EVIDENCE FOR PERIODIC BREAKUP OF A RADially MODULATED
0.35 µm LASER BEAM DUE TO THERMAL SELF-FOCUSING IN A PLASMA

Electrical Engineering Department, University of California, Los Angeles, CA 90024, USA

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Azimuthal periodic breakup of a radially modulated 0.35 µm laser beam has been inferred in plasmas produced from solid targets. The breakup is more severe in gold plasmas compared to glass or aluminum plasmas and occurs at rather modest laser intensities of ~ 5 × 10^12 W/cm^2. Thermal filamentation is suggested as the mechanism for the observed beam breakup.

1. Introduction

Laser beam self-focusing and breakup into filaments are readily observed phenomena in non-linear optics [1]. Unfortunately, unambiguous demonstration of these effects has been somewhat illusive in laser-plasma interaction. In particular, although perturbation analysis predicts a periodic breakup of optical beams due to filamentation in a plasma, when plasma emission is analyzed one often observes a complex and unpredictable distribution of hot spots [2]. For modest laser intensities, there are two mechanisms that can lead to whole beam or small-scale self-focusing: ponderomotive and thermal [3].

In a weakly collisional plasma, ponderomotive beam breakup can be understood by considering a beam that is non-uniform in the transverse direction. If such a laser beam is incident on the plasma, then the ponderomotive force

\[ F_p = -\left(\omega_p/\omega_0\right)^2 \nabla \langle E^2 \rangle / 8\pi \]  

exists which pushes the plasma electrons out of the region of highest laser intensity causing locally a density depression in the electron density \( n_e \). As ions follow the electrons, the refractive index \( n \) is raised in the region since \( n = (1 - \omega_p^2/\omega_0^2)^{1/2} \) and the phase velocity of the light is slowed down causing the light wave to be focused in this region and increasing the irradiance as the beam propagates.

Thermal self-focusing, on the other hand, is caused by localized heating due to collisional absorption of a non-uniform laser beam. Since the thermal pressure \( (n_e kT_e) \) of the plasma that is locally heated where the intensity is higher, is greater than its surroundings, it induces faster hydrodynamic expansion in order to achieve a pressure balance. The plasma density in the locally heated regions thus decreases leading to an increase in the refractive index. This in turn concentrates the laser in these regions which further exacerbates the heating.

Filamentation and whole-beam self-focusing may have detrimental effects on laser fusion because the increased intensity in a filament may exceed the threshold intensities for other instabilities, such as stimulated Raman scattering and the two-plasmon decay, which produce energetic electrons that can cause preheating of the fuel [4]. In addition, especially at shorter wavelengths, illumination nonuniformities due to filamentation may produce nonuniformities in the ablation pressure. Thus, the understanding of self-focusing and filamentation is crucial to their control for the success of direct-drive short wavelength laser fusion.

In this paper we present evidence for thermal filamentation of 0.35 µm laser light near its critical density layer in a plasma. At a modest laser intensity of \( \approx 5 \times 10^{12} \) W/cm^2, strong periodic beam breakup in the radial and azimuthal directions \( (r, \theta) \) is inferred from X-ray images of the plasma when planar gold targets are irradiated with a laser beam which has an intensity variation in \( r \) superimposed on it. This azimuthal symmetry is what we might expect...
from theory since any instability on a radially symmetric intensity pattern (ring) can be Fourier analyzed in angle.

2. Experimental conditions

The experiments described in this paper were carried out on the GDL laser facility at the Laboratory for Laser Energetics of the University of Rochester [4]. 0.35 μm laser pulses containing between 50–55 J of energy were focused to a spot size of ~1.5 mm. The laser pulse duration (fwhm) was approximately 700 ps and this gave an average irradiance of ~5 × 10¹² W/cm². In order to give a greater than 1 mm spot size the laser beam was focused in front of the flat targets using an f/3.6 lens (i.e., rays diverging at the target). The targets were tilted at 22° w.r.t. the laser beam. The X-ray emission from the targets was diagnosed using a ~20 μm resolution pinhole camera, a 30 ps resolution X-ray streak camera and a 25 μm resolution, space-resolving, KAP crystal spectrograph. A 6 μm Be filter was used on the pinhole camera whereas a 30 μm Be filter was used in front of the X-ray streak camera and the crystal spectrograph. Both line and continuum emission in the wavelength range 10–6 Å were spatially resolved by the crystal spectrograph which viewed the target in a direction parallel to its surface. This was done to measure the thickness of the X-ray emitting region.

A novel aspect of these experiments is that when the spot size is this large, the laser beam is essentially in the near field. We used this fact to superimpose a radial intensity variation on the beam by using a lens which has a damaged area 2.5 cm in diameter at the beam center. This reduces the average intensity at the target plane to ~3–4 × 10¹² W/cm². The diffraction pattern resulting from this circular damage spot leads to a ring pattern at the target with a kₘ = 465 cm⁻¹. Since the diffraction pattern is θ independent we expect an individual diffraction ring to breakup into spots having regular spacing and azimuthal symmetry. As we shall see later strong self-focusing was observed when gold targets were used but not when SiO₂ or Al targets (control) were used. We used plane SiO₂, Al and 2000° Au on SiO₂ targets.

3. Results

Before we present the evidence for what we believe to be thermal filamentation, we briefly discuss the plasma parameters which will be necessary to interpret the filamentation data later on. The important parameters which influence both thermal and ponderomotive self-focusing are: plasma temperature, scalelength, average density at which self-focusing occurs and the average ionization state of the plasma.

3.1. Plasma temperature, Tₑ

Plasma temperature was estimated for the SiO₂ targets from the slope of the X-ray continuum spectrum between 1.2 keV and 2 keV to be 200 eV at an average laser intensity of 5 × 10¹² W/cm². The spectrum showed in addition to free-free and free-bound continuum line radiation from He-like (strong) and H-like (weak) Si lines. We obtained similar spectra from Al targets. Although we do not have a direct measure of temperature of the Au plasma we expect from previous hydro-simulation work by others [5] that a gold plasma with Tₑ ~ 100 eV at I ~ 5 × 10¹² W/cm² is probably produced. The reason why a gold plasma is expected to be cooler than a SiO₂ or an Al plasma for comparable laser intensity is that a significant amount of energy is lost to radiation in the former.

3.2. Plasma scalelength, L

The relevant scalelength for calculating the thresholds for ponderomotive and thermal self-focusing is the smaller of the two: density scalelength and absorption length. There are two ways of estimating the plasma density scalelength. First the space-resolving X-ray crystal spectrograph showed that the width of the continuum emission was about 50 μm on a SiO₂ target. If on the other hand we assume that the plasma scalelength is given by $L \sim cₜ \tau$ where $cₜ \sim [(Zₑ + Tₑ)/M]^{1/2}$ is the ion sound speed and τ is the duration of the X-ray emission, ~0.7 ns, as recorded by the X-ray streak camera, then we obtain for SiO₂, Al, and Au, L ~ 70, 70 and 25 μm, respectively if we assume that $Z_{SiO₂} \sim 9$, $Z_{Al} \sim 12$, $Z_{Au} \sim 20$, and $Tₑ \sim T_t$. A more relevant parameter which influences the self-
focusing is the absorption length $L_{ab}$. If the absorption length is much smaller than the plasma density scale-length we might expect stabilization of the filamentation process by collisional absorption. The intensity threshold for self-focusing is effectively increased for both ponderomotive and thermal self-focusing. We calculate $L_{ab}$ using the following expression which assumes absorption by inverse bremsstrahlung:

$$\frac{1}{L_{ab} (\mu m)} \sim 1.65 \times 10^{-3} \left[ Z/T(keV)^{3/2} \right]$$

$$\times \left( \frac{n_0}{n_c} \right)^2 \left( 1 - \frac{n_0}{n_c} \right)^{1/2}.$$ (2)

These are listed in table 1 for various plasma parameters. In our experiments $L_{ab}$ is much smaller than the density scalelength $L$. So we use $L_{ab}$ for computing the threshold intensities in section 4.

3.3. Plasma density, $n_0$

Since the region of X-ray emission is confined very close to the target surface, which is roughly equal to or less than the plasma density scalelength, we may assume that the X-ray emission in all three cases basically comes from a plasma layer close to the critical density. So we use $n_0 \sim 0.9 n_c$ for our calculations.

3.4. Average ionization state, $Z$

The X-ray spectra of Al and SiO$_2$ contain strong line emission from He-like and weaker line emission from H-like Al and Si ions, respectively. So we assume the average $Z$ for these to be roughly 12 and 9, respectively. With gold targets we have no direct evidence for the ionization state of the plasma, so we extrapolate the previously published simulation results [5] which gave $Z_{Au} \sim 25 - 30$ at $I \sim 4 \times 10^{13}$ W/cm$^2$. Thus we assume $Z_{Au} \sim 20$.

3.5. Evidence for filamentation

Fig. 1 shows the X-ray pinhole photographs of the plasmas obtained from Al, SiO$_2$ and Au targets. There are several features of these images that are worth noting. First and most obvious feature, common to all three images, is that there is a hole in the center. Recall that the center 2.5 cm dia. portion of the beam is essentially scattered out of the main beam because of the damage at the lens center. The second feature, also common to all three images, is that the images are weaker in the top left hand corner. This is due to misalignment of the laser beam through the 1 $\mu$m amplifier chain. Consequently, even the frequency tripled light shows a similar signature of beam non-uniformity. The third common feature is the presence of certain hot spots in the beam. One in particular at roughly 2 o'clock shows an intensity enhancement on axis and intensity depletion around it. This effect is particularly noticeable in the Au target plasma.

The most dramatic aspect of these images is the one that is not common. We clearly see that the Al image shows no particular periodic intensity variation whereas it is already beginning to manifest itself

<table>
<thead>
<tr>
<th>Plasma parameter</th>
<th>Ponderomotive filamentation</th>
<th>Thermal filamentation</th>
<th>Absorption length $L_{ab} (\mu m)$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Collisional threshold $I_e$ (W/cm$^2$)</td>
<td>Growth rate $k_{th}$ (cm$^{-1}$)</td>
<td>Most unstable mode $k_{th}$ (cm$^{-1}$)</td>
</tr>
<tr>
<td>$n_0 = 0.9 n_c$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$Z = 9, T_e = 200$ eV SiO$_2$</td>
<td>$1.3 \times 10^{13}$</td>
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<td>2700</td>
</tr>
<tr>
<td>$Z = 12, T_e = 200$ eV Al</td>
<td>$1.7 \times 10^{13}$</td>
<td>60</td>
<td>2700</td>
</tr>
<tr>
<td>$Z = 20, T_e = 100$ eV Au</td>
<td>$4.0 \times 10^{13}$</td>
<td>120</td>
<td>3800</td>
</tr>
</tbody>
</table>
Fig. 1. X-ray pinhole photographs of gold, aluminum and SiO_2 targets at 0.35 μm laser intensity of ~5 × 10^{12} W/cm^2. Spatial resolution is ≈20 μm.

on the SiO_2 target. On the latter we see both the enhancement of the ring structure and the break up of rings in the azimuthal direction into dots. The effect is obvious on the Au target. Here we now observe radial intensity enhancement with \( k_r = 465 \text{ cm}^{-1} \) as well as a periodic breakup of the rings into smaller circular beamlets with \( k_\theta \approx 480 \text{ cm}^{-1} \).

The beamlets have varying diameters with the smallest beamlets having a spotsize of 45 μm to largest beamlets having a spotsize of 75 μm. Basically, the beamlet diameter is the same as the width of the ring. The periodicity in the \( \theta \) direction becomes apparent because the beam has a cylindrical symmetry and the beam intensity is constant (in an average sense) on at least a fraction of the ring circumference. We believe that this periodic beam breakup in the \( \theta \) direction as well as intensity enhancement of the rings in the \( r \) direction is evidence of regular filamentary breakup of the beam. Similar azimuthal breakup of an annular 0.35 μm laser beam has been previously observed by Willi and Lee [6]. However, their experiments were carried out at laser intensities in the mid 10^{13} W/cm^2 range where both thermal and ponderomotive filamentation were thought to be occurring. The present work is carried out at laser intensities equal to or less than 5×10^{12} W/cm^2 thereby making ponderomotive filamentation less likely than thermal filamentation. We shall now argue that the breakup observed in these experiments is consistent with thermal filamentation rather than ponderomotive filamentation.

4. Discussion

We shall analyze the data presented in fig. 1 using the plasma parameters given in the preceding section. We first compare the relative growth rates and threshold intensities for ponderomotive and thermal self-focusing assuming quasi-steady state conditions. We also assume that the plasma parameters vary slowly in distances comparable to filamentation growth length and that the perturbation theory is valid.

Since collisional absorption is extremely important especially near \( \omega_p \approx \omega_0 \) and in relatively cool plasmas, we compare the collisional thresholds for the two processes assuming that the perturbation exponentiates at least once, as given by Kruer [7]. These are obtained by assuming that \( 2k_iL_{ab} \approx 1 \) where \( L_{ab} \) is the collisional absorption length. This leads to

\[
I_{pc} = \frac{3 \times 10^{12}}{Z} \frac{Z}{(\text{keV})^{1/2}} \frac{n_0}{n_c},
\]

\[
I_{tc} = 6 \times 10^{13} \frac{n_0}{n_c} \frac{T(\text{keV})^2}{\lambda^2}.
\]

We also compare the transverse \( k_\perp \) and longitudinal \( k_\parallel \) wavenumbers of the most unstable perturbations.
Again we use the results given by Kruer [7]. Thus for ponderomotive self-focusing

\[ k_{1, p} = \frac{1}{2} \left( \frac{\omega_p}{v_e} \right) \frac{\omega_p}{c}, \quad (5) \]

\[ k_{2, p} = \frac{1}{2} \left( \frac{\omega_p}{v_e} \right)^2 \frac{\omega_p^2}{k_0 c^2}, \quad (6) \]

and for thermal self-focussing we obtain

\[ k_{1, t} \ll \left( \frac{\omega_p}{3.6c} \frac{v_o}{\lambda_{ei}} \right)^{1/2}, \quad (7) \]

\[ k_{2, t} \approx \frac{\omega_p}{7.5k_0c} \left( \frac{v_o}{v_e} \right) \frac{1}{\lambda_{ei}}. \quad (8) \]

Here we note that the maximum spatial gain coefficient for thermal self-focusing exceeds that for ponderomotive filamentation when \( v_o/v_e > \omega_p/c \) which is clearly the case in these experiments. All the symbols in eqs. (3) through (8) are as defined in ref. [7]. Thus we expect thermal filamentation to be important in this parameter regime. We use these expressions to tabulate the parameters \( L_{ab}, \ I_{ec}, \ I_{pc}, \) and \( k_{1, p}, \ k_{2, p}, \ k_{1, t}, \) and \( k_{2, t} \) for our plasma parameters. These are shown in table 1.

It is immediately clear from table 1 that the average incident laser intensity of \( 5 \times 10^{12} \) W/cm² is close to the collisional threshold for thermal filamentation, but far below the threshold for ponderomotive filamentation. It is also evident that the growth rate for thermal filamentation is larger than that for ponderomotive filamentation. Here we note that a factor of 2 uncertainty in \( L_{ab}, \ T_e, \) or \( n_0 \) (as long as \( n_0 < n_e \)) will not change this basic conclusion. We think that the plasma parameters are known to a greater accuracy than this as discussed in section 3. The reason why the X-ray emission from the filamentary structures is more enhanced in a gold plasma is because the growth rate is much higher in gold than in Al or SiO₂ because of the assumption of lower temperature of 100 eV.

One experimental observable is the periodicity of the filaments. In our experiments the beam is seen to breakup with periodicity in the \( \theta \) direction which we equate to \( k_{1, \perp} \) since the intensity is roughly constant on at least a section of the ring. Thus \( k_{1, \perp} = k_0 \leq 480 \) cm⁻¹. This is certainly much smaller than the value we obtain from eq. (6) as seen from table 1. A closer examination of the self focusing pattern in gold and the weaker pattern in SiO₂ in fact shows that the azimuthal breakup has the same orientation in either case. Ideally, we expect this orientation to be random from one laser pulse to the next for an instability truly growing from plasma noise. We believe that other Fourier modes (hot spots, etc.) which already exist in the beam cause the self-focusing pattern to develop a stable orientation [8].

Finally, we note that the intensity pattern of the laser beam even before it has a diffraction pattern superimposed on it, has large intensity variations with both large spatial scale and small spatial scale. The large scale spatial variations arise from misalignment through the amplifier system, and spatial fluctuations not filtered by the spatial filter whereas the small scale intensity variations arise from damage on optics and frequency upconversion crystals, dust, etc. The intensity fluctuations from these can easily be up to an order of magnitude greater than or less than the average intensity. Indeed some of these hot spots do self-focus quite independent of the instability of the ring pattern. Thus the periodic breakup is only observed on sections of the ring.

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References