Assessing the $2\omega_{pe}$ instability and other preheat considerations in ignition-scale hohlraums

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Abstract. In recent experiments[1] Sean Regan, et. al. for the first time observed the $2\omega_{pe}$ instability from window plasma in hohlraum targets. This instability can also operate[2] at peak power near the edge of the inner beams in the ablator plasma and near the edge of the outer beams in the liner plasma. Fortunately only a small fraction of the laser energy was estimated to be at risk. A more quantitative assessment of the energy at risk at peak power will here be given. We show that the instability threshold can be significantly reduced for laser beams with an angle of incidence of about 60 degrees due to the swelling of the laser field near its turning point. A simple model is given. It is also shown that for frequently cited plasma conditions, the Raman-scattered light wave can itself drive the $2\omega_{pe}$ instability. This effect is relevant for the nonlinear saturation of stimulated Raman scattering (SRS) and the resulting heated electron generation. Some estimates are given. Finally we conclude with a few remarks about hot electron preheat.

1. Introduction/Summary

The two plasmon decay instability can be operative in ignition scale hohlraums. The intensity threshold for this instability can be quite low and further reduced by overlapped beam effects discussed in direct drive applications[3-4] and by intensity swelling when the laser light is incident onto the quarter critical surface at ~60°. This instability is a particular concern since it can generate hot electrons with an effective temperature of ~70 keV, which are much more effective at preheating than are electrons with an effective temperature of ~30 keV (attributed to the stimulated Raman instability). To implode fuel to high density, preheating by high energy electrons needs to be minimized. These hotter electron distributions have indeed been observed in Omega experiments[1] in which gas-filled hohlraums are irradiated with a shaped laser pulse. Here these electrons were correlated with the measured emission near $3/2\omega_0$, a signature of the $2\omega_{pe}$ instability, and attributed to excitation of this instability near quarter critical density in the window plasma as it blows down to low density. Preheating by high energy electrons generated in the window plasma can be avoided by blowing up the window using lower intensity laser light.

The $2\omega_{pe}$ instability has been predicted[2] to be operative at other times and places; for example in the ablator plasma irradiated by the inner beams. A simple model for the laser energy reaching quarter-critical density with intensity above threshold has been developed and applied to monitor energy at risk to this instability. This energy at risk appears quite tolerable for a recent design for an ignition-scale hohlraum with a Be ablator. Finally, for common plasma conditions, the $2\omega_{pe}$ instability
can also be excited by modest levels of Raman-scattered light when this frequency down-shifted light reaches its quarter-critical density. Various consequences are discussed, including increased preheat by a component of electrons heated to higher temperature.

2. Some general features of the $2\omega_{pe}$ instability

The $2\omega_{pe}$ instability[5-8] corresponds to the decay of an incident light wave into two electron plasma waves, a process which occurs near $0.25n_c$ (the critical density). The threshold intensity for this instability can be rather low even for $0.35\mu m$ laser light. For normally incident light, the gradient threshold intensity ($I_G$) is

$$I_G = \frac{5.9 \times 10^{15} T_{keV} W}{\lambda_{\mu} L_{\mu} \text{ cm}^2},$$  \hspace{1cm} (1)$$

where $T_{keV}$ is the electron temperature in keV and $\lambda_{\mu}$ ($L_{\mu}$) is the laser wavelength (density scale length) in microns. As an example, consider $T_{keV}=2.5$, $\lambda_{\mu}=.35$ and $L_{\mu}=10^3$, giving $I_G \sim 4 \times 10^{13} \text{W/cm}^2$.

The collisional threshold intensity ($I_c$) can also be rather low in low Z plasmas:

$$I_c \approx \frac{1.4 \times 10^9 \left( Z \ln \Lambda \right)^2 W}{\alpha^2 \left( T_{keV}^{1/2} \mu^2 \right) \text{ cm}^2},$$  \hspace{1cm} (2)$$

where $Z$ is the charge state and $\ln \Lambda$ is the Coulomb logarithm. Here $\alpha$ is a function of how far above gradient threshold one is ($\alpha=1$ when $I >> I_G$). Again considering a Be plasma with $T_{keV}=2.5$ and $\lambda_{\mu}=.35$ and taking $\ln \Lambda=7$ and $\alpha=1/3$, $I_c \sim 5 \times 10^{13} \text{W/cm}^2$.

It’s interesting to note that for an angle of incidence of $\sim 60^\circ$ the threshold intensity can be significantly reduced. Obliquely incident light turns at $n=n_c \cos^2(\theta)$. As the light turns, its group velocity slows down and so the intensity locally swells. This swelling of the electric field is readily estimated using the Airy function solution for the propagation of a plane light wave obliquely incident with an angle of incidence $\theta$ onto a plasma with a linear density profile:

$$E_{\max}^2 \approx E_{FS}^2 \cdot 3.7 \cos^2(\theta)(\omega L/c)^{1/3}.$$  \hspace{1cm} (3)$$

Here $E_{\max}$ ($E_{FS}$) is the maximum value (free space value) of the electric field of the laser light with frequency $\omega$ in a plasma with a linear density scale length $L$. Hence for $\theta=60^\circ$ the electric field intensity swells by about $(\omega L/c)^{1/3}$. Typically $(\omega L/c)^{1/3} > 10$, giving rise to a significantly lower threshold intensity. It would be valuable to explore the reduction in threshold due to this swelling in simple experiments using disk targets. It has been found that the swelling of the electric field intensity of normally incident light near the critical density very significantly reduces the threshold for excitation of parametric instabilities by radiofrequency waves in the ionosphere [9].

It’s possible that this swelling effect significantly contributes to the observed lower intensity threshold usually attributed to overlapping beam effects. For example, in the Regan experiments one of the three cones struck the hohlraum window at $60^\circ$. Likewise, it is suggested that the beam overlap in directly driven targets be scrutinized to see if one can minimize any beams with an angle of incidence near $60^\circ$. Perhaps this might be done by adjusting the beam pointing and focal spot sizes.

3. A ray trace model to monitor energy at risk to the $2\omega_{pe}$ instability

A very simple model based on ray tracing is used to estimate the energy at risk to the $2\omega_{pe}$ instability at other times and places in a hohlraum. When a ray strikes the $0.25n_c$ surface, one checks to see if its
intensity is above both the gradient and collisional thresholds. If so, the energy remaining in this ray is counted as energy at risk. This model (without a collisional threshold and using overlapped beam intensity) was first used to help understand the window hot electrons and provides a simple early warning system for when the $2\omega_{pe}$ instability can become a concern.

As an example, Figure 1 shows the power at risk versus time for the inner beams (cones with angles of 23.5° and 30°) in a NIF ignition hohlraum design with a Be ablator driven with 1MJ laser energy in a shaped pulse. The energy estimated to be at risk in this design is about 4kJ, principally due to the 23.5° cone of beams. No energy at risk was found for the outer beams with cone angles of 44.5° and 50°. Since we expect[8] that the absorption efficiency of this instability is <10%, the fraction of the laser energy in $2\omega_{pe}$-generated hot electrons is estimated to be <.04% of the laser energy. This would be quite tolerable, since even for $T_{hot}$$\sim$70 keV, the preheat spec is an order of magnitude higher. This tool is continuing to be improved; for example, the thresholds are being refined.

![Figure 1: Power at risk for the $2\omega_{pe}$ instability in a NIF ignition design. The dashed curve is the power versus time in an inner quad; the black (red) curve is the power at risk for a 23.5° (30°) inner beam.](image)

4. Excitation of other instabilities by Raman-scattered light

For conditions commonly accessed by the inner beams in an ignition-scale hohlraum, the Raman-scattered light can in turn excite the $2\omega_{pe}$ instability (and/or the Raman instability near $.25n_{cr}$). For example, consider Raman backscatter in a plasma with density of $.1 n_{cr}$ and an electron temperature of 2.5keV. Then $\omega_{pe}=.316\omega_0$ and $\omega_{sc}=.633\omega_0$; i.e., $\omega_{sc}$$\sim$$2\omega_{pe}$! For scattering at higher density $\omega_{sc}$$<$$2\omega_{pe}$, but the scattered light still encounters its quarter-critical density as it propagates to lower density plasma. For even a modest level of scattering, the intensity of the Raman-scattered light ($I_{sc}$) can exceed the threshold for the $2\omega_{pe}$ instability. For example, assume a scattered intensity of $.2I_0$, where $I_0$=5x$10^{14}$W/cm². Then $I_{sc}$$\sim$10$^{14}$W/cm², well above the $2\omega_{pe}$ threshold. If one notes that $\lambda_{sc}$$\sim$.55µm and takes a density scale length of 1mm, the gradient threshold intensity would be ~2.5x10$^{13}$W/cm², and the collisional threshold even less. Perhaps the most important consequence would be the generation of a population of heated electrons with a higher effective temperature (~70keV when the instability is well above threshold). These higher energy electrons are a preheat concern. It is also possible that this generation of other instabilities can help reduce the magnitude of the Raman scattering.

5. Concluding remarks on hot electron preheat

For ignition-scale capsules electrons with an energy greater than about 150-200 keV penetrate the ablator[10]. The fraction of the hot electron population with such energies is quite dependent on $T_{hot}$. One can tolerate about a factor of about 5 fewer hot electrons with a temperature of 70keV as compared with a temperature of 30 keV. It is clearly important to better understand the magnitude and
dependences of \( T_{\text{hot}} \) (and the detailed heated energy distributions) as well as techniques for reducing \( T_{\text{hot}} \).

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