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Abstract

Imaging Thomson Scattering 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)]. Using a high resolution spectrometer and an intensified CCD the electron temperature profile, ranging from 1.5 keV to 3 keV, was measured along the axis of a CH gas filled hohlraum. The system integrates over 200 ps a region 2 mm in length and has a spatial resolution of 50 μm and a spectral resolution of 0.027nm. Data obtained from this diagnostic are compared to hydrodynamic simulations.

PACS numbers:

I. INTRODUCTION

Thomson Scattering has been a valuable diagnostic of plasma characteristics at the Omega Laser Facility[1]. It has recently been used to measure the electron temperature in a Kr gas-bag plasma[2] as well as the electron temperature and ion temperature in a CH filled hohlraum[3], both comparable to hydrodynamic simulations. The abilities of this diagnostic have recently been expanded to include Imaging Thomson Scattering (ITS) which allows spatially resolved measurements of electron temperature, T_e and density, n_e, along a region of plasma greater than $z = 2$ mm in length. This imaging capability will allow accurate gradient measurements facilitating comparisons between experimental results and hydrodynamic simulations used in designing future inertial confinement fusion targets. ITS will help address outstanding questions regarding T_e profiles in gas filled hohlraums and the effect of magnetic fields on electron thermal transport[4, 5].

Thomson Scattering uses a probe beam with frequency (ω_o) and wave number (k_o) to scatter from electron density fluctuations with a given wave number (k_a). When the correct wave number (k_a) is probed $(ZT_e/T_i > k_a^2\lambda_{De}^2)$ the electrons in the plasma that follow the motion of the ions dominate the scattering process. The light scattered by these electrons provides a measure of the dynamic ion structure factor, $S(\mathbf{k}, \omega)$, yielding the ion-acoustic sound speed, ion wave damping, as well as the local particle flow velocity. The sound speed is directly related to the electron temperature (T_e),

$$\left(\frac{\omega_a}{k_a}\right)^2 = \frac{T_e}{M}\left(\frac{Z}{1 + k_a^2\lambda_{De}^2} + \Gamma\frac{T_i}{T_e}\right) \tag{1}$$

where ω_a is the ion acoustic frequency, M is the ion mass, Z is the charge state, T_i is the ion temperature, λ_{De} is the electron Debye length, and Γ is the specific heat ratio. This technique has been widely used in the characterization of laser plasmas[6, 7].

II. EXPERIMENTAL SETUP

A. Laser Configuration

A high-energy, ultraviolet probe beam[8] is used for Thomson scattering at the Omega Facility. The probe operates at a wavelength of 264 nm (4ω) with a maximum energy of 200 J in a 1 ns square pulse. In addition to 1 ns-long probe laser pulses, 200 ps-long pulses may

also be applied with a corresponding maximum energy of 40 J. The beam is focused using a 4ω aspheric f/6.7 lens with a best vacuum focal spot of 60 μm.

B. Imaging 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-2) at a distance of 50 cm from the plasma. The angle between TIM-2 and the input port (P9) of the 4ω probe is 79°. A fused silica blast shield coated to reject the light from the heater beams (3ω) is mounted before the collection optic. The collected light is then transported by a series of turning mirrors to a 1 m spectrometer located 10 m from the target chamber. A 7.5 cm focusing mirror with a 75 cm focal length images the scattering light onto the slit of the spectrometer with a magnification of 1.5. The spectrometer uses a 3600 lines/mm grating and a 100 μm entrance slit. An intensified, gated 16-bit CCD, model I-MAX-512-T, is coupled to the output of the spectrometer.

To image the hohlraum axis along the entrance slit of the spectrometer we mounted the spectrometer on a stage to rotate it around the center of the entrance slit(Fig. 1). This procedure was preferred compared to a two-mirror periscope[9] to accommodate fast alignment. It is critical for imaging Thomson scattering to align the image of the spectrometer entrance slit in the plasma with the probe beam; if the slit is not aligned to the probe beam within 5° Thomson-scattered light will not propagate through the spectrometer. The Thomson scattering volume (60μm$\times60\mu$m$\times2000\mu$m) is defined by the overlap of the slit image (80μm$\times2000\mu$m) in the plasma with the probe beam (60μm diameter).

C. System Alignment

The Thomson-scattering volume is aligned using a 100 μm fiber positioned at TCC. Initial alignment is performed by injecting a 532nm 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 slit of the spectrometer using a series of turning mirrors and a focusing mirror. Final focussing and alignment of the CCD is accomplished by imaging the slit of the spectrometer onto the CCD. When light from TTC is visible on the CCD the

532nm laser is replaced with a 4ω laser. The system is achromatic and it is now possible to set the spectrometer grating to first order for 4ω and image the fiber at TCC through the complete system.

To confirm alignment of the 4ω probe beam a $100\mu m$ sphere is positioned at TCC. Light scattered from the sphere is then imaged on the CCD confirming overlap of the 4ω probe beam and the Thomson scattering volume. The amount of light scattered is insufficient for initial alignment, but once the system is aligned can be easily detected.

D.   System Characterization

The spectral resolution was measured using Hg lines around 310 nm to have a FWHM=0.027 nm using a 50 μm slit. The Hg spectra are 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.

To determine the magnification, resolution and focus of the collection system, a grid [shown in Fig. 1(a)] with known orientation to the probe beam is centered at TCC. Figure 1(b) shows an image of the grid back illuminated by 4ω light when the spectral slit has been rotated to be parallel to the probe beam axis. In this image the spectrometer is rotated by 52 degrees from its nominal vertical position used for streaked Thomson-scattering measurements. Features less than 60 μm are visible indicating a spatial resolution of this order. The magnification of the system (M=1.8) is measured by comparing the 1 mm spectral slit width to the 63.5 μm grid spacing in the detector plane. Figure 1 shows the system has a large field of view along the probe beam axis ($>$ 2 mm) which allows temperature measurements along the complete 2 mm hohlraum axis (limited by the length of the diagnostic window in the hohlraum wall).

III.   EXPERIMENTAL RESULTS

A.   Target

The targets (Fig. 2) are gas-filled (1 atm of 1% Ar, 29% CH_4, 70% C_3H_8) gold hohlraums with a length of 2 mm and a diameter of 1.6 mm. The heater beams penetrate the hohlraum at one or both ends through laser entrance holes with a diameter of 0.8 mm which are covered

with polyimide membranes. The targets are heated with 16-37 3ω beams with total energies of 8 kJ to 17 kJ in a 1 ns flat top laser pulse with 0.1 ns rising and falling edges. The hohlraums are aligned along the propagation direction of the 4ω probe beam (P9 axis). A slot 1.6 mm in length and 0.5 mm in width is cut into the side of the hohlraum oriented to face the Thomson-scattering collection optics (TIM-2). The slot is covered with a polyimide membrane that is blown out by a heater beam during the experiment.

B.   Results

In Figure 3 imaging Thomson-scattering data shows a large temperature gradient along the axis of the hohlraum. A 1 ns probe beam was used and an integration time of less than 200 ps was achieved by triggering the CCD gate late in the probe beam pulse. The probe beam is delayed 300 ps relative to the heater beams. This gradient was produced by only heating the target with the heater beams on one side of the hohlraum. Over a 1 mm region inside the hohlraum the electron temperature varies from 1.5 keV to 3 keV. These temperatures where measured by fitting a multiple ion species form factor[10] to the experimental data. The error bars are obtained by varying the fits within the noise of the experimental data. This temperature gradient is in agreement with HYDRA simulations using a flux limited diffusion model.

IV.   CONCLUSIONS

A new imaging Thomson-scattering diagnostic has been demonstrated at the Omega laser facility. The spatial, spectral, and temporal resolutions have all been carefully measured. This diagnostic has already begun to produce high-quality data on temperature profiles in dense, high-Z plasmas, that can be used to benchmark hydrodynamic simulations. Future experiments will strive to further differentiate between a flux limited diffusion model and a nonlocal diffusion model. This work was supported by LDRD 06-ERD-056 and was performed under the auspices of the U.S. Department of Energy by the Lawrence Livermore

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[1] J. M. Soures, R. L. McCrory, T. R. Boehly, R. S. Craxton, S. D. Jacobs, J. H. Kelly, T. J. Kessler, J. P. Knauer, R. L. Kremens, S. A. Kumpan, et al., Laser Particle Beams **11**, 317 (1993).

[2] 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).

[3] D. H. Froula, J. S. Ross, L. M. Divol, N. Meezan, A. J. Mackinnon, R. Wallace, and S. H. Glenzer (2006), submitted to Phys Plasmas.

[4] 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).

[5] P. D. Nicolai, J. L. A. Feugeas, and G. P. Schurtz, Physics of Plasmas **13**, (2006), 028CH Times Cited:0 Cited References Count:36.

[6] 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).

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

[8] 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).

[9] G. Gregori, S. H. Glenzer, J. Knight, C. Niemann, D. Price, D. H. Froula, M. J. Edwards, R. P. J. Town, W. Rozmus, A. Brantov, et al., Physical Review Letters **92** (2004).

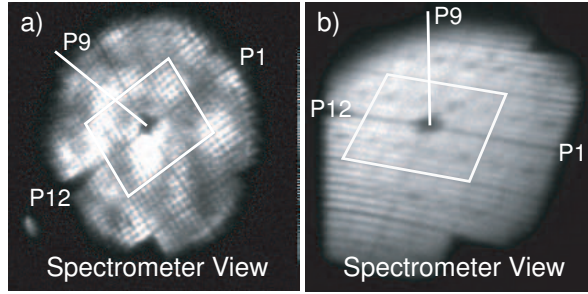[10] D. E. Evans, Plasma Physics **12**, 573 (1970).

Figures

FIG. 1: The grid located at TTC is imaged using a large spectrometer entrance slit. (a) Shows the grid with the spectral slit in the nominal vertical position and (b) shows the grid after the spectrometer has been rotated 52° aligning the probe beam (P9 axis) and the entrance slit.
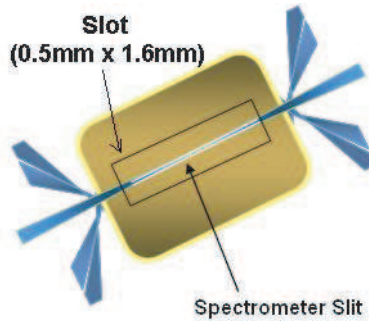

FIG. 2: 37 beams are used to heat the gas-filled hohlraum and the 4ω probe beam is aligned along the hohlraum axis. A slot 1.6 mm in length and 0.5 mm in width cut into the side of the hohlraum wall allows light scattered along the axis of the hohlraum to be collected by the imaging Thomson-scattering system.
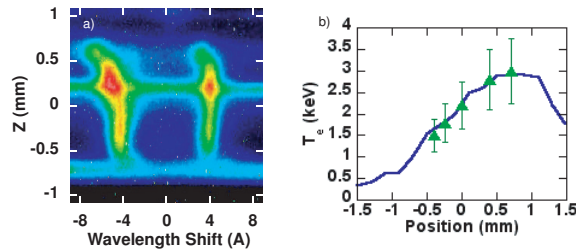

FIG. 3: (a) The Thomson-scattering spectrum shows a large temperature gradient along the axis of the hohlraum. (b) The electron temperature profile (triangles) shows close agreement with the HYDRA simulation (solid line) using a flux limited diffusion model with a flux limiter of 0.05.