A Case Study of Using X-Ray Thomson Scattering to Diagnose the In-Flight Plasma Conditions of DT Cryogenic Implosions

H. Poole,[1] D. Cao,[2] R. Epstein,[2] I. Golovkin,[3] T. Walton,[3] S. X. Hu,[2] M. Kasim,[1] S. M. Vinko,[1] J. R. Rygg,[2] V. N. Goncharov,[2] G. Gregori,[1] and S. P. Regan[2]

[1]Department of Physics, University of Oxford
[2]Laboratory Laboratory for Laser Energetics, University of Rochester
[3]Prism Computational Sciences

The design of inertial confinement fusion ignition targets requires radiation-hydrodynamic simulations with accurate models of the fundamental material properties (i.e., equation of state, opacity, and conductivity). Validation of these models are required via experimentation. A feasibility study of using spatially integrated, spectrally resolved, x-ray Thomson-scattering (XRTS) measurements to diagnose the temperature, density, and ionization of the compressed DT shell of a cryogenic DT implosion at two-thirds convergence was conducted. This study involved analyzing the x-ray scattering data produced by targets with very different adiabats, specifically 2.8 and 8.0, to determine if their conditions were distinguishable.

Synthetic scattering spectra were generated using 1-D implosion simulations from the *LILAC* code[1] that were post-processed with the x-ray scattering model, which is incorporated within *Spect3D*.[2] To model the x-ray emissivity, a 1-kJ laser with a 10-ps pulse length and a source diameter of 50 μm was used to produce a Gaussian x-ray source, with a FWHM of 10 eV (Ref. 3). The scattering geometry is shown in Fig. 1. The detectors captured scattering data at $\theta_F = 40°$ and $\theta_B = 120°$. Two x-ray photon energies, 2 keV and 3.5 keV, were considered.

Using the output spectra from *Spect3D*, synthetic experimental data were produced by assuming a detector efficiency of $\Gamma_{det} \sim 10^{-5}$ and a spectral resolution of 3 eV/bin, which gives ~300 inelastically scattered photons resolved by the detector. Synthetic experimental noise was added by removing the uniform background signal and using the Poisson statistic, which estimates the noise as $\sim 1/N_t$, where N_t is the number of photons per spectral resolution element.

Before extracting the plasma parameters from the spatially integrated simulated spectra, the inverse problem instability must first be addressed, which implies that the same measured spectra could be fitted equally well by very different plasma parameters. Bayesian inference, using Markov–Chain Monte Carlo (MCMC) to sample the multidimensional space, is a more-robust approach to exploring the behavior of the complex multiparameter simulations.[4]

The MCMC exploration fit the entire spectra, assuming two weighted uniform plasma regions, one containing DT and the other CH. The cost function used to determine the appropriateness of each MCMC spectrum calculates the maximum percentage error to allow equal weighting of the fitting to the elastic and inelastic peaks between the MCMC spectrum I_{fit}, and the synthetic experimental spectra I_{raw},

$$\beta_{cost} = \max\left(\frac{I_{fit} - I_{raw}}{I_{raw}} \frac{1}{\sqrt{2}\,\sigma}\right)^2,$$

where σ is the standard deviation representative of the noise of the synthetic scattering spectra. The σ is selected such that the noise of the scattering signal falls comfortably within the spread of the accepted fits. A value of 0.075 was chosen. The forward-

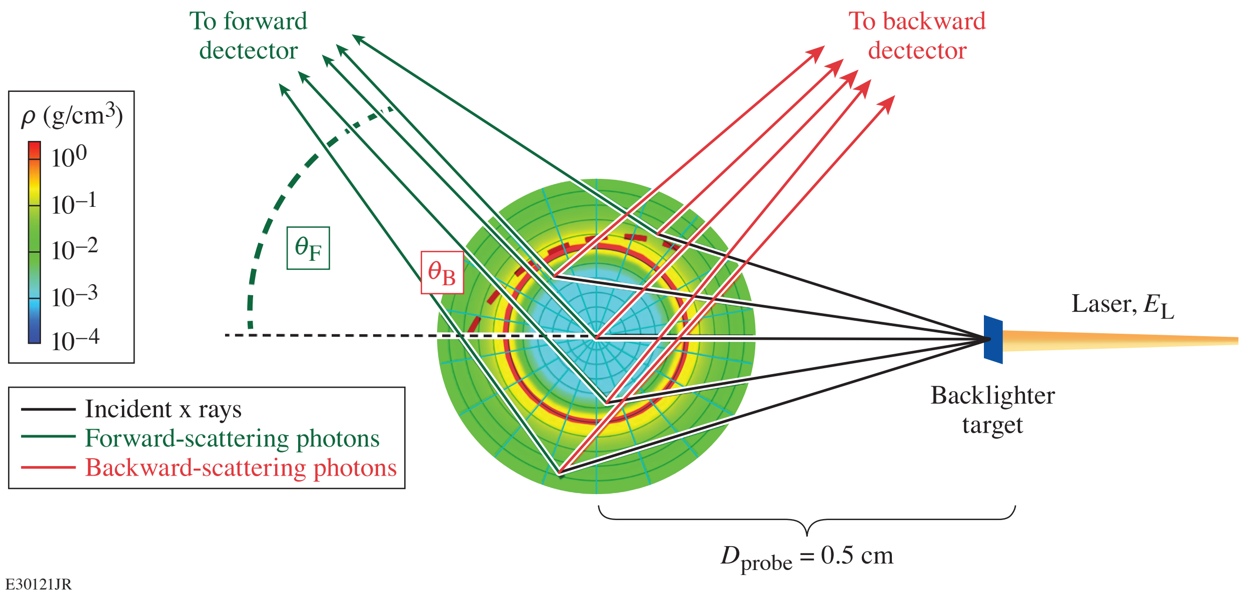

Figure 1
A sketch of the proposed experimental setup, with a laser of energy E_L incident on a backlighter target, producing x rays with a conversion efficiency of η_x. The scattering x rays are shown incident on the 3-D inferred density profile from *Spect3D* using the 1-D simulation data produced by the *LILAC* code. A schematic of the scattering events, recorded on the detector by *Spect3D*, from different zones throughout the implosion, is shown. The scattering geometry is demonstrated and not drawn to scale.

and backward-scattering spectra were analyzed separately, and their parameter distributions were combined to produce an overall distribution for each plasma parameter. The distributions for each adiabat and x-ray photon energy are shown in Table I.

Good agreement was found between the mass-averaged simulation parameter values and the MCMC distributions. There is, predictably, very little information regarding the CH plasma. This is due to its lower density compared to the DT compressed shell, meaning it does not contribute to the overall shape of the scattering. Overall, the optimum analysis presented in this summary to resolve the plasma conditions in the compressed shell, using a realistic laser probe from OMEGA EP, is performing MCMC analysis from spectra produced using a backward fielding detector. Since the collective forward-scattering detector is not required for sufficient convergence on the DT compressed shell parameters, either a 2-keV or 3.5-keV x-ray photon energy probe could be used. Better agreement may be achieved between the MCMC parameters and the simulations if a narrower bandwidth probe beam could be used.

Table I: The full spectral analysis of MCMC DT fitting parameters compared to the mass-weighted parameters from the *LILAC* 1-D simulations, focused on the compressed DT shell, for each adiabat and each probe.

DT parameter	T_e	n_e (cm^{-3})	Z
Adiabat = 2.8			
Simulation	25	5.5×10^{23}	0.97
MCMC 2 keV	33±8	$(5.2\pm0.6) \times 10^{23}$	0.94±0.03
MCMC 3.5 keV	25±3	$(5.0\pm0.3) \times 10^{23}$	0.95±0.03
Adiabat = 8.0			
Simulation	38	3.7×10^{23}	0.97
MCMC 2 keV	50±6	$(2.6\pm0.4) \times 10^{23}$	0.88±0.07
MCMC 3.5 keV	56±6	$(3.2\pm0.5) \times 10^{23}$	0.87±0.05

In summary, spatially integrated XRTS spectra for 1-D *LILAC*-simulated conditions of low- and high-adiabat, DT cryogenic implosions have been calculated at two-thirds convergence. Markov–Chain Monte Carlo analysis was performed for two different scattering setups. Information on the compressed shell conditions was obtained since it has been shown to be possible to use the spectral resolution in a spatially integrated measurement to discriminate between different regions in the plasma. Fielding just one detector in the noncollective scattering regime produces good agreement with the compressed shell mass-averaged parameters from the simulation. This technique can be used to resolve both the low- and high-adiabat implosions. In the future, similar analysis will be performed on the conditions at stagnation, the effect of mixing in the implosion, as well as investigations into 2-D and 3-D simulations using *DRACO* and *ASTER*.

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