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High-Power Laser Pump-Probe Experiments At The Linac Coherent Light Source

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Abstract: The Matter in Extreme Conditions end station at the Linac Coherent Light Source (LCLS) is a new tool enabling ultrafast pump-probe measurements of laser-matter interactions. This instrument combines the world's brightest x-ray source, the LCLS x-ray beam, with high-power lasers consisting of two nanosecond Nd:glass laser beams and a 25 TW short-pulse Ti:sapphire laser. These lasers produce short-lived states of matter with high pressures, high temperatures or high densities whose properties are investigated with highly accurate x-ray measurements. Here, we report on new results using x-ray imaging, diffraction, and scattering that resolve the short-pulse laser beam propagation and heating of matter.
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1. Introduction

Matter in extreme conditions is central to scientific research aimed at demonstrating nuclear fusion in the laboratory [1], for developing intense radiation sources with unique properties [2,3], and to many fundamental physics processes in astrophysics [4,5]. The capabilities of the Linac Coherent Light Source (LCLS) allow unprecedented explorations in this area of research enabling ultrafast probing with high-repetition rates and high x-ray photon energies [6]. It is particularly suited for a class of experiments that produces short-lived states of matter with extreme conditions using intense high-power laser beams where penetrating high-peak brightness x rays resolve the dynamic evolution of the target [7]. The x rays visualize structural changes and determine the physical properties with spectrally resolved x-ray scattering [7-9], x-ray diffraction [9] and x-ray imaging [10]. High repetition rates allow averaging and summation over many experiments to produce unprecedented data quality with large signal-to-noise ratios and high confidence in the results [8]. For this purpose, the LCLS x-ray beam has recently been combined with high-power lasers and a suite of optical and x-ray diagnostics at the Matter in Extreme Conditions (MEC) instrument located in the far experimental hall of LCLS.

The newly commissioned 25 TW Ti:sapphire short pulse laser beam has now been used for several target experiments. This laser is presently being upgraded to a 200 TW-class system. Here, we show first results from laser interactions with liquid hydrogen targets at a repetition rate of 5 Hz. These experiments resolve the ultrafast laser heating of hydrogen and provide a critical experimental test of particle-in-cell simulations and theory of matter in the high-energy density physics state.

2. LCLS experiment

Figure 1 show the experimental geometry for measurements of the structure factor of laser-heated hydrogen. Due to the small scattering cross section the experiments has to be performed at high repetition rates of 5 Hz to achieve sufficient signal-to-noise ratios in angularly and spectrally resolved data. We operate a cryostat at 17 K to achieve a steady-state jet of liquid hydrogen with a diameter of 5 μm. The jet flows with 100 m/s thus providing a suitable target for experiments at 5 Hz. Two spectrally resolved measurements in forward and backward scattering provide absolute scattering intensities from which we infer the structure factor. The intensity of the Compton scattering feature is determined by the f-sum rules $\int_{-\infty}^{\infty}\left(\frac{d^2\sigma}{d\Omega d\omega}\right)_C \omega d\omega = \frac{Z\hbar k^2}{2m_e}$, with $\boldsymbol{k} = 2\boldsymbol{k}_{X\text{-}ray}\,sin\theta$ and $k = 2\pi/\lambda$ providing the scale length of the measured density fluctuations. The Compton scattering intensity is solely calculated from the experimental geometry and x-ray probe energy and the calculated value provide the calibration for the measured Compton scattering feature. We can then use this information to calibrate the measurements of the forward scattering spectrometer. The latter shows the elastic (forward) scattering feature which scales as S (k) $(f+q)^2$ with f the atomic form factor and q being the screening functions. Thus, the two spectrometer provide the absolute value for S(k).

Combining this information with the angularly resolved measurements of the scattering intensity using the CSPAD area detector is thus providing the absolute structure factor, which reflects information of hydrogen bonding and dissociation in a dynamic laser heating experiment. By varying the delay between the optical drive laser and x-

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ray probing we find that hydrogen dissociates and heats over time scales of 25 ps. These measurements compare with particle in cell simulations that predict faster time scales for the heating of the ionic system. This is a first indication that the conductivity model and electron-ion coupling in dense system may evolve slower than hitherto applied in calculations.

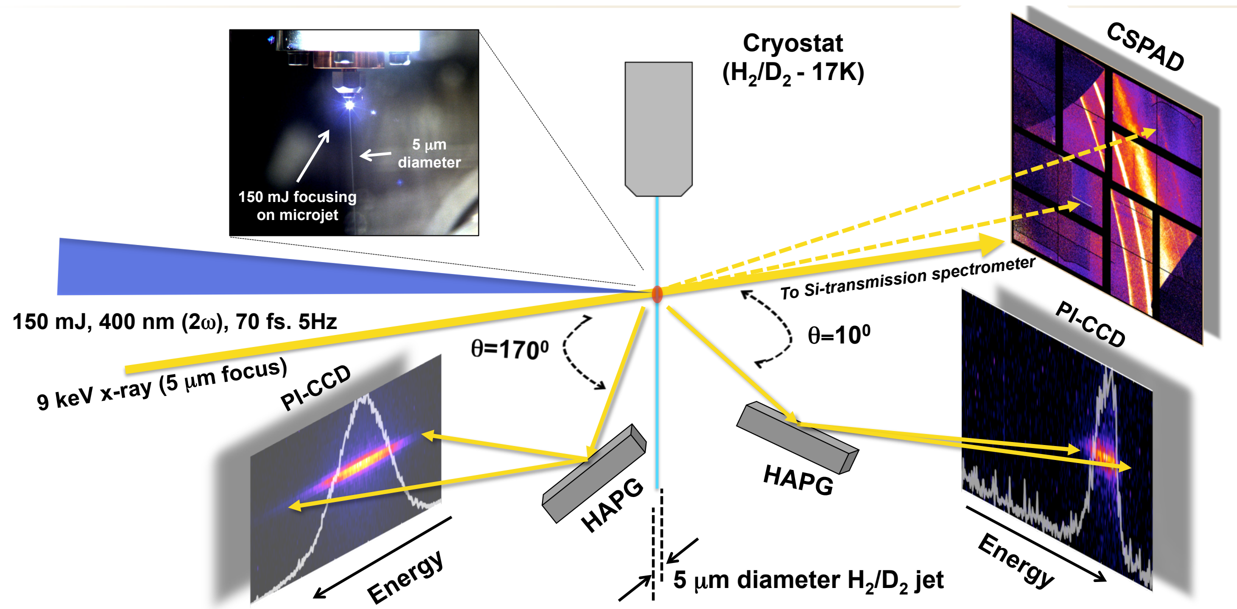

Figure 1. A schematic of experimental setup for high-power laser-plasma interaction studies at MEC is shown. The 70 fs short-pulse laser beam is heating a continuously flowing cryogenic hydrogen target at a repetition rate of 5 Hz and the interaction is visualized using LCLS x-ray scattering and diffraction. A CSPAD area detector observes the total wavenumber-resolved x-ray scattered intensity indicating the transition from Debye-Scherrer diffraction rings to a liquid correlation feature. Combined with spectrally resolved measurements we can infer the absolute structure factor. This is accomplished by measuring the 13˚ forward x-ray scattering spectrum that shows elastic scattering, which we calibrate with the inelastic Compton scattering feature measured in 130˚ backscattering geometry.

3. Conclusions

We have demonstrated a new experimental capability to measure the structure factor in laser-heated hydrogen using LCLS x-ray scattering techniques. The experiment applies novel high repetition-rate target, driver and diagnostics techniques allowing us to resolve the dynamic heating of matter with 50 fs temporal resolution and 5 micrometer spatial resolution. The analysis suggests slower than calculated electron-ion coupling indicating the potential for obtaining critical experimental tests of simulations of high-power laser-matter interactions.

4. References and Acknowledgements

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