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Demonstration of Successful X-ray Thomson Scattering Using Picosecond K-α X-ray Sources for the Characterization of Dense Heated Matter

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We discuss the first successful K-α x-ray Thomson scattering experiment from solid density plasmas for use as a diagnostic in determining the temperature, density, and ionization state of warm dense matter with picosecond resolution. The development of this source as a diagnostic and stringent requirements for successful K-α x-ray Thomson scattering are addressed. Data for the experimental techniques described in this paper [1] suggest the capability of single shot characterization of warm dense matter and the ability to use this scattering source at future Free Electron Lasers (FEL) where comparable scattering signal levels are predicted.

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Recently, x-ray scattering experiments have allowed characterization of dense matter, $n_e > 10^{21} cm^{-3}$, that is inaccessible using the previously well established technique of optical Thomson scattering [2, 3]. Spectrally resolved x-ray scattering in the collective and non-collective regimes provided information on the temperatures and densities of solid-density plasmas enabling, e.g., the measurements of the equation of state, phase transitions, and the compressibility of dense matter [4–6]. In these experiments, energetic nanosecond lasers were employed to irradiate foil targets producing spectrally narrow K-lines from helium-like or hydrogen-like atoms.

For the full characterization of strong shocks in dense matter, however, x-ray sources that provide picosecond temporal resolution are desirable. In this paper we discuss the first successful K-α x-ray scattering experiment from heated and compressed LiH using an ultra-short pulse laser produced Ti K$-\alpha$ source with a temporal resolution of $\sim$ 10 ps [7]. This source was used to probe laser heated material via a shaped long pulse heater beam at the Titan Laser Facility, LLNL [8]. Elastic and Inelastic scattering features were observed at different times during the shock, enabling measurement of the electron temperature and density during compression. Results suggest capability to use this diagnostic to test equation of state models, radiation-hydrodynamic codes, and characterize fusion capsules for the National Ignition Facility (NIF), LLNL [9].

The brightness of these K-α sources is two orders of magnitude less than previously used Ly-α or He-α sources which causes Thomson scattering via this line to be extremely difficult and poses stringent requirements on experimental techniques in order to obtain a sufficient scattering signal. Data from this experiment [1] show that accurate scattering signals can be achieved from 8 x 10^{10} scattering photons at target with about $\sim$2.0 x 10^{13} photons produced in 4π for typical scattering solid angles. In this case, future FELs with a predicted output of $\sim$1.0 x 10^{12} photons will be ideal for x-ray Thomson scattering with the additional benefit of 20 fs temporal resolution and a high repetition rate.

X-RAY THOMSON SCATTERING

Thomson scattering is the scattering of electromagnetic radiation by free, weekly bound, or tightly bound electrons to determine temperature, density, and ionization state of the plasma. Collective and non-collective scattering are scattering regimes, dependent on plasma conditions, that can be accessed by choosing the right probe energy and scattering angle. The collective scattering regime can be distinguished from the non-collective regime with the scattering parameter α

$$\alpha = \frac{1}{k\lambda_S} = \frac{\lambda}{2\pi\lambda_S} \tag{1}$$

where $\alpha > 1$ for collective scattering and $\alpha < 1$ for non-collective scattering. For small energy transfers, where the incident wave vector is approximately equal to the scattered wave vector, $k_0 \approx k_s$ and $k_0 = 2\pi E_0/hc$, the magnitude of the scattering vector, $\mathbf{k}$, can be approximated by

$$k = |\mathbf{k}| = 2k_0 \sin(\theta/2) = 4\pi \frac{E_0}{hc} \sin(\theta/2). \tag{2}$$

The parameter λ_S, plasma screening length, is the length at which local electric fields are screened out by mobile charge carriers, i.e., electrons.

X-ray scattering in the non-collective regime results in an unshifted Raleigh peak and Compton peak downshifted in energy. The former is a result of the elastic

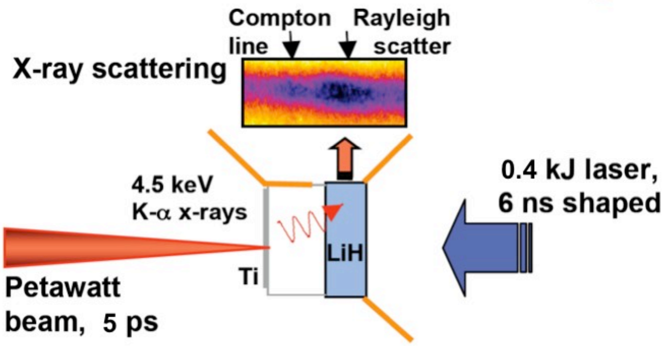

FIG. 1: A schematic of the scattering target and beam orientation. Gold shields were used to inhibit the direct view of Ti K-α source x-rays to the scattering detector. Low Z glass bodies were designed minimize background due to Bremsstrahlung radiation. The long pulse beam focuses onto the scattering target to shock compress the solid density material. Source x-rays are produced by short-pulse laser irradiation of a Ti backlighter foil and scattered from the shock compressed target where they are then collected from the side using a HOPG spectrometer.

scattering of incident radiation from tightly bound electrons moving together with the heavy ions. The ladder results from inelastic scattering from weakly bound or free electrons with a distribution proportional to the free electron temperature of the plasma. The ratio of the downshifted Compton peak to the unshifted Raleigh peak gives indication of the ionization state of the plasma.

In forward scatter, the scattering spectrum yields collective electron oscillation peaks, i.e. plasmons up-shifted and down-shifted from the incident x-ray energy. The plasma dispersion relation provides the plasmon energy shift from elastic Raleigh scattering and can be approximated by a modified Bohm-Gross relation [10] for small values of $\mathbf{k}$, i.e. large values of α. Here, the electron density can be obtained from the plasmon energy shift and the electron temperature from the relative intensity of the elastic to inelastic scattered radiation.

EXPERIMENT

A Ti K$-\alpha$ (4.510 keV) x-ray source was produced via intense $\sim$ 300 J, 1053 nm, 5ps square pulse laser irradiation of a 10 μm thick Ti foil displaced 500 μm from 300 μm thick LiH targets. This source was scattered from the LiH targets ($\rho_{Initial} = 0.78$ g/cc) that were compressed via a $\sim$ 400 J, 527 nm, 2ω, 6 ns shaped long-pulse heater beam, with a 600 μm phase plate, to almost 3 times solid density. Scattered radiation was observed side-on to the LiH targets at a scattering angle of 40 ±10 degrees. Low Z glass bodies were used to mount the Ti foils, LiH targets, and gold shields to reduce background from Bremsstrahlung radiation. Source radiation and blow-off plasma emission from the heater beam were shielded from the scattering spectrometer using 25 μm thick gold shields. Spectra from short-pulse irradiation of a scattering target without LiH confirmed that the source was not visible to the scattering spectrometer. See Fig.1 for a schematic of the experimental configuration.

The Ti K-α x-ray line was chosen as a scattering probe due to its high conversion efficiency [11] moderate energy allowing simultaneous scattering in the collective and non-collective regimes, small bandwidth to resolve scattered features, and sufficient energy to penetrate compressed targets. Since the usual Thomson scattering cross section is extremely low, $6.65x10^{-25}$ cm^2, and the conversion efficiency of incident laser energy into K-α x-ray production is about two orders of magnitude lower than previously used He-α or Ly-α scattering sources, the number of probe photons, scattered photons, and collected photons must be maximized in order to yield and acceptable signal-to-noise-ratio in the scattering spectra.

To maximize conversion efficiency of laser light into x-ray production, the short pulse laser intensity was varied by changing the pulse lengths and laser focus diameter. The maximum conversion efficiency of $5.3x10^{-5}$ was achieved for a pulse width of 0.5 ps at an intensity of $\sim 1x10^{18} W/cm^2$. However, due to restrictions on the laser, full energy could not be obtained at this pulse width. Alternatively, longer pulse lengths of 5 ps at a laser intensity of $\sim 4x10^{16} W/cm^2$ and a defocused laser diameter of 400 μm were used, where full laser energy could be obtained, yielding comparable conversion efficiencies of $\sim 5x10^{-5}$. An increase in conversion efficiency for defocused laser beams at a specific pulse width have also been observed by [12] with the cause of this effect still up for discussion.

To scatter in the collective and non-collective regimes simultaneously an energy bandwidth of $\Delta E/E \sim 0.002$ [13] and $\Delta E/E \sim 0.01$ [14], respectively, must be used to spectrally resolve the inelastic scattering features downshifted in energy from the elastically scattered radiation. The nearly mono-energetic Ti K-α line with $\Delta E/E \sim 0.003$ is desirable for scattering in both regimes, as opposed to previously used He-α and Ly-α sources with dielectric satellites and inter-combination lines in the source spectrum, that can blend with the down-scattered plasmon or Compton peak and distort the shape.

For example, scattering of Ti K-α in the collective regime at 40° from solid density LiH (0.78 g/cc) heated to about 2.2 eV and compressed to about 2.2 g/cc will yield an inelastic peak downscattered 25 eV from the elastic feature. In this case, the K-α source bandwidth of $\sim 15eV$ is sufficient to resolve the downscattered feature. In addition, the x-ray probe energy must be moderate in order to achieve an $\alpha > 1$ and < 1, Eq.1, simultaneously by choosing different scattering angles. For example, for the Ti K-α line and conditions used in the previous example, scattering at $> 40° \leq$ results in $\alpha < 1$ and $\alpha > 1$, respectively.

To maximize the collected scattering signal, a high collection efficiency, highly reflective, 70 mm curved graphite (HOPG) Bragg crystal in the mosaic focusing mode [5, 15] was used. The wide solid angle crystal with a spherically bent design offered more than an order of magnitude more collected photons than previously used crystals by collecting radiation over a larger solid angle and focusing it onto sensitive BAS-TR image plate detectors. To minimize the amount of background produced due to Bremsstrahlung, the crystal was operated in a free-standing geometry contrary to previous models that employed an Al spectrometer body to encase the crystal. The image plate detectors are ideal for use in the 4.5 keV energy regime, offering comparable quantum efficiencies to Charge Coupled Devices (CCDs) (about 70%), with the additional advantage of being able to withstand the high *emp* environment of a short-pulse laser experiment and ease of use.

Data for scattering at various times during shock compression for the experimental set-up described above yielded temperature and density measurements of ~ 2.2 eV and $1.7x10^{23}/cm^3$ with errors of 20% and 25% respectively [1]. The electron temperature and density were obtained from the elastic to inelastic scattering intensity ratio and energy shift of the plasmon from elastic scattering, respectively. Here the collective scattering regime was accessed with $\alpha \sim 1.1$. With a conversion efficiency of $\sim 5x10^{-5}$ and probe laser energy of 300 J, about $2x10^{13}$ source photons were produced in 4π and $8x10^{10}$ photons were incident on the scattering target. For this source strength a sufficient scattering signals of $3-5x10^{6}$ photons, depending on the target temperature and density during compression, were obtained enabling accurate plasma characterization. These experimental results show that the source signal levels needed for successful scattering can be achieved using future FELs that predict about $1x10^{12}$ photons at target.

CONCLUSIONS

In summary, we have developed a diagnostic that enables 10 ps resolution for characterization of shock compressed, solid density matter, including temperature, density, ionization state, and equation of state mesurements. The spectral properties of Ti K-α, ie. moderate energy and small bandwidth, are well suited for noncollective as well collective scattering applications. This diagnostic is opportune for ICF experiments such as NIF, that require high temporal resolution for characterization of short lived states of compression and can also be used to remotely test radiation hydrodynamic models. Also, the quality of scattering data that can be obtained from the photon source intensity described in this paper suggests the capability to use this diagnostic on future FELs where 20 fs temporal resolution and high repetition rates can be achieved.

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