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DIAGNOSTIC DEVELOPMENT AT LLNL FOR THE NATIONAL IGNITION FACILITY

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ICF implosions at the NIF will produce core plasma temperatures in excess of 10-keV and densities of order 100 g/cm^3. Properties of these plasmas can be measured using a variety of optical, x-ray and nuclear techniques similar to those now in use at facilities such as Nova and Omega. Some of these techniques will be directly applicable on NIF while others, particularly the nuclear-based techniques, will change significantly.

The National Ignition Facility (NIF) will deliver ~1.8 MJ of 0.35-μm light onto mm-scale hohlraum targets with the expectation of controlled thermonuclear ignition and gain (20-MJ yield). Ignition targets will achieve core plasma temperatures in excess of 10-keV and densities of order 100 g/cm^3. Under these conditions, the fusion yield will far surpass (by 4-5 orders of magnitude) the record neutron yields achieved at Nova (4 x 10^{13}) and, more recently, at Omega (10^{14}). However, long before the first ignition experiments occur, a comprehensive set of diagnostic measurements will be required to validate the performance of both the laser and the hohlraum targets. Many of these diagnostics have counterparts at laser facilities such as Nova; however, some will require the development of new techniques and instrumentation.

Apart from the standard laser system diagnostics (pointing, focusing and synchronization), the diagnostics required to validate NIF hohlraum targets fall into two distinct categories – those used to measure the hohlraum temperature and radiation drive spatial symmetry, and those used to characterize the performance of the imploding capsule. The first category of diagnostics will utilize x-ray imaging systems and shock break-out measurements; the second category will rely heavily on nuclear-based techniques and instrumentation. With ignition neutron yields approaching 10^{19}, the challenge will be to develop instrumentation and techniques which are both robust and reliable.

Fuel Areal Density

One of the most critical parameters used to assess both laser and hohlraum performance will be the fuel areal density, <ρR>, at burn time. On Nova, <ρR> is determined by measuring secondary neutron production.[1] This technique is appropriate for modest values of <ρR> (< 0.1 gm/cm^2) but fails at the higher NIF densities (~1.0 g/cm^2) where the range of the primary charged fusion products (p, t, α) is small relative to the size of the fuel core. Indeed, cryogenic d-t ignition capsules require that the primary d-t α's deposit their full kinetic energy in the fuel to initiate and sustain the thermodynamic burn. Consequently, a mechanism for probing the fuel density at burn time is the spectroscopic measurement of tertiary neutrons and protons.

Both tertiary neutrons and protons are produced with energies up to 30 MeV, easily escaping the dense fuel core. The production mechanism for tertiary neutrons (replace the triton with a ^{3}He in reaction 3 for tertiary protons; note too, that the d and t can be interchanged in reactions 2 and 3) proceeds according to the following reactions:

$$d + t \rightarrow \alpha\ (3.5\ \text{MeV}) + n\ (14.1\ \text{MeV}) \qquad (1)$$
$$n\ (14.1\ \text{MeV}) + d \rightarrow n' + d'\ (< 12.5\ \text{MeV; elastic scattering}) \qquad (2)$$
$$d'\ (< 12.5\ \text{MeV}) + t \rightarrow \alpha + n\ (< 30.8\ \text{MeV}) \qquad (3)$$

Spectroscopic measurement of these protons and neutrons samples the energy loss of the secondary deuteron in the high density fuel before the tertiary reaction occurs. The shape of the tertiary neutron energy spectrum is then a convolution of the two-body scattering kinematics in 2) with the deuteron fuel core energy loss distribution prior to the fusion in step 3). Figure 1 shows a calculated neutron energy spectrum from a Nova scale hohlraum target. The fuel areal density can be determined from the shape of the spectrum and the absolute yield of tertiary neutrons or protons (approximately proportional to $<\rho R>^2$ for small deutron and triton slowing).

In addition, measuring tertiary proton energy loss (up to 10 MeV) in the fuel further constrains the estimate of total $<\rho R>$. Since the protons sample the fuel density along their flight path, it is possible to estimate implosion asymmetries by comparing proton energy loss along different paths.[2]

A prototype proton spectrometer is currently being developed jointly by LLNL, MIT and LLE for near term tests on both Nova and Omega. The spectrometer will be based on a permanent sector magnet which bends the high energy protons ~30° into an array of CCD detectors placed along the magnet mid-plane. This detector should be implemented on Nova during the summer of 1997. Tertiary neutrons will be measured at NIF using an energy and time-of-flight array similar to LaNSA[3] currently in operation on Nova.

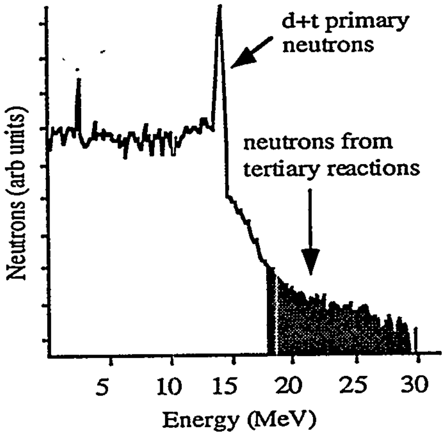

Figure 1. Calculated d-t neutron energy spectrum from a scale-1 hohlraum on Nova. The tertiary neutrons are simply those with a kinetic energy above a threshold of about 17 or 18 MeV (comfortably above the secondary neutron energy).

Imaging

Imaging diagnostics on NIF will include a variety of x-ray pin-hole cameras, gated imagers as well as Wölter and K-B optics. One of the primary difficulties with implementing most of the Nova imaging systems on NIF is the large standoff distance required between the target and pin-hole aperture.

A Wölter optic (such as the 22x microscope on Nova) can be placed a considerable distance from the target. However, the coated optic of a Wölter mirror is extremely expensive to fabricate using conventional techniques. Therefore, an alternative concept is being pursued at LLNL which is based on replica technology. A precision mandrel is fabricated with the required shape tolerance and surface finish. A multi-layer coating is deposited on the mandrel along with a backing for strength. The optic is then removed from the mandrel in multiple azimuthal sectors yielding a relatively large number (4 - 8) of individual x-ray mirrors. The mandrel can possibly be reused to fabricate additional optics amortizing the high cost of a single mandrel over a large number of relatively inexpensive individual mirrors. With replica technology and advanced coating techniques, it should be possible to manufacture a large number of nearly identical instruments capable of imaging x-rays up to 8 keV (important for the higher density NIF capsules). A prototype mandrel has been designed and work is currently focused on developing methods to recover the shape tolerance once the mirror is removed from the mandrel.

Another promising imaging technology for NIF is based on neutron coded apertures.[4] Neutron imaging will be particularly important for NIF cryogenic targets that achieve a high areal density when imploded and cannot be doped with high-Z gases to enhance x-ray emission. Such targets will be best imaged using neutron emission. A prototype device, the Neutron Penumbral-Aperture Microscope (NPAM) is being developed on Nova. This device consists of a specially shaped gold aperture, a high-precision (30-μm accuracy) alignment system, and a 35,000-element scintillator neutron detector array that incorporates a fiber-optic coupled CCD-camera readout.[5] The prototype device has a potential resolution of 10–15 μm. A number of alternative neutron imaging technologies are also being studied including annular coded-apertures and higher resolution detector strategies.

Burn History

One of the most critical measures of capsule performance will be the burn history (the fusion reaction rate as a function of time). On Nova, neutron-based measurements are made with 25-ps resolution using a scintillator-streak camera combination (NTD[6]) placed a few centimeters from the target. The close target proximity minimizes the influence of the plasma temperature-induced broadening of the neutron energy spectrum. On NIF, close proximity may mean several meters for ignition experiments so any burn history information carried by the neutrons will be completely obscured by the ~10-keV plasma temperature.

Consequently, considerable effort is underway at LLNL to develop a fast instrument sensitive to the direct d-t fusion γ-rays. Such an instrument would be insensitive to the plasma temperature and could be optimally located for the expected yield of each NIF experiment. Two experimental instruments, each based on a two-step conversion process, have recently been fielded on Nova. Each has observed direct γ-ray signals. In one instrument, MOLE (short for Moliere), a thin low-Z layer converts the incoming 16.7 MeV γ's into electron-positron pairs that then emit Cherenkov light in a lucite medium. The light is focused onto a MCP-PMT and the signal is recorded using a 5-GHz oscilloscope. Figure 2 shows data from the MOLE detector using both lead and beryllium converters as well as a "null" spectrum in which the cathode of the PMT is covered. The very low input signal (the fusion d-t γ branching ratio is 5×10^{-5} relative to the primary neutron production) compounds background issues. Future work will focus on reducing background sources, most notably, γ conversion in the lucite which is currently relatively unshielded from the target.

In a second instrument, electron-positron pairs are created in the high-Z Hevimet nose cone of the NTD. Cherenkov light is produced in a second-stage aerogel foam (the foam provides good background immunity) and recorded with a high-speed streak camera. The challenge for this instrument will be increasing the detector size and efficiency while maintaining temporal resolution.

LLNL will continue to maintain a vigorous program of diagnostic development for the NIF with the primary emphasis on γ-ray based burn history measurements, tertiary neutron and proton spectroscopy and both x-ray and neutron imaging systems.

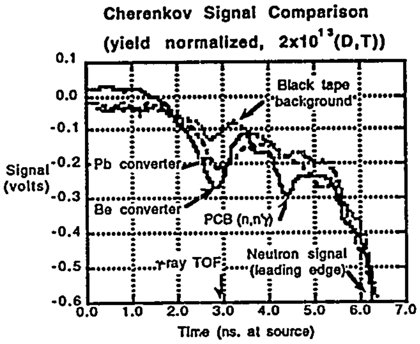

Figure 2. MOLE data from Nova high yield shots using both a lead and beryllium γ-ray converter. The background trace was taken with the PMT covered.

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1) M. D. Cable (1994), "Nuclear Measurements of ICF Implosions", in *Laser Plasma Interactions 5: Inertial Confinement Fusion*, edited by M. B. Hooper, Proceedings of the Forty Fifth Scottish Universities Summer School in Physics, St. Andrews, Scotland, 191-208.

2) R. D. Petrasso, C. K. Li, M. D. Cable, S. M. Pollaine, S. W. Haan, T. P Bernat, J. D. Kilkenny, S. Cremer, J. P. Knauer, C. P. Verdon and R. L. Kremens (1996), "Implosion Symmetry and ρR Measurements from Nascent 27-31 MeV Tertiary Protons", submitted to *Physical Review Letters*.

3) M. B. Nelson and M. D. Cable (1992), "LaNSA: A Large Neutron Scintillator Array for Neutron Spectroscopy at Nova", *Review of Scientific Instruments*, 63(10), 4874-4876.

4) D. Ress, R. A. Lerche, R. J. Ellis, S. M. Lane and K. A. Nugent, "Neutron Imaging of Laser Fusion Targets", *Science*, 241, 956-958.

5) D. Ress, R. A. Lerche, R. J. Ellis and G. W. Heaton (1995), "High-Sensitivity Scintillating-Fiber Imaging Detector for High Energy Neutrons", *Review of Scientific Instruments*, 66(10), 4943-4948.

6) R. A. Lerche, D. W. Phillion and G. L. Tietbohl (1995), "25 ps Neutron Detector for Measuring ICF-Target Burn History", *Review of Scientific Instruments,* 66(1), 933-935.