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Solid-Density Plasma characterization with X-ray scattering on the 200-J Janus Laser

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We present collective x-ray scattering (CXS) measurements using a Chlorine He-α x-ray source pumped with less than 200 J of laser energy. The experimental scattering spectra show plasmon resonances from shocked samples. These experiments use only 10^{12} x-ray photons at the sample of which 10^{-5} have been scattered and detected with a highly efficient curved crystal spectrometer. Our results demonstrate that x-ray scattering is a viable technique on smaller laser facilities making CXS measurements accessible to a broad scientific community.

I. INTRODUCTION

Laser generated x-ray scattering has become an important tool to diagnose properties of dense plasmas such as the electron temperature and the ionization balance. This technique was first demonstrated and applied at large laser facilities using multi-kJ laser pulses to generate the necessary high multi-keV photon fluxes for probing dense plasmas. Although the use of optical Thomson scattering with high power lasers allowed rapid progress measuring the properties of low-density plasmas, powerful x-ray sources are required for accessing dense plasmas with electron densities of $n_e > 10^{22}\mathrm{cm}^3$. The first proof-of-principal experiments applied 4.75 keV Ti He-α radiation enabling accurate scattering techniques to be extended to solid density states of matter[i] that are of interest in areas like high-energy density physics or inertial confinement fusion research.

The low Thomson scattering cross-section requires a strong backlighter source in order to obtain useful signal-to-noise ratios. For x-ray Thomson scattering this implied employing several kJ of laser pulse energy to pump the x-ray source and the first successful experiments have been performed with 10^{14} photons at the sample. This limited the use of the technique to large laser facilities like the Omega laser at the Laboratory for Laser Energetics (LLE).

In this paper we report demonstration of collective x-ray Thomson scattering using less than 200 J of laser pulse energy to drive the x-ray scattering source proving 10^{12} photons at the sample. With such low photon flux scattering spectra have been measured employing curved crystal and effective x-ray detectors (CCD or image plate)

II. EXPERIMENTAL SETUP

While scattering from individual particles can provide information on the electron velocity distribution, density and the average charge state, the so-called collective scattering off correlated density fluctuations gives resonances in the scattered spectrum that are due to excitations of fundamental modes of plasma oscillations, the Plasmon resonances and thus yields information on the dielectric function $\varepsilon(\omega,k)$ and eventually on the optical and electrical properties. Scattering in the collective regime requires that the wavelength associated with the momentum exchange $\hbar k = {}^{4\pi}/_{\lambda_0}\sin\left({}^{\Theta}/_{2}\right)$ of the scattered photons of wavelength λ_0 is larger than the correlation length λ_S of the fluctuations to be observed. The scattering angle Θ is the angle between the incident and the scattered radiation. With the scattering parameter defined as $\alpha = \left(k\lambda_S\right)^{-1}$ the condition for collective scattering is $\alpha>1$. For our experiment, the scattering source was chosen to be the Ly-alpha emission from Chlorine. While still having a large attenuation length of ~0.5 mm in low-Z solid density material and low-density Carbon foams the relatively low photon energy (2960eV) allows for collective scattering at solid-density at the relatively large scattering angles. High conversion efficiencies of a few 10^{-3} had been shown in previous measurements and satellite lines

on the low energy side are sufficiently week not to mask the Plasmon features to be observed[ii].

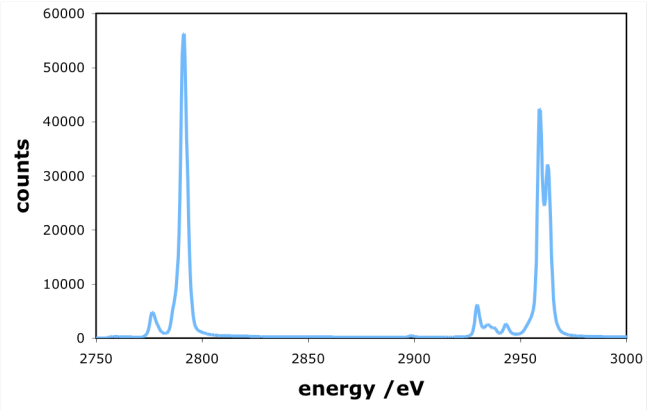

Figure 1:. Emission spectrum of the backlighter source featuring the Ly-α doublet with di-electronic satellites as well as strong emission from He-α and the intercombination line.

The experiment was performed using the Janus laser at the Jupiter Laser Facility (JLF) at the Lawrence Livermore National Laboratory (LLNL). The system delivers two synchronized laser pulses with energies of up to 200 J per beam at the second harmonic (2w, 527 nm) of the Nd:glass power amplifiers. Chlorine Ly-alpha emission was generated by irradiating Saran foils (Polydenchloride, $(C_2H_2Cl_2)_n$) of thickness 12.5 μm with laser pulses at a wavelength of 527 nm. At a pulse duration of 1ns and at best focus (50 μm) intensities on target were of order 10^{16} W/cm^2. The radiation was spectrally resolved using a highly-oriented pyrolytic graphite (HOPG, General Ceramics) crystal in mosaic focusing mode. The cylindrically curved crystal (ROC=115mm) was used in the van Hamos geometry providing spatial resolution in the direction perpendicular to the dispersion. The spectra were recorded on a scientific grade back-thinned charge-coupled device (DX-420BN, Andor Technology) or on low energy imaging plates (BAS-TR, Fujifilm) which were read out directly after irradiation. Figure 1 shows a typical spectrum obtained using 140 J of laser energy featuring the K-alpha doublet at 2.98 keV and satellite lines on the low energy side. At an incidence angle of 30° conversion efficiencies of more than 10^{-3} from laser energy into Cl-Ly-alpha photons were achieved, consistent with using both long (1ns) and short (200ps) laser pulses. The spatial extent of the source on the detector is on the order of 2.5 mm and is dominated by mosaic broadening due to the mosaic spread of γ=0.8 of the ZYB grade HOPG crystal used. Spectral broadening on the order of 7 eV is mainly due to spatial aberrations from the curved crystal geometry[ii].

Also strong He-alpha emission (at 2.79 keV) is obtained, the photon yields being comparable to those from the Ly-alpha.

For XRTS He-alpha emission is less suitable. The close-by intercombination line blends into the Compton-downshifted features. Also, in time-integrated measurements the long-lasting emission from He-like ions in the recombining plasma complicates interpretation of the scattering spectra from short-lived states of matter like shocked of heated samples.

The first intent was therefore to use Ly-alpha radiation. However, strong features in the spectral region of the Ly-alpha are found to completely mask the expected weak scattering spectrum. As measurements are time-integrated these features could be due to emission from gold ions late in time that are ablated from the gold shields nearby the x-ray generating plasma. The emission around 12 keV can be observed in 4th order diffraction from the HOPG crystal.

Further analysis of the scattered spectra therefore focuses on the scattering of the He-alpha emission from Chlorine.

To perform x-ray scattering a new target design was fielded. The scattering targets were enclosed in a housing made of chlorine-free plastic and covered with gold foil (50 μm thickness). A plastic stalk below the housing held a small piece of Saran foil. Two laser cut diagnostic holes in the gold foil collimated the x-ray radiation at the sample. The rectangular holes with dimensions 300μm x 500μm were optimized to maximize solid angle for high

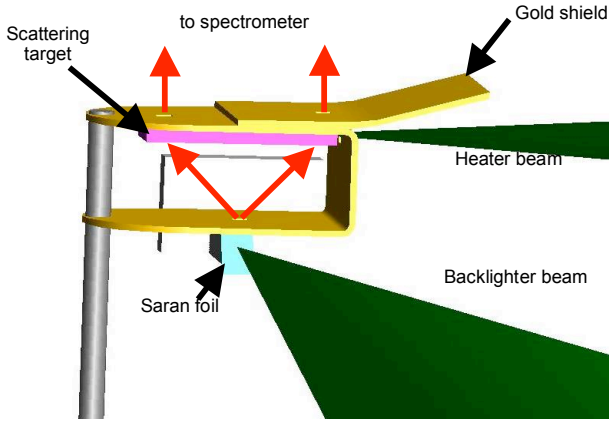

Figure 2: The target design allows to scatter off a shocked/heated and a cold portion of the scattering target.

efficiency while still sufficiently limiting the range of possible scattering angles as seen by the spectrometer. The two holes are separated by 2.5 mm, and the separation between source and the diagnostic holes could be chosen to be 1, 2 and 3 mm to allow variation of the scattering angle. Given the solid angle subtended by the diagnostic hole, the conversion efficiencies determined beforehand and the backlighter laser energy we can estimate a total of 10^{12} photons at the sample.

An additional hole (400 μm x 400 μm) in the side of the target mount allowed the second laser pulse to irradiate the scattering target side side-on. This way a shock-wave could be driven into the target. Fig.2 shows a sketch of the target assembly used for the scattering experiments.

Scattering targets were made of either pressed Lithium hydride powder or low-density (0.2 g/cc) carbon foams with dimensions 3x3mm and thicknesses of 300 and 500 micrometer. An optional side-on Aluminum coating served as x-ray converter to allow targets to be radiatively heated.

III. RESULTS

Figure 3 shows a spectrum from scattering on a cold Lithium hydride target with 500 μm thickness. The horizontal lineout in the spectral region of the He-α shows a down-shifted feature which is close to the position of the intercombination line. While the separation between He-α and intercombination line is 15 eV this feature is about 3-5 eV further down-shifted. Furthermore, the feature at the energy of the intercombination line is much stronger than the intercombination line on the source spectrum. It is therefore conceivable that there is elastic scattering of the intercombination line blend with Compton scattering from the He-α.

In this shot one of the diagnostic holes had been closed by a piece of Ti-foil. The increase in spatial width of the spectral features to about 5 mm can be explained by a slight misalignment of the spectrometer. Taking into account the number of photons at the scattering sample we find a fraction of ~10^{-5} of the incident light in the spectral feature. This compares well with the expected value $n_e\sigma_{Thomson}x$ ~$2x10^{-5}$, assuming an electron density n_e~$2x10^{23}$. Here $\sigma_{Thomson}$ is the Thomson scattering cross-section and x the thickness of the scattering target.

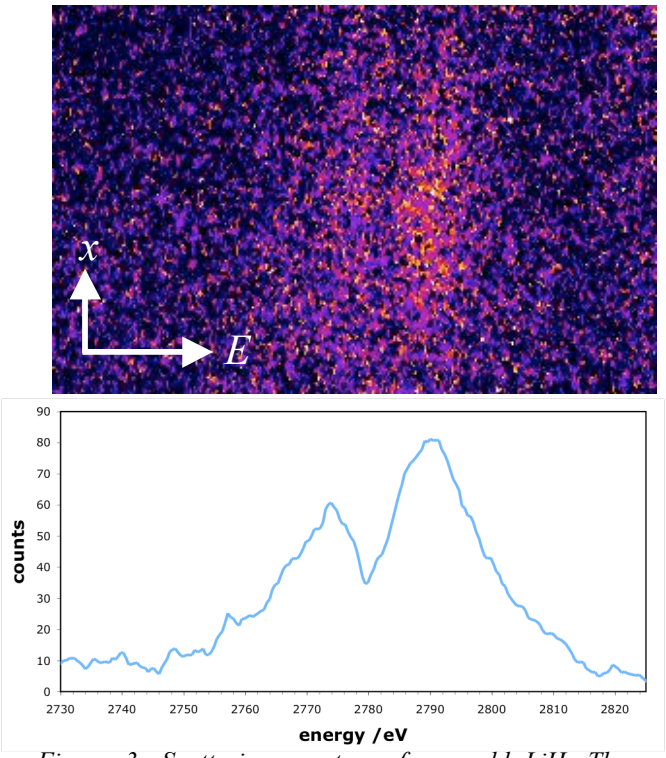

Figure 3: Scattering spectrum from cold LiH. The lineout is averaged over the spectral resolution of the spectrometer.

By varying the distance of the diagnostic hole to the x-ray source, the solid angle and thus the number of photons at the scattering target is varied. In Fig. 4 the integrated intensity in the scattering features is plotted for several shots as function of the hole distance. Normalized to the backlighter laser energy as well as to the density and thickness of the

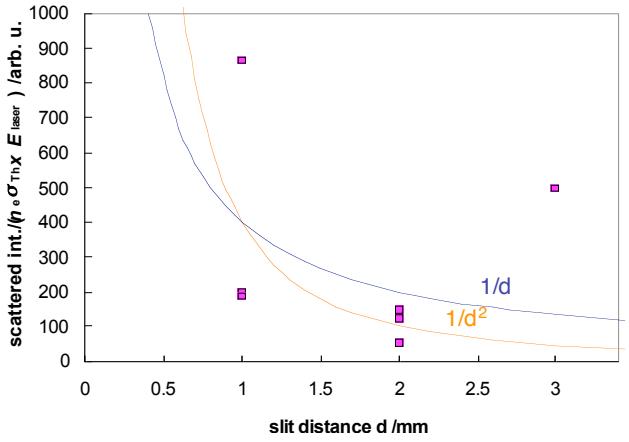

Figure 4: The scattered intensity decreases with increasing distance of the diagnostic holes due to the decrease in solid angle

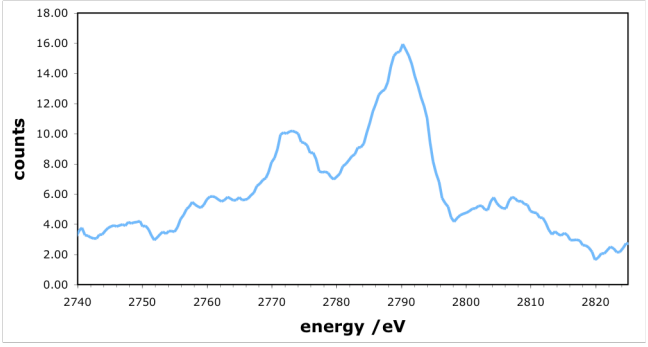

Figure 5: Scattering spectrum from radiatively heated LiH. Besides the down-shifted Plasmon peak an up-shifted feature can be observed.

scattering targets the scattered intensity decreases as expected with smaller solid angle.

Figure 5 shows a scattering spectrum from a radiatively heated LiH sample. The sample was irradiated by a 1 ns laser pulse with an energy of 155 J. A side-on Al coating acted as x-ray converter to provided radiative heating by x-rays. The backlighter pulse was delayed by 200 ps with respect to the heater beam. Besides the down-shifted Plasmon peak there seems to be an up-shifted feature. Assuming that this energy gain by scattering from a Plasmon, this would indicate a high temperature on the order of 10-20 eV. This could lead to the development of accurate and model independent temperature principle of detailed balance.

CONCLUSIONS

By greatly improving the overall detection efficiency we were able to show that the technique of x-ray Thomson scattering can be applied at few-hundred Joule class laser systems. Employing a novel target design evidence for collective x-ray scattering off cold and heated targets was found. Scattering spectra show elastic scattering features as well as down-shifted Plasmon resonances. Further analysis and fitting to theoretical spectra is expected to result in a measurement of the dispersion relation in warm-dense-matter Lithium hydride.

ACKNOWLEDGEMENTS

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[i] S.H. Glenzer et al. Phys. Rev. Lett. **90**, 175002 (2003).
[ii] M.K. Urry et al., J. Quant. Spectrosc. Radiat. Transfer **99**, 636 (2006).