DOE/SF/20140--T1

**The Ion Acoustic Decay Instability in a Large Scale, Hot Plasma
Relevant to Direct Drive Laser Fusion
-Application to a Critical Surface Diagnostic-**

by

K. Mizuno, J. S. DeGroot, R. P. Drake, W. Seka,
R. S. Craxton, and K. G. Estabrook

Applied Science
Univ. of Calif. Davis

Final Report
for Contract DOE FG03-93SF20140

Phone (916) 752-0360
Phone (510) 422-6891
E-mail mizuno1@LLNL.gov

PD Mizuno

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

Table of Content

I.	Introduction	3
II.	Electron Temperature Measurement using Ion Acoustic Decay Instability in a Hot Large Scale Plasma relevant to Laser Fusion	5
III.	Analysis of the Experiments	8
IV.	Summary	14
	References	15

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 interactions [2,3], microwave experiments [4] and ionospheric studies [5]. It is potentially significant in the large-scale plasmas relevant to laser fusion because anomalous electron heating can occur even when the instability is relatively weak, if the unstable volume is large enough. In addition, the instability can lead to anomalous DC resistivity and a reduction in electron thermal transport, and it has an application as a critical surface diagnostic. Nevertheless, all previous experiments have been carried out in relatively small-scale plasmas.

We report our results: the first direct observation of the epw excited by the IADI, 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.

In this report, we present a large angle, collective Thomson scattering (which is termed CTS) for electron temperature diagnostic in laser-produced high density plasmas. 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 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.

II. Electron Temperature Measurement using Ion Acoustic Decay Instability in a Hot Large Scale Plasma relevant to Laser Fusion.

Collective Thomson scattering [7] 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 $k_{iaw} \approx 2 k_i \sin(\theta/2)$. In our experiments, $\omega_i = 3 \omega_L$, where ω_L is the interaction laser frequency with the wavelength of $1.05 \mu\text{m}$. 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 calculated 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 $T_e \sim 1 \text{ keV}$.

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, the IADI dispersion relation is approximately given 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. 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 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 has been 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.

III. Analysis of the Experiments

The experiments were carried out using a large-scale (~ 1 mm), hot (~ 1 keV) plasma produced by the 24-beam, 1.5-kJ UV OMEGA laser at the University of Rochester. Two opposed sets of four beams, peaking at time $t=1.0$ ns, were used to explode a CH foil of $6\text{ }\mu\text{m}$ thickness and diameter $600\text{ }\mu\text{m}$ overcoated with $500\text{ }\text{\AA}$ of Al. Four beams each side were used as secondary heating beams, and were incident later at $t=1.6$ ns. The on-target laser energy was typically 50-60 J per beam with a pulse duration of 0.60 – 0.65 ns at a wavelength of 351 nm. One of the OMEGA beams was used as a $1.054\text{-}\mu\text{m}$ pump beam (at ω_0) to drive the IADI, timed to peak at $t=2.2$ ns. This beam was incident through a phase plate with 3-mm cells and an $f/3.6$ lens to produce a focal spot of diameter $210\text{ }\mu\text{m}$ (at half maximum), with 36 J in the central Airy lobe, giving a maximum intensity in space and time of $\sim 1.25 \times 10^{14}\text{ W/cm}^2$. Another beam was attenuated and used as the $3\omega_0$ probe. A waveplate was used to rotate the (elliptical) polarization of the pump beam to the optimum angle for exciting the epw's being diagnosed. The typical plasma had a center density of $1 - 2 \times 10^{21}\text{ cm}^{-3}$, which was maintained within a factor of two at $T_e \sim 1$ keV for approximately 1 ns. The scale length was of the order of 1 mm at $t=2.2$ ns.

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 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 $k_{epw}^2 = k_i^2 + k_s^2 - 2k_i k_s \cos\theta$. 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. 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 $560 \mu\text{m}$ along and $162 \mu\text{m}$ transverse to the z axis. Typical rays are incident at 21° to the ellipsoid normal and see flow velocities v_f of $1\text{--}2 \times 10^7 \text{ cm/sec}$ 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.

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 $\sim (1.4\text{--}2.8) \times 10^{12} \text{ W/cm}^2$. This is in satisfactory agreement with the theoretical value of $\sim (0.8\text{--}2.3) \times 10^{12} \text{ W/cm}^2$ 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 a CTS measurement 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 $4\omega_o$ 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 cascade process for a fixed k_{epw} is that $\omega^{(n)}_{epw} = \omega^{(n+1)}_{epw} + \omega^{(n+1)}_{iaw}$, and $k^{(n)}_{epw} = k^{(n+1)}_{epw} + k^{(n+1)}_{iaw}$ (which indicates that $|k^{(n)}_{epw}| = |k^{(n+1)}_{epw}| = 1/2 |k^{(n+1)}_{iaw}|$), where $n=1, 2 \dots$, and $n=1$ is the epw excited by the primary IADI process. The spectral density function at the time of the peak signal was measured against the normalized frequency shift $(\omega_o - \omega_{epw})/\Omega_{iaw}$, where Ω_{iaw} is chosen to center the spectrum on a normalized shift of 1. The IADI growth rate was calculated using the experimental parameters. Its peak is calculated to occur at $\omega_o - \omega_{epw} = \Omega_{iaw}$: 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 $k_o \sim k_{epw} + k_{iaw} \sim 0$, or $|k_{iaw}| \sim |k_{epw}|$. The ion acoustic wave frequency used for the normalization is given by $\Omega_{iaw} = 2\pi c \Delta\lambda / \lambda_4 \omega^2 \approx 9 \times 10^{12} \text{ Hz}$, 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 $3 \times 10^7 \text{ cm/sec}$. 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. Williams et al. 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 ($\mathbf{k}_{epw} = \mathbf{k}_s - \mathbf{k}_i$) 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.

IV. Summary

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 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.

References

1. W. L. Kruer, *The Physics of Laser Plasma Interactions* (Addison-Wesley, Reading, MA, 1988); K. Nishikawa, *J. Phys. Soc. Jpn.* **24**, 916 (1968); **24**, 1152 (1968).
2. C. Yamanaka et al, *Phys. Rev. Lett.* **30**, 594 (1973); K. Tanaka, et al., *Phys. Fluids* **27**, 2187 (1984).
3. K. Mizuno et al., *Phys. Rev. Lett.* **65**, 428 (1990); *Phys. Fluids B* **3**, 1983 (1991).
4. K. Mizuno et al., *Phys. Rev. Lett.* **52**, 271 (1984); *Phys. Rev. Lett.* **56**, 2184 (1986).
5. D. F. DuBois et al., *Phys. Rev. Lett.* **66**, 1970 (1991).
6. W. Seka et al., *Phys. Fluids B* **4**, 432 (1992).
7. J. Sheffield, *Plasma Scattering of Electromagnetic Radiation* (Academic Press, New York, San Francisco, London, 1975).
8. R. S. Craxton and R. L. McCrory, *J. Appl. Phys.* **58**, 108 (1984).