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Effects of density scale-length on laser–plasma instabilities and hot-electron generation for shock-ignition laser fusion

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Laser fusion can produce more fusion energy than the input laser energy through controlled thermonuclear reactions, potentially offering a clean and virtually limitless energy source for humanity. The shock ignition approach [1] to laser fusion holds promise for achieving higher target gains. However, achieving the necessary ignition conditions and enhanced target performance requires improving the efficiency of laser energy coupling to the target. This efficiency depends on controlling laser–plasma instabilities (LPIs), a particularly demanding requirement in shock ignition due to the higher laser intensities involved ($I_L = 5–10\times10^{15}$ W/cm^2). Among LPIs, stimulated Raman back-scattering (SRS) and two-plasmon decay (TPD) are of particular importance, as they generate hot electrons with suprathermal energies ranging from a few tens to a few hundreds of keV. These hot electrons can have both detrimental and beneficial effects on implosion efficiency—potentially preheating the hot spot or enhancing the ignitor-shock pressure. This dual role highlights the importance of effectively managing hot-electron generation through control of LPIs in shock ignition strategies.

In previous work by our group, we conducted several experimental campaigns using a planar geometry under conditions relevant to the shock ignition scheme at the GEKKO-XII laser facility [$I_L = (2–3) \times 10^{15}$ W/cm^2, $\lambda_L = 351$ nm (3ω), $L_n = n_e/(dn_e/dx) \approx 100$ μm, where I_L is the laser peak intensity, λ_L is the laser wavelength, and L_n is the density scale-legnth]. This experimental platform was primarily developed for evaluating LPIs and hot-electron generation [2]. Employing this platform, Cristoforetti *et al.* [3] investigated the effects of overlapping beams on SRS and TPD, as well as the characterization of hot electrons. Kawasaki *et al.* [4] demonstrated the influence of the hydrogen content in ablators on these instabilities and hot-electron characteristics. In the present study, we focused on characterizing LPIs and hot-electron generation as a function of the density scale-length [5]. We observed that increasing the density scale-length led to a reduction in both SRS and TPD signals near the quarter-critical density, which strongly correlates with a decrease in hot-electron generation. These results could be attributed to plasma-induced incoherence [6], which is considered to play a dominant role in reducing the coherence of the propagating laser light and suppressing the growth of LPIs. Plasma-induced incoherence is thought to originate from filamentation instability. In particular, the random phase plates (RPPs) [7] employed in this experiment introduce high-intensity speckles across the focal spot, making the beam more susceptible to ponderomotive self-focusing and the onset of filamentation. To further investigate this, we examined the effects of RPPs on SRS and TPD [8]. The experimental results showed that, with RPPs, both SRS and TPD were suppressed as the density scale-length increased, consistent with the findings of Ref. [5]. In contrast, without RPPs, TPD remained strongly suppressed, whereas SRS suppression became less sensitive to the density scale-length— demonstrating clear dependence of SRS on beam coherence. These findings offer critical insights into the control of hot-electron generation for laser fusion. In this invited talk, I will present our recent findings on the density scale-length dependence of LPIs and the role of RPPs.

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