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Neutron Detectors for Fusion Reaction-Rate Measurements

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ABSTRACT

Fusion reactions in an inertial-confinement fusion (ICF) target filled with deuterium or a deuterium/tritium fuel release nearly monoenergetic neutrons. Because most the neutrons leave the compressed target without collision, they preserve reaction-rate information as they travel radially outward from their point of origin. Three fast, neutron detector techniques, each capable of measuring the fusion reaction-rate of ICF targets, have been demonstrated. The most advanced detector is based on the fast rise-time of a commercial plastic scintillator material (BC-422) which acts as a neutron-to-light converter. Signals, which are recorded with a fast optical streak camera, have a resolution of 25 ps. Good signals can be recorded for targets producing only 5×10^7 DT neutrons. Two other detectors use knock-on collisions between neutrons and protons in a thin polyethylene (CH_2) converter. In one, the converter is placed in front of the photocathode of an x-ray streak camera. Recoil protons pass through the photocathode and knock out electrons which are accelerated and deflected to produce a signal. Resolutions < 25 ps are possible. In the other, the converter is placed in front of a microchannel plate (MCP) with a gated microstrip. Recoil protons eject electrons from the gold layer forming the microstrip. If a gate pulse is present, the signal is amplified. Present gate times are about 80 ps.

1. INTRODUCTION

In inertial-confinement fusion (ICF) experiments, spherical capsules filled with deuterium or a deuterium-tritium mixture are heated and compressed to conditions under which thermonuclear fusion occurs. At Livermore, submillimeter capsules are irradiated with up to 30-kJ of energy at a wavelength of 0.351 μm from the 10-beam Nova laser.[1] Experimental goals are to achieve 1000× liquid density and temperatures of 10 keV for confinement times on the order of 100 ps.[2] During the plasma confinement time, fuel atoms undergo fusion, releasing energetic charged particles, neutrons, and photons. The reaction-rate history depends on the coupling of the laser energy to the target, the hydrodynamics of the target implosion, and the

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plasma conditions during peak compression. We want to measure the burn history relative to the incident laser power because it is a sensitive indicator of our ability to model energy transport between laser and target.

Fusion neutrons can be used to measure the thermonuclear burn rate of an ICF target. Charged particles emitted in deuterium-deuterium (DD) and deuterium-tritium (DT) fusion reactions are slowed by coulomb interactions with plasma ions and electrons before leaving the fuel. Most neutrons, however, escape the target without collision. Since fusion neutrons are nearly monoenergetic, their temporal distribution at a point outside a target preserves burn history information with a time-of-flight delay. For this reason, burn history can be measured with a fast neutron detector some distance outside the target. Since confinement times are on the order of 100 ps, a detector with time resolution on the order of 20 ps is highly desirable.

Using fusion neutrons for a burn history measurement places two fundamental constraints on the detector system: Doppler broadening limits target-to-detector distance and neutron speed limits detector thickness. Thermal motion of reacting plasma ions in a target causes a Doppler broadening of the neutron energy spectrum. For neutrons leaving a target at the same instant in time, this causes a spread in arrival times at a detector that is proportional to the target-to-detector distance and the square root of the plasma temperature. To keep this time spread small, the detector must be placed close to the target. For example, a 20-ps spread for a 1-keV plasma occurs at a distance of 16.4 cm for DT neutrons and 2.6 cm for DD neutrons. The relatively slow speed of the neutrons requires a thin detector to maintain temporal resolution. In a thick detector, the uncertainty in the interaction point results in an uncertainty for the instant of interaction. Thus, the time a neutron takes to pass through a detector limits its temporal resolution. It takes a 14-MeV DT neutron 20 ps to travel 1 mm while it takes a 2.45-MeV DD neutron 46 ps. The penetrating nature of the neutrons allows substantial shielding against target debris and x rays without significant loss of neutron signal. This makes small target-to-detector distances practical.

The less stringent distance and thickness requirements for 14-MeV DT neutrons are a distinct advantage for using DT-filled capsules for burn history measurements. Furthermore, the larger fusion cross section for DT neutrons results in a neutron yield nearly 100 times greater than for a hydrodynamic equivalent DD-filled target, and thereby reduces statistical uncertainty in measurements. In this article, we briefly review three recently demonstrated fast neutron detectors. Each is sensitive enough to record ICF burn history with $<$ 40-ps resolution for DT filled targets yielding as few as 10^9 neutrons.

2. FAST SCINTILLATOR, OPTICAL STREAK CAMERA

Our most advanced detector is based on the fast rise-time of a plastic scintillator.[3,4] As monoenergetic neutrons expand radially outward from a small (~ 100-μm diameter) ICF target[5], they preserve target reaction-rate information. As the neutrons pass through a thin piece of plastic scintillator material, some of them have elastic collisions with hydrogen nuclei. The resulting recoil protons quickly transfer their kinetic energy to luminescent states in the scintillator. For

BC-422[6] the light output has a rise time < 20 ps and a decay time of ~ 1.2 ns. The temporal distribution of the emitted light is the neutron temporal distribution at the scintillator convolved with the scintillator response. Burn history information is encoded in the leading edge of the light pulse from the scintillator. A lens system images the scintillator light to a fast optical streak camera for recording.

Figure 1 shows the detector system. A 6-mm diameter, 1-mm thick piece of BC-422 is mounted in a retractable Hevimet (90% tungsten) nose cone. The front of the nose cone, which is 3-mm thick, shields the scintillator from target x rays, scattered laser light and target debris. An aluminized mirror deposited on one surface of the scintillator doubles the light output directed towards the streak camera. A piece of Pb glass shields the back side of the scintillator from scattered x rays. The retractable nose cone positions the scintillator at points between 1 and 50 cm from the target. For storage, the nose cone can be retracted to a point 82 cm from target chamber center. An achromatic f/2 zoom lens relays the 350- to 450-nm wavelength scintillator light along a 4-m optical path to the S-20 photocathode of the streak camera. This arrangement allows the camera to be totally outside the chamber. Lens coupling produces minimal temporal dispersion. In contrast, a 4-m coupler made of graded-index optical fibers would produce about 80 ps of dispersion. Baffling and a light shield prevent scattered laser light from entering the lens system. Scintillator light passes through a glass window at the vacuum chamber wall. Components inside the chamber can operate at either vacuum or atmospheric pressure. The streak camera output is recorded with a CCD camera. The relatively long distance between target and streak camera is an advantage of this configuration. Background caused by target x rays and neutrons interacting in the streak camera and the CCD readout decreases inversely with the square of the distance.

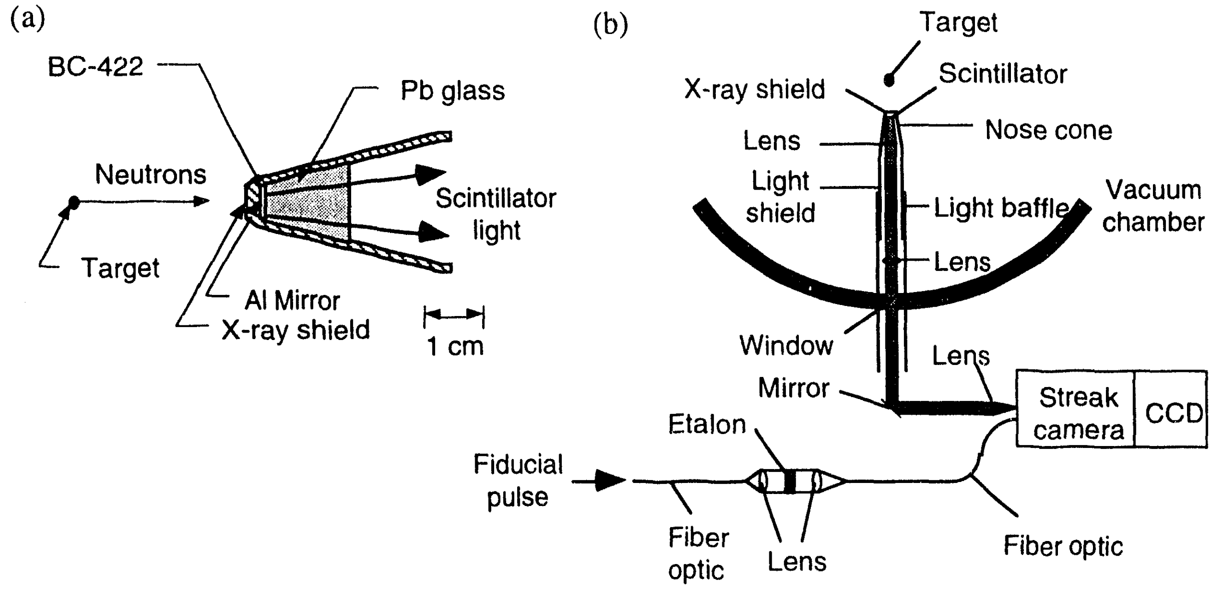

Figure 1. Fast neutron detector based on the fast rise time of a plastic scintillator. (a) Nose cone holding thin plastic scintillator. (b) Neutron detector system.

Besides the neutron signal, the streak camera also records an optical fiducial pulse. This allows the time base of the neutron signal to be related to the time of the incident Nova laser beams. The Nova laser facility generates a 100-ps, 0.53-μm, optical fiducial pulse that is synchronized with the main laser pulse. The fiducial pulse is split and fanned out to various diagnostic instruments via fiber optic cables. We insert a 527-ps etalon into the fiducial path to form a series of evenly spaced pulses. The first pulse in the series gives us the required timing reference to accurately relate the neutron-signal time base to the laser power history recorded with other streak cameras. The pulse train gives us a shot-by-shot check on the stability of the time base. The amplitude and timing of an optical fiducial are easy to control because they are independent of the target type, incident laser energy and target-to-detector distance. This is not the case when x-rays generated by the target are used as the fiducial. We can relate streak camera time bases with about ± 10 ps accuracy.[7]

Excellent neutron data have been recorded with this instrument. Figure 2a shows an image recorded with the scintillator 2 cm from a target producing 6×10^8 DT neutrons. The fiducial pulse train appears across the top of the image, while the 6-mm wide neutron signal appears directly below. Figure 2b shows the intensity versus time averaged across the neutron signal. Streak camera flat-field and time-base corrections are included in the signal processing. Information about the target burn history is encoded in the leading edge of the pulse; the pulse tail shows the characteristic decay of the scintillator. The burn history shown in figure 2c is

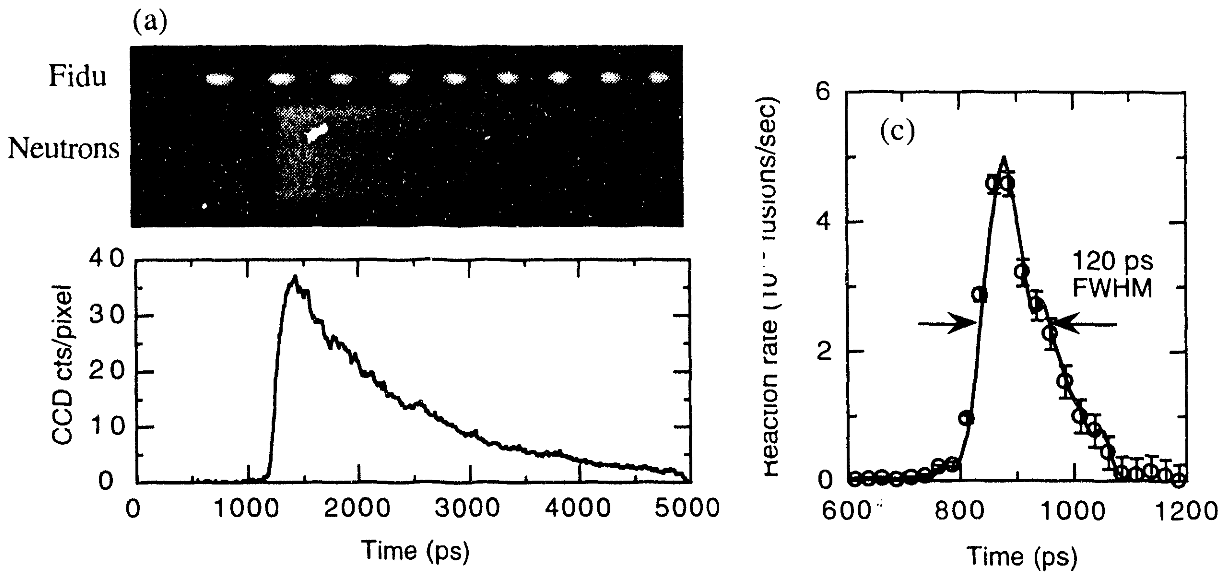

Figure 2. Fast scintillator data. (a) Streak camera image recorded for target producing 6×10^8 DT neutrons shows fiducial and neutron signals. (b) Average neutron-signal intensity versus time. Burn history information is encoded in the leading edge of the pulse. The pulse tail shows the characteristic decay of the plastic scintillator. (c) Neutron temporal distribution after deconvolving the effect of the scintillator decay from the signal in (b).

obtained by deconvolving the effect of the scintillator decay from the recorded signal and normalizing the integral of the signal to the total neutron yield. The fiducial pulse is used to relate the reaction-rate history time base to the incident laser power used to implode the target. This deconvolved pulse actually represents the convolution of the neutron temporal distribution with the scintillator rise time and the streak camera response. Since rise time and camera response are both < 20 ps, the fast pulse is a good representation of the fusion reaction rate. Absolute timing is done with a precision of ± 30 ps. In this example, the laser drive was nominally a 20-kJ, 2-ns square pulse illuminating a 360-μm diameter glass ball filled with DT gas. The burn history shows the target reached peak emission about 900 ps into the laser pulse and that the FWHM of the burn was 120 ps.

3. NEUTRON STREAK CAMERA

One way to build a neutron streak camera[8] is to combine a neutron-to-proton converter with a fast x-ray streak camera. For this instrument, a 1-mm thick polyethylene converter is placed adjacent to the CsI photocathode of an x-ray streak camera. When target neutrons pass through the CH_2 converter, some of them elastically collide with hydrogen atoms to produce recoil protons. Protons with sufficient kinetic energy pass through the converter material and the thin CsI photocathode. As the protons pass through the photocathode, they cause electrons to be ejected from the photocathode surface. These electrons are accelerated and deflected in the streak tube in the same manner as photoelectrons produced by x rays absorbed directly in the CsI photocathode. Filters can be selected to allow both neutron and x-ray signals to be recorded simultaneously. The x-ray signal can be used as a fiducial to determine the temporal relationship between the neutron signal and the incident laser power.

Figure 3a shows an image recorded with the neutron streak camera. It was obtained with the camera placed 30 cm from a target that produced 4×10^{10} DT neutrons. The image shows clear x-ray and neutron signals. From preliminary experiments, we estimate a neutron streak camera based on a CH_2 converter can record the burn history for ICF targets with yields as low as 10^9 DT neutrons. With proper selection of filter material, we believe temporal resolutions can be < 20 ps. To achieve a fast, sensitive neutron streak camera for ICF burn-history applications, the camera must be designed so that its photocathode can be positioned about 5 cm from the target.

4. GATED MICROCHANNEL PLATE

The final neutron detector also uses a polyethylene converter. It is coupled to a gated microchannel plate (MCP) image intensifier to provide signal amplification and gating. Figure 4 shows the basic neutron detection mechanism, which is similar to that of the neutron streak camera. A thin, 1-mm thick sheet of CH_2 converter is placed at the input surface of a MCP image intensifier. Fusion neutrons traveling radially outward from a target pass through the converter. Some of the neutrons have elastic collisions with hydrogen atoms and produce recoil protons. Protons leaving the back surface of the converter produce secondary electrons when they strike

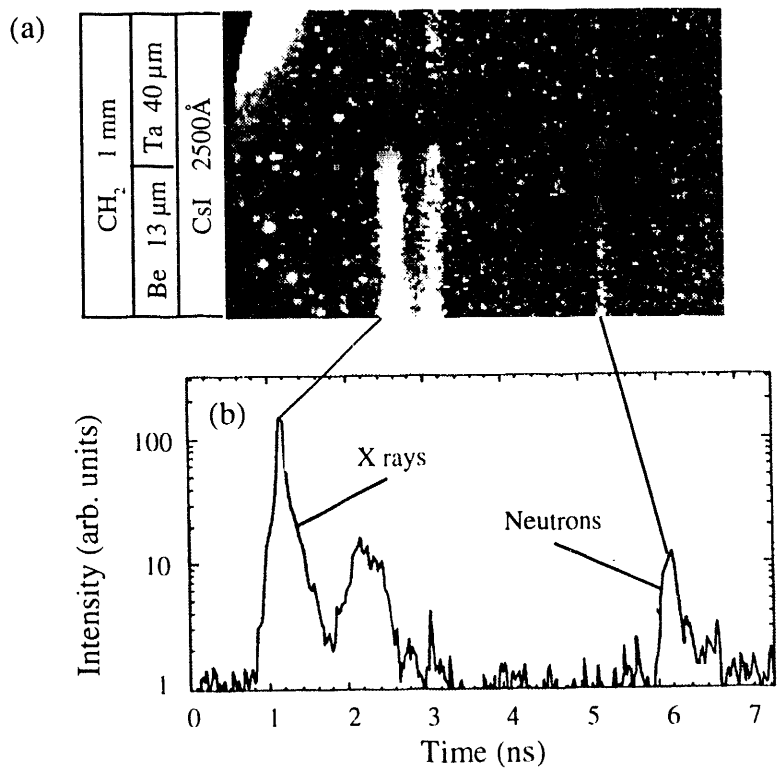

Figure 3. Neutron streak camera data. (a) Image recorded at the University of Roch-ester's Omega Laser with camera 30 cm from target emitting 4×10^{10} DT neutrons. (b) Lineout of the signal behind the Be filter show x-ray and neutron signals. Source of peak at 2.5 ns is unknown.

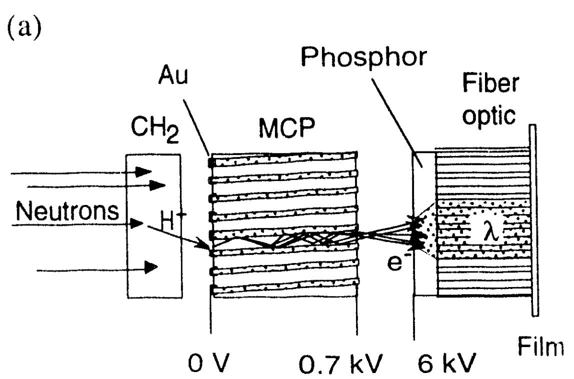

Figure 4. Neutron detection in detector that is based on a polyethylene converter and a MCP image intensifier.

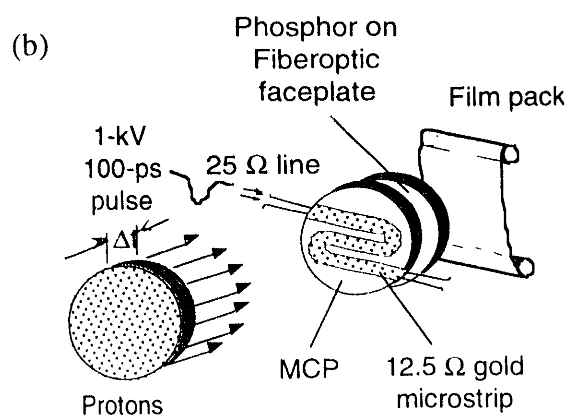

Figure 5. Gated MCP amplifies signal only at positions where the voltage pulse and proton burst intersect.

the gold electrode deposited on the input side of the MCP. The electron current is amplified by the MCP. Electrons leaving the MCP are accelerated into a phosphor screen where their kinetic energy is converted to a light signal that can be recorded on film.

The MCP amplifies a signal only at positions where a voltage gate pulse and recoil protons intersect (see figure 5). In our initial experiments, we used a MCP image intensifier originally developed for x-ray framing camera applications.[9] A 100-ps, 1-kV pulse is propagated along a serpentine microstrip plated on the MCP. Any point on the MCP can amplify a signal only when the gate pulse is present. Thus, when a burst of protons from the converter sheet strikes the input surface of the MCP, the signal is amplified only in the area where the gate pulse is present. The nonlinear relationship between gate-pulse voltage and MCP gain produces an effective gate width of 80 ps.

Figure 6a shows an image obtained with the MCP detector 17 cm from an ICF target that released 7×10^{11} DT neutrons. The distance along the microstrip corresponds to the time at which the signal arrived. Total propagation time along the microstrip is 750 ps. Figure 6b shows the fusion reaction rate determined from signal intensity along the microstrip. Signal processing includes flat-fielding, conversion of position to time, and normalization to target neutron yield. Superimposed on the MCP signal is the burn history obtained with the fast scintillator system. Our measurements with the MCP show that burn history for yields of 10^9 can be measured with a MCP 5 cm from the target.

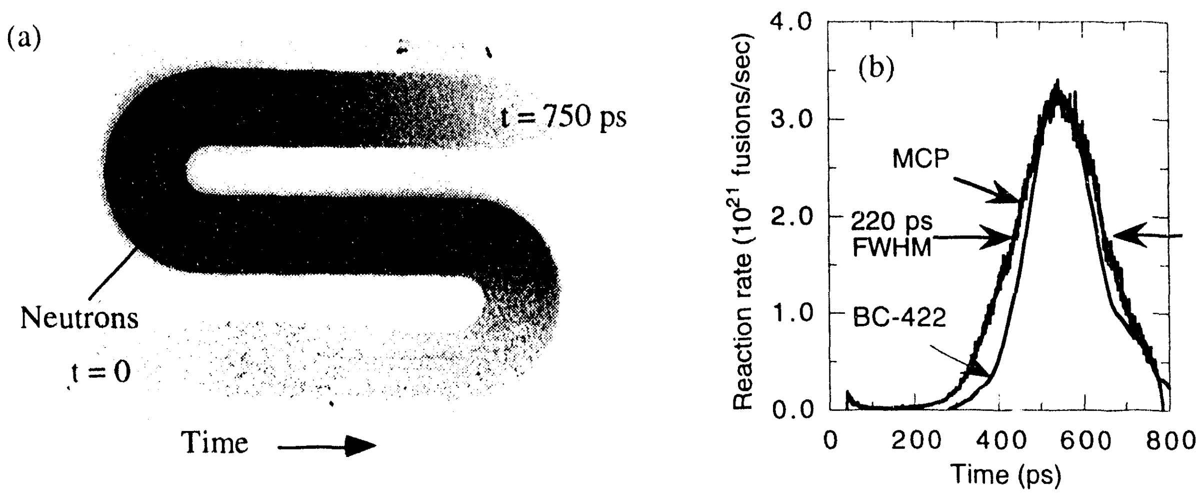

Figure 6. MCP neutron detector data. (a) Image recorded with fast MCP neutron detector 17 cm from a target producing 7×10^{11} DT neutrons. (b) Fusion reaction rate determined from MCP data with reaction rate determined from fast scintillator detector (BC-422) data.

5. DISCUSSION

Three fast neutron detectors for measuring reaction-rate history have been reviewed. The detector based on the fast rise time of a plastic scintillator is fully developed. The neutron streak camera and the MCP system still require further development to achieve routine operation.

The fast scintillator system can measure reaction-rate history with 25-ps resolution. Its primary advantages are a retractable nose cone, an optical fiducial, and a remote streak camera location. The retractable nose cone allows the detector to operate over a wide yield range —10^8 to 10^{13} DT neutrons. For low-yield targets the neutron-to-light converter can be conveniently positioned within centimeters of a target. The remote location of the streak camera reduces the effort required to shield the streak camera and CCD camera from target x rays and neutrons. An optical fiducial pulse allows the time base of the neutron signal to be related to the incident laser power signals with a precision of $\pm$ 10 ps. This detector represents a significant step forward in our ability to measure the reaction rate history for ICF targets.

The neutron streak camera and MCP detector have been demonstrated but are not yet sufficiently developed for routine reaction-rate measurements. Both of these detectors use a thin piece of polyethylene to convert target neutrons to detectable recoil protons. Unlike the scintillator detector, the neutron streak camera and MCP detector signals require no unfolding of a slow component of the detector response. The neutron streak camera can achieve < 20 ps resolution, but to be usable with targets producing only 10^9 DT neutrons, the camera must be designed to allow the photocathode to be positioned within 5 cm of a target. The gated MCP system must also be designed to operate within about 5 cm of the target to measure burn history for targets producing only 10^9 neutrons. Gate pulse width limits the resolution of our current system to 80 ps. Recent work with x-ray detectors suggests a response < 40 ps FWHM can be achieved. The MCP system has two advantages: its large area and ability to retain spatial information. These properties might allow the detector to be developed for time resolved neutron imaging.

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