X-ray Thomson Scattering Measurement in shock-compressed Beryllium

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Abstract. We have measured x-ray scattering spectra of shock-compressed beryllium. In these studies, 6 keV x-rays have been produced to perform spectrally resolved measurements of the plasmas employing both non-collective and collective scattering at the Omega laser facility. Laser beams with intensities of \(10^{14} < I < 10^{15}\) W cm\(^{-2}\) and 3-4 ns pulse width have irradiated beryllium to launch a strong shock and compress the target homogeneously. The x-ray scattering measurements of the shock-compressed matter have shown inelastic Compton and Plasmon scattered spectra indicating a dense Fermi-degenerate plasma state with a Fermi energy above 30 eV with temperatures in the range of \(10^{-15}\) eV. These findings reflect compression by a factor of 3 in agreement with radiation-hydrodynamic modeling.

Introduction

X-ray Thomson scattering technique has shown great success to determine plasma properties in dense matters [1-4]. As plasma becomes denser, one reaches regimes that are found in high energy density physics conditions, planetary interiors, and inertial fusion schemes. Since the study of dense plasmas has been severely limited due to the lack of an appropriate x-ray source and a lack of robust diagnostic technique, direct and accurate measurements of thermodynamic and physical properties by x-ray Thomson scattering diagnostics are promising to test dense plasma modeling and to address fundamental physics questions in dense matter [5].

In x-ray Thomson scattering study, the dense plasma created by intense nanosecond laser is irradiated by unpolarized x-rays with energy \(E_0\) (or wavelength \(\lambda_0\)) and scattered photons are detected by a Bragg crystal spectrometer coupled to CCD camera. During the scattering process, the incident photons transfer the momentum \(\hbar k\) and the energy \(\hbar \Omega = (\hbar^2 k^2 / 2m_e)\) to the electrons. The magnitude of the k-vector is given by \(k = 4\pi (E_0 / hc)\sin(\theta/2)\) with \(\theta\), scattering angle. Here, since \(k\) determines the scaling length by \(\lambda_s \sim 2\pi / k\), the ratio to the screening length \(\lambda_s\) distinguishes the scattering regime; collective and non-collective regime. The dimensionless scattering parameter \(\alpha\) is defined as

\[
\alpha = \frac{1}{k\lambda_s} \sim \frac{\lambda^*}{\lambda_s}
\]
When the scattering length is larger than the screening length (\(\alpha > 1\)), spatial and temporal correlation of electrons become important and scattered radiation reflects the collective fluctuation. In case of \(\alpha < 1\), the probe radiation is scattered from individual particle fluctuation of its velocity. Experimentally, the screening length by \(k\) can be determined through changing \(E_0\) (6.18 keV) and \(\theta\) (25° and 90°).

**Forward and backward scattering**

X-ray Thomson scattering experiment is understood in both forward and backward scattering geometry; that is collective and non-collective scattering regime. In the forward scattering geometry, the density fluctuation in the dense plasma behaves collectively and oscillates at a frequency

\[
\omega_{pl}^2 = \omega_0^2 + 3k^2 v_{th}^2 \left(1 + 0.088n_e \Lambda_e^2\right) + \left(\frac{\hbar k^2}{2m_e}\right)^2
\]

where \(\omega_0 = (n_e e^2/\epsilon_0 m_e c)\) is the plasma frequency, \(v_{th} = (k_B T_e/m_e)^{1/2}\) is the thermal velocity and \(\Lambda_e = \hbar (2\pi n_e k_B T_e)^{1/2}\) is the thermal wave length [2]. Here small value of \(k\) works in this regime. In such a regime strong intensity of collective motion governs the spectrum of fluctuations, that is a Plasmon feature.

**Figure 1.** A real target picture of x-ray Thomson scattering experiment. X-ray scattered spectra are observed in the downward direction with a gated highly oriented pyrolytic graphite crystal spectrometer.

In the backward scattering geometry, individual particle-like fluctuation is the major contribution and Compton feature is strong in this regime. The frequency shift of a scattered photon by a free electron is determined by the Compton and the Doppler effects

\[
\omega = \frac{-\hbar k^2}{2m_e} \pm kv
\]

In this Compton scattering regime, the scattering process is non-collective and the spectrum shows the Compton down-shifted response that is broadened by the thermal motion of the electrons and that reflects the electron velocity in the direction of the scattering vector \(k\). In shock-compressed Fermi-degenerate plasmas, the width of Compton scattering spectrum is proportional to the Fermi-energy, \(E_F^{1/2}\), and hence to \(n_e^{1/3}\) [5]. The intensity ratio of Compton to elastic peak in Fermi-degenerated plasma is sensitive to the ion temperature.
The total electron density fluctuation function can be described as total dynamic structure factor and further explained as scattering cross section. The total electron dynamic structure factor $S(k, \omega)$ includes bound electron and ion contributions in addition to the Compton scattering component by free electrons.

$$S(k, \omega) = |f(k) + q(k)|^2 S_{ii}(k, \omega) + Z_f S_{ee}^0(k, \omega) + Z_b \int d\omega' \tilde{S}_{ee}(k, \omega - \omega') S_{cb}(k, \omega')$$

Here, the $S_{ii}(k, \omega)$ denotes dynamic ion-ion structure factor, ion form factor $f(k)$ is for scattering from the tightly bound electrons, $q(k)$ is for screening cloud of valence electrons surrounding the ions, $S_{ee}^0(k, \omega)$ is the dynamic structure factor of free electrons, $Z_f$ is ionization state, and the last term is for the bound-free contribution.

**Figure 2.** (a) Plasmon and (b) Compton scattering spectrum from compressed Fermi-degenerate beryllium. Sensitivity analysis shows the electron density $7.5 \times 10^{23}$ cm$^{-3}$ with an error bar of $\pm$ 6 % and electron temperature $13 \pm 3$ eV.

**X-ray Thomson scattering on shock-compressed plasmas**

With powerful lasers in Omega laser facility, shock-compression resulting in a Fermi-degenerate plasma was achieved and measured in both collective and non-collective scattering regime. Figure 1 shows a real target picture of forward scattering. Twelve heater beams smoothed with phase plates irradiate 250 µm thick solid Be in ~1 mm diameter focal spot. Laser beams with intensities of $10^{14} < I < 10^{15}$ Wcm$^{-2}$ and 3-4 ns pulse width launch a strong shock and compress the target homogeneously. Delayed backlighter beams are focused on Mn foil to produce 6.18 keV x-ray that can penetrate through compressed matter reaching $n_e \sim 10^{24}$/cm$^3$. Ta sheet with about 400 µm aperture between Be and Mn foil limits the scattering angle $25^\circ \pm 7^\circ$ and confine the intersection area to the compressed Be. (Change of the incident angle of x-rays by putting Mn foil parallel to Ta sheet makes scattering angle of $90^\circ \pm 7^\circ$ available.) The scattered photons are collected using graphite Bragg crystal spectrometer coupled to x-ray framing camera and charge coupled device. Two gold shields block huge bremsstrahlung from Be and Mn foils so that only scattered photons from dense plasma are detected.
Radiation hydrodynamic calculations indicate that these irradiation conditions compress a target homogeneously at pressure in the range of 20-35 Mbar and shock breaks out about 4.5 ns. At 4.5 ns, the calculation shows compression by a factor of 3 with $7 \times 10^{23} < n_e < 8 \times 10^{23} \text{ cm}^{-3}$ for $3 \times 10^{14} \text{ Wcm}^{-2}$. The simulated temperature is between $12 < T_e < 14 \text{ eV}$ in the dense beryllium.

Figure 2 (a) and (b) show x-ray scattering spectra from compressed beryllium from forward and backward scattering geometry, respectively. In Fig. 2 (a) inelastic Plasmon feature due to a collective free electron motion is clearly stronger than satellite elastic response of Mn x-ray source spectrum in dash line. Sensitivity analysis using the theoretical form factor $S(k, \omega)$ (the inset of Fig. 2 (a)) provides that the position of Plasmon response is sensitive to the electron density of dense matter and an accurate measurement of the electron density of $n_e = 7.5 \times 10^{23} \text{ cm}^{-3}$ with an error bar of ± 6 %.

The Compton spectrum of Fig. 2 (b) shows parabolic shape in compressed dense state indicating Fermi-degenerate plasma. The Compton scattering spectrum directly reflects the electron distribution function. For the analysis, we assume $T_e = T_i$ and $Z = 2$ consistent with calculations and with the measurements from isochorically heated Be [2]. The comparison with theoretical calculations shows that the width of Compton peak is sensitive to the electron density change and the intensity of the peak is sensitive to the electron temperature. Density and temperature obtained in this way are $n_e = 7.5 \times 10^{23} \text{ cm}^{-3}$ and $T = 13 \text{ eV}$ for a Fermi temperature of $T_f = 30 \text{ eV}$; for a Fermi-degenerate system the width of the Compton spectrum yields the Fermi energy, $E_F = h^2 (3\pi^2 n_e)^{2/3} / (2m_e)$. These results are well agreed with the radiation hydrodynamic calculations. Structure factors according to the experimental conditions are summarized in Table 1.

| time (ns) | P (Mbar) | $n_e \times 10^{23}$/cc | $T_e$ (eV) | $Z$ | $S_{ii}(f+q)^2$ | f | q | $S_{ii}$ | $\alpha$ | k (Å$^{-1}$) | $\theta$ |
|----------|----------|------------------------|-------------|-----|-----------------|---|---|----------|--------|-------------|--------|
| 4.6      | 29       | 7.5                    | 13          | 2   | 1.783           | 1.67| 0.2 | 0.5      | 0.48   | 4.43        | 90     |
| 4.4      | 29       | 7.5                    | 13          | 2   | 0.778           | 1.97| 1.4 | 0.07     | 1.5    | 1.35        | 25     |

Table 1. Experimental conditions (scattering angle and vector) and analyzed results.

Conclusion

In this paper, we have demonstrated x-ray Thomson scattering diagnostics by measuring shock-compressed beryllium in both collective and non-collective regime. The agreement with radiation hydrodynamic calculation indicates the accurate and direct measurement of the degeneracy and adiabat in these single-shocked foils. This method allows application to a number of dense matter questions including future applications to measure degeneracy and adiabat, e.g., in ICF and high energy density physics studies.

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