Development of nuclear diagnostics for the National Ignition Facility (invited)

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The National Ignition Facility (NIF) will provide up to 1.8 MJ of laser energy for imploding inertial confinement fusion (ICF) targets. Ignited NIF targets are expected to produce up to 10^{19} DT neutrons. This will provide unprecedented opportunities and challenges for the use of nuclear diagnostics in ICF experiments. In 2005, the suite of nuclear-ignition diagnostics for the NIF was defined and they are under development through collaborative efforts at several institutions. This suite includes PROTEX and copper activation for primary yield measurements, a magnetic recoil spectrometer and carbon activation for fuel areal density, neutron time-of-flight detectors for yield and ion temperature, a gamma bang time detector, and neutron imaging systems for primary and downscattered neutrons. An overview of the conceptual design, the developmental status, and recent results of prototype tests on the OMEGA laser will be presented. © *2006 American Institute of Physics.* [DOI: 10.1063/1.2236281]

I. INTRODUCTION

The National Ignition Facility[1] (NIF) is a 1.8 MJ, 192-beam laser system currently under construction at Lawrence Livermore National Laboratory. The NIF project is now more than 80% complete. On the current schedule, the first neutron-producing experiments are expected in 2009. One of the primary missions of the NIF is to demonstrate thermonuclear ignition and gain using inertial confinement fusion (ICF).[2] Direct and indirect drives are the two primary approaches to achieving ICF ignition. In the indirect-drive approach, a capsule filled with deuterium (D_2), tritium (T_2), or a deuterium-tritium (DT) mixture is heated by soft x-ray radiation in a laser-heated *Hohlraum*. In the resulting implo-

sion, the target is compressed to conditions under which thermonuclear fusion occurs. The ignited NIF targets are expecting to produce up to 10^{19} DT neutrons providing unprecedented opportunities for high-density physics and placing severe demands on diagnostic instruments. In the direct-drive approach, the laser directly illuminates the target, compressing it to the required conditions.

The strategy to achieve ignition on the NIF was reviewed in 2005 by the JASON.[3] The National Ignition Campaign (NIC) was established in 2005 to integrate the activities required to perform credible ignition experiments on NIF. The first experimental campaign for ignition on the NIF
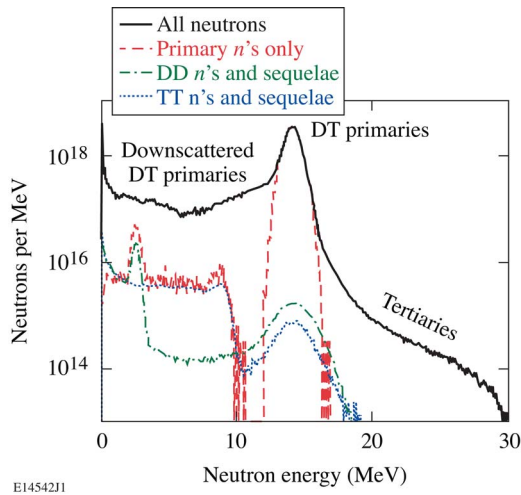
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FIG. 1. Neutron spectrum of the igniting DT implosion.

FIG. 2. Schematic view of two arm PROTEX.

will include experiments to measure and optimize the key laser and target conditions necessary for ignition. These "tuning campaigns" will be focused on *Hohlraum* energetics, *Hohlraum* symmetry, shock timing, and capsule hydrodynamics. In the energetics and symmetry campaigns, implosions of D_2-filled capsules are planned. Implosions of cryogenic targets filled with pure tritium are planned for the shock-timing campaign. The culmination of the NIC efforts will be implosions of cryogenic DT targets during the NIF ignition campaign.

The suite of ignition diagnostics for the NIF was defined in 2005. This suite is based primarily on fusion products and includes the PROTEX and copper activation to measure the primary yield, a magnetic recoil spectrometer and carbon activation to infer fuel areal density, neutron time-of-flight detectors for yield and ion temperature, a bang time detector, and neutron imaging systems for primary and downscattered neutrons. A high-energy x-ray imaging (HEXRI) diagnostic is also planned but will not be discussed in this article. A multilab effort is under way to specify the system design requirements and to develop and integrate these diagnostics on the NIF. This article gives an overview of the various working conceptual designs for the NIF nuclear diagnostics and the results from recent prototype tests on the 60-beam, 30 kJ OMEGA Laser Facility[4] at the University of Rochester's Laboratory for Laser Energetics. In most cases, the proposed NIF diagnostic can be built today to meet the stringent operational requirements for ignition.

II. ICF NEUTRON SPECTRUM

In ICF experiments, primary neutrons are produced via two reactions,

$$D + D \rightarrow n(2.45 \text{ MeV}) + {}^{3}\text{He} \tag{1}$$

and

$$D + T \rightarrow n(14.1 \text{ MeV}) + \alpha. \tag{2}$$
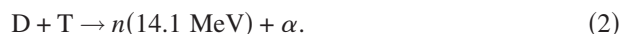
Neutrons from reaction (1) are referred to as D_2 neutrons and neutrons from reaction (2) are referred to as DT neutrons. 14.1 MeV primary neutrons from DT implosions can scatter
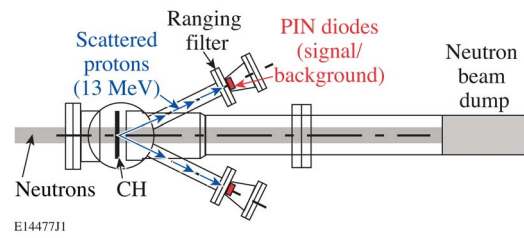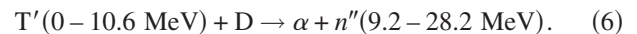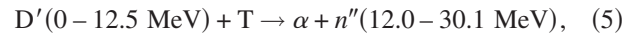
off fuel deuterons and tritons to create lower-energy, down-scattered neutrons. The ratio of downscattered neutrons (6–10 MeV) to primary neutrons is proportional to ρR, where ρR is the areal density of the DT fuel.[5] Imaging the scattered neutrons would also provide information on the distribution of the colder, dense fuel surrounding the hot spot.[6]

In a secondary reaction, a small fraction of the 14.1 MeV neutrons will scatter elastically from D or T ions in the fuel (prime notation indicates a scattered particle),

$$n + D \rightarrow n' + D'(0 - 12.5 \text{ MeV}), \tag{3}$$

$$n + T \rightarrow n' + T'(0 - 10.6 \text{ MeV}). \tag{4}$$

As these scattered ions pass through the fuel, some will undergo tertiary, in-flight fusion reactions and produce tertiary neutrons,

$$D'(0 - 12.5 \text{ MeV}) + T \rightarrow \alpha + n''(12.0 - 30.1 \text{ MeV}), \tag{5}$$

$$T'(0 - 10.6 \text{ MeV}) + D \rightarrow \alpha + n''(9.2 - 28.2 \text{ MeV}). \tag{6}$$

On the NIF, the yield of these high-energy tertiary neutrons is proportional to ρR and is about 10^{-6} of the primary 14.1 MeV neutron yield.[5] Therefore, by measuring the neutron yield above 20 MeV, where the yield is strictly tertiary, it is possible to infer the areal density of imploding targets during the ignition campaign.

Slowing of the alpha particles and to a lesser extent slowing of the upscattered deuterons and tritons introduces some strong temperature sensitivity into the neutron spectrum actually produced by these alpha-tertiary processes. An extensive hydrodynamic modeling[6,7] is under way to take these effects into account and to optimize the energy range for downscattered neutron imaging, downscattered neutron areal density measurement, and tertiary yield measurement. The typical neutron spectrum based on all possible reaction processes is shown in Fig. 1. The downscattered neutron energy region, from 6 to 10 MeV, for areal density measurements was chosen based on this calculation.

III. PROTEX

PROTEX (Ref. 8) is a diagnostic for absolute DT neutron yield measurements on ICF ignition experiments. A schematic view of PROTEX, which will be located outside the NIF target bay about 20 m from the target chamber center (TCC), is shown in Fig. 2. The neutrons pass through a collimator that allows the neutron beam to strike a polyethylene sheet about 2 m beyond the collimator where recoil protons are produced. The polyethylene sheet is followed by
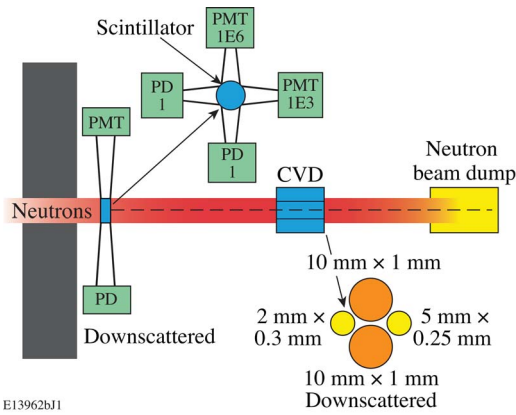
FIG. 3. Proposed nTOF configuration for the National Ignition Campaign.

FIG. 4. CVD diamond detector sensitivity scaled to a 20 m distance on the NIF.

a tube that is at least 1 m long. Multiple arms located at $25°–30°$ to the system axis extend with lengths from 20 to 50 cm. The arms are terminated by detector housings that each holds a pairs of Si p-i-n diodes for generating the signals. The first p-i-n diode measures the recoil protons (and background neutrons) from the polyethylene sheet while the second p-i-n diode measures the neutron background. The p-i-n diodes are biased at 1000 V and produce typical signal levels of tens of volts that are recorded on digital oscilloscopes. The PROTEX absolute sensitivity, which depends only on the (n,p) elastic cross section and the detector dimensions and can be calculated with high precision.[8] The main advantage of PROTEX is that it does not require calibration. The application of PROTEX technology to ICF experiments was demonstrated on Nova and OMEGA with better than 10% absolute yield accuracy.[8] During the NIF ignition campaign, PROTEX is expected to measure DT neutron yield from 5×10^{15} to 1×10^{19} with an absolute yield accuracy of 20% or better. This system will be able to record yields over a two decade range centered on the anticipated yield for a particular shot. The system sensitivity can be adjusted by a change of components: collimator diameter, polyethylene thickness, and oscilloscope settings. No future research and development for PROTEX is required.

IV. NEUTRON TIME-OF-FLIGHT SYSTEM

Every large ICF laser facility including the Nova, OMEGA, and GEKKO uses neutron time-of-flight (nTOF) systems to measure neutron yield and ion temperature. nTOF systems are usually based on current-mode detectors consisting of a fast plastic scintillator optically coupled to a fast photomultiplier tube (PMT). At high neutron yield, the PMT can be replaced with a vacuum photodiode (PD). Recently, chemical vapor deposition (CVD) diamond detectors[9,10] have emerged as an attractive choice for nTOF detectors to measure high neutron yields. Several channels of a high-bandwidth digital oscilloscope record the signal from the nTOF detector. nTOF systems are relatively inexpensive, have a large dynamic range, and have a fast time response. The absolute neutron yield can be determined with the appropriate system calibration. The nTOF detectors are reliable and the information they record is fundamental to most ICF implosion experiments.
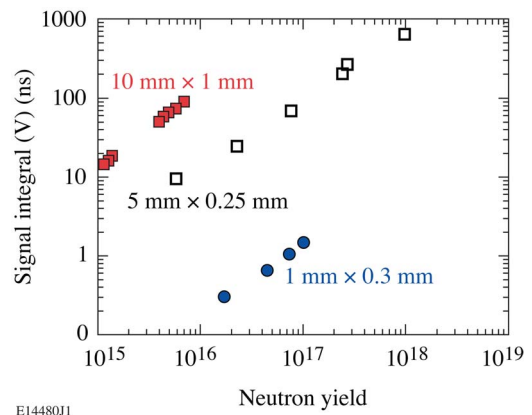
Unlike the PROTEX diagnostic, which measures only yield in the ignition campaign, the nTOF system will measure the D_2 and DT yields and the ion temperatures in the NIF campaigns with yields from 1×10^{11} to 2×10^{19}. To cover such a wide range of yields, different nTOF detectors and recording equipments will be located in different places. In the "tuning" campaigns, scintillator-based detectors described in Ref. 10 will be installed inside the NIF target bay at $5–12$ m from the TCC. For the *Hohlraum* symmetry campaign, the nTOF system is expected to measure D_2 primary neutron yield from 1×10^{11} to 5×10^{12} with a 25% absolute accuracy and a 10% relative shot-to-shot accuracy. For the shock-timing campaign, the nTOF system is expected to measure DT primary neutron yields (from residual DD gas) of "duded" ignition capsules over a range of 1×10^{12}–5×10^{14} with a 25% absolute yield accuracy and a 5% relative shot-to-shot accuracy. For the symmetry campaign, the nTOF system is expected to measure time- and space-averaged ion temperatures for imploding capsules with 20% accuracy.

For the ignition campaign, the nTOF system will have one collimated line of sight with the nTOF detectors located outside the target bay about 20 m from the target. A possible nTOF detector arrangement is shown on Fig. 3. The nTOF system will consist of a multichannel scintillator counter where one scintillator will be coupled with PD's and PMT's with different gains and four CVD diamond detectors of different sizes. One PD and the most sensitive CVD diamond detector will be reserved for possible downscattered neutron measurements. Four CVD diamond detectors will be installed next to a neutron imaging system about 40 m from the target for the highest yield measurements. This will enhance the reliability of the NIF nTOF system for the ignition campaign: two lines of sight, two sets of oscilloscopes, and at least two nTOF detectors will measure the same yield and ion temperature. For the ignition campaign, the nTOF system will measure the primary DT neutron yields over a range from 1×10^{15} to 2×10^{19} with 20% absolute yield accuracy and with 5% relative shot-to-shot accuracy.

CVD diamond detectors for the NIF are being developed on OMEGA. Figure 4 shows the sensitivity of the CVD diamond detectors calibrated inside the OMEGA target chamber

of 10–100 cm from the TCC and scaled to the equivalent DT neutron yields at 20 m on the NIF. The existing CVD diamond detectors can measure DT yields on the NIF from 1×10^{14} to 2×10^{18}. Less-sensitive detectors can be made from a smaller and thinner CVD wafer, from a neutron-hardened CVD wafer, or from a CVD wafer with impurities. All these factors decrease the sensitivity of the CVD diamonds and make their response faster. The development of less-sensitive CVD diamond detectors will continue on OMEGA.

The ratio of the downscattered neutron yield (6–10 MeV) to the primary 14.1 MeV neutron yield is proportional to ρR (assuming the neutrons only downscatter in the fuel).[5] The measurement of the downscattered yield is a very challenging task for the nTOF diagnostic and has not yet been demonstrated. The development of detectors for downscattered neutron yield measurement will continue on OMEGA.

V. BANG TIME/REACTION HISTORY DIAGNOSTIC

Fusion reaction rates have been measured in ICF experiments on Nova and OMEGA using the neutron temporal diagnostic (NTD).[11] The NTD uses a thin, plastic scintillator placed very close to the target coupled with an optical streak camera. A short flight path is required to measure the fusion reaction rate with neutrons because of time-of-flight broadening.[11] On the NIF, however, high-x-ray fluxes from targets and unconverted laser light near the TCC severely constrain the use of neutrons for measuring the fusion reaction history. Only bang time—the time interval from the beginning of the laser pulse to the maximum of neutron or fusion gamma emission—can be measured with neutrons.

Several prototype neutron bang time (NBT) detectors for the NIF have been tested on OMEGA.[12] In 2005, a high-yield neutron bang time[13] (HYNBT) detector was implemented on OMEGA. The HYNBT consists of three CVD diamond detectors of different sizes and sensitivities placed in a lead-shielded housing. The HYNBT is located in a re-entrant tube 50 cm from the TCC. The signals from the CVD diamond detectors are recorded by a 3 GHz, 10 Gsamples/s, Tektronix TDS-694 oscilloscope. The OMEGA optical fiducial pulse train[14] is recorded on a separate oscilloscope channel using a fast photodiode to provide the time reference to the laser. The HYNBT was tested five times during 2005 and in all cases demonstrated internal time resolution better than 20 ps. The HYNBT is able to measure bang time for yields above 10^{10} for DT and above 5×10^{10} for D_2 implosions on OMEGA.

The HYNBT can be converted into a NIF NBT detector with simple modifications. Since the HYNBT is compact (a 36-mm-diam, 254-mm-long cylinder), it can be located about 50 cm from the target in a diagnostic insertion manipulator (DIM) together with other NIF diagnostics (see Fig. 5). The dynamic range of the NIF NBT can be increased by raising the sensitivity of the first channel, decreasing the sensitivity of the third channel, and adding an even less-sensitive fourth channel. This least-sensitive channel can be made from a smaller and thinner CVD wafer, from a
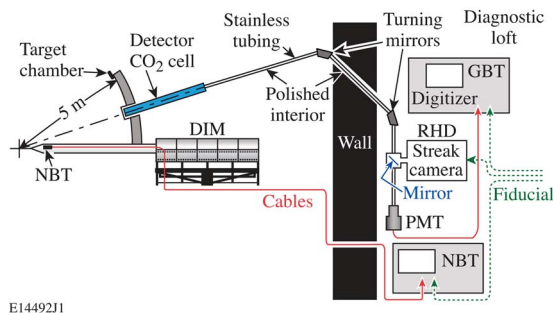

FIG. 5. Bang time/reaction history diagnostic on the NIF.

neutron-hardened CVD wafer, or from a CVD wafer with impurities. As a result, the upper yield range of the NIF NBT can be increased to $\sim 10^{17}$. The front shielding of the NIF NBT will be removable to accommodate x-ray temporal calibration using emission from a gold target irradiated by a short laser pulse. The feasibility of such a temporal calibration has been demonstrated.[12]

The reaction burn history can be determined by monitoring the 16.7 MeV gamma rays from the DT fusion reaction,

$$D + T \rightarrow \gamma + {}^5He. \tag{7}$$

The gammas have no time-of-flight dispersion along their flight path but the yield is quite low since the branching ratio for the reaction (7) is only about 5×10^{-5} (Ref. 15). Several detector systems based on gas Cherenkov cells have been tested on OMEGA. Fusion gamma rays interact with a converter and produce forward-directed, relativistic electrons at the entrance to a high-pressure (~ 100 psi) gas cell containing CO_2. The electrons generate Cherenkov light when they travel faster than the speed of light through the CO_2 gas. By changing the gas pressure, the index of refraction can be adjusted to set the gamma detection energy threshold and discriminate against lower-energy gammas from DT (n, γ) reactions. The Los Alamos National Laboratory-led team built two gas Cherenkov detectors (GCDs) with similar gas cells, reflective optics, and recording systems based on a fast PMT (GCD1) (Refs. 16 and 17) and a streak camera (GCD2).[18] The GCD1 recorded the first fusion gammas on OMEGA in 2000 and measured bang time in 2005.[19]

A Cherenkov gas cell was also used in the Fiber Fusion diagnostic[20] and light Pipe[21] experiments on OMEGA. In one of the Light Pipe experiments, a leading-edge 2.54-cm-diam, 163.1-cm-long cell with 100 psi of CO_2 was located 16 cm from the TCC on OMEGA. A 3-mm-thick tungsten cap was used as both a shield from hard x rays and a converter for fusion gammas. Cherenkov light was transmitted through a quartz window and stainless steel tubes with polished interiors and turning mirrors (Light Pipe) outside the target bay to a fast PMT with a gain of 10^4. The output of the PMT was recorded with a 6 GHz, 20 Gsamples/s, TDS 6604 oscilloscope. A second channel of the TDS 6604 was connected to the second channel (5×0.25 mm^2 CVD diamond) of the HYNBT recording DT neutrons on the same shots. The rms time difference between the two detectors is 16 ps. When scaled from 16 to 450 cm (the distance to the first wall on the NIF) with a PMT gain

increased to 10^5, the fusion gammas give a signal of 0.25 V for a yield of 10^{15}. This Light Pipe experiment demonstrated the feasibility of a gamma bang time (GBT) detector for the NIF with a better than 20 ps internal accuracy at ignition relevant yields. Experiments with GBT based on the Light Pipe will continue on OMEGA to gain operational experience and to optimize detector parameters.

Both the GCD2 and the Light Pipe teams have tried to record a gamma reaction history on OMEGA using streak cameras. The GCD2 was sensitive to the neutron background when the streak camera was inside the target bay. This prevented the GCD2 from measuring a gamma reaction history at the highest yields on OMEGA. In the Light Pipe experiment the streak camera was outside the target bay where the neutron background is small. However, the gamma signal was too weak for the streak camera sensitivity. Assuming a GBT gain of 10^5 and a streak camera gain of 10^3, the lowest yield for a credible reaction history diagnostic (RHD) based on a CO2 cell 450 cm from the TCC is 10^{17}.

The bang time/reaction history diagnostic system currently under consideration for the NIF is shown in Fig. 5. The NBT detector on the NIF will be similar to the HYNBT on OMEGA and will measure the neutron bang time for D_2 and DT neutron yields from 10^{10} to 10^{17}. The GBT/RHD system consists of a high-pressure gas cell located near the target chamber wall; relay optics in an enclosed system will transport an optical signal outside the target bay to a fast PMT with an oscilloscope or optical streak camera readout. The GBT detector will measure gamma bang time for yields from 10^{15} to 10^{18} and the RHD will record a gamma reaction history for yields from 10^{17} to 2×10^{19}.

The NIF optical fiducial will be recorded on the oscilloscopes and the streak camera. Cross timing of the GBT/RHD will likely be performed using dedicated shots in which a short 200 ps laser pulse is reflected or rescattered from a target to the CO_2 cell and relay optics of the GBT/RHD through a quartz window. X rays emitted from a gold target irradiated by a 200 ps laser pulse will be used to cross time the NBT. Based on OMEGA prototype tests, the time accuracy of neutron or gamma emission relative to the fiducial is expected be better than 20 ps for all systems. Having two bang time measurements from two detectors using different sources (gammas and neutrons) and different cross-calibration techniques should allow validation of the bang time requirement before the NIF ignition campaign begins. The absolute timing accuracy relative to the laser pulse will be determined mostly by the accuracy of the laser-pulse measurement, cross-calibration accuracy, and stability of the laser and fiducial systems. An absolute timing accuracy of 50 ps should be achievable on the NIF.

VI. NEUTRON ACTIVATION DIAGNOSTIC

The purpose of the neutron activation diagnostic (NAD) is to measure primary and tertiary neutron yields in ICF experiments on the NIF. The NAD will consist of copper activation and carbon activation diagnostics. The copper activation diagnostic[22] will measure the primary DT neutron yield via the reaction ^{63}Cu $(n, 2n)$ ^{62}Cu with a threshold neutron
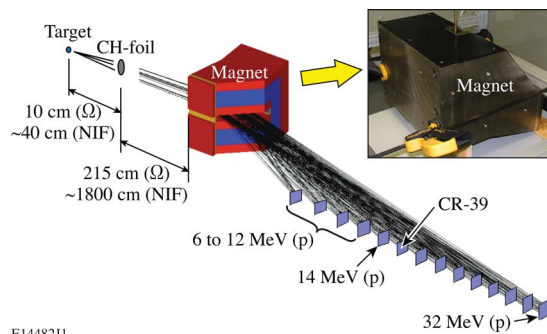
FIG. 6. Schematic view of the magnetic recoil spectrometer.

energy of 10.9 MeV. The ^{62}Cu decays into nickel ^{62}Ni and a positron with a half-life of 9.8 min. The positron annihilates with an electron and produces two gammas at 0.511 MeV. The carbon activation diagnostic[23] will measure tertiary neutron yield via the reaction ^{12}C $(n, 2n)$ ^{11}C with a threshold energy of about 22 MeV. The ^{11}C decays into boron ^{11}B and a positron with a half-life of 20.39 min. The subsequent positron annihilation again produces two 0.511 MeV gammas.

The activation from the tertiary neutrons in the carbon sample will be very low; therefore, the carbon samples should be located about 4.5 m from the target in a diagnostic well. Due to the high-activation threshold (~ 22 MeV), the carbon sample is insensitive to primary or rescattered neutrons. To measure tertiary neutrons, the carbon sample must be very pure and contain less than one part per million contaminants. One of the contaminants producing a positron emitter is ^{14}N from the air. To remove air from the graphite disks, a special purification facility was developed at SUNY Geneseo. Purified graphite disks are stored and shot in vacuum-sealed bags, never being exposed to air during the fabrication and use cycle.

The copper and carbon samples can be loaded manually before a NIF shot and retrieved from the target bay automatically after the shot using two similar or identical pneumatic retractors. The neutron background from the NIF shot will be crucial for carbon activation. The NAD counting room will be very well shielded and located as far as possible from the target. In the NAD counting room both copper activation and carbon activation diagnostics will use a gamma detection system consisting of two 3-in.-diam, 3-in.-thick NaI(Tl) scintillation detectors and associated commercial electronics. The copper activation will use one gamma-detection system and the carbon activation will use two identical systems, one to measure the tertiary signal and one to measure the shot-related background activation in the counting system itself.

VII. MAGNETIC RECOIL SPECTROMETER

A new type of neutron spectrometer, a magnetic recoil spectrometer (MRS), will be implemented on the NIF.[24] The MRS will measure the neutron spectrum (6–32 MeV) produced in cryogenic DT implosions on the NIF. This type of spectrometer[25,26] is currently operational only on the Joint European Torus and has never been installed on a laser facility.

The schematic view of the MRS is shown in Fig. 6. The

MRS has three basic components. The first component is a CH (or CD) foil, close to the target (about 40 cm from the target), to produce recoil protons (or deuterons) from incident neutrons. The second component is a magnet outside the target bay wall about 18 m from the target for energy dispersion and for focusing forward-scattered recoil particles onto a detector plane. The focusing of the recoil particles provides a clear mapping between their position in the plane and the energy of the scattered protons (or deuterons), and thus the energy of the neutron that scattered them. The third component is the detector, located at the focal plane of the spectrometer, which must record the position of each recoil particle and be insensitive to various sources of background. The MRS will use very well-established CR-39 detectors.[27] Several options are available for configuring the MRS even after the component positions are set: the foil composition determines whether proton or deuteron recoils are being used, and the foil area and thickness can be adjusted to change the energy resolution and detection efficiency.

The primary mission of the MRS is to measure the number of downscattered primary DT neutrons in the 6–10 MeV energy range from which the ρR of cryogenic DT implosions can be directly inferred. The MRS is expected to measure ρR from 0.3 to 2.0 g/cm^2 in the yield range from 1×10^{15} to 1×10^{19} with better than 10% accuracy. In addition, the MRS can measure ion temperature (from the primary neutron spectrum), absolute primary DT yield, and the tertiary neutron spectrum (20–32 MeV). These measurements depend on the instrument configuration and cannot be done simultaneously.

The MRS concept will be tested and validated on OMEGA. The MRS version designed for OMEGA is currently in production, and the plan is to have the MRS installed on OMEGA by the end of 2006. The most expensive and complicated component of the MRS—a 500 lb magnet—has been designed, manufactured, and characterized. A similar magnet will be installed on the NIF. Background calculations for OMEGA are in progress.[28]

The primary objective of the MRS on OMEGA is to measure the scattered neutron spectrum from cryogenic DT implosions. At an areal density of 100 mg/cm^2 and a yield of 1×10^{13}, the signal-to-background ratio is estimated to be ~10; the inferred areal density should be accurate to approximately 10%.

VIII. NEUTRON IMAGING SYSTEM

Images of both the primary and downscattered neutron distributions will provide valuable diagnostic information about the implosion core at ignition.[6] For example, these images can be used to distinguish different failure mechanisms such as poor drive symmetry or imprecise pulse shaping.[29] In this case, 14 MeV neutron images show the hot-spot asymmetries whereas the downscattered neutron images reveal the pusher density. ICF experiments require neutron images with resolutions below 10 and 20 μm for the primary and downscattered neutrons, respectively. A high signal-to-noise ratio (SNR) (~30) is required to provide an image quality sufficient to discriminate among the various failure modes of an ignition capsule.

Experimentally, the first ICF neutron images were recorded[30] on Nova using penumbral apertures.[31] A system resolution of approximately 60 μm was achieved.[32] In preparation for the ignition campaign on the NIF, several groups have been working to develop prototype neutron imaging systems. These systems are based on various coded apertures designs and imaging detectors. The Los Alamos National Laboratory group has tested[33] a double-pinhole assembly with a scintillating fiber bundle as a neutron detector on OMEGA. The Commissariat à l'Énergie Atomique group from France performed a number of tests[34,35] on OMEGA using penumbral and ring apertures and capillary neutron detectors. In 2005, the neutron images on OMEGA were recorded using a new detector[36] based on an array of 85-μm-diam capillary tubes filled with a liquid scintillator. The detector resolution is 650 μm full width at half maximum (FWHM) for 14 MeV neutrons. The resolution is limited by the track length of elastically scattered recoil protons. Using this detector, the first ring images[37] with a 20 μm resolution and SNR ~40 were recorded on OMEGA in 2005. Replacing the hydrogen in the scintillator with deuterium will improve detector spatial resolution to 325 μm and make higher source resolution achievable. The increased detector sensitivity allows single-event recording of 2.45 MeV neutron interactions. With the increased sensitivity, neutron images of D$_2$ warm and D$_2$ cryogenic target implosions were recorded[37] for the first time in 2005.

The introduction of energy resolution to neutron imaging for ICF introduces several challenges to an already difficult problem. The only feasible method for achieving energy resolution is by "gating" the image recording at times that correspond to flight times for neutron energies of interest. One significant problem is that the later-time images will follow the intense signal associated with the arrival of the 14.1 MeV neutrons. This means that the scintillator output from the 14.1 MeV signal must decay by at least three decades before an image can be recorded with the lower-energy neutrons. Decay times of different scintillators suitable for downscattered neutron imaging were measured[38] at Lawrence Livermore National Laboratory.

The end-to-end modeling of the whole NIF neutron imaging system is in progress[39,40] to ensure that the instrument will meet design requirements, to understand the possibilities and limitations of such a diagnostic, and to optimize the system design.

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