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Abstract. We are developing a target platform that utilizes short-pulse (10 ps) generated hot electrons (∼1 MeV) to isochorically heat solid density beryllium up to several 10 eV. X-ray Thomson scattering is employed to characterize the plasma conditions. X-rays from a Cl Ly-α line source at 2.96 keV are scattered off the plasma in forward direction where the inelastically scattered signal is sensitive to plasma oscillations. Besides Landau-damping the strong energy down-shifted plasmon signal is also broadened by collisions which, in turn, allows to infer the collision rate and thus the conductivity in these plasmas. Recently, we demonstrated that from the ratio of the energy up-shifted to the down-shifted plasmon signals the plasma temperature can be inferred from the detailed balance relation which is based on first principles. Thus from the Plasmon shift and detailed balance we will be able to consistently determine plasma density and temperature, and relate this to the collisionality inferred from the Plasmon broadening. A precise knowledge of the collisionality in the parameter regime we are aiming at with these experiments is important to correctly model the conditions encountered during capsule implosions at the National Ignition Facility.

1. Introduction

Accurate characterization of warm dense matter is important for high energy density physics experiments in general [1], and for inertial confinement fusion (ICF) [2] and astrophysical problems in particular. Warm dense matter is challenging to describe theoretically, since coupling becomes important. It can be characterized by the fact that the potential energy of the interaction between electrons and nuclei and the kinetic energy of electrons are of roughly the same magnitude. Plasmas in this regime are typically at solid density and above with temperatures of order few eV.

One plasma property of particular interest is the thermal conductivity. A precise knowledge of this quantity is important, for example, to correctly model the hydrodynamic instability sensitivity of capsule implosions on the National Ignition Facility [3, 4]. So far, benchmarking of models that calculate the conductivity for beryllium and deuterium is lacking. Predictions of various models for conditions relevant for ICF vary by up to a factor of six [5, 6, 7, 8].

X–ray Thomson scattering (cf. Ref. [9] for a recent review) has been developed on the Omega laser facility to access matter at and above solid density approaching electron densities on order of $n_e = 10^{24}$ cm^{-3}. Using isochorically heated [10, 11] and laser shock-compressed matter [1, 12], these experiments have shown the capability to reliably measure electron temperature and density. This allowed for the validation of models that calculate ion-ion structure factors [13] and of radiation hydrodynamic codes by, for example, testing their predictions for shock-timing. Here, we will describe how x-ray Thomson scattering can be utilized to measure the collisionality in warm dense matter.

Besides plasma conditions and x-ray probe energy E_0, the scattering angle θ determines whether the experiment will probe the collective or non-collective regime. The collectivity parameter $\alpha = 1/(k\lambda_{scr})$ allows to discriminate between these two regimes, with λ_{scr} the screening length, and $k = 4\pi(E_0/hc)\sin(\theta/2)$ the momentum transfer in the scattering process. For $\alpha < 1$ the scattering is non-collective, i.e. sensitive to the individual motion of the electrons. Here we will restrict the discussion to the collective regime ($\alpha > 1$) where x-rays are scattered from plasmons, i.e. electron plasma oscillations. The plasmon signal up-shifted in energy is reduced by a factor of $\exp(-(\hbar\omega_{res})/(k_B T_e)$ compared to the down-shifted plasmon signal as given by detailed balance [14]. How the plasmon shift ω_{res} depends on n_e and T_e for solid density Be is described in Ref. [15].

2. Collective scattering experiment

To illustrate the principle of detailed balance, in this section we describe a collective scattering experiment that reached sufficiently high temperatures to observe an up-shifted plasmon signal. The experiment was performed at the Omega laser facility at the Laboratory for Laser Energetics at the University of Rochester. Fig. 1a shows a schematic of the target and the laser beam configuration. To isochorically heat a 250 μm thick Be foil with Ag L-shell radiation (3.2 - 3.6 keV), 10 drive beams with a total energy of 4.7 kJ at 351 nm in a 1 ns pulse width were incident on a 1 μm silver foil glued to the Be. Distributed phase plates (DPP, type SG4) were used to achieve a smooth beam spot with a diameter of 800 μm yielding a drive intensity of 7×10^{14} W cm^{-2}. To generate the Cl Ly-α x-ray probe at 2.96 keV, 16 beams with a total energy of 7.4 kJ at 351 nm were focused nominally to a 150 μm spot on a 12 μm Saran foil. The x–ray photons are collimated by a 50 μm thick, rectangular Ta pinhole in front of the Be which defines the scattering angle to 40°.

The plasma conditions are probed very close after the end of the heater beams when the Ag L-shell emission has ceased while the highest plasma temperatures can be expected. Due to the 250 μm mean free path at 3 keV, the x-ray photons scatter predominantly from a 40 μm-deep Be region on the undriven side. An 11° tilt is introduced so scattered x-rays can exit towards the spectrometer with minimal reabsorption. The scattered signal is collected by a high–efficiency Bragg spectrometer utilizing highly oriented pyrolytic graphite (HOPG) for dispersion. For detection we use an x–ray framing camera with a 180 ps gate. The measured signal is read out by a CCD camera fiber coupled to the framing camera. We flat–fielded the spectrometer using bremsstrahlung emission from an aluminum plasma to account for reflectivity inhomogeneities of the HOPG crystal and the multichannel plate detector. Gold shields are used to block the direct line of sight of the spectrometer to the plasmas generated by the heater and the backlighter beams.

The measured scattering spectrum is shown in Fig. 1b. For comparison, the source spectrum that was measured on a dedicated saran disk shot is plotted. In addition to the main Cl Ly-α line a red–shifted satellite is present. However, the down-shifted inelastically scattered signal recorded on the full target shot is much stronger than the naturally occurring He–like satellite in the source spectrum. In addition to the down–shifted plasmon signal a clear inelastically scattered, up–shifted signal is observed whose strength is governed by the detailed balance

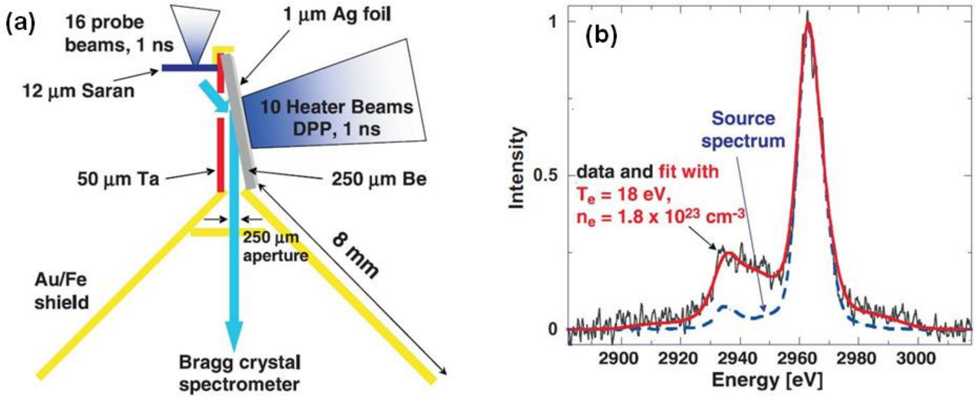

Figure 1. (a) Target design; (b) Measured x-ray Thomson scattering spectrum of isochorically heated beryllium. The synthetic spectrum (solid line), obtained with $n_e = 1.8 \times 10^{23}$ cm^{-3} and $T_e = 18$ eV, represents the best fit to the data. For comparison, the source spectrum recorded on a Saran disk shot is shown (dashed line) [reproduced from T. Döppner *et al.*, High Energy Density Physics **5**, 182 (2009)].

relation. The plasmon signals are broadened because the collectivity parameter $\alpha = 1.22$ is rather close to one at the transition to non-collective scattering.

To infer density and temperature, synthetic scattering spectra were generated and fit to the experimental data. To model the spectra we applied the random phase approximation for the electron structure factor [16], and convoluted the result with the measured source spectrum. The best agreement between the measured scattering signal was obtained for $n_e = 1.8\times10^{23}$ cm^{-3} and an electron temperature $T_e = 18$ eV (cf. Fig. 1b). A sensitivity analysis yields error bars of 15% and 20% for T_e and n_e, respectively [14].

3. New target platform to measure Be collisionality

There are two drawbacks to the experiment described in the previous section. First, the isochoric heating scheme based on x-ray converter foils limits the attainable plasma temperatures. Second, the heater beams launch a shock wave into the foil which can lead to density inhomogeneities. In the experiment described above this was avoided by applying a sufficiently thick Be foil, which in turn limits the heating efficiency at the rear surface due to the $\sim$400 μm absorption length of the heater x-rays. In addition, to achieve sufficiently high temperatures, the heater pulse length limited by peak power achievable has to be on order of 1 ns long which leads to significant undesirable rarefaction at the rear surface where the plasma conditions are probed [14].

In order to mitigate these issues we are developing a new target platform that utilizes hot electrons produced by powerful short-pulse laser beams to isochorically heat matter. If laser light interacts with matter at intensities of 10^{18} W/cm^2 and above, at the critical surface up to 30% of the laser pulse energy is converted into hot electrons with energies on order of 1 MeV that are accelerated in forward direction. These electrons are very efficiently (close to 100%) absorbed within the target which is heated on a time scale of order 10 ps [17].

Only very recently, laser facilities were coming online that in addition to a powerful short pulse beam provide additional laser beams that can create x-ray probes that fulfill the stringent requirements to characterize plasmas with x-ray Thomson scattering. We are proposing an experiment at the Omega Laser in Rochester that employs a 10 ps short pulse beam, with up to 1 kJ pulse energy, to isochorically heat a 200 μm Be cube, and up to 20 long pulse beams at 351 nm with 200 ps pulse length that create the Cl Ly-α line source. Due to the short-pulse

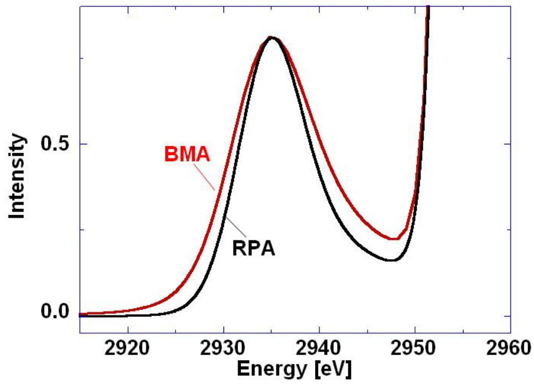

Figure 2. Simulated scattering spectra with (BMA) and without (RPA) collisions for solid Be ($n_e = 2.8{\times}10^{23}$ cm^{-3}) isochorically heated to 20 eV, assuming an 2.96 keV x-ray probe with 7 eV instrument function, and a scattering angle of 25°, resulting in a collectivity parameter $\alpha = 2.23$.

environment an imaging plate detector has to be used, so the time resolution is determined by the probe-beam pulse length. In order for the width of the plasmon signal to be sensitive to collisions the scattering has to be well in the collective regime, i.e. $\alpha > 1.7$. To achieve this for given plasma parameters ($T_e \approx 20$ eV, $n_e \approx 2.8 \times 10^{23}$ cm^{-3}) and given x-ray probe energy (2.96 keV), the scattering angle has to be $\theta \leq 30°$.

To account for collisional effects, we use the Born-Mermin approximation (BMA), that is the dielectric function is modified via the Mermin approach, and the collision frequency is calculated in Born-approximation, for details see Ref. [18]. Fig. 2 shows synthetic scattering spectra obtained with BMA (with collisions) and RPA (no collisions). For clarity, only the strong down-shifted plasmon signal is shown. Its width is broadened by 30% when the effect of collisions is included. Hence with such a measurement models that calculate collision rates can be benchmarked. It will further allow to infer the conductivity in these plasmas which can then linked to other plasma properties like electron density and temperature which can be inferred from the same data with high accuracy. Besides validating plasma physics models, precise conductivity measurements are important to improve our understanding how to correctly simulate the conditions encountered during capsule implosions at the National Ignition Facility.

Acknowledgments

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