

# Inferring the Electron Temperature and Density of Shocked Liquid Deuterium Using Inelastic X-Ray Scattering

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**Abstract.** An experiment designed to launch laser-ablation-driven shock waves (10 to 70 Mbar) in a planar liquid-deuterium target on the OMEGA Laser System and to diagnose the shocked conditions using inelastic x-ray scattering is described. The electron temperature ( $T_e$ ) is inferred from the Doppler-broadened Compton-downshifted peak of the noncollective ( $\alpha_s = 1/k\lambda_D > 1$ ) x-ray scattering for  $T_e > T_{\text{Fermi}}$ . The electron density ( $n_e$ ) is inferred from the downshifted plasmon peak of the collective ( $\alpha_{\text{scatter}} > 1$ ) x-ray scattering. A cylindrical layer of liquid deuterium is formed in a cryogenic cell with 8- $\mu\text{m}$ -thick polyimide windows. The polyimide ablator is irradiated with peak intensities in the range of  $10^{13}$  to  $10^{15}$  W/cm<sup>2</sup> and shock waves are launched. Predictions from a 1-D hydrodynamics code show the shocked deuterium has a thickness of  $\sim 0.1$  mm with spatially uniform conditions. For the drive intensities under consideration, electron density up to  $\sim 5 \times 10^{23}$  cm<sup>-3</sup> and electron temperature in the range of 10 to 25 eV are predicted. A laser-irradiated saran foil produces Cl Ly $_{\alpha}$  emission. The spectrally resolved x-ray scattering is recorded at 90° for the noncollective scattering and at 40° for the collective scattering with a highly oriented pyrolytic graphite (HOPG) crystal spectrometer and an x-ray framing camera.

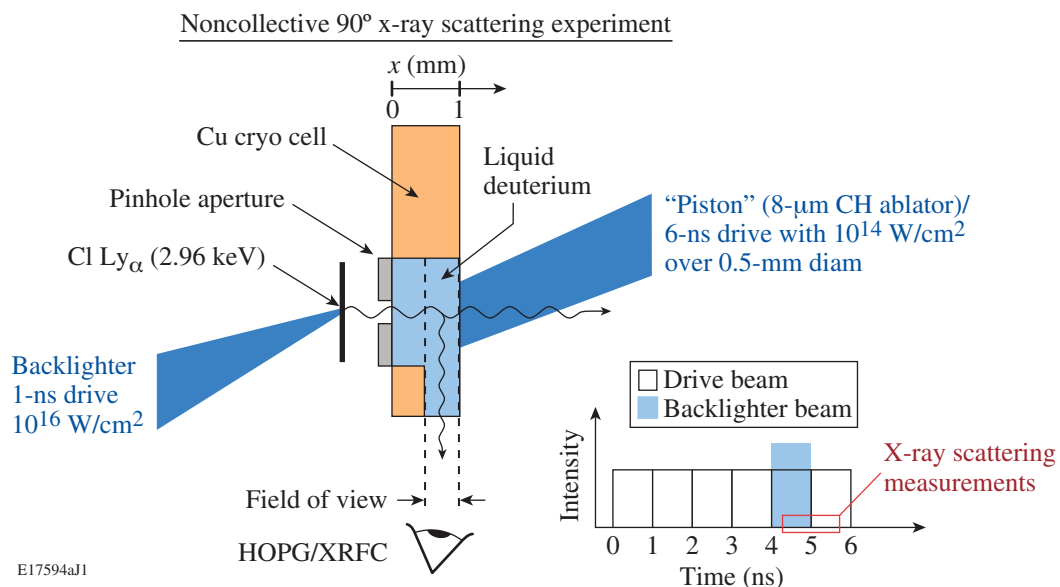
## 1. Introduction

An experimental platform to study inelastic x-ray scattering from shocked deuterium is being developed on the 60-beam, 30-kJ, 351-nm OMEGA Laser System [1]. Inelastic x-ray scattering [2,3] is a powerful diagnostic for equation-of-state (EOS) measurements in inertial confinement fusion (ICF). Laser-ablation-driven shock waves are launched into planar liquid-deuterium targets creating warm dense matter with conditions similar to an imploding shell of thermonuclear fuel in ICF during the shock propagation and acceleration phases. Diagnosing the plasma conditions of the shocked deuterium is important because the minimum energy needed to achieve ignition ( $E_{\text{min}}$ ) depends on the

plasma conditions in the shell [4]: The ratio of the pressure in the shell to the Fermi-degenerate pressure is defined as the shell's adiabat ( $\alpha$ ) and  $E_{\min} \sim \alpha^{1.8}$  [4]. A saran foil is irradiated with a group of tightly focused beams having an overlapped intensity of  $\sim 10^{16}$  W/cm<sup>2</sup> and producing Cl Ly $_{\alpha}$  emission at 2.96 keV. The electron density ( $n_e$ ) and temperature ( $T_e$ ) are inferred from the spectral line shapes of the inelastic x-ray scattering of the Cl Ly $_{\alpha}$  emission from the shocked deuterium. The  $T_e$  and average ionization ( $Z$ ) of the shocked deuterium are inferred from the noncollective scattering (i.e., scattering from the electrons) [2] recorded at a 90° scattering angle. The  $n_e$  of the shocked deuterium is inferred from the collective scattering (i.e., scattering from electron plasma waves or plasmons) [3] recorded at a 40° scattering angle. The design of the experiment, including predictions of the shocked plasma conditions from the 1-D hydrodynamics code *LILAC* [5], is presented in Sec. 2. A brief discussion of the inelastic x-ray scattering is given in Sec. 3. Future experiments combining inelastic x-ray-scattering observations with shock-velocity measurements [6–9] are described in Sec. 4.

## 2. Experimental configuration

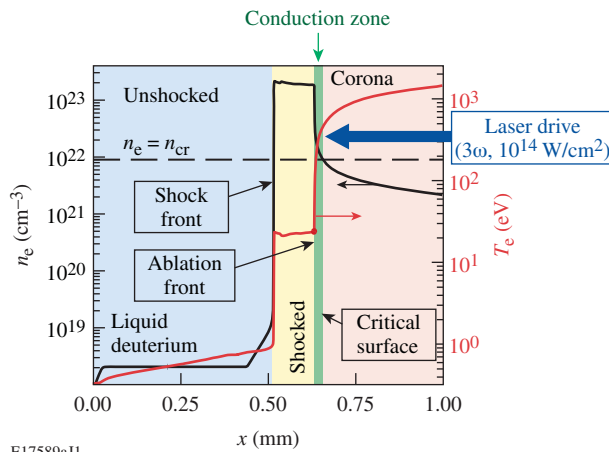
The experimental configuration is shown in Fig. 1 for the  $\theta = 90^\circ$  scattering geometry. The 8- $\mu$ m-thick plastic ablator containing the planar layer of liquid deuterium is irradiated with a constant intensity UV laser drive with  $10^{14}$  W/cm<sup>2</sup>. The laser drive, formed with six pairs of beams staggered in time as shown in the lower right of Fig. 1, is uniform over a 0.5-mm diameter. A laser-ablation driven shock wave is launched through the liquid deuterium creating warm dense matter. Twelve tightly focused beams irradiate a saran backlighter with  $10^{16}$  W/cm<sup>2</sup> generating Cl Ly $_{\alpha}$  emission ( $\lambda_0 = 4.188$  Å), which is scattered at  $\theta = 90^\circ$  and detected with an x-ray framing camera (XRFC) outfitted with a HOPG crystal spectrometer [2,3]. The timing of the backlighter beams is also shown. The integration time of the x-ray scattering measurements is  $\sim 200$  ps.



**Figure 1.** The CH ablator of a planar layer of liquid deuterium target is irradiated with a constant intensity ( $10^{14}$  W/cm<sup>2</sup>) 6-ns UV laser drive. A laser-ablation-driven shock wave is launched through the liquid deuterium creating warm dense matter. Twelve tightly focused beams irradiate a saran backlighter with  $10^{16}$  W/cm<sup>2</sup>. Cl Ly $_{\alpha}$  emission scattered at 90° is detected with an x-ray framing camera (XRFC) outfitted with a HOPG crystal spectrometer. The timing of the drive and backlighter beams as well as the x-ray scattering observations are shown in the lower right.

The 1-D hydrodynamics code *LILAC* [5] is used to model the plasma conditions of the warm dense matter presented in Fig. 2. Laser absorption via inverse bremsstrahlung is calculated using a ray-trace

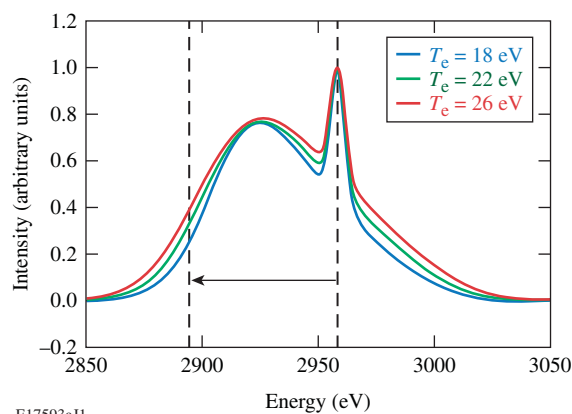
algorithm. Electron thermal conduction is calculated using a flux-limited diffusion model. Radiative transport is calculated using the Los Alamos Astrophysical tables. The *SESAME* tables are used to determine the EOS. Uniform conditions are predicted in the  $\sim 100\text{-}\mu\text{m}$ -thick shocked region with  $n_e = 2.0 \times 10^{23} \text{ cm}^{-3}$ ,  $\rho \sim 0.8 \text{ g/cm}^3$ ,  $T_e = 22 \text{ eV}$ ,  $Z = 1$ , and  $P = 12 \text{ Mbar}$ .



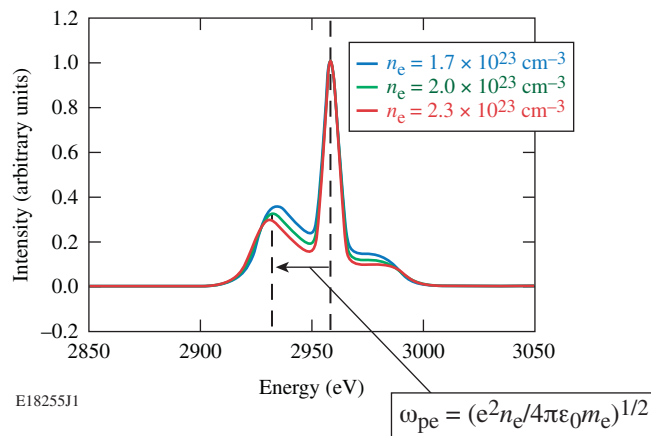
**Figure 2.** A laser-ablation-driven shock wave is launched in a liquid-deuterium target with a constant intensity laser drive of  $\sim 10^{14} \text{ W/cm}^2$ . The shocked conditions at  $t = 5 \text{ ns}$  are predicted with the 1-D hydrodynamics code *LILAC* [5]. Uniform conditions in the shocked region ( $100\text{-}\mu\text{m}$ -thick,  $500\text{-}\mu\text{m}$ -diam cylinder) with  $n_e = 2.0 \times 10^{23} \text{ cm}^{-3}$ ,  $\rho \sim 0.8 \text{ g/cm}^3$ ,  $T_e = 22 \text{ eV}$ , and  $P = 12 \text{ Mbar}$  are predicted.

### 3. Inelastic x-ray scattering

Inelastic x-ray scattering is defined as collective or noncollective depending on the scattering parameter  $\alpha_s = 1/k\lambda_D$ , where the probe wave number  $k = 4\pi/\lambda_0 \sin(\theta/2)$  and  $\lambda_D$  is the Debye length. If  $\alpha_s < 1$  the scattering is from the free electrons and it is referred to as noncollective [2,3]. Figure 3 shows the calculated x-ray scattering of  $\text{Cl Ly}\alpha$  emission ( $\lambda_0 = 4.188 \text{ \AA}$ ) from electrons in the shocked deuterium for fixed electron density  $n_e = 2.0 \times 10^{23} \text{ cm}^{-3}$  and average ionization  $Z = 1$ , with the electron temperature varied from  $T_e = 18 \text{ eV}$  to  $T_e = 26 \text{ eV}$ . The scattering angle is  $\theta = 90^\circ$  and the scattering parameter is  $\alpha_s = 0.61$ . The Compton peak (inelastic) is on the low energy side of the Rayleigh peak (elastic) at  $2.96 \text{ keV}$ . The width of the Compton-downshifted ( $\Delta E_C = \hbar^2 k^2 / 2m_e$ ), Doppler-broadened component indicates the electron temperature and the ratio of the inelastic-to-elastic peaks indicates the average ionization ( $Z$ ) of the plasma. All of the  $T_e$ -sensitive features shown in Fig. 3 can be resolved with the gated x-ray spectrometer. If  $\alpha_s > 1$  the scattering is from the electron plasma waves or plasmons and is referred to as collective. Figure 4 shows the calculated x-ray scattering of  $\text{Cl Ly}\alpha$  emission from plasmons for fixed electron temperature  $T_e = 22 \text{ eV}$  and average ionization  $Z = 1$ , with the electron density varied from  $n_e = 1.7 \times 10^{23} \text{ cm}^{-3}$  to  $n_e = 2.3 \times 10^{23} \text{ cm}^{-3}$ . To lowest order, the energy-downshifted plasmon feature is related to the electron plasma frequency  $\omega_{pe} = (e^2 n_e / 4\pi\epsilon_0 m_e)^{1/2}$ . Again these  $n_e$ -sensitive differences can be resolved in the experiment.



**Figure 3.** For shocked deuterium the x-ray scattering of  $\text{Cl Ly}\alpha$  emission at  $2.96 \text{ keV}$  ( $\lambda_0 = 4.188 \text{ \AA}$ ) from electrons has been calculated for the following conditions: The electron density and ionization are kept fixed at  $n_e = 2.0 \times 10^{23} \text{ cm}^{-3}$  and  $Z = 1$ , while the electron temperature is varied from  $T_e = 18 \text{ eV}$  to  $T_e = 26 \text{ eV}$ . The scattering angle is  $\theta = 90^\circ$  and the scattering parameter is  $\alpha_s = 0.61$ . The Compton peak is on the low energy side of the Rayleigh peak at  $2.96 \text{ keV}$ .



**Figure 4.** For shocked deuterium the x-ray scattering of Cl Ly $\alpha$  emission at 2.96 keV ( $\lambda_0 = 4.188 \text{ \AA}$ ) from plasmons has been calculated for the following conditions: The electron temperature and ionization are kept fixed at  $T_e = 22 \text{ eV}$  and  $Z = 1$ , while the electron density is varied from  $n_e = 1.7 \times 10^{23} \text{ cm}^{-3}$  to  $n_e = 2.3 \times 10^{23} \text{ cm}^{-3}$ . The scattering angle is  $\theta = 40^\circ$  and the scattering parameter is  $\alpha_s = 1.26$ .

#### 4. Future directions

Typical EOS measurements diagnose the shock velocity and infer the velocity of the particles [6–9]. Experiments on OMEGA will combine inelastic x-ray-scattering observations with shock-velocity measurements for  $P < 10 \text{ Mbar}$ ; consequently,  $P$ ,  $\rho$ ,  $n_e$ ,  $T_e$ , and  $Z$  of the shocked deuterium will be measured. They will also involve multiple shock waves launched by shaped-laser-pulse drives. The comparison with visible diagnostic measurements may only be possible for laser drive intensities as low as  $\sim 10^{13} \text{ W/cm}^2$ , which have negligible levels of target preheat. Systematic differences between the plasma conditions inferred by the two diagnostic techniques for the shocked deuterium will be studied. Ideally, accuracies of the plasma condition measurements  $\sim 10\%$  are needed for this research.

#### 5. Conclusions

An experiment designed to launch laser-ablation-driven shock waves (10 to 70 Mbar) in a planar liquid-deuterium target on the OMEGA Laser System [1] and diagnose the shocked conditions using inelastic x-ray scattering [2,3] has been designed. Inelastic x-ray scattering is a powerful diagnostic for high-pressure ( $P > 10 \text{ Mbar}$ ) EOS research, which is inaccessible to optical shock-velocity measurements [6–9].

#### Acknowledgment

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