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CHARACTERIZATION OF HIGH-TEMPERATURE LASER-PRODUCED PLASMAS USING THOMSON SCATTERING

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Ultraviolet Thomson scattering has been fielded at the Omega Laser Facility to achieve accurate measurements of the plasma conditions in laser-produced high-temperature plasmas. Recent applications to hohlraum targets that have been filled with CH gas or SiO_2 foams have demonstrated a new high temperature plasma regime of importance to laser-plasma interaction studies in a strongly damped regime such as those occurring in indirect drive inertial confinement fusion experiments. The Thomson scattering spectra show the collective ion acoustic features that fit the theory for two ion species plasmas and from which we infer the electron and ion temperature. We find that the electron temperature scales from 2 – 4 keV when increasing the heater beam energy into the hohlraum from 8 - 17 kJ, respectively. Simultaneous measurements of the stimulated Raman scattering from a green 527 nm interaction beam show that the reflectivity decreases from 20% to 1% indicating that this instability is strongly damped at high temperatures. These findings support green laser beams as possible driver option for laser-driven fusion experiments.

1. Introduction

Inertial confinement fusion and high energy density science experiments require direct and accurate measurements of the plasma conditions. In the indirect drive approach to inertial confinement fusion, high-Z hohlraums are used as radiation enclosures converting high-power laser energy into a soft x-ray radiation field that drives the fusion capsule implosion by x-ray ablation pressure.[1] This approach requires that energetic laser beams propagate efficiently through the inside of the hohlraum before sticking the high-Z wall and producing x rays. The inside of the hohlraum will be filled with low-Z or mid-Z plasmas from initial fill material and from ablated material off the capsule and other lined hohlraum surfaces. The fill plasma reduces the inward motion of the high-Z wall plasma, which is the source of the x rays, thus obtaining a highly symmetric soft x-ray radiation pressure for symmetric high-convergence implosions. The physics in these ignition hohlraums is largely dominated by the laser-plasma interactions in the fill plasma where laser back scattering, beam deflection, laser beam filamentation and self focusing may occur when driving these parametric instabilities beyond their thresholds. To determine these thresholds and to model the laser-plasma interaction processes we apply plasma parameters from collective Thomson scattering measurements with an ultraviolet probe beam (266 nm) of present hohlraum experiments.

The experiments provide temporally and spatially resolved measurements of the electron temperature T_e, ion temperature T_i, and plasma flow **v** in high-temperature hohlraums.[2] The data are directly applied to calculate the gain of parametric instabilities and for comparisons with measurements of laser backscattering and transmission through the plasma.[3] Moreover, comparisons with radiation-hydrodynamic simulations provide a benchmark for calculations of hohlraum plasma conditions for future inertial confinement fusion experiments on the National Ignition Facility.[4]

In this study, the hohlraum plasmas have been produced at the Omega laser facility[5] using a range of heater beam energies from 8 -17 kJ to heat two millimeter long gold cavities filled with CH gas. By varying the heater beam energy two distinct regimes for 2ω laser-plasma interactions have been accessed; these are two ion species plasmas that scale from weak to strong Landau damping for electron plasma waves when electron temperatures increase from 1.8 keV to 3.5 keV with increasing heater beam energy. We observe nearly complete suppression of scattering losses by stimulated Raman scattering (SRS). In addition, CH plasmas provide strong ion Landau damping of the ion acoustic plasma waves in which case scattering losses by stimulated Brillouin scattering (SBS) are also expected to be less important than for mid-Z foam fills. To accurately calculate these damping increments and to assess the gain for scattering instabilities we quantitatively measure the electron and ion temperatures in these plasmas with ultraviolet Thomson scattering.

2. Experiment

The experiments were performed with the Omega laser facility at the Laboratory for Laser Energetics. The laser facility consists of 60 frequency triplet Nd:glass laser beams providing approximately 500 J of 351 nm laser light (3ω) in a single beam on target. The targets were heated with 37 ω beams with total energies of 8 - 17 kJ in a 1ns flat top laser pulse with 0.1 ns rising and falling edges. These are gas-filled or foam-filled hohlraum targets with a length of 2 mm and a diameter of 1.6 mm. The heater beams penetrate the hohlraum at both ends through laser entrance holes (LEH) of 0.8 mm diameter (Fig. 1), which are covered with 0.35 μm thick polyimide membranes. The hohlraums are aligned along the propagation direction of the interaction or probe beam. The latter can be chosen to operate at 2ω (526 nm) or 3ω (351 nm) for laser plasma interaction studies or at 4ω (266 nm) for Thomson scattering measurements, cf. Fig.1.[6] While Thomson scattering provides the plasma parameters, subsequent experiments in well-diagnosed conditions measure the propagation and backscatter of the interaction beam with a complete set of optical diagnostics, i.e., Transmitted Beam Diagnostics (TBD), Full Aperture Backscatter Station (FABS) and Near Backscatter Imager (NBI).[7-9]

Radiation hydrodynamic simulations indicate peak temperatures in the range of 3 - 4 keV along a 2 mm long plateau on the hohlraum axis with a rather flat density profile. Previous experiments at Omega in open geometry gasbag plasmas with roughly the same length and density have resulted in a considerably lower plasma temperature of ~1.8 keV due to the much larger volume of plasma heated when using a spherical target geometry. In the high-temperature hohlraum plasmas, present capabilities to predict the plasma conditions are limited by the approximations in heat transport modeling. Although, recent code developments make use of nonlocal modeling and magnetic field packages only few tests of these codes exists and direct measurements of the plasma conditions with Thomson scattering are required to be confident in predicting target performance.[2]

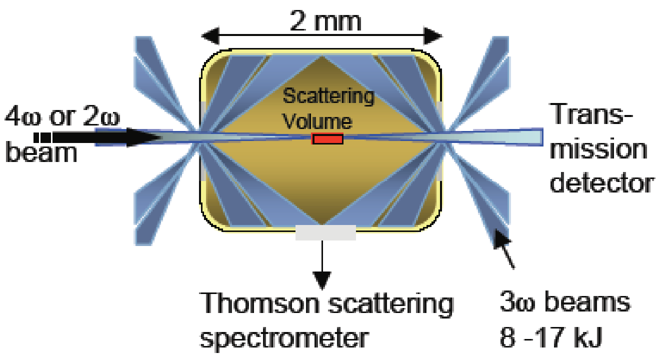

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Figure 1: Schematic of the hohlraum setup. The 37 heater beams heat the hohlraum from 0 to 1 ns and probed from 0.3 to 1.3 ns by Thomson scattering with 4ω probe laser in the center. In subsequent experiments the 4ω probe has been replaced by a 2ω interaction beam measuring laser backscattering and transmission. An electron temperature contour in units of keV calculated by the radiation-hydrodynamics code HYDRA for a gas-filled hohlraum is included for t = 1 ns.

For this purpose, one of the 60 Omega beams has been reconfigured as a Thomson scattering probe beam operating at 4ω.[6] Typical energies of E = 200 J have been employed with a focal spot size of 60 μm at the scattering volume. The effect of the probe laser on the plasma conditions is estimated to be small and of similar order as the effect of the 2ω interactions beam.

The scattered light has been imaged at a scattering angle of $\theta = 101^o$ with f/10 optics and a 1:1 magnification onto the entrance slit of a 1m spectrometer. An optical streak camera has been used to record spectra with 50 ps temporal resolution and 0.05 nm spectral resolution. Collective Thomson scattering is expected for the parameters of the experiments (electron density, temperature, scattering angle, and probe laser wavelength). Typical scattering parameters are $\alpha = 1/k\lambda_D > 1$, and light is predominantly scattered into the narrow ion feature of the Thomson scattering spectrum.

3. Experimental Results and Discussion

Figure 2 shows the Thomson scattering data from a CH-filled hohlraum heated with heater beam energies of 13 kJ. The scattering volume is in the center of the hohlraum (cf. Fig. 1) and the Thomson scattered light is observed through a diagnostic window (700 □m x 500 □m), which is cut into the hohlraum wall and also covered with polyimide. For the whole duration of the probe two symmetric ion acoustic features are observed from light scattering off the CH-plasma indicating a Maxwellian distribution during the probing. Late during the experiment, at t > 0.9 ns, we observe that the spectral shape of the ion acoustic features broadens, which is due to the fact that the ion temperature is steadily rising so that the fast ion acoustic mode (hydrogen) is strongly damped and the slow mode (carbon) grows. Fitting the data with the form factor for a two ion species plasma, which has been tested in previous open geometry experiments, yields the separation and the relative damping of both waves measuring accurately the electron and ion temperature of the plasma.[7] The data show that the wavelength separation of the two outer peaks from the fast mode is steadily increasing during the heating providing the electron temperature while the ratio of the amplitude of the inner to the outer peaks yields the ion temperature evolution.

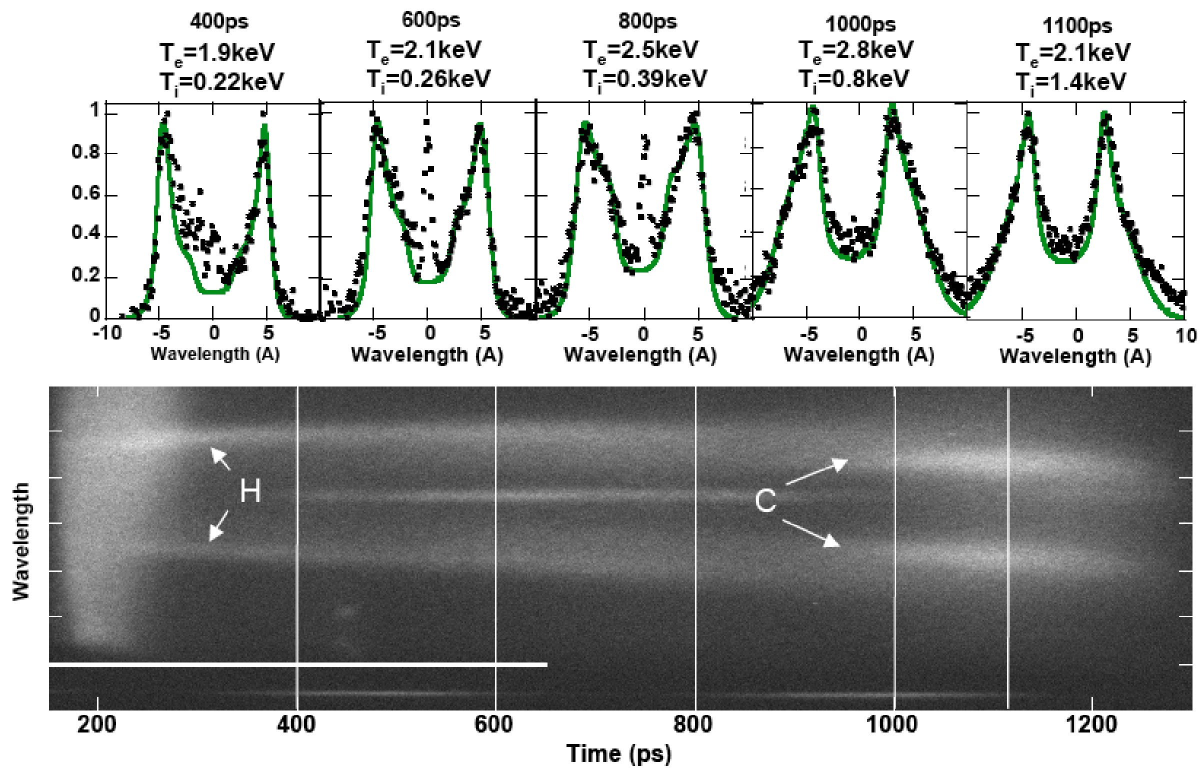

Figure 2: Time-resolved Thomson scattering spectrum for a shot with 13 kJ heater beam energy. The spectra have been fit with the form factor for two-ion species providing the electron and ion temperature of the plasma.

For the data analysis it is assumed that light scattering occurs on a fully ionized CH-plasma since temporally resolved two-dimensional x-ray images observing the Au-plasma emission at energies of E > 2.5 keV show that Au-ions have not been present in the scattering volume. We find that the electron and ion temperatures from Thomson scattering agree with radiation hydrodynamic HYDRA simulations using flux limited heat transport. Calculations are shown in Fig. 1 for a constant free streaming electron heat transport flux limiter of f = 0.05 showing a homogeneous temperature of 3.5 keV. The left hand side of the hohlraum shows slightly higher temperatures because there are 3 additional heater beams on that side. Calculations with nonlocal transport show steeper gradients particularly in the laser entrance hole area. Such gradients have also been observed in previous Thomson scattering measurements on the Nova laser facility.[2] The present experimental studies the conditions in the center of the target, where the laser plasma interactions occur. In this volume, the nonlocal modeling provides a similar answer to the flux-limited case. Future work is planned to compare these advanced heat transport models with spatially resolved Thomson scattering measurements.

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Figure 3: Experimental 2ω interaction beam transmission at peak T_e (averaged over 0.8 - 1 ns) through the 2 mm hohlraum plasma as function of the electron temperature. For $T_e \sim 3.3$ keV, the transmission is of order 80% and agrees with calculations indicating that these conditions are suitable for ignition experiments.

Figure 3 shows experimental and calculated laser beam transmission of the 2ω interaction beam through the hohlraum as a function of the measured plasma electron temperature. The 2ω beam has been operated at a laser intensity of 4×10^{14} Wcm^{-2} and has been smoothed with a phase plate. The transmission increases from ~20% for a temperature of $T_e = 1.8$ keV to 80% for $T_e \sim 3.3$ keV (scaled to 15 kJ heater beam energy). This strong dependence on the plasma temperature is due to the onset of significant SRS losses at low T_e that are suppressed at high T_e due to increased Landau damping. For $T_e = 1.8$ keV we find that the gain for SRS is G = 80 and the measured SRS losses are 20%. This values represent a lower bound because of possible re-absorption of the SRS light in the plasmas; the reflectivity inside the target may be larger than 50%.[3] Here it is important to note that the high temperature transmission data are close to the calculated value (neglecting possible absorption due to stagnating plasma late in time) from inverse bremsstrahlung absorption using detailed HYDRA profiles for density and temperature. These calculations do not include scattering losses by laser plasma interactions. Clearly, these results show that the high temperature conditions are suitable to propagate 2ω beam through ignition plasmas without undergoing energetically significant scattering losses.

4. Conclusions

We have fielded Thomson scattering to measure plasma parameters of inertial confinement fusion plasmas. We find that the temperatures in gas-filled hohlraum plasmas approach ignition conditions of 3 – 4 keV when increasing the heater beam energy to 17 kJ. Simultaneously, beam transmission and backscatter measurements of a 2ω interaction that has been operated at intensities consistent with 2ω ignition hohlraum designs show that SRS is strongly suppressed at the highest temperature consistent with increased Landau damping and a reduced gain. The measured beam transmission approach 80% with modest levels of SBS and negligible SRS indicating good laser coupling into ignition targets at high plasma temperatures.

Acknowledgments

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