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SCALING OF LASER-PLASMA INTERACTIONS WITH LASER WAVELENGTH AND PLASMA SIZE

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1. THE ROLE OF PLASMA SIZE IN WAVELENGTH SCALING EXPERIMENTS

Laboratory experiments on the wavelength scaling of laser-plasma interactions have thus far been restricted to relatively modest laser energies ($E_L < 200$ J), short pulse lengths ($\tau_L < 2$ nsec), and small focal spot diameters ($d \leq 200$ μ m). Thus the plasma sizes have been quite modest. Under those conditions, wavelength scaling data using Livermore's Argus laser show classical absorption physics and little evidence of instabilities, in good agreement with simple models and with computer hydrodynamics calculations. Absorption and preheat behave much more favorably at short laser wavelengths.

However, theory predicts¹ that experiments producing larger-size plasmas will begin to exceed gradient thresholds for various laser-plasma instabilities, if the laser intensity is sufficiently high. In the present paper we describe the conditions for this to occur, and we show preliminary evidence of the Raman and filamentation instabilities from experiments where the plasma size was deliberately made large. We show that these instability processes occur at laser wavelengths $\lambda_L = 0.53$ μ m and 0.35 μ m under some circumstances, indicating that short laser wavelength alone cannot prevent instabilities when the plasma size is large enough. Both size and wavelength must be taken into account, when predicting instability behavior.

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II. THRESHOLDS FOR INSTABILITIES

Fig. 1 illustrates this point more directly. The figure shows estimated thresholds for the major laser-plasma instabilities, as a function of both laser wavelength and plasma size. The vertical axis represents the gradient length L of the plasma divided by the laser's vacuum wavelength λ_L . The horizontal axis is the product of the incident laser intensity I_L and the square of the laser wavelength λ_L , in units of $10^{14} \text{ W-cm}^2/\text{cm}^2$. An instability is above threshold when the experimental parameters lie above the relevant threshold curve on the graph. In actual experiments, the local values of L and I_L are only known approximately, and the temperature T_e is not well established. Thus in practice the locations of experimental points on plots such as Fig. 1 are subject to rather large error bars.

The individual curves in Fig. 1 were obtained as follows:

(a) Convective Raman Scatter.

The density-gradient threshold is²

$$\frac{L}{\lambda_L} > \frac{1}{\pi} \left(\frac{c}{v_0} \right)^2, \quad (1)$$

where $v_0 \equiv eE_L/m_e\omega_L$ (E_L is the laser electric field, and ω_L is the laser frequency). The density gradient scale length is L . In the units of Fig. 1 this becomes

$$L/\lambda_L > 4.4 \times 10^3 (I_{14}\lambda_\mu^2)^{-1}, \quad (2)$$

where I_{14} is the laser intensity in units of 10^{14} W/cm^2 , and λ_μ is the laser wavelength in microns. To be in the convective regime, it is assumed that the electron density n_e is less than one-fourth of the critical density n_c , where $n_c = (1.1 \times 10^{21}/\lambda_\mu^2) \text{ cm}^{-3}$.

(b) Absolute Raman Scatter at $n_e = n_c/4$, and Raman Sidescatter.

The density gradient threshold is³

$$\frac{L}{\lambda_L} > \left(\frac{1}{2\pi} \right) \left(\frac{c}{v_0} \right)^{3/2}, \text{ or} \quad (3)$$

$$L/\lambda_L > 2.0 \times 10^2 (I_{14}\lambda_\mu^2)^{-3/4}. \quad (4)$$

Fig. 1. Threshold curves for various laser-plasma instabilities. Vertical axis is gradient scale length L , divided by vacuum laser wavelength λ_L . Horizontal axis is laser intensity I_L times square of laser wavelength λ_L , measured in units of $10^{14} \text{ W-}\mu\text{m}^2/\text{cm}^2$. Points labeled S represent parameters of recent Shiva laser experiments at $\lambda_L = 1.06 \mu\text{m}$. Points labelled A1, A2, A3 represent parameters of Argus laser experiment at wavelengths $1.06 \mu\text{m}$, $0.53 \mu\text{m}$, and $0.35 \mu\text{m}$ respectively. Derivation of threshold curves is described in text. Positions of experimental points are only approximate, because L , I_L , and T_e are not measured locally.

Note that there is a discrepancy of a factor of two for this threshold in the literature, due to differing definitions of v_0^2 .

(c) Stimulated Brillouin Scatter.

The threshold due to a velocity gradient length L is⁴

$$\frac{L}{\lambda_L} > \left(\frac{8}{\pi}\right) \left(\frac{\omega_L^2}{\omega_p^2}\right) \left(\frac{V}{c_s}\right) \left(\frac{v_t^2}{v_0^2}\right), \quad (5)$$

where $\omega_p^2 \equiv 4\pi n_e e^2/m_e$, V/c_s is the ratio of the expansion velocity to the sound speed, and $v_t^2 \equiv kT_e/m_e$.

To evaluate this expression, we use the typical parameters $n_e = n_0/4$, $V = c_s$. We obtain a phenomenological estimate of the electron temperature T_e by equating the absorbed laser intensity to the quantity $f n_e m_e v_t^2$,

with $f = 0.1$ and an average absorption fraction of 0.5. This yields

$$kT_e \cong 1.7 (I_{14} \lambda_\mu^2)^{2/3} \text{ keV}, \quad (6)$$

$$\frac{v_0^2}{v_t^2} \cong 2.4 \times 10^{-2} (I_{14} \lambda_\mu^2)^{1/3}. \quad (7)$$

Thus Eqn (5) becomes

$$L/\lambda_L > 4.3 \times 10^2 (I_{14} \lambda_\mu^2)^{-1/3}. \quad (8)$$

Note that Eqn. (6) overestimates the temperature at the highest values of $I_{14} \lambda_\mu^2$, where the actual absorption is less than 50% and other nonlinear effects become important.

(d) Two-Plasmon Decay Instability ("2 ω_p ").

The density gradient threshold is⁵

$$\frac{L}{\lambda_L} > \left(\frac{6}{\pi}\right) \left(\frac{v_t^2}{v_0^2}\right), \quad \text{or from Eqn. (7)} \quad (9)$$

$$L/\lambda_L > 81(I_{14}\lambda_\mu^2)^{-1/3}. \quad (10)$$

For the sake of simplicity we have neglected collisional damping of the decay plasma waves. In the experiments using $\lambda_L = 1/3 \mu\text{m}$, this damping is predicted to be significant for the parameters of the Argus laser.

(e) Filamentation due to Ponderomotive Force.

Here instead of a gradient threshold, we have a condition for the filament to grow exponentially by a significant factor.⁶ The size of this factor is somewhat arbitrary. Since the laser beams used for wavelength-scaling experiments have had clear, bright hot-spots in the incident beam pattern, one can argue that the initial hot-spot would only have to exponentiate twice to produce a large contrast-ratio inside the plasma. If we equate the plasma size to L , we obtain the threshold

$$\frac{L}{\lambda_L} > \left(\frac{8}{\pi}\right) \left(\frac{\omega_L^2}{\omega_p^2}\right) \left(\frac{v_t^2}{v_o^2}\right) \quad (11)$$

At an average electron density $n_e = n_c/4$, Eqns. (7) and (11) yield

$$L/\lambda_L > 2.2 \times 10^2 (I_{14}\lambda_\mu^2)^{-1/3} \quad (12)$$

For very short laser wavelengths or low laser intensities, one must take into account filamentation due to the Joule heating nonlinearity.⁷ This will be discussed separately in Section V.

We have also estimated the parameters for which inverse bremsstrahlung absorption will stabilize the instability processes (i.e., make their thresholds go to infinity). Such stabilization is indicated in Fig. 1 by the up-turn in the threshold curves in the upper left-hand corner of the Figure. It is calculated as follows.

We crudely hypothesize that an instability is turned off when the inverse bremsstrahlung absorption optical depth between $n_e = 0$ and $n_e = n_c/4$ is unity:

$$\int_{n_e=0}^{n_e=n_c/4} \kappa_{ib}(x) dx \geq 1, \quad (13a)$$

$$\kappa_{ib} = \left(\frac{3 \times 10^{-21} n_c Z \ln \Lambda}{(kT_e / 1 \text{ kev})^{3/2}} \right) \frac{(n_e / n_c)^2}{(1 - n_e / n_c)^{1/2}} \quad (13b)$$

We assume an exponential density profile $n_e/n_c = \exp(-x/L)$, an ionic charge $Z = 4$ and a Coulomb logarithm $\ln \Lambda = 6$. Using Eqn. 6 to find the temperature T_e , we estimate that the inverse bremsstrahlung optical depth from $n_e = 0$ to $n_e = n_c/4$ exceeds unity when

$$L/\lambda_L \geq 4.9 \times 10^4 (I_{14} \lambda_\mu^2) \lambda_\mu. \quad (14)$$

The stabilization shown in Fig. 1 was obtained by tilting the threshold curves upward toward a vertical direction at the point where Eqn. (14) intersects the relevant threshold lines, Eqns. (2), (4), (8), (10), and (12). This criterion depends on the laser wavelength λ_μ explicitly [due to the extra factor of λ_μ on the right side of Eqn. (14)]. The broadened vertical regions in the upper left-hand corner of Fig. 1 thus correspond to a range of wavelengths $\lambda_L = 1/3 \mu\text{m}$ to $\lambda_L = 2 \mu\text{m}$ in the inverse bremsstrahlung stabilization criterion (14).

By this time the reader will have correctly concluded that Fig. 1 gives at best a schematic feel for the threshold behavior, since many more or less arbitrary assumptions were used in order to plot all the thresholds on one graph. Thus this figure should not be regarded as a rigorous "last word" on instability thresholds, but rather as a suggestive picture. In particular, parameters of the experimental points are subject to considerable uncertainty, since neither L nor I_L is measured locally.

Nevertheless some interesting conclusions emerge when we plot on Fig. 1 the parameters for some recent experiments done on Livermore's Argus and Shiva lasers. The Argus points designated A1, A2, and A3, represent wavelength-scaling experiments using light of respectively 1, 2, and 3 times the fundamental laser frequency $\omega_L = 1.78 \times 10^{15} \text{ sec}^{-1}$. The gradient length L was taken equal to the minimum of the sound speed times the pulse length, and the focal spot diameter. One sees that the Argus points are either at or slightly below threshold for Brillouin scatter and ponderomotive filamentation, if one uses a large-scale average of the incident intensity to determine I_L (the horizontal axis of Fig. 1). The higher-intensity Argus points begin to exceed threshold for absolute Raman scatter, however only the three highest-intensity points exceed threshold by more than a factor of 2. As plotted on Fig. 1 most of the Argus points are a factor of 2-3 above threshold for the two-plasmon decay process. We must caution in the latter case that the local density gradient exactly at $n_e = n_c/4$ is very poorly known, and the $2\omega_{pe}$ instability threshold is sensitive to the value of this quantity. Thus it is

not surprising that nearly classical behavior was seen in these experiments. In Section III, we shall show evidence that a small amount of Raman scatter occurred for the A2 experimental point lying at $L/\lambda_L = 230$, $I_L \lambda_L^2 = 2.8$, and in Section V we shall discuss filamentation for the A3 points.

Fig. 1 also shows experimental points (S) obtained using the Shiva laser, at a wavelength $\lambda_L = 1.06 \mu\text{m}$. Parameters typical of three experiments are illustrated. The highest-intensity point, at $I_L \lambda_L^2 = 34$, $L/\lambda_L = 425$, is above threshold for all the instabilities. In Section IV, we shall show evidence that a population of very hot electrons was produced in this experiment, consistent with predictions from the Raman and two-plasmon decay instabilities. The two Shiva points at $I_L \lambda_L^2 = 1$ will be discussed in an accompanying paper by E. M. Campbell et al. (in the present volume).

The circular region in the upper left corner of Fig. 1 represents an estimate of the possible parameter space typical of directly driven reactor-scale targets. While the boundaries of this region are quite uncertain at present, it is clear that the parameter regime for reactor targets lies well above the thresholds for Brillouin scatter, two-plasmon decay, and ponderomotive filamentation, and may or may not exceed threshold for Raman scatter. The substantial gap between the part of parameter space assumed by the experimental points and that characterizing reactor targets emphasizes the need for further new experiments to address laser-plasma instabilities in the reactor range $L/\lambda_L \sim 10^4$, $I_L \lambda_L^2 \sim 10^{14} \text{ W-}\mu\text{m}^2/\text{cm}^2$.

III. RAMAN SCATTER IN AN ARGUS LASER EXPERIMENT, $\lambda_L = 0.53 \mu\text{m}$

In this and the following section, we show evidence for stimulated scattering instabilities in recent experiments on Livermore's Argus and Shiva lasers, for experimental parameters where L/λ_L and $I_L \lambda_L^2$ were respectively in the ranges 100-500 and $1-3 \times 10^{15} \text{ W-}\mu\text{m}^2/\text{cm}^2$. For these parameters one is approaching or exceeding the various threshold curves shown in Fig. 1.

The Argus experiment⁸ used a laser wavelength $\lambda_L = 0.53 \mu\text{m}$, a laser energy of 132 J, and intensity $I_L = 5 \times 10^{15} \text{ W/cm}^2$, and a spot diameter $d_S \approx 60 \mu\text{m}$ on a gold disc target. Thus $L/\lambda_L \approx 115$, and $I_L \lambda_L^2 \approx 1.4 \times 10^{15} \text{ W-}\mu\text{m}^2/\text{cm}^2$, assuming that in Eqns. 1-4 it is appropriate to estimate the overall gradient length L by the spot diameter d_S . These

Fig. 2. Streak camera record⁸ of Raman-scattered light from a gold disc target, irradiated with 132 J on the Argus laser, $\lambda_L = 0.53 \mu\text{m}$. The incident intensity was $5 \times 10^{15} \text{ W/cm}^2$, and the pulse length was 900 psec.

a) Wavelength-vs.-time history (light at $\lambda_L = 1.06 \mu\text{m}$ is a timing fiducial).

b) Time history of total power in Raman light, integrated over wavelength. Raman emission occurs after the peak of the laser pulse ($t = 0$).

parameters on Fig. 1 suggest that the experiment was somewhat above threshold for the two-plasmon and absolute Raman instabilities, slightly below threshold for Brillouin and filamentation, and well below threshold for convective Raman scatter.

A clear signature of Raman-scattered light was observed⁸, but the scattering was at a very low level. Fig. 2, from Ref. 8, shows the spectral and temporal history of the Raman scattered light. Fig. (2a) shows a streak-camera record of the time-evolution of the frequency spectrum. (The narrow emission at $1.06 \mu\text{m}$ is a $\lambda_L = 1.06 \mu\text{m}$ timing fiducial.) Fig. (2b) shows an integration of this spectrum over all frequencies, yielding the temporal history of the total Raman emission. Zero time is defined as the peak of the laser pulse, which had a width of about 900 psec FWHM.

One sees that the Raman scatter begins only after the peak of the laser pulse. This is consistent with the requirement that a large underdense plasma have time to establish itself, in order to achieve a high value of L/λ_L . After a time +400 psec the intensity of the incident laser beam is beginning to decrease substantially, so that $I_L \lambda_L^2$ is no longer large enough to approach instability threshold. Hence the Raman scatter decreases in amplitude. It is interesting to note that for $t > +300$ psec the Raman light decreases much more slowly than the laser intensity falls off. As a result, the fraction of I_L that is Raman scattered increases with time, late in the laser pulse. The total energy in Raman-scattered light was estimated to be 0.05J, or only 0.04% of the incident laser energy. This is consistent with the prediction of Fig. 1 that the instability was not far above threshold in this experiment.

The broadband spectrum and spikey temporal structure are notable features of the spectrum in Fig. 2a. They would seem to imply that the Raman scattering occurs at a variety of different places in the plasma density profile. The strong temporal modulations spanning a broad wavelength range may perhaps be explained by the appearance and disappearance of laser beam hotspots or by a strong temporal relaxation cycle inherent in the scattering itself.⁹

IV. EVIDENCE FOR STRONG INSTABILITIES IN A SHIVA LASER EXPERIMENT, $\lambda_L = 1.06 \mu\text{m}$.

In this experiment an effort was made to attain conditions exceeding most of the instability thresholds in Fig. 1. A thin CH

foil was irradiated by the Shiva laser in a $400\text{ }\mu\text{m}$ diameter focal spot. The laser intensity ($I_L = 2 \times 10^{15}\text{ W/cm}^2$) and pulse length ($\tau_L = 1\text{ nsec}$) were chosen so that the $6900\text{ }\text{\AA}$ -thick foil would burn through and become underdense to the $\lambda_L = 1.06\text{ }\mu\text{m}$ laser light sometime near the peak of the laser pulse. Fig. 3 illustrates the target and focusing scheme.

Although the plasma density was not measured directly, computer hydrodynamics calculations by K. Estabrook using Livermore's target-design code LASNEX¹⁰ indicate that at the peak of the laser pulse there was a region of plasma $400\text{--}500\text{ }\mu\text{m}$ long, at a nearly constant density of $1/10 - 1/5$ times the critical density n_C . These parameters give $L/\lambda_L \cong 425$, $I_L \lambda_L^2 \cong 35$, so that on Fig. 1 all thresholds are exceeded.

Harmonic and sub-harmonic emission were monitored on this experiment.¹¹ The Raman scattered light energy was large, representing about 10% of the incident laser energy. In addition a

Fig. 3 Schematic of set-up for thin-foil experiment on Shiva laser, $\lambda_L = 1.06\text{ }\mu\text{m}$.

larger signal than usual was detected near $3\omega_L/2$ (about 4×10^{-4} of the laser energy). The temporal structure of the $3\omega_L/2$ light¹¹ was very similar to that of the hard x-rays observed simultaneously.

We have evidence from the hard x-ray spectrum that a population of very hot electrons was created during this experiment. Fig. 4 shows the x-ray spectrum in the 10-350 keV region. These x-rays are produced when hot electrons, which have been heated in the irradiated region of the CH foil, encounter the surrounding gold washer and emit bremsstrahlung radiation there. (The high-Z washer was added to enhance the bremsstrahlung emissivity. Without it, emission in the thin CH foil alone would have been difficult to measure in our detectors.) Rough estimates from the slope of the x-ray spectrum suggest a hot-electron temperature $T_h \sim 40$ keV, whereas one might have expected a temperature only 1/4-1/5 this value from the resonance absorption process alone.

Fig. 4 Hard x-ray spectrum from thin-foil experiment on Shiva laser showing high (~ 40 keV) hot-electron temperature. Error bars represent experimental data; lower two lines represent hydrodynamics simulations using the computer code LASNEX. The gold ring (actually a gold washer) surrounding the CH foil enhances the bremsstrahlung x-ray emission rate.

The most probable source of the hot electrons is either stimulated Raman scatter or the two-plasmon decay instability. Both are capable of yielding hot-electron temperatures in the 40 keV range, for the laser parameters in question. For example in Fig. 4, we show the hard x-ray spectrum calculated by K. Estabrook using his Raman-scatter model in LASNEX.¹² The spectral slope (i.e., the inferred hot-electron temperature) is similar to that measured experimentally and is much higher than that calculated from resonance absorption alone. The absolute magnitude of the calculated x-ray fluence does not correspond with the experimental value because most of the x-ray emission comes from the gold washer, which was not included in this LASNEX calculation.

More detailed understanding of this type of experiment will require a measurement of the density-profile evolution, to distinguish instabilities occurring at $n_e = n_c/4$ ($2\omega_p$ and absolute Raman scatter) from those occurring at lower electron densities. Additional modeling of hot-electron transport from the CH foil to the gold washer is necessary in order to interpret the absolute level of the hard x-ray fluence in terms of the energy in hot electrons.

V. FILAMENTATION IN ARGUS LASER EXPERIMENTS AT $\lambda_L = 0.35 \mu\text{m}$.

Thus far we have discussed evidence for stimulated scattering processes, in experiments where L/λ_L is high enough to approach or exceed gradient thresholds for instability. In the present section we describe data from a series of experiments using the Argus laser at $\lambda_L = 0.35 \mu\text{m}$. The data show frequent, intense hot-spots in images of the backreflected light, as well as a hot-electron temperature that is higher than the prediction from resonance absorption alone. We discuss possible interpretations of these data.

Fig. 5 shows images of the incident laser beam and the backreflected light pattern from 5a) a Be disc target, and 5b) an Au disc target, irradiated by $\lambda_L = 0.35 \mu\text{m}$ light. In both cases the backreflected light appears as an array of intense hot-spots, each having a diameter of 10-20 μm (above the resolution limit of the collecting optics). The contrast ratio of these hotspots is considerably larger than the contrast ratio of hotspots on the incident laser beam.

We have many other examples where there are hotspots in the backreflected light image; it is quite a common feature at $\lambda_L = 0.35 \mu\text{m}$. For high-Z targets, ring structures on the incident beam are frequently backreflected as a sequence of spots formed into the same ring pattern. (One is reminded of the paintings of Seurat and

Fig. 5 Images of the incident and backreflected light from Argus laser, $\lambda_L = 0.35 \mu\text{m}$. a) A laser shot using a Be disc target, laser energy $E_L = 30 \text{ J}$, $I_L \approx 10^{14} \text{ W/cm}^2$, $\tau_L \approx 600 \text{ psec}$. b) A shot using an Au disc target, $E_L = 20 \text{ J}$, $I_L \approx 10^{14} \text{ W/cm}^2$, $\tau_L \approx 600 \text{ psec}$. Both shots show hot-spot structure on backreflected image.

the French Impressionist school.) For some of these high-Z targets, hot-spots are clearly seen in x-ray microscope images of these irradiations.

Fig. 6 shows the hard x-ray spectra measured in $\lambda_L = 0.35$ μm and 1.06 μm laser irradiations under similar conditions: $I_L = 4-8 \times 10^{14}$ W/cm^2 , laser energy 35-45 joules, focal spot diameters 90-120 μm , laser pulse lengths 600-700 psec, on gold disc targets. Two features are notable. 1) The x-ray fluence above 20 keV is a factor of 10-20 lower for $\lambda_L = 0.35$ μm , and represents $< 10^{-3}$ of the absorbed laser energy in a hot-electron population. 2) The slope of the hard x-rays is nearly the same for the two laser wavelengths, implying a hot-electron temperature $T_h \sim 10$ keV in both cases. Predictions of the hot-electron temperature based on the resonance absorption mechanism at the beam-averaged laser intensity would have yielded a temperature 4-5 times lower than this, for the $\lambda_L = 0.35$ μm case.

Fig. 6 Hard x-ray spectra from similar Argus laser irradiations of gold disc targets at $\lambda_L = 1.06$ μm (---) and 0.35 μm (—). Error bars represent reproducibility over 4-5 shots at each wavelength. Experimental parameters were: $I_L = 4-8 \times 10^{14}$ W/cm^2 , $E_L = 35-45$ J, focal spot diameters 90-120 μm . The $\lambda_L = 0.35$ μm spectrum implies an energy in hot electrons $< 10^{-3}$ of the absorbed laser energy, but a high hot-electron temperature $T_h \cong 10$ keV.

How can we understand the hotspots and the large hot-electron temperature at $\lambda_L = 0.35 \mu\text{m}$? Referring to Fig. 1, we see that all the A3 points lie slightly below threshold for ponderomotive filamentation and Brillouin scatter, the two highest intensity A3 points are marginal for absolute Raman scatter, and all but the lowest-intensity A3 point are a factor of 2-3 above threshold for two-plasmon decay.

However this is not the whole story because until now we have neglected the effect of thermal filamentation and of fine-scale structure on the incident laser beam. We discuss these in turn.

A. Thermal Filamentation

Recent work by the group at the Naval Research Laboratory^{13,7} has re-emphasized the possible role of self-focusing or filamentation driven by the Joule-heating nonlinearity. Although this instability can be absolute under some circumstances¹⁴, here we refer to the results for convective growth.⁷ The maximum spatial growth rate occurs for large transverse wavelengths, when thermal transport is assumed classical:

$$\alpha_{\text{max}} (\text{cm}^{-1}) = \frac{n_e/n_c}{(1-n_e/n_c)^{3/4}} \left(\frac{\nu_{ei} I_L}{2\kappa k T_e (1 + 1/Z)} \right)^{1/2} \quad (15)$$

where κ is the classical thermal conductivity¹⁵ and ν_{ei} is the electron-ion collision frequency. In the units of Fig. 1, this becomes

$$\alpha_{\text{max}} = 4.2 \left(\frac{Z \ln \Lambda}{\sqrt{\phi(Z)(1+1/Z)}} \right) \left(\frac{n_e/n_c}{\sqrt{1-n_e/n_c}} \right)^{3/2} \left(\frac{(I_{14} \lambda_\mu^2)^{1/2}}{\lambda_\mu^2 (kT_e/1 \text{ keV})^{5/2}} \right)^{1/2} \quad (16)$$

Here $\phi(Z) \equiv (Z + 0.24)/(1 + 0.24Z)$.

If we once again assume $n_e = n_c/4$ and $\ln \Lambda = 6$ and evaluate the temperature from Eqn. (6), we obtain

$$\alpha_{\text{max}} (\text{cm}^{-1}) = \begin{cases} 2.4 \lambda_\mu^{-2} (I_{14} \lambda_\mu^2)^{-7/6}, & Z = 4 \\ 15.2 \lambda_\mu^{-2} (I_{14} \lambda_\mu^2)^{-7/6}, & Z = 30. \end{cases} \quad (17)$$

A rough idea of the threshold can be obtained from requiring $L_{\alpha\text{max}} > 2$, or

$$L/\lambda_L > 8.3 \times 10^3 \lambda_\mu (I_{14} \lambda_\mu^2)^{7/6}, Z = 4 \quad (18a)$$

$$L/\lambda_L > 1.3 \times 10^2 \lambda_\mu (I_{14} \lambda_\mu^2)^{7/6}, Z = 30. \quad (18b)$$

Fig. 7 plots these threshold curves in a fashion analogous to Fig. 1, for $\lambda_L = 1/3 \mu\text{m}$ and $1/2 \mu\text{m}$. For comparison we show the threshold for ponderomotive filamentation. (At any point in parameter space, the lower of the two thresholds is the most relevant. This is because in reality there is a continuous transition between the two forms of filamentation.⁷) One sees that thermal filamentation is dominant at low values of $I_L \lambda_L^2$, and for high-Z targets.

Fig. 7 Threshold curves for thermal and ponderomotive filamentation. Axes and parameters are same as in Fig. 1. Points represent Argus and Shiva experiments.

When we examine the parameters typical of the Argus wavelength-scaling series, we see that with low-Z targets, the two lowest-intensity A3 points are above threshold for thermal filamentation. For high-Z targets, three A3 points and three A2 points are above threshold. There are no Argus experimental points above threshold for ponderomotive filamentation, although two A2 points are quite close.

While only a subset of the experimental parameters is predicted to show thermal filamentation, in fact hotspots in the backreflected light were also seen for the A3 point on Fig. 7 which was predicted to be below threshold for both types of filamentation. We suggest that this phenomenon is related to the presence of large inhomogeneities on the incident $\lambda_L = 0.35 \mu\text{m}$ laser beam, as discussed in the following section.

B. Role of Inhomogeneities on the Incident Laser Beam.

The Argus beam at $\lambda_L = 0.35 \mu\text{m}$ was not uniform in its intensity structure. Fig. 8 shows a comparison of the "intensity distribution function" for typical $\lambda_L = 0.35 \mu\text{m}$, $0.53 \mu\text{m}$, and $1.06 \mu\text{m}$ laser beams. The vertical axis represents the fraction of total beam energy having an intensity $< I_L$, while the horizontal axis is the local intensity I_L . If we define a beam-averaged intensity $\langle I_L \rangle$ as the total laser power divided by the focal spot area, the beams at all three wavelengths had the same average intensity $\langle I_L \rangle = 3 \times 10^{14} \text{ W/cm}^2$, and a spot size of about $140 \mu\text{m}$.

One can see from Fig. 8 that 92% of the energy in the $\lambda_L = 1.06 \mu\text{m}$ beam was at a local intensity less than $6 \times 10^{14} \text{ W/cm}^2$, whereas only about 73% of the energy at $\lambda_L = 0.35 \mu\text{m}$ was below this local intensity. Stated differently, 27% of the $\lambda_L = 0.35 \mu\text{m}$ beam energy had a local intensity more than twice $\langle I_L \rangle$, and fully 12% of the beam energy had a local intensity more than three times $\langle I_L \rangle$.

The effect of these localized high-intensity regions at $\lambda_L = 0.35 \mu\text{m}$ can be discerned from Figs. 1 and 7. The threshold for ponderomotive filamentation decreases when intensity increases. Thus several of the A3 points which were below threshold when the intensity used on the horizontal axis was taken to be $\langle I_L \rangle$ are in fact at or above threshold for the $\sim 10\%$ of the beam which is at a local intensity of 3-4 times $\langle I_L \rangle$. We would therefore expect about 10% of the beam energy to form localized filaments driven by the ponderomotive force, for $\langle I_L \rangle \geq 3 \times 10^{14} \text{ W/cm}^2$.

Fig. 8 Intensity distribution functions for incident Argus laser beams at wavelengths $\lambda_L = 1.06, 0.53$, and $0.35 \mu\text{m}$. Each of the incident beams had a beam-averaged intensity $\langle I_L \rangle = 3 \times 10^{14} \text{ W/cm}^2$. The $\lambda_L = 0.35 \mu\text{m}$ beam has a larger fraction of its energy at high values of the local intensity I_L .

At low laser intensity ($\langle I_L \rangle \sim 3 \times 10^{13} \text{ W/cm}^2$) the $\lambda_L = 0.35 \mu\text{m}$ beam is smoother, but here the thermal filamentation mechanism can operate. Thus one expects to see evidence of filamentary structures for a wide range of average beam intensities.

This phenomenon suggests two possible mechanisms to explain the high hot-electron temperature seen at $\lambda_L = 0.35 \mu\text{m}$ in Fig. 6: 1) The laser light could undergo two-plasmon decay or absolute Raman scatter, perhaps enhanced by the presence of the filaments¹⁶, and thereby accelerate a small high-energy tail of the electron population. 2) If the filament continues to intensify all the way up to the critical surface, the intense light at the center of the filament could undergo resonance absorption there, resulting in a larger value of T_{hot} than one would have predicted from $\langle I_L \rangle$ alone. The group at the University of

Rochester has suggested that an experimental test of the latter alternative would consist of measuring the hot-electron temperature as one varied the angle of incidence of the laser beam, since the second mechanism should fail when the filament no longer encounters the critical surface.

VI. SUMMARY

Plasma size is an important parameter in wavelength-scaling experiments because it determines both the threshold and potential gain for a variety of laser-plasma instabilities. Most experiments to date have of necessity produced relatively small plasmas, due to laser energy and pulse-length limitations. Fig. 1 illustrates graphically that a concerted effort is needed to field experiments with larger plasmas, so as to begin approaching the parameters typical of reactor-scale targets.

We have discussed in detail three recent Livermore experiments which had large enough plasmas that some instability thresholds were exceeded or approached. Our evidence for Raman scatter, filamentation, and the two-plasmon decay instability needs to be confirmed in experiments which measure several instability signatures simultaneously, and which produce more quantitative information about the local density and temperature profiles than we have today. Work in these directions is now being planned and begun at several different laboratories.

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