

Novel physics of wavelength-dependent electron collision times in plasma for laser-matter interactions

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Abstract: We present an experimental and theoretical study of wavelength-dependent electron collision times in plasma and its striking effects on laser-matter interactions during laser filamentation in a solid.

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Filamentary propagation of an intense laser occurs due to the dynamic balance between optical Kerr effect (self-focusing) and plasma defocusing/diffraction [1]. For plasma generation, which is a crucial factor for filament formation, its density is expected to decrease with increasing wavelength since plasma defocusing and diffraction are larger at longer wavelengths [2,3]. Theoretical analyses in air/gases have shown a monotonic decrease in the plasma density with wavelength [4,5], and recent experimental work has reported low-density plasma filaments at 10 μm in air [6]. For solids, a theoretical study has shown a similar reduction of plasma density at longer wavelengths as long as the drive wavelengths are in the same dispersion regime [7]. Here we report wavelength dependence of plasma dynamics (both plasma density and electron collision time) during laser filamentation in a solid by varying the drive wavelength spanning near and mid-infrared. Our measurement shows a negligible change in plasma density at different wavelengths, which is in sharp contrast to the expected trend. The critical parameter for the unexpected plasma density scaling is electron collision time which we measured to be less than one femtosecond (fs) and decrease with increasing wavelength. The simulations with the measured electron collision times agree well with the observed plasma densities.

In our time-resolved experiment, the drive (pump) wavelength from an optical parametric amplifier (OPA) is varied from $\lambda = 1.2$ to 2.3 μm and the probe is a 800-nm Ti:Sapphire pulse. The OPA beam is focused slightly before the input face of a 2.5-cm-long fused silica sample to generate a single filament. Using single-shot time-resolved interferometry, we are able to simultaneously determine plasma densities and electron collision times in filaments by measuring the change in the probe phase and amplitude caused by pump-produced plasma. Abel inversion, assuming cylindrical symmetry, is used to retrieve the refractive index change (Δn) from the measured phase. According to the Drude model, the change in refractive index due to plasma with the assumption of $\omega_{pr}\tau_c \gg 1$ (ω_{pr} is the 800-nm probe angular frequency, τ_c is the electron collision time) is given by $\Delta n = -\rho/2\rho_c$, where ρ is the plasma density, $\rho_c = \epsilon_0 m_e^* \omega_{pr}^2 / e^2$, ϵ_0 is the vacuum permittivity, e is the electron charge, and m_e^* is the reduced electron mass. Figure 1a shows the measured plasma density versus wavelength, which reveals an unexpected trend of almost constant plasma densities at different wavelengths. Furthermore, the measured electron collision time versus wavelength shown in Fig. 1b, reveals that the electron collision times are less than 1 fs and decrease from $\tau_c \sim 0.7$ fs to $\tau_c \sim 0.4$ fs with increasing wavelength.

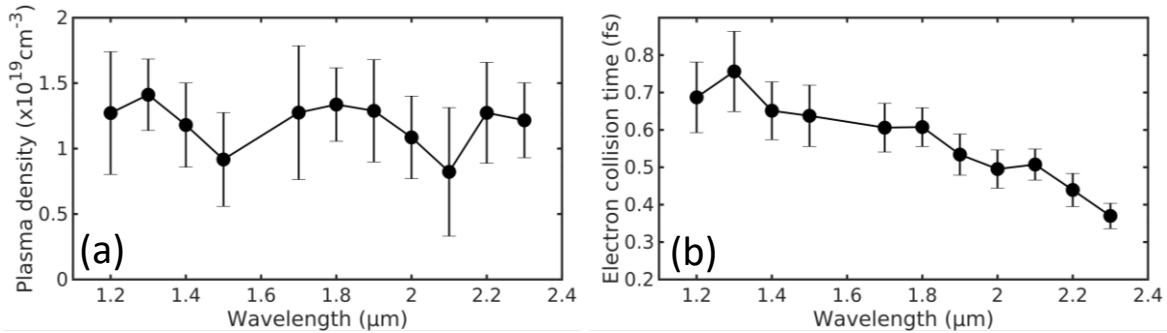


Fig.1: Measured (a) plasma density and (b) electron collision time scaling with wavelength. The data in (a and b) is averaged over 35 shots. The error bars represent standard deviations.

Since our measured τ_c is smaller than 1 fs, $\omega_{pr}\tau_c \gg 1$ is not valid anymore. Therefore, we reanalyze the plasma density extraction using the index change $\Delta n = -\rho/2\rho_c^*$, where $\rho_c^* = \epsilon_0 m_e^* \omega_{pr}^2 (1 + (\omega_{pr}\tau_c)^{-2}) / e^2$ is the modified

critical plasma density considering electron collision [Fig. 2a (black solid line)], which still shows almost constant plasma densities at different wavelengths. We perform numerical simulations by solving the nonlinear envelope equation (NEE) [8,9] in fused silica. For plasma generation, we use the Keldysh optical-field ionization rate, collisional ionization and plasma recombination. The simulations with the measured collision times agree well with the experiments, as shown in Fig. 2b (black solid line). In contrast, assuming constant $\tau_c = 0.7$ and 0.4 fs for all wavelengths, the simulations show a decrease in plasma density with increasing wavelength [$\tau_c = 0.4$ (red dashed line) and 0.7 fs (blue dotted line) in Fig. 2b].

In summary, we experimentally and theoretically study the wavelength-dependent plasma dynamics using laser filamentation in fused silica by varying the drive wavelength. The measured plasma densities are almost constant for all the wavelengths, which is in sharp contrast to the expected trend. The unexpected plasma density scaling is explained by the observation in which the electron collision time is smaller than 1 fs and decreases as the drive wavelength increases.

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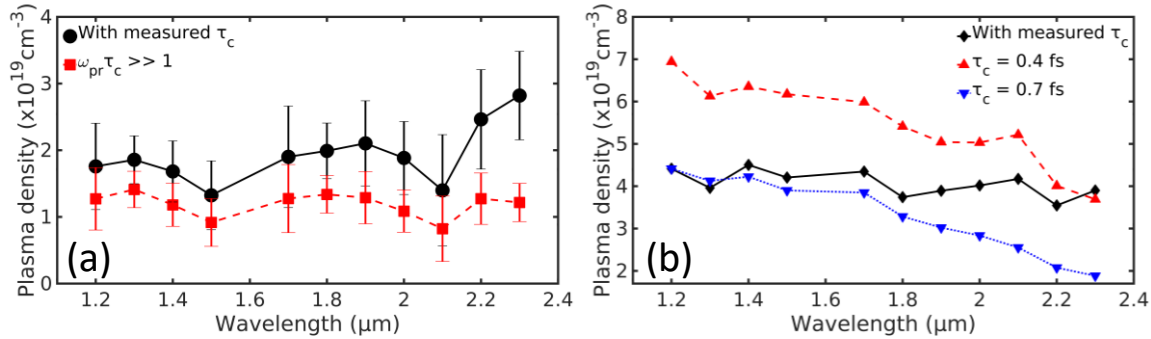


Fig. 2: (a) Measured plasma density analysis with (black solid line) and without (red dashed line) considering the measured electron collision times. (b) Calculated plasma densities versus wavelength with measured τ_c (black solid line) and with constant $\tau_c = 0.4$ fs (red dashed line), $\tau_c = 0.7$ fs (blue dotted line).

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