LLNL-JRNL-489959

LAWRENCE LIVERMORE NATIONAL LABORATORY

Ultraviolet Thomson scattering measurements of the electron feature with an energetic 263 nm probe

J. S. Ross, L. Divol, C. Sorce, D. H. Froula, S. H. Glenzer

June 29, 2011

Journal of Instrumentation (JIST)

Disclaimer

Ultraviolet Thomson scattering measurements of the electron feature with an energetic 263 nm probe

J. S. Ross[1], L. Divol[1], C. Sorce[1], D. H. Froula[2], and S. H. Glenzer[1]
[1] *L-493, Lawrence Livermore National Laboratory, University of California, P.O. Box 808, Livermore, California 94551 and*
[2] *Laboratory for Laser Energetics, University of Rochester, Rochester, New York 14623*

A new Thomson scattering diagnostic has been implemented on the Omega Laser facility at the Laboratory for Laser Energetics, University of Rochester[J. M. Soures, et al., Laser and Particle Beams **11**, 317 (1993)] to measure the electron feature in the ultraviolet wavelength range 200 nm - 263 nm. A pair of imaging spectrometers and streak cameras collect light scattered from electron plasma fluctuations and ion-acoustic fluctuations simultaneously. This spectrum allows an accurate measurement of the electron temperature, density, average charge state and plasma flow velocity in a high-density laser plasma regime perviously inaccessible.

PACS numbers:

I. INTRODUCTION

Thomson Scattering is a valuable diagnostic of plasma characteristics at large laser facilities [1] and has been used to measure the electron temperature in a range of important laser produced plasmas. For example, Thomson scattering measurements have been made from disk targets [2, 3], large scale length gas-bag plasmas [4] and closed geometry gas-filled and vacuum hohlraums [5]. Thomson scattering has been used extensively at the Nova laser facility [2], the Omega laser facility [6], and recently at the Titan laser facility [7] using a 4ω probe laser. A Thomson scattering diagnostic is currently being developed for the National Ignition Facility. The abilities of this diagnostic at the Omega Laser Facility have recently been expanded to include the measurement of the Thomson scattering electron feature using a 4ω probe [6].

The diagnostic now allows spatially resolved measurements of electron temperature, T_e, ion temperature, T_i, density, n_e, and average charge state, Z. In this paper measurements at the Omega laser facility from a Vanadium foil blow-off plasma will be discussed. Scattering from the electron feature has seen limited application at large laser facilities due to its low scattered intensity coupled with the large spectral range of the measurement over which stray light sources must be minimized. Previous measurements of the electron feature have been made at the Nova Laser Facility using a 2ω probe laser [2]. A 4ω probe beam is being used at the Omega Laser facility which has reduced absorption and refraction compared to a 2ω probe allowing measurements at densities up to 1×10^{22} cm^{-3}. This density regime is important for inertial confinement fusion hohlraums and eventual experiments on the National Ignition Facility. Previous measurements using a 2ω probe were limited to a maximum density of 4×10^{21} cm^{-3} [2].

Thomson Scattering uses a probe beam with frequency (ω_o) and wave number ($\vec{k}_o$) to scatter from electron density fluctuations with a given wave number ($\vec{k}$).

$$\vec{k} = \vec{k}_s - \vec{k}_0 \tag{1}$$

The light scattered (with wave vector $\vec{k}_s$) by these electrons provides a measure of the dynamic structure factor, $S(\mathbf{k}, \omega)$, yielding a measurement of local plasma parameters. Assuming maxwellian velocity distributions, the dynamic structure factor is then,

$$S(\mathbf{k}, \omega) = \frac{2\pi}{k}\left|1 - \frac{\chi_e}{\epsilon}\right|^2 f_{e0}\left(\frac{\omega}{k}\right) + \frac{2\pi Z}{k}\left|\frac{\chi_e}{\epsilon}\right|^2 f_{i0}\left(\frac{\omega}{k}\right) \tag{2}$$

where ω and $\mathbf{k}$ are the frequency and wave vector of the scattering wave, Z is the charge state, χ_e is the electron component of the dielectric function, $\epsilon = 1 + \chi_i + \chi_e$, and f_{e0} and f_{i0} are the maxwellian distributions for electrons and ions respectively. This technique has been widely used in the characterization of laser plasmas by measuring scattering from ion-acoustic fluctuations [1–9]. The wavelength separation between two ion-acoustic resonances ($\Delta\lambda_{IAW}$) [10] is approximately,

$$\frac{\Delta\lambda_{IAW}}{\lambda_0} \cong \frac{4}{c}\sin\left(\frac{\theta}{2}\right)\sqrt{\frac{T_e}{M}\left(\frac{Z}{1 + k^2\lambda_D^2} + \gamma\frac{T_i}{T_e}\right)}, \tag{3}$$

where λ_0 is the probe laser wavelength, θ is the scattering angle, γ is the specific heat ratio, T_e and T_i are the electron and ion temperatures respectively, $\lambda_D = \sqrt{\kappa_b T_e / 4\pi n_e e^2}$ is the Debye length, and κ_b is the Boltzman constant. The separation between ion-acoustic resonances is used primarily to measure ZT_e and in a multiple ion species plasma the shape of the ion-acoustic resonances can be used to measure T_i [11]. It is also possible to measure the electron density by measuring a pair of ion-acoustic resonances with significantly different k-vectors [12]. For comparison, an expression for the wavelength separation between electron-plasma resonances ($\Delta\lambda_{EPW}$) [13], assuming $\theta = 90°$ and $n_e/n_c \lesssim 0.05$,

$$\frac{\Delta\lambda_{EPW}}{\lambda_0} \approx 2\left[\frac{n_e}{n_c} + 6\left(\frac{v_{th}}{c}\right)^2\right]^{1/2}\left(1 + \frac{3}{2}\frac{n_e}{n_c}\right), \tag{4}$$

where $v_{th} = \sqrt{\kappa_b T_e / m_e}$ is the electron thermal velocity, n_c is the critical density and m_e is the mass of an electron.

II. EXPERIMENTAL SETUP

A. Target and Beams

The target (Fig. 1) is a vanadium foil with a length and width of 2 mm and a thickness of 0.1 mm respectively. A single 351 nm (3ω) beam is used to irradiate the target producing a blow-off plasma. The target is heated with 500 J in a 1 ns flat top laser pulse with 0.1 ns rising and falling edges. An elliptical phase plate is used to generate a 300 μm diameter laser spot on the target. The angle between the incident beam and the target normal is 6.4°. A 1 ns, 263 nm (4ω) beam[6] with a maximum energy of 200 J is used as the Thomson scattering probe for this experiment. The Thomson scattering probe beam is delayed 1 ns relative to the 3ω heater beam. The foil is aligned such that the 4ω probe beam (P9 axis) and the direction of scattered light collection (TIM-6) are tangent to the foil surface and at a distance of 400 μm from that surface. This results in a k-vector parallel to the target surface.

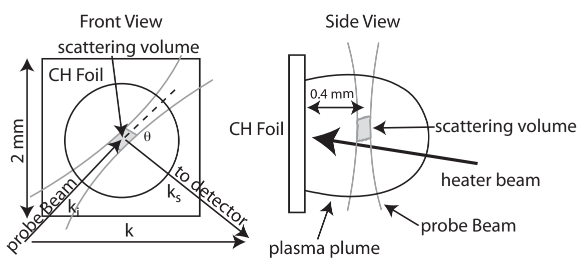

FIG. 1: The target configuration is shown. The angle between the incident heater beam and the target normal is 6.4°. The angle between the probe beam and the collection optics is 116.8°. The Thomson scattering volume is located 400 μm from the foil surface.

B. Thomson Scattering Diagnostic

The Thomson-scattered light of the probe laser in the plasma is collected with an achromatic fused silica f/10 lens with a focal length of 50 cm. The optic is mounted in a Ten Inch Manipulator (TIM-6) at a distance of 50 cm from the plasma. The angle between TIM-6 and the input port (P9) of the TS probe is 116.8°. A fused silica blast shield is mounted before the collection optic. The collimated light is then transported by a series of turning mirrors to a 1 m spectrometer and a 1/3 m spectrometer located 3 meters from the target chamber. A polka dot beam splitter, used to minimize wavelength sensitivity, splits the scattered signal between the two spectrometers. A 7.5 cm focusing mirror with a 75 cm focal length

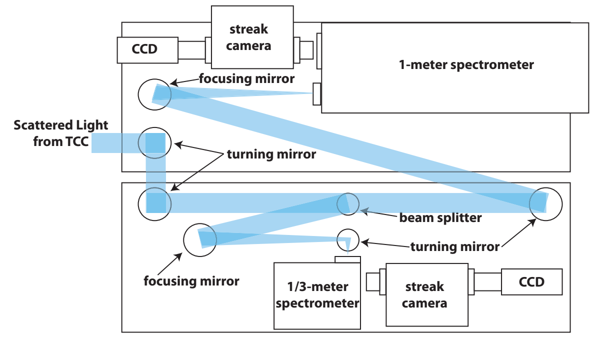

FIG. 2: The diagnostic setup is shown, the beam path is shown in blue. The system is fielded on two 6'x2' bread-boards.

images the scattered light onto the entrance slit of the 1 m spectrometer with a magnification of 1.5:1. The spectrometer uses a 3600 lines/mm grating and a 100 μm entrance slit. A Hamamatsu 7700 streak camera is coupled to the output of both spectrometers. A 7.5 cm focusing mirror with a 45 cm focal length images onto the entrance slit of the 1/3-meter spectrometer with a magnification of 0.9:1. The 1/3-meter spectrometer uses a 150 lines/mm grating and a 100 μm entrance slit. The Thomson scattering volume (100μm$\times100\mu$m$\times300\mu$m) is defined by the overlap of both slit images (100μm$\times100\mu$m), the streak camera slit and the spectrometer slit, in the plasma with the probe beam (300μm diameter).

C. System Alignment

The system is aligned using a 400 μm fiber positioned at the Thomson-scattering volume. Initial alignment is performed by injecting a CW 532nm ~5 mW laser into the fiber which is directed towards the collection lens. The lens is positioned to collimate the light collected from the fiber. The light is then imaged on the slits of the spectrometers using a series of turning mirrors and a pair of focusing mirrors. When light from the Thomson-scattering volume is visible on the streak camera systems the 532nm laser is replaced with a 4ω alignment laser. The system is achromatic and the 4ω light is visible on the streak camera.

The filber is then retracted 40 mm and a grid is positioned at the Thomson-scattering volume. Both systems are then focused using this grid target which is also used to measure the magnification of the system. Finally the grid is replaced with a 100μm sphere and imaged on both systems. The spectrometer and streak camera slits are closed around the sphere defining the Thomson-scattering volume in the target plane.

D. System Characterization

The spectral resolution of the 1-meter system was measured using Hg lines around 310 nm and found to be $\delta\lambda/\lambda = 1 \times 10^{-4}$. The Hg spectra is also used to measure the spectral dispersion; the dispersion increases by 9% from 310 nm to the measurement region (0.0055 nm/pix at 264 nm) due to the change in the grating angle. The spectral resolution of the 1/3-meter system is $\delta\lambda/\lambda = 8.2 \times 10^{-3}$.

To determine the in situ resolution and focus of the collection system, a grid is centered at the Thomson-scattering volume. Figure 3(a) shows an image of the grid back illuminated through the 1/3-meter system and Figure 3(b) through the 1-meter system. Features less than 60 μm are visible indicating a spatial resolution of this order. The magnification of the system is measured by comparing a known spectral slit width to the 63.5 μm grid spacing.

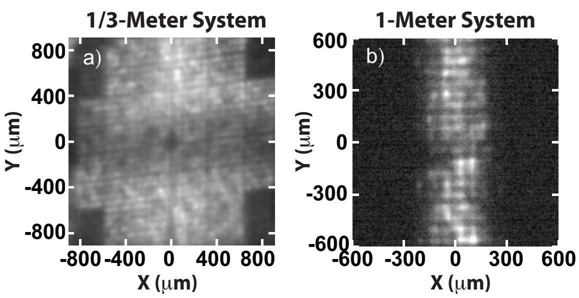

FIG. 3: A grid is imaged to focus the system and measure the magnification. Both the 1/3-meter system (a) and the 1-meter system (b) can resolve the fine grid lines which have a spacing of 63.5 μm. The grid in image is shown with a partially closed spectrometer slit for the 1-meter system.

III. EXPERIMENTAL RESULTS

Thomson scattering from ion-acoustic waves and electron plasma wave fluctuations has been measured simultaneously providing a local and simultaneous measurement of the electron and ion temperatures, the electron density, and plasma flow velocity as a function of time. The raw Thomson scattering spectrum of the electron feature is shown in Figure 4. The Thomson scattering signal starts at 1 ns into the experiment consistent with the timing of the 4ω probe beam. The electron plasma wave resonance is peaked at 225 nm at 1 ns with the wavelength increasing to 235 nm at 2 ns. The observed wavelength of the electron-plasma wave resonance is determined by the Bohm Gross relation and proportional to the square root of the electron density. The spectrum at 1.7 ns is compared with the Thomson scattering dynamic structure factor (Eq. 2) allowing a measurement of the plasma characteristics.

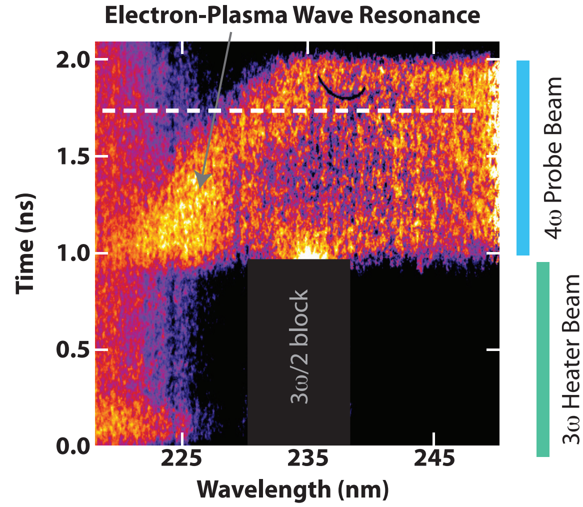

FIG. 4: High-frequency Thomson scattering data measured from a Vanadium foil target at the Omega Laser Facility using a 4ω probe beam. A $3\omega/2$ block is used to suppress light generated by the 3ω heater beam. The spectrum at 1.7 ns (white dashed line) is shown in Fig. 6 (a).

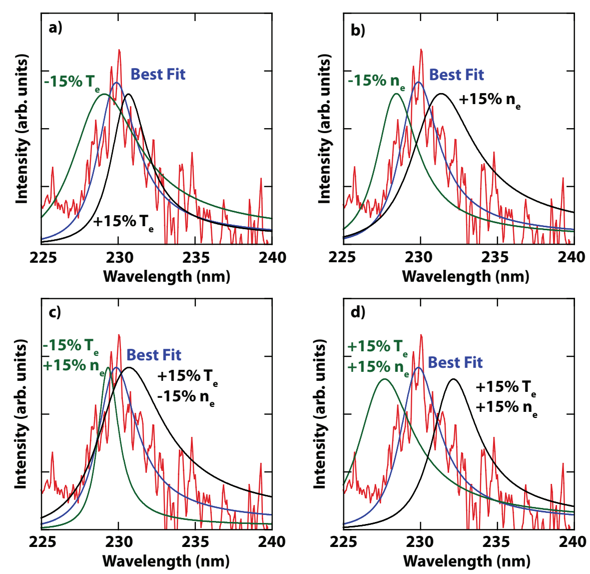

FIG. 5: The electron feature is measured from a Vanadium foil target at 1.7 ns and compared to the Thomson scattering form factor (Eq. 2) with a best fit (blue lines) electron temperature of 0.9 keV and an electron density of 1.9×10^{20} cm^{-3}. The electron temperature is varied by $\pm 15\%$ (a), the electron density is varied by $\pm 15\%$ and then both are varied simultaneously (c, d) showing sensitivity of the calculated spectrum.

The measured electron and ion temperatures are shown in Figure 7 (a) and the electron density in Figure 7 (b). The electron density is compared to previous 2ω Thomson scattering measurements made from a gold foil by Glenzer et al, [2] before 1.5 ns the densities agree to better than 10%, after 1.5 ns the agreement is within

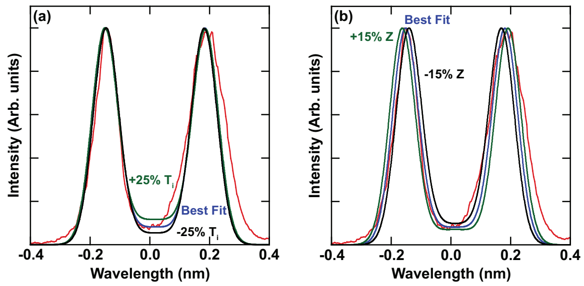

FIG. 6: The ion feature (red line) is measured from a Vanadium foil target at 1.7 ns and compared to the Thomson scattering form factor (Eq. 2, blue line) with an electron temperature of 0.9 keV, an ion temperature of 0.6 keV, an electron density of 1.9×10^{20} cm^{-3}, and an average ionization state of Z = 21. (a) The ion temperature and (b) average ionization state are varied to show the sensitivity of the fit. The wavelength is measured relative to the Thomson scattering probe wavelength of 264 nm.

25%. Both measurement were made 400 μm from the target surface. The average ionization state of the vanadium plasma is measured to be nearly fully ionized with $Z = 22^{+1}_{-3}$ for all measured times.

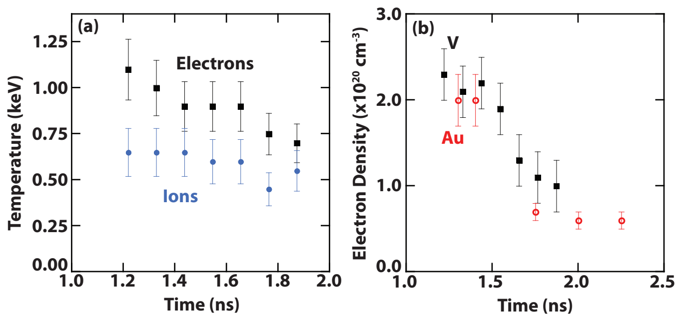

FIG. 7: (a) The Vanadium foil measurements of the electron (squares) and ion (circles) temperatures and the (b) electron density (squares) as a function of time are shown. The electron density is compared to 2ω measurements made in gold (open circles) by Glenzer et al.[2].

IV. CONCLUSIONS

A new Thomson-scattering diagnostic has been demonstrated at the Omega laser facility allowing the characterization of high-density plasmas. The spatial, spectral, and temporal resolutions of the system has been measured. The blow-off plasma from a vanadium foil was characterized and the measured density compares well to previous Thomson scattering measurements using a 2ω probe laser. Future foil experiments are planned to study nuclear excitation from atomic transitions in hot plasma and the generation of collisionless shocks via the Weibel instability. This work was performed under the auspices of the Department of Energy by Lawrence Livermore National Laboratory under Contract No. DE-AC52-07NA27344. W-7405-ENG-48.

[1] S. H. Glenzer, W. E. Alley, K. G. Estabrook, J. S. De Groot, M. G. Haines, J. H. Hammer, J. P. Jadaud, B. J. MacGowan, J. D. Moody, W. Rozmus, et al., Physics of Plasmas **6** (1999).

[2] S. H. Glenzer, W. Rozmus, B. J. MacGowan, K. G. Estabrook, J. D. De Groot, G. B. Zimmerman, H. A. Baldis, J. A. Harte, R. W. Lee, E. A. Williams, et al., Physical Review Letters **82**, 97 (1999).

[3] J. L. Kline, D. S. Montgomery, R. P. Johnson, and T. Shimada, J Instrum **5**, P11005 (2010).

[4] K. B. Fournier, C. Constantin, C. A. Back, L. Suter, H. K. Chung, M. C. Miller, D. H. Froula, G. Gregori, S. H. Glenzer, E. L. Dewald, et al., Journal of Quantitative Spectroscopy and Radiative Transfer **99**, 186 (2006).

[5] D. H. Froula, J. S. Ross, L. M. Divol, N. Meezan, A. J. Mackinnon, R. Wallace, and S. H. Glenzer, Phys Plasmas **13**, 052704 (2006).

[6] A. J. MacKinnon, S. Shiromizu, G. Antonini, J. Auerbach, H. Haney, D. H. Froula, J. Moody, G. Gregori, C. Constantin, C. Sorce, et al., Review of Scientific Instruments **75**, 3906 (2004).

[7] J. S. Ross, J. L. Kline, S. Yang, M. Henesian, T. Weiland, D. Price, B. B. Pollock, and S. H. Glenzer, *4 omega thomson scattering probe for high-density plasma characterization at titan* (2010).

[8] D. Montgomery, R. P. Johnson, J. A. Cobble, J. Fernandez, E. L. Lindman, H. A. Rose, and K. G. Estabrook, Laser and Particle Beams p. 349 (1999).

[9] H. A. Baldis, C. J. Walsh, and R. Benesch, Applied Optics **21**, 297 (1982).

[10] D. H. Froula, J. S. Ross, L. Divol, and S. H. Glenzer, Rev Sci Instrum **77**, 10E522 (2006).

[11] S. Glenzer, C. Back, K. Estabrook, R. Kirkwood, R. Wallace, B. MacGowan, B. Hammel, R. Cid, and J. DeGroot, *Thomson scattering from two-species laser-produced plasmas (invited)* (1997).

[12] D. Froula, P. Davis, L. Divol, J. Ross, N. Meezan, D. Price, and S. Glenzer, Phys Rev Lett **95**, 195005 (2005).

[13] J. S. Ross, S. H. Glenzer, J. P. Palastro, B. B. Pollock,

D. Price, G. R. Tynan, and D. H. Froula, *Thomson-scattering measurements in the collective and noncollective regimes in laser produced plasmas (invited)* (2010).