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HIGH RESOLUTION NEUTRON IMAGING OF LASER FUSION TARGETS USING BUBBLE DETECTORS

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The results of proof-of-principle neutron imaging experiments using bubble detectors are reported. Bubble detectors, which detect neutrons with a spatial resolution as small as 5 µ, were used to image the neutrons from laser-driven compressed deuterium-tritium target plasmas in OMEGA [Boehly, et al., Opt. Commun. 133, 495 (1997)]. The results demonstrate that bubble detectors should revolutionize the design of coded aperture neutron imaging systems. Prospects for imaging target plasmas in the National Ignition Facility [Kilkenny, et al., Rev. Sci. Instrum. 66, 288 (1995)] with 5 µ spatial resolution in the target plane appear excellent.
1. INTRODUCTION

In inertial confinement fusion (ICF) research, small deuterium-tritium (DT) targets are compressed to very high densities using high power laser or particle beams. At the center of the highly compressed fuel, the ion temperature reaches several kiloelectron volts. Fusion is initiated in this hot spot, producing energetic neutrons and alpha particles. If the surrounding fuel density is sufficient to absorb a significant fraction of the alpha particle energy before they leave the target, a thermonuclear burn wave will propagate into the surrounding colder fuel. The mission of the National Ignition Facility (NIF), presently under construction at the Lawrence Livermore Laboratory, is to produce ignition and modest energy gain in ICF targets.

Neutron imaging of inertial fusion plasmas will provide a direct measurement of the spatial location and extent of the fusion reactions and allow rapid evaluation of target performance. Neutron imaging will become easier as neutron yields increase, while the x-ray imaging techniques relied on extensively in today’s ICF experiments will become more difficult due to neutron and gamma-ray induced background noise in the x-ray detectors [1], and the need to image higher energy x-rays that can escape from the target core. High-resolution neutron imaging will be one of the most useful diagnostics during the early implosion studies on NIF. Images of the burning fuel can verify calculations of implosion physics and determine the existence of asymmetries. Neutron imaging has long been recognized for its potential to diagnose unambiguously both compression and hot-spot formation in the burning fuel [2]. Modeling of NIF targets shows neutron images will have diameters as small as 25 \( \mu \) with even smaller scale features due to compression asymmetries. A neutron imaging diagnostic with 5 \( \mu \) spatial resolution in the target plane is needed [3].

The first neutron images of ICF targets were obtained on NOVA using penumbral aperture imaging [4,5]. Penumbral aperture imaging was used to increase the signal levels since conventional pinhole imaging was not sensitive enough to produce neutron images of NOVA targets. Penumbral imaging is conceptually similar to pinhole imaging, except that the aperture is larger than the neutron source as illustrated in Fig. 1 from Ref. 4. The resultant coded image consists of a uniform bright region surrounded by a partially illuminated penumbra, which contains all the information about the neutron source profile. The NOVA imaging diagnostic achieved a spatial resolution of \( \sim 80 \mu \), limited primarily by the spatial resolution in the plastic scintillation detector array and the system magnification \( M \), defined as the ratio of the aperture-to-detector distance divided by the aperture-to-source distance. The scintillator array elements
had 2-mm square cross sections, which were selected to match the maximum recoil range of protons elastically scattered by 14 MeV neutrons. The system magnification was 58 in the NOVA experiments. In experiments at the OMEGA laser facility at the University of Rochester, Dr. L. Disdier and colleagues at Commissariat à l’Energie Atomique (CEA) have recently obtained neutron images of target plasmas with 20 μ resolution using a plastic scintillator-based penumbral aperture imaging system with magnification of ~88. They also plan experiments at OMEGA utilizing deuterated scintillators in a capillary array, which should improve the detector resolution to ~0.5 mm due to the shorter range of the recoil deuterons.

Imaging NIF targets with 5 μ resolution using deuterated scintillators would require a system magnification of 100 to 200. Magnifications this high are possible in present-day ICF experiments, but will be impractical on NIF. To prevent materials ablated from components that are close to the target from coating and damaging the high power laser optics, NIF is expected to have an exclusion zone around the target with a radius in the range of 1 to 5 m. If the neutron aperture cannot be located closer than 1 m from the target, the deuterated scintillators would have be placed an impractical 100 m or more from the target. To maximize the resolution possible in a scintillator-based system, the Laser MegaJoule (LMJ) Facility has a 100 m line-of-sight reserved for neutron imaging. Neutron detectors with improved spatial resolution would allow high resolution neutron imaging of LMJ target plasmas from multiple directions.
2. BUBBLE DETECTORS

A bubble detector is essentially a bubble chamber that has been specifically designed to detect neutrons. Bubble detectors (BDs), which can detect neutrons with a spatial resolution as small as 5 µ, will dramatically impact the design and prospects for the success of coded-aperture neutron imaging of NIF and other ICF targets. In addition to reducing the required system magnification and allowing the aperture to be outside the target exclusion zone, the use of BDs will allow a significantly larger aperture diameter, making the aperture much easier to fabricate and characterize, and allowing more accurate “through the aperture” alignment techniques. BDs should also allow the use of advanced coded aperture imaging techniques [6] that will improve the signal-to-noise ratio.

The bubble detectors used for the proof-of-principle experiments on OMEGA are a customized version of the BDs used as personnel neutron dosimeters and sold commercially by Bubble Technology Industries (BTI) in Chalk River, Ontario, Canada. These BTI “gel” detectors consist of ~100,000 approximately 3 µm diameter droplets of a superheated liquid suspended in an elastic polymer matrix support gel. Each of the superheated droplets behaves like an independent bubble chamber. Once a bubble is formed, the entire droplet is vaporized into a single bubble. The neutron-induced bubbles in gel detectors last indefinitely, avoiding the need to photograph the bubbles on the millisecond time-scale that would be required for a conventional liquid bubble chamber detector. Gel detectors operate at atmospheric pressure. There is no requirement for an external magnetic field on the bubble detector since there are no charged particle tracks to measure.

Bubble production [7] requires that sufficient heat (critical energy ~10s of kiloelectron volts) be deposited in a very short distance (critical radius ~10^-5 cm). The bubble formation only involves a few thousand atoms. The BTI gel detectors utilize a freon-like superheated liquid. The primary neutron interaction mechanism leading to bubble production is elastic scattering of neutrons on fluorine or chlorine atoms in the detector liquid. Since the specific energy loss dE/dx of the recoil ions in the energy range of interest is an increasing function of energy, only neutrons above a selectable energy threshold deposit sufficient heat to create bubbles. The neutron energy threshold results in the incident neutrons either creating zero or one bubble. The bubble is created within ~5 µ of the scattering event due to the short range of the recoil high Z ion in the detector liquid.
Bubble detectors have the additional advantage in that they are nearly insensitive to the large background flux of gamma rays resulting from neutron capture reactions in structures surrounding the target. Gamma rays of energies up to 14 MeV will produce electrons via pair production and or Compton scattering. But the resultant electrons have a dE/dx that is too small to create bubbles. In a test of a similar bubble chamber [8] used to detect 2.5 MeV neutrons from DD plasmas, the measured gamma sensitivity was ~$10^{-12}$ of the neutron sensitivity. BTI reports that their bubble detectors show no response to 250 rad of $^{60}$Co gamma rays, or a gamma detection sensitivity of $\leq 10^{-14}$ bubbles per incident gamma ray.
3. TESTS ON OMEGA

Disk-shaped gel BDs, 8.5 cm in diameter and 1 cm thick were installed behind the penumbral neutron aperture and just outside the OMEGA target chamber. The aperture was biconical with a 0.75-mm inner diameter. The target-to-detector distance was 362 cm and the target to aperture distance was 8 cm, so the system magnification $M \sim 45.3$. Figure 2(a) shows a low power microscope photograph of a 6.8 by 6.8 mm region of the bubble detector, taken one day after the

![Bubble detector images](image_url)

Fig. 2. Bubble detector images from a $6 \times 10^{13}$ yield Omega shot, including (a) microscope photograph of 60 $\mu$m diameter bubbles in a single grid location, (b) x-y plot of bubble locations, (c) coded false color image in detector plane, (d) and (e) unfolded neutron image in target plane.
neutron exposure. The average bubble diameter is ~60 µm. Approximately 150 microscope photographs were taken in a rectangular grid pattern that covered the entire bubble detector. The location of each bubble was recorded using an image analysis program written in IDL. Figure 2(b) shows a composite photograph constructed by combining the ~150 analyzed grid photographs, with the bubbles locations shown in white against a black background. The bright circular region of the image inside the penumbra contains ~300 b’s/cm² for shots with neutron yields of ~ 6·10¹³. This corresponds to a measured detector response of ~ 8·10⁻⁶ bubbles per incident neutron, in very good agreement with the expected sensitivity. In regions well outside the penumbra, we observed an average background level of ~120 b’s/cm², resulting from neutrons leaking through the aperture or scattering from surrounding structures. This result is consistent with the ~40% background measured by the CEA scintillation detector array. Figure 2(c) shows a false color image of the bubble density distribution in the detector. To reduce the noise due to counting statistics, the bubbles were binned into 1.3 mm by 1.3-mm portions of the detector area. The unfolded image in the target plane, shown in Figures 2(d) and 2(e), is obtained from the coded penumbral image by deconvolution in the Fourier transform domain using the point spread function of the neutron aperture [5].

The images obtained using the bubble detectors show the FWHM of the neutron source function to be ~140 µ. Data taken using the CEA-built scintillation detector array for the same high-yield OMEGA DT shots show that the actual neutron source FWHM is ~80 µ (see Fig. 3). The spatial resolution in the gel bubble detector images on OMEGA is significantly decreased due to the limited neutron counting statistics. There are only ~ 5700 bubbles in the entire detector image, and only ~ 450 of these are in the penumbral region that carries all the information about the neutron source distribution. The impact of counting statistics on the image spatial resolution was investigated using Monte Carlo simulations. Results obtained for hundreds of simulated shots show a FWHM of 192±49, 152±20, and 127±15 µ at bubble densities of 100, 300, and 1000 bubbles/cm², respectively. Sample results are shown in Fig. 4. The top row shows simulated penumbral images in detector plane calculated at the three different bubble densities. Simulations use a 100 µ FWHM Gaussian source distribution with an ideal aperture that has 40% leakage through its opaque region. The calculations use the same binning and filtering that was used to obtain the experimental results of Fig. 2. The bottom row shows the corresponding unfolded images of the neutron source distribution in the target plane obtained by inverting the simulated penumbral images. The results, 152 ± 20 µ at 300 b/cm², are consistent with images obtained in OMEGA experiments at ~300 bubbles/cm². The simulations demonstrate that counting statistics account for image broadening from the true source width (80 µ) to the experimentally measured 141 µ FWHM.
Fig. 3. Scintillation detector image recorded simultaneously with BD image presented in Fig. 2. Scintillation detector comprised of 1.5-mm square scintillator elements is along the same line-of-sight axis as BD, but at a target-to-detector distance of 9 m. (a) raw coded image at detector plane, and (b) unfolded false color image in target plane.

Fig. 4. Calculated images for a 100 µm diameter neutron source at three different signal levels. Results show that at detected bubble densities close to the OMEGA experimental conditions, part of the measured 141 µm FWHM is a result of the limited counting statistics.

The more efficient scintillation detector array produced better quality neutron images than the gel bubble detectors used on OMEGA. The larger aperture-to-target distance required on NIF, however, would require impractical detector-to-target distances in order for a scintillation detector based imaging diagnostic to achieve the magnification necessary for 5 µm spatial
resolution in the target plane. A bubble detector based system, on the other hand, appears capable of achieving this resolution with very low magnification.

The counting statistics will be greatly improved on NIF, which is designed to achieve DT neutron yields up to \(10^{18}\) per shot. Assuming the bubble locations can be determined to within 30 \(\mu\), neutron imaging with 5 \(\mu\) resolution in the target plane would require a system magnification of \(~12\). If we assume the neutron aperture is placed 1 meter from the target, the detector-to-target distance should be 12 meters. Using the analysis presented in Ref. 5, a 6.7-cm diameter image created by a 25 \(\mu\) diameter source emitting \(1\cdot10^{18}\) neutrons would yield a signal-to-noise ratio of \(~6\) at 5 \(\mu\) resolution using gel bubble detectors. Ring aperture imaging [6] would improve the SNR to \(~24\) for the same neutron yield and source diameter.
4. HIGH EFFICIENCY LIQUID BUBBLE DETECTOR

Neutron imaging would be very useful to identify possible failure modes during the early implosion studies on NIF, when neutron yields are expected to be of the order of $10^{15}$ neutrons [3]. Imaging these lower yield shots on NIF at high resolution would be possible using a liquid bubble detector. Gel detectors were chosen for the initial imaging tests on OMEGA because they retain the bubble distribution information and allow the detectors to be photographed several hours or more after the neutron exposure. This ease of use comes, however, at the expense of a very low neutron detection efficiency ($\sim 10^{-5}$ bubbles/incident neutron). Bubbles can only be produced in the $\sim 1\%$ of the detector volume occupied by the droplets of superheated detector liquid while the other $99\%$ of the detector volume is inactive support gel. Liquid bubble detectors have been used for millimeter-resolution imaging of neutrons from a plasma pinch experiment [8]. A liquid bubble detector offers the unique combination of outstanding spatial resolution and a detection efficiency comparable to that for scintillators. By “photographing” the neutron-induced bubbles when they are less than 30 $\mu$ in diameter, neutron images of NIF target plasmas with yields as low as $10^{15}$ neutrons should be possible with 5 $\mu$ spatial resolution and SNR $\sim 10$. 
5. CONCLUSIONS

We report the results of proof-of-principle experiments on OMEGA that demonstrate the first use of bubble neutron detectors for neutron imaging of laser fusion targets. With their ability to detect neutrons with a spatial resolution far superior to that of scintillation and other high efficiency detectors, bubble detectors should revolutionize the design of coded aperture neutron imaging systems and allow imaging of NIF fusion targets with a spatial resolution of 5 \( \mu \) in the target plane.
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