Collisional Losses in a Variable Specific-Impulse Magnetoplasma Rocket

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Abstract

A variable specific-impulse magnetoplasma rocket (VASIMR) is a potential means of powering future deep space missions. The engine uses radiofrequency (RF) energy to first ionize argon with a helicon antenna and to subsequently heat the resulting plasma through ion cyclotron heating (ICH) which then creates thrust in a magnetic nozzle. Our previous studies have modeled the increased specific impulse and thrust generated in a collisionless plasma. This work includes ion-neutral collisions in the simulation, which reduces the number of ions in the plasma stream and thus reduces thrust. This study analyzes the loss of thruster efficiency caused by such collisions in the nozzle region of the VASIMR. The plasma is considered weakly ionized, and other plasma effects, such as ion-ion and ion-electron collisions, are ignored. Monte-Carlo methods are used to determine ion losses from a stream of individual argon ions as they move along the engine. Neutral densities are inferred from stipulated mass flow rates and ionization fractions. These are functions of the initial ionization process involving a helicon antenna, whose properties are inferred from this study, but not directly dealt with. Ion temperatures, and hence velocities, are determined as

products of the ICH process. Efficiency of the engine varies widely with initial mass flow rates and the subsequent neutral backgrounds these produce, but in this simple study, collisional losses are large, for even moderate neutral backgrounds. An effective VASIMR thus requires an extremely efficient initial ionization mechanism.

Background

A VASIMR (variable specific-impulse magnetoplasma rocket) thruster is an electrically powered engine that uses plasma as a propellant [1]. The VASIMR engine is designed to provide higher specific impulse and greater thrust efficiency compared with traditional chemical rockets.

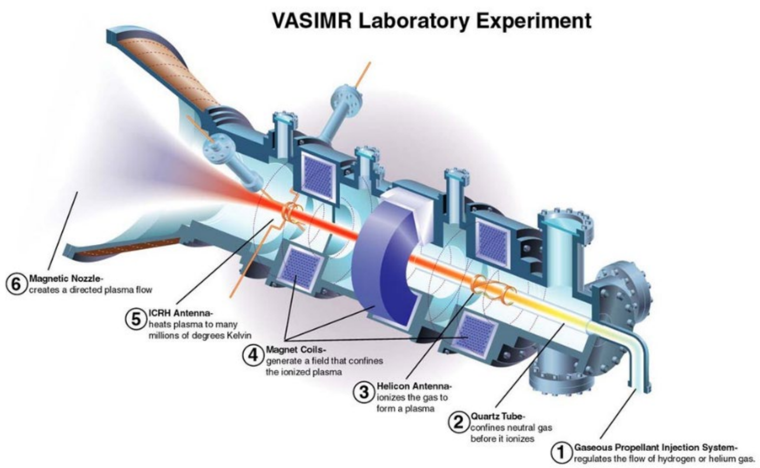

Figure 1. Diagram showing the operation of a VASIMR (variable specific-impulse magnetoplasma rocket). NASA, Public Domain, via Wikimedia Commons.

An experimental prototype version of the engine, the VX-200, has been undergoing development and testing for many years by the Ad Astra Rocket Company [2, 3]. We consider this device to establish the base marks for comparison studies. The engine works by ionizing a gas, such as hydrogen, helium, or, in our simulation, argon, using a helicon antenna [4] (circle 3 in Figure 1). An axial magnetic field keeps the plasma traveling along the axis of the engine (circle 4 in Figure 1). The ions gyrate with frequency $\omega_L = \frac{qB}{m}$, where q is the ion charge, B the magnitude of the magnetic field, and m is the mass of the ion. In the absence of accelerating electric fields, the magnetic moment of the ion, $\mu = 1/2\frac{mv_\perp^2}{B}$, and the total kinetic energy, $E = \frac{1}{2}mv_\parallel^2 + \frac{1}{2}mv_\perp^2 = \frac{1}{2}mv_\parallel^2 + \mu B$, are constants of the motion. Consequently, the axial velocity of the ions, $v_\parallel$, increases as the magnetic field, B, decreases in the expansion region of the magnetic nozzle (circle 6 in Figure 1). This is the source of thrust. The key element to the VASIMR is in using a circularly polarized electric field that rotates in synchrony with the ion gyrofrequency ω_L, increasing $v_\perp$ and, hence, the magnetic moment of the ion. This is ICH heating indicated by circle 5 in Figure 1. The energy injected into the ions in this manner is then converted to thrust in the nozzle region as the pumped component of the ion velocity, $v_\perp$, is converted to increased axial $v_\parallel$. Exit velocities as high as 50 km/s are possible, or reckoned in terms of specific impulse, $I_{sp} = 5000\ s$, which is more than an order of magnitude larger than those possible from chemical rockets [5]. At such high values of specific impulse, the thrust generated is necessarily small, but just as with electric ion engines, it can be maintained over long times. An additional advantage to the VASIMR engine over an electric ion thruster is that the specific impulse and thrust parameters can be varied from relatively high thrust and low specific impulse (such as might be used in exiting a planetary gravity well) to low thrust and high specific impulse (such as might be used in the interplanetary phase of a mission). There remain, however, substantial obstacles to the practical deployment of a VASIMR, such as the development of reliable, large-scale power supplies for long-term space use [6].

In previous studies [7], we have examined the efficiency of ICH heating by following individual ions as they pass through a simple computational model of a circularly polarized, rotating E-field. That study confirmed the results of other fluid-based plasma studies that high specific-impulse values are possible even with relatively small ICH heating regions. Those studies were "collisionless" in that the ions were simply integrated along their single particle trajectories and the resultant plasma properties were inferred by statistically averaging the properties of those individual ions. The same model is used here but is modified to eliminate some fraction of the ion population through simulation collisions with a neutral background.

The basic elements of the engine are modeled by a cylindrical tube having two current loops at either end that represent the confining magnets and a small ICH region just outside the exit loop (on the right in Figure 2). Our choice of model does not reflect the more uniform axial field produced by superconducting solenoids in the experimental VASIMR engines currently under study, but this model is accessible to simple computational resources and is appropriate for heuristic discussion of plasma phenomena at an undergraduate level. The plasma is assumed to be initiated using a helicon antenna. However, these devices have a wide range of operating conditions and effectiveness [4,8], so that we characterize this source only by specifying an initial flow rate, ionization energy, and ionization fraction of the injected gas.

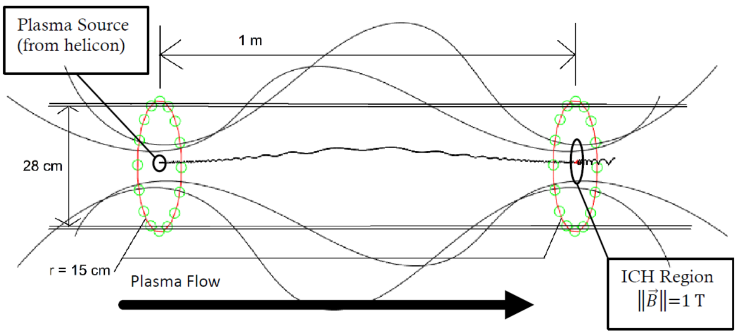

Figure 2. Diagram of the simulation setup and parameters. Red rings are current loops acting as superconducting magnets, approximated as regular polygons with corners marked by green circles. Four magnetic field lines are shown in black curves. The simulated path of one ion through the engine is shown. The black double-lines are the walls of the engine.

A thermal distribution of argon ions is generated at the entrance (left side of Figure 2), and the Lorentz force law, $m\,\vec{a} = q(\vec{v} \times \vec{B})$, is used to integrate the path of each ion through the engine. A Gaussian distribution of ions with a mean thermal speed of $v_0 = 1.7$ km/s is used as the source of particles. Only those ions in the narrow axial region along the center (that do not hit the wall) are used for subsequent analysis.

The ICH region is shown enlarged in Figure 3. During ICH, an electric field rotates in resonance with the ions in cyclotron motion. This has the effect of increasing in the ions' perpendicular velocity, which in turn increases their gyration radius, as seen in Figure 3. The ICH region is taken to be 1 cm in length, normal to the z axis with an electric field of uniform magnitude that abruptly falls to zero outside of that region. In reality, the ICH region would not be so simple, and the boundary between the inside and outside of the ICH region would not be so sharply

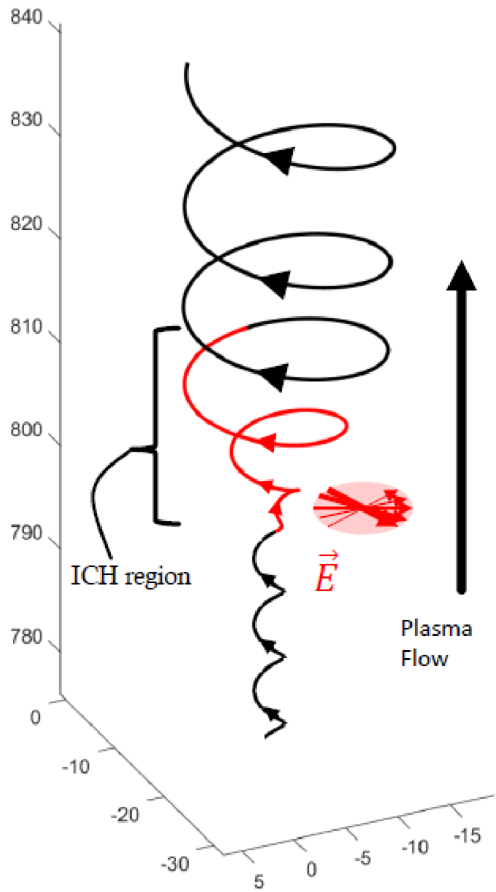

Figure 3. A zoomed-in view of the ICH (ion cyclotron heating) region shown in Figure 2, oriented so the engine nozzle is above. The magnetic field is aligned with the vertical axis, pointing upward. The electric field is rotating about the vertical axis. The ion's path is shown in red while inside the ICH region. The increase in the ion's magnetic moment is manifest in the increasing gyroradius of the ion, which shows an acceleration of the velocity in the direction perpendicular to the magnetic field. As the ion continues into regions of weakening magnetic field, the kinetic energy associated with this motion will be converted into kinetic energy parallel to the axis of the engine, thus producing enhanced thrust. Note that one distance unit along any of the three axes is approximately 0.628 mm.

delineated; however this simple model serves our purpose of investigating the basic physics of ICH heating. Figure 4 shows the nominal change in the distribution of the asymptotic values of the axial ion velocity for a collisionless plasma. The increased asymptotic axial velocity is a direct indicator of increased specific impulse of the propellant.

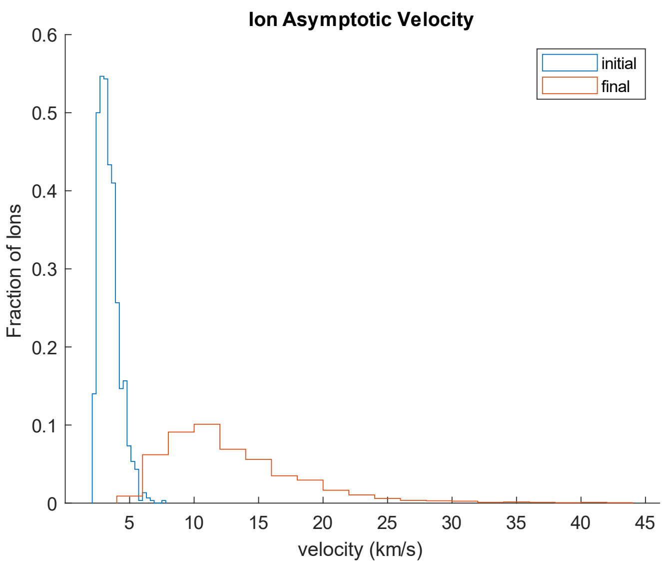

Figure 4. Ion velocity increase without accounting for collisions (equivalent to initial ionization fraction = 100%)

Using these simulation parameters, estimates of the upper limit of the engine's thrust and specific impulse were obtained for a variety of assumed mass flow rates and initial ionization fractions. Both of these parameters are contingent upon the physics of the helicon antenna, whose performance is then inferred from these results. A study of the Ad Astra VASIMR rocket [3] indicates that a mass flow rate of 120 mg/sec may be a nominal operating point for the engine during a planetary mission, and so we have based our study on this value.

MHD models or more sophisticated kinetic models of plasma flow in a VASIMR must deal with transport issues of collisional and diffusive loss. In our simple single particle model, we can approach these effects using Monte-Carlo methods with various transport and collision processes to modify individual particle behaviors. In this case, we assume the major loss to the plasma will be through ion-neutral collisions and neglect all other forms of plasma interactions. For a plasma with neutrals much colder than ions, as they would be in the ICH region, the collision frequency is given by

$$f = n_0\, \sigma_{\alpha|0}\, v_{\alpha,therm} \tag{1}$$

Here, f is the collisional frequency, n_0 is the neutral density, $\sigma_{\alpha|0}$ is the cross-section of an ion-neutral collision, taken as 5×10^{-19} m^2, and $v_{\alpha,therm}$ is the ion thermal velocity,

$$v_{\alpha,therm} = \sqrt{k_B T_\alpha / m_\alpha}, \tag{2}$$

where k_B is Boltzmann's constant, T_α is the ion temperature, and m_α is the ion mass. If each simulation time step has duration of Δt, in the limit $\Delta t \ll 1/f$, then the probability of collision, p, within the time step is

$$p = f\, \Delta t \ll 1. \tag{3}$$

Then 1-p is the probability of not experiencing a collision. Using a simple random number generator, we compare (1-p) to the "roll of the dice," and if the random number exceeds (1-p), the ion is assumed to be lost from the distribution; otherwise, it is retained.

The efficiency of the engine is thus modified by the direct fractional loss of ions from the propellant stream.

The ion temperature, $T_\alpha(z)$, is calculated at each point along the z-axis by averaging over the velocity distribution of the ions. The neutral density is taken to be constant inside the engine, and is calculated as

$$n_0 = (1 - x)\frac{\rho}{\pi R^2 v_z}, \tag{4}$$

the mass-flow rate ρ divided by the volume flow rate (cross-sectional area of the engine πR^2 times the z-velocity of the neutrals v_z), times the initial neutral fraction (one minus the initial ionization fraction x). Outside the nozzle of the engine, the neutral density, $n(z)$, is taken to fall off exponentially with distance z from the nozzle as

$$n(z) = n_0 e^{-\frac{z}{2R}}. \tag{5}$$

In all, 2376 different engine configurations were examined using mass flow rates ρ from 10 to 240 mg/sec in increments of 10 mg/sec and initial ionization fractions x from 0.01 to 0.99 in increments of 0.01

Results

Without accounting for collisions or other many-particle interactions within the engine, we observed an operating specific impulse of approximately 1300 seconds and a thrust of 1.6 newtons, with a thruster jet power of 10 kW at a mass flow rate of 120 mg/s. Despite minimal assumptions, these parameters are consistent with observed operating parameters of the VASIMR prototype VX-200 [3] (Figure 5).

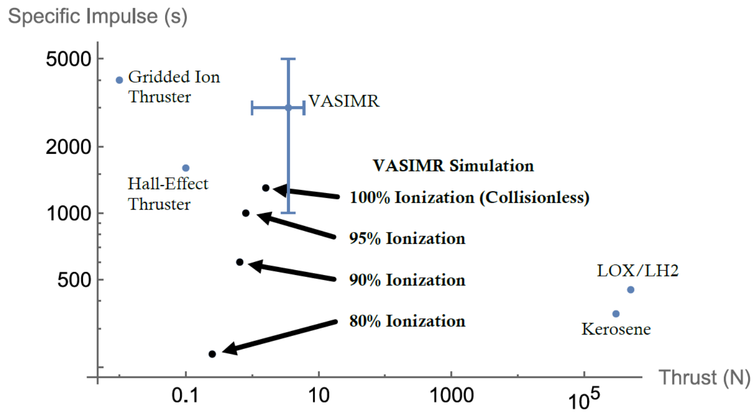

Figure 5. Specific impulse versus thrust for a few types of rocket and propellants. The measured VASIMR operating parameters [3] are shown, along with examples of our simulated results.

The ICH process in our model was observed to produce heating from 30,000 K to 500,000 K.

Figure 4 shows the change in the velocity distribution of the ions after passing through the engine. The nominal operating points given in Figure 4 are compared with VASIMR operating parameters given by Ad Astra [3] in Figure 5 by displaying the specific impulse achieved as a function of thrust produced. In short, the results displayed show that the initial ionization fraction of the plasma in the helicon must be near 100% to achieve reasonable performance.

In this study, we account for collision effects in the form of ion-neutral collisions. Collisions of any sort would tend to reduce the performance of the engine, and ion-neutral collisions are assumed to be the greatest contributor to performance loss. We naively assume that in any collision between an ion and a neutral atom, the ion is lost to the thrust stream.

To model these effects, we generated batches of ions in sets of 1000 ions and used Monte-Carlo methods to discard ions that experienced a collision. We simulated 2376 different combinations of the engine's mass flow rate and initial ionization fraction values to gain some insight into the limiting effects of ion-neutral collisions. The resulting engine operating parameters are shown below in Figures 6 and 7.

Figure 6 covers the parameter space giving the ionized fraction of matter in the exit plume as determined from the input mass flow rate to the engine and the initial ionization rate in the helicon. Our crude model shows strong losses under nearly all circumstances. For instance, at a mass flow rate of 120 mg/sec with an initial ionization fraction of 80 percent (0.8), only 20% (0.2 contour line) survive as ions to contribute thrust to the engine. With an initial ionization fraction of 90%, the surviving fraction increases to 50%; even at 98% initial ionization, the mass fraction in ions in the thrust column only approaches 80%.

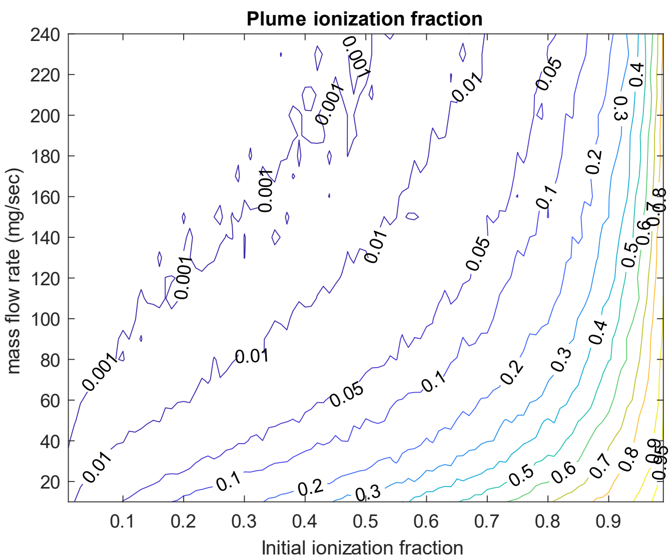

Figure 6. Plume ionization fraction versus mass flow rate and initial ionization fraction. Only a low initial neutral density leads to a large ionization fraction in the plume.

Figure 7 displays contours of constant thrust derived in the same parameter space. In a nominal collisional simulation, a mass flow rate of 120 mg of ions per second would develop roughly 1 N of thrust. With strong collisional losses, a feed rate of 120 mg/sec of argon with an initial ionization fraction of 80% reduces the generated thrust to 200 mN. The significant point again is that, unless the initial ionization fraction is in the high 90% range, ion-neutral collisions as modeled here can easily deplete the plasma column.

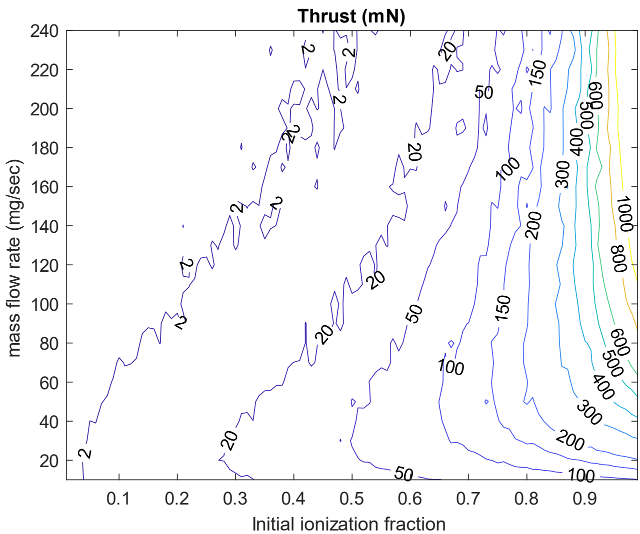

Figure 7. Thrust calculated from plume ionization fraction versus initial ionization fraction and mass flow rate.

Conclusion

It is apparent that collisional losses due to ion-neutral collisions in this model are overwhelming, except at high initial ionization fractions and low mass flow rates. Our model is simplistic. In addition to assuming a constant neutral density along the length of the engine, we assume that any ion-neutral collision results in the loss of that ion from the plasma stream. We neglect all other plasmas processes, including further ionization processes that may mitigate some of the losses discussed here. Other kinetic properties would act to remove the anisotropies in $v_{\perp}$ and $v_{\parallel}$. These would also tend to reduce the thrust efficiency. Nevertheless, Ad Astra's most recent results with VX-200SS [9] developed thrust with such high efficiencies that if subject to the constraints of our simple model it is implied that the helicon ionization antenna must develop an initial ionization fraction on the order of 95% or more.

The intent of this study is to illustrate that simple, single-particle codes using elementary physics may be used to check or highlight results obtained with more elaborate fluid and kinetic codes. Some obvious extensions and improvements to our approach would be to also include other effects such as further ionization, explicit charge exchange and re-energization of these particles, and other kinetic processes.

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