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Scintillating-fiber imaging detector for 14-MeV neutrons

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Abstract

We have created a detector to image the neutrons emitted by imploded inertial-confinement fusion targets. The 14-MeV neutrons, which are produced by deuterium-tritium fusion events in the target, pass through an aperture to create an image on the detector. The neutron radiation is converted to blue light (430 nm) with a 20-cm-square array of plastic scintillating fibers. Each fiber is 10-cm long with a 1-mm-square cross section; approximately 35-thousand fibers make up the array. The resulting blue-light image is reduced and amplified by a sequence of fiber-optic tapers and image intensifiers, then acquired by a CCD camera. The fiber-optic readout system was tested optically for overall throughput and resolution. We plan to characterize the scintillator array using an ion-beam neutron source as well as DT-fusion neutrons emitted by inertial confinement targets. Characterization experiments will measure the light-production efficiency, spatial resolution, and neutron scattering within the detector. Several neutron images of laser-fusion targets have been obtained with the detector. We describe the detector and our characterization methods, present characterization results, and give examples of the neutron images.

In inertial confinement fusion (ICF) experiments, a small capsule containing hydrogen-isotope fuel is imploded when it is irradiated with either laser light or x rays.¹ The implosion heats the fuel, often a mixture of deuterium and tritium, to ion temperatures in excess of 1 keV, and produces a substantial number (typically between 10^9 and 10^{13}) of 14-MeV DT-fusion neutrons. The spatial distribution of neutron emission from the target reveals useful information about the uniformity of the implosion and the radial dependence of the ion-temperature profile in the DT fuel. Although much of this information is presently obtained from x-ray imaging, neutron imaging will become more important for advanced targets that achieve areal densities high enough to block most x-ray emission. At the Nova laser facility, we want to demonstrate the feasibility of high-resolution neutron imaging, with the ultimate goal of obtaining 10–15- μm spatial resolution images from targets yielding as few as 10^{11} DT neutrons.

The Nova neutron imager is a penumbral coded-aperture microscope.² Neutrons emitted from the target pass through a 6-cm-long aperture formed through a 6.4-mm-diam gold cylinder. The axial profile of the aperture increases monotonically from a 500- μm -diam at the entrance to an 880- μm -diam at the exit. The azimuthally symmetric taper is described by a differential equation that requires the radius of curvature of the surface to vary inversely with the axial distance from the source plane.³ A large fraction of the neutrons that pass through the aperture's gold substrate are scattered. Because the aperture is small and located a large distance (12 m) from the detector, a negligible number of the scattered neutrons are detected. The specially tapered aperture provides a sufficiently constant point-spread function over a 200- μm -diam field-of-view, allowing the coded image to be unfolded by deconvolution.

The neutron detector is a large (20-cm square) array of approximately 35,000 scintillating fibers. Each fiber has a 1-mm square cross section. Elastic scattering reactions between the incident neutrons and hydrogen nuclei in the fibers produce blue light. Experiments are in progress to measure the scintillation efficiency, pulse-

height distribution, and spatial resolution of the array. For the typical Nova implosion, the blue-light image produced by the array is quite dim, ≈ 3600 photons-per-square-millimeter; the readout system must therefore be very sensitive. A schematic diagram of our detector is shown in Fig. 1. We use a set of four fiber-optic tapers to segment and reduce the image into a set of four 4-cm-diam sub-images. Each sub-image is then separately intensified by a micro-channel-plate (MCP) image-intensifier tube. The intensified sub-images are reduced again with a second fiber-optic taper, then recombined using a flexible fiber-optic image guide. The output of this guide is again intensified, this time by a high-resolution electrostatic image intensifier. The final image is fiber-optically coupled to a cryogenically-cooled CCD camera to form a digital image. The throughput of the readout system has been measured and found to be satisfactory to detect single neutron interactions in the scintillator array. Substantial image processing is required to recombine and correct the sub-images for geometric distortion and spatial variations in gain (flat-field correction).

Neutron Detector Hardware

The DT-fusion neutrons are detected by a 20-cm-square array of scintillating fibers (this array was constructed by Bicon, Inc.). The scintillators convert a small fraction, $<3\%$, of the incident neutron energy into blue light (spectrum centered at 430 nm). Each fiber has a 1-mm-square cross-section and is separated from its neighbor by a layer of white paint (EMA) that is about 0.07-mm thick. The fibers have a numerical aperture of 0.68 and a light-collection efficiency of about 4%. The fiber array is enclosed in a light-tight aluminum housing with a front cover that is thinned to a 3.2-mm thickness to minimize scattering of the incident neutrons. The housing also holds a 3.2-mm-thick glass mirror in front of the scintillator array to improve the light-collection efficiency. The entire arrangement is open on its back face, which is pressed into contact with the fiber-optic readout.

A set of four fiber-optic tapers segment and reduce the scintillator image.

(This and all of the fiber-optic components were fabricated by Schott Fiber Optics, Inc.) Each taper has an 11.5-cm-diam input face and a 4-cm-diam output face, but two orthogonal edges were formed on each taper by grinding. The four tapers are cemented together on the ground edges to form a clover-leaf pattern; see Fig. 2.

Four MCP image intensifiers are pressed against the 4-cm-diam output faces of the fiber-optic tapers. An optical coupling grease is used here and at all subsequent fiber-optic interfaces to avoid the formation of interference fringes. The intensifiers have bi-alkali photo-cathodes (response similar to S-20) that have a quantum efficiency of about 17% at 430 nm. Green output light comes from a P-20 phosphor (spectrum centered at 560 nm). The bias voltage on the intensifiers is set to provide a gain of approximately 10^4 . The photocathode voltage is used to gate the intensifier on for a 100 μ s period that starts about 0.5 μ s before the implosion is initiated.

Next, the intensified sub-images are reduced by a second 7:1 fiber-optic taper. The small ends of these tapers, about 6.5-mm in diameter, are, in turn, coupled to a flexible, four-branch coherent image guide. This guide recombines the four sub-images into a 14-mm square region. The guide uses 6- μ m-diam glass fibers to achieve high spatial resolution.

All of the above fiber-optic tapers and image-intensifier tubes are held together in a single rectangular enclosure that we shall refer to as the primary detector. The large, clover-leaf-shaped fiber-optic reducers protrude a few mm from the front of the enclosure to allow coupling to the scintillator array; the output ends of the small fiber-optic tapers protrude a few mm from the rear surface of the enclosure. The tapers and intensifiers are pressed together by a set of nested cylinders and gaskets that allow rotational freedom while maintaining a normal force. In this way, the glass-to-glass interfaces remain parallel and tightly coupled. The four branches of the image guide are coupled to the small tapers using a similar set of cylinders that mount to the back face of the rectangular enclosure. This components of the primary detector are all supported by a metal plate that is tilted at an 18° angle above the horizontal; the plate can be rotated along two axes to allow fine pointing

adjustment. The primary detector is aimed at the center of the Nova target chamber through a 46-cm-diam hole cut through a 150-cm-thick concrete shield wall that surrounds the target-chamber bay. A pair of 20-cm-thick plastic doughnuts, one inserted into the front and the second into the back of the hole, further reduce to the aperture to about 18 cm. The aperture acts as a collimator, reducing the flux of neutrons scattered from the target chamber and other structures in the target-chamber bay. The primary detector is mounted so that the center of the scintillator array is 12 m from the center of the target chamber.

For high-yield operation, the flexible image guide is directly coupled to the CCD camera. For very low-yield operation, an additional intensifier tube is used (Hamamatsu model V3843). This tube, which is electrostatically focussed, has a 20-mm-diam input window and a 13-mm-diam output window. The input photocathode is S-25, and the output screen is again P-20. When biased at 15 kV, the tube provides a luminous gain >100 , but we typically use a bias voltage of about 5 kV to provide a gain of approximately 40. We find that the tube is noisy when biased to full voltage. Spatial resolution of this tube is 150 μm full-width-at-half-maximum (FWHM). To avoid undersampling at the CCD camera, the output image from the tube was coupled to a final 1:2 fiber-optic expander that gives an image about 17.5-mm in diameter. These components are supported by a set of nested cylinders that again provide a normal coupling force while allowing proper registration of the glass surfaces. The cylinders are attached to the front face of the CCD camera, and the entire structure is mounted vertically on a set of four posts behind the primary detector. The posts hold the CCD camera high enough so that it is outside the path of collimated neutron emission.

The neutron image is finally acquired by a cryogenically cooled, fiber-optically coupled CCD camera (custom built by Photometrics, Ltd.). The CCD chip is a TK1024, a 1024×1024 array of 24- μm -square pixels. When the camera is cooled to its normal operating temperature of -140°C , the read noise was measured to be <5 electrons/pixel, and the dark current is negligible during all our exposures

(typically 20s). Quantum efficiency of the CCD is about 24% at 560 nm. The camera is interfaced to an Apple Macintosh computer and the CCD images are stored on an attached hard-disk drive.

Neutron-Image Processing

The segmented neutron image recorded by the CCD camera must be corrected for spatial gain variations and geometric distortion, then reassembled. A typical raw neutron image is shown in Fig. 3(a). We have written software to carry out these operations. The calculations are done on a Sun Sparc-10 workstation. The processing is not entirely automatic, and some intelligent operator interaction is required.

The spatial gain corrections are applied first. The corrections are obtained directly from a flat-field image [Fig. 3(b)], produced by operating the neutron detector without the coding aperture during a high-yield ($>10^{12}$ neutrons) implosion. Typically, we record about 300 neutron interactions per scintillator element during such a implosion. Because of the broad pulse-height distribution of the neutron interactions, the accuracy of the flat-field image is about $\pm 9\%$ (as opposed to $1/\sqrt{300} = 6\%$). Eventually, we hope to use the average of a series of flat-field shots to reduce this noise contribution. Low values in the flat-field image are first clipped to avoid enhancing the low-intensity parts of the image, then the raw neutron image is corrected by dividing it by the clipped flat-field image.

Next, we remove geometric distortion from the image. Because each sub-image is distorted by a different sequence of fiber-optic components, the sub-images must be separated and processed independently. To measure the distortion, the scintillator array is removed from the fiber-optic reducers and a mask is placed against them. The mask, formed in a dark sheet of photographic film, is a uniform array of 0.2-mm-diam holes spaced on 2-mm centers. We obtain an image by exposing the masked detector to a bright fiber-optic light source placed several meters away. The dot-pattern image [Fig. 3(c)] is then processed to locate the central pixel location of each dot in the distorted image. Next, row and column indices of

the undistorted array are assigned to each point. This step is only semi-automatic. An operator must enter a few points to define an anchor row and an anchor column that pass near the center of the dot-pattern image. The anchor points are interpolated to form a smooth curve, and the program then seeks points that fall within a pre-specified offset from the anchor curve. The new points are assigned an index of zero, and the points are again interpolated to form a smooth curve. The search then proceeds to work away from this new reference curve with a larger offset. All points found within the new search region are assigned an index of 1, the new points are interpolated to form a new reference curve, and an estimate of the proper offset is calculated from the displacement between the old reference curve and the new one. The process is repeated to find the index 2 curve, the index 3 curve, and so forth until no more points can be found in the image. A similar sequence is used to assign negative indices to points below the anchor curve. The operator monitors this procedure by watching a graphical representation of the search. As each new distorted row or column of points is located, the dots are overlaid by a colored symbol. Each index is given a different color to assure proper identification of the distorted lines. Operator intervention is also required to remove defects from the dot-pattern image before processing begins. Once the indices have been obtained, reference coordinates are obtained by scaling the indices to correspond to the 2-mm spacing of the dots, and assigning an origin in a convenient location. A two-dimensional polynomial is fit to describe the distorted coordinates as a function of the reference coordinates, and a polynomial warping routine is applied to remove the distortion from each sub-image.

Finally, the four sub-images are reassembled. Presently this is done using a distorted image of a rectilinear grid [Fig. 3(d)]. The grid image is processed to remove distortion as described above. The resulting four sub-images are then manually offset and concatenated together until the lines of the grid match, and the spacing of the lines is uniform. It should be possible to automate this procedure using the dot-mask image and an appropriate assignment of origin. The final corrected neutron

image is shown in Fig. 3(e).

Neutron Detector Characterization

The detector was characterized in two different ways, and two additional experiments are planned. The overall throughput of the fiber-optic readout system was measured using a filtered light source and an absolutely calibrated optical power meter; spatial resolution was measured using a 3-bar mask. Flat-field shots with a known neutron yield have also given us a measure of the overall efficiency of the scintillator array; these values are in good agreement with calculated values. In future experiments, we plan to characterize scintillation efficiency, pulse-height distribution, and spatial resolution by exciting the entire detector with a low fluence of neutrons that produces a sparse, "single-hit" image. Similar measurements will be carried out for the scintillator array alone, using a collimated neutron source and a set of photo-multiplier tubes to read out the signals from various scintillator elements.

We characterized the fiber-optic readout system using a white-light source transmitted through a narrowband filter centered at 436 nm. The blue light was lens-coupled to a 1-mm-square plastic fiber with a composition similar to the scintillator elements, but without any scintillating dopant. Using an absolutely calibrated optical power meter, the power level of light emitted by the fiber was adjusted to a particular value, typically ≈ 10 nW. The fiber was then pressed against various points on one of the large fiber-optic tapers, and the appropriate micro-channel-plate image intensifier was triggered while an exposure was being integrated by the CCD camera. The majority of the optical signal was recorded by between one and four CCD pixels, as expected. The total charge recorded by these pixels was summed, and the ratio between acquired charge and the photons emitted by the fiber during the intensifier gate time gives the absolute sensitivity of the readout system. These measurements were taken without using the second stage image intensifier; the output of the image guide was directly coupled to the CCD

camera. The readout sensitivity was measured to be $\epsilon_t = 0.12$ electrons/photon. The largest uncertainty in this measurement is the power-meter calibration at very low power levels. To reduce the uncertainty, the meter was calibrated immediately before the measurement. We estimate the residual uncertainty to be less than $\pm 10\%$.

The spatial resolution of the readout system was measured by recording an image of a 3-bar mask with bar spacing of 2 mm (0.5 lp/mm). Without the second-stage intensifier, the average contrast was found to be 56%. Assuming a gaussian MTF, this would correspond to a spatial resolution of 0.81 mm (FWHM). Resolution is degraded to 1.1 mm (FWHM) by adding the second-stage intensifier.

The measured efficiency is in good agreement with calculated values based on the specifications of the individual components. The transmission of the first taper can be approximated by

$$\tau_1 = \epsilon_0^2 \tau_c \left(\frac{NA_t}{NA_f} \right)^2, \quad (1)$$

where τ_c is the collimated-light transmission of the taper, ϵ_0 is the coupling efficiency between the two optical surfaces, and NA_t and NA_f are the numerical apertures of the taper and the exciting fiber, respectively. The specifications call for $\tau_c > 15\%$ at taper center, and $\tau_c > 10\%$ at the edge, the NA of the exciting fiber is 0.58, the NA of taper is the ratio of the output diameter to its input diameter ($4/11.5 = 0.35$), and we estimate the coupling efficiency to be 0.92. The resulting estimate is $\tau_1 \approx 4.6\%$ at the center, and $\approx 3\%$ at the edge. The light exiting the tapers is intensified by a factor $G \approx 10^4$, then it is attenuated by transmission and aperture losses through a second taper. In this case, $NA_f = 1$, and $NA_t \approx 0.14$, while τ_c was specified as $\geq 40\%$ at the center of the taper. Altogether, we estimate $\tau_2 \approx 0.69\%$. Next, the light enters the fiber-optic image guide that has a specified transmission $\tau_g \geq 40\%$ together with two more interfaces. Finally, the light passes another two interfaces and a fiber-optic faceplate before coupling to the CCD camera that has a quantum efficiency $\epsilon_{ccd} \approx 0.24$ electrons/photon. The overall efficiency of the readout can now be estimated as $\epsilon_t \approx \tau_1 G \tau_2 \tau_g \epsilon_0^3 \epsilon_{ccd} \geq 0.24$ electrons/photon. This rough estimate is a factor of two larger than the measured value of 0.12 electrons/photon; the coupling efficiencies at

the interfaces may be lower than 0.92.

We can estimate the scintillation efficiency by observing the signal strength in a flat-field image, and dividing by the measured throughput efficiency of the readout system and known neutron fluence on the detector. The yield estimates come from a Cu-activation system, and from a variety of scintillation detectors that have been calibrated against the activation system. The accuracy of the yield measurement is $\pm 20\%$.

To calculate the neutron fluence at the detector, we must take into account all materials in the flight path that can scatter the neutrons: a 4.8-mm-thick piece of glass at the vacuum chamber wall; a 6-m air path; and 3.2-mm-thick aluminum and glass plates that cover the scintillator array at the detector. We assume that all of the neutrons scattered by the glass window and air path are not detected, but that only half the neutrons scattered by the detector housing components are lost (the remainder are assumed to scatter into the scintillator array). The resulting transmission, τ_0 , calculated using tabulated cross-sections,⁴ is 88%. We must also take into account the dead space in the scintillator array. Each fiber is clad with inactive plastic that has a thickness of 40 μm . Also, there is a 35- μm -thick layer of EMA surrounding each fiber. As a result, only $\eta = 74\%$ of the array area is active. The number of neutrons that can excite an individual scintillator is related to the yield N_0 by

$$N_1 = \tau_0 \eta \frac{d_a^2}{4\pi R^2} N_0, \quad (2)$$

where d_a is the cross-sectional area of the active part of the scintillator, and R is source-detector separation. Substituting numbers in Eq. 2 gives $N_1 = 3.0 \times 10^{-10} N_0$. Again using cross-section tables and knowing the formula of the plastic fibers to be very close to CH with a density of 1.06, we estimate the fraction of the available neutrons that will interact with a hydrogen ion to be 20%. Thus, for a neutron yield of 10^{11} , we expect to get an average number of 6 neutron-proton (n-p) interactions in each scintillator element.

We have five flat-field neutron images with the detector configured without

the second-stage image intensifier. To use these images, we take the average signal level, in electrons/pixel, and multiply it by 6.9, the number of CCD pixels that map back to a single scintillator element. Next, we divide the detector throughput of 0.12 to give the number of photons emitted by the scintillator. Finally, we divide by the number of n-p interactions per scintillator to give the scintillator efficiency. The average value for the five images is 580 ± 160 photons/n-p. This compares well to a calculated value of 630 photons/n-p.

We have two experiments planned to more accurately characterize the scintillator array. In the first scheme, the detector will be excited by low-yield implosion producing about 5×10^8 neutrons. This will excite a small fraction, about 3%, of the scintillator elements in the array. The resulting image will show about 1000 n-p interactions, most of which will be spatially localized. This data can be analyzed by producing a histogram of the interactions. The histogram itself is the pulse-height distribution of the np-interactions, while its average value gives the efficiency of the scintillator elements. By analyzing the average diameters of the scintillation light, we can determine the spatial resolution of the scintillator array and the overall neutron detector. The second experiment will utilize a ion-beam neutron generator. To electronically collimate the neutron emission, we will use an alpha-particle detector to view the neutron emission through a pair of 1-mm-square collimating apertures that mimic the solid angle of a single scintillator element. The scintillator array will be instrumented with a 5 by 5 array of photo-multiplier tubes that are coupled to the scintillator array with un-doped plastic fibers of similar shape and composition. By looking only at coincidence events, we can measure the scintillator efficiency, pulse-height distribution, and point-spread function. Also, we will characterize the effects of scattering using several photo-tubes that view scintillator elements far away (> 5 cm) from the electronically collimated beam.

Sample Images

We have produced several coded neutron images with the neutron microscope.

Two sample images are shown in Fig. 4. The first [4(a)] was produced by an implosion of a glass microballoon with a 1-mm diameter and a 3- μ m-thick shell surrounding an equimolar mixture of deuterium and tritium gas at a pressure of 50 atm. When imploded, this target yielded about 2×10^{13} neutrons. The second image [4(b)] was produced by the implosion of a radiation-driven target. This target capsule is smaller, 420- μ m-diam, consisting of a 25- μ m-diam outer layer of plastic, a 9- μ m-thick glass shell, and again filled with 50 atm of DT gas. The radiation drive was provided by mounting the capsule in the center of a cylindrical gold hohlraum, then focusing the 10 beams of the Nova laser at the walls of the hohlraum to fill the cavity with x rays. The implosion yielded 1.3×10^{11} neutrons.

The coded images are unfolded by deconvolution. The point-spread function is calculated by ray-tracing through an aperture axial profile that is assumed to be azimuthally symmetric. The profile is actually measured from the copper mandrel that is used to form the gold aperture by electroplating. Unfortunately, recent aperture characterization experiments indicate that the apertures were subsequently distorted by later machining operations. The unfolded neutron image corresponding to the radiation-driven implosion is shown in Fig. 4(c). Because of the mechanical distortion in the aperture, this unfold can be only be regarded as a rough approximation to the actual neutron source distribution. To carry out a more accurate unfold, we will need accurate aperture characterization data that should soon be available.

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Figure Captions

Fig. 1. Schematic drawing of the 14-MeV neutron-imaging detector.

Fig. 2. Four 11.5-cm-diam tapers are cemented together along flat edges formed by grinding. The large input face of this assembly has the clover-leaf shape depicted in the figure.

Fig. 3. A set of images illustrating the neutron image processing: (a) raw image; (b) flat-field image obtained from an unobstructed implosion; (c) dot-pattern image for quantifying the geometric distortion; (d) uniform grid pattern for sub-image realignment; and (e) final image.

Fig. 4. Sample neutron images: (a) coded image of a directly driven target implosion; (b) coded image of a radiation-driven target implosion; (c) approximately unfolded image of the radiation-driven implosion.

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