be utilized as probes. Since the microparticles can be observed in the plasma sheath easily, they can serve, in particular, as electrostatic probes for the characterization of the potential surfaces and electric fields in this region.[937,978,979] Usually, the plasma sheath, which is an important zone of energy consumption and, hence, often the essential part of a discharge for applications, is difficult to monitor by common plasma diagnostics, such as Langmuir-probes or optical spectroscopy. By monitoring the dependence of the position and motion of the particles on the discharge parameters, information can be obtained on the electric field in front of electrodes or substrate surfaces, respectively, where other plasma diagnostic methods fail.

The optical tweezers approach[963,980] allows us to determine the sheath width and the forces acting on a single charged particle. Furthermore, combining this technique with a so-called dual-frequency discharge,[981] different forces in the plasma sheath can be determined depending on the frequency combination of the discharge.[982] The vertical movement of a particle by optical traps through the sheath region of a rf plasma toward the electrode surface opens up new possibilities to study the electric field forces, the ion drag force, or the influence of secondary electrons by using different electrode materials. Probing the sheath region with single particles provides data and information for theoretical models and simulations (see Secs. II and III) and gives new insight into the physics of this space charge region. It demonstrates that the technologically important plasma sheath becomes experimentally accessible using particles as probes. Especially, if these are combined with recent developments in electrostatic particle manipulation, the sheath properties can be studied in more detail.

Using a stepwise electric excitation of the particle[983] gives an optimum with respect to accuracy and minimum measurement time. It allows us to probe the particle charge in the plasma sheath as a function of distance to the confining electrode and to quantify the repulsive Coulomb interaction force acting between two microparticles including the screening length.[940]

ACKNOWLEDGMENTS

The editors of this Perspective article, Job Beckers and Mikhail Pustylnik, are thankful to Ph.D. student Tim Donders for his support during the editing process.

Job Beckers acknowledges the financial support from the Dutch Research Council NWO (Project No. 15710).

Johannes Berndt and Eva Kovačević acknowledge the project PEGASUS (Plasma Enabled and Graphene Allowed Synthesis of Unique nano-structures), funded by the European Union's Horizon research and innovation program under Grant Agreement No. 766894 and the EU Graphene Flagship FLAG-ERA III JTC 2021 project VEGA (No. PR-11938), as well as the support obtained via ARD MATEX Region Center, France and project Orleans Metropole, France.

Dietmar Block acknowledges funding by the Deutsche Forschungsgemeinschaft (DFG) in Project Nos. BL555 3-2 and BL555 4-2.

Peter J. Bruggeman acknowledges the U.S. Department of Energy under Award No. DE-SC-0020232, the National Science Foundation under Award No. PHYS 1903151, and the Army Research Office under Grant No. W911NF-20-1-0105.

Lénaïc Couëdel acknowledges the support of the Natural Sciences and Engineering Research Council of Canada (NSERC) (Grant No. RGPIN-2019-04333).

Gian Luca Delzanno acknowledges the Laboratory Directed Research and Development Program of Los Alamos National Laboratory under Project No. 20230668ER. Los Alamos National Laboratory is operated by Triad National Security, LLC, for the National Nuclear Security Administration of U.S. Department of Energy (Contract No. 89233218CNA000001).

Yan Feng acknowledges the support from the National Natural Science Foundation of China (Grant No. 12175159).

Ranganathan Gopalakrishnan acknowledges the funding support from U.S. Department of Energy Early Career (Award No. DE-SC0021146) from the Office of Fusion Energy Sciences, U.S. Army Research Office (Award No. W911NF-23-2-0013), and NSF Plasma Physics (Award No. 1903432).

Franko Greiner thanks the Deutsche Forschungsgemeinschaf (DFG) for funding of Project No. GR1608/8-1 Dusty plasmas with high electron depletion: Investigation of fundamental mechanisms and properties through particle and plasma diagnostic.

Peter Hartmann acknowledges the Hungarian National Office for Research, Development and Innovation (NKFIH) (Grant No. K134462).

Mihaly Horányi acknowledges the NASA Solar System Exploration Research Virtual Research Institute's (SSERVI), Institute for Modeling Plasmas, Atmospheres, and Cosmic Dust (IMPACT).

Christina A. Knapek acknowledges Funding (Grant No. DLR/BMWi FKZ 50WM2161).

Uwe Konopka acknowledges that his work was supported by NASA-JPL (Subcontract Nos. 1679198 and 1655063).

Uwe Kortshagen acknowledges the support from the Army Research Office under MURI (Grant No. W911NF-18-1-0240) and from the U.S. Department of Energy under Grant No. DE-SC0022242.

Evdokiya G. Kostadinova acknowledges the U.S. National Science Foundation 2694 (Nos. NSF-1903450 and NSF-2308742).

Sergei I. Krasheninnikov acknowledges the support of the work by the U.S. Department of Energy, Office of Science, Office of Fusion Energy Sciences under Award No. DE-FG02-06ER54852 at UCSD.

I. Mann was supported by the Research Council of Norway through Grant Nos. NFR 275503 and NFR 240065.

Davide Mariotti acknowledges EPSRC (Award No. EP/V055232/1).

Lorin Swint Matthews acknowledges the U.S. Department of Energy, Office of Science, Office of Fusion Energy Sciences (Award No. DE-SC-0021334), U.S. Department of Energy Grant No. DE-SC0021334, NVIDIA Corporation Applied Research Accelerator

Program, and the U.S. National Science Foundation (No. NSF-1903450).

André Melzer acknowledges the DLR German Space Agency (50 WM 2161 and 50 WM 1962).

Maxime Mikikian acknowledges the funding (Grant Nos. DLR/BMBF 50WM9852, CNES 02/CNES/4800000059, ANR-11-JS09-0010, and ANR-19-CE40-0023).

Volodymyr Nosenko, Mikhail Y. Pustylnik, and Hubertus M. Thomas acknowledge the funding (Grant Nos. DLR/BMWi FKZ's 50WM1441, 50WP1203, 50WP0700, 50WP0203, and 50WP9852).

The work of Svetlana Ratynskaia and Panagiotis Tolias has been carried out within the framework of the EUROfusion Consortium, funded by the European Union via the Euratom Research and Training Program (Grant Agreement No. 101052200-EUROfusion). Views and opinions expressed are, however, those of the author(s) only and do not necessarily reflect those of the European Union or the European Commission. Neither the European Union nor the European Commission can be held responsible for them.

R. Mohan Sankaran acknowledges the U.S. Department of Energy under Grant No. DE-SC0018202 and the Air Force Office of Scientific Research under Grant No. FA9550-19-1-0088.

Elijah J. Thimsen acknowledges the financial support from the Army Research Office (ARO) MURI (Grant No. W911NF-18-1-0240).

Edward Thomas, Jr. acknowledges the U.S. Department of Energy (No. SC-0019176) and the U.S. National Science Foundation (No. OIA-2148653).

AUTHOR DECLARATIONS

Conflict of Interest

Yes, Dr. Andre Melzer is a co-author of this paper and associate editor at Physics of Plasmas. Hence, editing duties for Dr. Melzer regarding this paper should be avoided.

Author Contributions

Job Beckers and Mikhail Pustylnik, the authors of Sec. I, are the editors and co-first authors of this Perspective.

Job Beckers: Writing – original draft (equal); Writing – review & editing (equal). **Franko Greiner:** Writing – original draft (equal). **Peter Hartmann:** Writing – original draft (equal). **Mihaly Horanyi:** Writing – original draft (equal). **Holger Kersten:** Writing – original draft (equal). **Christina A. Knapek:** Writing – original draft (equal). **Uwe Konopka:** Writing – original draft (equal). **Uwe R. Kortshagen:** Writing – original draft (equal). **Evdokiya G. Kostadinova:** Writing – original draft (equal). **Eva Kovacevic:** Writing – original draft (equal). **Sergei Krasheninnikov:** Writing – original draft (equal). **Johanes Berndt:** Writing – original draft (equal). **Ingrid Mann Mann:** Writing – original draft (equal). **Davide Mariotti:** Writing – original draft (equal). **Lorin Swint Matthews:** Writing – original draft (equal). **Andre Melzer:** Writing – original draft (equal). **Maxime Mikikian:** Writing – original draft (equal). **Volodymyr Nosenko:** Writing – original draft (equal). **Mikhail Pustylnik:** Writing – original draft (equal); Writing – review & editing (equal). **Svetlana Ratynskaia:** Writing – original draft (equal). **R. Mohan Sankaran:** Writing – original draft (equal). **Viktor Schneider:** Writing – original draft (equal). **Dietmar Block:** Writing – original draft (equal). **Elijah Thimsen:** Writing – original draft (equal). **Edward Thomas, Jr.:** Writing – original draft (equal). **Hubertus M. Thomas:** Writing – original draft (equal). **Panagiotis Tolias:** Writing – original draft (equal). **M. A. van de Kerkhof:** Writing – original draft (equal). **Michael Bonitz:** Writing – original draft (equal). **Peter J. Bruggeman:** Writing – original draft (equal). **Lénaïc Couëdel:** Writing – original draft (equal). **Gian Luca Delzanno:** Writing – original draft (equal). **Yan Feng:** Writing – original draft (equal). **Ranganathan Gopalakrishnan:** Writing – original draft (equal).

DATA AVAILABILITY

Data sharing is not applicable to this article as no new data were created or analyzed in this study.

REFERENCES

[1] I. Adamovich, S. Agarwal, E. Ahedo, L. L. Alves, S. Baalrud, N. Babaeva, A. Bogaerts, A. Bourdon, P. J. Bruggeman, C. Canal, E. H. Choi, S. Coulombe, Z. Donkó, D. B. Graves, S. Hamaguchi, D. Hegemann, M. Hori, H.-H. Kim, G. M. W. Kroesen, M. J. Kushner, A. Laricchiuta, X. Li, T. E. Magin, S. M. Thagard, V. Miller, A. B. Murphy, G. S. Oehrlein, N. Puac, R. M. Sankaran, S. Samukawa, M. Shiratani, M. Šimek, N. Tarasenko, K. Terashima, E. Thomas, J. Trieschmann, S. Tsikata, M. M. Turner, I. J. van der Walt, M. C. M. van de Sanden, and T. von Woedtke, "The 2022 plasma roadmap: Low temperature plasma science and technology," J. Phys. D: Appl. Phys. **55**, 373001 (2022).
[2] M. Pustylnik, A. Pikalev, A. Zobnin, I. Semenov, H. Thomas, and O. Petrov, "Physical aspects of dust–plasma interactions," Contrib. Plasma Phys. **61**, e202100126 (2021).
[3] U. de Angelis, "The physics of dusty plasmas," Phys. Scr. **45**, 465 (1992).
[4] D. A. Mendis and M. Rosenberg, "Cosmic dusty plasma," Annu. Rev. Astron. Astrophys. **32**, 419–463 (1994).
[5] Ya. L. Al'pert, A. V. Gurevich, and L. P. Pitaevskii, *Space Physics with Artificial Satellites* (Plenum Press, New York, 1965).
[6] J. Laframboise, "Theory of spherical and cylindrical Langmuir probes in a collisionless, Maxwellian plasma at rest," UTIAS Report No. 100 (Institute for Aerospace Studies, Toronto University, Ontario, 1966).
[7] R. Kennedy and J. Allen, "The floating potential of spherical probes and dust grains. II. Orbital motion theory," J. Plasma Phys. **69**, 485–506 (2003).
[8] G. L. Delzanno, A. Bruno, G. Sorasio, and G. Lapenta, "Exact orbital motion theory of the shielding potential around an emitting, spherical body," Phys. Plasmas **12**, 062102 (2005).
[9] H. Mott-Smth and I. Langmuir, "The theory of collectors in gaseous discharges," Phys. Rev. **28**, 0727–0763 (1926).
[10] Z. Zakrzewski and T. Kopiczynski, "Effect of collisions on positive ion collection by a cylindrical Langmuir probe," Plasma Phys. **16**, 1195 (1974).
[11] J.-S. Chang and J. G. Laframboise, "Probe theory for arbitrary shape in a large Debye length, stationary plasma," Phys. Fluids **19**, 25 (1976).
[12] A. V. Zobnin, A. P. Nefedov, V. A. Sinel'shchikov, and V. E. Fortov, "On the charge of dust particles in a low-pressure gas discharge plasma," JETP **91**, 483 (2000).
[13] M. Lampe, R. Goswami, Z. Sternovsky, S. Robertson, V. Gavrishchaka, G. Ganguli, and G. Joyce, "Trapped ion effect on shielding, current flow, and charging of a small object in a plasma," Phys. Plasmas **10**, 1500 (2003).
[14] S. A. Khrapak, S. V. Ratynskaia, A. V. Zobnin, A. D. Usachev, V. V. Yaroshenko, M. H. Thoma, M. Kretschmer, H. Höfner, G. E. Morfill, O. F. Petrov, and V. E. Fortov, "Particle charge in the bulk of gas discharges," Phys. Rev. E **72**, 016406 (2005).
[15] S. A. Khrapak, G. E. Morfill, A. G. Khrapak, and L. G. D'yachkov, "Charging properties of a dust grain in collisional plasmas," Phys. Plasmas **13**, 052114 (2006).
[16] S. A. Khrapak and G. E. Morfill, "An interpolation formula for the ion flux to a small particle in collisional plasmas," Phys. Plasmas **15**, 114503 (2008).
[17] S. Ratynskaia, S. Khrapak, A. Zobnin, M. H. Thoma, M. Kretschmer, A. Usachev, V. Yaroshenko, R. A. Quinn, G. E. Morfill, O. Petrov, and V. Fortov,

"Experimental determination of dust-particle charge in a discharge plasma at elevated pressures," Phys. Rev. Lett. **93**, 085001 (2004).
[18]S. A. Khrapak, P. Tolias, S. Ratynskaia, M. Chaudhuri, A. Zobnin, A. Usachev, C. Rau, M. H. Thoma, O. F. Petrov, V. E. Fortov, and G. E. Morfill, "Grain charging in an intermediately collisional plasma," EPL **97**, 35001 (2012).
[19]H. M. Thomas, M. Schwabe, M. Y. Pustylnik, C. A. Knapek, V. I. Molotkov, A. M. Lipaev, O. F. Petrov, V. E. Fortov, and S. A. Khrapak, "Complex plasma research on the International Space Station," Plasma Phys. Controlled Fusion **61**, 014004 (2019).
[20]U. Konopka, G. E. Morfill, and L. Ratke, "Measurement of the interaction potential of microspheres in the sheath of a RF discharge," Phys. Rev. Lett. **84**, 891 (2000).
[21]V. E. Fortov, A. V. Ivlev, S. A. Khrapak, A. G. Khrapak, and G. E. Morfill, "Complex (dusty) plasmas: Current status, open issues, perspectives," Phys. Rep. **421**, 1–103 (2005).
[22]T. Bystrenko and A. Zagorodny, "Effects of bound states in the screening of dust particles in plasmas," Phys. Lett. A **299**, 383–391 (2002).
[23]X. Z. Tang and G. L. Delzanno, "Orbital-motion-limited theory of dust charging and plasma response," Phys. Plasmas **21**, 123708 (2014).
[24]S. Ratynskaia, U. de Angelis, S. Khrapak, B. Klumov, and G. E. Morfill, "Electrostatic interaction between dust particles in weakly ionized complex plasmas," Phys. Plasmas **13**, 104508 (2006).
[25]S. Khrapak and G. E. Morfill, "Basic processes in complex (dusty) plasmas: Charging, interactions, and ion drag force," Contrib. Plasma Phys. **49**, 148 (2009).
[26]I. L. Semenov, S. A. Khrapak, and H. M. Thomas, "Approximate expression for the electric potential around an absorbing particle in isotropic collisionless plasma," Phys. Plasmas **22**, 053704 (2015).
[27]C. H. Su and S. H. Lam, "Continuum theory of spherical electrostatic probes," Phys. Fluids **6**, 1479 (1963).
[28]A. V. Filippov, A. G. Zagorodny, A. F. Pal', and A. N. Starostin, "Screening of the dust-particle charge in a plasma with an external ionization source," JETP Lett. **81**, 146 (2005).
[29]A. V. Filippov, A. G. Zagorodny, A. F. Pal', A. N. Starostin, and A. I. Momot, "Kinetic description of the screening of the charge of macroparticles in a nonequilibrium plasma," JETP Lett. **86**, 761 (2007).
[30]S. A. Khrapak, B. A. Klumov, and G. E. Morfill, "Electric potential around an absorbing body in plasmas: Effect of ion-neutral collisions," Phys. Rev. Lett. **100**, 225003 (2008).
[31]A. V. Filippov, A. G. Zagorodny, A. I. Momot, A. F. Pal', and A. N. Starostin, "Interaction of two macroparticles in a nonequilibrium plasma," J. Exp. Theor. Phys. **105**, 831 (2007).
[32]A. I. Momot and A. G. Zagorodny, "Toward analytical description of the electrostatic potential of charged macroparticle in weakly ionized plasma," EPL **114**, 65004 (2016).
[33]G. L. Delzanno, G. Lapenta, and M. Rosenberg, "Attractive potential around a thermionically emitting microparticle," Phys. Rev. Lett. **92**, 350021–350024 (2004).
[34]C. Castaldo, U. de Angelis, and V. N. Tsytovich, "Screening and attraction of dust particles in plasmas," Phys. Rev. Lett. **96**, 075004 (2006).
[35]V. Tsytovich, R. Kompaneets, U. de Angelis, and C. Castaldo, "Collective grain interactions for constant ionization source," Contrib. Plasma Phys. **46**, 280 (2006).
[36]M. Chaudhuri, R. Kompaneets, and G. E. Morfill, "On the possibility of collective attraction in complex plasmas," Phys. Plasmas **17**, 063705 (2010).
[37]U. de Angelis, G. Regnoli, and S. Ratynskaia, "Long-range attraction of negatively charged dust particles in weakly ionized dense dust clouds," Phys. Plasmas **17**, 043702 (2010).
[38]S. A. Khrapak, A. V. Ivlev, G. E. Morfill, and H. M. Thomas, "Ion drag force in complex plasmas," Phys. Rev. E **66**, 046414 (2002).
[39]S. A. Khrapak, A. V. Ivlev, G. E. Morfill, S. K. Zhdanov, and H. M. Thomas, "Scattering in the attractive Yukawa potential: Application to the ion-drag force in complex plasmas," IEEE Trans. Plasma Sci. **32**, 555 (2004).
[40]S. A. Khrapak, "Accurate momentum transfer cross section for the attractive Yukawa potential," Phys. Plasmas **21**, 044506 (2014).
[41]I. L. Semenov, S. A. Khrapak, and H. M. Thomas, "Momentum transfer cross-section for ion scattering on dust particles," Phys. Plasmas **24**, 033710 (2017).
[42]A. V. Ivlev, S. A. Khrapak, S. K. Zhdanov, G. E. Morfill, and G. Joyce, "Force on a charged test particle in a collisional flowing plasma," Phys. Rev. Lett. **92**, 205007 (2004).
[43]A. V. Ivlev, S. K. Zhdanov, S. A. Khrapak, and G. E. Morfill, "Kinetic approach for the ion drag force in a collisional plasma," Phys. Rev. E **71**, 016405 (2005).
[44]S. A. Khrapak, A. V. Ivlev, S. K. Zhdanov, and G. E. Morfill, "Hybrid approach to the ion drag force," Phys. Plasmas **12**, 042308 (2005).
[45]I. H. Hutchinson, "Collisionless ion drag force on a spherical grain," Plasma Phys. Controlled Fusion **48**, 185 (2006).
[46]L. Patacchini and I. H. Hutchinson, "Fully self-consistent ion-drag-force calculations for dust in collisional plasmas with an external electric field," Phys. Rev. Lett. **101**, 025001 (2008).
[47]I. H. Hutchinson and C. B. Haakonsen, "Collisional effects on nonlinear ion drag force for small grains," Phys. Plasmas **20**, 083701 (2013).
[48]J. Allen, B. Annaratone, and U. de Angelis, "On the orbital motion limited theory for a small body at floating potential in a maxwellian plasma," J. Plasma Phys. **63**, 299–309 (2000).
[49]G. L. Delzanno and X.-Z. Tang, "Comparison of dust charging between orbital-motion-limited theory and particle-in-cell simulations," Phys. Plasmas **22**, 113703 (2015).
[50]G. L. Delzanno and X.-Z. Tang, "Dust-plasma interaction: A review of dust charging theory and simulation," in *Plasma Modeling*, 2nd ed. (IOP Publishing Ltd., 2022), p. 18–1.
[51]J. Winter, "Dust in fusion devices-experimental evidence, possible sources and consequences," Plasma Phys. Controlled Fusion **40**, 1201 (1998).
[52]J. Sharpe, D. Petti, and H.-W. Bartels, "A review of dust in fusion devices: Implications for safety and operational performance," Fusion Eng. Des. **63–64**, 153–163 (2002).
[53]Z. Wang, C. H. Skinner, G. L. Delzanno, S. I. Krasheninnikov, G. M. Lapenta, A. Y. Pigarov, P. K. Shukla, R. D. Smirnov, C. M. Ticos, and W. Phil West, "Physics of dust in magnetic fusion devices," in *New Aspects of Plasma Physics* (World Scientific, 2010), pp. 394–475.
[54]S. I. Krasheninnikov, R. D. Smirnov, and D. L. Rudakov, "Dust in magnetic fusion devices," Plasma Phys. Controlled Fusion **53**, 083001 (2011).
[55]S. Ratynskaia, A. Bortolon, and S. I. Krasheninnikov, "Dust and powder in fusion plasmas: Recent developments in theory, modeling, and experiments," Rev. Mod. Plasma Phys. **6**, 20 (2022).
[56]G. L. Delzanno and X.-Z. Tang, "Charging and heat collection by a positively charged dust grain in a plasma," Phys. Rev. Lett. **113**, 035002 (2014).
[57]N. Rizopoulou and M. Bacharis, "Emitting large dust grains: Floating potential and potential wells," Phys. Plasmas **25**, 063703 (2018).
[58]A. Autricque, S. A. Khrapak, L. Couëdel, N. Fedorczak, C. Arnas, J.-M. Layet, and C. Grisolia, "Electron collection and thermionic emission from a spherical dust grain in the space-charge limited regime," Phys. Plasmas **25**, 063701 (2018).
[59]A. A. Autricque, N. Fedorczak, S. A. Khrapak, L. Couedel, B. Klumov, C. Arnas, N. Ning, J.-M. Layet, and C. Grisolia, "Magnetized electron emission from a small spherical dust grain in fusion related plasmas," Phys. Plasmas **24**, 124502 (2017).
[60]L. Vignitchouk, S. Ratynskaia, and P. Tolias, "Analytical model of particle and heat flux collection by dust immersed in dense magnetized plasmas," Plasma Phys. Controlled Fusion **59**, 104002 (2017).
[61]G. Lapenta, "Linear theory of plasma wakes," Phys. Rev. E **62**, 1175 (2000).
[62]D. Winske, W. Daughton, D. S. Lemons, and M. S. Murillo, "Ion kinetic effects on the wake potential behind a dust grain in a flowing plasma," Phys. Plasmas **7**, 2320 (2000).
[63]M. Lampe, T. B. Röcker, G. Joyce, S. K. Zhdanov, A. V. Ivlev, and G. E. Morfill, "Ion distribution function in a plasma with uniform electric field," Phys. Plasmas **19**, 113703 (2012).
[64]R. Kompaneets, G. E. Morfill, and A. V. Ivlev, "Interparticle attraction in 2D complex plasmas," Phys. Rev. Lett. **116**, 125001 (2016).
[65]R. Kompaneets, G. E. Morfill, and A. V. Ivlev, "Wakes in complex plasmas: A self-consistent kinetic theory," Phys. Rev. E **93**, 063201 (2016).
[66]I. H. Hutchinson, "Forces on a small grain in the nonlinear plasma wake of another," Phys. Rev. Lett. **107**, 095001 (2011).

[67]I. H. Hutchinson, "Intergrain forces in low-Mach-number plasma wakes," Phys. Rev. E **85**, 066409 (2012).
[68]W. J. Miloch and D. Block, "Dust grain charging in a wake of other grains," Phys. Plasmas **19**, 123703 (2012).
[69]S. Sundar and Z. Moldabekov, "Plasma-grain interaction mediated by streaming non-Maxwellian ions," Phys. Rev. E **99**, 063202 (2019).
[70]G. A. Hebner and M. E. Riley, "Structure of the ion wakefield in dusty plasmas," Phys. Rev. E **69**, 026405 (2004).
[71]H. Jung, F. Greiner, O. H. Asnaz, J. Carstensen, and A. Piel, "Exploring the wake of a dust particle by a continuously approaching test grain," Phys. Plasmas **22**, 053702 (2015).
[72]L. S. Matthews, K. Vermillion, P. Hartmann, M. Rosenberg, S. Rostami, E. G. Kostadinova, T. W. Hyde, M. Y. Pustylnik, A. M. Lipaev, A. D. Usachev, A. V. Zobnin, M. H. Thoma, O. F. Petrov, H. M. Thomas, and O. V. Novitskiy, "Effect of ionization waves on dust chain formation in a DC discharge," J. Plasma Phys. **87**, 905870618 (2021).
[73]A. Melzer, V. A. Schweigert, I. V. Schweigert, A. Homann, S. Peters, and A. Piel, "Structure and stability of the plasma crystal," Phys. Rev. E **54**, R46 (1996).
[74]A. Melzer, V. A. Schweigert, and A. Piel, "Transition from attractive to repulsive forces between dust molecules in a plasma sheath," Phys. Rev. Lett. **83**, 3194 (1999).
[75]A. V. Ivlev, J. Bartnick, M. Heinen, C.-R. Du, V. Nosenko, and H. Löwen, "Statistical mechanics where Newton's third law is broken," Phys. Rev. X **5**, 011035 (2015).
[76]N. P. Kryuchkov, A. V. Ivlev, and S. O. Yurchenko, "Dissipative phase transitions in systems with nonreciprocal effective interactions," Soft Matter **14**, 9720 (2018).
[77]A. V. Zampetaki, H. Huang, C.-R. Du, H. Löwen, and A. V. Ivlev, "Buckling of two-dimensional plasma crystals with nonreciprocal interactions," Phys. Rev. E **102**, 043204 (2020).
[78]E. A. Lisin, O. F. Petrov, E. A. Sametov, O. S. Vaulina, K. B. Statsenko, M. M. Vasiliev, J. Carmona-Reyes, and T. W. Hyde, "Experimental study of the nonreciprocal effective interactions between microparticles in an anisotropic plasma," Sci. Rep. **10**, 13653 (2020).
[79]M. Nambu, M. Salimullah, and R. Bingham, "Effect of a magnetic field on the wake potential in a dusty plasma with streaming ions," Phys. Rev. E **63**, 056403 (2001).
[80]J.-P. Joost, P. Ludwig, H. Kählert, C. Arran, and M. Bonitz, "Screened coulomb potential in a flowing magnetized plasma," Plasma Phys. Controlled Fusion **57**, 025004 (2015).
[81]P. Ludwig, H. Jung, H. Kählert, J.-P. Joost, F. Greiner, Z. Moldabekov, J. Carstensen, S. Sundar, M. Bonitz, and A. Piel, "Non-Maxwellian and magnetic field effects in complex plasma wakes," Eur. Phys. J. D **72**, 82 (2018).
[82]A. Piel, D. Block, A. Melzer, M. Mulsow, J. Schablinski, A. Schella, F. Wieben, and J. Wilms, "Microphysics of liquid complex plasmas in equilibrium and non-equilibrium systems," Eur. Phys. J. D: At. Mol. Opt. Phys. **72**, 80 (2018).
[83]A. Piel, H. Jung, and F. Greiner, "Molecular dynamics simulations of wake structures behind a microparticle in a magnetized ion flow. II. Effects of velocity spread and ion collisions," Phys. Plasmas **25**, 083703 (2018).
[84]L. James and M. Coppins, "Suppression of the ion drag force on dust in magnetized plasmas," Phys. Plasmas **27**, 063704 (2020).
[85]L. Patacchini and I. H. Hutchinson, "Ion-collecting sphere in a stationary, weakly magnetized plasma with finite shielding length," Plasma Phys. Controlled Fusion **49**, 1719 (2007).
[86]L. Patacchini and I. H. Hutchinson, "Spherical conducting probes in finite Debye length plasmas and $E \times B$ fields," Plasma Phys. Controlled Fusion **53**, 025005 (2011).
[87]W. J. Miloch, H. Jung, D. Darian, F. Greiner, M. Mortensen, and A. Piel, "Dynamic ion shadows behind finite-sized objects in collisionless magnetized plasma flows," New J. Phys. **20**, 073027 (2018).
[88]D. Darian, W. J. Miloch, M. Mortensen, Y. Miyake, and H. Usui, "Numerical simulations of a dust grain in a flowing magnetized plasma," Phys. Plasmas **26**, 043701 (2019).
[89]V. Demidov, S. Ratynskaia, and K. Rypdal, "Electric probes for plasmas: The link between theory and instrument," Rev. Sci. Instrum. **73**, 3409 (2002).
[90]S. Takamura, S. Mizoshita, and N. Ohno, "Suppression of secondary electron emission from the material surfaces with grazing incident magnetic field in the plasma," Phys. Plasmas **3**, 4310 (1996).
[91]M. Komm, P. Tolias, S. Ratynskaia, R. Dejarnac, J. P. Gunn, K. Krieger, A. Podolnik, R. A. Pitts, and R. Panek, "Simulations of thermionic suppression during tungsten transient melting experiments," Phys. Scr. **T170**, 014069 (2017).
[92]S. Robertson, "Sheaths in laboratory and space plasmas," Plasma Phys. Controlled Fusion **55**, 093001 (2013).
[93]M. Komm, S. Ratynskaia, P. Tolias, and A. Podolnik, "Space-charge limited thermionic sheaths in magnetized fusion plasmas," Nucl. Fusion **60**, 054002 (2020).
[94]S. D. Baalrud, B. Scheiner, B. T. Yee, M. M. Hopkins, and E. Barnat, "Interaction of biased electrodes and plasmas: Sheaths, double layers, and fireballs," Plasma Sources Sci. Technol. **29**, 053001 (2020).
[95]P. Tolias, M. Komm, S. Ratynskaia, and A. Podolnik, "ITER relevant multiemissive sheaths at normal magnetic field inclination," Nucl. Fusion **63**, 026007 (2023).
[96]W. Xu, N. D'Angelo, and R. L. Merlino, "Dusty plasmas: The effect of closely packed grains," J. Geophys. Res. **98**, 7843, https://doi.org/10.1029/93JA00309 (1993).
[97]A. Barkan, N. D'Angelo, and R. L. Merlino, "Charging of dust grains in a plasma," Phys. Rev. Lett. **73**, 3093 (1994).
[98]P. K. Shukla and B. Eliasson, "Colloquium: Fundamentals of dust-plasma interactions," Rev. Mod. Phys. **81**, 25 (2009).
[99]S. A. Khrapak, H. M. Thomas, and G. E. Morfill, "Multiple phase transitions associated with charge cannibalism effect in complex (dusty) plasmas," EPL **91**, 25001 (2010).
[100]R. Merlino, "Dusty plasmas: From Saturn's rings to semiconductor processing devices," Adv. Phys.: X **6**, 1873859 (2021).
[101]V. N. Tsytovich and U. de Angelis, "Kinetic theory of dusty plasmas. III. Dust-dust collision integrals," Phys. Plasmas **8**, 1141 (2001).
[102]P. Tolias and S. Ratynskaia, "Screening in weakly ionized dusty plasmas; effect of dust density perturbations," Phys. Plasmas **20**, 023702 (2013).
[103]D. Block and W. J. Miloch, "Charging of multiple grains in subsonic and supersonic plasma flows," Plasma Phys. Controlled Fusion **57**, 014019 (2015).
[104]D. Block and A. Melzer, "Dusty (complex) plasmas-routes towards magnetized and polydisperse systems," J. Phys. B: At. Mol. Opt. Phys. **52**, 063001 (2019).
[105]R. Kompaneets, A. Ivlev, V. Nosenko, and G. Morfill, "Wakes in inhomogeneous plasmas," Phys. Rev. E **89**, 043108 (2014).
[106]T. Nitter, "Levitation of dust in RF and DC glow discharges," Plasma Sources Sci. Technol. **5**, 93 (1996).
[107]M. Puttscher and A. Meltzer, "Dust particles under the influence of crossed electric and magnetic fields in the sheath of an RF discharge," Phys. Plasmas **21**, 123704 (2014).
[108]J. E. Colwell, S. Batiste, M. Horanyi, S. Robertson, and S. Sture, "Lunar surface: Dust dynamics and regolith mechanics," Rev. Geophys. **45**, RG2006, https://doi.org/10.1029/2005RG000184 (2007).
[109]S. I. Popel, A. P. Golub', A. I. Kassem, and L. M. Zelenyi, "Dust dynamics in the lunar dusty plasmas: Effects of magnetic fields and dust charge variations," Phys. Plasmas **29**, 013701 (2022).
[110]C. M. Hartzell, P. Bellan, D. Bodewits, G. L. Delzanno, M. Hirabayashi, T. Hyde, U. Konopka, E. Thomas, H. M. Thomas, I. Hahn, and U. Israelsson, "Payload concepts for investigations of electrostatic dust motion on the lunar surface," Acta Astronaut. **207**, 89 (2023).
[111]A. Shalpegin, F. Brochard, S. Ratynskaia, P. Tolias, M. De Angeli, L. Vignitchouk, I. Bykov, S. Bardin, K. Bystrov, T. Morgan, and G. De Temmerman, "Highly resolved measurements of dust motion in the sheath boundary of magnetized plasmas," Nucl. Fusion **55**, 112001 (2015).
[112]S. Ratynskaia, P. Tolias, M. De Angeli, V. Rohde, A. Herrmann, D. Ripamonti, G. Riva, E. Thoren, L. Vignitchouk, B. Sieglin, K. Krieger, R. Neu, ASDEX-Upgrade team, and EUROfusion MST1 team, "Interaction of metal dust adhered on castellated substrates with the ELMy H-mode plasmas of ASDEX-Upgrade," Nucl. Fusion **58**, 106023 (2018).
[113]J.-E. Wahlund, M. André, A. Eriksson, M. Lundberg, M. Morooka, M. Shafiq, T. Averkamp, D. Gurnett, G. Hospodarsky, W. Kurth, K. Jacobsen, A.

Pedersen, W. Farrell, S. Ratynskaia, and N. Piskunov, "Detection of dusty plasma near the E-ring of Saturn," Planet. Space Sci. **57**, 1795 (2009).
[114]Z. Zhang, R. T. Desai, Y. Miyake, H. Usui, and O. Shebanits, "Particle-in-cell simulations of the Cassini spacecraft's interaction with Saturn's ionosphere during the Grand Finale," Mon. Not. R. Astron. Soc. **504**, 964 (2021).
[115]P. Tolias, S. Ratynskaia, M. De Angeli, G. De Temmerman, D. Ripamonti, G. Riva, I. Bykov, A. Shalpegin, L. Vignitchouk, F. Brochard, K. Bystrov, S. Bardin, and A. Litnovsky, "Dust remobilization in fusion plasmas under steady state conditions," Plasma Phys. Controlled Fusion **58**, 025009 (2016).
[116]L. Vignitchouk, K. Paschalidis, S. Ratynskaia, P. Tolias, and R. A. Pitts, "Remobilized dust dynamics and inventory evolution in ITER-like start-up plasmas," Plasma Phys. Controlled Fusion **65**, 015014 (2023).
[117]A. A. Sickafoose, J. E. Colwell, M. Horányi, and S. Robertson, "Experimental levitation of dust grains in a plasma sheath," J. Geophys. Res. **107**(A11), 1408, https://doi.org/10.1029/2002JA009347 (2002).
[118]C. M. Hartzell and D. J. Scheeres, "The role of cohesive forces in particle launching on the moon and asteroids," Planet. Space Sci. **59**, 1758 (2011).
[119]G. Riva, P. Tolias, S. Ratynskaia, G. Daminelli, R. Donde, M. De Angeli, E. Vassallo, and M. Pedroni, "Adhesion measurements for tungsten dust deposited on tungsten surfaces," Nucl. Mater. Energy **12**, 593 (2017).
[120]P. Tolias, "Lifshitz calculations of Hamaker constants for fusion relevant materials," Fusion Eng. Des. **133**, 110 (2018).
[121]P. Tolias, "Non-retarded room temperature Hamaker constants between elemental metals," Surf. Sci. **700**, 121652 (2020).
[122]Z. Wang, D. Tian, Z. Ma, C. Zhao, Y. Liu, Y. Liu, Y. Ding, and Z. Shen, "An electrostatic lofting model based on adhesion separation characteristics for lunar dust," Planet. Space Sci. **184**, 104883 (2020).
[123]I. M. Bronshtein and B. C. Fraiman, *Secondary Electron Emission* (Nauka, Moscow, 1969).
[124]D. Hasselkamp, *Particle Induced Electron Emission II* (Springer-Verlag, 1992).
[125]R. Baragiola, *Ionization of Solids by Heavy Particles* (Springer-Science, 1993).
[126]W. Eckstein, *Reflection (Backscattering)* (Max Planck Institute for Plasma Physics-Garching, 2009).
[127]R. Behrisch and W. Eckstein, *Sputtering by Particle Bombardment: Experiments and Computer Calculations from Threshold to MeV Energies* (Springer, 2007).
[128]L. Vignitchouk, P. Tolias, and S. Ratynskaia, "Dust-wall and dust-plasma interaction in the migraine code," Plasma Phys. Controlled Fusion **56**, 095005 (2014).
[129]L. Vignitchouk, G. L. Delzanno, P. Tolias, and S. Ratynskaia, "Electron reflection effects on particle and heat fluxes to positively charged dust subject to strong electron emission," Phys. Plasmas **25**, 063702 (2018).
[130]P. Tolias, M. Komm, S. Ratynskaia, and A. Podolnik, "Origin and nature of the emissive sheath surrounding hot tungsten tokamak surfaces," Nucl. Mater. Energy **25**, 100818 (2020).
[131]P. Tolias, "On secondary electron emission and its semi-empirical description," Plasma Phys. Controlled Fusion **56**, 123002 (2014).
[132]P. Tolias, "On electron backscattering from dust grains in fusion plasmas," Plasma Phys. Controlled Fusion **56**, 045003 (2014).
[133]L. Yang, A. Hussain, S. Mao, B. Da, K. Tokesi, and Z. J. Ding, "Electron backscattering coefficients of molybdenum and tungsten based on the Monte Carlo simulations," J. Nucl. Mater. **553**, 153042 (2021).
[134]F. X. Bronold and H. Fehske, "Absorption of an electron by a dielectric wall," Phys. Rev. Lett. **115**, 225001 (2015).
[135]F. X. Bronold and H. Fehske, "Microscopic theory of electron absorption by plasma-facing surfaces," Plasma Phys. Controlled Fusion **59**, 014011 (2017).
[136]H. Krüger, C. Killer, S. Schütt, and A. Melzer, "Characterization of injected aluminum oxide nanoparticle clouds in an RF discharge," Plasma Sources Sci. Technol. **27**, 025004 (2018).
[137]L. Vignitchouk, S. Ratynskaia, M. Kantor, P. Tolias, M. De Angeli, H. van der Meiden, J. Verminnen, F. Brochard, A. Shalpegin, E. Thoren, and J.-P. Banon, "Validating heat balance models for tungsten dust in cold dense plasmas," Plasma Phys. Controlled Fusion **60**, 115002 (2018).
[138]M. Bonitz, A. Filinov, J.-W. Abraham, K. Balzer, H. Kählert, E. Pehlke, F. X. Bronold, M. Pamperin, M. Becker, D. Loffhagen, and H. Fehske, "Towards an integrated modeling of the plasma-solid interface," Front. Chem. Sci. Eng. **13**, 201 (2019).
[139]F. X. Bronold, K. Rasek, and H. Fehske, "Electron microphysics at plasma-solid interfaces," J. Appl. Phys. **128**, 180908 (2020).
[140]J. Mahmoodi, P. K. Shukla, N. L. Tsintsadze, and D. D. Tskhakaya, "Dispersion properties of a dusty plasma containing nonspherical rotating dust grains," Phys. Rev. Lett. **84**, 2626 (2000).
[141]P. K. Shukla, "Interaction potentials in a plasma with streaming ions and non-spherical dust rods," Phys. Lett. A **289**, 89 (2001).
[142]A. V. Ivlev, A. G. Khrapak, S. A. Khrapak, B. M. Annaratone, G. Morfill, and K. Yoshino, "Rodlike particles in gas discharge plasmas: Theoretical model," Phys. Rev. E **68**, 026403 (2003).
[143]S. I. Krasheninnikov, "On the dynamics of nonspherical dust grain in plasma," Phys. Plasmas **17**, 033703 (2010).
[144]S. I. Krasheninnikov, "On the force exerted on a non-spherical dust grain from homogeneous magnetized plasma," Phys. Plasmas **30**, 040701 (2023).
[145]B. T. Draine and A. Lazarian, "Diffuse galactic emission from spinning dust grains," Astrophys. J. **494**, L19 (1998).
[146]S. I. Krasheninnikov, V. I. Shevchenko, and P. K. Shukla, "Spinning of a charged dust particle in a magnetized plasma," Phys. Lett. A **361**, 133 (2007).
[147]T. Hoang, B. T. Draine, and A. Lazarian, "Improving the model of emission from spinning dust: Effects of grain wobbling and transient spin-up," Astrophys. J. **715**, 1462 (2010).
[148]E. S. Dzlieva, V. Y. Karasev, and O. F. Petrov, "Direct observation of dynamics of single spinning dust grains in weakly magnetized complex plasma," JETP **114**, 167 (2012).
[149]J. T. Holgate, L. Simons, Y. Andrew, C. K. Stavrou, and JET Contributors, "Spontaneous rapid rotation and breakup of metal droplets in tokamak edge plasmas," EPL **127**, 45004 (2019).
[150]G. L. Delzanno, E. Camporeale, J. D. Moulton, J. E. Borovsky, E. A. MacDonald, and M. F. Thomsen, "CPIC: A curvilinear particle-in-cell code for plasma-material interaction studies," IEEE Trans. Plasma Sci. **41**, 3577 (2013).
[151]C. S. Meierbachtol, D. Svyatskiy, G. L. Delzanno, L. J. Vernon, and J. D. Moulton, "An electrostatic particle-in-cell code on multi-block structured meshes," J. Comput. Phys. **350**, 796–823 (2017).
[152]A. V. Ivlev, G. Morfill, and V. E. Fortov, "Potential of a dielectric particle in a flow of a collisionless plasma," Phys. Plasmas **6**, 1415 (1999).
[153]M. De Angeli, E. Lazzaro, P. Tolias, S. Ratynskaia, L. Vignitchouk, C. Castaldo, M. L. Apicella, G. Gervasini, G. Giacomi, E. Giovannozzi, G. Granucci, M. Iafrati, D. Iraji, G. Maddaluno, G. Riva, and A. Uccello, "Pre-plasma remobilization of ferromagnetic dust in FTU and possible interference with tokamak operations," Nucl. Fusion **59**, 106033 (2019).
[154]A. Bogaerts and R. Gijbels, "The role of fast argon ions and atoms in the ionization of argon in a direct-current glow discharge: A mathematical simulation," J. Appl. Phys. **78**, 6427–6431 (1995).
[155]E. Shidoji, H. Ohtake, N. Nakano, and T. Makabe, "Two-dimensional self-consistent simulation of a DC magnetron discharge," Jpn. J. Appl. Phys., Part 1 **38**, 2131 (1999).
[156]F. Sigeneger, Z. Donkó, and D. Loffhagen, "Boltzmann equation and particle-fluid hybrid modelling of a hollow cathode discharge," Eur. Phys. J. Appl. Phys. **38**, 161–167 (2007).
[157]J. P. Boeuf, "Ionization waves (striations) in a low-current plasma column revisited with kinetic and fluid models," Phys. Plasmas **29**, 022105 (2022).
[158]A. V. Zobnin, A. D. Usachev, O. F. Petrov, and V. E. Fortov, "Two-dimensional positive column structure in a discharge tube with radius discontinuity," Phys. Plasmas **21**, 113503 (2014).
[159]A. V. Zobnin, A. D. Usachev, O. F. Petrov, V. E. Fortov, and M. A. Bukharin, "Simulations of the DC-discharge plasma with dusty structure," AIP Conf. Proc. **1397**, 150–151 (2011).
[160]A. V. Zobnin, A. D. Usachev, O. F. Petrov, V. E. Fortov, M. H. Thoma, and M. A. Fink, "Two-dimensional positive column structure with dust cloud: Experiment and nonlocal kinetic simulation," Phys. Plasmas **25**, 033702 (2018).
[161]C. K. Birdsall, J. Hammel, and J. Verboncoeur, "1D and 2D PIC-MCC simulations of DC discharges between planar electrodes," in *Proceedings of the IEEE Conference Record–Abstracts, IEEE International Conference on Plasma Science* (IEEE, 2005), pp. 284–284.
[162]P. Hartmann, M. Rosenberg, Z. Juhasz, L. S. Matthews, D. L. Sanford, K. Vermillion, J. C. Reyes, and T. W. Hyde, "Ionization waves in the PK-4 direct current neon discharge," Plasma Sources Sci. Technol. **29**, 115014 (2020).

[163]V. K. Gandi, R. Verma, G. Singh, M. K. Warrier, and A. Sharma, "Experimental study and 3d PIC-MCC simulation of DC discharge in various concentrations of SF6 admixture," IEEE Trans. Dielectr. Electr. Insul. **30**, 1096–1104 (2023).
[164]M. M. Becker, H. Kählert, A. Sun, M. Bonitz, and D. Loffhagen, "Advanced fluid modeling and PIC/MCC simulations of low-pressure CCRF discharges," Plasma Sources Sci. Technol. **26**, 044001 (2017).
[165]E. D. Held, J. D. Callen, C. C. Hegna, C. R. Sovinec, T. A. Gianakon, and S. E. Kruger, "Nonlocal closures for plasma fluid simulations," Phys. Plasmas **11**, 2419–2426 (2004).
[166]A. P. Jovanović, D. Loffhagen, and M. M. Becker, "Introduction and verification of fedm, an open-source fenics-based discharge modelling code," Plasma Sources Sci. Technol. **32**, 044003 (2023).
[167]R. D. White, R. E. Robson, S. Dujko, P. Nicoletopoulos, and B. Li, "Recent advances in the application of boltzmann equation and fluid equation methods to charged particle transport in non-equilibrium plasmas," J. Phys. D: Appl. Phys. **42**, 194001 (2009).
[168]M. J. Kushner, "Hybrid modelling of low temperature plasmas for fundamental investigations and equipment design," J. Phys. D: Appl. Phys. **42**, 194013 (2009).
[169]D. Tskhakaya, K. Matyash, R. Schneider, and F. Taccogna, "The particle-in-cell method," Contrib. Plasma Phys. **47**, 563–594 (2007).
[170]J. P. Verboncoeur, "Particle simulation of plasmas: Review and advances," Plasma Phys. Controlled Fusion **47**, A231 (2005).
[171]H. C. Kim, F. Iza, S. S. Yang, M. Radmilović-Radjenović, and J. K. Lee, "Particle and fluid simulations of low-temperature plasma discharges: Benchmarks and kinetic effects," J. Phys. D: Appl. Phys. **38**, R283 (2005).
[172]A. Sun, M. M. Becker, and D. Loffhagen, "PIC/MCC simulation of capacitively coupled discharges: Effect of particle management and integration," Comput. Phys. Commun. **206**, 35–44 (2016).
[173]M. Vass, P. Palla, and P. Hartmann, "Revisiting the numerical stability/accuracy conditions of explicit PIC/MCC simulations of low-temperature gas discharges," Plasma Sources Sci. Technol. **31**, 064001 (2022).
[174]J. van Dijk, G. M. W. Kroesen, and A. Bogaerts, "Plasma modelling and numerical simulation," J. Phys. D: Appl. Phys. **42**, 190301 (2009).
[175]J. G. Laframboise and L. W. Parker, "Probe design for orbit-limited current collection," Phys. Fluids **16**, 629–636 (1973).
[176]J. E. Allen, "Probe theory—The orbital motion approach," Phys. Scr. **45**, 497–503 (1992).
[177]E. C. Whipple, "Potentials of surfaces in space," Rep. Prog. Phys. **44**, 1197 (1981).
[178]L. S. Matthews, D. L. Sanford, E. G. Kostadinova, K. S. Ashrafi, E. Guay, and T. W. Hyde, "Dust charging in dynamic ion wakes," Phys. Plasmas **27**, 023703 (2020).
[179]M. Bacharis, M. Coppins, and J. E. Allen, "Dust in tokamaks: An overview of the physical model of the dust in tokamaks code," Phys. Plasmas **17**, 042505 (2010).
[180]G. Lapenta, "Nature of the force field in plasma wakes," Phys. Rev. E **66**, 026409 (2002).
[181]L. Couëdel, V. Nosenko, A. V. Ivlev, S. K. Zhdanov, H. M. Thomas, and G. E. Morfill, "Direct observation of mode-coupling instability in two-dimensional plasma crystals," Phys. Rev. Lett. **104**, 195001 (2010).
[182]V. Nosenko, A. V. Ivlev, R. Kompaneets, and G. Morfill, "Stability and size of particle pairs in complex plasmas," Phys. Plasmas **21**, 113701 (2014).
[183]K. Vermillion, D. Sanford, L. Matthews, P. Hartmann, M. Rosenberg, E. Kostadinova, J. Carmona-Reyes, T. Hyde, A. M. Lipaev, A. D. Usachev, A. V. Zobnin, O. F. Petrov, M. H. Thoma, M. Y. Pustylnik, H. M. Thomas, and A. Ovchinin, "Influence of temporal variations in plasma conditions on the electric potential near self-organized dust chains," Phys. Plasmas **29**, 023701 (2022).
[184]V. R. Ikkurthi, K. Matyash, A. Melzer, and R. Schneider, "Computation of charge and ion drag force on multiple static spherical dust grains immersed in RF discharges," Phys. Plasmas **17**, 103712 (2010).
[185]W. J. Miloch, M. Kroll, and D. Block, "Charging and dynamics of a dust grain in the wake of another grain in flowing plasmas," Phys. Plasmas **17**, 103703 (2010).
[186]K. S. Ashrafi, R. Yousefi, M. Chen, L. S. Matthews, and T. W. Hyde, "Dust as probes: Determining confinement and interaction forces," Phys. Rev. E **102**, 043210 (2020).
[187]A. Melzer, A. Schella, and M. Mulsow, "Nonequilibrium finite dust clusters: Connecting normal modes and wakefields," Phys. Rev. E **89**, 013109 (2014).
[188]K. Qiao, J. Kong, E. V. Oeveren, L. S. Matthews, and T. W. Hyde, "Mode couplings and resonance instabilities in dust clusters," Phys. Rev. E **88**, 043103 (2013).
[189]K. Qiao, J. Kong, Z. Zhang, L. Matthews, and T. Hyde, "Mode couplings and conversions for horizontal dust particle pairs in complex plasmas," IEEE Trans. Plasma Sci. **41**, 745–753 (2013).
[190]T. Matsoukas and M. Russell, "Particle charging in low-pressure plasmas," J. Appl. Phys. **77**, 4285–4292 (1995).
[191]C. Cui and J. Goree, "Fluctuations of the charge on a dust grain in a plasma," IEEE Trans. Plasma Sci. **22**, 151–158 (1994).
[192]T. Matsoukas and M. Russell, "Fokker-Planck description of particle charging in ionized gases," Phys. Rev. E **55**, 991–994 (1997).
[193]L. S. Matthews, B. Shotorban, and T. W. Hyde, "Cosmic dust aggregation with stochastic charging," Astrophys. J. **776**, 103 (2013).
[194]L. S. Matthews, B. Shotorban, and T. W. Hyde, "Discrete stochastic charging of aggregate grains," Phys. Rev. E **97**, 053207 (2018).
[195]L. S. Matthews and T. W. Hyde, "Effect of dipole-dipole charge interactions on dust coagulation," New J. Phys. **11**, 063030 (2009).
[196]L. S. Matthews, V. Land, and T. W. Hyde, "Charging and coagulation of dust in protoplanetary plasma environments," Astrophys. J. **744**, 8 (2012).
[197]X. Wang, J. Schwan, H.-W. Hsu, E. Grün, and M. Horányi, "Dust charging and transport on airless planetary bodies," Geophys. Res. Lett. **43**, 6103–6110, https://doi.org/10.1002/2016GL069491 (2016).
[198]L. S. Matthews, D. A. Coleman, and T. W. Hyde, "Multipole expansions of aggregate charge: How far to go?," IEEE Trans. Plasma Sci. **44**, 519–524 (2016).
[199]R. Tian, Y. Liang, S. Hao, J. Feng, X. Jiang, H. Li, C. Yuan, and J. Wu, "Simulation of dc glow discharge plasma with radially free moving dust particles," Plasma Sci. Technol. **25**, 095401 (2023).
[200]J. Schleede, L. Lewerentz, F. X. Bronold, R. Schneider, and H. Fehske, "Plasma flow around and charge distribution of a dust cluster in a RF discharge," Phys. Plasmas **25**, 043702 (2018).
[201]G. Tallents, *An Introduction to the Atomic and Radiation Physics of Plasmas* (Cambridge University Press, 2018).
[202]S. B. Thapa, S. Basnet, and R. Khanal, "Dust charge fluctuation and ion acoustic wave propagation in dusty plasma with q-nonextensive hot and Maxwellian cold electrons," AIP Adv. **12**, 085205 (2022).
[203]X. Zhao, B. Zhang, and C. Wang, "Dust charging and levitating in a magnetized plasma sheath containing superextensive electrons," Phys. Plasmas **27**, 113705 (2020).
[204]M. Y. Pustylnik, M. A. Fink, V. Nosenko, T. Antonova, T. Hagl, H. M. Thomas, A. V. Zobnin, A. M. Lipaev, A. D. Usachev, V. I. Molotkov, O. F. Petrov, V. E. Fortov, C. Rau, C. Deysenroth, S. Albrecht, M. Kretschmer, M. H. Thoma, G. E. Morfill, R. Seurig, A. Stettner, A. Alyamovskaya, A. Orr, E. Kufner, E. G. Lavrenko, G. I. Padalka, E. O. Serova, A. M. Samokutyaev, and S. Christoforetti, "Plasmakristall-4: New complex (dusty) plasma laboratory on board the international space station," Rev. Sci. Instrum. **87**, 093505 (2016).
[205]J. Méndez Harper, G. Gogia, B. Wu, Z. Laseter, and J. C. Burton, "Origin of large-amplitude oscillations of dust particles in a plasma sheath," Phys. Rev. Res. **2**, 033500 (2020).
[206]L. Couëdel and V. Nosenko, "Stability of two-dimensional complex plasma monolayers in asymmetric capacitively coupled radio-frequency discharges," Phys. Rev. E **105**, 015210 (2022).
[207]C. A. Knapek, M. Schwabe, V. Yaroshenko, P. Huber, D. P. Mohr, and U. Konopka, "Dust acoustic wave properties in varying discharge volumes," Phys. Plasmas **30**, 033703 (2023).
[208]J. C. A. van Huijstee, P. Blom, and J. Beckers, "Position dependent microparticle charge in a spatiotemporal afterglow plasma," Phys. Plasmas **30**, 033704 (2023).
[209]I. B. Denysenko, M. Mikikian, and N. A. Azarenkov, "Modeling results on the dust charge distribution in a plasma afterglow," Phys. Plasmas **29**, 093702 (2022).

[210]R. Banka, K. Vermillion, L. Matthews, T. Hyde, and L. Couëdel, "Dependence of ion wake characteristics on experimental conditions," Plasma Phys. Controlled Fusion **65**, 044006 (2023).
[211]M. V. Salnikov, G. I. Sukhinin, and A. V. Fedoseev, "Wake formation in a polarized dusty plasma," Plasma Phys. Rep. **49**, 41–48 (2023).
[212]L. G. Silvestri, L. J. Stanek, G. Dharuman, Y. Choi, and M. S. Murillo, "Sarkas: A fast pure-python molecular dynamics suite for plasma physics," Comput. Phys. Commun. **272**, 108245 (2022).
[213]D. Kolotinskii and A. Timofeev, "Opendust: A fast GPU-accelerated code for the calculation of forces acting on microparticles in a plasma flow," Comput. Phys. Commun. **288**, 108746 (2023).
[214]Z. Ding, L. S. Matthews, and T. W. Hyde, "A machine learning based bayesian optimization solution to non-linear responses in dusty plasmas," Mach. Learn.: Sci. Technol. **2**, 035017 (2021).
[215]W. Yu, J. Cho, and J. C. Burton, "Extracting forces from noisy dynamics in dusty plasmas," Phys. Rev. E **106**, 035303 (2022).
[216]V. A. Godyak and V. I. Demidov, "Probe measurements of electron-energy distributions in plasmas: What can we measure and how can we achieve reliable results?," J. Phys. D: Appl. Phys. **44**, 233001 (2011).
[217]N. Bilik, R. Anthony, B. A. Merritt, E. S. Aydil, and U. R. Kortshagen, "Langmuir probe measurements of electron energy probability functions in dusty plasmas," J. Phys. D: Appl. Phys. **48**, 105204 (2015).
[218]M. Lackner, "Tunable diode laser absorption spectroscopy (TDLAS) in the process industries—A review," Rev. Chem. Eng. **23**, 65–147 (2007).
[219]O. Havnes, C. K. Goertz, G. E. Morfill, E. Grün, and W. Ip, "Dust charges, cloud potential, and instabilities in a dust cloud embedded in a plasma," J. Geophys. Res.: Space Phys. **92**, 2281–2287, https://doi.org/10.1029/JA092iA03p02281 (1987).
[220]A. Petersen, O. H. Asnaz, B. Tadsen, and F. Greiner, "Decoupling of dust cloud and embedding plasma for high electron depletion in nanodusty plasmas," Commun. Phys. **5**, 308 (2022).
[221]A. A. Howling, J. Dorier, and C. Hollenstein, "Negative ion mass spectra and particulate formation in radio frequency silane plasma deposition experiments," Appl. Phys. Lett. **62**, 1341–1343 (1993).
[222]S. J. Choi and M. J. Kushner, "The role of negative ions in the formation of particles in low-pressure plasmas," J. Appl. Phys. **74**, 853–861 (1993).
[223]L. Boufendi, J. Gaudin, S. Huet, G. Viera, and M. Dudemaine, "Detection of particles of less than 5 nm in diameter formed in an argon-silane capacitively coupled radio-frequency discharge," Appl. Phys. Lett. **79**, 4301–4303 (2001).
[224]B. Sikimić, I. Stefanović, I. B. Denysenko, and J. Winter, "A non-invasive technique to determine ion fluxes and ion densities in reactive and non-reactive pulsed plasmas," Plasma Sources Sci. Technol. **22**, 045009 (2013).
[225]S. Hong, J. Berndt, and J. Winter, "Growth precursors and dynamics of dust particle formation in the Ar/CH_4 and Ar/C_2H_2 plasmas," Plasma Sources Sci. Technol. **12**, 46 (2002).
[226]M. Himpel, C. Killer, B. Buttenschön, and A. Melzer, "Three-dimensional single particle tracking in dense dust clouds by stereoscopy of fluorescent particles," Phys. Plasmas **19**, 123704 (2012).
[227]C. Killer, M. Himpel, and A. Melzer, "Computer tomography of large dust clouds in complex plasmas," Rev. Sci. Instrum. **85**, 103711 (2014).
[228]C. Killer, F. Greiner, S. Groth, B. Tadsen, and A. Melzer, "Long-term spatio-temporal evolution of the dust distribution in dusty argon RF plasmas," Plasma Sources Sci. Technol. **25**, 055004 (2016).
[229]S. Barbosa, F. R. A. Onofri, L. Couëdel, M. Wozniak, C. Montet, C. Pelcé, C. Arnas, L. Boufendi, E. Kovacevic, J. Berndt *et al.*, "An introduction to light extinction spectrometry as a diagnostic for dust particle characterisation in dusty plasmas," J. Plasma Phys. **82**, 615820403 (2016).
[230]S. Mitic, M. Y. Pustylnik, G. E. Morfill, and E. Kovačević, "In situ characterization of nanoparticles during growth by means of white light scattering," Opt. Lett. **36**, 3699–3701 (2011).
[231]S. H. Hong and J. Winter, "Size dependence of optical properties and internal structure of plasma grown carbonaceous nanoparticles studied by in situ Rayleigh-Mie scattering ellipsometry," J. Appl. Phys. **100**, 064303 (2006).
[232]S. Groth, F. Greiner, B. Tadsen, and A. Piel, "Kinetic Mie ellipsometry to determine the time-resolved particle growth in nanodusty plasmas," J. Phys. D: Appl. Phys. **48**, 465203 (2015).
[233]S. Groth, F. Greiner, and A. Piel, "Spatio-temporally resolved investigations of layered particle growth in a reactive argon-acetylene plasma," Plasma Sources Sci. Technol. **28**, 115016 (2019).
[234]F. M. J. H. van de Wetering, W. Oosterbeek, J. Beckers, S. Nijdam, E. Kovacevic, and J. Berndt, "Laser-induced incandescence applied to dusty plasmas," J. Phys. D: Appl. Phys. **49**, 295206 (2016).
[235]L. Boufendi, J. Hermann, A. Bouchoule, B. Dubreuil, E. Stoffels, W. W. Stoffels, and M. L. de Giorgi, "Study of initial dust formation in an Ar-SiH_4 discharge by laser induced particle explosive evaporation," J. Appl. Phys. **76**, 148–153 (1994).
[236]O. H. Asnaz, N. Kohlmann, H. Folger, F. Greiner, and J. Benedikt, "Growth and treatment of hydrogenated amorphous carbon nanoparticles in a low-pressure plasma," Plasma Processes Polym. **19**, 2100190 (2022).
[237]S. Stoykov, C. Eggs, and U. Kortshagen, "Plasma chemistry and growth of nanosized particles in a C_2H_2 RF discharge," J. Phys. D: Appl. Phys. **34**, 2160 (2001).
[238]C. Deschenaux, A. Affolter, D. Magni, C. Hollenstein, and P. Fayet, "Investigations of CH_4, C_2H_2 and C_2H_4 dusty RF plasmas by means of FTIR absorption spectroscopy and mass spectrometry," J. Phys. D: Appl. Phys. **32**, 1876 (1999).
[239]J. Kousal, A. Shelemin, M. Schwartzkopf, O. Polonskyi, J. Hanuš, P. Solař, M. Vaidulych, D. Nikitin, P. Pleskunov, Z. Krtouš, T. Strunskus, F. Faupel, S. V. Roth, H. Biederman, and A. Choukourov, "Magnetron-sputtered copper nanoparticles: Lost in gas aggregation and found by in situ x-ray scattering," Nanoscale **10**, 18275–18281 (2018).
[240]H. Krüger, E. Thiessen, F. X. Bronold, H. Fehske, and A. Melzer, "Charge measurement of sio_2 nanoparticles in an RF plasma by IR absorption," Phys. Rev. E **104**, 045208 (2021).
[241]T. J. A. Staps, T. J. M. Donders, B. Platier, and J. Beckers, "In-situ measurement of dust charge density in nanodusty plasma," J. Phys. D: Appl. Phys. **55**, 08LT01 (2021).
[242]G. Friedrichs, "Sensitive absorption methods for quantitative gas phase kinetic measurements. I. Frequency modulation spectroscopy," Z. Phys. Chem. **222**, 1–30 (2008).
[243]M. Pal, M. Stuhr, N. Faßheber, A. Petersen, F. Greiner, and G. Friedrichs, "Mid-IR frequency modulation spectroscopy for sensing C_2H_2 in a dusty plasma," in *Proceedings of the Optical Sensors and Sensing Congress (AIS, LACSEA, Sensors, ES)* (Optica Publishing Group, 2022), p. LM4B.4.
[244]J. Benedikt, "Plasma-chemical reactions: Low pressure acetylene plasmas," J. Phys. D: Appl. Phys. **43**, 043001 (2010).
[245]J. Beckers, F. M. J. H. van de Wetering, B. Platier, M. A. W. van Ninhuijs, G. J. H. Brussaard, V. Y. Banine, and O. J. Luiten, "Mapping electron dynamics in highly transient EUV photon-induced plasmas: A novel diagnostic approach using multi-mode microwave cavity resonance spectroscopy," J. Phys. D: Appl. Phys. **52**, 034004 (2018).
[246]B. Tadsen, F. Greiner, S. Groth, and A. Piel, "Self-excited dust-acoustic waves in an electron-depleted nanodusty plasma," Phys. Plasmas **22**, 113701 (2015).
[247]P. Agarwal and S. L. Girshick, "Numerical modeling of an RF argon–silane plasma with dust particle nucleation and growth," Plasma Chem. Plasma Process. **34**, 489 (2014).
[248]G. Tetard, A. Michau, S. Prasanna, J. Mougenot, P. Brault, and K. Hassouni, "Discharge dynamics, plasma kinetics and gas flow effect in argon-acetylene discharges," Plasma Sources Sci. Technol. **30**, 105015 (2021).
[249]K. De Bleecker, A. Bogaerts, and W. Goedheer, "Modelling of nanoparticle coagulation and transport dynamics in dusty silane discharges," New J. Phys. **8**, 178 (2006).
[250]E. Kovacevic, J. Berndt, T. Strunskus, and L. Boufendi, "Size dependent characteristics of plasma synthesized carbonaceous nanoparticles," J. Appl. Phys. **112**, 013303 (2012).
[251]C. F. Bohren and D. R. Huffman, *Absorption and Scattering of Light by Small Particles* (John Wiley and Sons, New York, 1983).
[252]C. Mätzler, *MATLAB Functions for Mie Scattering and Absorption* (University Bern, Bern, 2002), Version 2.
[253]J. Berndt, E. Kovačević, I. Stefanović, and L. Boufendi, "Controlled dust formation in pulsed RF plasmas," J. Appl. Phys. **106**, 063309 (2009).

[254]M. N. Shneider and S. F. Gimelshein, "Application of coherent Rayleigh-Brillouin scattering for in situ nanoparticle and large molecule detection," Appl. Phys. Lett. **102**, 173109 (2013).
[255]M. Gensch, M. Schwartzkopf, W. Ohm, C. J. Brett, P. Pandit, S. K. Vayalil, L. Bießmann, L. P. Kreuzer, J. Drewes, O. Polonskyi, T. Strunskus, F. Faupel, A. Stierle, P. Müller-Buschbaum, and S. V. Roth, "Correlating nanostructure, optical and electronic properties of nanogranular silver layers during polymer-template-assisted sputter deposition," ACS Appl. Mater. Interfaces **11**, 29416–29426 (2019).
[256]V. I. Molotkov, A. P. Nefedov, V. M. Torchinskii, V. E. Fortov, and A. G. Khrapak, "Dust acoustic waves in a dc glow-discharge plasma," J. Exp. Theor. Phys. **89**, 477–480 (1999).
[257]E. Thomas, "Measurements of spatially growing dust acoustic waves in a dc glow discharge plasma," Phys. Plasmas **13**, 042107 (2006).
[258]V. E. Fortov, A. D. Usachev, A. V. Zobnin, V. I. Molotkov, and O. F. Petrov, "Dust-acoustic wave instability at the diffuse edge of radio frequency inductive low-pressure gas discharge plasma," Phys. Plasmas **10**, 1199–1208 (2003).
[259]J. Goree, B. Liu, M. Y. Pustylnik, H. M. Thomas, V. E. Fortov, A. M. Lipaev, V. I. Molotkov, A. D. Usachev, O. F. Petrov, M. H. Thoma, E. Thomas, U. Konopka, and S. Prokopiev, "Correlation and spectrum of dust acoustic waves in a radio-frequency plasma using PK-4 on the International Space Station," Phys. Plasmas **27**, 123701 (2020).
[260]A. Piel, O. Arp, D. Block, I. Pilch, T. Trottenberg, S. Käding, A. Melzer, H. Baumgartner, C. Henning, and M. Bonitz, "Complex plasmas: Forces and dynamical behaviour," Plasma Phys. Controlled Fusion **50**, 124003 (2008).
[261]M. Schwabe, M. Rubin-Zuzic, S. Zhdanov, H. M. Thomas, and G. E. Morfill, "Highly resolved self-excited density waves in a complex plasma," Phys. Rev. Lett. **99**, 095002 (2007).
[262]K. O. Menzel, O. Arp, and A. Piel, "Spatial frequency clustering in nonlinear dust-density waves," Phys. Rev. Lett. **104**, 235002 (2010).
[263]S. Jaiswal, M. Y. Pustylnik, S. Zhdanov, H. M. Thomas, A. M. Lipaev, A. D. Usachev, V. I. Molotkov, V. E. Fortov, M. H. Thoma, and O. V. Novitskii, "Dust density waves in a dc flowing complex plasma with discharge polarity reversal," Phys. Plasmas **25**, 083705 (2018).
[264]V. Nosenko, S. K. Zhdanov, S.-H. Kim, J. Heinrich, R. L. Merlino, and G. E. Morfill, "Measurements of the power spectrum and dispersion relation of self-excited dust acoustic waves," Europhys. Lett. **88**, 65001 (2009).
[265]U. R. Kortshagen, "On the use of dust plasma acoustic waves for the diagnostic of nanometer-sized contaminant particles in plasmas," Appl. Phys. Lett. **71**, 208–210 (1997).
[266]F. Melandsù, T. K. Aslaksen, and O. Havnes, "A kinetic model for dust acoustic waves applied to planetary rings," J. Geophys. Res.: Space Phys. **98**, 13315–13323, https://doi.org/10.1029/93JA00789 (1993).
[267]M. Rosenberg, "Ion- and dust-acoustic instabilities in dusty plasmas," Planet. Space Sci. **41**, 229–233 (1993).
[268]M. Rosenberg, "Ion-dust streaming instability in processing plasmas," J. Vac. Sci. Technol. A **14**, 631–633 (1996).
[269]M. Rosenberg, "A note on ion-dust streaming instability in a collisional dusty plasma," J. Plasma Phys. **67**, 235–242 (2002).
[270]A. Piel, M. Klindworth, O. Arp, A. Melzer, and M. Wolter, "Obliquely propagating dust-density plasma waves in the presence of an ion beam," Phys. Rev. Lett. **97**, 205009 (2006).
[271]A. Piel, M. Klindworth, O. Arp, A. Melzer, and M. Wolter, "Erratum: Obliquely propagating dust-density plasma waves in the presence of an ion beam [Phys. Rev. Lett. **97**, 205009 (2006)]," Phys. Rev. Lett. **99**, 209903 (2007).
[272]V. V. Yaroshenko, "Nonlinear dispersion relation for dust-acoustic waves in complex plasmas," Phys. Rev. E **102**, 023201 (2020).
[273]S. Khrapak and V. Yaroshenko, "Ion drift instability in a strongly coupled collisional complex plasma," Plasma Phys. Controlled Fusion **62**, 105006 (2020).
[274]K. Quest, M. Rosenberg, and A. Levine, "Simulations of ion–dust streaming instability in a highly collisional plasma," J. Plasma Phys. **86**, 905860605 (2020).
[275]C.-R. Du, H. M. Thomas, A. V. Ivlev, U. Konopka, and G. E. Morfill, "Agglomeration of microparticles in complex plasmas," Phys. Plasmas **17**, 113710 (2010).
[276]S. Dap, D. Lacroix, R. Hugon, L. de Poucques, J.-L. Briancon, and J. Bougdira, "Cluster agglomeration induced by dust-density waves in complex plasmas," Phys. Rev. Lett. **109**, 245002 (2012).
[277]B. Tadsen, F. Greiner, and A. Piel, "Probing a dusty magnetized plasma with self-excited dust-density waves," Phys. Rev. E **97**, 033203 (2018).
[278]G. Praburam and J. Goree, "Experimental observation of very low-frequency macroscopic modes in a dusty plasma," Phys. Plasmas **3**, 1212–1219 (1996).
[279]D. Samsonov and J. Goree, "Instabilities in a dusty plasma with ion drag and ionization," Phys. Rev. E **59**, 1047 (1999).
[280]M. Mikikian, M. Cavarroc, L. Couëdel, and L. Boufendi, "Low frequency instabilities during dust particle growth in a radio-frequency plasma," Phys. Plasmas **13**, 092103 (2006).
[281]M. Mikikian, L. Couëdel, M. Cavarroc, Y. Tessier, and L. Boufendi, "Plasma emission modifications and instabilities induced by the presence of growing dust particles," IEEE Trans. Plasma Sci. **36**, 1012–1013 (2008).
[282]H. Tawidian, T. Lecas, and M. Mikikian, "Zoom into dusty plasma instabilities," IEEE Trans. Plasma Sci. **41**, 754–758 (2013).
[283]H. Tawidian, T. Lecas, and M. Mikikian, "Characterization of low frequency instabilities in a krypton dusty plasma," Plasma Sources Sci. Technol. **23**, 065009 (2014).
[284]M. Cavarroc, M. C. Jouanny, K. Radouane, M. Mikikian, and L. Boufendi, "Self-excited instability occurring during the nanoparticle formation in an Ar-SiH_4 low pressure radio frequency plasma," J. Appl. Phys. **99**, 064301 (2006).
[285]M. Cavarroc, M. Mikikian, G. Perrier, and L. Boufendi, "Single-crystal silicon nanoparticles: An instability to check their synthesis," Appl. Phys. Lett. **89**, 013107 (2006).
[286]M. Cavarroc, M. Mikikian, Y. Tessier, and L. Boufendi, "Instabilities during the growth of dust successive generations in silane-based plasmas," Phys. Plasmas **15**, 103704 (2008).
[287]H. Tawidian, M. Mikikian, L. Couëdel, and T. Lecas, "Plasma inhomogeneities near the electrodes of a capacitively-coupled radio-frequency discharge containing dust particles," Eur. Phys. J. Appl. Phys. **56**, 24018 (2011).
[288]J. F. Lagrange, I. Géraud-Grenier, F. Faubert, and V. Massereau-Guilbaud, "Optical diagnostic and electrical analysis in dusty rf discharges containing plasmoids," J. Appl. Phys. **118**, 163302 (2015).
[289]M. Mikikian, L. Couedel, Y. Tessier, and L. Boufendi, "Carousel instability in a capacitively coupled RF dusty plasma," IEEE Trans. Plasma Sci. **39**, 2748–2749 (2011).
[290]M. Mikikian, H. Tawidian, and T. Lecas, "Merging and splitting of plasma spheroids in a dusty plasma," Phys. Rev. Lett. **109**, 245007 (2012).
[291]A. V. Zobnin, A. D. Usachev, A. M. Lipaev, O. F. Petrov, V. E. Fortov, M. Y. Pustylnik, H. M. Thomas, M. A. Fink, M. H. Thoma, and G. I. Padalka, "Transverse ionization instability of the elongated dust cloud in the gas discharge uniform positive column under microgravity conditions," J. Phys.: Conf. Ser. **774**, 012174 (2016).
[292]A. D. Usachev, A. V. Zobnin, O. F. Petrov, V. E. Fortov, M. H. Thoma, M. Y. Pustylnik, M. A. Fink, and G. E. Morfill, "Elongated dust clouds in a uniform DC positive column of low pressure gas discharge," Plasma Sources Sci. Technol. **25**, 035009 (2016).
[293]J. Berndt, S. Hong, E. Kovačević, I. Stefanović, and J. Winter, "Dust particle formation in low pressure Ar/CH_4 and Ar/C_2H_2 discharges used for thin film deposition," Vacuum **71**, 377–390 (2003).
[294]Y. Qin, N. Bilik, U. R. Kortshagen, and E. S. Aydil, "Laser light scattering from silicon particles generated in an argon diluted silane plasma," J. Phys. D: Appl. Phys. **49**, 085203 (2016).
[295]S. Labidi, T. Lecas, E. Kovacevic, J. Berndt, T. Gibert, and M. Mikikian, "Nanoparticle growth in ethanol based plasmas," AIP Conf. Proc. **1925**, 020025 (2018).
[296]J.-L. Dorier, C. Hollenstein, and A. A. Howling, "Spatiotemporal powder formation and trapping in radio frequency silane plasmas using two-dimensional polarization-sensitive laser scattering," J. Vac. Sci. Technol. A **13**, 918–926 (1995).
[297]G. E. Morfill, H. M. Thomas, U. Konopka, H. Rothermel, M. Zuzic, A. Ivlev, and J. Goree, "Condensed plasmas under microgravity," Phys. Rev. Lett. **83**, 1598–1601 (1999).

[298]A. M. Lipaev, S. A. Khrapak, V. I. Molotkov, G. E. Morfill, V. E. Fortov, A. V. Ivlev, H. M. Thomas, A. G. Khrapak, V. N. Naumkin, A. I. Ivanov, S. E. Tretschev, and G. I. Padalka, "Void closure in complex plasmas under microgravity conditions," Phys. Rev. Lett. **98**, 265006 (2007).
[299]M. R. Akdim and W. J. Goedheer, "Modeling the effect of dust on the plasma parameters in a dusty argon discharge under microgravity," Phys. Rev. E **67**, 066407 (2003).
[300]V. Land and W. J. Goedheer, "The plasma inside a dust free void: Hotter, denser, or both?," New J. Phys. **9**, 246–246 (2007).
[301]W. J. Goedheer and V. Land, "Simulation of dust voids in complex plasmas," Plasma Phys. Controlled Fusion **50**, 124022 (2008).
[302]V. Land and W. J. Goedheer, "How to make large, void-free dust clusters in dusty plasma under micro-gravity," New J. Phys. **10**, 123028 (2008).
[303]W. J. Goedheer, V. Land, and J. Venema, "Hydrodynamic and kinetic modelling of complex radio-frequency plasmas," J. Phys. D: Appl. Phys. **42**, 194015 (2009).
[304]W. Goedheer, V. Land, and J. Venema, "Modelling of voids in complex radio frequency plasmas," Contrib. Plasma Phys. **49**, 199–214 (2009).
[305]M. Y. Pustylnik, I. L. Semenov, E. Zähringer, and H. M. Thomas, "Capacitively coupled RF discharge with a large amount of microparticles: Spatiotemporal emission pattern and microparticle arrangement," Phys. Rev. E **96**, 033203 (2017).
[306]A. Pikalev, I. Semenov, M. Pustylnik, C. Räth, and H. Thomas, "Dim and bright void regimes in capacitively-coupled RF complex plasmas," Plasma Sources Sci. Technol. **30**, 035014 (2021).
[307]F. M. J. H. van de Wetering, J. Beckers, and G. M. W. Kroesen, "Anion dynamics in the first 10 milliseconds of an argon–acetylene radio-frequency plasma," J. Phys. D: Appl. Phys. **45**, 485205 (2012).
[308]J. Goree, R. Quinn, G. Morfill, H. Thomas, T. Hagl, U. Konopka, H. Rothermel, and M. Zuzic, "Plasma dust crystallization," in *Proceedings of the 4th Microgravity Fluid Physics and Transport Phenomena Conference* (Cleveland, 1998), pp. 105–106.
[309]S. K. Zhdanov, M. Schwabe, R. Heidemann, R. Sütterlin, H. M. Thomas, M. Rubin-Zuzic, H. Rothermel, T. Hagl, A. V. Ivlev, G. E. Morfill, V. I. Molotkov, A. M. Lipaev, O. F. Petrov, V. E. Fortov, and T. Reiter, "Auto-oscillations in complex plasmas," New J. Phys. **12**, 043006 (2010).
[310]R. Heidemann, L. Couëdel, S. K. Zhdanov, R. K. Sütterlin, M. Schwabe, H. M. Thomas, A. V. Ivlev, T. Hagl, G. E. Morfill, V. E. Fortov, O. F. Petrov, A. M. Lipaev, V. Tokarev, T. Reiter, and P. Vinogradov, "Comprehensive experimental study of heartbeat oscillations observed under microgravity conditions in the PK-3 Plus laboratory on board the International Space Station," Phys. Plasmas **18**, 053701 (2011).
[311]M. Mikikian and L. Boufendi, "Experimental investigations of void dynamics in a dusty discharge," Phys. Plasmas **11**, 3733–3737 (2004).
[312]M. Mikikian, L. Couëdel, M. Cavarroc, Y. Tessier, and L. Boufendi, "Self-excited void instability in dusty plasmas: Plasma and dust cloud dynamics during the heartbeat instability," New J. Phys. **9**, 268 (2007).
[313]M. Mikikian, M. Cavarroc, L. Couëdel, Y. Tessier, and L. Boufendi, "Mixed-mode oscillations in complex-plasma instabilities," Phys. Rev. Lett. **100**, 225005 (2008).
[314]M. Mikikian, L. Couëdel, M. Cavarroc, Y. Tessier, and L. Boufendi, "Threshold phenomena in a throbbing complex plasma," Phys. Rev. Lett. **105**, 075002 (2010).
[315]M. Y. Pustylnik, A. V. Ivlev, N. Sadeghi, R. Heidemann, S. Mitic, H. M. Thomas, and G. E. Morfill, "On the heterogeneous character of the heartbeat instability in complex (dusty) plasmas," Phys. Plasmas **19**, 103701 (2012).
[316]A. Pikalev, M. Pustylnik, C. Räth, and H. Thomas, "Heartbeat instability as auto-oscillation between dim and bright void regimes," arXiv:2103.06795 (2021).
[317]J. Goree, G. Morfill, V. Tsytovich, and S. Vladimirov, "Theory of dust voids in plasmas," Phys. Rev. E **59**, 7055 (1999).
[318]K. Avinash, A. Bhattacharjee, and S. Hu, "Nonlinear theory of void formation in colloidal plasmas," Phys. Rev. Lett. **90**, 075001 (2003).
[319]S. Vladimirov, V. Tsytovich, and G. Morfill, "Stability of dust voids," Phys. Plasmas **12**, 052117 (2005).
[320]Z. Hu, Y. Chen, X. Zheng, F. Huang, G.-F. Shi, and M. Yu, "Theory of void formation in dusty plasmas," Phys. Plasmas **16**, 063707 (2009).
[321]C. Arnas, M. Mikikian, G. Bachet, and F. Doveil, "Sheath modification in the presence of dust particles," Phys. Plasmas **7**, 4418–4422 (2000).
[322]C. Arnas, M. Mikikian, and F. Doveil, "Micro-sphere levitation in a sheath of a low pressure continuous discharge," Phys. Scr. **T89**, 163 (2001).
[323]V. N. Naumkin, D. I. Zhukhovitskii, A. M. Lipaev, A. V. Zobnin, A. D. Usachev, O. F. Petrov, H. M. Thomas, M. H. Thoma, O. I. Skripochka, and A. A. Ivanishin, "Excitation of progressing dust ionization waves on PK-4 facility," Phys. Plasmas **28**, 103704 (2021).
[324]D. I. Zhukhovitskii, "Dispersion relation for the dust ionization and dust acoustic waves in the gas discharge complex plasma," Phys. Plasmas **29**, 073701 (2022).
[325]M. Y. Pustylnik, "Comment on 'Dispersion relation for the dust ionization and dust acoustic waves in the gas discharge complex plasma' [Phys. Plasmas **29**, 073701 (2022)]," Phys. Plasmas **29**, 114701 (2022).
[326]D. I. Zhukhovitskii, "Response to 'Comment on "Dispersion relation for the dust ionization and dust acoustic waves in the gas discharge complex plasma"' [Phys. Plasmas **29**, 114701 (2022)]," Phys. Plasmas **29**, 114702 (2022).
[327]D. L. Goodman and N. M. P. Benjamin, "Active control of instabilities for plasma processing with electronegative gases," J. Phys. D: Appl. Phys. **36**, 2845–2852 (2003).
[328]C. A. Knapek, U. Konopka, D. P. Mohr, P. Huber, A. M. Lipaev, and H. M. Thomas, "'Zyflex': Next generation plasma chamber for complex plasma research in space," Rev. Sci. Instrum. **92**, 103505 (2021).
[329]G. E. Morfill and A. V. Ivlev, "Complex plasmas: An interdisciplinary research field," Rev. Mod. Phys. **81**, 1353–1404 (2009).
[330]M. Bonitz, C. Henning, and D. Block, "Complex plasmas: A laboratory for strong correlations," Rep. Prog. Phys. **73**, 066501 (2010).
[331]M. Chaudhuri, A. V. Ivlev, S. A. Khrapak, H. M. Thomas, and G. E. Morfill, "Complex plasma-the plasma state of soft matter," Soft Matter **7**, 1287–1298 (2011).
[332]A. Ivlev, H. Löwen, G. Morfill, and C. Royall, *Complex Plasmas and Colloidal Dispersions: Particle-Resolved Studies of Classical Liquids and Solids* (World Scientific, 2012).
[333]E. B. Tomme, B. M. Annaratone, and J. E. Allen, "Damped dust oscillations as a plasma sheath diagnostic," Plasma Sources Sci. Technol. **9**, 87–96 (2000).
[334]B. Liu, J. Goree, V. Nosenko, and L. Boufendi, "Radiation pressure and gas drag forces on a melamine-formaldehyde microsphere in a dusty plasma," Phys. Plasmas **10**, 9–20 (2003).
[335]J. Goree, "Ion trapping by a charged dust grain in a plasma," Phys. Rev. Lett. **69**, 277–280 (1992).
[336]M. Lampe, V. Gavrishchaka, G. Ganguli, and G. Joyce, "Effect of trapped ions on shielding of a charged spherical object in a plasma," Phys. Rev. Lett. **86**, 5278–5281 (2001).
[337]A. V. Zobnin, A. D. Usachev, O. F. Petrov, and V. E. Fortov, "Ion current on a small spherical attractive probe in a weakly ionized plasma with ion-neutral collisions (kinetic approach)," Phys. Plasmas **15**, 043705 (2008).
[338]M. Bonitz, D. Block, O. Arp, V. Golubnychiy, H. Baumgartner, P. Ludwig, A. Piel, and A. Filinov, "Structural properties of screened Coulomb balls," Phys. Rev. Lett. **96**, 075001 (2006).
[339]A. Piel, "Plasma crystals: Experiments and simulation," Plasma Phys. Controlled Fusion **59**, 014001 (2017).
[340]A. Melzer, *Physics of Dusty Plasmas* (Springer-Verlag GmbH, 2019).
[341]A. Melzer, A. Homann, and A. Piel, "Experimental investigation of the melting transition of the plasma crystal," Phys. Rev. E **53**, 2757–2766 (1996).
[342]H. M. Thomas and G. E. Morfill, "Melting dynamics of a plasma crystal," Nature **379**, 806–809 (1996).
[343]S. A. Khrapak, "Lindemann melting criterion in two dimensions," Phys. Rev. Res. **2**, 012040 (2020).
[344]S. Hamaguchi, R. T. Farouki, and D. H. E. Dubin, "Triple point of Yukawa systems," Phys. Rev. E **56**, 4671–4682 (1997).
[345]R. L. Merlino, A. Barkan, C. Thompson, and N. D'Angelo, "Laboratory studies of waves and instabilities in dusty plasmas," Phys. Plasmas **5**, 1607–1614 (1998).
[346]S. Nunomura, D. Samsonov, and J. Goree, "Transverse waves in a two-dimensional screened-Coulomb crystal (dusty plasma)," Phys. Rev. Lett. **84**, 5141–5144 (2000).

[347]V. Nosenko, J. Goree, Z. Ma, D. Dubin, and A. Piel, "Compressional and shear wakes in a two-dimensional dusty plasma crystal," Phys. Rev. E **68**, 056409 (2003).
[348]E. Thomas and J. Williams, "Applications of stereoscopic particle image velocimetry: Dust acoustic waves and velocity space distribution functions," Phys. Plasmas **13**, 055702 (2006).
[349]V. Nosenko, S. Zhdanov, A. V. Ivlev, G. Morfill, J. Goree, and A. Piel, "Heat transport in a two-dimensional complex (dusty) plasma at melting conditions," Phys. Rev. Lett. **100**, 025003 (2008).
[350]Y. Feng, J. Goree, and B. Liu, "Identifying anomalous diffusion and melting in dusty plasmas," Phys. Rev. E **82**, 036403 (2010).
[351]E. V. Vasilieva, O. F. Petrov, and M. M. Vasiliev, "Laser-induced melting of two-dimensional dusty plasma system in RF discharge," Sci. Rep. **11**, 523 (2021).
[352]J. Goree, B. Liu, and Y. Feng, "Diagnostics for transport phenomena in strongly coupled dusty plasmas," Plasma Phys. Controlled Fusion **55**, 124004 (2013).
[353]Y. Feng, J. Goree, and B. Liu, "Viscoelasticity of 2D liquids quantified in a dusty plasma experiment," Phys. Rev. Lett. **105**, 025002 (2010).
[354]L. I, W.-T. Juan, C.-H. Chiang, and J. H. Chu, "Microscopic particle motions in strongly coupled dusty plasmas," Science **272**, 1626–1628 (1996).
[355]D. Samsonov, J. Goree, Z. W. Ma, A. Bhattacharjee, H. M. Thomas, and G. E. Morfill, "Mach cones in a Coulomb lattice and a dusty plasma," Phys. Rev. Lett. **83**, 3649–3652 (1999).
[356]C. Durniak and D. Samsonov, "Plastic deformations in complex plasmas," Phys. Rev. Lett. **106**, 175001 (2011).
[357]L. Couëdel, D. Samsonov, C. Durniak, S. Zhdanov, H. M. Thomas, G. E. Morfill, and C. Arnas, "Three-dimensional structure of Mach cones in monolayer complex plasma crystals," Phys. Rev. Lett. **109**, 175001 (2012).
[358]A. Melzer, V. A. Schweigert, and A. Piel, "Measurement of the wakefield attraction for 'dust plasma molecules'," Phys. Scr. **61**, 494 (2000).
[359]P. Ludwig, W. J. Miloch, H. Kählert, and M. Bonitz, "On the wake structure in streaming complex plasmas," New J. Phys. **14**, 053016 (2012).
[360]P. Ludwig, H. Kählert, and M. Bonitz, "Ion-streaming induced order transition in three-dimensional dust clusters," Plasma Phys. Controlled Fusion **54**, 045011 (2012).
[361]L. Couëdel, S. K. Zhdanov, A. V. Ivlev, V. Nosenko, H. M. Thomas, and G. E. Morfill, "Wave mode coupling due to plasma wakes in two-dimensional plasma crystals: In-depth view," Phys. Plasmas **18**, 083707 (2011).
[362]S. O. Yurchenko, E. V. Yakovlev, L. Couëdel, N. P. Kryuchkov, A. M. Lipaev, V. N. Naumkin, A. Y. Kislov, P. V. Ovcharov, K. I. Zaytsev, E. V. Vorob'ev, G. E. Morfill, and A. V. Ivlev, "Flame propagation in two-dimensional solids: Particle-resolved studies with complex plasmas," Phys. Rev. E **96**, 043201 (2017).
[363]L. Couëdel, V. Nosenko, M. Rubin-Zuzic, S. Zhdanov, Y. Elskens, T. Hall, and A. V. Ivlev, "Full melting of a two-dimensional complex plasma crystal triggered by localized pulsed laser heating," Phys. Rev. E **97**, 043206 (2018).
[364]M. Schwabe, U. Konopka, P. Bandyopadhyay, and G. E. Morfill, "Pattern formation in a complex plasma in high magnetic fields," Phys. Rev. Lett. **106**, 215004 (2011).
[365]E. Thomas, U. Konopka, D. Artis, B. Lynch, S. Leblanc, S. Adams, R. L. Merlino, and M. Rosenberg, "The magnetized dusty plasma experiment (MDPX)," J. Plasma Phys. **81**, 345810206 (2015).
[366]A. Melzer, H. Krüger, D. Maier, and S. Schütt, "Physics of magnetized dusty plasmas," Rev. Mod. Plasma Phys. **5**, 11 (2021).
[367]S. Krasheninnikov, A. Smolyakov, and A. Kukushkin, "Dust in fusion plasmas," in *On the Edge of Magnetic Fusion Devices* (Springer International Publishing, Cham, 2020), pp. 89–113.
[368]H.-B. Li, "Magnetic fields in molecular clouds-observation and interpretation," Galaxies **9**, 41 (2021).
[369]M. Menati, U. Konopka, and E. Thomas, "Variation of filamentation phenomenon in strongly magnetized plasma with various discharge parameters," Contrib. Plasma Phys. **61**, e202100083 (2021).
[370]S. Williams, S. C. Thakur, M. Menati, and E. Thomas, "Experimental observations of multiple modes of filamentary structures in the magnetized dusty plasma experiment (MDPX) device," Phys. Plasmas **29**, 012110 (2022).
[371]J. Carstensen, F. Greiner, D. Block, J. Schablinski, W. J. Miloch, and A. Piel, "Charging and coupling of a vertically aligned particle pair in the plasma sheath," Phys. Plasmas **19**, 033702 (2012).
[372]A. Melzer, H. Krueger, S. Schuett, and M. Mulsow, "Finite dust clusters under strong magnetic fields," Phys. Plasmas **26**, 093702 (2019).
[373]J. Carstensen, F. Greiner, and A. Piel, "Ion-wake-mediated particle interaction in a magnetized-plasma flow," Phys. Rev. Lett. **109**, 135001 (2012).
[374]H. Jung, F. Greiner, A. Piel, and W. J. Miloch, "Experiments on wake structures behind a microparticle in a magnetized plasma flow," Phys. Plasmas **25**, 073703 (2018).
[375]A. Melzer, H. Krüger, S. Schütt, and M. Mulsow, "Dust-density waves in radio-frequency discharges under magnetic fields," Phys. Plasmas **27**, 033704 (2020).
[376]M. Choudhary, R. Bergert, S. Mitic, and M. H. Thoma, "Influence of external magnetic field on dust acoustic waves in a capacitive rf discharge," Contrib. Plasma Phys. **60**, e201900115 (2020).
[377]H. Kählert, J. Carstensen, M. Bonitz, H. Löwen, F. Greiner, and A. Piel, "Magnetizing a complex plasma without a magnetic field," Phys. Rev. Lett. **109**, 155003 (2012).
[378]M. Bonitz, H. Kählert, T. Ott, and H. Löwen, "Magnetized strongly coupled plasmas and how to realize them in a dusty plasma setup," Plasma Sources Sci. Technol. **22**, 015007 (2013).
[379]P. Hartmann, Z. Donkó, T. Ott, H. Kählert, and M. Bonitz, "Magnetoplasmons in rotating dusty plasmas," Phys. Rev. Lett. **111**, 155002 (2013).
[380]P. Hartmann, J. C. Reyes, E. G. Kostadinova, L. S. Matthews, T. W. Hyde, R. U. Masheyeva, K. N. Dzhumagulova, T. S. Ramazanov, T. Ott, H. Kählert, M. Bonitz, I. Korolov, and Z. Donkó, "Self-diffusion in two-dimensional quasi-magnetized rotating dusty plasmas," Phys. Rev. E **99**, 013203 (2019).
[381]U. R. Kortshagen, R. M. Sankaran, R. N. Pereira, S. L. Girshick, J. J. Wu, and E. S. Aydil, "Nonthermal plasma synthesis of nanocrystals: Fundamental principles, materials, and applications," Chem. Rev. **116**, 11061–11127 (2016).
[382]L. Mangolini and U. Kortshagen, "Selective nanoparticle heating: Another form of nonequilibrium in dusty plasmas," Phys. Rev. E **79**, 026405 (2009).
[383]G. S. Selwyn, "Light scattering in dusty plasmas: A new use for Mie," in *Proceedings of the Optical Society of America Annual Meeting* (Optica Publishing Group, 1991), p. TuP2.
[384]H. M. Anderson and S. B. Radovanov, "Dynamic laser light scattering studies of dusty plasmas in the gaseous electronics conference reference cell," J. Vac. Sci. Technol. A **14**, 608–614 (1996).
[385]M. Pustylnik, V. Nosenko, S. Mitic, and G. Morfill, *Applications of Light Scattering in Complex (Dusty) Plasmas: Diagnostic and Manipulation Techniques* (Nova Publishers, 2013), p. 15.
[386]L. P. T. Schepers, J. Beckers, T. W. Tukker, and W. L. IJzerman, "Light scattering on dusty plasmas: How to improve the quality of white leds?," in *Proceedings of the IEEE International Conference on Plasma Sciences (ICOPS)* (IEEE, 2015), p. 1.
[387]O. F. Petrov, R. E. Boltnev, and M. M. Vasiliev, "Experimental evolution of active Brownian grains driven by quantum effects in superfluid helium," Sci. Rep. **12**, 6085 (2022).
[388]H. Huang, V. Nosenko, H.-X. Huang-Fu, H. M. Thomas, and C.-R. Du, "Machine learning in the study of phase transition of two-dimensional complex plasmas," Phys. Plasmas **29**, 073702 (2022).
[389]V. Nosenko, J. Meyer, S. K. Zhdanov, and H. M. Thomas, "New radio-frequency setup for studying large 2D complex plasma crystals," AIP Adv. **8**, 125303 (2018).
[390]G. S. Selwyn, J. Singh, and R. S. Bennett, "In situ laser diagnostic studies of plasma-generated particulate contamination," J. Vac. Sci. Technol. A **7**, 2758–2765 (1989).
[391]G. S. Selwyn, J. E. Heidenreich, and H. L. Haller, "Particle trapping phenomena in radio frequency plasmas," Appl. Phys. Lett. **57**, 1876 (1990).
[392]T. Matsoukas, "The coagulation rate of charged aerosols in ionized gases," J. Colloid Interface Sci. **187**, 474–483 (1997).
[393]V. A. Schweigert and I. V. Schweigert, "Coagulation in a low-temperature plasma," J. Phys. D: Appl. Phys. **29**, 655–659 (1996).
[394]L. Mangolini, E. Thimsen, and U. Kortshagen, "High-yield plasma synthesis of luminescent silicon nanocrystals," Nano Lett. **5**, 655–659 (2005).

[395]A. Alvarez Barragan, N. V. Ilawe, L. Zhong, B. M. Wong, and L. Mangolini, "A non-thermal plasma route to plasmonic TiN nanoparticles," J. Phys. Chem. C **121**, 2316–2322 (2017).
[396]A. J. Cendejas, H. Sun, S. E. Hayes, U. Kortshagen, and E. Thimsen, "Predicting plasma conditions necessary for synthesis of γ-Al_2O_3 nanocrystals," Nanoscale **13**, 11387–11395 (2021).
[397]M. Otobe, T. Kanai, T. Ifuku, H. Yajima, and S. Oda, "Nanocrystalline silicon formation in a SiH_4 plasma cell," J. Non-Cryst. Solids **198–200**, 875–878 (1996).
[398]C. R. Gorla, S. Liang, G. S. Tompa, W. E. Mayo, and Y. Lu, "Silicon and germanium nanoparticle formation in an inductively coupled plasma reactor," J. Vac. Sci. Technol. A **15**, 860 (1997).
[399]R. M. Sankaran, D. Holunga, R. C. Flagan, and K. P. Giapis, "Synthesis of blue luminescent si nanoparticles using atmospheric-pressure microdischarges," Nano Lett. **5**, 537–541 (2005).
[400]L. Mangolini, "Synthesis, properties, and applications of silicon nanocrystals," J. Vac. Sci. Technol. B **31**, 020801 (2013).
[401]S. C. Erwin, L. Zu, M. I. Haftel, A. L. Efros, T. A. Kennedy, and D. J. Norris, "Doping semiconductor nanocrystals," Nature **436**, 91–94 (2005).
[402]A. R. Stegner, R. N. Pereira, K. Klein, H. Wiggers, M. S. Brandt, and M. Stutzmann, "Phosphorus doping of Si nanocrystals: Interface defects and charge compensation," Physica B **401**, 541–545 (2007).
[403]X. D. Pi, R. Gresback, R. W. Liptak, S. A. Campbell, and U. Kortshagen, "Doping efficiency, dopant location, and oxidation of Si nanocrystals," Appl. Phys. Lett. **92**, 123102 (2008).
[404]Z. Tong, M. Bu, Y. Zhang, D. Yang, and X. Pi, "Hyperdoped silicon: Processing, properties, and devices," J. Semicond. **43**, 093101 (2022).
[405]H. Zhang, R. Zhang, K. S. Schramke, N. M. Bedford, K. Hunter, U. R. Kortshagen, and P. Nordlander, "Doped silicon nanocrystal plasmonics," ACS Photonics **4**, 963–970 (2017).
[406]R. Limpens, G. F. Pach, and N. R. Neale, "Nonthermal plasma-synthesized phosphorus–boron co-doped Si nanocrystals: A new approach to nontoxic NIR-emitters," Chem. Mater. **31**, 4426–4435 (2019).
[407]N. B. Uner and E. Thimsen, "In-flight size focusing of aerosols by a low temperature plasma," J. Phys. Chem. C **121**, 12936–12944 (2017).
[408]N. B. Uner and E. Thimsen, "Nonequilibrium plasma aerotaxy of size controlled GaN nanocrystals," J. Phys. D: Appl. Phys. **53**, 095201 (2019).
[409]N. B. Uner, D. M. Niedzwiedzki, and E. Thimsen, "Nonequilibrium plasma aerotaxy of inn nanocrystals and their photonic properties," J. Phys. Chem. C **123**, 30613–30622 (2019).
[410]N. B. Uner and E. Thimsen, "Phase mixing in GaSb nanocrystals synthesized by nonequilibrium plasma aerotaxy," Plasma Processes Polym. **17**, 1900233 (2020).
[411]G. S. Selwyn, "Optical characterization of particle traps," Plasma Sources Sci. Technol. **3**, 340 (1994).
[412]E. Kovačević, I. Stefanović, J. Berndt, and J. Winter, "Infrared fingerprints and periodic formation of nanoparticles in Ar/C_2H_2 plasmas," J. Appl. Phys. **93**, 2924–2930 (2003).
[413]Z. Xiong, S. Lanham, E. Husmann, G. Nelson, M. A. Eslamisaray, J. Polito, Y. Liu, J. Goree, E. Thimsen, M. J. Kushner, and U. R. Kortshagen, "Particle trapping, size-filtering, and focusing in the nonthermal plasma synthesis of sub-10 nanometer particles," J. Phys. D: Appl. Phys. **55**, 235202 (2022).
[414]M. A. Eslamisaray, P. R. Wray, Y. Lee, G. M. Nelson, O. Ilic, H. A. Atwater, and U. R. Kortshagen, "A single-step bottom-up approach for synthesis of highly uniform mie-resonant crystalline semiconductor particles at visible wavelengths," Nano Lett. **23**, 1930–1937 (2023).
[415]S. J. Lanham, J. Polito, Z. Xiong, U. R. Kortshagen, and M. J. Kushner, "Pulsed power to control growth of silicon nanoparticles in low temperature flowing plasmas," J. Appl. Phys. **132**, 073301 (2022).
[416]J. Schwan, B. Wagner, M. Kim, and L. Mangolini, "Controlled growth of silicon particles via plasma pulsing and their application as battery material," J. Phys. D: Appl. Phys. **55**, 094002 (2022).
[417]N. J. Kramer, R. J. Anthony, M. Mamunuru, E. S. Aydil, and U. R. Kortshagen, "Plasma-induced crystallization of silicon nanoparticles," J. Phys. D: Appl. Phys. **47**, 075202 (2014).
[418]N. B. Uner and E. Thimsen, "Low temperature plasma as a means to transform nanoparticle atomic structure," Plasma Sources Sci. Technol. **27**, 074005 (2018).
[419]N. B. Uner and E. Thimsen, "Superlocal chemical reaction equilibrium in low temperature plasma," AIChE J. **66**, e16948 (2020).
[420]X. Chen and E. Thimsen, "Stationary states of hydrogen-producing reactions in nonequilibrium plasma," AIChE J. **69**, e17952 (2022).
[421]H. Seat and J. Sharp, "Dedicated temperature sensing with c-axis oriented single-crystal ruby (Cr/sup 3+/:Al/sub 2/O/sub 3/) fibers: Temperature and strain dependences of r-line fluorescence," IEEE Trans. Instrum. Meas. **53**, 140–154 (2004).
[422]A. Cendejas, D. Niedzwiedzki, and E. Thimsen, "Synthesis of ultrafine Al-rich corundum nanocrystals" (unpublished 2023).
[423]J. E. Daugherty and D. B. Graves, "Particulate temperature in radio frequency glow discharges," J. Vac. Sci. Technol. A **11**, 1126–1131 (1993).
[424]E. Tatarova, A. Dias, J. Henriques, M. Abrashev, N. Bundaleska, E. Kovacevic, N. Bundaleski, U. Cvelbar, E. Valcheva, B. Arnaudov *et al.*, "Towards large-scale in free-standing graphene and n-graphene sheets," Sci. Rep. **7**, 10175 (2017).
[425]M. Santos, P. L. Michael, E. C. Filipe, A. H. Chan, J. Hung, R. P. Tan, B. S. Lee, M. Huynh, C. Hawkins, A. Waterhouse *et al.*, "Plasma synthesis of carbon-based nanocarriers for linker-free immobilization of bioactive cargo," ACS Appl. Nano Mater. **1**, 580–594 (2018).
[426]E. Kovacevic, T. Strunskus, N. M. Santhosh, J. Zavašnik, W. E. Unger, T. Sauvage, M.-R. Ammar, U. Cvelbar, and J. Berndt, "Thermal stability studies of plasma deposited hydrogenated carbon nitride nanostructures," Carbon **184**, 82–90 (2021).
[427]C. Pattyn, E. Kovacevic, S. Hussain, A. Dias, T. Lecas, and J. Berndt, "Nanoparticle formation in a low pressure argon/aniline RF plasma," Appl. Phys. Lett. **112**, 013102 (2018).
[428]Z. Marvi, T. J. M. Donders, M. Hasani, G. Klaassen, and J. Beckers, "Quantum dot photoluminescence as a versatile probe to visualize the interaction between plasma and nanoparticles on a surface," Appl. Phys. Lett. **119**, 254104 (2021).
[429]E. Kovačević, I. Stefanović, J. Berndt, Y. Pendleton, and J. Winter, "A candidate analog for carbonaceous interstellar dust: Formation by reactive plasma polymerization," Astrophys. J. **623**, 242 (2005).
[430]V. J. Herrero, M. Jiménez-Redondo, R. J. Peláez, B. Maté, and I. Tanarro, "Structure and evolution of interstellar carbonaceous dust. insights from the laboratory," Front. Astron. Space Sci. **9**, 1083288 (2022).
[431]J. P. Girard, W. Gulden, B. Kolbasov, A.-J. Louzeiro-Malaquias, D. Petti, and L. Rodriguez-Rodrigo, "Summary of the 8th IAEA technical meeting on fusion power plant safety," Nucl. Fusion **48**, 015008 (2008).
[432]J. Roth, E. Tsitrone, A. Loarte, T. Loarer, G. Counsell, R. Neu, V. Philipps, S. Brezinsek, M. Lehnen, P. Coad, C. Grisolia, K. Schmid, K. Krieger, A. Kallenbach, B. Lipschultz, R. Doerner, R. Causey, V. Alimov, W. Shu, O. Ogorodnikova, A. Kirschner, G. Federici, and A. Kukushkin, "Recent analysis of key plasma wall interactions issues for ITER," J. Nucl. Mater. **390–391**, 1 (2009).
[433]R. A. Pitts, B. Bazylev, J. Linke, I. Landman, M. Lehnen, D. Loesser, T. Loewenhoff, M. Merola, R. Roccella, G. Saibene, M. Smith, and V. S. Udintsev, "Final case for a stainless steel diagnostic first wall on ITER," J. Nucl. Mater. **463**, 748 (2015).
[434]R. A. Pitts, S. Bardin, B. Bazylev, M. A. van den Berg, P. Bunting, S. Carpentier-Chouchana, J. W. Coenen, Y. Corre, R. Dejarnac, F. Escourbiac, J. Gaspar, J. P. Gunn, T. Hirai, S.-H. Hong, J. Horacek, D. Iglesias, M. Komm, K. Krieger, C. Lasnier, G. F. Matthews, T. W. Morgan, S. Panayotis, S. Pestchanyi, A. Podolnik, R. E. Nygren, D. L. Rudakov, G. De Temmerman, P. Vondracek, and J. G. Watkins, "Physics conclusions in support of ITER W divertor monoblock shaping," Nucl. Mater. Energy **12**, 60 (2017).
[435]R. A. Pitts, X. Bonnin, F. Escourbiac, H. Frerichs, J. P. Gunn, T. Hirai, A. S. Kukushkin, E. Kaveeva, M. A. Miller, D. Moulton, V. Rozhansky, I. Senichenkov, E. Sytova, O. Schmitz, P. C. Stangeby, G. De Temmerman, I. Veselova, and S. Wiesen, "Physics basis for the first ITER tungsten divertor," Nucl. Mater. Energy **20**, 100696 (2019).
[436]E. Fortuna-Zaleśna, T. Plocinski, S. W. Moon, P. Petersson, M. Rubel, A. Widdowson, and JET Contributors, "Dust generation and accumulation in JET-ILW: Morphology and stability of co-deposits on main plasma-facing components and wall probes," Phys. Scr. **96**, 124038 (2021).

[437]M. Rubel, A. Widdowson, J. Grzonka, E. Fortuna-Zalesna, S. Moon, P. Petersson, N. Ashikawa, N. Asakura, D. Hamaguchi, Y. Hatano, K. Isobe, S. Masuzaki, H. Kurotaki, Y. Oya, M. Oyaidzu, M. Tokitani, and JET Contributors, "Dust generation in tokamaks: Overview of beryllium and tungsten dust characterisation in JET with the ITER-like wall," Fusion Eng. Des. **136**, 579 (2018).

[438]E. Fortuna-Zaleśna, J. Grzonka, S. Moon, M. Rubel, P. Petersson, A. Widdowson, and JET Contributors, "Fine metal dust particles on the wall probes from JET-ILW," Phys. Scr. **T170**, 014038 (2017).

[439]E. Fortuna-Zaleśna, J. Grzonka, M. Rubel, A. Garcia-Carrasco, A. Widdowson, A. Baron-Wiechec, L. Ciupiński, and JET Contributors, "Studies of dust from JET with the ITER-like wall: Composition and internal structure," Nucl. Mater. Energy **12**, 582 (2017).

[440]J. C. Flanagan, M. Sertoli, M. Bacharis, G. F. Matthews, P. C. de Vries, A. Widdowson, I. H. Coffey, G. Arnoux, B. Sieglin, S. Brezinsek, J. W. Coenen, S. Marsen, T. Craciunescu, A. Murari, D. Harting, A. Cackett, E. Hodille, and JET-EFDA Contributors, "Characterising dust in JET with the new ITER-like wall," Plasma Phys. Controlled Fusion **57**, 014037 (2015).

[441]A. Baron-Wiechec, E. Fortuna-Zaleśna, J. Grzonka, M. Rubel, A. Widdowson, C. Ayres, J. P. Coad, C. Hardie, K. Heinola, G. F. Matthews, and JET Contributors, "First dust study in JET with the ITER-like wall: Sampling, analysis and classification," Nucl. Fusion **55**, 113033 (2015).

[442]M. Balden, N. Endstrasser, P. W. Humrickhouse, V. Rohde, M. Rasinski, U. von Toussaint, S. Elgeti, R. Neu, and ASDEX Upgrade Team, "Collection strategy, inner morphology, and size distribution of dust particles in ASDEX upgrade," Nucl. Fusion **54**, 073010 (2014).

[443]C. Arnas, J. Irby, S. Celli, G. De Temmerman, Y. Addab, L. Couedel, C. Grisolia, Y. Lin, C. Martin, C. Pardanaud, and S. Pierson, "Characterization and origin of large size dust particles produced in the alcator C-Mod tokamak," Nucl. Mater. Energy **11**, 12 (2017).

[444]S. Peillon, G. Dougniaux, M. Payet, E. Bernard, G. Pieters, S. Feuillastre, S. Garcia-Argote, F. Gensdarmes, C. Arnas, F. Miserque, N. Herlin-Boime, C. Grisolia, and O. Pluchery, "Dust sampling in WEST and tritium retention in tokamak-relevant tungsten particles," Nucl. Mater. Energy **24**, 100781 (2020).

[445]Y. Lei, D. Zhu, C. Li, G. Ma, B. Gao, B. Wang, R. Ding, J. Chen, B. Yu, and C. Xuan, "Result and discussion on the evolution of in-situ leading edge-induced melting on W divertor targets in EAST," Nucl. Mater. Energy **27**, 100997 (2021).

[446]V. Rohde, M. Balden, R. Neu, and ASDEX Upgrade Team, "Arc behaviour on different materials in ASDEX Upgrade," Nucl. Mater. Energy **29**, 101083 (2021).

[447]C. Castaldo, S. Ratynskaia, V. Pericoli, U. de Angelis, K. Rypdal, L. Pieroni, E. Giovannozzi, G. Maddaluno, C. Marmolino, A. Rufoloni, A. Tuccillo, M. Kretschmer, and G. E. Morfill, "Diagnostics of fast dust particles in tokamak edge plasmas," Nucl. Fusion **47**, L5 (2007).

[448]S. Ratynskaia, C. Castaldo, E. Giovannozzi, D. Rudakov, G. Morfill, M. Horanyi, J. H. Yu, and G. Maddaluno, "In situ dust detection in fusion devices," Plasma Phys. Controlled Fusion **50**, 124046 (2008).

[449]D. L. Rudakov, J. H. Yu, J. A. Boedo, E. M. Hollmann, S. I. Krasheninnikov, R. A. Moyer, S. H. Muller, A. Y. Pigarov, M. Rosenberg, R. D. Smirnov, W. P. West, R. L. Boivin, B. D. Bray, N. H. Brooks, A. W. Hyatt, C. P. C. Wong, A. L. Roquemore, C. H. Skinner, W. M. Solomon, S. Ratynskaia, M. E. Fenstermacher, M. Groth, C. J. Lasnier, A. G. McLean, and P. C. Stangeby, "Dust measurements in tokamaks (invited)," Rev. Sci. Instrum. **79**, 10F303 (2008).

[450]F. Brochard, A. Shalpegin, S. Bardin, T. Lunt, V. Rohde, J. L. Briancon, G. Pautasso, C. Vorpahl, R. Neu, and ASDEX Upgrade Team, "Video analysis of dust events in full-tungsten ASDEX Upgrade," Nucl. Fusion **57**, 036002 (2017).

[451]F. Brochard, V. Rohde, T. Lunt, G. Suárez López, A. Shalpegin, R. Neu, and ASDEX Upgrade Team, "Intrinsic dust transport in ASDEX upgrade studied by fast imaging," Nucl. Mater. Energy **18**, 268 (2019).

[452]N. S. Klimov, V. L. Podkovyrov, A. M. Zhitlukhin, V. M. Safronov, D. V. Kovalenko, A. A. Moskacheva, and I. M. Poznyak, "Tungsten splashing under intense plasma flow," Probl. At. Sci. Technol. **32**, 52 (2009).

[453]N. Klimov, V. Podkovyrov, A. Zhitlukhin, D. Kovalenko, J. Linke, G. Pintsuk, I. Landman, S. Pestchanyi, B. Bazylev, G. Janeschitz, A. Loarte, M. Merola, T. Hirai, G. Federici, B. Riccardi, I. Mazul, R. Giniyatulin, L. Khimchenko, and V. Koidan, "Experimental study of PFCs erosion and eroded material deposition under ITER-like transient loads at the plasma gun facility QSPA-T," J. Nucl. Mater. **415**, S59 (2011).

[454]G. De Temmerman, J. Daniels, K. Bystrov, M. A. van den Berg, and J. J. Zielinski, "Melt-layer motion and droplet ejection under divertor-relevant plasma conditions," Nucl. Fusion **53**, 023008 (2013).

[455]V. A. Makhlai, I. E. Garkusha, S. S. Herashchenko, N. N. Aksenov, O. V. Byrka, V. V. Chebotarev, N. V. Kulik, S. I. Lebedev, P. B. Shevchuk, V. V. Staltsov, and Y. V. Petrov, "Influence of surface tension on macroscopic erosion of castellated tungsten surfaces during repetitive transient plasma loads," Nucl. Mater. Energy **19**, 493 (2019).

[456]V. A. Makhlai, S. S. Herashchenko, N. N. Aksenov, O. V. Byrka, I. E. Garkusha, M. Wirtz, and B. Spilker, "Damaging of inclined/misaligned castellated tungsten surfaces exposed to a large number of repetitive QSPA plasma loads," Phys. Scr. **T171**, 014047 (2020).

[457]P. Siemroth, M. Laux, H. Pursch, J. Sachtleben, M. Balden, V. Rohde, and R. Neu, "Diameters and velocities of droplets emitted from the Cu cathode of a vacuum arc," IEEE Trans. Plasma Sci. **47**, 3470 (2019).

[458]S. Rosanvallon, C. Grisolia, P. Andrew, S. Ciattaglia, P. Delaporte, D. Douai, D. Garnier, E. Gauthier, W. Gulden, S. Hong, S. Pitcher, L. Rodriguez, N. Taylor, A. Tesini, S. Vartanian, A. Vatry, and M. Wykes, "Dust limit management strategy in tokamaks," J. Nucl. Mater. **390–391**, 57 (2009).

[459]M. Shimada, R. A. Pitts, S. Ciattaglia, S. Carpentier, C. H. Choi, G. D. Orco, T. Hirai, A. Kukushkin, S. Lisgo, J. Palmer, W. Shu, and E. Veshchev, "In-vessel dust and tritium control strategy in ITER," J. Nucl. Mater. **438**, S996 (2013).

[460]S. Ratynskaia, L. Vignitchouk, P. Tolias, I. Bykov, H. Bergsåker, A. Litnovsky, N. den Harder, and E. Lazzaro, "Migration of tungsten dust in tokamaks: Role of dust-wall collisions," Nucl. Fusion **53**, 123002 (2013).

[461]S. Ratynskaia, P. Tolias, A. Shalpegin, L. Vignitchouk, M. De Angeli, I. Bykov, K. Bystrov, S. Bardin, F. Brochard, D. Ripamonti, N. den Harder, and G. De Temmerman, "Elastic-plastic adhesive impacts of tungsten dust with metal surfaces in plasma environments," J. Nucl. Mater. **463**, 877 (2015).

[462]P. Tolias, S. Ratynskaia, A. Shalpegin, L. Vignitchouk, F. Brochard, M. De Angeli, and H. van der Meiden, "Experimental validation of the analytical model for tungsten dust-wall mechanical impacts incorporated in the MIGRAINe dust dynamics code," Nucl. Mater. Energy **12**, 524 (2017).

[463]S. Ratynskaia, P. Tolias, M. De Angeli, V. Weinzettl, J. Matejicek, I. Bykov, D. L. Rudakov, L. Vignitchouk, E. Thorén, G. Riva, D. Ripamonti, T. Morgan, R. Panek, and G. De Temmerman, "Tungsten dust remobilization under steady-state and transient plasma conditions," Nucl. Mater. Energy **12**, 569 (2017).

[464]P. Tolias, "Retarded room temperature Hamaker coefficients between bulk elemental metals," Surf. Sci. **723**, 122123 (2022).

[465]P. Tolias, G. Riva, M. De Angeli, S. Ratynskaia, G. Daminelli, C. P. Lungu, and C. Porosnicu, "Adhesive force distributions for tungsten dust deposited on bulk tungsten and beryllium-coated tungsten surfaces," Nucl. Mater. Energy **15**, 55 (2018).

[466]S. Peillon, A. Autricque, M. Redolfi, C. Stancu, F. Gensdarmes, C. Grisolia, and O. Pluchery, "Adhesion of tungsten particles on rough tungsten surfaces using atomic force microscopy," J. Aerosol Sci. **137**, 105431 (2019).

[467]P. Tolias, M. De Angeli, G. Riva, S. Ratynskaia, G. Daminelli, L. Laguardia, M. Pedroni, D. Ripamonti, A. Uccello, and E. Vassallo, "The adhesion of tungsten dust on plasma-exposed tungsten surfaces," Nucl. Mater. Energy **18**, 18 (2019).

[468]P. Tolias, M. De Angeli, S. Ratynskaia, G. Riva, P. Bassani, D. Ripamonti, A. Nardone, M. Pedroni, and D. Ricci, "Diffusion bonding effects on the adhesion of tungsten dust on tungsten surfaces," Nucl. Mater. Energy **24**, 100765 (2020).

[469]S. Ratynskaia, L. Vignitchouk, and P. Tolias, "Modelling of dust generation, transport and remobilization in full-metal fusion reactors," Plasma Phys. Controlled Fusion **64**, 044004 (2022).

[470]S. Pestchanyi, I. Garkusha, and I. Landman, "Simulation of tungsten armour cracking due to small ELMs in ITER," Fusion Eng. Des. **85**, 1697 (2010).

[471]S. Pestchanyi, V. Makhlaj, and I. Landman, "Specific features of mechanism for dust production from tungsten armor under action of ELMs," Fusion Sci. Technol. **66**, 150 (2014).

[472]N. S. Klimov, V. L. Podkovyrov, I. B. Kupriyanov, J. Linke, R. A. Pitts, V. M. Safronov, D. V. Kovalenko, T. Loewenhoff, C. P. Lungu, G. Pintsuk, G. De Temmerman, A. D. Muzichenko, A. A. Markin, P. N. Taratorkin, N. E. Zabirova, and A. M. Zhitlukhin, "Beryllium layer response to ITER-like ELM plasma pulses in QSPA-Be," Nucl. Mater. Energy **12**, 433 (2017).
[473]I. Bykov, C. P. Chrobak, T. Abrams, D. L. Rudakov, E. A. Unterberg, W. R. Wampler, E. M. Hollmann, R. A. Moyer, J. A. Boedo, B. Stahl, E. T. Hinson, J. H. Yu, C. J. Lasnier, M. Makowski, and A. G. McLean, "Tungsten erosion by unipolar arcing in DIII-D," Phys. Scr. **T170**, 014034 (2017).
[474]V. Rohde, M. Balden, N. Endstrasser, U. von Toussaint, and ASDEX Upgrade Team, "Arc erosion on W plasma facing components in ASDEX Upgrade," J. Nucl. Mater. **438**, S800–S804 (2013).
[475]V. Rohde, M. Balden, and ASDEX Upgrade Team, "Arc erosion of full metal plasma facing components at the inner baffle region of ASDEX Upgrade," Nucl. Mater. Energy **9**, 36–39 (2016).
[476]D. L. Rudakov, C. P. Chrobak, R. P. Doerner, S. I. Krasheninnikov, R. A. Moyer, K. R. Umstadter, W. R. Wampler, and C. P. C. Wong, "Arcing and its role in PFC erosion and dust production in DIII-D," J. Nucl. Mater. **438**, S805 (2013).
[477]G. A. Mesyats and I. V. Uimanov, "Hydrodynamics of the molten metal during the crater formation on the cathode surface in a vacuum arc," IEEE Trans. Plasma Sci. **43**, 2241 (2015).
[478]H. T. C. Kaufmann, M. D. Cunha, M. S. Benilov, W. Hartmann, and N. Wenzel, "Detailed numerical simulation of cathode spots in vacuum arcs: Interplay of different mechanisms and ejection of droplets," J. Appl. Phys. **122**, 163303 (2017).
[479]L. Vignitchouk, A. Khodak, S. Ratynskaia, and I. D. Kaganovich, "Numerical benchmark of transient pressure-driven metallic melt flows," Nucl. Mater. Energy **25**, 100826 (2020).
[480]S. Ratynskaia, E. Thorén, P. Tolias, R. A. Pitts, K. Krieger, L. Vignitchouk, D. Iglesias, ASDEX-Upgrade Team, JET Contributors, and EUROfusion MST1 Team, "Resolidification-controlled melt dynamics under fast transient tokamak plasma loads," Nucl. Fusion **60**, 104001 (2020).
[481]J. Coburn, E. Thorén, R. A. Pitts, H. Anand, M. Lehnen, L. Kos, M. Brank, S. Ratynskaia, and P. Tolias, "First wall energy deposition during vertical displacement events on ITER," Phys. Scr. **T171**, 014076 (2020).
[482]E. Thorén, S. Ratynskaia, P. Tolias, R. A. Pitts, JET Contributors, and EUROfusion MST1 Team, "The MEMOS-U code description of macroscopic melt dynamics in fusion devices," Plasma Phys. Controlled Fusion **63**, 035021 (2021).
[483]S. Ratynskaia, E. Thorén, P. Tolias, R. A. Pitts, K. Krieger, ASDEX-Upgrade Team, and EUROfusion MST1 Team, "The MEMOS-U macroscopic melt dynamics code-benchmarking and applications," Phys. Scr. **96**, 124009 (2021).
[484]L. Vignitchouk, S. Ratynskaia, R. A. Pitts, and M. Lehnen, "Simulations of liquid metal flows over plasma-facing component edges and application to beryllium melt events in JET," Nucl. Fusion **62**, 036016 (2022).
[485]S. I. Krasheninnikov and R. D. Smirnov, "On interaction of large dust grains with fusion plasma," Phys. Plasmas **16**, 114501 (2009).
[486]B. T. Brown, R. D. Smirnov, and S. I. Krasheninnikov, "On vapor shielding of dust grains of iron, molybdenum, and tungsten in fusion plasmas," Phys. Plasmas **21**, 024501 (2014).
[487]L. Vignitchouk, S. Ratynskaia, P. Tolias, R. A. Pitts, G. De Temmerman, M. Lehnen, and D. Kiramov, "Survival and in-vessel redistribution of beryllium droplets after ITER disruptions," Nucl. Fusion **58**, 076008 (2018).
[488]R. D. Smirnov, A. Y. Pigarov, M. Rosenberg, S. I. Krasheninnikov, and D. A. Mendis, "Modelling of dynamics and transport of carbon dust particles in tokamaks," Plasma Phys. Controlled Fusion **49**, 347 (2007).
[489]J. D. Martin, M. Bacharis, M. Coppins, G. F. Counsell, and J. E. Allen, "Modelling dust transport in tokamaks," Europhys. Lett. **83**, 65001 (2008).
[490]G. Gervasini, E. Lazzaro, and A. Uccello, "Physical and numerical model for calculation of ensembles of trajectories of dust particles in a tokamak," J. Fusion Energy **36**, 25 (2017).
[491]A. Autricque, S. H. Hong, N. Fedorczak, S. H. Son, H. Y. Lee, I. Song, W. Choe, and C. Grisolia, "Simulation of W dust transport in the KSTAR tokamak, comparison with fast camera data," Nucl. Mater. Energy **12**, 599 (2017).
[492]G. L. Delzanno and X.-Z. Tang, "Survivability of dust in tokamaks: Dust transport in the divertor sheath," Phys. Plasmas **21**, 022502 (2014).
[493]S. I. Krasheninnikov, "On dust spin up in uniform magnetized plasma," Phys. Plasmas **13**, 114502 (2006).
[494]L. Simons and A. Long, "Rotational motion of spherical dust in plasmas with magnetic fields," Phys. Plasmas **28**, 093702 (2021).
[495]E. Thorén, P. Tolias, S. Ratynskaia, R. A. Pitts, and K. Krieger, "Self-consistent description of the replacement current driving melt layer motion in fusion devices," Nucl. Fusion **58**, 106003 (2018).
[496]M. De Angeli, P. Tolias, S. Ratynskaia, D. Ripamonti, L. Vignitchouk, F. Causa, G. Daminelli, B. Esposito, E. Fortuna-Zalesna, F. Ghezzi, L. Laguardia, G. Maddaluno, G. Riva, and W. Zielinski, "Evidence for high-velocity solid dust generation induced by runaway electron impact in FTU," Nucl. Fusion **63**, 014001 (2023).
[497]V. P. Budaev, Y. V. Martynenko, S. A. Grashin, R. N. Giniyatulin, I. I. Arkhipov, A. V. Karpov, P. V. Savrukhin, E. A. Shestakov, R. Y. Solomatin, L. B. Begrambekov, N. E. Belova, S. D. Fedorovich, L. N. Khimchenko, and V. M. Safronov, "Tungsten melting and erosion under plasma heat load in tokamak discharges with disruptions," Nucl. Mater. Energy **12**, 418 (2017).
[498]J. Mlynar, O. Ficker, E. Macusova, T. Markovic, D. Naydenkova, G. Papp, J. Urban, M. Vlainic, P. Vondracek, V. Weinzettl, O. Bogar, D. Bren, D. Carnevale, A. Casolari, J. Cerovsky, M. Farnik, M. Gobbin, M. Gospodarczyk, M. Hron, P. Kulhanek, J. Havlicek, A. Havranek, M. Imrisek, M. Jakubowski, N. Lamas, V. Linhart, K. Malinowski, M. Marcisovsky, E. Matveeva, R. Panek, V. V. Plyusnin, M. Rabinski, V. Svoboda, P. Svihra, J. Varju, and J. A. Zebrowski, "Runaway electron experiments at COMPASS in support of the EUROfusion ITER physics research," Plasma Phys. Controlled Fusion **61**, 014010 (2019).
[499]S. M. S. M. Kathmann, G. K. Schenter, B. C. Garrett, B. Chen, and J. I. Siepmann, "Thermodynamics and kinetics of nanoclusters controlling gas-to-particle nucleation," J. Phys. Chem. C **113**, 10354 (2009).
[500]A. Michau, G. Lombardi, C. Arnas, L. C. Delacqua, M. Redolfi, X. Bonnin, and K. Hassouni, "Modelling of dust grain formation in a low-temperature plasma reactor used for simulating parasitic discharges expected under tokamak divertor domes," Plasma Sources Sci. Technol. **19**, 034023 (2010).
[501]A. Michau, G. Lombardi, L. C. Delacqua, M. Redolfi, C. Arnas, X. Jestin, X. Bonnin, and K. Hassouni, "Field reversal and particle growth in a DC discharge," Plasma Chem. Plasma Process. **32**, 451 (2012).
[502]A. Michau, C. Arnas, and K. Hassouni, "Aerosol dyanmics in a DC sputtering discharge," J. Appl. Phys. **121**, 163301 (2019).
[503]I. Bykov, D. L. Rudakov, S. Ratynskaia, P. Tolias, M. De Angeli, E. M. Hollmann, A. G. McLean, C. J. Lasnier, and G. Riva, "Modification of adhered dust on plasma-facing surfaces due to exposure to ELMy H-mode plasma in DIII-D," Nucl. Mater. Energy **12**, 379 (2017).
[504]S. Ratynskaia, P. Tolias, I. Bykov, D. Rudakov, M. De Angeli, L. Vignitchouk, D. Ripamonti, G. Riva, S. Bardin, H. van der Meiden, J. Vernimmen, K. Bystrov, and G. De Temmerman, "Interaction of adhered metallic dust with transient plasma heat loads," Nucl. Fusion **56**, 066010 (2016).
[505]M. De Angeli, P. Tolias, S. Ratynskaia, D. Ripamonti, G. Riva, S. Bardin, T. Morgan, and G. De Temmerman, "Remobilization of tungsten dust from castellated plasma-facing components," Nucl. Mater. Energy **12**, 536 (2017).
[506]S. Ratynskaia, P. Tolias, M. De Angeli, D. Ripamonti, G. Riva, D. Aussems, and T. W. Morgan, "Interaction of adhered beryllium proxy dust with transient and stationary plasmas," Nucl. Mater. Energy **17**, 222 (2018).
[507]T. Ohkawa, "Dust particles as a possible source of impurities in tokamaks," Kakuyugo Kenkyu **37**, 117 (1977).
[508]D. L. Rudakov, A. Litnovsky, W. P. West, J. H. Yu, J. A. Boedo, B. D. Bray, S. Brezinsek, N. H. Brooks, M. E. Fenstermacher, M. Groth, E. M. Hollmann, A. Huber, A. W. Hyatt, S. I. Krasheninnikov, C. J. Lasnier, A. G. McLean, R. A. Moyer, A. Y. Pigarov, V. Philipps, A. Pospieszczyk, R. D. Smirnov, J. P. Sharpe, W. M. Solomon, J. G. Watkins, and C. P. C. Wong, "Dust studies in DIII-D and TEXTOR," Nucl. Fusion **49**, 085022 (2009).
[509]M. De Angeli, D. Ripamonti, F. Ghezzi, P. Tolias, C. Conti, C. Arnas, M. Jerab, D. L. Rudakov, C. P. Chrobak, J. Irby, B. LaBombard, B. Lipschultz, and G. Maddaluno, "Cross machine investigation of magnetic tokamak dust: Morphological and elemental analysis," Fusion Eng. Des. **166**, 112315 (2021).
[510]M. De Angeli, P. Tolias, C. Conti, D. Ripamonti, F. Ghezzi, C. Arnas, J. Irby, M. Jerab, B. LaBombard, S. Lecci, and G. Maddaluno, "Cross machine

investigation of magnetic tokamak dust; structural and magnetic analysis," Nucl. Mater. Energy **28**, 101045 (2021).
[511]J. Roth, K. Sugiyama, V. Alimov, T. Höschen, M. Baldwin, and R. Doerner, "EUROFER as wall material: Reduced sputtering yields due to W surface enrichment," J. Nucl. Mater. **454**, 1 (2014).
[512]G.-J. Niu, G. Kawamura, Q. Xu, T. He, F.-F. Nian, R. Wang, Z.-S. Yang, and G.-N. Luo, "A numerical study on the effect of dust particles on tritium deposition on plasma-facing materials," Nucl. Mater. Energy **31**, 101169 (2022).
[513]S. Peillon, M. Sow, C. Grisolia, F. Miserque, and F. Gensdarmes, "Mobilization of tungsten dust by electric forces and its bearing on tritiated particles in the ITER tokamak," J. Electrostat. **88**, 111 (2017).
[514]A. Grisolia, F. Gensdarmes, and S. Peillon, "Current investigations on tritiated dust and its impact on tokamak safety," Nucl. Fusion **59**, 086061 (2019).
[515]G. Dougniaux, M. Sow, S. Peillon, C. Grisolia, and F. Gensdarmes, "Evolution of nitrogen concentration and ammonia production in N_2-seeded H-mode discharges at ASDEX Upgrade," J. Phys.: Conf. Ser. **1322**, 012027 (2019).
[516]E. A. Hodille, M. Payet, V. Marascu, S. Peillon, J. Mougenot, Y. Ferro, R. Delaporte-Mathurin, F. Leblond, E. Bernard, and C. Grisolia, "Modelling tritium adsorption and desorption from tungsten dust particles with a surface kinetic model," Nucl. Fusion **61**, 086030 (2021).
[517]D. K. Mansfield, A. L. Roquemore, H. Schneider, J. Timberlake, H. Kugel, and M. G. Bell, "A simple apparatus for the injection of lithium aerosol into the scrape-off layer of fusion research devices," Fusion Eng. Des. **85**, 890 (2010).
[518]T. H. Osborne, G. L. Jackson, Z. Yan, R. Maingi, D. K. Mansfield, B. A. Grierson, C. P. Chrobak, A. G. McLean, S. L. Allen, D. J. Battaglia, A. R. Briesemeister, M. E. Fenstermacher, G. R. McKee, P. B. Snyder, and DIII-D Team, "Enhanced H-mode pedestals with lithium injection in DIII-D," Nucl. Fusion **55**, 063018 (2015).
[519]R. Lunsford, V. Rohde, A. Bortolon, R. Dux, A. Herrmann, A. Kallenbach, R. McDermott, P. David, A. Drenik, F. Laggner, R. Maingi, D. K. Mansfield, A. Nagy, R. Neu, E. Wolfrum, and ASDEX Upgrade Team, "Active conditioning of ASDEX Upgrade tungsten plasma-facing components and discharge enhancement through boron and boron nitride particulate injection," Nucl. Fusion **59**, 126034 (2019).
[520]Z. Sun, R. Maingi, J. S. Hu, W. Xu, G. Z. Zuo, Y. W. Yu, C. R. Wu, M. Huang, X. C. Meng, L. Zhang, L. Wang, S. T. Mao, F. Ding, D. K. Mansfield, J. Canik, R. Lunsford, A. Bortolon, X. Z. Gong, and EAST Team, "Real time wall conditioning with lithium powder injection in long pulse H-mode plasmas in EAST with tungsten divertor," Nucl. Mater. Energy **19**, 124 (2019).
[521]A. Bortolon, V. Rohde, R. Maingi, E. Wolfrum, R. Dux, A. Herrmann, R. Lunsford, R. McDermott, A. Nagy, A. Kallenbach, D. Mansfield, R. Nazikian, R. Neu, and ASDEX Upgrade Team, "Real-time wall conditioning by controlled injection of boron and boron nitride powder in full tungsten wall ASDEX Upgrade," Nucl. Mater. Energy **19**, 384 (2019).
[522]A. Bortolon, R. Maingi, A. Nagy, J. Ren, J. D. Duran, A. Maan, D. C. Donovan, J. A. Boedo, D. L. Rudakov, A. W. Hyatt, T. W. Wilks, M. W. Shafer, C. M. Samuell, M. E. Fenstermacher, E. P. Gilson, R. Lunsford, D. K. Mansfield, T. Abrams, and R. Nazikian, "Observations of wall conditioning by means of boron powder injection in DIII-D H-mode plasmas," Nucl. Fusion **60**, 126010 (2020).
[523]R. Maingi, J. S. Hu, Z. Sun, A. Diallo, K. Tritz, Y. Z. Qian, W. Xu, G. Z. Zuo, C. L. Li, M. Huang, Y. Ye, A. Bortolon, E. P. Gilson, R. Lunsford, D. K. Mansfield, A. Nagy, J. P. Qian, X. Z. Gong, and T. E. Team, "Elm suppression by boron powder injection and comparison with lithium powder injection on east," J. Fusion Energy **39**, 429 (2020).
[524]R. Lunsford, C. Killer, A. Nagy, D. A. Gates, T. Klinger, A. Dinklage, G. Satheeswaran, G. Kocsis, S. A. Lazerson, F. Nespoli, N. A. Pablant, A. von Stechow, A. Alonso, T. Andreeva, M. Beurskens, C. Biedermann, S. Brezinsek, K. J. Brunner, B. Buttenschön, D. Carralero, G. Cseh, P. Drewelow, F. Effenberg, T. Estrada, O. P. Ford, O. Grulke, U. Hergenhahn, U. Höfel, J. Knauer, M. Krause, M. Krychowiak, S. Kwak, A. Langenberg, U. Neuner, D. Nicolai, A. Pavone, A. Puig Sitjes, K. Rahbarnia, J. Schilling, J. Svensson, T. Szepesi, H. Thomsen, T. Wauters, T. Windisch, V. Winters, D. Zhang, L. Zsuga, and W7-X Team, "Characterization of injection and confinement improvement through impurity induced profile modifications on the Wendelstein 7-X stellarator," Phys. Plasmas **28**, 082506 (2021).
[525]E. P. Gilson, H. H. Lee, A. Bortolon, W. Choe, A. Diallo, S. H. Hong, H. M. Lee, J. Lee, R. Maingi, D. K. Mansfield, A. Nagy, S. H. Park, I. W. Song, J. I. Song, S. W. Yun, S. W. Yoon, and R. Nazikian, "Wall conditioning and ELM mitigation with boron nitride powder injection in KSTAR," Nucl. Mater. Energy **28**, 101043 (2021).
[526]G. Bodner, A. Gallo, A. Diallo, R. Lunsford, P. Moreau, A. Nagy, F.-P. Pellissier, C. Guillemaut, J. P. Gunn, C. Bourdelle, C. Desgranges, P. Manas, A. Bortolon, C. C. Klepper, E. Tsitrone, E. A. Unterberg, L. Vermare, and WEST Team, "Initial results from boron powder injection experiments in WEST lower single null L-mode plasmas," Nucl. Fusion **62**, 086020 (2022).
[527]S. I. Krasheninnikov and A. S. Kukushkin, "Physics of ultimate detachment of a tokamak divertor plasma," J. Plasma Phys. **83**, 155830501 (2017).
[528]H. Thomas, D. Goldbeck, T. Hagl, A. Ivlev, U. Konopka, G. Morfill, H. Rothermel, R. Sutterlin, and M. Zuzic, "Complex plasmas under microgravity conditions: Parabolic flights," Phys. Scr. **T89**, 16–19 (2001).
[529]M. H. Thoma, H. Hoefner, M. Kretschmer, S. Ratynskaia, G. E. Morfill, A. Usachev, A. Zobnin, O. Petrov, and V. Fortov, "Parabolic flight experiments with PK-4," Microgravity Sci. Technol. **18**, 47–50 (2006).
[530]M. Klindworth, O. Arp, and A. Piel, "Langmuir probe system for dusty plasmas under microgravity," Rev. Sci. Instrum. **78**, 033502 (2007).
[531]M. Wolter, A. Melzer, O. Arp, M. Klindworth, M. Kroll, and A. Piel, "Laser manipulation of the void edge in dusty plasmas under microgravity," IEEE Trans. Plasma Sci. **35**, 266–270 (2007).
[532]M. Wolter, A. Melzer, O. Arp, M. Klindworth, and A. Piel, "Force measurements in dusty plasmas under microgravity by means of laser manipulation," Phys. Plasmas **14**, 123707 (2007).
[533]A. D. Usachev, A. V. Zobnin, O. F. Petrov, V. E. Fortov, B. M. Annaratone, M. H. Thoma, H. Hoefner, M. Kretschmer, M. Fink, and G. E. Morfill, "Formation of a boundary-free dust cluster in a low-pressure gas-discharge plasma," Phys. Rev. Lett. **102**, 045001 (2009).
[534]M. H. Thoma, S. Mitic, A. Usachev, B. M. Annaratone, M. A. Fink, V. E. Fortov, H. Hoefner, A. V. Ivlev, B. A. Klumov, U. Konopka, M. Kretschmer, G. E. Morfill, O. F. Petrov, R. Suetterlin, S. Zhdanov, and A. V. Zobnin, "Recent complex plasma experiments in a dc discharge," IEEE Trans. Plasma Sci. **38**, 857–860 (2010).
[535]S. Zhdanov, R. Heidemann, M. H. Thoma, R. Suetterlin, H. M. Thomas, H. Hoefner, K. Tarantik, G. E. Morfill, A. D. Usachev, O. F. Petrov, and V. E. Fortov, "Dissipative dark solitons in a dc complex plasma," EPL **89**, 25001 (2010).
[536]M. A. Fink, M. H. Thoma, and G. E. Morfill, "PK-4 science activities in microgravity," Microgravity Sci. Technol. **23**, 169–171 (2011).
[537]S. A. Khrapak, M. H. Thoma, M. Chaudhuri, G. E. Morfill, A. V. Zobnin, A. D. Usachev, O. F. Petrov, and V. E. Fortov, "Particle flows in a DC discharge in laboratory and microgravity conditions," Phys. Rev. E **87**, 063109 (2013).
[538]M. Himpel, S. Schuett, W. J. Miloch, and A. E. Melzer, "Layered structures in extended dust clouds under microgravity," Phys. Plasmas **25**, 083707 (2018).
[539]C. Dietz, M. Kretschmer, B. Steinmueller, and M. H. Thoma, "Recent microgravity experiments with complex direct current plasmas," Contrib. Plasma Phys. **58**, 21–29 (2018).
[540]H. M. Thomas, G. E. Morfill, A. V. Ivlev, A. P. Nefedov, V. E. Fortov, H. Rothermel, M. Rubin-Zuzic, A. M. Lipaev, V. I. Molotkov, and O. F. Petrov, "PKE-Nefedov—Complex plasma research on the International Space Station," Microgravity Sci. Technol. **16**, 317–321 (2005).
[541]H. M. Thomas, G. E. Morfill, V. E. Fortov, A. V. Ivlev, V. I. Molotkov, A. M. Lipaev, T. Hagl, H. Rothermel, S. A. Khrapak, R. K. Suetterlin, M. Rubin-Zuzic, O. F. Petrov, V. I. Tokarev, and S. K. Krikalev, "Complex plasma laboratory PK-3 Plus on the International Space Station," New J. Phys. **10**, 033036 (2008).
[542]S. A. Khrapak, B. A. Klumov, P. Huber, V. I. Molotkov, A. M. Lipaev, V. N. Naumkin, A. V. Ivlev, H. M. Thomas, M. Schwabe, G. E. Morfill, O. F. Petrov, V. E. Fortov, Y. Malentschenko, and S. Volkov, "Fluid-solid phase transitions in three-dimensional complex plasmas under microgravity conditions," Phys. Rev. E **85**, 066407 (2012).
[543]A. Nefedov, G. Morfill, V. Fortov, H. Thomas, H. Rothermel, T. Hagl, A. Ivlev, M. Zuzic, B. Klumov, A. Lipaev, V. Molotkov, O. Petrov, Y. Gidzenko, S. Krikalev, W. Shepherd, A. Ivanov, M. Roth, H. Binnenbruck, J. Goree, and

Y. Semenov, "PKE-Nefedov: Plasma crystal experiments on the International Space Station," New J. Phys. **5**, 33 (2003).
[544]D. Samsonov, G. Morfill, H. Thomas, T. Hagl, H. Rothermel, V. Fortov, A. Lipaev, V. Molotkov, A. Nefedov, O. Petrov, A. Ivanov, and S. Krikalev, "Kinetic measurements of shock wave propagation in a three-dimensional complex (dusty) plasma," Phys. Rev. E **67**, 036404 (2003).
[545]W. Sun, M. Schwabe, H. M. Thomas, A. M. Lipaev, V. I. Molotkov, V. E. Fortov, Y. Feng, Y.-F. Lin, J. Zhang, Y. Guo, and C.-R. Du, "Dissipative solitary wave at the interface of a binary complex plasma," Europhys. Lett. **122**, 55001 (2018).
[546]M. Schwabe, K. Jiang, S. Zhdanov, T. Hagl, P. Huber, A. V. Ivlev, A. M. Lipaev, V. I. Molotkov, V. N. Naumkin, K. R. Sütterlin, H. M. Thomas, V. E. Fortov, G. E. Morfill, A. Skvortsov, and S. Volkov, "Direct measurement of the speed of sound in a complex plasma under microgravity conditions," Europhys. Lett. **96**, 55001 (2011).
[547]M. Schwabe, S. Zhdanov, C. Raeth, D. B. Graves, H. M. Thomas, and G. E. Morfill, "Collective effects in vortex movements in complex plasmas," Phys. Rev. Lett. **112**, 115002 (2014).
[548]M. Schwabe, C. R. Du, P. Huber, A. M. Lipaev, V. I. Molotkov, V. N. Naumkin, S. K. Zhdanov, D. I. Zhukhovitskii, V. E. Fortov, and H. M. Thomas, "Latest results on complex plasmas with the PK-3 Plus laboratory on board the International Space Station," Microgravity Sci. Technol. **30**, 581–589 (2018).
[549]K. R. Sütterlin, A. Wysocki, A. V. Ivlev, C. Räth, H. M. Thomas, M. Rubin-Zuzic, W. J. Goedheer, V. E. Fortov, A. M. Lipaev, V. I. Molotkov, O. F. Petrov, G. E. Morfill, and H. Löwen, "Dynamics of lane formation in driven binary complex plasmas," Phys. Rev. Lett. **102**, 085003 (2009).
[550]S. Zhdanov, M. Schwabe, C. Raeth, H. M. Thomas, and G. E. Morfill, "Wave turbulence observed in an auto-oscillating complex (dusty) plasma," EPL **110**, 35001 (2015).
[551]V. Nosenko, S. Zhdanov, M. Pustylnik, H. M. Thomas, A. M. Lipaev, and O. V. Novitskii, "Heat transport in a flowing complex plasma in microgravity conditions," Phys. Plasmas **28**, 113701 (2021).
[552]A. Ivlev, M. Kretschmer, M. Zuzic, G. Morfill, H. Rothermel, H. Thomas, V. Fortov, V. Molotkov, A. Nefedov, A. Lipaev, O. Petrov, Y. Baturin, A. Ivanov, and J. Goree, "Decharging of complex plasmas: First kinetic observations," Phys. Rev. Lett. **90**, 055003 (2003).
[553]M. Mikikian, L. Boufendi, A. Bouchoule, H. Thomas, G. Morfill, A. Nefedov, V. Fortov, and P.-N. Team, "Formation and behaviour of dust particle clouds in a radio-frequency discharge: Results in the laboratory and under microgravity conditions," New J. Phys. **5**, 19 (2003).
[554]U. Konopka, F. Mokler, A. Ivlev, M. Kretschmer, G. Morfill, H. Thomas, H. Rothermel, V. Fortov, A. Lipaev, V. Molotkov, A. Nefedov, Y. Baturin, Y. Budarin, A. Ivanov, and M. Roth, "Charge-induced gelation of microparticles," New J. Phys. **7**, 227 (2005).
[555]C. Killer, T. Bockwoldt, S. Schuett, M. Himpel, A. Melzer, and A. Piel, "Phase separation of binary charged particle systems with small size disparities using a dusty plasma," Phys. Rev. Lett. **116**, 115002 (2016).
[556]S. Schuett and A. Melzer, "Simulations and experiments of phase separation in binary dusty plasmas," Phys. Rev. E **103**, 053203 (2021).
[557]A. V. Ivlev, S. K. Zhdanov, H. M. Thomas, and G. E. Morfill, "Fluid phase separation in binary complex plasmas," EPL **85**, 45001 (2009).
[558]M. Y. Pustylnik, B. Klumov, M. Rubin-Zuzic, A. M. Lipaev, V. Nosenko, D. Erdle, A. D. Usachev, A. V. Zobnin, V. I. Molotkov, G. Joyce, H. M. Thomas, M. H. Thoma, O. F. Petrov, V. E. Fortov, and O. Kononenko, "Three-dimensional structure of a string-fluid complex plasma," Phys. Rev. Res. **2**, 033314 (2020).
[559]M. Schwabe, S. A. Khrapak, S. K. Zhdanov, M. Y. Pustylnik, C. Raeth, M. Fink, M. Kretschmer, A. M. Lipaev, V. I. Molotkov, A. S. Schmitz, M. H. Thoma, A. D. Usachev, A. V. Zobnin, G. I. Padalka, V. E. Fortov, O. F. Petrov, and H. M. Thomas, "Slowing of acoustic waves in electrorheological and string-fluid complex plasmas," New J. Phys. **22**, 083079 (2020).
[560]S. Mitic, M. Y. Pustylnik, D. Erdle, A. M. Lipaev, A. D. Usachev, A. Zobnin, V. M. H. Thoma, H. M. Thomas, O. F. Petrov, V. E. Fortov, and O. Kononenko, "Long-term evolution of the three-dimensional structure of string-fluid complex plasmas in the PK-4 experiment," Phys. Rev. E **103**, 063212 (2021).
[561]E. Joshi, M. Y. Pustylnik, M. H. Thoma, H. M. Thomas, and M. Schwabe, "Recrystallization in string-fluid complex plasmas," Phys. Rev. Res. **5**, L012030 (2023).
[562]T. Antonova, S. A. Khrapak, M. Y. Pustylnik, M. Rubin-Zuzic, H. M. Thomas, A. M. Lipaev, A. D. Usachev, V. I. Molotkov, and M. H. Thoma, "Particle charge in PK-4 DC discharge from ground-based and microgravity experiments," Phys. Plasmas **26**, 113703 (2019).
[563]M. Himpel, T. Bockwoldt, C. Killer, K. O. Menzel, A. Piel, and A. Melzer, "Stereoscopy of dust density waves under microgravity: Velocity distributions and phase-resolved single-particle analysis," Phys. Plasmas **21**, 033703 (2014).
[564]V. V. Yaroshenko, S. A. Khrapak, M. Y. Pustylnik, H. M. Thomas, S. Jaiswal, A. M. Lipaev, A. D. Usachev, O. F. Petrov, and V. E. Fortov, "Excitation of low-frequency dust density waves in flowing complex plasmas," Phys. Plasmas **26**, 053702 (2019).
[565]M. H. Thoma, H. M. M. Thomas, C. A. A. Knapek, A. Melzer, and U. Konopka, "Complex plasma research under microgravity conditions," NPJ Microgravity **9**, 13 (2023).
[566]N. P. Oxtoby, E. J. Griffith, C. Durniak, J. F. Ralph, and D. Samsonov, "Ideal gas behavior of a strongly coupled complex (dusty) plasma," Phys. Rev. Lett. **111**, 015002 (2013).
[567]F. Wieben and D. Block, "Entropy measurement in strongly coupled complex plasmas," Phys. Rev. Lett. **123**, 225001 (2019).
[568]V. Nosenko, M. Pustylnik, M. Rubin-Zuzic, A. M. Lipaev, A. V. Zobnin, A. D. Usachev, H. M. Thomas, M. H. Thoma, V. E. Fortov, O. Kononenko, and A. Ovchinin, "Shear flow in a three-dimensional complex plasma in microgravity conditions," Phys. Rev. Res. **2**, 033404 (2020).
[569]S. Nunomura, D. Samsonov, S. Zhdanov, and G. Morfill, "Self-diffusion in a liquid complex plasma," Phys. Rev. Lett. **96**, 015003 (2006).
[570]A. V. Ivlev, G. E. Morfill, H. M. Thomas, C. Räth, G. Joyce, P. Huber, R. Kompaneets, V. E. Fortov, A. M. Lipaev, V. I. Molotkov, T. Reiter, M. Turin, and P. Vinogradov, "First observation of electrorheological plasmas," Phys. Rev. Lett. **100**, 095003 (2008).
[571]A. C. Levi and M. Kotrla, "Theory and simulation of crystal growth," J. Phys.: Condens. Matter **9**, 299 (1997).
[572]A. Cavagna, "Supercooled liquids for pedestrians," Phys. Rep. **476**, 51–124 (2009).
[573]L. Berthier and G. Biroli, "Theoretical perspective on the glass transition and amorphous materials," Rev. Mod. Phys. **83**, 587–645 (2011).
[574]P.-C. Lin, W.-J. Chen, and L. I, "Percolating transition to acoustic wave turbulence in dusty plasmas," Phys. Plasmas **27**, 010703 (2020).
[575]Y.-Y. Tsai, J.-Y. Tsai, and L. I, "Generation of acoustic rogue waves in dusty plasmas through three-dimensional particle focusing by distorted waveforms," Nat. Phys. **12**, 573–577 (2016).
[576]A. Kananovich and J. Goree, "Shocks propagate in a 2d dusty plasma with less attenuation than due to gas friction alone," Phys. Plasmas **27**, 113704 (2020).
[577]M. Schwabe, S. Zhdanov, and C. Räth, "Instability onset and scaling laws of an auto-oscillating turbulent flow in a complex plasma," Phys. Rev. E **95**, 041201 (2017).
[578]V. Nosenko, F. Luoni, A. Kaouk, M. Rubin-Zuzic, and H. Thomas, "Active janus particles in a complex plasma," Phys. Rev. Res. **2**, 033226 (2020).
[579]B. M. Annaratone, A. G. Khrapak, A. V. Ivlev, G. Söllner, P. Bryant, R. Sütterlin, U. Konopka, K. Yoshino, M. Zuzic, H. M. Thomas, and G. E. Morfill, "Levitation of cylindrical particles in the sheath of an RF plasma," Phys. Rev. E **63**, 036406 (2001).
[580]C. K. Goertz and G. Morfill, "A model for the formation of spokes in Saturn's ring," Icarus **53**, 219–229 (1983).
[581]C. K. Goertz, "Dusty plasmas in the solar system," Rev. Geophys. **27**(2), 271–292, https://doi.org/10.1029/RG027i002p00271 (1989).
[582]A. V. Ivlev, A. Burkert, A. Vasyunin, and P. Caselli, "Compact dusty clouds and efficient H_2 formation in diffuse interstellar medium," Astrophys. J. **861**, 30 (2018).
[583]Z. Wu, A. Wang, W. M. Farrell, Y. Yan, K. Wang, J. Houghton, and A. W. Jackson, "Forming perchlorates on mars through plasma chemistry during dust events," Earth Planet. Sci. Lett. **504**, 94–105 (2018).
[584]NASA, "Artemis plan 'NASA'S lunar exploration program overview; September 2020'" (NASA, 2020).

[585]M. Henault, G. Wattieaux, T. Lecas, J. P. Renouard, and L. Boufendi, "Electrical method for the measurements of volume averaged electron density and effective coupled power to the plasma bulk," Phys. Plasmas **23**, 023504 (2016).
[586]G. Wattieaux and L. Boufendi, "Discharge impedance evolution, stray capacitance effect, and correlation with the particles size in a dusty plasma," Phys. Plasmas **19**, 033701 (2012).
[587]C. A. Knapek, L. Couedel, A. Dove, J. Goree, U. Konopka, A. Melzer, S. Ratynskaia, M. H. Thoma, and H. M. Thomas, "COMPACT—A new complex plasma facility for the ISS," Plasma Phys. Controlled Fusion **64**, 124006 (2022).
[588]C. E. Carr, N. C. Bryan, K. N. Saboda, S. A. Bhattaru, G. Ruvkun, and M. T. Zuber, "Acceleration profiles and processing methods for parabolic flight," NPJ Microgravity **4**, 14 (2018).
[589]J. Chu and L. I, "Direct observation of Coulomb crystals and liquids in strongly coupled RF dusty plasmas," Phys. Rev. Lett. **72**, 4009–4012 (1994).
[590]H. Thomas, G. Morfill, V. Demmel, J. Goree, B. Feuerbacher, and D. Mohlmann, "Plasma crystal—Coulomb crystallization in a dusty plasma," Phys. Rev. Lett. **73**, 652–655 (1994).
[591]Y. Hayashi and K. Tachibana, "Observation of Coulomb-crystal formation from carbon particles grown in a methane plasma," Jpn. J. Appl. Phys., Part 2 **33**, L804–L806 (1994).
[592]A. Melzer, T. Trottenberg, and A. Piel, "Experimental-determination of the charge on dust particles forming Coulomb lattices," Phys. Lett. A **191**, 301–308 (1994).
[593]C.-S. Wong, J. Goree, Z. Haralson, and B. Liu, "Strongly coupled plasmas obey the fluctuation theorem for entropy production," Nat. Phys. **14**, 21–24 (2018).
[594]D. Huang, S. Lu, X.-Q. Shi, J. Goree, and Y. Feng, "Fluctuation theorem convergence in a viscoelastic medium demonstrated experimentally using a dusty plasma," Phys. Rev. E **104**, 035207 (2021).
[595]Y. Feng, J. Goree, B. Liu, L. Wang, and W.-D. Tian, "Pressure of two-dimensional Yukawa liquids," J. Phys. D: Appl. Phys. **49**, 235203 (2016).
[596]Y. Feng, W. Lin, W. Li, and Q. Wang, "Equations of state and diagrams of two-dimensional liquid dusty plasmas," Phys. Plasmas **23**, 093705 (2016).
[597]Y. Feng, W. Li, Q. Wang, and W. Lin, "Strong coupling effects on the relationship between internal energy and pressure for two-dimensional liquid dusty plasmas," Phys. Plasmas **23**, 113705 (2016).
[598]F. L. Castello and P. Tolias, "Structure and thermodynamics of two-dimensional Yukawa liquids," Phys. Rev. E **103**, 063205 (2021).
[599]W. Li, W. Lin, and Y. Feng, "Bulk modulus of two-dimensional liquid dusty plasmas and its application," Phys. Plasmas **24**, 043702 (2017).
[600]D. Huang, W. Li, W. Lin, and Y. Feng, "Specific heat and Gruneisen parameter for 2d liquid dusty plasmas," Phys. Plasmas **24**, 093707 (2017).
[601]Y. Feng, D. Huang, and W. Li, "Adiabatic bulk modulus of elasticity for 2d liquid dusty plasmas," Phys. Plasmas **25**, 057301 (2018).
[602]K. Wang, D. Huang, and Y. Feng, "Shear modulus of two-dimensional Yukawa or dusty-plasma solids obtained from the viscoelasticity in the liquid state," Phys. Rev. E **99**, 063206 (2019).
[603]D. Huang, S. Lu, and Y. Feng, "Reply to 'Comment on "Shear modulus of two-dimensional Yukawa or dusty-plasma solids obtained from the viscoelasticity in the liquid state,"'" Phys. Rev. E **101**, 057202 (2020).
[604]S. Lu, D. Huang, A. Shahzad, and Y. Feng, "Bulk moduli of two-dimensional Yukawa solids and liquids obtained from periodic compressions," Plasma Sci. Technol. **25**, 035002 (2023).
[605]D. Huang, M. Baggioli, S. Lu, Z. Ma, and Y. Feng, "Revealing the supercritical dynamics of dusty plasmas and their liquidlike to gaslike dynamical crossover," Phys. Rev. Res. **5**, 013149 (2023).
[606]C.-R. Du, V. Nosenko, H. M. Thomas, Y.-F. Lin, G. E. Morfill, and A. V. Ivlev, "Slow dynamics in a quasi-two-dimensional binary complex plasma," Phys. Rev. Lett. **123**, 185002 (2019).
[607]Y.-F. Lin, A. Ivlev, H. Löwen, L. Hong, and C.-R. Du, "Structure and dynamics of a glass-forming binary complex plasma with non-reciprocal interaction," Europhys. Lett. **123**, 35001 (2018).
[608]Y.-F. He, B.-Q. Ai, C.-X. Dai, C. Song, R.-Q. Wang, W.-T. Sun, F.-C. Liu, and Y. Feng, "Experimental demonstration of a dusty plasma ratchet rectification and its reversal," Phys. Rev. Lett. **124**, 075001 (2020).
[609]D. Huang, S. Lu, and Y. Feng, "Determination of viscosity in shear-induced melting two-dimensional dusty plasmas using Green-Kubo relation," Phys. Rev. E **103**, 013211 (2021).
[610]J. Berumen and J. Goree, "Experiment and model for a Stokes layer in a strongly coupled dusty plasma," Phys. Rev. E **104**, 035208 (2021).
[611]J. Berumen and J. Goree, "Frequency-dependent complex viscosity obtained for a liquid two-dimensional dusty plasma experiment," Phys. Rev. E **105**, 015209 (2022).
[612]D. Huang, S. Lu, M. S. Murillo, and Y. Feng, "Origin of viscosity at individual particle level in Yukawa liquids," Phys. Rev. Res. **4**, 033064 (2022).
[613]S. Lu, D. Huang, and Y. Feng, "Plastic strain rate quantified from dislocation dynamics in dusty plasma shear flows," Phys. Rev. E **103**, 063214 (2021).
[614]S. Lu, D. Huang, and Y. Feng, "Shear softening and hardening of a two-dimensional Yukawa solid," Phys. Rev. E **105**, 035203 (2022).
[615]M. Marciante and M. S. Murillo, "Thermodynamic and kinetic properties of shocks in two-dimensional Yukawa systems," Phys. Rev. Lett. **118**, 025001 (2017).
[616]W. Lin, M. S. Murillo, and Y. Feng, "Pressure and energy of compressional shocks in two-dimensional Yukawa systems," Phys. Rev. E **100**, 043203 (2019).
[617]W. Lin, M. S. Murillo, and Y. Feng, "Universal relationship of compression shocks in two-dimensional Yukawa systems," Phys. Rev. E **101**, 013203 (2020).
[618]T. Sun and Y. Feng, "Shock-induced melting of two-dimensional Yukawa systems from T_H–P_H Hugoniot curves," Phys. Plasmas **28**, 063702 (2021).
[619]P. Qiu, T. Sun, and Y. Feng, "Observation of the solid and liquid separation after the shock propagation in a two-dimensional Yukawa solid," Phys. Plasmas **28**, 113702 (2021).
[620]J. Shen, S. Lu, T. Sun, and Y. Feng, "Elastic-plastic transition of compressional shocks in a perfect 2d Yukawa crystal," Phys. Plasmas **29**, 053701 (2022).
[621]P. Qiu and Y. Feng, "Fast particles overtaking shock front in two-dimensional Yukawa solids," Phys. Rev. E **106**, 015203 (2022).
[622]X. Ding, S. Lu, T. Sung, M. S. Murillo, and Y. Feng, "Head-on collision of compressional shocks in two-dimensional Yukawa systems," Phys. Rev. E **103**, 013202 (2021).
[623]T. Sun, M. S. Murillo, and Y. Feng, "Evolution of unsupported shocks in a two-dimensional Yukawa solid," Phys. Plasmas **28**, 103703 (2021).
[624]A. Kananovich and J. Goree, "Experimental determination of shock speed versus exciter speed in a two-dimensional dusty plasma," Phys. Rev. E **101**, 043211 (2020).
[625]A. Kananovich and J. Goree, "Shock width measured under liquid and solid conditions in a two-dimensional dusty plasma," Phys. Rev. E **104**, 055201 (2021).
[626]H. Huang, A. Ivlev, V. Nosenko, W. Yang, and C.-R. Du, "Dissipative solitary waves in a two-dimensional complex plasma: Amorphous versus crystalline," Phys. Rev. E **107**(4–2), 045205 (2023).
[627]W. Li, D. Huang, K. Wang, C. Reichhardt, C. J. O. Reichhardt, M. S. Murillo, and Y. Feng, "Phonon spectra of two-dimensional liquid dusty plasmas on a one-dimensional periodic substrate," Phys. Rev. E **98**, 063203 (2018).
[628]K. Wang, W. Li, D. Huang, C. Reichhardt, C. J. O. Reichhardt, M. S. Murillo, and Y. Feng, "Structures and diffusion of two-dimensional dusty plasmas on one-dimensional periodic substrates," Phys. Rev. E **98**, 063204 (2018).
[629]W. Li, C. Reichhardt, C. J. O. Reichhardt, M. S. Murillo, and Y. Feng, "Oscillation-like diffusion of two-dimensional liquid dusty plasmas on one-dimensional periodic substrates with varied widths," Phys. Plasmas **27**, 033702 (2020).
[630]W. Li, K. Wang, C. Reichhardt, C. J. O. Reichhardt, M. S. Murillo, and Y. Feng, "Depinning dynamics of two-dimensional dusty plasmas on a one-dimensional periodic substrate," Phys. Rev. E **100**, 033207 (2019).
[631]L. Gu, W. Li, C. Reichhardt, C. J. O. Reichhardt, M. S. Murillo, and Y. Feng, "Continuous and discontinuous transitions in the depinning of two-dimensional dusty plasmas on a one-dimensional periodic substrate," Phys. Rev. E **102**, 063203 (2020).
[632]W. Li, D. Huang, C. Reichhardt, C. Reichhardt, and Y. Feng, "Bidirectional flow of two-dimensional dusty plasma under asymmetric periodic substrates driven by unbiased external excitations," Phys. Rev. Res. **5**, 023008 (2023).

[633]Y. Huang, W. Li, C. Reichhardt, C. J. O. Reichhardt, and Y. Feng, "Phonon spectra of a two-dimensional solid dusty plasma modified by two-dimensional periodic substrates," Phys. Rev. E **105**, 015202 (2022).
[634]W. Zhu, C. Reichhardt, C. J. O. Reichhardt, and Y. Feng, "Directional locking in a two-dimensional Yukawa solid modulated by a two-dimensional periodic substrate," Phys. Rev. E **106**, 015202 (2022).
[635]W. Zhu, C. Reichhardt, C. J. O. Reichhardt, and Y. Feng, "Dynamical commensuration effect in a two-dimensional Yukawa solid modulated by periodic substrates," Phys. Plasmas **30**, 043702 (2023).
[636]Y. Huang, C. Reichhardt, C. J. O. Reichhardt, and Y. Feng, "Superlubric-pinned transition of a two-dimensional solid dusty plasma under a periodic triangular substrate," Phys. Rev. E **106**, 035204 (2022).
[637]V. Nosenko, S. K. Zhdanov, J. Carmona-Reyes, and T. W. Hyde, "Mode-coupling instability in a single-layer complex plasma crystal: Strong damping regime," Phys. Plasmas **25**, 093702 (2018).
[638]J. K. Meyer, I. Laut, S. K. Zhdanov, V. Nosenko, and H. M. Thomas, "Coupling of noncrossing wave modes in a two-dimensional plasma crystal," Phys. Rev. Lett. **119**, 255001 (2017).
[639]N. P. Kryuchkov, E. V. Yakovlev, E. A. Gorbunov, L. Couedel, A. M. Lipaev, and S. O. Yurchenko, "Thermoacoustic instability in two-dimensional fluid complex plasmas," Phys. Rev. Lett. **121**, 075003 (2018).
[640]H. Huang, A. V. Ivlev, V. Nosenko, Y. F. Lin, and C. R. Du, "Wave spectra of square-lattice domains in a quasi-two-dimensional binary complex plasma," Phys. Plasmas **26**, 013702 (2019).
[641]S. Singh, P. Bandyopadhyay, K. Kumar, and A. Sen, "Square lattice formation in a monodisperse complex plasma," Phys. Rev. Lett. **129**, 115003 (2022).
[642]K. Arkar, M. M. Vasiliev, O. F. Petrov, E. A. Kononov, and F. M. Trukhachev, "Dynamics of active Brownian particles in plasma," Molecules **26**, 561 (2021).
[643]V. Nosenko, "Two-dimensional complex (dusty) plasma with active janus particles," Phys. Plasmas **29**, 123701 (2022).
[644]J. Bartnick, A. Kaiser, H. Loewen, and A. V. Ivlev, "Emerging activity in bilayered dispersions with wake-mediated interactions," J. Chem. Phys. **144**, 224901 (2016).
[645]Z. Donko, J. Goree, P. Hartmann, and B. Liu, "Time-correlation functions and transport coefficients of two-dimensional Yukawa liquids," Phys. Rev. E **79**, 026401 (2009).
[646]C.-R. Du, V. Nosenko, H. M. Thomas, A. Müller, A. M. Lipaev, V. I. Molotkov, V. E. Fortov, and A. V. Ivlev, "Photophoretic force on microparticles in complex plasmas," New J. Phys. **19**, 073015 (2017).
[647]H. Gao, G. Wang, B. Chen, Y. Zhang, D. Liu, X. Lu, G. He, and K. K. Ostrikov, "Atmospheric-pressure non-equilibrium plasmas for effective abatement of pathogenic biological aerosols," Plasma Sources Sci. Technol. **30**, 053001 (2021).
[648]W.-H. Chiang, D. Mariotti, R. M. Sankaran, J. G. Eden, and K. K. Ostrikov, "Microplasmas for advanced materials and devices," Adv. Mater. **32**, 1905508 (2020).
[649]F. Fanelli and F. Fracassi, "Aerosol-assisted atmospheric pressure cold plasma deposition of organic-inorganic nanocomposite coatings," Plasma Chem. Plasma Process. **34**, 473–487 (2014).
[650]Y. Sui, C. A. Zorman, and R. M. Sankaran, "Plasmas for additive manufacturing," Plasma Processes Polym. **17**, 2000009 (2020).
[651]A. Stancampiano, T. Gallingani, M. Gherardi, Z. Machala, P. Maguire, V. Colombo, J.-M. Pouvesle, and E. Robert, "Plasma and aerosols: Challenges, opportunities and perspectives," Appl. Sci. **9**, 3861 (2019).
[652]H. J. Jang, E. Y. Jung, T. Parsons, H.-S. Tae, and C.-S. Park, "A review of plasma synthesis methods for polymer films and nanoparticles under atmospheric pressure conditions," Polymers **13**, 2267 (2021).
[653]F. Palumbo, C. Lo Porto, F. Fracassi, and P. Favia, "Recent advancements in the use of aerosol-assisted atmospheric pressure plasma deposition," Coatings **10**, 440 (2020).
[654]M. Domonkos, P. Tichá, J. Trejbal, and P. Demo, "Applications of cold atmospheric pressure plasma technology in medicine, agriculture and food industry," Appl. Sci. **11**, 4809 (2021).
[655]D. Mariotti, T. Belmonte, J. Benedikt, T. Velusamy, G. Jain, and V. Švrček, "Low-temperature atmospheric pressure plasma processes for "green" third generation photovoltaics," Plasma Processes Polym. **13**, 70–90 (2016).
[656]P. D. Maguire, C. M. O. Mahony, C. P. Kelsey, A. J. Bingham, E. P. Montgomery, E. D. Bennet, H. E. Potts, D. C. E. Rutherford, D. A. McDowell, D. A. Diver, and D. Mariotti, "Controlled microdroplet transport in an atmospheric pressure microplasma," Appl. Phys. Lett. **106**, 224101 (2015).
[657]E. Bennet, C. Mahony, H. Potts, P. Everest, D. Rutherford, S. Askari, D. McDowell, D. Mariotti, C. Kelsey, F. Perez-Martin, N. Hamilton, P. Maguire, and D. Diver, "Precision charging of microparticles in plasma via the Rayleigh instability for evaporating charged liquid droplets," J. Aerosol Sci. **100**, 53–60 (2016).
[658]N. J. Kramer, E. S. Aydil, and U. R. Kortshagen, "Requirements for plasma synthesis of nanocrystals at atmospheric pressures," J. Phys. D: Appl. Phys. **48**, 035205 (2015).
[659]S. Askari, I. Levchenko, K. Ostrikov, P. Maguire, and D. Mariotti, "Crystalline Si nanoparticles below crystallization threshold: Effects of collisional heating in non-thermal atmospheric-pressure microplasmas," Appl. Phys. Lett. **104**, 163103 (2014).
[660]M. Meyer, G. Nayak, P. J. Bruggeman, and M. J. Kushner, "Sheath formation around a dielectric droplet in a He atmospheric pressure plasma," J. Appl. Phys. **132**, 083303 (2022).
[661]G. Nayak, M. Meyer, G. Oinuma, M. J. Kushner, and P. J. Bruggeman, "The transport dynamics of tens of micrometer-sized water droplets in rf atmospheric pressure glow discharges," Plasma Sources Sci. Technol. **32**, 045005 (2023).
[662]A. J. Wagner, D. Mariotti, K. J. Yurchenko, and T. K. Das, "Experimental study of a planar atmospheric-pressure plasma operating in the microplasma regime," Phys. Rev. E **80**, 065401 (2009).
[663]P. J. Bruggeman, F. Iza, and R. Brandenburg, "Foundations of atmospheric pressure non-equilibrium plasmas," Plasma Sources Sci. Technol. **26**, 123002 (2017).
[664]J. Winter, R. Brandenburg, and K.-D. Weltmann, "Atmospheric pressure plasma jets: An overview of devices and new directions," Plasma Sources Sci. Technol. **24**, 064001 (2015).
[665]S. Askari, M. Macias-Montero, T. Velusamy, P. Maguire, V. Svrcek, and D. Mariotti, "Silicon-based quantum dots: synthesis, surface and composition tuning with atmospheric pressure plasmas," J. Phys. D: Appl. Phys. **48**, 314002 (2015).
[666]G. Sharma, N. Abuyazid, S. Dhawan, S. Kshirsagar, R. M. Sankaran, and P. Biswas, "Characterization of particle charging in low-temperature, atmospheric-pressure, flow-through plasmas," J. Phys. D: Appl. Phys. **53**, 245204 (2020).
[667]V. Suresh, Z. Liu, Z. Perry, and R. Gopalakrishnan, "Modeling particle-particle binary coagulation rate constants for spherical aerosol particles at high volume fractions using Langevin dynamics simulations," J. Aerosol Sci. **164**, 106001 (2022).
[668]T. J. A. Staps, "A review of nanoparticle decharging in atmospheric pressure plasma afterglows," Front. Phys. **10**, 1–8 (2022).
[669]S. Dhawan, A. Vidwans, G. Sharma, N. H. Abuyazid, R. Mohan Sankaran, and P. Biswas, "Enhancing charging and capture efficiency of aerosol nanoparticles using an atmospheric-pressure, flow-through RF plasma with a downstream DC bias," Aerosol Sci. Technol. **54**, 1249–1254 (2020).
[670]S. Ghosh, T. Liu, M. Bilici, J. Cole, I.-M. Huang, D. Staack, D. Mariotti, and R. M. Sankaran, "Atmospheric-pressure dielectric barrier discharge with capillary injection for gas-phase nanoparticle synthesis," J. Phys. D: Appl. Phys. **48**, 314003 (2015).
[671]N. H. Abuyazid, X. Chen, D. Mariotti, P. Maguire, C. J. Hogan, and R. M. Sankaran, "Understanding the depletion of electrons in dusty plasmas at atmospheric pressure," Plasma Sources Sci. Technol. **29**, 075011 (2020).
[672]Y. Fan, K. Zhang, H. Xiao, C. J. Hogan, and C. Li, "Sintering of metallic nanoaggregates in an atmospheric pressure non-thermal plasma," J. Aerosol Sci. **171**, 106167 (2023).
[673]T. Gallingani, N. H. Abuyazid, V. Colombo, M. Gherardi, and R. M. Sankaran, "Online ion mobility spectrometry of nanoparticle formation by non-thermal plasma conversion of metal salts in liquid aerosol droplets," J. Aerosol Sci. **150**, 105631 (2020).
[674]M. E. Hassan, M. Janda, and Z. Machala, "Transport of gaseous hydrogen peroxide and ozone into bulk water vs. electrosprayed aerosol," Water **13**, 182 (2021).

[675]P. Maguire, D. Rutherford, M. Macias-Montero, C. Mahony, C. Kelsey, M. Tweedie, F. Pérez-Martin, H. McQuaid, D. Diver, and D. Mariotti, "Continuous in-flight synthesis for on-demand delivery of ligand-free colloidal gold nanoparticles," Nano Lett. **17**, 1336–1343 (2017).
[676]A. Dey, A. Lopez, G. Filipič, A. Jayan, D. Nordlund, J. Koehne, S. Krishnamurthy, R. P. Gandhiraman, and M. Meyyappan, "Plasma jet based in situ reduction of copper oxide in direct write printing," J. Vac. Sci. Technol. B **37**, 031203 (2019).
[677]K. Nitta, Y. Shimizu, K. Terashima, and T. Ito, "Plasma-assisted synthesis of size-controlled monodisperse submicron gold particles using inkjet droplets," J. Phys. D: Appl. Phys. **54**, 33LT01 (2021).
[678]S. Keniley, N. B. Uner, E. Perez, R. M. Sankaran, and D. Curreli, "Multiphase modeling of the DC plasma-water interface: Application to hydrogen peroxide generation with experimental validation," Plasma Sources Sci. Technol. **31**, 075001 (2022).
[679]Y. Sui, A. Hess-Dunning, A. Radwan, R. Sankaran, and C. Zorman, "Engineering the surface morphology of inkjet printed Ag by controlling solvent evaporation during plasma conversion of $AgNO_3$ inks," J. Mater. Chem. C **10**, 5257–5265 (2022).
[680]H. Gao, G. Wang, Z. Huang, L. Nie, D. Liu, X. Lu, G. He, and K. K. Ostrikov, "Plasma-activated mist: Continuous-flow, scalable nitrogen fixation, and aeroponics," ACS Sustainable Chem. Eng. **11**, 4420–4429 (2023).
[681]J. R. Toth, N. H. Abuyazid, D. J. Lacks, J. N. Renner, and R. M. Sankaran, "A plasma-water droplet reactor for process-intensified, continuous nitrogen fixation at atmospheric pressure," ACS Sustainable Chem. Eng. **8**, 14845–14854 (2020).
[682]M. Janda, K. Hensel, P. Tóth, M. E. Hassan, and Z. Machala, "The role of HNO_2 in the generation of plasma-activated water by air transient spark discharge," Appl. Sci. **11**, 7053 (2021).
[683]A. Bisag, P. Isabelli, G. Laghi, R. Laurita, G. Dirani, F. Taddei, C. Bucci, F. Capelli, M. Gherardi, A. Paglianti, V. Sambri, and V. Colombo, "Cold atmospheric plasma decontamination of SARS-CoV-2 bioaerosols," Plasma Processes Polym. **19**, e2100133 (2022).
[684]G. Nayak, J. Wang, R. Li, D. Aranzales, S. M. Thagard, and P. J. Bruggeman, "Non-OH-driven liquid-phase chemistry in water microdroplets," Plasma Processes Polym. **20**, 2200222 (2023).
[685]J. Kruszelnicki, A. M. Lietz, and M. J. Kushner, "Atmospheric pressure plasma activation of water droplets," J. Phys. D: Appl. Phys. **52**, 355207 (2019).
[686]G. Oinuma, G. Nayak, Y. Du, and P. J. Bruggeman, "Controlled plasma-droplet interactions: A quantitative study of OH transfer in plasma-liquid interaction," Plasma Sources Sci. Technol. **29**, 095002 (2020).
[687]G. Nayak, G. Oinuma, Y. Yue, J. S. Sousa, and P. J. Bruggeman, "Plasma-droplet interaction study to assess transport limitations and the role of OH, O, H, $O_2(a^1\ \Delta_g)$, O_3, $He(2^3s)$ and $Ar(1s^5)$ in formate decomposition," Plasma Sources Sci. Technol. **30**, 115003 (2021).
[688]I. Sremački, G. Bruno, H. Jablonowski, C. Leys, A. Nikiforov, and K. Wende, "Influence of aerosol injection on the liquid chemistry induced by an RF argon plasma jet," Plasma Sources Sci. Technol. **30**, 095018 (2021).
[689]T.-R. Lin, Y.-S. Hsieh, R.-Z. Zhang, and Y.-C. Cheng, "Enhancing the OH generation of atmospheric pressure plasma jets by mixing water aerosols at downstream region," Plasma Processes Polym. **20**, e2200214 (2023).
[690]G. Nayak, A. J. Andrews, I. Marabella, H. A. Aboubakr, S. M. Goyal, B. A. Olson, M. Torremorell, and P. J. Bruggeman, "Rapid inactivation of airborne porcine reproductive and respiratory syndrome virus using an atmospheric pressure air plasma," Plasma Processes Polym. **17**, 1900269 (2020).
[691]T. Xia, A. Kleinheksel, E. M. Lee, Z. Qiao, K. R. Wigginton, and H. L. Clack, "Inactivation of airborne viruses using a packed bed non-thermal plasma reactor," J. Phys. D: Appl. Phys. **52**, 255201 (2019).
[692]N. D. Vaze, S. Park, A. D. Brooks, A. Fridman, and S. G. Joshi, "Involvement of multiple stressors induced by non-thermal plasma-charged aerosols during inactivation of airborne bacteria," PLoS One **12**, e0171434 (2017).
[693]F. Prehn, E. Timmermann, M. Kettlitz, K. Schaufler, S. Günther, and V. Hahn, "Inactivation of airborne bacteria by plasma treatment and ionic wind for indoor air cleaning," Plasma Processes Polym. **17**, 2000027 (2020).
[694]T. Kikuchi, A. Guionet, K. Takahashi, T. Koichi, S. Ishida, and T. Terazawa, "Elimination effect of airborne fungi using dielectric barrier discharges driven by a pulsed power generator," Plasma Med. **10**, 169–180 (2020).
[695]X. Song, C. Basheer, and R. N. Zare, "Making ammonia from nitrogen and water microdroplets," Proc. Natl. Acad. Sci. **120**, e2301206120 (2023).
[696]M. A. Mehrgardi, M. Mofidfar, and R. N. Zare, "Sprayed water microdroplets are able to generate hydrogen peroxide spontaneously," J. Am. Chem. Soc. **144**, 7606–7609 (2022).
[697]M. M. Iqbal, C. P. Stallard, D. P. Dowling, and M. M. Turner, "Three-dimensional coupled fluid-droplet model for atmospheric pressure plasmas," Plasma Processes Polym. **12**, 201–213 (2015).
[698]V. Suresh, L. Li, J. Redmond Go Felipe, and R. Gopalakrishnan, "Modeling nanoparticle charge distribution in the afterglow of non-thermal plasmas and comparison with measurements," J. Phys. D: Appl. Phys. **54**, 275205 (2021).
[699]N. H. Abuyazid, N. B. Üner, and S. M. Peyres *et al.*, "Charge decay in the spatial afterglow of plasmas and its impact on diffusion regimes," Nat. Commun. **14**, 6776 (2023).
[700]U. K. Krieger, C. Marcolli, and J. P. Reid, "Exploring the complexity of aerosol particle properties and processes using single particle techniques," Chem. Soc. Rev. **41**, 6631–6662 (2012).
[701]C. Heinert, R. Sankaran, and D. Lacks, "Decay of electrostatic charge on surfaces due solely to gas phase interactions," J. Electrostat. **115**, 103663 (2022).
[702]O. Havnes, "Dusty plasmas in the ionosphere and its environment," AIP Conf. Proc. **649**, 13–21 (2002).
[703]I. Garrick-Bethell, J. W. Head, and C. M. Pieters, "Spectral properties, magnetic fields, and dust transport at lunar swirls," Icarus **212**, 480–492 (2011).
[704]J. P. Vallée, "Cosmic magnetic fields–as observed in the universe, in galactic dynamos, and in the milky way," New Astron. Rev. **48**, 763–841 (2004).
[705]R. L. Merlino, A. Barkan, C. Thompson, and N. D'Angelo, "Experiments on waves and instabilities in dusty plasma," Plasma Phys. Controlled Fusion **39**, A421 (1997).
[706]Y. Nakamura, H. Bailung, and P. Shukla, "Ovbservation of ion-acoustic shocks in a dusty plasma," Phys. Rev. Lett. **83**, 1602 (1999).
[707]Y. Nakamura and A. Sarma, "Observation of ion-acoustic solitary waves in a dusty plasma," Phys. Plasmas **8**, 3921 (2001).
[708]R. S. A. Sarma, Y. Saitou, and Y. Nakamura, "Observation of the ionization instability and its suppression mechanism in a dusty double plasma device," Plasma Phys. Controlled Fusion **47**, 1415 (2005).
[709]S. Nunomura, N. Ohno, and S. Takamura, "Effects of ion flow by $e \times b$ drift on dust particle behaviour in magnetized cylindrical electron cyclotron resonance plasmas," Jpn. J. Appl. Phys., Part 1 **36**, 877 (1997).
[710]U. Konopka, D. Samsonov, A. V. Ivlev, J. Goree, V. Steinberg, and G. Morfill, "Rigid and differential plasma crystal rotation induced by magnetic fields," Phys. Rev. E **61**, 1890 (2000).
[711]N. Sato, G. Uchida, T. Kaneko, S. Shimizu, and S. Iizuka, "Dynamics of fine particles in magnetized plasmas," Phys. Plasmas **8**, 1786–1790 (2001).
[712]F. Cheung, A. Samarian, and B. James, "The rotation of planar-2 to planar-12 dust clusters in an axial magnetic field," New J. Phys. **5**, 75 (2003).
[713]J. Carstensen, F. Greiner, L.-J. Hou, H. Maurer, and A. Piel, "Effect of neutral gas motion on the rotation of dust clusters in an axial magnetic field," Phys. Plasmas **16**, 013702 (2009).
[714]E. S. Dzlieva, V. Y. Kaasev, and A. I. Eikhvald, "The onset of rotational motion of dusty plasma structures in strata of a glow discharge in a magnetic field," Opt. Spectrosc. **100**, 456 (2006).
[715]V. Y. Karasev, E. S. Dzlieva, A. Y. Ivanov, and A. I. Eikhvald, "Rotational motion of dusty structures in glow discharge in longitudinal magnetic field," Phys. Rev. E **74**, 066403 (2006).
[716]T. Reichstein, J. Wilms, F. Greiner, A. Piel, and A. Melzer, "Experiments and simulations of particle flows in a magnetized dust torus," Contrib. Plasma Phys. **52**, 813 (2012).
[717]I. Pilch, T. Reichstein, and A. Piel, "Torus-shaped dust clouds trapped in a magnetized anodic plasma," Phys. Plasmas **15**, 103706 (2008).
[718]J. Wilms, T. Reichstein, and A. Piel, "Experimental observation of crystalline particle flows in toroidal dust clouds," Phys. Plasmas **22**(6), 063701 (2015).
[719]A. Piel and J. Wilms, "Hydraulic jumps in inhomogeneous strongly coupled toroidal dust flows," Phys. Plasmas **23**, 073701 (2016).
[720]E. Thomas, U. Konopka, R. L. Merlino, and M. Rosenberg, "Initial measurements of two- and three-dimensional ordering, waves, and plasma

filamentation in the magnetized dusty plasma experiment," Phys. Plasmas **23**, 055701 (2016).
[721]E. Thomas, B. Lynch, U. Konopka, M. Menati, S. Williams, R. L. Merlino, and M. Rosenberg, "Pattern formation in strongly magnetized plasmas: observations from the magnetized dusty plasma experiment (MDPX) device," Plasma Phys. Controlled Fusion **62**, 014006 (2019).
[722]S. Jaiswal, M. Menati, L. Coudel, V. H. Holloman, V. Rangari, and E. Thomas, "Effect of growing nanoparticle on the magnetic field induced filaments in a radio-frequency Ar/C_2H_2 discharge plasma," Jpn. J. Appl. Phys., Part 1 **59**, SHHC07 (2020).
[723]M. Menati, E. Thomas, and M. J. Kushner, "Filamentation of capacitively coupled plasmas in large magnetic fields," Phys. Plasmas **26**, 063515 (2019).
[724]M. Menati, B. Rasoolian, E. Thomas, and U. Konopka, "Experimental observation and numerical investigation of filamentary structures in magnetized plasmas," Phys. Plasmas **27**, 022101 (2020).
[725]B. Tadsen, F. Greiner, and A. Piel, "Preparation of magnetized nanodusty plasmas in a radio frequency-driven parallel-plate reactor," Phys. Plasmas **21**, 103704 (2014).
[726]E. Thomas, B. Lynch, U. Konopka, R. L. Merlino, and M. Rosenberg, "Observations of imposed ordered structures in a dusty plasma at high magnetic field," Phys. Plasmas **22**, 030701 (2015).
[727]T. Hall, E. Thomas, K. Avinash, R. Merlino, and M. Rosenberg, "Methods for the characterization of imposed, ordered structures in MDPX," Phys. Plasmas **25**, 103702 (2018).
[728]T. Hall and E. Thomas, "Dynamics of dust particles confined in imposed potential structures in strongly magnetized, low-temperature plasmas," Phys. Rev. E **102**, 023208 (2020).
[729]E. S. Dzlieva, L. G. Dyachkov, L. A. Novikov, S. I. Pavlov, and V. Y. Karasev, "Complex plasma in glow discharge in a strong magnetic field," Europhys. Lett. **123**, 15001 (2018).
[730]V. Karasev, E. Dzlieva, L. D'yachkov, L. Novikov, S. Pavlov, and S. Tarasov, "The effect of magnetic field on plasma particles in dusty plasma," Contrib. Plasma Phys. **59**, e201800136 (2019).
[731]S. Jaiswal, T. Hall, S. LeBlanc, R. Mukherjee, and E. Thomas, "Effect of magnetic field on the phase transition in a dusty plasma," Phys. Plasmas **24**, 113703 (2017).
[732]S. I. Pavlov, E. S. Dzlieva, M. A. Ermolenko, L. A. Novikov, and V. Y. Karasev, "The influence of magnetic field on the geometrical dimensions of dusty structure in striations," J. Phys.: Conf. Ser. **1556**, 012081 (2020).
[733]Y. Saitou, "Motions of dust particles in a complex plasma with an axisymmetric nonuniform magnetic field," Phys. Plasmas **23**, 013709 (2016).
[734]M. Choudhary, R. Bergert, S. Mitic, and M. H. Thoma, "Three-dimensional dusty plasma in a strong magnetic field: Observation of rotating dust tori," Phys. Plasmas **27**, 063701 (2020).
[735]L. Simons and M. Coppins, "Modeling of spherical dust charging in collisionless magnetized plasmas with DiMPL," Phys. Plasmas **27**, 063702 (2020).
[736]D. Lange, "Floating surface potential of spherical dust grains in magnetized plasmas," J. Plasma Phys. **82**, 905820101 (2016).
[737]S. V. Vladimirov and M. Nambu, "Attraction of charged particles in plasmas with finite flows," Phys. Rev. E **52**, R2172–R2174 (1995).
[738]M. Nambu, S. V. Vladimirov, and P. K. Shukla, "Attractive forces between charged particulates in plasmas," Phys. Lett. A **203**, 40–42 (1995).
[739]V. A. Schweigert, "The microparticle within electrode sheath of rf discharge," Pis'ma Zh. Tech. Fis. **21**, 69 (1995) , [Tech. Phys. Lett. **21**, 476 (1995)].
[740]V. A. Schweigert, I. V. Schweigert, A. Melzer, A. Homann, and A. Piel, "Alignment and instability of 'dust' crystals in plasmas," Phys. Rev. E **54**, 4155 (1996).
[741]M. Salimullah, M. Torney, P. K. Shukla, and A. K. Banerjee, "Three-dimensional wakefields in a magnetized dusty plasma with streaming ions," Phys. Scr. **67**, 534 (2003).
[742]M. Salimullah, A. M. Rizwan, H. Nitta, M. Nambu, and P. K. Shukla, "On the Shukla-Nambu-Salimullah potential in a streaming dusty magnetoplasma," Phys. Plasmas **11**, 4148–4150 (2004).
[743]P. Shukla, "Waves and instabilities in magnetized dusty plasmas," in *Plasma Astrophysics and Space Physics*, edited by J. Büchner, I. Axford, E. Marsch, and V. Vasyliunas (Springer, Dordrecht, 1999), p. 235.
[744]W. J. Miloch, D. Darian, and M. Mortensen, "Wake potential of a dust particle in magnetised plasmas," Phys. Scr. **92**, 114006 (2017).
[745]N. N. Rao, P. K. Shukla, and M. Y. Yu, "Dust-acoustic waves in dusty plasmas," Planet. Space Sci. **38**, 543–546 (1990).
[746]N. D'Angelo and R. Merlino, "Current-driven dust-acoustic instability in a collisional plasma," Planet. Space Sci. **44**, 1593–1598 (1996).
[747]P. K. Kaw and A. Sen, "Low frequency modes in strongly coupled dusty plasmas," Phys. Plasmas **5**, 3552 (1998).
[748]R. L. Merlino, "25 years of dust acoustic waves," J. Plasma Phys. **80**, 773–786 (2014).
[749]N. D'Angelo, "Dusty plasma ionization instability with ion drag," Phys. Plasmas **5**, 3155 (1998).
[750]P. Bezbaruah and N. Das, "Collisional effects on interaction potential in complex plasma in presence of magnetic field," Phys. Plasmas **23**, 043701 (2016).
[751]J. Winter and G. Gebauer, "Dust in magnetic confinement fusion devices and its impact on plasma operation," J. Nucl. Mater. **266–269**, 228–233 (1999).
[752]S. I. Krasheninnikov, A. Y. Pigarov, R. D. Smirnov, and T. K. Soboleva, "Theoretical aspects of dust in fusion devices," Contrib. Plasma Phys. **50**, 410–425 (2010).
[753]*Protoplanetary Dust: Astrophysical and Cosmochemical Perspectives*, edited by D. Apai and D. S. Lauretta (Cambridge, Cambrige, 2014).
[754]M. Wardle, "Magnetic fields in protoplanetary disks," Astrophys. Space Sci. **311**, 35–45 (2007).
[755]A. Makar, "An audit of occurrence of dust in tokamak and stability of fusion plasmas," Plasma Fusion Res. **15**, 1405019 (2020).
[756]N. D'Angelo, "Current-driven electrostatic dust-cyclotron instability in a collisional plasma," Planet. Space Sci. **46**, 1671–1676 (1998).
[757]R. Bharuthram and T. Pather, "The kinetic dust-acoustic instability in a magnetized dusty plasma," Planet. Space Sci. **44**, 137–146 (1996).
[758]M. Salimullah and M. Salahuddin, "Dust-acoustic waves in a magnetized dusty plasma," Phys. Plasmas **5**, 828–829 (1998).
[759]M. Rosenberg, "A note on the electrostatic dust cyclotron instability in a collisional plasma with warm dust," Phys. Scr. **82**, 035505 (2010).
[760]P. Shukla and H. Rahman, "Instability of electrostatic dust-cyclotron waves and associated wake potential," Planet. Space Sci. **46**, 541–543 (1998).
[761]See https://photojournal.jpl.nasa.gov/catalog/PIA02275 for "Ring spokes, nasa solar system exploration, 2000;" accessed 08 May 2023.
[762]M. Robberto, see https://hubblesite.org/contents/media/images/2006/01/1826-Image.html?news=true for "Webbtelescope.org: Central region of orion nebula (vlt), 2006;" accessed 08 May 2023.
[763]See http://parkersolarprobe.jhuapl.edu/Multimedia/Images.php for "In depth, Parker solar probe, NASA solar system exploration;" accessed 08 May 2023.
[764]M. J. McCaughrean, see https://webbtelescope.org/contents/media/images/2020/24/4650-Image for "information@eso.org: Hubble's sharpest view of the orion nebula, 2020;" accessed 08 May 2023.
[765]P. Simons, see https://en.wikipedia.org/wiki/File:Helkivadööpilved_Kuresoo_kohal.jpg for "Noctilucent clouds: A warning sign of climate change, 2023;" accessed 08 May 2023.
[766]See http://www.iter.org/ for "ESA—tokamak;" accessed 08 May 2023.
[767]R. Chen, see https://www.space.com/35240-moon-dust-levitates-nasa-study.html for "Dust "floats" above lunar surface, 2016, 13 December 2016;" accessed 08 May 2023.
[768]Soderman, see https://moon.nasa.gov/news/48/lunar-swirl-features-reproduced-by-modeling-solar-wind-standoff/ for "NASA—Reiner gamma region of interest, 2018;" accessed 08 May 2023.
[769]See https://www.apsgec.org/main/ for "GEC general home;" accessed 08 May 2023.
[770]J. L. Mestel and L. Spitzer, "Star formation in magnetic dust clouds," Mon. Not. R. Astron. Soc. **116**, 503 (1956).
[771]B. T. Draine, "Interstellar dust grains," Annu. Rev. Astron. Astrophys. **41**, 241 (2003).
[772]J. R. Szalay, P. Pokorni, S. D. Bale, E. R. Christian, K. Goetz, K. Goodrich, M. E. Hill, M. Kuchner, R. Larsen, D. Malaspina, D. J. McComas, D. Mitchell, B. Page, and N. Schwadron, "The near-sun dust environment: Initial observations from parker solar probe," Astrophys. J. Suppl. Ser. **246**, 27 (2020).
[773]F. S. Mozer, O. V. Agapitov, S. D. Bale, J. W. Bonnell, K. Goetz, K. A. Goodrich, R. Gore, P. R. Harvey, P. J. Kellogg, D. Malaspina, M. Pulupa, and

G. Schumm, "Time domain structures and dust in the solar vicinity: Parker solar probe observations," Astrophys. J. Suppl. Ser. **246**, 50 (2020).
[774]I. Mann and A. Czechowski, "Dust observations from parker solar probe: Dust ejection from the inner solar system," Astron. Astrophys. **650**, A29 (2021).
[775]J.-M. Wang, Y.-Y. Songsheng, Y.-R. Li, P. Du, and Z. Yu, "Dynamical evidence from the sub-parsec counter-rotating disc for a close binary of supermassive black holes in NGC1068," Mon. Not. R. Astron. Soc. **497**, 1020 (2020).
[776]A. M. A. Zahrani, "Charged particle circular orbits around weakly charged and magnetized kerr black holes," Astrophys. J. **937**, 50 (2022).
[777]L. Couëdel, D. Artis, M. P. Khanal, C. Pardanaud, S. Coussan, S. LeBlanc, T. Hall, E. Thomas, U. Konopka, M. Park, and C. Arnas, "Influence of magnetic field strength on nanoparticle growth in a capacitively-coupled radio-frequency Ar/C_2H_2 discharge," Plasma Res. Express **1**, 015012 (2019).
[778]A. A. Mamun, P. K. Shukla, and G. E. Morfill, "Theory of Mach cones in magnetized dusty plasmas with strongly correlated charged dust grains," Phys. Rev. Lett. **92**, 095005 (2004).
[779]M. M. Hossen, L. Nahar, M. Alam, S. Sultana, and A. Mamun, "Electrostatic shock waves in a nonthermal dusty plasma with oppositely charged dust," High Energy Density Phys. **24**, 9–14 (2017).
[780]E. E. Behery, S. K. El-Labany, M. M. Selim, T. H. Khalil, and M. A. Eissa, "Investigation of dust ion acoustic shock waves in dusty plasma using cellular neural network," Phys. Scr. **96**, 095606 (2021).
[781]N. Rao, "Hydromagnetic waves and shocks in magnetized dusty plasmas," Planet. Space Sci. **41**, 21–26 (1993).
[782]A. Roy, K. K. Mondal, P. Chatterjee, and S. Raut, "Influence of external periodic force on ion acoustic waves in a magnetized dusty plasma through forced KP equation and modified forced KP equation," Braz. J. Phys. **52**, 65 (2022).
[783]G.-S. Chae, W. Scales, G. Ganguli, P. Bernhardt, and M. Lampe, "Numerical model for low-frequency ion waves in magnetized dusty plasmas," IEEE Trans. Plasma Sci. **28**, 1694–1705 (2000).
[784]E. El-Shamy and M. Selim, "Dust-acoustic periodic travelling waves in a magnetized dusty plasma with trapped ions and nonthermal electrons in astrophysical situations: Oblique excitationss," Astrophys. Space Sci. **367**, 100 (2022).
[785]G. Foroutan, H. Mehdipour, and H. Zahed, "Simulation study of the magnetized sheath of a dusty plasma," Phys. Plasmas **16**, 103703 (2009).
[786]M. I. Zimmerman, W. M. Farrell, and A. R. Poppe, "Kinetic simulations of kilometer-scale mini-magnetosphere formation on the moon," J. Geophys. Res.: Planets **120**, 1893–1903, https://doi.org/10.1002/2015JE004865 (2015).
[787]C. R. Choi, K. Dokgo, C. H. Woo, and K. W. Min, "Simulation study of solar wind interaction with lunar magnetic fields," J. Astron. Space Sci. **37**, 35–42 (2020).
[788]S. I. Popel, A. P. Golub', and L. M. Zelenyi, "Dusty plasmas above the sunlit surface of Mercury," Phys. Plasmas **30**, 043701 (2023).
[789]S. I. Popel, L. M. Zelenyi, A. P. Golub', and A. Y. Dubinskii, "Lunar dust and dusty plasmas: Recent developments, advances, and unsolved problems," Planet. Space Sci. **156**, 71–84 (2018).
[790]I. A. Kuznetsov, A. V. Zakharov, L. M. Zelenyi, S. I. Popel, T. I. Morozova, I. A. Shashkova, G. G. Dolnikov, A. N. Lyash, A. E. Dubov, M. E. Viktorov, A. P. Topchieva, B. A. Klumov, A. D. Usachev, E. A. Lisin, M. M. Vasiliev, O. F. Petrov, and A. Y. Poroikov, "Dust particles in space: Opportunities for experimental research," Astron. Rep. **67**, 35–60 (2023).
[791]D. A. Mendis and M. Horányi, "Plasma processes at comet Churyumov-Gerasimenko: Expectations for Rosetta," J. Plasma Phys. **79**, 1067–1070 (2013).
[792]M. Horányi, T. W. Hartquist, O. Havnes, D. A. Mendis, and G. E. Morfill, "Dusty plasma effects in Saturn's magnetosphere," Rev. Geophys. **42**, RG4002, https://doi.org/10.1029/2004RG000151 (2004).
[793]F. Verheest, "Waves and instabilities in dusty space plasmas," Space Sci. Rev. **77**, 267–302 (1996).
[794]M. Friedrich, M. Rapp, J. M. C. Plane, and K. M. Torkar, "Bite-outs and other depletions of mesospheric electrons," J. Atmos. Sol. Terr. Phys. **73**, 2201–2211 (2011).
[795]M. W. Morooka, J. E. Wahlund, A. I. Eriksson, W. M. Farrell, D. A. Gurnett, W. S. Kurth, A. M. Persoon, M. Shafiq, M. André, and M. K. G. Holmberg, "Dusty plasma in the vicinity of Enceladus," J. Geophys. Res.: Space Phys. **116**, A12221, https://doi.org/10.1029/2011JA017038 (2011).
[796]S. I. Kopnin, S. I. Popel, and M. Y. Yu, "Phenomena associated with complex (dusty) plasmas in the ionosphere during high-speed meteor showers," Phys. Plasmas **16**, 063705 (2009).
[797]M. E. Hervig, J. M. Plane, D. E. Siskind, W. Feng, C. G. Bardeen, and S. M. Bailey, "New global meteoric smoke observations from sofie: Insight regarding chemical composition, meteoric influx, and hemispheric asymmetry," J. Geophys. Res.: Atmos. **126**, e2021JD035007, https://doi.org/10.1029/2021JD035007 (2021).
[798]J. M. Russell III, S. M. Bailey, L. L. Gordley, D. W. Rusch, M. Horányi, M. E. Hervig, G. E. Thomas, C. E. Randall, D. E. Siskind, M. H. Stevens *et al.*, "The aeronomy of ice in the mesosphere (aim) mission: Overview and early science results," J. Atmos. Sol. Terr. Phys. **71**, 289–299 (2009).
[799]P. Dalin, H. Suzuki, N. Pertsev, V. Perminov, D. Efremov, P. Voelger, V. Narayanan, I. Mann, I. Häggström, M. Zalcik *et al.*, "Studies of noctilucent clouds from the stratosphere during the sonc balloon-borne experiment in 2021," J. Atmos. Sol. Terr. Phys. **240**, 105959 (2022).
[800]M. E. Hervig, L. E. Deaver, C. G. Bardeen, J. M. Russell III, S. M. Bailey, and L. L. Gordley, "The content and composition of meteoric smoke in mesospheric ice particles from sofie observations," J. Atmos. Sol. Terr. Phys. **84**, 1–6 (2012).
[801]T. Antonsen, O. Havnes, and I. Mann, "Estimates of the size distribution of meteoric smoke particles from rocket-borne impact probes," J. Geophys. Res.: Atmos. **122**, 12353, https://doi.org/10.1002/2017JD027220 (2017).
[802]J. Gumbel and L. Megner, "Charged meteoric smoke as ice nuclei in the mesosphere. I. A review of basic concepts," J. Atmos. Sol. Terr. Phys. **71**, 1225–1235 (2009).
[803]B. Strelnikov, T. Staszak, R. Latteck, T. Renkwitz, I. Strelnikova, F.-J. Lübken, G. Baumgarten, J. Fiedler, J. L. Chau, J. Stude *et al.*, "Sounding rocket project "PMWE" for investigation of polar mesosphere winter echoes," J. Atmos. Sol. Terr. Phys. **218**, 105596 (2021).
[804]R. Latteck, T. Renkwitz, and J. L. Chau, "Two decades of long-term observations of polar mesospheric echoes at 69°N," J. Atmos. Sol. Terr. Phys. **216**, 105576 (2021).
[805]V. L. Narayanan, I. Häggström, and I. Mann, "Effects of particle precipitation on the polar mesospheric summer echoes observed by EISCAT VHF 224 MHz radar," Adv. Space Res. **69**, 3350–3361 (2022).
[806]T. L. Gunnarsdottir and I. Mann, "Charged dust in the D-region incoherent scatter spectrum," J. Plasma Phys. **87**, 905870502 (2021).
[807]M. Horanyi, "Charged dust dynamics in the solar system," Annu. Rev. Astron. Astrophys. **34**, 383–418 (1996).
[808]O. E. Berg, F. F. Richardson, J. W. Rhee, and S. Auer, "Preliminary results of a cosmic dust experiment on the Moon," Geophys. Res. Lett. **1**, 289–290, https://doi.org/10.1029/GL001i007p00289 (1974).
[809]H. A. Zook and J. E. McCoy, "Large scale lunar horizon glow and a high altitude lunar dust exosphere," Geophys. Res. Lett. **18**, 2117–2120, https://doi.org/10.1029/91GL02235 (1991).
[810]J. Schwan, X. Wang, H. W. Hsu, E. Grün, and M. Horányi, "The charge state of electrostatically transported dust on regolith surfaces," Geophys. Res. Lett. **44**, 3059–3065, https://doi.org/10.1002/2017GL072909 (2017).
[811]N. Hood, A. Carroll, R. Mike, X. Wang, J. Schwan, H. W. Hsu, and M. Horányi, "Laboratory investigation of rate of electrostatic dust lofting over time on airless planetary bodies," Geophys. Res. Lett. **45**, 13206–13212, https://doi.org/10.1029/2018GL080527 (2018).
[812]A. Carroll, N. Hood, R. Mike, X. Wang, H. W. Hsu, and M. Horányi, "Laboratory measurements of initial launch velocities of electrostatically lofted dust on airless planetary bodies," Icarus **352**, 113972 (2020).
[813]J. Gumbel, L. Megner, O. M. Christensen, N. Ivchenko, D. P. Murtagh, S. Chang, J. Dillner, T. Ekebrand, G. Giono, A. Hammar *et al.*, "The mats satellite mission–gravity wave studies by mesospheric airglow/aerosol tomography and spectroscopy," Atmos. Chem. Phys. **20**, 431–455 (2020).
[814]I. McCrea, A. Aikio, L. Alfonsi, E. Belova, S. Buchert, M. Clilverd, N. Engler, B. Gustavsson, C. Heinselman, J. Kero *et al.*, "The science case for the EISCAT_3D radar," Prog. Earth Planet. Sci. **2**, 21 (2015).

[815]I. Mann, I. Häggström, A. Tjulin, S. Rostami, C. Anyairo, and P. Dalin, "First wind shear observation in pmse with the tristatic EISCAT VHF radar," J. Geophys. Res.: Space Phys. **121**, 11271, https://doi.org/10.1002/2016JA023080 (2016).
[816]M. Horanyi and D. A. Mendis, "Space debris: Electrodynamic effects," Adv. Space Res. **6**, 127–130 (1986).
[817]G. Ganguli, C. Crabtree, L. Rudakov, and S. Chappie, "A concept for elimination of small orbital debris," Trans. Jpn. Soc. Aeronaut. Space Sci. Aerosp. Technol. Jpn. **10**, 23–27 (2012).
[818]S. I. Popel and L. M. Zelenyi, "Future lunar missions and investigation of dusty plasma processes on the Moon," J. Plasma Phys. **79**, 405–411 (2013).
[819]T. Hoshino, S. Wakabayashi, M. Ohtake, Y. Karouji, T. Hayashi, H. Morimoto, H. Shiraishi, T. Shimada, T. Hashimoto, H. Inoue, R. Hirasawa, Y. Shirasawa, H. Mizuno, and H. Kanamori, "Lunar polar exploration mission for water prospection—JAXA's current status of joint study with ISRO," Acta Astronaut. **176**, 52–58 (2020).
[820]A. Witze, "Fifty years after astronauts left the Moon, they are going back. Why?," Nature **612**, 397–399 (2022).
[821]J. Pickrell, "These six countries are about to go to the Moon—Here's why," Nature **605**, 208–211 (2022).
[822]"India's Moon landing is a stellar achievement—And a win for science," Nature **620**, 921–921 (2023).
[823]D. Castelvecchi, "Jupiter mission will be first to orbit moon of another planet," Nature **616**, 420–421 (2023).
[824]W. Goode, S. Kempf, and J. Schmidt, "Mapping the surface composition of Europa with SUDA," Planet. Space Sci. **227**, 105633 (2023).
[825]K. E. Mandt, "The first dedicated ice giants mission," Science **379**, 640–642 (2023).
[826]M. Horányi and T. E. Cravens, "The structure and dynamics of Jupiter's ring," Nature **381**, 293–295 (1996).
[827]M. Horányi, A. Juhász, and G. E. Morfill, "Large-scale structure of Saturn's E-ring," Geophys. Res. Lett. **35**, L04203, https://doi.org/10.1029/2007GL032726 (2008).
[828]M. Horanyi, G. Morfill, and E. Grun, "Mechanism for the acceleration and ejection of dust grains from Jupiter's magnetosphere," Nature **363**, 144–146 (1993).
[829]M. Horanyi, G. Morfill, and E. Gruen, "The dusty ballerina skirt of Jupiter," J. Geophys. Res. **98**, 21245–21252, https://doi.org/10.1029/93JA02588 (1993).
[830]J. E. Colwell, M. Horanyi, and E. Gren, "Capture of interplanetary and interstellar dust by the Jovian magnetosphere," Science **280**, 88 (1998).
[831]A. Czechowski and I. Mann, "Dynamics of nanodust in the vicinity of a stellar corona: Effect of plasma corotation," Astron. Astrophys. **652**, A131 (2021).
[832]A. Czechowski and J. Kleimann, "Nanodust dynamics during a coronal mass ejection," *Annales Geophysicae* (Copernicus Publications, Göttingen, Germany, 2017), Vol. 35, pp. 1033–1049.
[833]G. H. Rieke, A. Gáspár, and N. P. Ballering, "Magnetic grain trapping and the hot excesses around early-type stars," Astrophys. J. **816**, 50 (2016).
[834]J. Lebreton, R. Van Lieshout, J.-C. Augereau, O. Absil, B. Mennesson, M. Kama, C. Dominik, A. Bonsor, J. Vandeportal, H. Beust *et al.*, "An interferometric study of the fomalhaut inner debris disk. III. Detailed models of the exozodiacal disk and its origin," Astron. Astrophys. **555**, A146 (2013).
[835]J. Stamm, A. Czechowski, I. Mann, C. Baumann, and M. Myrvang, "Dust trajectory simulations around the sun, vega, and fomalhaut," Astron. Astrophys. **626**, A107 (2019).
[836]V. J. Sterken, L. R. Baalmann, B. T. Draine, E. Godenko, K. Herbst, H.-W. Hsu, S. Hunziker, V. Izmodenov, R. Lallement, and J. D. Slavin, "Dust in and around the heliosphere and astrospheres," Space Sci. Rev. **218**, 71 (2022).
[837]P. Strub, V. J. Sterken, R. Soja, H. Krüger, E. Grün, and R. Srama, "Heliospheric modulation of the interstellar dust flow on to Earth," Astron. Astrophys. **621**, A54 (2019).
[838]H. Krüger, P. Strub, N. Altobelli, V. J. Sterken, R. Srama, and E. Grün, "Interstellar dust in the solar system: Model versus in situ spacecraft data," Astron. Astrophys. **626**, A37 (2019).
[839]D. J. McComas, E. R. Christian, N. A. Schwadron, N. Fox, J. Westlake, F. Allegrini, D. N. Baker, D. Biesecker, M. Bzowski, G. Clark, C. M. S. Cohen, I. Cohen, M. A. Dayeh, R. Decker, G. A. de Nolfo, M. I. Desai, R. W. Ebert, H. A. Elliott, H. Fahr, P. C. Frisch, H. O. Funsten, S. A. Fuselier, A. Galli, A. B. Galvin, J. Giacalone, M. Gkioulidou, F. Guo, M. Horanyi, P. Isenberg, P. Janzen, L. M. Kistler, K. Korreck, M. A. Kubiak, H. Kucharek, B. A. Larsen, R. A. Leske, N. Lugaz, J. Luhmann, W. Matthaeus, D. Mitchell, E. Moebius, K. Ogasawara, D. B. Reisenfeld, J. D. Richardson, C. T. Russell, J. M. Sokół, H. E. Spence, R. Skoug, Z. Sternovsky, P. Swaczyna, J. R. Szalay, M. Tokumaru, M. E. Wiedenbeck, P. Wurz, G. P. Zank, and E. J. Zirnstein, "Interstellar mapping and acceleration probe (IMAP): A new NASA mission," Space Sci. Rev. **214**, 116 (2018).
[840]H. Krüger, P. Strub, R. Srama, M. Kobayashi, T. Arai, H. Kimura, T. Hirai, G. Moragas-Klostermeyer, N. Altobelli, V. J. Sterken, J. Agarwal, M. Sommer, and E. Grün, "Modelling destiny$^+$ interplanetary and interstellar dust measurements en route to the active asteroid (3200) phaethon," Planet. Space Sci. **172**, 22–42 (2019).
[841]A. Zaslavsky, I. Mann, J. Soucek, A. Czechowski, D. Píša, J. Vaverka, N. Meyer-Vernet, M. Maksimovic, E. Lorfèvre, K. Issautier *et al.*, "First dust measurements with the solar orbiter radio and plasma wave instrument," Astron. Astrophys. **656**, A30 (2021).
[842]B. Farr, X. Wang, J. Goree, I. Hahn, U. Israelsson, and M. Horányi, "Dust mitigation technology for lunar exploration utilizing an electron beam," Acta Astronaut. **177**, 405–409 (2020).
[843]B. Farr, X. Wang, J. Goree, I. Hahn, U. Israelsson, and M. Horányi, "Improvement of the electron beam (e-beam) lunar dust mitigation technology with varying the beam incident angle," Acta Astronaut. **188**, 362–366 (2021).
[844]B. Farr, X. Wang, J. Goree, I. Hahn, U. Israelsson, and M. Horányi, "Dust removal from a variety of surface materials with multiple electron beams," Acta Astronaut. **200**, 42–47 (2022).
[845]J. Gaier, D. Waters, B. Banks, R. Misconin, and M. Crowder, "Evaluation of surface modification as a lunar dust mitigation strategy for thermal control surfaces," AIAA Paper No. 2011-5183, 2011.
[846]T. W. Murphy, R. J. McMillan, N. H. Johnson, and S. D. Goodrow, "Lunar eclipse observations reveal anomalous thermal performance of Apollo reflectors," Icarus **231**, 183–192 (2014).
[847]M. Hirabayashi, C. M. Hartzell, P. M. Bellan, D. Bodewits, G. L. Delzanno, T. W. Hyde, U. Konopka, E. Thomas, H. M. Thomas, I. Hahn, and U. E. Israelsson, "Electrostatic dust remediation for future exploration of the Moon," Acta Astronaut. **207**, 392–402 (2023).
[848]H. Kawamoto, M. Uchiyama, B. L. Cooper, and D. S. McKay, "Mitigation of lunar dust on solar panels and optical elements utilizing electrostatic traveling-wave," J. Electrostat. **69**, 370–379 (2011).
[849]P. Oudayer, L. Monnin, J. C. Matéo-Vélez, S. L. G. Hess, P. Sarrailh, G. Murat, and J. F. Roussel, "Multiscale modeling of dust charging in simulated lunar environment conditions," IEEE Trans. Plasma Sci. **47**, 3710–3716 (2019).
[850]A. A. Sickafoose, J. E. Colwell, M. Horányi, and S. Robertson, "Photoelectric charging of dust particles in vacuum," Phys. Rev. Lett. **84**, 6034–6037 (2000).
[851]A. A. Sickafoose, J. E. Colwell, M. Horányi, and S. Robertson, "Experimental investigations on photoelectric and triboelectric charging of dust," J. Geophys. Res.: Space Phys. **106**, 8343–8356, https://doi.org/10.1029/2000JA000364 (2001).
[852]T. J. Stubbs, W. M. Farrell, J. S. Halekas, J. K. Burchill, M. R. Collier, M. I. Zimmerman, R. R. Vondrak, G. T. Delory, and R. F. Pfaff, "Dependence of lunar surface charging on solar wind plasma conditions and solar irradiation," Planet. Space Sci. **90**, 10–27 (2014).
[853]M. Lercel, C. Smeets, M. van de Kerkhof, A. Chen, T. van Empel, and V. Banine, "EUV reticle defectivity protection options," Proc. SPIE **11148**, 111480Y (2019).
[854]M. van de Kerkhof, E. Galutschek, A. Yakunin, S. Cats, and C. Cloin, "Particulate and molecular contamination control in EUV-induced H_2-plasma in EUV lithographic scanner," Proc. SPIE **11489**, 114890K (2020).
[855]M. van de Kerkhof, A. M. Yakunin, V. Kvon, A. Nikipelov, D. Astakhov, P. Krainov, and V. Banine, "EUV-induced hydrogen plasma and particle release," Radiat. Eff. Defects Solids **177**, 486–512 (2022).
[856]R. Van Der Horst, J. Beckers, E. Osorio, D. Astakhov, W. Goedheer, C. Lee, V. Ivanov, V. Krivtsum, K. Koshelev, D. Lopaev, F. Bijkerk, and V. Banine, "Exploring the electron density in plasma induced by EUV radiation. I. Experimental study in hydrogen," J. Phys. D: Appl. Phys. **49**, 145203 (2016).
[857]D. Astakhov, W. Goedheer, C. Lee, V. Ivanov, V. Krivtsun, K. Koshelev, D. Lopaev, R. Van Der Horst, J. Beckers, E. Osorio, and F. Bijkerk, "Exploring the electron density in plasma induced by EUV radiation. II. Numerical studies in argon and hydrogen," J. Phys. D: Appl. Phys. **49**, 295204 (2016).

[858]M. A. van de Kerkhof, T. van Empel, M. Lercel, C. Smeets, F. van de Wetering, A. Nikipelov, C. Cloin, A. Yakunin, and V. E. Banine, "Advanced particle contamination control in EUV scanners," Proc. SPIE **10957**, 10957OU (2019).
[859]J. Beckers, T. van de Ven, R. van der Horst, D. Astakhov, and V. Banine, "EUV-induced plasma: A peculiar phenomenon of a modern lithographic technology," Appl. Sci. **9**, 2827 (2019).
[860]M. van de Kerkhof, A. Yakunin, V. Kvon, F. van de Wetering, S. Cats, L. Heijmans, A. Nikipelov, A. Lassise, and V. Banine, "Understanding EUV-induced plasma and application to particle contamination control in EUV scanners," Proc. SPIE **11323**, 113230Y (2020).
[861]A. A. Howling, C. Hollenstein, and P. Paris, "Direct visual observation of powder dynamics in RF plasma-assisted deposition," Appl. Phys. Lett. **59**, 1409–1411 (1991).
[862]M. S. Barnes, J. H. Keller, J. C. Forster, J. A. O'Neill, and D. K. Coultas, "Transport of dust particles in glow-discharge plasmas," Phys. Rev. Lett. **68**, 313–316 (1992).
[863]H. G. Parks and J. F. O'Hanlon, "The evolving role of defects and contamination in semiconductor manufacturing," Microelectron. J. **24**, 313–327 (1993).
[864]M. P. Garrity, T. W. Peterson, L. M. Garrett, and J. F. O'Hanlon, "Fluid simulations of particle contamination in postplasma processes," J. Vac. Sci. Technol. A **13**, 2939–2944 (1995).
[865]S. M. Collins, D. A. Brown, J. F. O'Hanlon, and R. N. Carlile, "Postplasma particle dynamics in a gaseous electronics conference RF reference cell," J. Vac. Sci. Technol. A **13**, 2950–2953 (1995).
[866]C. Yeon, J. Kim, and K. Whang, "Dynamics of particulates in the afterglow of a radio frequency excited plasma," J. Vac. Sci. Technol. A **13**, 927–930 (1995).
[867]S. J. Choi, D. J. Rader, and A. S. Geller, "Massively parallel simulations of Brownian dynamics particle transport in low pressure parallel-plate reactors," J. Vac. Sci. Technol. A **14**, 660–665 (1996).
[868]S. M. Collins, D. A. Brown, J. F. O'Hanlon, and R. N. Carlile, "Particle trapping, transport, and charge in capacitively and inductively coupled argon plasmas in a gaseous electronics conference reference cell," J. Vac. Sci. Technol. A **14**, 634–638 (1996).
[869]G. S. Selwyn, C. A. Weiss, F. Sequeda, and C. Huang, "Particle contamination formation in magnetron sputtering processes," J. Vac. Sci. Technol. A **15**, 2023–2028 (1997).
[870]G. S. Selwyn, C. A. Weiss, F. Sequeda, and C. Huang, "In-situ analysis of particle contamination in magnetron sputtering processes," Thin Solid Films **317**, 85–92 (1998).
[871]H. Setyawan, M. Shimada, K. Ohtsuka, and K. Okuyama, "Visualization and numerical simulation of fine particle transport in a low-pressure parallel plate chemical vapor deposition reactor," Chem. Eng. Sci. **57**, 497–506 (2002).
[872]H. Setyawan, M. Shimada, and K. Okuyama, "Characterization of fine particle trapping in a plasma-enhanced chemical vapor deposition reactor," J. Appl. Phys. **92**, 5525–5531 (2002).
[873]H. Setyawan, M. Shimada, Y. Imajo, Y. Hayashi, and K. Okuyama, "Characterization of particle contamination in process steps during plasma-enhanced chemical vapor deposition operation," J. Aerosol Sci. **34**, 923–936 (2003).
[874]H. Setyawan, M. Shimada, Y. Hayashi, K. Okuyama, and S. Yokoyama, "Particle formation and trapping behavior in a TEOS/O_2 plasma and their effects on contamination of a Si wafer," Aerosol Sci. Technol. **38**, 120–127 (2004).
[875]J. So, M. Kim, H. Kwon, S. Maeng, E. Choi, C.-W. Chung, and J.-Y. Yun, "Investigation of contamination particles generation and surface chemical reactions on Al_2O_3, Y_2O_3, and YF_3 coatings in F-based plasma," Appl. Surf. Sci. **629**, 157367 (2023).
[876]J. Beckers, B. van Minderhout, P. Blom, G. Kroesen, and T. Peijnenburg, "Particle contamination control by application of plasma," Proc. SPIE **11323**, 558–563 (2020).
[877]J. C. A. van Huijstee, B. van Minderhout, R. M. H. Rompelberg, P. Blom, T. Peijnenburg, and J. Beckers, "Plasma assisted particle contamination control: Plasma charging dependence on particle morphology," Proc. SPIE **11611**, 116113A (2021).
[878]P. Blom, J. C. A. van Huijstee, F. Medini, R. Baade, and J. Beckers, "Plasma-assisted removal of particles: Taming the beast," Mikroniek **6**, 15–18 (2021).
[879]J. Beckers, J. van Huijstee, P. Blom, F. Medini, and T. Peijnenburg, "The role of neutral drag force in pulsed plasma enabled particle contamination control," Proc. SPIE **12496**, 1249631 (2023).
[880]T. E. Sheridan, J. Goree, Y. T. Chiu, R. L. Rairden, and J. A. Kiessling, "Observation of dust shedding from material bodies in a plasma," J. Geophys. Res.: Space Phys. **97**, 2935–2942, https://doi.org/10.1029/91JA02801 (1992).
[881]T. M. Flanagan and J. Goree, "Dust release from surfaces exposed to plasma," Phys. Plasmas **13**, 123504 (2006).
[882]T. E. Sheridan and A. Hayes, "Charge fluctuations for particles on a surface exposed to plasma," Appl. Phys. Lett. **98**, 91501 (2011).
[883]L. C. J. Heijmans and S. Nijdam, "Dust on a surface in a plasma: A charge simulation," Phys. Plasmas **23**, 043703 (2016).
[884]D. Shefer, A. Nikipelov, M. van de Kerkhof, V. Banine, and J. Beckers, "Morphology change and release of tin and lead micro-particles from substrates in hydrogen plasma," Proc. SPIE **11609**, 116091F (2021).
[885]D. Shefer, A. Nikipelov, M. van de Kerkhof, Z. Marvi, V. Banine, and J. Beckers, "The impact of hydrogen plasma on the structure and morphology of tin and lead micrometer sized particles," J. Phys. D: Appl. Phys. **56**, 85204 (2023).
[886]H. Yu, X. Wu, H. Li, Y. Yuan, and J. Yang, "Particle removal is explored by the motion of individual particles based on laser-induced plasma shock wave," Opt. Commun. **460**, 125205 (2020).
[887]C. M. Ticoş, A. Scurtu, and D. Ticoş, "A pulsed "plasma broom" for dusting off surfaces on Mars," New J. Phys. **19**, 063006 (2017).
[888]X. Wang, M. Horányi, and S. Robertson, "Investigation of dust transport on the lunar surface in a laboratory plasma with an electron beam," J. Geophys. Res.: Space Phys. **115**(A11), A11102, https://doi.org/10.1029/2010JA015465 (2010).
[889]X. Wang, M. Horányi, and S. Robertson, "Dust transport near electron beam impact and shadow boundaries," Planet. Space Sci. **59**, 1791–1794 (2011).
[890]N. C. Orger, K. Toyoda, H. Masui, and M. Cho, "Experimental investigation on silica dust lofting due to charging within micro-cavities and surface electric field in the vacuum chamber," Adv. Space Res. **63**, 3270–3288 (2019).
[891]P. V. Krainov, V. V. Ivanov, D. I. Astakhov, V. V. Medvedev, V. V. Kvon, A. M. Yakunin, and M. A. van de Kerkhof, "Dielectric particle lofting from dielectric substrate exposed to low-energy electron beam," Plasma Sources Sci. Technol. **29**, 085013 (2020).
[892]P. V. Krainov, V. V. Ivanov, D. I. Astakhov, V. V. Medvedev, V. V. Kvon, A. M. Yakunin, and M. A. van de Kerkhof, "Particle lofting from substrate exposed to plasma and electron beam," arXiv:2011.09204 (2020).
[893]P. Krainov, V. Ivanov, D. Astakhov, S. Medvedev, and M. van de Kerkhof, "Role of ion accumulation in lofting of submicrometer-sized dielectric particle from dielectric surface by plasma and low-energy electron beam," Proc. SPIE **12051**, 1205103 (2022).
[894]H. Gan, X. Zhang, X. Li, H. Jin, L. Xie, and Y. Zou, "Experiments on the electrostatic transport of charged anorthite particles under electron beam irradiation," Astrophys. J. **930**, 42 (2022).
[895]T. Yokota, N. Sato, and A. Ando, "Control experiment of positively charged fine particles at the atmospheric pressure," AIP Conf. Proc. **799**, 530–533 (2005).
[896]M. Shoyama, H. Yoshioka, and S. Matsusaka, "Charging and levitation of particles using UV irradiation and electric field," IEEE Trans. Ind. Appl. **58**, 776–782 (2022).
[897]H. Masuda, K. Gotoh, H. Fukada, and Y. Banba, "The removal of particles from flat surfaces using a high-speed air jet," Adv. Powder Technol. **5**, 205–217 (1994).
[898]K. Gotoh, K. Mizutani, Y. Tsubota, J. Oshitani, M. Yoshida, and K. Inenaga, "Enhancement of particle removal performance of high-speed air jet by setting obstacle in jet flow," Part. Sci. Technol. **33**, 567–571 (2015).
[899]M. Kobayakawa, S. Kiriyama, M. Yasuda, and S. Matsusaka, "Microscopic analysis of particle detachment from an obliquely oscillating plate," Chem. Eng. Sci. **123**, 388–394 (2015).
[900]W. Theerachaisupakij, S. Matsusaka, M. Kataoka, and H. Masuda, "Effects of wall vibration on particle deposition and reentrainment in aerosol flow," Adv. Powder Technol. **13**, 287–300 (2002).
[901]M. Hohlfeld, "Das Niederschlagen des Rauches durch Elektricitat," Arch. gesammte Nat. **2**, 205–206 (1824).

[902] A. S. M. Sayem, M. M. K. Khan, M. G. Rasul, and N. M. S. Hassan, "Performance assessment of an electrostatic precipitator of a coal-fired power plant—A case study for collecting smaller particles," in *Application of Thermo-fluid Processes in Energy Systems: Key Issues and Recent Developments for a Sustainable Future* edited by M. M. K. Khan, A. A. Chowdhury, and N. M. S. Hassan (Springer, Singapore, 2018), pp. 109–138.

[903] A. Sudrajad and A. F. Yusof, "Review of electrostatic precipitator device for reduce of diesel engine particulate matter," Energy Proc. **68**, 370–380 (2015).

[904] A. Afshari, L. Ekberg, L. Forejt, J. Mo, S. Rahimi, J. Siegel, W. Chen, P. Wargocki, S. Zurami, and J. Zhang, "Electrostatic precipitators as an indoor air cleaner—A literature review," Sustainability **12**, 8774 (2020).

[905] L. Couëdel, A. Mezeghrane, A. A. Samarian, M. Mikikian, Y. Tessier, M. Cavarroc, and L. Boufendi, "Complex plasma afterglow," Contrib. Plasma Phys. **49**, 235–259 (2009).

[906] I. B. Denysenko, I. Stefanovic, B. Sikimic, J. Winter, and N. A. Azarenkov, "Discharging of dust particles in the afterglow of plasma with large dust density," Phys. Rev. E **88**, 023104 (2013).

[907] I. B. Denysenko, I. Stefanovic, N. A. Azarenkov, and G. P. Burmaka, "Effect of secondary emission on the argon plasma afterglow with large dust density," Phys. Plasmas **22**, 023702 (2015).

[908] J. K. Meyer and R. L. Merlino, "Evolution of dust clouds in afterglow plasmas," IEEE Trans. Plasma Sci. **44**, 473–478 (2016).

[909] I. B. Denysenko, M. Mikikian, and N. A. Azarenkov, "Dust dynamics during the plasma afterglow," J. Phys. D: Appl. Phys. **55**, 95201 (2022).

[910] L. Couëdel, "Temporal dusty plasma afterglow: A review," Front. Phys. **10**, 1–13 (2022).

[911] B. Van Minderhout, A. T. A. Peijnenburg, P. Blom, J. M. Vogels, G. M. W. Kroesen, and J. Beckers, "The charge of micro-particles in a low pressure spatial plasma afterglow," J. Phys. D: Appl. Phys. **52**, 32LT03 (2019).

[912] B. van Minderhout, J. C. A. van Huijstee, R. M. H. Rompelberg, A. Post, A. T. A. Peijnenburg, P. Blom, and J. Beckers, "Charge of clustered microparticles measured in spatial plasma afterglows follows the smallest enclosing sphere model," Nat. Commun. **12**, 4692 (2021).

[913] B. Van Minderhout, J. C. A. Van Huijstee, A. T. A. Peijnenburg, P. Blom, G. M. W. Kroesen, and J. Beckers, "Charge neutralisation of microparticles by pulsing a low-pressure shielded spatial plasma afterglow," Plasma Sources Sci. Technol. **30**, 045016 (2021).

[914] J. C. A. van Huijstee, P. Blom, A. T. A. Peijnenburg, and J. Beckers, "Spatio-temporal plasma afterglow induces additional neutral drag force on microparticles," Front. Phys. **10**, 13–16 (2022).

[915] R. Gopalakrishnan and C. J. Hogan, "Coulomb-influenced collisions in aerosols and dusty plasmas," Phys. Rev. E **85**, 26410 (2012).

[916] F. Fanelli, A. M. Mastrangelo, and F. Fracassi, "Aerosol-assisted atmospheric cold plasma deposition and characterization of superhydrophobic organic-inorganic nanocomposite thin films," Langmuir **30**, 857–865 (2014).

[917] P. J. Bruggeman, M. J. Kushner, B. R. Locke, J. G. E. Gardeniers, W. G. Graham, D. B. Graves, R. C. H. M. Hofman-Caris, D. Maric, J. P. Reid, E. Ceriani, D. Fernandez Rivas, J. E. Foster, S. C. Garrick, Y. Gorbanev, S. Hamaguchi, F. Iza, H. Jablonowski, E. Klimova, J. Kolb, F. Krcma, P. Lukes, Z. Machala, I. Marinov, D. Mariotti, S. Mededovic Thagard, D. Minakata, E. C. Neyts, J. Pawlat, Z. L. Petrovic, R. Pflieger, S. Reuter, D. C. Schram, S. Schröter, M. Shiraiwa, B. Tarabová, P. A. Tsai, J. R. R. Verlet, T. von Woedtke, K. R. Wilson, K. Yasui, and G. Zvereva, "Plasma-liquid interactions: A review and roadmap," Plasma Sources Sci. Technol. **25**, 053002 (2016).

[918] E. Husmann, E. Thimsen, and X. Chen, "Particle charge distributions in the effluent of a flow-through atmospheric pressure low temperature plasma," Plasma Sources Sci. Technol. **30**, 075030 (2021).

[919] X. Chen and C. J. Hogan, "Nanoparticle dynamics in the spatial afterglows of nonthermal plasma synthesis reactors," Chem. Eng. J. **411**, 128383 (2021).

[920] A. Bouchoule and L. Boufendi, "Particulate formation and dusty plasma behaviour in argon-silane RF discharge," Plasma Sources Sci. Technol. **2**, 204 (1993).

[921] L. Boufendi, A. Bouchoule, R. K. Porteous, J. P. Blondeau, A. Plain, and C. Laure, "Particle-particle interactions in dusty plasmas," J. Appl. Phys. **73**, 2160–2162 (1993).

[922] L. Boufendi and A. Bouchoule, "Particle nucleation and growth in a low-pressure argon–silane discharge," Plasma Sources Sci. Technol. **3**, 262 (1994).

[923] L. Boufendi, A. Bouchoule, and T. Hbid, "Electrical characterization and modeling of a dust forming plasma in a radio frequency discharge," J. Vac. Sci. Technol. A **14**, 572–576 (1996).

[924] E. Stoffels, W. W. Stoffels, G. M. W. Kroesen, and F. J. de Hoog, "Dust formation and charging in an Ar/SiH_4 radio-frequency discharge," J. Vac. Sci. Technol. A **14**, 556–561 (1996).

[925] I. Stefanovic, E. Kovacevic, J. Berndt, and J. Winter, "H alpha emission in the presence of dust in an Ar-C_2H_2 radio-frequency discharge," New J. Phys. **5**, 39 (2003).

[926] I. V. Schweigert, A. L. Alexandrov, D. A. Ariskin, F. M. Peeters, I. Stefanovic, E. Kovacevic, J. Berndt, and J. Winter, "Effect of transport of growing nanoparticles on capacitively coupled RF discharge dynamics," Phys. Rev. E **78**, 026410 (2008).

[927] L. Boufendi, M. C. Jouanny, E. Kovacevic, J. Berndt, and M. Mikikian, "Dusty plasma for nanotechnology," J. Phys. D: Appl. Phys. **44**, 174035 (2011).

[928] J. Beckers and G. Kroesen, "Surprising temperature dependence of the dust particle growth rate in low pressure Ar/C_2H_2 plasmas," Appl. Phys. Lett. **99**, 181503 (2011).

[929] F. Van De Wetering, W. Oosterbeek, J. Beckers, S. Nijdam, T. Gibert, M. Mikikian, H. Rabat, E. Kovačević, and J. Berndt, "Interaction of nanosecond ultraviolet laser pulses with reactive dusty plasma," Appl. Phys. Lett. **108**, 213103 (2016).

[930] N. Kashihara, H. Setyawan, M. Shimada, Y. Hayashi, C. S. Kim, K. Okuyama, and S. Winardi, "Suppression of particle generation in a plasma process using a sine-wave modulated RF plasma," J. Nanopart. Res. **8**, 395–403 (2006).

[931] Y. Watanabe, M. Shiratani, and H. Makino, "Powder-free plasma chemical vapor deposition of hydrogenated amorphous silicon with high RF power density using modulated RF discharge," Appl. Phys. Lett. **57**, 1616–1618 (1990).

[932] H. A. Perko, J. D. Nelson, and J. R. Green, "Review of Martian dust composition, transport, deposition, adhesion, and removal," in *Proceedings of the Space 2002 and Robotics* (ASCE Library, 2002), pp. 176–189.

[933] M. Y. Pustylnik, Z. Marvi, and J. Beckers, "On the optical measurement of microparticle charge using quantum dots," J. Phys. D: Appl. Phys. **55**, 095202 (2022).

[934] M. Hasani, G. Klaassen, Z. Marvi, M. Pustylnik, and J. Beckers, "Quantum dot photoluminescence as charge probe for plasma exposed surfaces," J. Phys. D: Appl. Phys. **56**, 025202 (2023).

[935] A. A. Samarian and B. W. James, "Dust as fine electrostatic probes for plasma diagnostic," Plasma Phys. Controlled Fusion **47**, B629–B639 (2005).

[936] J. Benedikt, H. Kersten, and A. Piel, "Foundations of measurement of electrons, ions and species fluxes toward surfaces in low-temperature plasmas," Plasma Sources Sci. Technol. **30**, 033001 (2021).

[937] B. M. Annaratone, T. Antonova, H. M. Thomas, and G. E. Morfill, "Diagnostics of the electronegative plasma sheath at low pressures using microparticles," Phys. Rev. Lett. **93**, 185001 (2004).

[938] R. Basner, F. Sigeneger, D. Loffhagen, G. Schubert, H. Fehske, and H. Kersten, "Particles as probes for complex plasmas in front of biased surfaces," New J. Phys. **11**, 013041 (2009).

[939] J. Beckers, T. Ockenga, M. Wolter, W. W. Stoffels, J. Van Dijk, H. Kersten, and G. M. W. Kroesen, "Microparticles in a collisional RF plasma sheath under hypergravity conditions as probes for the electric field strength and the particle charge," Phys. Rev. Lett. **106**, 115002 (2011).

[940] P. Meijaard, "Hyper-gravity controlled microparticles probing the plasma sheath," Ph.D. thesis (Applied Physics and Science Education, 2023).

[941] V. Nosenko, A. V. Ivlev, S. K. Zhdanov, M. Fink, and G. E. Morfill, "Rotating electric fields in complex (dusty) plasmas," Phys. Plasmas **16**, 083708 (2009).

[942] L. Wörner, V. Nosenko, A. V. Ivlev, S. K. Zhdanov, H. M. Thomas, G. E. Morfill, M. Kroll, J. Schablinski, and D. Block, "Effect of rotating electric field on 3d complex (dusty) plasma," Phys. Plasmas **18**, 063706 (2011).

[943] D. H. E. Dubin and T. M. O'Neil, "Trapped nonneutral plasmas, liquids, and crystals (the thermal equilibrium states)," Rev. Mod. Phys. **71**, 87–172 (1999).

[944] P. Hartmann, A. Z. Kovács, J. C. Reyes, L. S. Matthews, and T. W. Hyde, "Dust as probe for horizontal field distribution in low pressure gas discharges," Plasma Sources Sci. Technol. **23**, 045008 (2014).

[945] L. Talbot, R. K. Cheng, R. W. Schefer, and D. R. Willis, "Thermophoresis of particles in a heated boundary layer," J. Fluid Mech. **101**, 737–758 (1980).

[946] H. Rothermel, T. Hagl, G. E. Morfill, M. H. Thoma, and H. M. Thomas, "Gravity compensation in complex plasmas by application of a temperature gradient," Phys. Rev. Lett. **89**, 175001 (2002).

[947]A. Homann, A. Melzer, S. Peters, R. Madani, and A. Piel, "Laser-excited dust lattice waves in plasma crystals," Phys. Lett. A **242**, 173–180 (1998).
[948]A. Melzer, "Laser manipulation of particles in dusty plasmas," Plasma Sources Sci. Technol. **10**, 303–310 (2001).
[949]V. Nosenko, J. Goree, Z. W. Ma, and A. Piel, "Observation of shear-wave Mach cones in a 2D dusty-plasma crystal," Phys. Rev. Lett. **88**, 135001 (2002).
[950]M. Wolter and A. Melzer, "Laser heating of particles in dusty plasmas," Phys. Rev. E **71**, 036414 (2005).
[951]V. Nosenko, J. Goree, and A. Piel, "Laser method of heating monolayer dusty plasmas," Phys. Plasmas **13**, 032106 (2006).
[952]J. Schablinski, D. Block, A. Piel, A. Melzer, H. Thomsen, H. Kählert, and M. Bonitz, "Laser heating of finite two-dimensional dust clusters: A. Experiments," Phys. Plasmas **19**, 013705 (2012).
[953]H. Thomsen, H. Kählert, M. Bonitz, J. Schablinski, D. Block, A. Piel, and A. Melzer, "Laser heating of finite two-dimensional dust clusters: B. Simulations," Phys. Plasmas **19**, 023701 (2012).
[954]A. Schella, M. Mulsow, A. Melzer, J. Schablinski, and D. Block, "From transport to disorder: Thermodynamic properties of finite dust clouds," Phys. Rev. E **87**, 063102 (2013).
[955]Z. Haralson and J. Goree, "Laser heating of 2-D dusty plasmas using a random arc pattern," IEEE Trans. Plasma Sci. **44**, 549–552 (2016).
[956]P. Lebedew, "Untersuchungen über die Druckkräfte des Lichtes," Ann. Phys. **311**, 433–458 (1901).
[957]E. F. Nichols and G. F. Hull, "Über Strahlungsdruck," Ann. Phys. **317**, 225–263 (1903).
[958]F. Wieben and D. Block, "Photophoretic force measurement on microparticles in binary complex plasmas," Phys. Plasmas **25**, 123705 (2018).
[959]A. Ashkin, "Acceleration and trapping of particles by radiation pressure," Phys. Rev. Lett. **24**, 156–159 (1970).
[960]T. Ito, K. Koga, D. Yamashita, K. Kamataki, N. Itagaki, G. Uchida, and M. Shiratani, "Plasma etching of single fine particle trapped in Ar plasma by optical tweezers," J. Phys. Conf. Ser. **518**, 012014 (2014).
[961]J. Schablinski, F. Wieben, and D. Block, "An optical tweezer for complex plasmas," Phys. Plasmas **22**, 043703 (2015).
[962]D. Block, F. Wieben, and J. Schablinski, "Mode excitation in finite dust clusters using an optical trap," IEEE Trans. Plasma Sci. **44**, 479–482 (2016).
[963]V. Schneider and H. Kersten, "On the use of optically trapped dust particles as micro-probes in process plasmas," Probl. At. Sci. Technol. **1**, 164–167 (2013).
[964]V. Nosenko, A. V. Ivlev, and G. E. Morfill, "Laser-induced rocket force on a microparticle in a complex (dusty) plasma," Phys. Plasmas **17**, 123705 (2010).
[965]L. Couëdel, M. Mikikian, L. Boufendi, and A. A. Samarian, "Residual dust charges in discharge afterglow," Phys. Rev. E **74**, 026403 (2006).
[966]O. Arp, D. Block, A. Piel, and A. Melzer, "Dust Coulomb balls: Three-dimensional plasma crystals," Phys. Rev. Lett. **93**, 165004 (2004).
[967]O. Arp, D. Block, M. Klindworth, and A. Piel, "Confinement of Coulomb balls," Phys. Plasmas **12**, 122102 (2005).
[968]S. Mitic, R. Sütterlin, A. V. I. H. Höfner, M. H. Thoma, S. Zhdanov, and G. E. Morfill, "Convective dust clouds driven by thermal creep in a complex plasma," Phys. Rev. Lett. **101**, 235001 (2008).
[969]T. M. Flanagan and J. Goree, "Gas flow driven by thermal creep in dusty plasma," Phys. Rev. E **80**, 046402 (2009).
[970]M. Schwabe, L.-J. Hou, S. Zhdanov, A. V. Ivlev, H. M. Thomas, and G. E. Morfill, "Convection in a dusty radio-frequency plasma under the influence of a thermal gradient," New J. Phys. **13**, 083034 (2011).
[971]J. Held, M. Eslamisaray, and U. Kortshagen, "Particle trapping enables the dusty plasma synthesis of highly monodisperse nanocrystals," Bull. Am. Phys. Soc. **67**, 15 (2022).
[972]V. Nosenko and J. Goree, "Shear flows and shear viscosity in a two-dimensional Yukawa system (dusty plasma)," Phys. Rev. Lett. **93**, 155004 (2004).
[973]B. Liu and J. Goree, "Shear viscosity of two-dimensional Yukawa systems in the liquid state," Phys. Rev. Lett. **94**, 185002 (2005).
[974]Z. Donkó, J. Goree, P. Hartmann, and K. Kutasi, "Shear viscosity and shear thinning in two-dimensional Yukawa liquids," Phys. Rev. Lett. **96**, 145003 (2006).
[975]H.-W. Hu, Y.-X. Zhang, and L. I, "Multiscale cooperative micro-excitations and structural rearrangements in cold dusty plasma liquids," Rev. Mod. Plasma Phys. **5**, 13 (2021).
[976]Y. Liu, N. Blosczyk, and D. Block, "Viscosity of finite Yukawa liquids," Phys. Plasmas **30**, 043705 (2023).
[977]F. Wieben, J. Schablinski, and D. Block, "Generation of two-dimensional binary mixtures in complex plasmas," Phys. Plasmas **24**, 033707 (2017).
[978]S. V. Vladimirov, K. Ostrikov, and A. A. Samarian, *Physics and Applications of Complex Plasmas* (Imperial College Press, London, 2005).
[979]A. Samarian and B. James, "Sheath measurement in rf-discharge plasma with dust grains," Phys. Lett. A **287**, 125–130 (2001).
[980]V. Schneider and H. Kersten, "An optical trapping system for particle probes in plasma diagnostics," Rev. Sci. Instrum. **89**, 103505 (2018).
[981]T. Lafleur, "Tailored-waveform excitation of capacitively coupled plasmas and the electrical asymmetry effect," Plasma Sources Sci. Technol. **25**, 013001 (2016).
[982]J. Schleitzer, V. Schneider, and H. Kersten, "Investigations of the sheath in a dual-frequency capacitively coupled rf discharge by optically trapped microparticles," Phys. Plasmas **28**, 083506 (2021).
[983]P. Meijaard, T. J. A. Staps, and J. Beckers, "Step-wise excitation for the determination of the resonance frequency of a microparticle confined in a low pressure plasma," Phys. Plasmas **28**, 083502 (2021).