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PLASMA NEUTRON DIAGNOSTIC TECHNIQUES WITH GOOD SPATIAL AND ENERGY RESOLUTION*

Dennis R. Slaughter†

Abstract

A neutron-detection system has been assembled to provide both spatial and energy information from the neutrons produced in advanced fusion experiments. Techniques described are applicable to experiments where the neutron pulse is on the order of one-second duration. The system gives spatial resolution of about 1 cm at distances of 1 to 2 m and energy resolution of 0.6 MeV at 14 MeV. In all cases, pulse-shape discrimination is used to distinguish neutrons from gamma rays.

Introduction

Advanced magnetic confinement fusion experiments are approaching the size required for commercial power generation. Accompanying this growth are dramatic increases in plasma ion density and increases in plasma volume. Diagnostics based on escaping ions or neutral atoms are becoming increasingly difficult as the mean free paths of these species become small compared to the plasma dimensions. Similarly, rf and laser probes are substantially attenuated in these denser, larger plasmas. On the other hand, neutron yields are substantial in some of these experiments, and the neutrons have mean free paths that are long compared to the plasma dimensions. Neutron diagnostics to measure plasma parameters are more attractive because of increased yields. The purpose of the work reported here was to assemble and characterize a neutron-detection system that might be useful in determining some plasma variables.

The objectives addressed here are:

- Measurement of the spatial distribution of the neutron yield
- Development of a neutron spectrometer system capable of high-count-rate operation so that energy spectra can be obtained during an 0.5-s plasma pulse
- Attainment of good energy resolution to reduce interferences resulting from nonthermonuclear neutrons and to allow measurement of ion temperature

We have been only partially successful thus far in our effort to attain these goals. The systems described below handle neutron count rates up to 5×10^5 counts/s and provide energy resolutions on the order of 160 keV for 2.5-MeV neutrons and 600 keV for 14-MeV neutrons. They also allow us to obtain an image of the neutron yield, with spatial resolution of a few centimetres for an object plane 3 m from the detection system. While we have obtained neutron spectra during a 1.0-s pulse, and the energy resolutions indicated above are a considerable improvement over earlier such systems, further improvements in both data rate and energy resolution will be required for the measurement of ion temperature during short intervals. Below we describe the design of our neutron system and its characteristics for neutron diagnostics.

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Background of Neutron Plasma Measurements

Deuterium and deuterium-tritium plasmas generate neutrons by the $D(d,n)$ and $T(d,n)$ reactions. The neutron energies are nominally 2.5 and 14 MeV, respectively. The cross section for the $D(d,n)$ reaction is a rapidly increasing function of ion energy up to about 5 MeV, and the $T(d,n)$ cross section rises rapidly up to about 100 keV.¹ As a result, the yield of thermonuclear neutrons is a sensitive indicator of the number of energetic ions in a plasma and thus provides some information about the ion energy distribution. If the ion energy distribution is Maxwellian, then the ion temperature can be obtained directly from the thermonuclear neutron yield and ion density.

In principle, the ion energy distribution can also be inferred from the neutron energy spectrum because the spectrum of thermonuclear neutrons depends only on the kinematics of the $D(d,n)$ and $T(d,n)$ reactions and the differential cross sections for the reactions. For the case of isotropic Maxwellian ions, the spectrum of emitted neutrons is peaked near either 2.5 or 14 MeV and has a width whose moments increase in a simple way with temperature.^{2,3} Following the calculations of Refs. 2 or 3, it is simple to show that the FWHM of the neutron spectrum generated by isotropic Maxwellian ions at temperature T_i (in keV) is:

For deuterium plasma,

$$\Delta E_n = 82.5 \text{ keV} \sqrt{T_i (\text{keV})} \quad (1)$$

For deuterium-tritium plasma,

$$\Delta E_n = 192 \text{ keV} \sqrt{T_i (\text{keV})} \quad (2)$$

Neither the spectrum nor the yield is easy to measure on advanced fusion experiments. Many magnetically confined plasmas are heated by neutral-beam injectors. Energetic injected deuterons react with the deuterium imbedded in charged particle and neutral beam dumps, and with the plasma itself to produce abundant nonthermonuclear neutron yield. Deuteron scattering and slowing in the injected beam make the energy spectrum of these neutrons broad. Ion energy distributions can vary greatly with position because of injectors or instabilities causing hot spots with very high yields. Toroidal confinement systems sometimes generate runaway electrons, which cause $D(e,n)$ decomposition and which generate energetic bremsstrahlung radiation in the limiters, where abundant neutrons are produced by (γ,n) reactions. Finally, many neutron detectors respond to the hard x-rays generated by the plasma.

Thus our task was to develop a system that distinguishes thermonuclear neutrons from interfering radiations and measures plasma parameters in as short a time as possible. The next section describes a simple pinhole camera that can be used to obtain a two-dimensional image of the thermonuclear neutron yield. Then the following section describes the performance of a high-rate neutron spectrometer.

This report was prepared as an account of work sponsored by the United States Department of Energy. It contains certain information that may be confidential as to the source of the information, but it does not contain any information that is classified or controlled by any law, regulation, executive order, or otherwise. It is hereby declared to be unclassified, and its contents are hereby released to the public.

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Fig. 1. Polyethylene-water collimator showing pinhole design and positions of neutron detectors.

Neutron-Yield Imaging

Neutrons produced by (γ, n) reactions in a limiter, or by deuteron-induced reactions in an injector-beam dump are expected to be generated from specific locations. An image of the neutron yield would allow separation of these sources from neutrons generated within the plasma. In addition, a neutron image should help to identify hot spots in the plasma, which could produce high response in a neutron detector located near the hot spot. For these reasons, we have constructed and partially characterized a simple neutron pinhole camera. Basic considerations in neutron-collimator and pinhole design are discussed in detail by Langsdorf.⁴ Recent designs of collimators and pinholes have been described by Bernstein⁵ and by Bauer and Weingart,⁶ respectively. Both designs obtained about 1-mm spatial resolution at the object plane. However, a collimated system requires either an array of collimators or a scanning system to produce an image. Therefore we chose a pinhole design similar to that of Ref. 6. In an effort to fabricate the pinhole with minimum effort and cost, we chose a water-polyethylene construction, which could use a water tank already available.

Figure 1 shows the pinhole design. The surrounding water tank is somewhat larger than is required and could be reduced if space was restricted. The pinhole consists of a series of 12.8-cm-o.d. polyethylene disks, each 5.1 cm thick and with holes for the appropriate aperture diameter. Disks were available with 1-mm, 3-mm, and 10-mm holes, allowing several different aperture diameters. Entrance and exit zones were constructed from disks with tapered holes to form conical entrance and exit zones. The imaging capability of the pinhole could be used by placing an array of small neutron detectors behind the aperture and using their signals to construct the inverted image of the source.⁶

In our work, we placed a single small detector on axis and rotated the whole system about both a vertical axis and a horizontal axis to map the spatial response of the system with respect to the ob-

ject plane. The neutron source used for these experiments was the LLL Rotating Target Neutron Source,^{7,8} which supplies up to 6×10^{12} n/s at 14 MeV. At each position of the system (Fig. 2), a laser was aimed through the aperture and its projection on the accelerator target was observed. The distance between this projection and the source spot on the target was used to determine the location of the neutron source in the object plane.

Figure 3 shows measured object-plane responses for apertures 3 mm and 10 mm in diameter. Data obtained with a 1-mm aperture was discarded because the peak transmitted signal was only about ten times the neutron background at the detector position. The neutron detector used was a small stilbene crystal,

Fig. 2. Experimental configuration for measuring pinhole spatial resolution.

Fig. 3. Response of pinhole detector as a function of source position in the object plane.

10 mm thick by 15 mm in diameter. Pulse-shape discriminating and counting electronics are described later. Pulse-height data was unfolded using the Lawrence Livermore Laboratory code NUTSPEC⁸ and the area of the 14-MeV neutron peak was used to infer the response at each point in the object plane.

There are two important features to note in Fig. 3. First, the spatial resolution (FWHM) at an object plane 2.5 m from the aperture is approximately 35 mm for the 10-mm aperture and about 25 mm for the 3-mm aperture. These values might possibly be reduced if a detector less than 15 mm in diameter were used or if the detector were further removed from the aperture. Second, the response falls to less than 1% of peak response at about 30 mm from the centerline in the case of the 10-mm aperture. Off-axis data obtained with the 3-mm aperture is more ambiguous because of the background, which is about 10% of the total signal when the source is 40 to 50 mm off axis. Figure 4 shows a typical unfolded neutron spectrum obtained using the stilbene crystal.

Fig. 4. Unfolded neutron spectrum obtained from stilbene crystal located behind pinhole and on axis.

Neutron Energy-Spectrum Measurements

Spatial imaging and collimation are helpful in discriminating against neutron sources outside the plasma, but the energy spectrum or the time history of the yield is required to separate D(d,n) and T(d,n) neutron sources from D(e,n) and T(T,n) sources or to identify neutron yield generated in a non-Maxwellian ion-energy distribution. Spectrum measurements must have good energy resolution to eliminate interferences and must have very high energy resolution if ion temperature is to be deduced from the neutron spectral width. Finally, very high data rates will be required to obtain neutron energy spectra in one plasma pulse.

We have developed a neutron spectrometer system based on a liquid organic scintillator (NE213). Recoil protons produced by (n,p) elastic scattering cause scintillation in the organic liquid. The scintillation is pulse-height analyzed and unfolded to obtain the neutron spectrum. Several small scintillators have been investigated here. Table 1 gives the inside dimensions of the scintillator vessels, which range from 1 to 4.5 cm. Similar scintillators are readily available with dimensions up to 15 cm. The scintillator detectors in Table 1 were mated to selected photomultiplier tubes (PMT's). In this

*Reference to a company or product name does not imply approval or recommendation of the product by the University of California or the U.S. Department of Energy to the exclusion of others that may be suitable.

Table 1. Characteristics of scintillator detectors used for measuring neutron energy spectra.

Detector	Diameter, cm	Thickness, cm	Energy Resolution at high rate (FWHM), keV		Neutron Intensity, ^a 10 ⁶ n/cm ² s	
			2.5 MeV	14 MeV	2.5 MeV	14 MeV
Stilbene No. 401	1.5	1.0	900	1000	3	10
NE213 No. 106	1.0	1.0	200	1000	6	20
NE213 No. 107	2.0	1.6	214	650	1	5
NE213 No. 108	4.5	1.0	210	830	0.3	1

^aTo yield 5×10^5 counts/s in the detector.

For the unfiltered results to be reliable and have moderately good energy resolution, the pulse-height spectrum must contain about 10^5 recoil proton events; thus high data rates are required. We have developed a high-rate PMT voltage divider along the lines of that proposed by Kerns.¹⁰ This divider relies on transistor regulation of individual dynode currents, and should be easily employed. Note that the linear signal is derived from the tenth dynode. Saturation effects distort the signal at later dynodes, such that their signal voltages are no

Many neutron detectors, including organic scintillators such as NE213 and stilbene, are γ -ray sensitive. However, these two particular media produce scintillation output with a slow decay component whose relative strength increases with dE/dx of the charged particle. Pulse-shape discrimination (PSD) is used to distinguish energetic electrons produced by γ -ray interactions from recoil protons produced by neutrons. Figure 6 shows a typical block diagram of the electronics modules used for pulse-height analysis and PSD.

The electronics for linear-signal analysis are conventional and use a short (0.25- μ s) Gaussian shaping to minimize pulse pile-up at high data rates. The PMT anode signal is used for discriminating pulse shapes. Events with long rise times are identified as neutron interactions, while short-rise-time events are identified as γ -ray interactions. Figure 7 shows an oscilloscope trace of the signal at the inspection point of the pulse-shape discriminator (to anode amplifier) for two data rates of 10⁵ and 10⁶ cts/s, and two cross-over time groups are evident. The early group is due to γ -ray interactions in the detector, and the later is due to neutron interactions.

Because the pulse-shape discrimination can lead to incorrect identification of two piled-up γ -ray events as a single neutron event, a coincidence unit is employed to inhibit storage of events whose anode signal has a rise time above that of a typical neutron pulse. This performs pulse pile-up rejection. A time-to-amplitude converter (TAC) can be used to display the distribution of cross-over times for PMT anode pulses, and this distribution may be used to estimate the error rate. As the pulse-counting rate is increased, a greater fraction of γ -ray-induced pulses pile up and appear as single long-rise-time events. Figure 8 shows the error rate as a function of pulse-counting rate. The ordinate expresses the fraction of input γ -ray pulses which can be erroneously identified as neutron events. The lower curve shows the improvement obtained when pile-up rejection is used. At the highest rates used here for spectrum measurements, the error rate may be as high as 10%. In those cases where the neutron intensity is as large as or larger than the γ -ray intensity, this error rate is not a serious problem as long as the γ rays have energies less than a few hundred keV. However, if counting rates begin to approach 10^6 counts/s or if the γ -ray intensity significantly exceeds the neutron intensity, then the PSD error rate would be unacceptable. The rejection rate of bona-fide neutron events was not determined.

Strong magnetic fields that reach the PMT can also degrade system performance. Detectors and PMT's are enclosed in 1-mm-thick mumetal shields. Magnetic fields up to 10^{-2} T have no effect on PMT output, but larger fields saturate the shield and significantly degrade PMT gain.

Energy resolution has been determined for the system with each of the scintillators listed in Table 1 at both low and high data rates. The resolutions were determined by exposing each system to 2.5- and 14-MeV neutrons generated by the Rotating Target Neutron Source (RTNS). In each case, a conical target was used on the RTNS, and the detectors were placed at 100° relative to the 400-keV deuteron beam to minimize energy dispersion of neutrons from the source. Source dispersion was also reduced by dropping deuteron-beam energy from 400 to 200 keV for the Ti-D target. As a result, source energy dispersion was estimated to be less than 75 keV in all cases. Pulse-height data were obtained at data rates (measured at the constant-fraction discriminator output) ranging from 2×10^4 to 1.2×10^6 counts/s. Generally about half these events were identified as γ -ray interactions.

Fig. 5. Circuit diagram of high-rate voltage-divider base on RCA 8850 photomultiplier tube.

Fig. 6. Block diagram of neutron spectrometer electronics. Dashed boxes show units to produce pile-up rejection and cross-over time distribution.

Fig. 7. Oscilloscope trace of signal at the inspection port of the pulse-shape discriminator. Data rate is 4×10^5 countr/s, and two cross-over time groups are clearly resolved.

Fig. 8. PSD error rate as a function of data rate. Upper curve shows the percentage of γ -ray events incorrectly identified as proton events when no pile-up rejection is used; lower curve shows this percentage when pile-up rejection is used.

Fig. 9. Unfolded neutron spectra obtained with 2-cm-diameter $\times$ 1-cm NE213 detector at low rates (0.2 to 1×10^5 counts/s): (a) 2.5-MeV source, (b) 14-MeV source.

All pulse-height spectra were unfolded using the NUTSPEC⁹ unfolding code, and the energy resolution (FWHM) of the spectral peak was determined. Data obtained at rates above 7×10^5 counts/s showed very significant pulse pile-up and resolution loss, as well as high PSD error rates. At low data rates, the energy resolution in the best cases was 150 keV at 2.5 MeV and 550 keV at 14 MeV. Figure 9 shows unfolded spectra that are more typical of these data, taken at rates between 2 and 10×10^4 counts/s. Figure 10 shows unfolded spectra that are typical of data taken at high rates, in the range 4 to 6×10^5 counts/s. Energy resolutions obtained with each detector system are indicated in Table 1.

Finally, Fig. 11 shows D(d,n) and T(d,n) spectra obtained during a 1.0-s irradiation at data rates between 4 and 5×10^5 counts/s. The spectra shown are typical of many such runs taken on different days.

Conclusion

The neutron spectrometer/camera described here has been assembled and partially characterized. Spectrum measurements have been made both with the scintillator located in the pinhole assembly of Figs. 1 and 2 and with the pinhole assembly removed. No

Fig. 10. Unfolded neutron spectra obtained with 2-cm-diameter $\times$ 1-cm NE213 detector at high rates (4 to 6×10^5 counts/s): (a) 2.5-MeV source, (b) 14-MeV source.

differences in these spectra were observed for neutron energies above about 2 MeV with a 14-MeV source. This system has been used to obtain neutron spectra in periods as short as 1.0 s and will probably function effectively down to periods of 0.2 to 0.3 s. The system could be gated to measure spectra during much shorter time intervals (a few milliseconds), but data would have to be accumulated over many such windows, for a total acquisition time of about 200 to 500 ms, to obtain unfolded spectra reasonably free of oscillations.

The system described here has several virtues: The spectrometer is assembled from commercially available equipment, except for the PMT voltage divider, and the pinhole is constructed from readily available and easily worked materials. Spatial resolution obtained by imaging the neutron source is adequate for most magnetic-confinement experiments and should allow discrimination against neutron sources outside the plasma. Energy resolution obtained is adequate to distinguish D(d,n) and T(d,n) sources in the plasma from other sources. An unambiguous measurement of thermonuclear neutron yield in the plasma should be possible with this system.

There are nevertheless a number of significant limitations in the system described here. First,

Fig. 11. Unfolded neutron spectra obtained during a 1.0-s irradiation: (a) 2.5-MeV source, (b) 14-MeV source.

this system does not tolerate large data-rate variations. Data rates exceeding 6×10^5 counts/s significantly degrade the pulse-height spectra and unfolded results. On the other hand, because about 10^5 recoil proton events are required for analysis, low data rates require a long acquisition time and must continue over several plasma pulses. This need not be a problem if the neutron yield is reasonably stable and predictable, because the system efficiency scales with the pinhole aperture size and approximately with the volume of the NE213 scintillator. An appropriate choice of these dimensions could be made to assure a data rate between 3 and 6×10^5 counts/s. A lower limit on detector dimensions is imposed by the proton range in the scintillator (0.1 mm at 2.5 MeV, 2 mm at 14 MeV) and an upper limit is imposed by the desired spatial resolution. If the neutron yield is not stable and predictable, then the dimensions must be chosen so that the maximum data rate will not be exceeded. For the experiments described here, the neutron intensity at the detector (at high count rates) is indicated in Table I.

Finally, the energy resolution for this system is adequate for D(d,n) and T(d,n) yield measurements and the elimination of most interferences. However, it is clear from Eqs. (1) and (2) that ion temperature can be determined from neutron spectral width only if the ion temperature is greater than about 20 keV for a deuterium plasma or about 45 keV for a deuterium-tritium plasma. Experiments at lower temperature, those in which non-Maxwellian ion-energy distributions occur, or those in which a significant neutron yield is produced in the plasma by neutral-beam injection will require significantly better energy resolution.

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