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**Development of Critical Surface Diagnostic based on the Ion Acoustic
Decay Instability in Laser Produced High Density Plasma**

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We developed second harmonic (SH) emission diagnostic, and collective Thomson scattering (CTS) diagnostic to study the important features of the IADI in OMEGA upgrade plasma. The important features of the diagnostics are discussed below.

We developed a large angle, collective Thomson scattering. Since the frequency ratio of the probe beam and the electron plasma wave is small (≈ 3), the scattering is collective (i.e. $\alpha \gg 1$) even though the scattering angle is large. The diagnostic is based on the measurements of the scattering from the plasma waves excited by the ion acoustic decay instability. The Ion Acoustic Parametric Decay Instability [1] (IADI), 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. Plasma waves have been studied by numerous authors in laser plasma interactions [2-4], microwave experiments [5], and ionosphere studies near critical density. The CTS diagnostic is based on scattering measurements of the real parts (frequency, and wavelength) of plasma waves excited by the IADI. The real parts of the waves are, in general, more reliable than the imaginary parts such as the damping and growth rates. The several features of the CTS are as follows: (1) A local electron temperature (T_e) can be measured near the critical density of the interaction laser. It requires no averaging over plasma density. Laser produced plasma is small, so it was often hard to measure a local electron temperature. (2) Scattering cross section is large since the scattering is from a wave. (3) It can be a large angle scattering. It also minimizes the stray signal. (4) T_e is obtained by measuring the peak frequency of the scattered signal rather than measuring a spectral width in the conventional Thomson scattering.

Collective Thomson scattering [6] from plasma wave is a three wave process satisfying the k-matching conditions $k_s = k_i \pm (k_{epw} \text{ or } k_{iaw})$, and the energy conservation $\omega_s = \omega_i \pm (\omega_{epw} \text{ or } \Omega_{iaw})$. The k's and ω 's are the wave vectors and frequencies of the three waves; the subscripts i and s refer to the incident and scattered electromagnetic waves for a probe beam, and the subscript epw, and iaw refer to electron plasma, and ion acoustic waves. The scattering angle θ is given by $k_{epw}^2 = k_i^2 + k_s^2 - 2k_i k_s \cos\theta$. For the scattering from ion acoustic wave, since $\Omega_{iaw} \ll \omega_s$ or ω_i , we have $|k_s| \approx |k_i|$, so that $k_{iaw} \approx 2 k_i \sin(\theta/2)$. For the up-shifted scattering from the electron plasma wave, we have, $\omega_s \approx 4/3 \omega_i$, and $|k_s| \approx 4/3 |k_i|$. The scattering angle θ is given by $k_{epw}^2 = k_i^2 (25/9 - (8/3) \cos(\theta))$. These yield simple equations: $T_e = 1.4 \times 10^4 \times (k_{iaw} \lambda_{De})^2 / \sin^2(\theta/2)$ (eV) for scattering from the iaw, and $T_e = 5.7 \times 10^4 \times (k_{epw} \lambda_{De})^2 / (25/9 - (8/3) \cos(\theta))$ (eV) for scattering from the epw. We can calculate T_e vs scattering angle for several values of $k \lambda_{De}$. Our past experiments, and theory show that the most prevalent values for k_{epw} ($\approx k_{iaw}$) are found near the Landau damping cut-off, $k_{epw} \lambda_{De} \approx 0.23$, being independent of T_e . Therefore, we can estimate the scattering angle of the most unstable IADI using the above equation. Good electron temperature measurements are expected at large angle scattering. The optimum CTS will be at about 90 degree scattering angle for $T_e \sim 1$ keV.

The frequencies of the epw, and the iaw are determined from the IADI decay condition, and ion wave dispersion relation. In a large scale plasma [3], the IADI dispersion relation is approximately given [1] by

$$(\omega^2 + i\omega v_i - \Omega_{ia}^2) \left[\left(\omega + \frac{iv_e}{2} \right)^2 - \delta^2 \right] + \omega_{pi}^2 \frac{k^2 v_{os}^2}{4} \frac{\delta}{\omega_L} = 0 \quad (1)$$

In our typical experiments, ion acoustic frequency is larger than the damping rate, $\Omega_{iaw} \gg v_i, v_e$, where $v_i = 2\Gamma_i$, (Γ_i is ion wave Landau damping rate), and v_e is

collisional damping rate of the epw. We have calculated the growth rate of the IADI and the ion wave frequency vs. $(\omega_L - \omega_{epw})/\Omega_{iaw}$ for the several intensities of the interaction laser in Fig. 1 (B). If the pump laser intensity I_L is less than 10 times of the threshold value I_{th} , the growth rate peak appears at $\omega_L = \omega_{epw} + \Omega_{iaw}$, and the frequency of the iaw is $\omega = \Omega_{iaw}$. The IADI decay resonance condition is satisfied, and the normal mode of the iaw will be excited. On the other hand, a driven ion wave [2] will be excited, so the frequency increases with laser intensity, when the interaction laser intensity is much larger than 10 times of the threshold value. We also notice that the dipole approximation is valid in our experimental parameters ($k_L \ll k_{iaw}, k_{epw}$): $k_L = k_{iaw} + k_{epw} \sim 0$, or $|k_{epw}| \sim |k_{iaw}|$. Therefore, the frequency and the phase velocity of the iaw can be obtained by measuring either the epw or the iaw.

The ion wave dispersion relation in CH plasma is solved. We have a slow, and a fast ion acoustic waves associated with C, and H ions. In typical laser produced plasma, the (ion to electron) temperature ratio will be $0.3 < T_i/T_e < 1$. In this regime, the damping rate of the slow wave is about $\Gamma_i/\Omega_{iaw} \sim 0.1$ independent of the temperature ratio, which is much smaller than the damping rate 0.8 of the fast wave. The IADI threshold I_{th} with the fast wave is 8 times larger than that with the slow wave. Therefore, the slow wave is easily excited. Furthermore, the phase velocity of the slow wave is almost independent of the temperature ratio in the regime of $0.3 < T_i/T_e < 1$. It is proportional only to electron thermal velocity (independent of T_i). The slow wave is good for electron temperature diagnostic. The electron thermal velocity v_e is approximately given by

$$v_e \approx 53.5 \times \Omega_{iaw}/k_{iaw} \text{ or } v_e \approx 53.5 \times (\omega_L - \omega_{epw})/k_{epw} \quad (2)$$

for the slow wave. The second part of the equation is obtained using the IADI resonance condition, and the dipole approximation. The electron thermal velocity (or T_e) can be estimated by measuring the iaw or the epw. The electron density is approximately given by $\frac{(n_p)_{IADI}}{n_c} \approx 1 - 8.6 \times 10^3 (3 \text{ (or } 4) \times \frac{\Omega_{iaw}}{\omega_o})^2$ using the IADI resonant condition, the dipole approximation, the Bohm-Gross equation, and Eq. (2). Thus the electron temperature is measured for a local plasma density given by the equation near the critical density. The plasma density is about $0.86 n_c$ for the most unstable IADI ($k_{epw} \lambda_{De} \sim 0.23$).

There are several conditions to consider for the CTS in CH plasma. (1) the interaction laser intensity should be $1 < I_L/I_{th} < 8$, so that only the slow wave is excited, and the IADI resonance condition is satisfied. (2) The plasma waves which are propagating nearly perpendicular to the plasma density gradient are measured by the CTS to minimize the plasma flow effect. (3) The refraction of the probe beam is small. It is about 10 (6) % for $\omega_i/\omega_L = 3$, and about 5 (3) % for $\omega_i/\omega_L = 4$, if the incident probe beam angle is 60 (40) degree. (4) The scattering rate, and the probe beam intensity are large enough to observe a well-defined spectrum in one shot of the laser system.

We have developed the multi-channel UV Thomson scattering system for the measurements of the IADI in laser produced high density plasma. Scattered signal is focused into an optical fiber using a focusing mirror. The signals from the 6 channel detectors are fed to a spectrometer. By varying the length of the optical fiber, we can produce relative time delay between each channel. With this method, we can measure 3 parameters simultaneously: the multi-channel signals (the angle distribution), the spectrum (the spectral density function), and the time evolution. The signals from the spectrometer are fed to a streak camera, then measured, and analyzed using a CCD camera, and a computer. The interaction laser incident normally onto a CH target. The ion acoustic wave, and the electron

plasma wave are strongly excited along the electric field of the interaction laser. The Thomson scattering system is designed to measure ion acoustic wave, and electron plasma wave propagating nearly parallel to the laser electric field, or perpendicular to the density gradient. We also measure the conventional second harmonic signal [2-4] simultaneously with the CTS to confirm the excitation of the IADI.

In summary, we have developed a large angle, UV collective Thomson scattering diagnostic for high density, hot plasma relevant to laser fusion. The CTS measured the basic parameters of the plasma waves (the frequency, and the wave number), or the spectral density function for selected wave vectors of plasma waves, which were excited by the IADI. It is a good diagnostic tool for a local electron temperature measurement. The electron temperature was estimated by measuring either ion acoustic wave or electron plasma wave in the laser intensity window of $1 < I_L/I_{th} < 8$.

The CTS diagnostic is also useful to study important physics of plasma waves in laser produced high density plasma. The detail experimental results will be published elsewhere in the future.

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