Ultra-fast probing has recently received much attention for the in situ measurement of the structure and physical properties of matter at extreme conditions [1, 2]. These states of matter are of great interest to the physics of planetary formation [3] and modeling of planetary composition [4]. Contemporary experiments are designed to determine the equation of state (EOS) of light elements and to measure effects of shock waves on matter, for example to investigate astrophysical phenomena [5]. In addition, recent observations of phase transitions have attracted a lot of interest for testing theoretical predictions of fundamental properties of matter.

Here, we show the results of a new experiment to directly measure thermodynamic properties and dynamic structure factors of strongly coupled matter (also known as warm dense matter). In particular, we have used Thomson scattering [6] on liquid hydrogen to study the dispersion relation and collisional effects in hydrogen at near-solid density (~10^{22} cm^{-3}). While previous experiments on dense hydrogen have been restricted to measure particle and shock velocities [4], the results of this work become possible due to the advent of powerful free-electron laser probes in the XUV spectral range, as the one operating at the FLASH facility.

Dense hydrogen states of matter with few eV temperatures were achieved by irradiation of a cryogenic hydrogen beam with ~120 fs (FWHM), ~8 mJ optical laser pulses and probing with the (delayed) free electron laser beam at 13.5 nm. Scattering spectra were measured with high efficiency spectrometers both at 90° and 16° scattering angles. In addition, the transmitted spectrum was monitored for each FEL shot. These experiments showed the capability for studying forward and large angle scattering of XUV-FEL pulses from liquid (or solid) hydrogen to measure the dynamic heating and cooling. In particular, first XUV Thomson scattering spectra from cryogenic hydrogen have been observed showing strong elastic and plasmon scattering features (publication in preparation). The inelastic scattering from plasmon features up and down shifted in wavelength might show the characteristic asymmetry due to detailed balance [7], allowing for the most direct measurement of the electron temperature independently of any additional assumptions of the plasma state. Figure 1 shows the experimental scattering spectrum at 90°, where the broadening due to inelastic scattering from the plasmon features is clearly visible.

Experimentally we have determined the elastic scattered amplitude as function of scattering angle (i.e., at 90° and 16° scattering angle). The wavelength-integrated intensity of the elastic x-ray Thomson scattering is given as [8]:

$$I_{el} = (f + q)^2 S_0(k)$$

(1)

$S_0(k)$ is the static ion-ion structure factor, $k = 4\pi\sin(\theta/2)/\lambda$ is the scattering vector, $f$ the number of bound electrons participating in bound-bound scattering events, and $q$ is the number of free electrons in the shielding cloud around ions and that are participating in elastic scattering. Variation of scattering angle $\theta$ (hence $k$) allows testing theoretical models for the structure factor and EOS data can be determined, e.g. through the excess internal energy in the one component plasma
approximation

\[ P = nk_B T + \frac{n}{12 \pi^2} \int \frac{Z^2 e^2}{k^2} \left[ S_0(k) - 1 \right] dk \]

Here, \( n \) and \( T \) are electron density and temperature, \( k_B \) is Boltzmann's constant, and \( e \) is the charge of the electron. The electron density can be determined from the energy shift of the plasmon peak in the spectra thus providing a direct and independent measurement.

Data analysis is still in progress, but the experimental results clearly indicate that we have conducted a successful proof-of-principle experiment. The experimental procedures for soft x-ray inelastic scattering experiments on cryogenic liquid hydrogen jets using FEL radiation have been developed. The observation of scattering spectra, even in single-shot using efficient spectrometers is found to be possible. First results have been obtained for the time-resolved investigation of the parameters of an infrared laser prepared hydrogen plasma.

Figure 1: The scattered spectrum (solid line) from dense hydrogen plasma shows a broadening of the probing FEL beam (dashed line) due to inelastic scattering from plasmons.

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