Impact of Spatiotemporal Smoothing on the Two-Plasmon–Decay Instability

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Higher levels of hot electrons from the two-plasmon–decay (TPD) instability are observed when smoothing by spectral dispersion (SSD)[1] is turned off in directly driven inertial confinement fusion experiments at the Omega Laser Facility. This finding is explained using a hot-spot model based on speckle statistics and simulation results from *LPSE*. The model accurately reproduces the relative increase in hot-electron activity at two different drive intensities, although it slightly overestimates the absolute number of hot electrons in all cases. Extrapolating from the current ≈360-GHz system while adhering to the logic of the hot-spot model suggests that larger SSD bandwidth should significantly mitigate hot-electron generation; legacy 1-THz OMEGA experiments appear to support this conclusion. These results demonstrate that it is essential to account for laser speckles and spatiotemporal smoothing to obtain quantitative agreement with experiments.

The TPD instability—in which an electromagnetic pump decays into two electron plasma waves near the quarter-critical density $n_c/4$—has long been a concern for directly driven inertial confinement fusion. This stems primarily from its tendency to generate hot electrons[2] that can preheat the fuel and decrease the areal density of the compressed shell.[3] Although there has been extensive effort to understand many aspects of TPD, little consideration has been given to the impact of laser beam speckles and spatiotemporal smoothing schemes, despite the fact that they are ubiquitous features of modern experiments.

In this summary, we present experimental evidence that SSD does partially mitigate TPD (conversely, turning off SSD enhances TPD) in implosions at the Omega Laser Facility. The experiments used 860-μm-diam, 27-μm-thick, vacuum-filled spherical CH targets illuminated by all 60 OMEGA beams. On every shot, the beams were conditioned with distributed polarization rotators (i.e., polarization smoothing) and "SG5" phase plates. Both high- and low-power versions of a similar pulse shape [cf. Fig. 1(a)] were used in order to see how the impact of SSD on TPD activity varied with proximity to the TPD threshold. For each pulse shape, the SSD bandwidth was also tuned between shots from 100% (of the current ≈360 GHz) down to 50% and, ultimately, to zero. While varying the SSD bandwidth, laser amplifier settings were adjusted to reproduce the same delivered pulse shape. Radiation-hydrodynamic simulations using the *LILAC* code, including nonlocal and cross-beam energy transfer models, give the following quarter-critical conditions during the period of TPD activity: overlapped intensity $I_{14} = 3.5$ (in units of 10^{14} W/cm^2), electron temperature $T_e = 2.4$ keV, and density scale length $L = 160$ μm for the high-power case (respectively, $I_{14} = 2.8$, $T_e = 2.25$ keV, and $L = 160$ μm for the low-power case).

The time-resolved hot-electron power for both the full-SSD and no-SSD shots of the two different pulse shapes are shown in Fig. 1(a), which shows that turning SSD off increased hot electrons in both cases. The total energy in hot electrons for each shot is shown in Fig. 1(b), with high power giving a more-than-twofold increase over the low-power pulse shape. The impact of SSD on TPD activity is most clearly seen in Fig. 1(c), which shows the change in hot electrons for each of the reduced-SSD shots relative to their full-SSD companions. There is a modest increase in TPD activity at 50% SSD and a much larger increase when SSD is turned off completely. It also shows that the relative effect of SSD on TPD is consistently larger at low power, closer to the TPD threshold. These measurements were obtained using the hard x-ray detector (HXRD). Note that the data have small relative error (≈1%, comparable to the marker width) dominated by noise, but the systematic error could be as large as ≈50%.

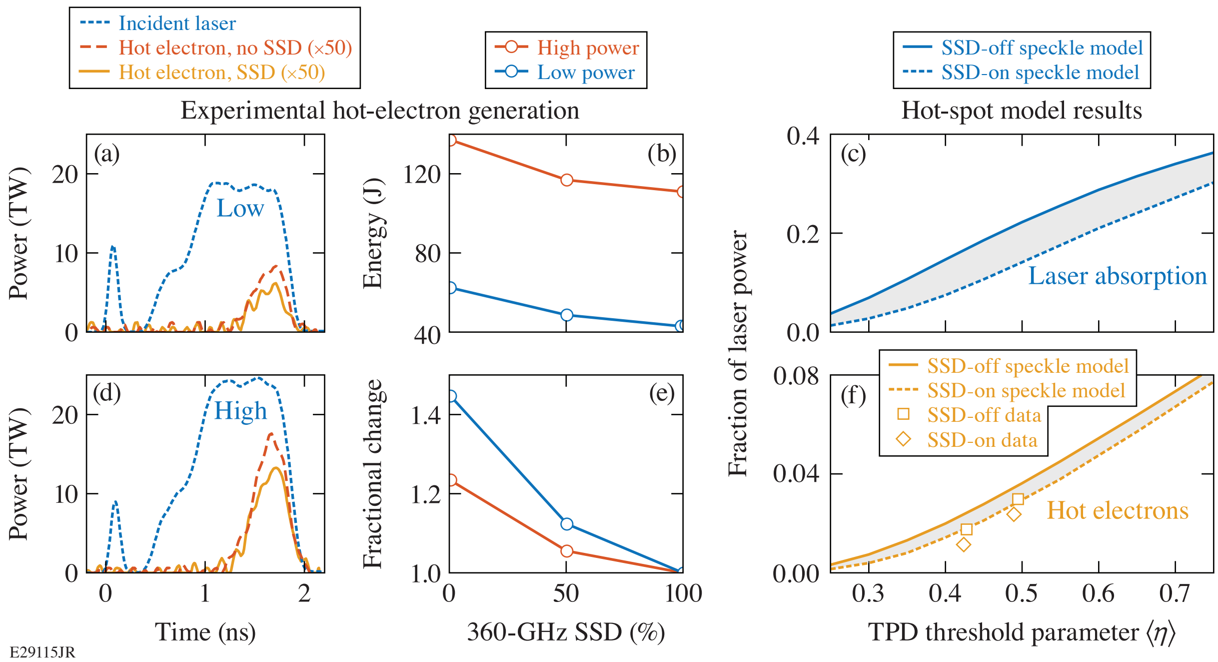

Figure 1
(a) For each pulse shape (high and low power), the SSD-off delivered laser pulse is shown alongside the hot-electron power for both the SSD-on and SSD-off cases. (b) The total energy in hot electrons for each shot is plotted as a function of the percentage of the current maximum SSD bandwidth. Reducing SSD increases the number of hot electrons. (c) The same hot-electron energies are shown normalized by their full-SSD companions, which shows that SSD has a relatively larger effect at low power. [(d),(e)] The hot-spot model. TPD activity, with (dashed) and without (solid) current OMEGA SSD, predicted as a function of average TPD threshold parameter, both in terms of (d) laser absorption, and (e) hot-electron generation. The data from the experiments (symbols) are in reasonably good agreement but all lie ≈20% below their respective curves.

It has long been recognized that in many situations laser–plasma instability growth is primarily determined by high-intensity speckles.[4] If intense speckles dominate instability growth, the speckle motion induced by spatiotemporal smoothing schemes can potentially mitigate instability growth. The lowest-order effect is the elimination of filamentation. Absent filamentation, it was found that speckle motion can reduce stimulated Brillouin scattering (SBS) directly if the laser coherence time is less than the time it takes the instability to reach steady state.[5–7] Stimulated Raman scattering (SRS), on the other hand, was thought to grow too quickly for speckle motion to provide direct mitigation. Like SRS, TPD produces electron plasma waves as primary daughter waves, so one might naively assume that TPD also grows too quickly for direct mitigation. It is important to recognize, however, that absolute instability plays a key role in OMEGA-scale TPD,[8] which implies that growth is unbounded until nonlinear saturation mechanisms set in. Since the strongest such mechanism is mode coupling to low-frequency ion-acoustic waves, saturation actually occurs on ion time scales more similar to SBS or filamentation, thereby facilitating direct mitigation by speckle motion.

Simulations with *LPSE* show that the speckles resulting from beam smoothing reduce the absolute TPD threshold by about a factor of 3 compared to the single-beam plane-wave[9] threshold $\eta = I_{14}L/(233T_e)$, where I_{14} is the intensity in units of 10^{14} W/cm^2, L is the scale length in μm, and T_e is the electron temperature in keV (all specified at the quarter-critical density). This is due to the fact that a significant fraction of the laser power is carried by speckles with a maximum intensity of more than 3× the average, and such speckles can therefore exceed the threshold locally. The region in parameter space in between the speckled-beam threshold and the plane-wave threshold (which is also where OMEGA experiments are situated) is exactly where spatiotemporal smoothing can have a big impact.

The *LPSE* simulations provided the following information to guide a hot-spot model: (1) the single-speckle TPD threshold is $\eta \approx 1.31$, where the speckle's peak intensity is used in the Simon threshold formula; (2) speckles in the range $1.31 < \eta < 2$ take ≈20 ps to reach saturation (much longer than the laser coherence time with SSD: ≈360 GHz^{-1} ≈ 3 ps) and are therefore likely to be stabilized by SSD, whereas speckles with $\eta > 2$ take less than 3 ps to reach saturation; (3) the scaling for laser absorption versus speckle intensity is $A = 0.66[(\eta - 1.31)/\eta]^{0.5}$; and (4) the scaling for hot-electron generation is $f_{\mathrm{hot}} = 0.07[(\eta - 1.31)^{0.09}$. Applied to a power-weighted speckle probability distribution derived from Garnier,[10] the scalings can be used to determine total TPD laser absorption and hot-electron generation, for any average laser intensity, with SSD on (integrating only the activity in speckles with $\eta > 2$) or off (integrating all activity in speckles with $\eta > 1.31$). The results are shown in Figs. 1(d) and 1(e).

The experimental data included in Fig. 1(e) show that the fraction of laser power into hot electrons is as high as 3% for the case of high intensity without SSD. Definitions are very important here, and these values were obtained by comparing the average hot-electron power over 200 ps of the maximum TPD activity shown in Figs. 1(a) and 1(c) to the average laser power reaching $n_{\mathrm{c}}/4$ according to the *LILAC* simulations over that same duration. The data lie below the speckle model by ≈20%. It is apparent, however, that the speckle model accurately reproduces the expected changes in TPD activity going both from low to high power, as well as from SSD on to SSD off. There are many possible explanations for the small remaining discrepancy, the most likely being the large systematic errors in quantifying the hot-electron activity (≈50%), as well as the fact that the hot-spot model is trained on 2-D rather than 3-D simulations.

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