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Title: Development on the National Ignition Facility of a High Energy Density Opacity Platform

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X-ray opacity is a crucial factor in all radiation-hydrodynamics calculations, yet it is one of the least validated of the material properties in simulation codes for high-energy-density plasmas. Recent opacity experiments at the Sandia Z-machine have shown up to factors of two discrepancies between theory and experiment for various mid-Z elements (Fe, Cr, Ni). These discrepancies raise doubts regarding the accuracy of the opacity models which are used in ICF and stewardship as well as in astrophysics. Therefore, a new experimental opacity platform has been developed on the National Ignition Facility (NIF), not only to verify the Z-machine experimental results, but also to extend the experiments to other temperatures and densities.

Within the context of the national opacity strategy, the first NIF experiments were directed towards measuring the opacity of iron at a temperature of ~160 eV and an electron density of $\sim 7 \times 10^{21}$ cm^{-3}(Anchor 1). The Z data agree with theory at these conditions, providing a reference point for validation of the NIF platform. Development shots on NIF have demonstrated the ability to create a sufficiently bright point backlighter using an imploding plastic capsule, and also a combined hohlraum, sample and laser drive able to produce iron plasmas at the desired conditions.

Spectrometer qualification has been completed, albeit with additional improvements planned, and the first iron absorption spectra have now been obtained.

To complete the Level 2 Milestone, this consolidated report documents both the platform development leading up to the first NIF iron opacity experiments and the initial analysis of the first iron shots. The report comprises this summary document and the appended copies of the team's publications and key presentations documenting completion of the four subtopics of the milestone:

A. Sample and hohlraum design and characterization [Sections 2 and 4 of this report],

B. Backlighter design and characterization [Section 3],

C. Spectrometer development and fielding [Section 5], and

D. Data analysis and assessment [Section 6]

1. Introduction

Opacity calculations for high-energy-density physics entail approximations to myriad atomic processes in a plasma environment, many of which have not been tested by experiments at relevant conditions. Earlier opacity experiments have established requirements for successful measurements, and a limited number of opacity experiments have shown good agreement with theory [1-8]. However, recent experiments performed at the Sandia National Laboratory's Z-machine, at higher temperature and density than previously studied, have shown serious discrepancies between measurements and theory for iron [9]. Despite a decade of effort, it has not been possible to reconcile these Z results with theory. Consequently, the national opacity strategy began plans in 2013 to replicate the experiment on NIF as the closest match to Z for this class of experiment. NIF platform development began in FY14, leading to initial iron measurements in FY17 through a LANL-led multi-lab collaboration, resulting in the current DOE L2 milestone.

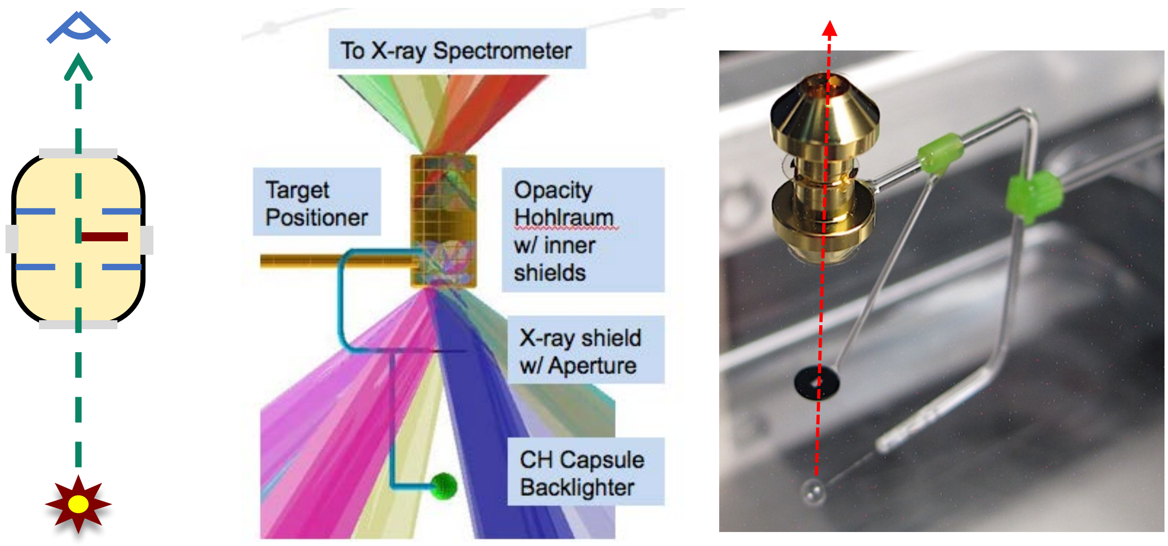
2. Experimental Approach

Opacity experiments on lasers have a long history [1-5] and the basic techniques are detailed elsewhere [4,8]. Figure 1 shows the key experimental elements and the NIF approach [15,16]. A hydrodynamically tamped opacity sample is heated, uniformly and in LTE conditions, inside a laser-driven hohlraum designed to shield the sample from NLTE emission by the laser spots. Additional laser beams drive a continuum x-ray backlighter. Some of the backlighter x-rays pass directly through the sample and others go around the sample. Both sets of x-rays fall on the same spectrally-resolving detector. After correcting for backgrounds, dividing the attenuated spectrum by the unattenuated spectrum yields the spectrally dependent transmission of the sample.

The transmission is related to the opacity by the relation $T(h\nu) = \exp[-\rho L\kappa(h\nu)]$, where $h\nu$ is the photon energy, ρ is the plasma mass density, L is the path length through the sample, and $\kappa(h\nu)$ is the opacity (mass absorption coefficient of X-rays) as a function of photon energy. The opacity is then $\kappa = -\ln(T) / \rho L$.

To make meaningful comparison with theory, the opacity must be measured to an accuracy of ±10%. This requires that the sample must be fully characterized, with the areal mass density, ρL, known to ±7%, and the X-ray transmission, T, measured to ±0.02. In addition, the sample temperature must be determined to ±5% and the density to ±20%; both must remain stable over the duration of the measurement. Further details on the experimental approach and early platform development can be found in Appendix A. A detailed description of the target fabrication and assembly is provided in appendix B.

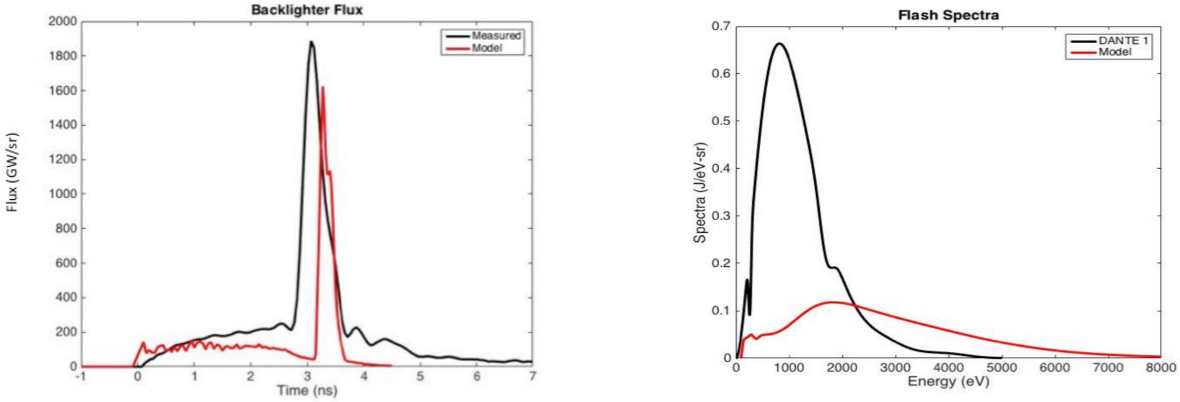
Figure 1: Opacity experimental approach, initial design and current NIF target.



3. The Backlighter

At temperatures of 150-200 eV the opacity sample itself emits copious x-rays, and the backlighter must be significantly brighter than the sample. To address this on NIF, a new spectrally uniform continuum x-ray source was developed [17] based on CH capsule implosions as pioneered at Omega [10-12]. Here a plastic shell 2 mm in diameter and ~20 microns in shell thickness is directly driven by 64 beams using ~200 kJ. Despite the 2-D nature of the capsule implosion the backlighter design was developed using 1-D HYDRA simulations; the simulations could not predict the implosion performance perfectly but were invaluable in guiding the design. Figure 2 includes the measured flux from the capsule compared with 1-D HYDRA simulation. An x-ray image showed a tight implosion core <100 um diameter. The DANTE x-ray diodes showed an x-ray pulse with a FWHM duration of 350 ps (left). The DANTE and VIRGLE spectrometers showed a non-thermal output spectrum (right) with a peak in the desired 0.5-1.0 keV band. Having the emission peaked below 1 keV helps reduce second order diffraction from the crystal and thus reduces background. It was very fortuitous that the actual spectrum was softer than what was predicted. Photometrics appear adequate for measurements at 150-180 eV, but more X-ray yield may be required for samples at higher temperatures. There are 64 additional NIF beams which could be added to the backlighter drive to increase output.

Figure 2: Measured backlighter flux and pre-shot model; Measured spectra (DANTE and VIRGIL).



4. The hohlraum

The axially symmetric NIF platform required considerable evolution in hohlraum design (Figure 3). The initial design was based on the hohlraums used on the Nova opacity experiments [4]. Various issues led to a series of redesigns [16] resulting in the final McFee-style hohlraum with LEH cavities shaped like the Apollo space capsule. The concept was suggested many years ago by Ron McFee and Bernie Wilde but had not been used extensively for opacity experiments. Figure 4 shows pre-shot LASNEX simulations by Dodd et al. (paper in preparation, Appendix D) in fairly good agreement with X-ray emission flux data. Some modifications are still being made to the laser pulse shapes but the hohlraum appears to meet all requirements for opacity measurements at sample temperatures up to 200 eV.

Figure 3: Evolution of Opacity Hohlraum Design from Nova to NIF. From left to right: traditional ICF hohlraum design, opacity hohlraum used on Nova & Omega, "LampShade " concept, McFee or DogBone concept, McFee-LampShade Hybrid, and finally " Apollo"-McFee hybrid design currently used on NIF.

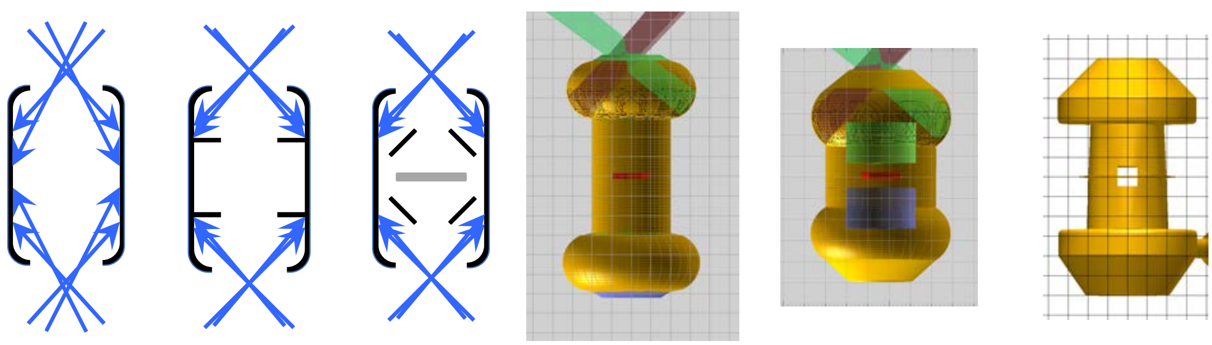
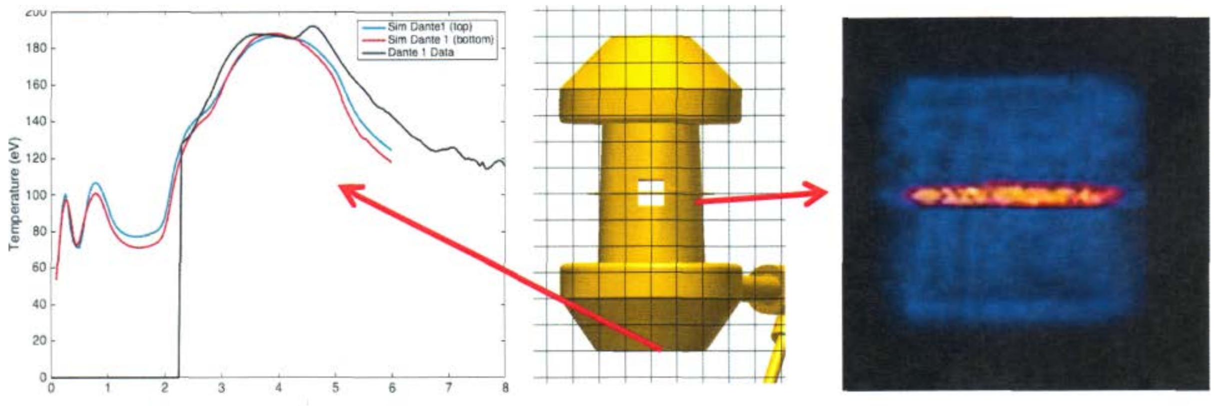


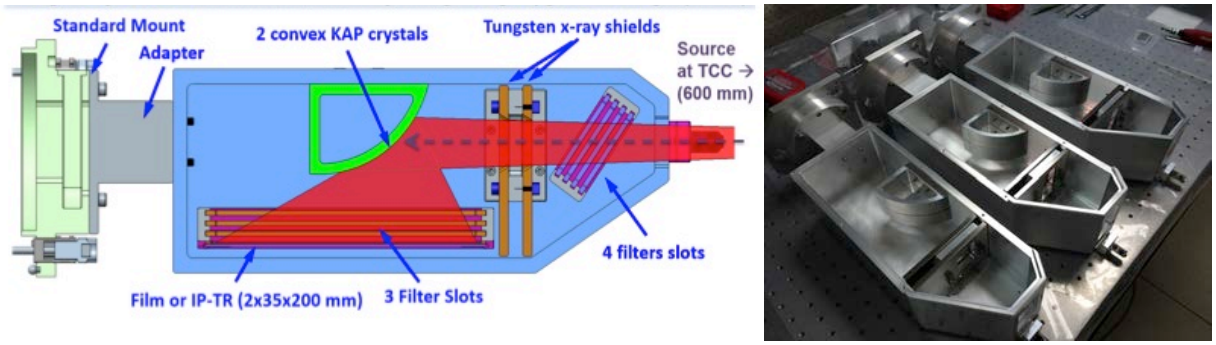
Figure 4: Left: DANTE-1 measured temperature and capsule flash time, with pre-shot simulations. Middle: View of hohlraum from mid-plane gated imager. Right: Time-resolved X-ray pinhole camera image of the expanding sample inside the hohlraum, taken at the same time as the backlighter flash. Data imply an electron density of $6x10^{21}$ cm^{-3} (Anchor 1).



5. Spectrometer Development and Fielding

The final element in the new NIF opacity platform is the Opacity Spectrometer [13, 14] with the original design illustrated in Figure 5. This is a time-and space-integrated crystal spectrometer covering an energy range from 540 to 2100 eV using two 35x180 mm detectors, with an energy resolution E/dE > 700 (using X-ray film) or E/dE > 300 (using imaging plate). Initial absorption spectra for iron-magnesium plasmas were obtained in March and May 2017, with the Mg Ly-α feature indicating temperatures near Anchor 1 requirements, but with a high background from hard X-ray scattering off the aluminum crystal mounts. Modifications were made to the spectrometer which led to higher quality data. For the most recent shots in August 2017, the background was reduced by roughly a factor of 3 by replacing the aluminum mounts with plastic ones. Also implemented in August was an improved forward filter module to increase the spacing from the front-most filter to the crystals and detector cartridge. X-ray heating vaporizes the front-most filter and the resulting debris tended to damage the detector cartridge (compromising the data) unless thicker rear filters were used, which in turn reduced signal at lower energies. The new filter module enabled data to be obtained using 3x thinner filters, extending the spectral range below 1000 eV for the first time. Preliminary photometrics on these initial data (using image plate) data indicate ~40,000 photons per 25x25 micron pixel, for a noise level of ~0.5%, significantly lower than the scanner noise. This meets the primary design goal for the Opacity Spectrometer.

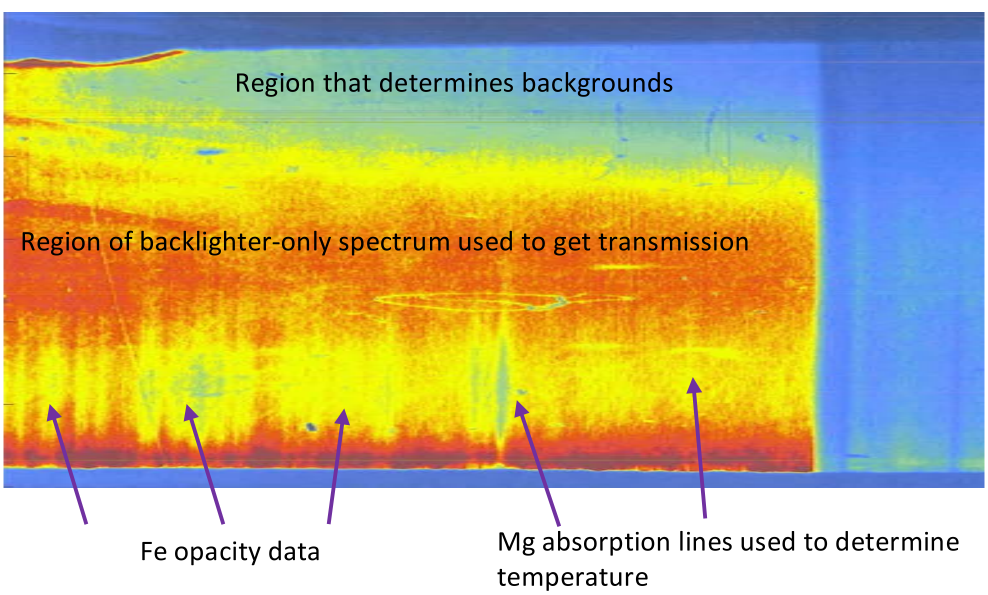
Figure 5: NIF Opacity Spectrometer design from [Ross 2016], and first 3 units.



Section 6 – Data Analysis and Assessment

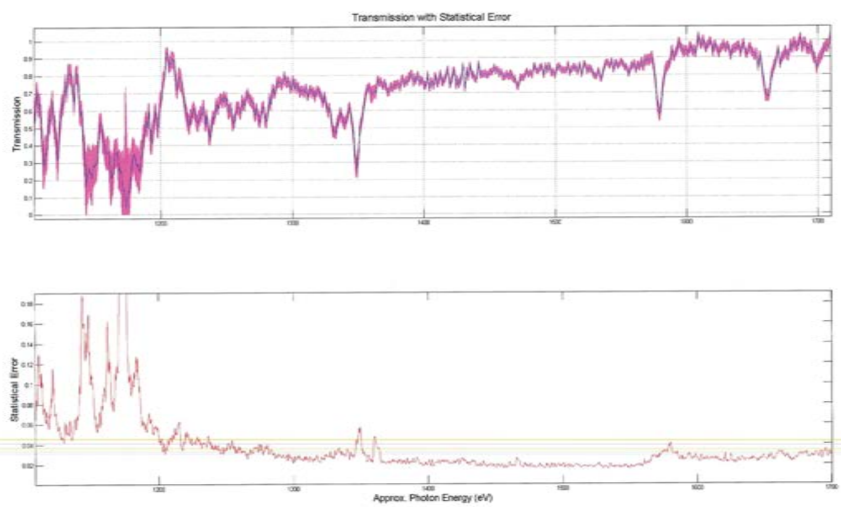
Figure 6 shows a portion of the data from the August 2017 shot day. Significant effort went into reducing the background signal and improving the transmission signal to get this data. This includes the addition of plastic windows over the hohlraum LEH (prevents stagnating gold plasma from hohlraum walls obstructing line-of-sight), increased collimator thickness (reduces unwanted x-rays from backlighter getting to spectrometer) and additional spectrometer modifications (removes additional hard x-ray scattering to image plate/film). In processing these data, a geometric model of the hard X-ray background was computed and subtracted from the data after fitting to the regions of the image sensitive only to the hard X-rays. The hard X-ray background arises from near-isotropic non-Bragg scattering off the X-ray illuminated portion of the crystal mount, and is exacerbated on these initial shots by the use of imaging plate (which is more sensitive to higher-energy X-rays than lower energy X-rays). The background should be greatly reduced on future shots using X-ray film, but the background subtraction model will continue to be useful to optimize data quality.

Figure 6. Data from N170822-002.



After hard X-ray subtraction, the lineouts were generated and aligned using the known energy of the aluminum K-edge from the filters. The self-emission background was subtracted from both the absorption and backlighter spectra as outlined in the experimental design [Heeter 2017]. The ratio of these spectra is the transmission. For each photon energy, the standard deviation of the data within the lineout bands are also computed, and used to assess the statistical error in the transmission. A preliminary transmission analysis is plotted in Figure 7, and the statistical error meets the ±0.02 requirement over much of the spectral range. The statistical error will decrease further using X-ray film and/or an improved image plate scanner with lower noise. The transmission in Figure 7 remains “preliminary” because there remain several potential systematic error sources which need to be quantified (and, if necessary, used to adjust the data). Among these are the potential for 2nd and 3rd order diffraction, residual error in the hard X-ray background subtraction, and (especially below 1200 eV) the presence of data artifacts originating from the edges of the crystal. These edges will be covered on future experiments to eliminate this source of data contamination.

Figure 7. ***Preliminary*** *transmission analysis of N170822-002. Even with image plate, statistical error levels meet platform requirements (<0.02) from 1370-1550 eV, and are close to meeting platform requirements elsewhere in the spectrum. Statistical data quality is expected to improve in FY18 using film and/or a better image plate scanner. Systematic error sources are still being assessed and corrections are expected to have some effect on the overall transmission level.*



These measurements satisfy the Level 2 Milestone goal of making iron opacity measurements by the end of FY2017. Going forward the primary goals for FY18 are to demonstrate 10% accuracy in opacity using iron, and to begin studying other materials, and to initiate development of capabilities needed to make high quality measurements at the higher temperatures, ~180 eV, where the Z data for iron disagree with theory. The plan is to obtain these higher temperature iron measurements in FY19

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