Demonstration of X-ray Thomson Scattering on Shenguang-II Laser Facility*

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Abstract  X-ray Thomson scattering technique for diagnosing dense dense plasma was demonstrated on Shenguang-II laser facility. Laser plasma x-ray source of titanium He-α lines (∼4.75 keV), generated by laser beam (1.5 kJ/527 nm/2 ns) heated titanium thin foil, was used as x-ray probe beam. The x-ray probe was then scattered by cold CH foam column of 1 g/cm³ density. The scattered radiation at 90° was diffracted by polyethylene terephthalate (PET) crystal and recorded on x-ray charge-coupled device. Well-defined scattering spectra were obtained with good signal to noise ratio.

Keywords: Thomson scattering, x-rays, strongly-coupled plasma

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1 Introduction

High energy density plasma in the range of solid density or higher, which existed only in astrophysical systems in the past, can be generated now in laboratory by using high power lasers, particle beams, and Z-pinch generators [1]. Accurate diagnostic of high energy density plasma is particularly important for the experiments of inertial confinement fusion [2] and high energy dense physics [3,4]. Since optical laser probe cannot penetrate overdense plasmas [4], x-ray or energetic particle including ion and neutron are needed to measure the state of dense plasma. Neutron [5] can be used only in the diagnostic of fusion plasma where the plasma temperature can be inferred from the energy spectrum of fusion neutron. Energetic ion probe beam was used to measure the magnetic field [6] or the density distribution of dense plasmas [7,8]. X-ray plasma spectroscopy is the most widely used approach to diagnose the dense plasma, i.e., its temperature, density, and ionization state, etc. For the technique of x-ray plasma spectroscopy [9,10], tracing materials are introduced in the dense plasma. The emission spectrum or the absorption spectrum of the tracing element can reflect the conditions of the dense plasma by fitting the spectrum with complex atomic spectra codes. However, the atomic energy level changes significantly in the strongly-coupled dense plasmas [11], which make the plasma spectroscopy very intricate. A new diagnostic technique of x-ray Thomson scattering [12–18], with simpler theory in comparison to that of the x-ray plasma spectroscopy, has recently been developed to give accurate and precise plasma conditions, even for strongly-coupled dense plasmas. This technique is similar to the optical Thomson scattering [19–21] for the diagnostic of underdense plasmas. X-ray sources with enough photon number and suitable spectral bandwidth take the place of optical laser probe beam to penetrate the dense plasma. The scattered radiation was diffracted by crystal instead of optical grating. X-ray Thomson scattering technique has been widely used to measure the plasma conditions of radiation heated [12–14] or shock-compressed [22–29] solid matter and to address basic physical questions of dense plasmas [12–14,22–28] such as equation-of-state [14,16], etc. Here we present the first x-ray Thomson scattering experiment performed in China on Shenguang-II (SG-II) laser facility. X-ray Thomson scattering spectra of cold CH foam sample with solid density of 1 g/cm³ were obtained by using laser plasma x-ray source of titanium He-α lines (∼4.75 keV) as the x-ray probe beam.

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2 Characterization of x-ray Thomson scattering, theory and experiment

The theory of x-ray Thomson scattering \cite{14,15,17,18,33,38} is similar to that of the optical Thomson scattering \cite{19-21}, but there are some differences in the dynamic structure factor. The dynamic structure factor of x-ray Thomson scattering is composed of three parts \cite{14,15,18},

$$S(k, ω) = |f(k) + q(k)|^2 S_0(k, ω) + Z_c S_{ce}(k, ω) + Z_c \int S_{ce}(k, ω, ω') S_n(k, -ω') dω'. \quad (1)$$

The first part is the ion feature which accounts for the electrons that dynamically follow the ion motion, including the bound electrons \( f(k) \) and the screening cloud of free and valence electrons \( g(k) \) surrounding the ion. It is similar to the Rayleigh feature of optical Thomson scattering in that the spectral position does not shift and the measured width of the feature is mainly determined by the instrumental resolution. (In fact, the ion feature of x-ray Thomson scattering corresponds to the Rayleigh scattering of bound electrons and the low-frequency component of ion thermal motion or ion plasma oscillation in the case of optical Thomson scattering. But the low-frequency component cannot be resolved since the instrumental resolution is too low to resolve the present experiments of x-ray Thomson scattering). The second part is the electron feature contributed by free and valence electrons that do not follow the ion motion. It is normal electron feature in the case of optical Thomson scattering, but in the case of x-ray Thomson scattering the concerned feature is Cowan down-shifted. The third part is the Raman wing (bound-free feature) which arises from Raman transitions to the continuum of core electron within the ions modulated by the self-motion of the ions. It does not exist in the case of optical Thomson scattering since it is caused by x-ray induced photoionization. Collective plasmon oscillations \cite{39} and the plasma conditions \cite{12-18,22-38} of electron temperature, density, ionization state, and collisions yielding conductivity and so on can be accessed from the electron feature and the ion feature.

The small cross section of Thomson scattering, the expansion of laser plasma x-ray source \cite{40-43}, and the isotropic emission of the laser plasma x-rays \cite{44} make it very difficult to get a fine spectrum of x-ray Thomson scattering. When solid or gas target is irradiated with nanosecond laser pulse, thermal emission multi-keV x-rays of He-α lines \cite{40-42} with nanosecond duration are generated in the hot underdense coronal plasma by the process of electron collision excitation and spontaneous emission. The conversion efficiency of thermal emission x-ray source is in the order of 1%, and the pulse duration of thermal emission x-rays is close to that of the laser pulse. In the interaction of ultra-intense short pulse laser with solid target (including clusters), Kα fluorescence \cite{45} x-rays with maximal \( 10^{-4} \) conversion efficiency and femtosecond to picosecond duration can be produced by hot electron created electron holes and inner-shell transitions in relatively cold atom. Kα x-rays (\( ΔE/E\sim0.2\% \)) have narrower line width relative to the He-α lines (\( ΔE/E\sim0.5\% \)), but with a lower conversion efficiency \cite{18,45}. In order to obtain useful data, x-ray sources must provide a narrow bandwidth of \( ΔE/E\sim1\% \) for non-collective scattering experiments and \( ΔE/E\sim0.2\% \) for collective scattering experiments \cite{18}. So thermal emission x-rays of He-α lines are used as the probe beam in most cases of non-collective x-ray Thomson scattering experiments except that picosecond temporal resolution is concerned. The cross section of Thomson scattering \cite{18,39} is \( σ_{Th} = \frac{σ_{Th}^0}{4} = 0.665 \times 10^{-24} \text{ cm}^2 \), where \( r_0 \) is the classical electron radius. Typical conditions \cite{18} with electron density of \( n_e \sim 10^{23} \text{ cm}^{-3} \) and path length of \( l \sim 500 \mu\text{m} \) of interest with solid density and temperature of several eV in the experiments of x-ray Thomson scattering. The scattering fraction is about \( σ_{Th} n_e/ l \sim 3 \times 10^{-3} \). Thermal emission x-ray source and Kα x-ray source are isotropic \cite{40-45}. For the dense plasma that subtends a solid angle of \( dΩ \sim 1 \text{ sr} \), a very large value for the experiment of x-ray Thomson scattering, only 10% x-rays emitted from the He-α or Kα x-ray source can interact with the dense plasma. Considering that the typical Thomson scattering fraction is about \( 3 \times 10^{-3} \), only 2×10^{-4} x-rays produced by the laser plasma x-ray source is scattered by the dense plasma. Due to the very small scattering efficiency, shielding of x-ray noise is crucial for the experiment of x-ray Thomson scattering. To get a signal with \( S/N \sim 100 \), the x-ray noise appeared in the view field of detector is not allowed to go beyond \( 10^{-6} \) relative to the x-ray source, which is very difficult to achieve. Our experiments \cite{40-43} show that the noise signal coming from the thermal emission x-ray probe source of He-α lines can expand in three dimensions to a very large distance such as 1 cm in front of the target due to the expansion of coronal plasma even after the laser pulse, and 1 mm behind the target due to the rocket motion of target and the target disassembly caused by shock wave. Large size high-Z shielding plate must be used to shade the x-ray noise. Low-Z materials must be used to block the plasma expansion or target motion that can emit multi-keV x-rays. Any plasma that can emit multi-keV x-rays noise should not emerge in the view field of detector or appear near the scattering sample. For the x-ray probe beam of hot electron induced Kα lines, noise signal of Kα or bremsstrahlung x-rays also expands due to the hot electron motion in metal solid target \cite{45}. Target with limited size \cite{46} is proposed to reduce the x-ray noise caused by hot electron expansion. The very small scattering efficiency and low conversion efficiency of laser plasma x-ray source require that the laser beam that generates the x-ray probe beam can output hundreds Joules energy even when the Highly
Oriented Pyrolytic Graphite (HOPG) crystal is used which has the highest diffraction efficiency. Such laser beam can be provided only by large-scaled laser facility.

3 Experimental setup

The experiments are performed on SG-II laser facility located at Shanghai Institute of Optics and Fine Mechanics (SIOM) which can deliver 260 J \( \times \) 8 energy by the eight ultraviolet laser beams with 351 nm wavelength (3\( \omega \)) and 1 ns pulse duration. Additional 1.5 kJ energy can be delivered by the green backlighting laser beam (No. 9) with 527 nm wavelength (2\( \omega \)), 2 ns pulse duration, and 400 \( \mu \)m \( \times \) 400 \( \mu \)m focus spot after being smoothed with a lens array. The backlighting green laser beam (No. 9, 1.5 kJ/527 nm/2 ns) is used to generate the x-ray probe of titanium He-\( \alpha \) lines, and four beams of the eight ultraviolet laser beams (260 J/3/351 nm/1 ns) are planned to produce the multi-keV Au M-shell x-rays for volumetrically heating the solid sample.

3.1 X-ray probe beam

The backlighting laser beam irradiates titanium thin foil with 1.5 \( \mu \)m thickness to produce the x-ray probe of titanium He-\( \alpha \) (~4.75 keV) lines. Multi-keV thermal emission x-rays of He-\( \alpha \) lines are generated from hot underdense coronal plasma which is usually in the laser channel. Our previous works found that the x-ray flux and the emission region of multi-keV x-rays, emitted by laser heated thick foil target, evolved into a steady state very quickly (such as 1 ns duration) due to the three dimension expansion of coronal plasma. In the case of steady state, the longitudinal scale length of the coronal plasma is nearly twice the size of laser focus spot. So the emission region is proportional to the cube of the laser spot size \( (V \propto R^3, V \text{ and } R \text{ are the emission volume of multi-keV x-rays and the laser focus spot size, respectively}) \). This phenomenon is found for various laser focus spots and various target materials. Based on steady state, a series of analytic scaling laws were developed which were in good agreement with the experimental results. The x-ray flux generated by laser heated thick foil target has the relation of \( P_x \propto n_{e}^{2/3} \rho_{c}^{-2/3} (E_{\lambda}/\tau)^{2/3} R^{2/3} \), where \( P_x \), \( n_{e} \), \( \rho_{c} \), \( E_{\lambda} \) and \( \tau \) are the x-ray flux, electron density, critical density, laser energy, and pulse duration, respectively. Since \( n_{e} \propto \rho_{c} \) and \( \rho_{c} = 1.11 \times 10^{21}/\lambda (\mu \text{m})^2 \text{ cm}^{-3} \), where \( \lambda \) is the laser wavelength, there is \( P_x \propto \lambda^{-8/3} (E_{\lambda}/\tau)^{2/3} R^{2/3} \). Slighter larger laser focus spot size and shorter laser wavelength can enhance the x-ray emission. But the laser focus spot cannot be too large, otherwise the electron temperature of coronal plasma is too low to ionize the inner shell electrons. Ultraviolet laser with 351 nm wavelength (3\( \omega \)) can significantly increase the multi-keV x-ray emission even when the laser harmonic conversion efficiency is included. But forth harmonic laser is improper since the harmonic conversion efficiency of 263 nm wavelength (4\( \omega \)) is very small.

To further increase the multi-keV x-ray flux, the volume of the emission region (hot coronal plasma) should be enhanced markedly. Underdense targets including gas and doped aerogel are the extreme case in which the whole target is underdense coronal plasma, and there is no overdense plasma. The x-ray flux can be increased by several times to one order using underdense targets. But the concept of underdense targets is limited to gas kind and doped aerogel fabrication technique.

We proposed a new concept of thin foil target to enhance the multi-keV x-ray emission that is suitable for the K-shell x-ray source of any solid materials. Our experimental results show that the rocket motion and burnthrough of thin foil can weaken the limitation of laser focus spot to the emission region that appeared in the case of thick foil target. The increased emission region of thin foil enhances the multi-keV x-ray emission such as titanium He-\( \alpha \) and Ly-\( \alpha \) x-rays. We found that there is an optimal thickness for the thin foil. A too-thin or too-thick foil will decrease the x-ray emission. For the laser parameters in our experiments, the optimal thickness of the thin foil of titanium materials is about 2.8 \( \mu \)m. But limited by the foil kinds available in our experiment, 1.5 \( \mu \)m thin foils of titanium materials are used to produce the x-ray probe of titanium He-\( \alpha \) and Ly-\( \alpha \) x-ray lines. The x-ray flux absorbed by the scattering sample of dense plasma is about 1.3 times that emitted by 6 \( \mu \)m thick foil target. X-ray diodes show that the conversion efficiency of titanium K-shell x-ray (\( >4 \text{ keV} \)) of 1.5 \( \mu \)m thin foil target in 4\( \pi \) space is about 1.7% in our experiments.

3.2 Target design and noise shielding

Fig. 1 shows the target configuration in our experiments. Gold hohlraum with \( \phi 1600 \mu \text{m} \) diameter, 2200 \( \mu \text{m} \sim 2400 \mu \text{m} \) length, and 20 \( \mu \text{m} \sim 50 \mu \text{m} \) thickness is used as shield to shade the x-rays noise coming from the plasma generated by titanium thin foil. A Titanium thin foil of 1.5 \( \mu \)m in thickness is stuck on the front hole of the gold hohlraum, which will be ablated by the No. 9 green laser beam to generate the x-ray probe of titanium He-\( \alpha \) lines. Since the titanium thin foil will be burned through by the laser beam, the titanium plasma can also expand behind the titanium foil. So a CH foil with 5 \( \mu \)m thickness is attached at the rear hole of the gold hohlraum to damp the motion of the titanium plasma which can emits x-ray noise. A CH (C\(_6\)H\(_{12}\)) foam (amorphous) column with 1 g/cm\(^3\) density, 600 \( \mu \text{m} \) diameter, and 600 \( \mu \text{m} \) length is attached using epoxy glue on the surface of the CH foil (at the position of the rear hole of the gold hohlraum with 600 \( \mu \text{m} \) diameter). Gold foil with designed 0.1 \( \mu \text{m} \) thickness is coated on the surface of the CH foam column. Four beams of the eight ultraviolet laser beams are planned to irradiate the gold foil and generate the
Au M-band emission (2 keV∼3 keV). The Au M-band emission heats the CH foam column volumetrically and produces warm plasma with solid density. K-shell x-rays including He-α and Ly-α lines emitted by the titanium thin foil penetrate the CH foil block, and are scattered by the CH foam column. Another gold shielding plate with 5 mm height, 1 cm width, and 50 µm thickness is attached on the target stick to further shade the x-rays noise coming from the titanium plasma.

![Fig.1 Schematic of x-ray Thomson scattering experiments (color online)](image)

One should notice that the present target can be used to obtain the scattering spectrum of cold samples though it is designed to measure the scattering spectrum of radiation heated warm samples. Four beams of the eight ultraviolet laser beams are planned to irradiate the 0.1 µm Au foil coated on the surface of the CH column to generate Au M-band radiation. Then the Au M-band x-rays heat the CH column volumetrically. But bremsstrahlung radiation in the range of 1∼10 keV is also generated by laser irradiated Au foil besides the M-band (2∼3 keV) x-rays. All of the bremsstrahlung radiation is in the view field of spectrometer, and its spectral range cover the wavelength of the x-ray probe beam (~4.75 keV for He-α lines and ~4.9 keV for Ly-α lines). Any dim x-rays emitted by Au plasma can overwhelm the scattering signal because the scattering efficiency is just in the order of 10^{-4}. So we just obtain the scattering spectra of cold CH sample in the experiments.

### 3.3 Spectrometer and detection

Spectrometer composed of polyethylene terephthalate (PET) crystal (2d=0.8742 nm) and an x-ray charged-coupled device (CCD) made by Princeton Instruments is used to record the scattering spectrum at 90° scattering geometry, which is perpendicular to the axes of the hohlraum. The distance between the target and the PET crystal is 150 mm, which is equal to the distance between the PET crystal and the CCD. The dispersive direction of scattering spectra is perpendicular to the axes of the hohlraum. Be filters (2×100 µm) are used to protect the PET crystal and the CCD. A slit with 2 mm width is placed at the entrance of spectrometer to block target debris. The slit can also provide some spatial resolution at the penumbra region if the target deflects to one side of the view field of the spectrometer, which is helpful to separate the x-rays noise from the scattering spectrum.

### 4 Results and discussions

The signal of x-ray Thomson scattering are shown in Fig. 2. Fig. 2(a) is the image recorded by CCD with the CH foam sample. The upper part of the image is the x-rays noise coming from the titanium coronal plasma (source plasma) that expands beyond the region of Au shielding plate. The maximal count is about 14000, as shown in Fig. 2(d). Titanium He-α and Ly-α lines can be resolved clearly. Since the coronal plasma that emits x-ray noise departs from the CH column sample (the center of the spectrometer’s view field) about 4 mm, it locates in the penumbra region of the spectrometer. So the x-ray noise can be resolved spatially from the scattering signal. The lower part of the image is the scattering signal of CH column. To affirm that

![Fig.2 X-ray Thomson scattering signal measured by CCD with CH (C_6H_{12}) foam sample (a), and without CH foam sample (b). (c) and (d) are the scattering spectra corresponding to (a) and (b), i.e. the scattering spectra of CH sample and the x-rays noise spectra coming from the titanium coronal plasma (source plasma of x-ray probe) with and without CH sample (color online)](image)
the scattering signal comes from the CH column, another shot without the scattering sample of CH foam column was performed but the 5 μm CH foil block is reserved. As can be seen in Fig. 2(b), (c) and (d), the x-rays noise coming from the titanium coronal plasma still exists, but the scattering signal in the lower part of the image vanishes. In some shots in which the CH foam column is replaced by a little epoxy glue dropped on the 5 μm CH foil block, the scattering signal reappears though it is very weak. So it is convinced that the lower part of the image is the x-ray Thomson scattering signal of CH foam column. Due to the crystal defect, the image of the scattering signal has some unwanted break in the lower part. The pattern of the break on the scattering signal is coincident with the picture of the defect on the surface of the PET crystal. The S/N of the scattering spectra is about 1000. The background of the scattering spectra is about 200.

It is found that the height of the Au shielding plate that attached on the target stick is a crucial factor in the experiments. As shown in Fig. 3, the x-rays noise coming from the coronal plasma increases from 14000 to 65000 (saturated) so that it overwhelms the scattering signal (S/N decreases from 4 to 1) when we decrease the size of the Au shielding plate from 5 mm height to 4 mm height. To get a scattering spectrum with very good signal to noise ratio, we think that the height of the Au shielding plate should be increased to 1 cm to completely shade the x-ray noise of the coronal plasma.

X-ray Thomson scattering spectra taken from Fig. 2(a) are shown in Fig. 4, where the source spectra of the titanium He-α x-ray probe are also depicted, which was measured by the same spectrometer in another shot with the same laser and target parameters. The theory spectrum is calculated by collisional-radiative atomic spectra code FLYCHK [52]. The plasma parameters used in the calculation of source spectra of x-ray probe are \( n_e \sim 6 \times 10^{21} \text{ cm}^{-3} \), and \( T_e \sim 1.5 \text{ keV} \). The spectral resolution is set at \( E/\Delta E \sim 500 \). Obviously down-shifted Compton feature of x-ray Thomson scattering in the range of 4.5~4.7 keV is found in Fig. 4. The scattering spectra at the red-shifted side extend beyond the source spectrum of the x-ray probe with 100 eV.

In Fig. 5, the scattering spectra are fitted by theoretical spectra [14,15]. The ion feature, electron feature, and Raman wing are shown separately. The source spectra of x-ray probe calculated by FLYCHK code shown in Fig. 4 are used in the theoretical fitting. The plasma conditions derived from the scattering spectrum are \( T_e = 5 \text{ eV} \), and \( Z_{f, C} = Z_{f, H} = 1 \) with 1 g/cm³ density, where \( Z_{f, C} \) and \( Z_{f, H} \) are the ionization states of carbon and hydrogen, respectively. It can see that the ion feature accounts for the most part of the scattering spectra. The Compton down-shifted feature is mainly contributed by Raman wing. The electron feature is very weak because there are few free electrons and valence electrons in the cold sample. It can be found that the width of the ion feature was obviously broader than that of the x-ray probe of titanium He-α lines though the same spectrometer was used. It should be caused by the finite size of the laser plasma x-ray probe.
source and the isotropic emission of the x-ray probe, which can decrease the spectral resolution of the scattering signal. It is also shown that the Compton downshifted feature is not fitted perfectly, which may be induced by the Au matter which coated on the surface of the CH foam column. The Au impurity that we do not consider in the fitting can add additional Rayleigh scattering and increase the ion feature relative to the electron feature. We will investigate it in the future.

Fig.5 Experimental x-ray scattering spectra and the fitting spectra of CH (C$_{6}$H$_{12}$) foam sample. Contributions from different scattering mechanism are shown separately. Best fitting parameters are $T_e$ = 5 eV, and $Z_{fC} = Z_{fH} = 1$ with 1 g/cm$^3$ density (color online)

5 Conclusions

X-ray Thomson scattering of cold CH foam sample with solid density of 1 g/cm$^3$ was performed for the first time in China on SG-II laser facility. Characterization and enhancement of the thermal emission x-ray probe source based on laser plasma interaction are discussed. The target design should be improved in the future to further decrease the x-rays noise. Any plasma that can emit multi-keV x-rays should not appear in the view field of the spectrometer. Highly Oriented Pyrolitic Graphite (HOPG) [13] with higher diffraction efficiency, which is more than one order of magnitude larger than PET crystal, is planned to be used in the coming experiment to enhance the scattering signal.

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