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Thomson scattering diagnostic for the measurement of ion species fraction*

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Simultaneous Thomson scattering measurements of collective electron-plasma and ion-acoustic fluctuations have been utilized to determine ion species fraction from laser produced CH plasmas. The CH_2 foil is heated with 10 laser beams, 500 J per beam, at the Omega Laser facility. Thomson scattering measurements are made 4 mm from the foil surface using a 30 J 2ω probe laser with a 1 ns pulse length. Using a series of target shots the plasma evolution is measured from 2.5 ns to 9 ns after the rise of the heater beams. Measuring the electron density and temperature from the electron-plasma fluctuations constrains the fit of the two-ion species theoretical form factor for the ion feature such that the ion temperature, plasma flow velocity and ion species fraction are determined. The ion species fraction is determined to an accuracy of ± 0.06 in species fraction.

INTRODUCTION

Thomson scattering [1] has demonstrated its utility as a valuable diagnostic for understanding plasma conditions in high energy density experiments. This technique provides a non-invasive way to measure bulk plasma parameters such as electron and ion temperature, electron density, plasma flow, and ionization state [2–4]. Thomson scattering has also been used to determine ion species fraction in the presence of a background magnetic field [5]. We show that it is possible to measure the ion species fraction to better than ± 0.06 for a range of non-magnetized plasmas using Thomson scattering. A direct measurement of ion species fraction can be useful when studying a wide range of multi-ion species plasmas, a few exampeles include ion species separation in a capsule ablator [6] or collisionless shock creation from counterstreaming plasma flows [7].

Thomson scattering [1, 8, 9] is used to characterize the laser-produced [10] plasma by fitting the measured data with the Thomson scattering cross-section defined by the dynamic structure factor, $S(\mathbf{k},\omega)$. The dynamic structure factor is,

$$\frac{|\epsilon|^2}{2\pi} S(\mathbf{k},\omega) = |1+\chi_i|^2 F_e\left(\frac{\omega}{k}\right) + |\chi_e|^2 \sum_{j\in ions} \frac{n_j}{n_e} Z_j^2 F_j\left(\frac{\omega}{k}\right) \tag{1}$$

where ω is the frequency of the scattering wave, Z_j is the charge state of ion species j, n_e is the electron density, n_j is the ion density of species j, $\epsilon = 1+\chi_i+\chi_e$, χ_i and χ_e are the ion and electron susceptibility respectively, $F_j \equiv \int d^3v f_j(\vec{v})\delta(\omega + \vec{k}\cdot\vec{v})$, f_e and f_j are the particle distributions for electrons and ion species j respectively, $\vec{k} = \vec{k}_s - \vec{k}_0$, $\vec{k}_o$ is the wave number of probe beam, and $\vec{k}_s$ is the wave number of the scattered light. The

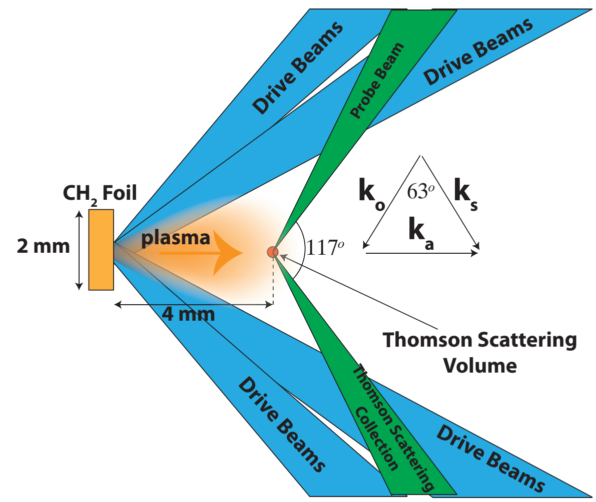

FIG. 1: The experimental configuration is shown. The CH_2 foil is heated with 10 drive beams. The plasma is probed 4 mm from the foil surface using Thomson scattering. The Thomson scattering k-vector diagram is also shown.

complete Thomson scattering spectrum, scattering from high frequency fluctuations (electron feature) and low frequency fluctuations (ion feature), is measured. The electron temperature and density, the ion temperature (T_i), the plasma flow velocity, and the ion species fraction are then determined with high accuracy by comparing the Thomson scattering cross section, calculated using Eq. 1, to the scattered spectra.

A CH_2 foil is positioned 4 mm from the target chamber center (TCC) as shown in Figure 1. The foil is 2 mm in diameter and 0.5 mm in thickness. It is heated with ten 351 nm, laser beams. Each beam delivers 500 J in a 1 ns square pulse. The beams use distributed phase plates to produce supergaussian focal spots with a supergaussian exponent of 4.3 and a diameter of ~250 μm. This results in an overlapped laser intensity of ~10^{16} W/cm^2 with a smooth spatial profile.

A 527 nm laser beam is used as a Thomson scattering

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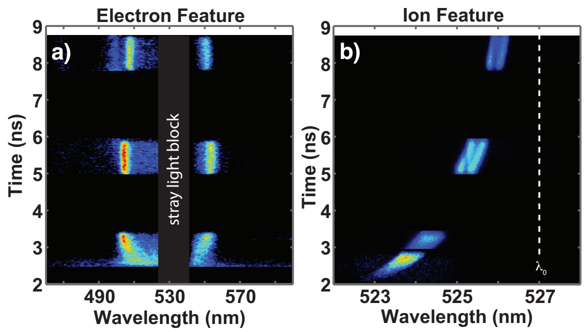

FIG. 2: A composite image is shown of the electron feature (a), and the ion feature (b). A notch filter centered at 532 ns is used to reject stray light from the electron feature measurement. A dashed line in (b) is shown at the wavelength of the Thomson scattering probe beam.

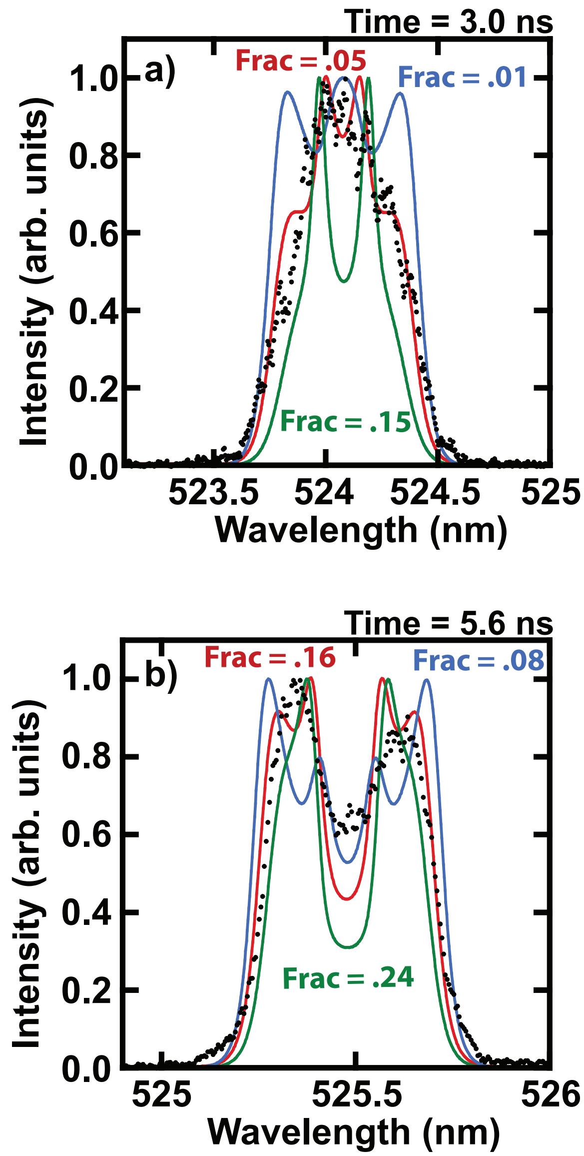

FIG. 3: The Thomson scattering cross section defined by Eq. 1 is compared to the experimental data ion feature (black dots) for a range of ion species fractions. a) The best fit to the experimental data at 3.0 ns using an electron temperature of 140 eV and an electron density of 2.8×10^{18} cm^{-3}, both measured from the electron feature, has a carbon fraction of 0.05 (red line) and an ion temperature of 60 eV, carbon fractions of 0.01 (blue line) and 0.15 (green line) are also shown. (b) The best fit at 5.6 ns using an electron temperature of 95 eV and an electron density of 5.6×10^{18} cm^{-3} has a carbon fraction of 0.16 (red line) and an ion temperature of 35 eV, carbon fractions of 0.08 (blue line) and 0.24 (green line) are also shown.

probe. The probe beam is focused at TCC and has a 70 μm diameter focal spot and a pulse length of 1 ns. A total probe energy of 30 J was used. The Thomson scattered light is collected 116.8° relative to the probe resulting in a probed k-vector normal to the target surface, as shown in Figure 1.

The raw Thomson scattering data are shown as a composite image in Figure 2. The electron feature [Fig. 2 (a)] is use to measure the electron temperature and density [7] which range from 250 eV to 80 eV and 1.7×10^{18} cm^{-3} to 5.5×10^{18} cm^{-3} respectively. The electron temperature and density are measured with an uncertainty of $\pm 15\%$. The separation of the peaks observed in the electron feature is dominated by the electron density. The width of the peak is a function of the electron temperature. Once the electron temperature and density have been measured from the electron feature it is possible to determine the ion temperature, the flow velocity, and the ion species fraction from the ion feature. The wavelength shift of the ion feature from the incident wavelength is used to measure the flow velocity. The shape of the ion feature can then be used to measure the ion temperature and ion species fraction.

In Figure 3 the experimental data ion feature at 3.0 ns [Fig. 3 (a)] and 5.6 ns [Fig. 3 (b)] is compared to the Thomson scattering form factor for a range of ion species fractions. The electron feature is insensitive to the ion species fraction. As the fraction of carbon to hydrogen is varied the Thomson scattering ion feature spectrum changes from two slow mode peaks with a small wavelength separation for a high carbon fraction [green curve, Fig. 3 (b)]. Four peaks are observed when the damping is similar for the slow mode and fast mode peaks [red curve, Fig. 3 (b)]. Finally for very low carbon fraction the spectrum is dominated by fast mode peaks with a large spectral separation [blue curve, Fig. 3 (b)]. Where this transition from two slow mode peaks to four peaks to two fast mode peaks is governed by the relative damping between modes and is sensitive to the ion species fraction as well as the ion temperature. The uncertainty in the ion species fraction measurement is determined by calculating a series of Thomson scattered spectra with electron temperature and electron density values ranging

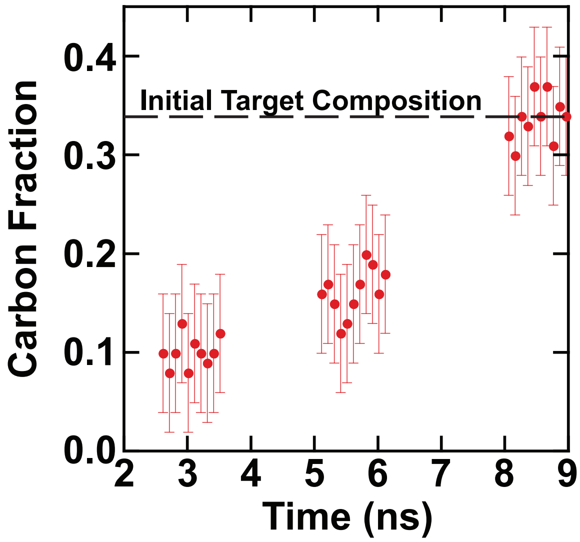

FIG. 4: The ion species fraction is measured from 2.5 ns until 9 ns using a series of target shots. Early in time predominately hydrogen in measured. The initial target composition of 33% carbon and 67% hydrogen is shown as the dashed line.

over their respective uncertainties determined from the electron feature, the ion species fraction and ion temperature are then varied to fit the experimental data ion feature within the experimental noise. Systematic uncertainties, for example, the absolute calibration of the wavelength, are also taken into account.

Figure 4 shows the ion species fraction measurement for a CH_2 foil target. At 2.5 to 3.5 ns the plasma is measured to be predominantly hydrogen with a species fraction of 0.9 hydrogen and 0.1 carbon. As time progresses the fraction of carbon increases to ~ 0.18 carbon at 5.5 ns and ~ 0.33 carbon after 8 ns which is the initial target composition. Ion species separation effects in inertial confinement fusion targets is an active field of research [6] where this Thomson scattering technique can make a significant contribution.

CONCLUSIONS

Thomson scattering is a powerful diagnostic for characterizing laser plasmas. It has been used extensively to measure the ion and electron temperatures, the electron density, and the plasma flow velocity. We show that it can also be used to measure the ion species fraction to an accuracy of ± 0.06 in species fraction for CH_2 laser ablated plasma. Experiments are plans to measure ion species mixing and separation to better understand laser ablated plasma. This work was performed under the auspices of the Department of Energy by Lawrence Livermore National Laboratory under Contract No. DE-AC52-07NA27344.

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