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LOCAL MEASUREMENT OF ELECTRON DENSITY AND TEMPERATURE IN HIGH TEMPERATURE LASER PLASMA USING THE ION-ACOUSTIC DISPERSION

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The dispersion of ion-acoustic fluctuations has been measured using a novel technique that employs multiple color Thomson-scattering diagnostics to measure the frequency spectrum for two separate thermal ion-acoustic fluctuations with significantly different wave vectors. The plasma fluctuations are shown to become dispersive with increasing electron temperature. We demonstrate that this technique allows a time resolved local measurement of electron density and temperature in inertial confinement fusion plasmas.

1. Introduction

In high-temperature plasmas[1], the frequency of ion-acoustic fluctuations is sensitive to both the local electron temperature and density. The use of Thomson-scattering diagnostics at multiple probe wavelengths allows us to measure the local frequency of the ion-acoustic fluctuations for large and small wave vectors, **k**. The dispersion of ion-acoustic fluctuations with large **k** vectors are sensitive to Debye shielding, therefore, this technique is shown to be a powerful diagnostic of both the local electron density, n_e, and local electron temperature, T_e, with high temporal and spatial resolution, which could be adapted for a variety of applications across the fields of plasma physics where other diagnostics have failed to provide accurate measurements.

The advantage of applying two spectrometers measuring the ion acoustic feature in the Thomson scattering spectrum is the fact that these fluctuations provide the most intense features in the collective scattering spectrum and their frequency separation has been a proven signature for measurements of the electron temperature[2]. In the present application, one detector measure the ion acoustic frequency for small **k**-vector fluctuations providing T_e, the second detector measures the acoustic frequency for large **k**-vector fluctuations providing n_e, from the $k\lambda_D$ term in the dispersion relation. Alternative techniques that measure both the local temperature and density employ absolute calibration by Rayleigh scattering or consist of measurements of electron plasma fluctuations that provide a measure of the electron density from the frequency of the electron plasma wave. The first technique is not applicable at large laser facilities while the second makes use of a relatively small scattering signal thus requiring a high power probe laser. We present a new technique for simultaneously measuring local electron temperature and density using the frequency of the ion-acoustic feature and therefore, standard low power probe lasers can be employed ensuring that the plasma conditions are not perturbed.

2. Experiment

The experiments have used a four-laser beam configuration at the recently upgraded Janus Long Pulse Facility at the Lawrence Livermore National Laboratory. Figure 1 shows a schematic. The nitrogen gas-jet plasmas were produced by two high-power (λ = 1054 nm) laser beams. The neutral gas density was well-characterized using a Mach-Zender interferometer. The heater beams were pointed through the center of the 1 mm diameter gas jet, 1.5 mm from the jet exit. The primary heater beam used 450 J in a 1.2 ns laser pulse. The beam was focused to a 1.2 mm diameter focal spot at the target chamber center (TCC) through a phase zone plate (PZP) using a f/6.7 lens producing plasmas with a range of electron temperatures (100 eV $< T_e <$ 700 eV) and densities (10^{19} cm^{-3} $< n_e < 10^{20}$ cm^{-3}). The second heater beam used 100 J in 1.2 ns, 0.3 ns after the falling edge of the primary heater beam (Fig. 1(b)). This beam was focused using a f/6.7 lens with a continuous phase plate (CPP) to a 200 micron diameter focal spot at the TCC.

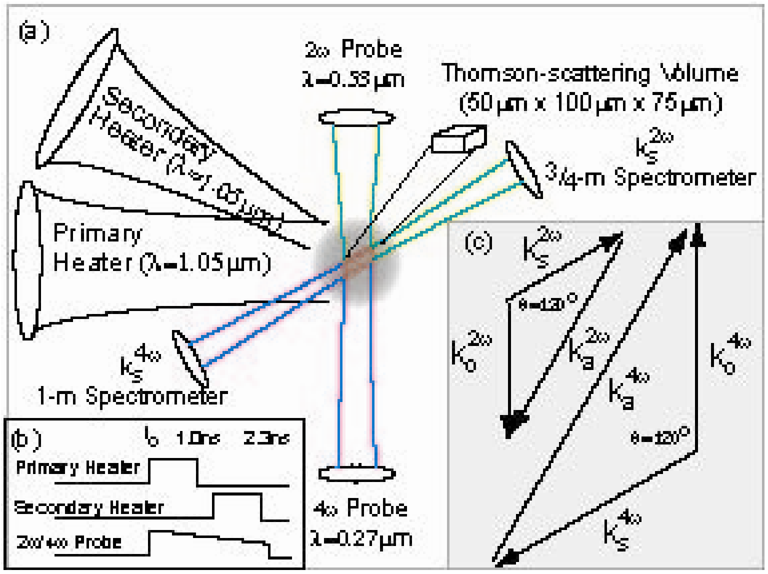

Figure 1: (a) Schematic of the experimental setup. (b) Beam timing. (c) A k-vector diagram shows the ion-acoustic waves, $k_a^{ts} = 4\pi\ \lambda_{ts} \sin(\theta/2)$ that are probed.

Two 0.5 J Thomson-scattering probe lasers at two different wavelengths, $\lambda_{2\omega}$ = 532 nm and $\lambda_{4\omega}$ = 266 nm were used to probe thermal ion-acoustic fluctuations with significantly different wave vectors. Two f/5 collection lenses collimated light scattered from a single Thomson-scattering volume in the plasma. The scattered light was then focused onto the slit of a 3/4-meter (for 2ω) and a 1-meter (for 4ω) imaging spectrometers using two f/10 focusing lenses, and the spectra were recorded with Hamamatsu streak cameras. The spectral resolution was 0.056 nm (for 2ω) and 0.021 nm (for 4ω). To assure that the two spectrometers measure the Thomson-scattering light from the same volume, we defined TCC with a 100 micron glass ball that was suspended over the center of the gas jet. All beams where aligned to the ball at the TCC. The glass ball was back-lit and imaged through the spectrometers with the streak camera in focus mode.

3. Experimental Results and Discussion

Figure 2 shows the Thomson-scattering data from the nitrogen plasma. For the duration of the probe beams two symmetric ion-acoustic features are observed. The data show that the wavelength separation of the ion-acoustic peaks is steadily increasing during the heating providing the electron temperature evolution of the plasma. In addition, the wavelength separation of the ion acoustic fluctuation probed with the 2ω laser (small k vector) increases faster than for the 4ω laser (large k vector). This effect of the dispersion allows us to infer the electron density of the plasma.

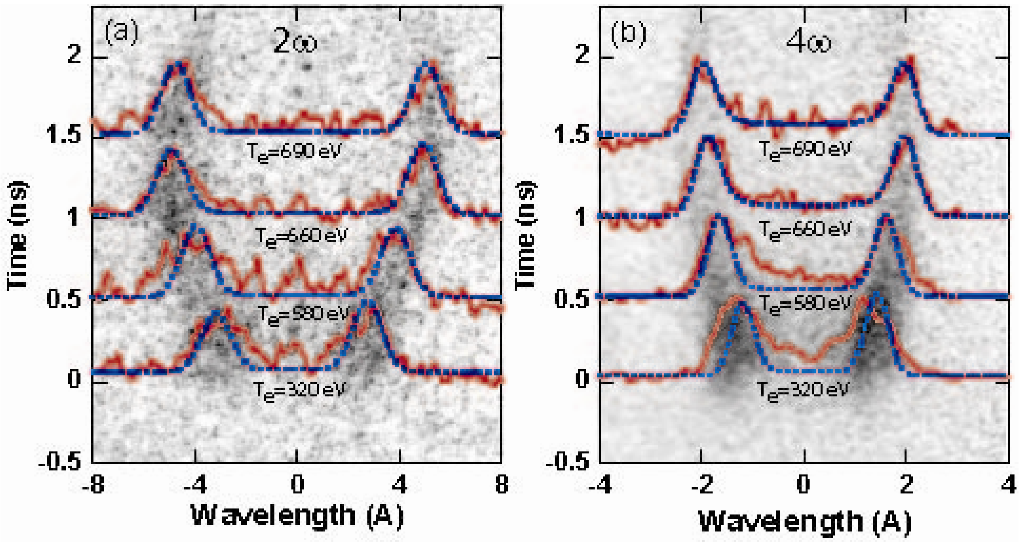

Figure 2: Time-resolved Thomson scattering spectra from the same scattering volume (r=500 μm) in the gas-jet plasma showing the dispersive nature of the plasma; as the plasma temperature increases, the wavelength separation of the ion acoustic peak probed with the 2ω laser increase faster than those probed with the 4ω laser. The theoretical form factor is fit for each time (dashed-blue line).

The density profile in the gas jet was measured (Figure 3) using the multiple wavelength Thomson-scattering diagnostics that simultaneously measure two independent ion-acoustic frequencies. These measurements show good agreement to the independent interferometer results. For each data shot, the electron density was determined at the time of peak temperature where the system is most sensitive to electron density. The relative error in the position of the density measurement is shown by the horizontal error bars; the absolute radial position of the data set was moved by 200 μm which is within the positioning error previously discussed. The density profiles are shown to vary by less than 20% over the time of the experiment using a hydrodynamic simulation performed with the code HYDRA (Figure 3). The HYDRA simulations used the experimental laser parameters and the 3-dimensional neutral gas density profile measured using interferometry as initial conditions.

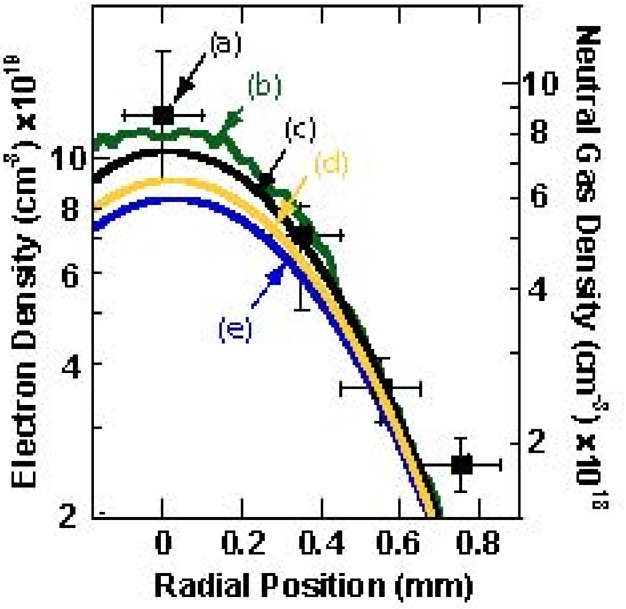

Figure 3: (a) Two Thomson-scattering diagnostics were used to measure the electron density profile of the plasma (squares). (b) The 3-D neutral density profile (green curve) for the gas jet was measured using interferometry 1.5 mm above the gas jet (right axis). Hydrodynamic simulations used the initial measured 3-D profile to calculate the electron density; (c) t=0.25ns, (d) t=0.5ns, (e) t=1.0ns.

Using Thomson scattering to probe ion-acoustic frequencies with significantly different wave vectors allows the measure of the local electron density and temperature. This technique is well suited for large laser facilities[3,4] where other diagnostics have not been successful in measuring local electron plasma density and temperature. Two ion-acoustic frequencies can be measured by either using two probe wavelengths or a single probe laser with two different scattering angles. A small angle diagnostic ($\mathbf{k}_a^1$) can be chosen to provide a good measure of the electron temperature with a small dependence on the density ($\mathbf{k}_a^1\lambda_{De} < 1$) while a large angle diagnostic ($\mathbf{k}_a^2$) would provide a good measure of the electron density ($\mathbf{k}_a^2\lambda_{De} > 1$). There is a limitation for large angles (for a given probe wavelength) given by the constraint of remaining in the collective Thomson scattering regime (ZT_e/T_i >> $k_a^2\lambda_{De}^2$) while there is a practical limit for small angles given by the instruments ability to resolve the spectral peaks (i.e. the wavelength separation scales with the angle).

For a typical inertial confinement fusion plasma[1] (T_e=5 keV, n_e=5x10^{20} cm^{-3}) the optimal scattering angles for the two collection optics are $40^o < \theta_{k2} < 80^o$ ($0.4 < k_2\lambda_{De} < 0.7$) and $\theta_{k1} > 140^o$ ($k_1\lambda_{De} > 0.9$); using these scattering angles, a single 4ω probe laser, and typical instrument resolutions, the local density could be measured to better than 25% with an electron temperature measurement to within 10%.

4. Conclusions

We have fielded Thomson scattering to measure plasma parameters of laser-produced plasmas by making use of the fact that the phase velocity of ion-acoustic fluctuations is dependent on their frequency; this measure of the dispersion of ion-acoustic fluctuations is of great importance for the understanding of ion-acoustic fluctuations in dense high-temperature plasmas. We have demonstrated a novel technique for measuring the electron density and temperature, which is in good agreement with independent interferometry measurements and hydrodynamic simulations

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References

1. J. D. Lindl, Phys. Plasmas **2**, 3933 (1995); J. D. Lindl *et al*., ibid **11**, 339 (2004).
2. S. H. Glenzer *et al*., Phys. Rev. Lett. **77**, 1496 (1996); ibid **97**, 1277 (1997); ibid **82**, 97 (1999); Phys. Plasmas **6**, 2117 (1999);
3. J. Soures *et al*., Fusion Technol. **30**, 492 (1996).
4. A. J. Mackinnon *et al*., Rev. Sci. Instrum. **75**, 3906 (2004).