DOE/SF/20140--T3

**A New Electron Temperature Diagnostic of Critical Surface based on
the Ion Acoustic Decay Instability in Hot, High Density Plasma
relevant to Laser Fusion**

by

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Semiannual Reports 1S/94 (4/1/94-9/29/94)
for Contract DOE-FG03-93SF20140

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We made analysis of the IADI experiments previously made using OMEGA laser system. We obtained two important new results: the first direct observation of the epw excited by the Ion Acoustic Decay Instability (IADI)[1-5], and the first study of the IADI in a plasma that approaches laser-fusion conditions, in the sense of having a density scale length of order 1 mm and an electron temperature, T_e , in excess of 1 keV. Previous observations of the epw's have been based on the second harmonic emission, from which little can be inferred because the emission is produced by unknown pairs of epw's, integrated in a complicated way over wavenumber space and real space. In contrast, we have directly observed the epw by using the 90°, collective Thomson scattering (CTS) of a UV laser (at the third harmonic of the pump) from the epw's. Because the ratio of probe frequency to electron plasma frequency is only about three, the scattering is collective (i.e. $k_{epw}\lambda_{De}$ is small, where k_{epw} is the epw wave number and λ_{De} is the Debye length), even though the scattering angle is large. The electron temperature can then be deduced from the ion sound velocity, obtained from the measurement of the frequency at which growth is maximum at the scattering wavenumber.

The CTS signal was collected by a focusing mirror at 90° to the Thomson scattering beam and focused on to the detector system (at the opposite port), which included a one-meter spectrometer, a UV streak camera, and a CCD camera. The measured wave vector k_{epw} was nearly parallel to the pump electric field. Simultaneously, the time-resolved second harmonic spectrum (through the Thomson-scattering port) was measured using a 1/3 meter spectrometer, a streak camera, and another CCD camera.

Collective Thomson scattering [7] is a three-wave process satisfying the k-matching condition $k_s = k_i \pm k_{epw}$ and the energy conservation law $\omega_s = \omega_i \pm \omega_{epw}$. (The k's and ω 's are the wave vectors and frequencies of the three waves;

the subscripts i, s, and epw refer to the incident and scattered probe beam, and the electron plasma wave.) We have measured the up-shifted signal at $4\omega_0$ ($=\omega_i+\omega_{epw}$) to reduce the problems of incoherent harmonic emission and refraction. The scattering angle θ is given from the k-matching condition by $k_{epw}^2=k_i^2+k_s^2-2k_ik_s\cos\theta$. For the up-shifted scattering, we have $\omega_s \sim 4/3 \omega_i$ and $k_s \sim 4/3 k_i$. The geometry of the experiment selected a 90° scattering angle and $k_{epw} = 2.9 \times 10^5 \text{ cm}^{-1}$. At this angle the CTS signal intensity is maximum (very small) for out-of- (in-) plane polarization of the probe beam [7]. For $T_e \sim 1 \text{ keV}$, the observed angle is close to the optimum scattering angle of 89° for measurement of the most unstable IADI mode, which has $k_{epw}\lambda_{De} \sim 0.23$. The density at which the observed k_{epw} is resonant for IADI depends upon T_e , becoming higher as T_e decreases.

Our experiments were guided by two-dimensional calculations using the computer code SAGE [8]. We calculated spatial profiles of n_e , T_e , and ion temperature T_i along the center, z axis at a time of 2.2 ns, corresponding to the peak of the pump beam. This timing was chosen so that the center plasma density would be slightly higher than the critical density $n_c \sim 10^{21} \text{ cm}^{-3}$ of the pump laser. When the pump laser is applied to the preformed plasma, no significant density change is predicted, but the electrons in its path are heated by classical electron-ion collisions as is shown by the hump on the right hand side of the T_e curve. The peak value of T_e is just above 1 keV. SAGE calculations indicate that 15 - 70 % of the pump laser energy reaches the instability region depending on the laser intensity.

On account of the three-dimensional nature of the experiment, some approximations were necessary. The pump beam was modeled as incident along the target normal (z), for consistency with the cylindrical symmetry about this direction assumed by SAGE, although the actual angle of incidence was

69°. At 2.2 ns the 0.86 n_c contour, at which the measured epw ($k_{epw} = 2.9 \times 10^5 \text{ cm}^{-1}$) is resonantly excited, is close to a prolate ellipsoid with diameters 560 μm along and 162 μm transverse to the z axis. Typical rays are incident at 21° to the ellipsoid normal and see flow velocities v_f of $1-2 \times 10^7 \text{ cm/sec}$ generally directed away from the plasma center. The experimental geometry is such that $v_f \cdot k_{epw} \approx 0$.

We have verified that the measured signals were indeed due to CTS from the epw excited by the IADI as follows: (1) the $4\omega_0$ intensity decreased rapidly as the pump laser intensity decreased, and the signal disappeared when the pump was below the IADI threshold (as determined by conventional second harmonic emission measurements); (2) when the probe beam was turned off, no $4\omega_0$ signal was observed; and (3) the $4\omega_0$ intensity varied drastically (decreased about 10 times) when the probe beam polarization was changed from out-of-plane to in-plane. Moreover, the measurements discussed in the remainder of this paper are all consistent with standard instability theory for a uniform plasma [1].

The experimental threshold value of the spatially-averaged intensity in the instability region was estimated from the measured threshold laser energy for a CTS signal (5 J), taking into account the collisional attenuation and refraction as estimated by SAGE. This yields a value of $\sim (1.4-2.8) \times 10^{12} \text{ W/cm}^2$. This is in satisfactory agreement with the theoretical value of $\sim (0.8-2.3) \times 10^{12} \text{ W/cm}^2$ calculated using $T_e = 0.8 \text{ keV}$ (appropriate for a low pump intensity), taking into account the swelling at the instability region and the multiple-species ion sound theory.

We made CTS measurements of the time evolution of the epw spectral density function with $k_{epw} = 2.9 \times 10^5 \text{ cm}^{-1}$. A clear red shift relative to the $4\omega_0$ wavelength is evident. This Stokes peak is due to the primary IADI decay

process: in these experiments, where the pump laser energy is less than 50 J, no cascade decay process is observed. The spectral density function at the time of the peak signal was estimated against the normalized frequency shift $(\omega_0 - \omega_{epw})/\Omega_{iaw}$, where Ω_{iaw} is chosen to center the spectrum on a normalized shift of 1. Its peak is calculated to occur at $\omega_0 - \omega_{epw} = \Omega_{iaw}$: the IADI resonance condition is thus satisfied, and the normal mode of the iaw is excited. The measured CTS spectral width agrees reasonably well with that of the growth rate curve. On the other hand, if the pump laser intensity were much larger than 10 times the threshold, the growth rate peak would shift towards higher frequency and the iaw frequency would increase with the laser intensity (driven mode).

We can now estimate the phase velocity of the iaw. In these experiments, the dipole approximation is valid, so the pump laser wave number $k_0 \sim k_{epw} + k_{iaw} \sim 0$, or $|k_{iaw}| \sim |k_{epw}|$. The ion acoustic wave frequency used for the normalization is given by $\Omega_{iaw} = 2\pi c \Delta\lambda / \lambda_4 \omega^2 \approx 9 \times 10^{12}$ Hz, where $\Delta\lambda$ is the wavelength shift of the peak of the CTS signal ($3.3 \pm 0.2 \text{ \AA}$). Therefore, the phase velocity Ω_{iaw}/k_{iaw} of the iaw is about 3×10^7 cm/sec. We will use this below to estimate the electron temperature.

For greater accuracy, the multiple-ion nature of the plasma was included in the calculation of the ion-acoustic dispersion relation. We have obtained fast and slow wave solutions for CH plasmas, and shown that the slow wave is the important one as it is 8 times less damped than the fast wave. The phase velocity of the slow wave is effectively independent of T_i in the range $0.3 < T_i/T_e < 1$, being about $0.8 (k_B T_e / M)^{1/2}$ or $1.87 \times 10^{-2} v_e$, where M is the proton mass, k_B is Boltzmann's constant, and v_e is the electron thermal velocity. The slow iaw frequency at a given wavenumber is thus an excellent diagnostic for T_e : from the measured peak-signal frequency shift and the

scattering wavevector (known from the geometry), one immediately obtains the slow iaw velocity and hence T_e . In this experiment, the iaw phase velocity is 3×10^7 cm/sec, giving $T_e = 1.5$ keV and $v_e = 1.6 \times 10^9$ cm/sec. The theoretical values ($v_e = 1.4 \times 10^9$ cm/sec and $T_e = 1.1$ keV) given by the SAGE calculation are somewhat lower than the experimental values (about 13% for v_e and 27% for T_e). However, taking into account the complicated nature of the large-scale plasma produced, the possibility of hot spots within the focal spot, and the three-dimensional nature of the experiment, this should be considered reasonably good agreement.

Several conditions were met that enabled the diagnostic to work well. First, the scattering angle was chosen to be large to measure the most unstable epw. Second, between the thresholds for the slow ion wave IADI (I_{th}) and the fast ion wave IADI ($8 I_{th}$), only the slow ion wave was significantly excited. Third, the refraction of the probe beam itself was small (less than 7% for this experiment) and that of the up-shifted signal even smaller. Fourth, the complications of plasma flow effects on the diagnostic were minimized because the detection vector ($k_{epw} = k_s - k_i$) was perpendicular to the direction of plasma expansion. Fifth, because this is a collective scattering, the scattering rate is much larger than that from thermal electrons and it is relatively easy to exceed the background bremsstrahlung emissions. Sixth, the experimental design assured that only a narrow range of densities could contribute to the observed signals.

We have also measured the conventional second harmonic signal (from the coupling between two epw's). Its threshold laser energy was comparable to that of the CTS threshold energy, consistent with the presence of the IADI. The Stokes signal is spread over a large wavelength range, and decreases gradually

without a distinct peak. This indicates that the epw intensity is spread over a wide range of wave numbers in the large-scale plasma.

In summary, we have studied the ion acoustic decay instability in a large (~ 1 mm) scale, hot (~ 1 keV) plasma, which is relevant to a laser fusion reactor target. We have shown that the instability threshold is low. We have developed a novel collective Thomson scattering diagnostic near its critical density, at a 90° scattering angle. The scattering is nonetheless coherent, because of the modest ratio of the frequency of the probe laser to that of the pump laser, such that even for such a large angle, $(k\lambda_{De})^2$ is much less than one. With this system we have measured the electron plasma wave excited by the ion acoustic decay instability near the critical density ($n_e \sim 0.86 n_c$). This allows us to use the frequency of the detected wave to measure the electron temperature in the interaction region, obtaining a result reasonably close to that predicted by the SAGE computer code.

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