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**The Ion Acoustic Decay Instability, and Anomalous Laser Light
Absorption for the OMEGA Upgrade, Large Scale Hot Plasma
-Application to a Critical Surface Diagnostic, and Instability at the
Quarter Critical Density**

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I. INTRODUCTION

The Ion Acoustic Parametric Decay Instability (IADI)¹, in which an electromagnetic wave decays into an electron plasma wave (epw) and an ion acoustic wave (iaw) near the critical density n_c (where the electromagnetic wave frequency equals the plasma frequency), is a fundamentally important subject in plasma physics. It has been studied by numerous authors in laser plasma interactions²⁻³, microwave experiments⁴, and ionospheric studies. One of the main issues of the IADI in laser produced plasmas is to understand whether or not it is important in the large scale plasmas relevant to laser fusion. The IADI is important because significant hot and/or warm electron heating can occur even when it is relatively weak, if the unstable volume is large enough³. If it is excited, it has important applications as plasma diagnostic in addition to anomalous laser light absorption, hot and warm electron heating, anomalous enhancement of lateral heat transport, and anomalous DC resistivity.

When electromagnetic wave excites an epw, the energy is deposited in hot/warm electrons. Previously, hot electron heating was calculated⁵ in a plasma irradiated by a high intensity laser ($10^{15} \sim 10^{18}$ W- $\mu\text{m}^2/\text{cm}^2$). The IADI was excited at a steep plasma. The plasma wave amplitude was large, and the instability width was small. The self-consistent plasma density was steep, and the instability was localized in a small region. Because of the strong excitation of the epw, a significant amount of hot electrons was heated even in the small heating region. It was thought relatively easy to avoid the hot electron heating since a high intensity laser were needed to heat them. In contrast, we find that the IADI threshold is quite low and reaches homogeneous plasma collisional values in a laser produced large scale

plasma.³ Because of the weak laser intensity, the epw is excited only moderately. However, the density profile modification is also weak, and the plasma density gradient is gentle near the instability region, implying that the instability width can be large. The electron heating is mostly determined by the product of the plasma wave amplitude, and the instability width (of the interaction time of the electron with the instability). For high intensity laser, we have a large amplitude epw, and a small instability width. On the other hand, for moderate intensity laser, we have a moderate amplitude epw, and a large instability width. An important point is that a relatively weak instability in a large region can heat (hot and warm) electrons as much as a strong instability heats them in a small region. When the IADI is excited on a shallow long scale length plasma, relatively low intensity laser can anomalously heat electrons.

It is shown that laser light can be anomalously absorbed with a moderate intensity laser ($I\lambda^2 \sim 10^{14}$ W/cm²-μm²). in a large scale, laser produced plasma. The heating regime, which is characterized by a relatively weak instability in a large region, is different from the regime studied previously, which is characterized by a strong instability in a narrow region. The two dimensional geometrical effect (lateral heating) has an important consequence on the anomalous electron heating. The characteristics of the IADI, and the anomalous absorption of the laser light were studied in a large scale, hot plasma applicable to OMEGA upgrade plasma. These results are important for the diagnostic application of the IADI.

II. EXPERIMENTAL ARRANGEMENT

We made the simulation experiments using the Janus Laser facility, which is similar to GDL system at University of Rochester. The experiments were made with a large scale length, hot plasma, which simulated the IADI in OMEGA upgrade plasma. Laser wavelength $\lambda_L = 1.06 \mu\text{m}$ and $0.53 \mu\text{m}$, the laser pulse length $\tau_L = 1.0 \text{ nsec}$, and the maximum laser energy 200 J. The laser intensity I_L was varied from 10^{12} - $3 \times 10^{15} \text{ W/cm}^2$ by controlling the laser energy, and the spot size independently. The laser normally irradiates a planar CH target. The laser light was focused through an $f/2$ lens onto the target. The target was thick enough ($50 \mu\text{m}$) that no burn through was observed. We measured the emission spectrum near the second harmonic ($2\omega_L$) of the incident laser, which was collected at 135° and 180° from the axis of the incident laser, and in the plane of the laser electric field. A focusing lens of 2 inches diameter were used to measure the emissions near the second harmonic. The signal was fed through a optical fiber into a spectrometer. The spectrum was streaked using a streak camera. The typical spectral and time resolutions are $1 \text{ \AA}$, and 30 psec.

III. EXPERIMENTS

(a) Second Harmonic Spectrum

FIGURE 1. Second harmonic spectrum: (A) $I_L = 3 \times 10^{13} \text{ W/cm}^2$, and (B) $2 \times 10^{14} \text{ W/cm}^2$.

We have measured emission spectrum near the second harmonic of laser light in large scale, hot plasma. The IADI excites the epw and the iaw, which satisfy the relation $\omega_L = \omega_{epw} + \Omega_{iaw}$, where ω_L , ω_{epw} , and Ω_{iaw} are the frequencies of the laser light, the epw, and the iaw. Two electron plasma waves ($\omega_{epw} = \omega_L - \Omega_{iaw}$ and $\omega_{epw'} = \omega_L - \Omega_{iaw'}$) coupled to produce an electromagnetic wave emission. The frequency is approximately $2\omega_{epw} \approx 2\omega_L - 2\Omega_{iaw}$. In our previous paper, we reported the IADI near the threshold, when it was excited weakly. When the IADI is excited weakly near the threshold, we saw well defined Stokes

peaks. Figure 1 shows the second harmonic spectra for two laser intensities; a weak intensity slightly above the IADI threshold, and a moderately high intensity. The left-hand peak is $2\omega_L$ signal which is attributed to resonance absorption. The right-hand signal is a Stokes signal emitted from the electron plasma waves excited by the IADI. A sharp well-defined Stokes mode is excited with the weak intensity laser irradiation (curve (a) in Fig. 1). The peak appears near the Landau damping cutoff of the epw at $k\lambda_{De} \sim 0.23$. When the incident laser intensity increases, the spectral shape is quite different from one shown in curve (a). The spectrum becomes broad (curve (b) in Fig. 1), and the original Stokes peak is now barely distinguishable. In Fig. 1, the second harmonic signals are plotted versus the measured wavelength $\Delta\lambda (= \lambda_L - \lambda)$. It is interesting to consider the horizontal axis as k_{epw} . The Stokes signal has a red shift by $2\Omega_{iaw} (\approx 2k_{iaw}c_s)$, where k_{iaw} , and c_s are the wave number of the iaw, and sound speed. In our experiments, dipole approximation is valid: $0 \approx \mathbf{k}_L = \mathbf{k}_{epw} + \mathbf{k}_{iaw}$, or $|\mathbf{k}_{epw}| \approx |\mathbf{k}_{iaw}|$, where $\mathbf{k}_L$ and $\mathbf{k}_{epw}$ are the wave vectors of the laser light, and the epw. The $\Delta\lambda$ may be considered to be proportional to k_{epw} when it is less than the Landau damping cut off. Therefore, Fig. 1 indicates that the wave number spectrum become broad as the laser intensity increases. The spectral intensity was large at small k_{epw} , and gradually decreased with the increasing k_{epw} . The measured spectrum is the results of the signals integrated over the plasma density ($0.8 n_c - n_c$), and the propagation angle of the epw.

The spectral broadening of the Stokes mode is of interest. It may be relevant to the degree of turbulence of the epw. In order to quantify the broadening, we introduce a following definition. We define the peak

intensity of the Stokes mode as $I_{\max}$, and the minimum intensity between $2\omega_L$ and the Stokes peak as $I_{\min}$. We can then quantify the broadness of the Stokes mode using the value $I_{\min}/I_{\max}$. If it is nearly one (or small), the spectrum is almost flat (or sharp). When laser intensity was less than $2 \times 10^{13} \text{ W/cm}^2$, the $I_{\min}/I_{\max}$ increased strongly with the laser intensity. Above the laser intensity, the $I_{\min}/I_{\max}$ reached a value nearly equal to unity with only moderately high laser intensity. The spectrum was built up at smaller k_{epw} to make a uniform spectrum. It is also interesting to note that the peak value of the Stokes mode moved towards smaller k_{epw} as laser intensity increased. The spectral intensity gradually decreases with the measured wavelength (or k_{epw}) as shown in Fig. 1 (b). The epw's with smaller k_{epw} interact with higher energy electrons because they have higher phase velocities. These small k_{epw} 's could be either produced by the mode couplings of the plasma waves (turbulent like spectrum) or excited by the IADI at higher density.

(B) Second Harmonic Emission versus Plasma Scale Length

As shown in the previous paper³, the IADI shifted from convective-loss regime to uniform plasma regime when laser spot size increased. The IADI can be excited in a large volume. Hence , we expect to see the increase of the IADI emissions. We have seen that the Stokes intensity increases with the laser spot size. For the small spot of the diameter $D=100 \mu \text{ m}$, no Stokes spectrum was seen because the laser intensity is lower than the IADI threshold (Notice that the IADI threshold increased with the decreasing laser spot size). Only $2\omega_0$ signal

is detected. When the laser spot size is large enough that the laser intensity is above the IADI threshold values, the Stokes signal increased with D . In order to keep the laser intensity constant, we increased the total incident laser energy with increasing D . Therefore, we have measured the normalized Stokes intensity $I_{\text{Sto}}/\pi (D/2)^2$, the Stokes intensity divided by the laser spot area. The normalized Stokes signal increased with the laser spot diameter D .

Although, we did not rule out other possible explanations, these results may imply that the instability width L_{IADI} increased (because the plasma scale length increased) with D , so the measured Stokes intensity (which is integrated over space in the instability width L_{IADI}) increased. The Instability width L_{IADI} is an important parameter to determine the anomalous laser absorption as is shown in the following sections.

The IADI causes anomalous absorption of laser. It is shown in the following chapter that the anomalous attenuation length of laser can be shorter than the IADI instability width in a large scale length plasma. Then, most of the laser energy will be absorbed by the IADI before it reaches the critical surface. Therefore, resonance absorption which happens close to the critical surface should be less important in a large scale plasma.

We have measured the intensity ratio of Stokes mode to $2\omega_0$ signal vs laser spot diameter. The intensity ratio increased with the spot diameter. The Stokes intensity increased much faster than $2\omega_0$ intensity with the spot diameter. The value decreased strongly with laser spot size. Notice that no IADI was excited with the laser spot diameter of $100\ \mu\text{m}$. The results are qualitatively consistent with the large scale plasma

where the laser energy is absorbed anomalously by the IADI before it reaches the critical density.

The large reduction of the resonance absorption with plasma scale length should not be attributed to the nature of characteristic resonance function¹ of resonance absorption. The fractional absorption of laser f_A by resonance absorption¹ is approximately given by $\phi^2(\tau)/2$, where $\phi(\tau) \approx 2.3 \tau \exp(-2\tau^3/3)$ is the characteristic resonance function describing the strength of the excitation, and $\tau = (\omega_L/c)^{1/3} \sin\theta$. The L is plasma scale length, θ is the incident angle of laser, and c is speed of light. The optimum resonance absorption happens at $\tau = 0.8$. In our experiments, laser is normally incident onto plasma through an $f/2$ lens. Hence the maximum incident angle of laser is 14° . The fractional absorption f_A is estimated versus plasma scale length L for the incident laser angles of 14° , 7° , and 3.5° using our experimental parameters. The optimum absorption just shifts from large to small angles, as the value of L increases. Therefore, we don't expect a strong reduction of the resonance absorption as L increases, from the nature of the characteristic resonance function.

IV. ANOMALOUS ABSORPTION OF LASER LIGHT

(a) Anomalous Collision Frequency Estimated from One-Dimensional Particle in Cell (PIC) Computer Simulation

An important parameter to characterize anomalous absorption of laser light is anomalous collision frequency ν^* . The anomalous collision frequency is the heating rate of electrons by electron plasma wave. We have the definition of the anomalous collision frequency.

$$\nu^* = (dT/dt)(\omega_0^2/\omega_{pe}^2)(8\pi/E_L^2) \quad (1)$$

We estimated the ν^* by measuring the temporal increase of the total plasma energy density, dT/dt , using one dimensional electrostatic PIC computer simulation code, where E_L is laser electric field. Figure 2 shows the ν^* vs the local laser intensity I (laser intensity at $0.9 n_c$) for a fixed plasma density, $n/n_c \sim 0.9$, which is the mid point between $0.8 n_c$, and n_c , and it is slightly above the $0.86 n_c$, where the IADI is most unstable. We plotted the ν^* versus the normalized laser intensity $I\lambda_L^2/T_e$. The swelling effect of the laser light was included. The ν^* increases with $I\lambda_L^2/T_e$ until the shifting point intensity of $3 \times 10^{14} \text{ W-}\mu\text{m}^2/\text{cm}^2\text{keV}$, and above the intensity ν^* increases slowly. In the moderate (laser) intensity regime below the shifting point, the anomalous collision frequency scales as

$$\frac{\nu^*}{\omega_L} \approx 4.1 \times 10^{-10} \times \left(\frac{I\lambda_L^2}{T_e} \right)^{0.56} \quad (2)$$

FIGURE 2. Anomalous collision frequency vs. the normalized laser intensity $I\lambda_L^2/T_e$ (W-μm²/cm²keV) obtained from one dimensional particle simulations.

(b) Anomalous attenuation of the laser light

The transfer of energy from laser to electrons via the IADI (the rate of energy loss from laser light) is given by $\nu^* E_L^2 / 8\pi$. When we consider the spatial problem, the (e-folding) attenuation length of laser energy δ is given by v_g / ν^* in term of the group velocity v_g of laser light in plasma. Therefore we have

$$\frac{\delta}{\lambda_L} \approx 6 \times 10^{-2} \frac{1}{\left(\frac{\nu^*}{\omega_L}\right)} \quad (3)$$

, which depends strongly on the anomalous collision frequency ν^* . In deriving the equation (3), the group velocity of the laser light is assumed to be $0.37c$ (c is

the speed of light), which is estimated at a plasma density $n/n_c = 0.86$, where the IADI linear growth rate has a peak value.

By combining Eqs. (2), and (3), we can estimate the laser attenuation length due to the IADI as

$$\frac{\delta}{\lambda_L} \approx 1.5 \times 10^8 \times \left(\frac{I \lambda_L^2}{T_e} \right)^{-0.56} \quad (4).$$

For a simple estimate, we ignore the plasma density dependence of v^* . This simple approximation will be justified, since $\delta \ll L_{\text{IADI}}$ as is discussed in the following section. The accurate value depends on the detail of the density profile, and local value of v^* . The important point is that our simple estimates indicate that the attenuation length of the laser can be much smaller than the instability width as shown in the following section.

(c) Plasma Density Profile

We have made computer calculations of the plasma density profile using the 2-dimensional LASNEX computer code⁶. The calculations were made using our experimental parameters: the 1.06 μm laser, with 1 nsec Gaussian pulse, was focused onto a 50 μm thick planar CH target using $f/2$ lens (the laser spot size was 500 μm). The laser intensity was 3×10^{13} , and 10^{14} W/cm^2 , and the flux limiter was $f = 0.1$.

The plasma scale length was long near the instability region. The electron temperature was about 0.7 keV. It is well known that the IADI can be excited³ at the densities $0.8 < n/n_c < 1$. The lower limit density is determined

by the Landau damping cut off of the epw near the $k_{epw}\lambda_{De} \approx 0.3$ (k_{epw} , and λ_{De} are wave number of the epw, and Debye length). Let's define the length between n_c and $0.8 n_c$ as the instability width, LIADI. For the above parameters, the length LIADI was quite large, about 30 μm for the both laser intensities of 3×10^{13} , and 10^{14} W/cm².

(d) Laser Light Attenuation Length, and the Instability Width

We can now compare the laser attenuation length and the instability width. For laser intensity 3×10^{13} W/cm² (10^{14}), the electron temperature is about 0.7 keV (1), so we have $\delta/\lambda_L \sim 3$ (2) using Eq. (4). On the other hand, $LIADI/\lambda_L \sim 30$ for the both laser intensities. The attenuation length is much smaller than the instability width. Therefore, we predict without the accurate spatial profile of v^* that the most laser energy which reaches the instability region is absorbed by the IADI. The absorbed energy is deposited to hot and warm electrons.

(e) Two-Dimensional Electromagnetic Computer Simulation Results

These results are consistent with the calculations using the two-dimensional relativistic particle and electromagnetic field simulation code ZOHAR⁷. Figure 2 shows laser absorption versus LIADI. It shows that the instability width LIADI of only a few laser wavelengths may be sufficient to absorb most of laser energy. The ZOHAR simulations were made with high laser intensities to minimize the numerical noise. However, v^* saturates at high laser intensity as shown in Fig. 2, so that the results should be insensitive to the laser intensity. In fact, when we increased the laser intensity from 5×10^{15}

to $1 \times 10^{16} \text{ W/cm}^2$, no significant change of the absorption was seen. For comparison, we plotted the theoretical values calculated using the ν^* given in Fig. 2. The simple estimates give reasonably good agreements with ZOHAR results. The important point is that there was no drastic change of the anomalous absorption as laser intensity increased from 10^{14} to $5 \times 10^{15} \text{ W/cm}^2$.

FIGURE 3. The solid circles are fraction of laser absorption calculated by ZOHAR simulations. The curves are the theoretical values for (a) : $5 \times 10^{15} \text{ W/cm}^2$ and 4 keV, and (b): $I = 10^{14} \text{ W/cm}^2$, and $T_e = 1 \text{ keV}$.

V. SUMMARY

In summary, anomalous absorption in a large scale plasma is quite different from those of small scale plasmas. The Ion Acoustic Decay Instability (IADI) may cause anomalous laser absorption with a relatively weak laser intensity in a large scale plasma. The anomalous attenuation length of the laser can be only a few laser wavelengths in width. These are consistent with the 2-dimensional electromagnetic field computer simulation results. The experiments indicate that the threshold of the IADI is low, so that the IADI is excited on a shallow, long scale length plasma. The measured results of the second harmonic signals are consistent with a strong anomalous absorption by the IADI in a large scale plasma.

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