X-ray Thomson Scattering for measuring Dense Beryllium Plasma Collisionality

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Abstract. We are developing a target platform that utilizes short-pulse (10 ps) generated hot electrons (~200 keV) to isochorically heat solid density beryllium up to temperatures of several 10 eV. We use x-ray Thomson scattering to characterize the plasma conditions. X-rays from a Cu 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 electron-ion collisions which, in turn, allows to infer the collision rate and thus the conductivity in these plasmas. 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 [1], for inertial confinement fusion (ICF) [2], and for astrophysical studies. Plasmas in this regime are typically at solid density and above with temperatures on the order of a few eV to a few tens of 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 to access plasmas at solid density and greater, approaching electron densities of \( n_e \approx 10^{24} \) cm\(^{-3}\). The characterization of isochorically heated [10, 11] and laser shock-compressed matter [1, 12] has shown the capability to reliably measure electron temperature and density. This also enabled the validation of models that calculate ion-ion structure factors [13] and radiation hydrodynamic codes, by testing shock-timing predictions. Here, we will outline how x-ray Thomson scattering can be utilized to measure the collisionality in warm dense matter.
To achieve this, the experiment has to be in the collective scattering regime where x-rays are scattered from plasmons, i.e. electron plasma oscillations. The collectivity parameter, defined as $\alpha = 1/(k\lambda_{\text{scr}})$ with $\lambda_{\text{scr}}$ the screening length, and $k = 4\pi(E_0/hc)\sin(\theta/2)$ the momentum transfer in the scattering process, enables to discriminate between the collective ($\alpha > 1$) and the non-collective scattering regimes ($\alpha < 1$). $\alpha$ mainly depends on the x-ray probe energy $E_0$, the scattering angle $\theta$, and the plasma conditions. The inelastic collective scattering signal consists of two plasmon features, up- and down-shifted by $\hbar\omega_{\text{res}}$ from the quasi-elastic Rayleigh signal. The up-shifted plasmon is reduced by a factor of $\exp\{-\hbar\omega_{\text{res}}/(k_BT_e)\}$ compared to the down-shifted feature as given by detailed balance [14] which is a powerful tool to measure $T_e$ since it is based on first principles. In addition, the plasmon shift $\hbar\omega_{\text{res}}$ depends on $n_e$ and $T_e$ which, for solid density Be, is described in Ref. [15].

2. Collective scattering experiment

First we describe a successful collective scattering experiment that achieved sufficiently high temperature plasmas allowing to observe an up-shifted plasmon signal. The experiment was performed at the Omega laser facility at the Laboratory for Laser Energetics (LLE) at the University of Rochester. Fig. 1a shows a schematic of the target and the laser beam configuration. To isochorically heat a 250 $\mu$m 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 are incident on a 1 $\mu$m silver foil glued to the Be. We use distributed phase plates (DPP, type SG4) to achieve a smooth beam spot with a diameter of 800 $\mu$m yielding a drive intensity of $7 \times 10^{14}$ W cm$^{-2}$. To generate the Cl Ly-$\alpha$ x-ray probe at 2.96 keV, 16 beams with a total energy of 7.4 kJ at 351 nm are focused to a 150 $\mu$m spot on a 12 $\mu$m Saran foil. The x-ray photons are collimated by a 50 $\mu$m thick, rectangular Ta pinhole in front of the Be which defines the scattering angle to 40$^\circ$.

The plasma conditions are probed $\sim0.5$ ns after the end of the heater beams when the highest plasma temperatures are predicted. Because of the 250 $\mu$m mean free path of 3 keV x-rays in Be, an 11$^\circ$ tilt is introduced so that scattered x-rays can exit at the rear surface with minimal reabsorption. The scattered signal is collected using a high–efficiency Bragg spectrometer with a highly oriented pyrolytic graphite (HOPG) crystal. 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. Au shields are used to block the direct line of sight of the spectrometer to the plasmas generated by the heater and the probe beams.
The measured scattering spectrum is shown in Fig. 1b. Note that the source spectrum (dashed line) shows a red–shifted satellite in addition to the main Cl Ly-α line. However, the down–shifted inelastically scattered plasmon signal is much stronger than that naturally occurring He–like satellite. In addition to the down–shifted plasmon signal a clear inelastically scattered, up–shifted signal is observed with a strength that is governed by the detailed balance relation. The plasmon signals are quite broad because the collectivity parameter $\alpha = 1.22$ is close to 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 (RPA) for the electron structure factor [16], and included the measured instrument function. The best agreement between the measured scattering signal was obtained for $n_e = 1.8 \times 10^{23} \text{ cm}^{-3}$ and an electron temperature $T_e = 18 \text{ eV}$ (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, isochoric heating based on x-ray converter foils limits the attainable plasma temperatures. Secondly, the heater beams launch a shock wave into the foil which can lead to density inhomogeneities. In the experiment described above, probing the latter was avoided by using a sufficiently thick Be foil, which in turn limits the heating efficiency at the rear surface. In addition, due to optics damage thresholds the heater pulse width has to be on order of 1 ns to maximize pulse energy and peak power and thus plasma heating. However, this 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 fast electrons produced by powerful short-pulse laser beams to isochorically heat matter. If laser light interacts with a solid at intensities of $10^{18} \text{ W/cm}^2$ and above, at the critical surface up to 30% of the laser pulse energy is converted into high energy electrons. These are very efficiently (close to 100%) absorbed within the target, which is heated on a time scale of order 10 ps [17].

The LLE in Rochester recently commissioned the OmegaEP laser, capable of delivering up to 1 kJ in 10 ps at 1054 nm on target that can be combined with additional laser beams to create the x-ray probe for Thomson scattering. We are proposing an experiment that employs the short pulse beam to heat a 200 x 200 x 250 $\mu$m$^3$ Be cube, and up to 14 long pulse beams at 351 nm to create the Cl Ly-α x-ray probe at 2.96 keV. 250 J pulse energy within 10 ps and at best focus (50 $\mu$m) yields $\sim 10^{18} \text{ W/cm}^2$ on target, creating fast electrons with $T_{\text{hot}} \approx 200 \text{ keV}$ that are capable of penetrating 250 $\mu$m Be. Assuming a conversion efficiency of 20% into hot electrons we expect to heat the Be cube to about 35 eV. The front surface will be much hotter at several 100 eV, and has to be shielded from the scattering experiment.

To record the scattering data, we have developed a highly-efficient spectrometer utilizing a cylindrical curved HOPG crystal in von-Hamos geometry with an image plate detector. The time resolution is determined by the 200 ps probe-beam pulse length. The scattering signal will compete with bremsstrahlung created by the fast electrons circulating in the Be, and a general high energy background due to the short-pulse environment. While we estimate the bremsstrahlung at most on same order of magnitude as the scattering signal, the latter is hard to quantify. Since we are expecting a scattering signal of $\sim 10,000$ photons per resolution element, even a tenfold stronger background would still give an acceptable signal-to-noise ratio of 10.

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 ($T_e \approx 20 \text{ eV}$, $n_e \approx 2.8 \times 10^{23} \text{ cm}^{-3}$) and given x-ray probe energy (2.96 keV), we will observe the signal at scattering angles of $\theta \leq 30^\circ$. To account for effects from electron-ion collisions, 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 Refs. [18, 19]. 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 collisions are included.

In conclusion, the proposed experiment will enable to benchmark models that calculate collision rates. It will further allow to infer the conductivity in solid density Be and link it to electron density and plasma temperature which can be extracted from the same scattering data with high accuracy. In addition to validating plasma physics models, precise conductivity measurements are important for improving our understanding on how to correctly simulate the conditions encountered during capsule implosions at the National Ignition Facility.

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