Review of
Scientific Instruments

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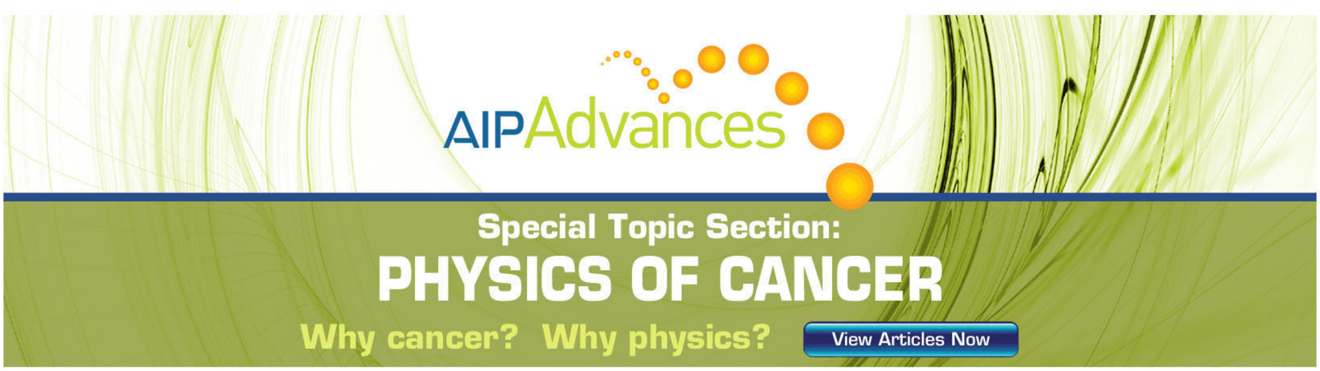
Citation: Rev. Sci. Instrum. **83**, 10E124 (2012); doi: 10.1063/1.4739410
View online: http://dx.doi.org/10.1063/1.4739410
View Table of Contents: http://rsi.aip.org/resource/1/RSINAK/v83/i10
Published by the American Institute of Physics.



Neutron field parameter measurements on the JET tokamak by means of super-heated fluid detectors[a)]

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(Presented 9 May 2012; received 4 May 2012; accepted 11 July 2012; published online 2 August 2012)

The neutron field parameters (fluence and energy distribution) at a specific location outside the JET Torus Hall have been measured by means of super-heated fluid detectors (or "bubble detectors") in combination with an independent, time-of-flight, technique. The bubble detector assemblies were placed at the end of a vertical line of sight at about 16 m from the tokamak mid plane. Spatial distributions of the neutron fluence along the radial and toroidal directions have been obtained using two-dimensional arrays of bubble detectors. Using a set of three bubble detector spectrometers the neutron energy distribution was determined over a broad energy range, from about 10 keV to above 10 MeV, with an energy resolution of about 30% at 2.5 MeV. The very broad energy response allowed for the identification of energy features far from the main fusion component (around 2.45 MeV for deuterium discharges). [http://dx.doi.org/10.1063/1.4739410]

I. INTRODUCTION

The measurement of the neutron field parameters around a large fusion machine is important for both radiation protection and nuclear facility de-commissioning. Neutron energy distribution and neutron fluence in such cases are usually estimated by means of complex neutron transport calculations. These calculations can be validated by neutron measurements made at specific locations around the fusion machine. A measuring method that provides absolutely calibrated data is highly recommended. A method that is not sensitive to the ubiquitous gamma radiation background would provide an additional incentive.

The superheated fluid detectors (also known as "bubble detectors") have characteristics that make them useful for such an application. They show high neutron detection efficiency (counts/unit fluence) that ranges from about 4×10^{-2} to 4×10^{-5} and a threshold-type energy response almost roughly flat over a broad energy range (10's keV to 10's MeV). The bubble detectors are practically non-sensitive to gamma-radiation. They also provide a good spatial resolution (sub-centimetre resolution in the image plane).

The super-heated fluid detectors, SHFD's, are suspensions of metastable droplets which readily vaporise into bubbles when they are nucleated by radiation interactions.[1] The SHFD's have a threshold-type energy response with the threshold energy depending on droplet composition, detector operating temperature, and detector operating pressure. For a standard bubble detector such as the BD-PND type,[2] the energy response is approximately flat within the range 0.1–15 MeV. Using detectors with different energy thresholds, a bubble detector spectrometer (BDS) (Ref. 2) is obtained. A bubble detector spectrometer consists of 36 neutron detectors that cover a broad energy range from 0.01 to 20 MeV and provide six energy thresholds in this range. Six detectors are used for each of the following energy thresholds: 0.01, 0.1, 0.6, 1.0, 2.5, and 10.0 MeV. The energy thresholds define six energy bins: E1: 10–100 keV, E2: 100–600 keV, E3: 0.6–1.0 MeV, E4: 1.0–2.5 MeV, E5: 2.5–10.0 MeV, and E6: 10.0–20.0 MeV. The energy resolution at 2.5 MeV is about 30%.

II. EXPERIMENTAL SETUP

The neutron field parameters (fluence and energy distribution) at a specific location outside the JET Torus Hall has been measured by means of super-heated fluid detectors in combination with an independent, time-of-flight, technique. The bubble detector assemblies were placed on a vertical line of sight, behind the Time-Of-Flight Optimized Rate (TOFOR) (Ref. 3) spectrometer at the end of the JET KM11 neutron diagnostics. The field-of-view for both detection systems can be changed by means of a variable pre-collimator located on top

a)Contributed paper, published as part of the Proceedings of the 19th Topical Conference on High-Temperature Plasma Diagnostics, Monterey, California, May 2012.

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c)See the Appendix of F. Romanelli *et al.*, Proceedings of the 23rd IAEA Fusion Energy Conference 2010, Daejeon, Korea.

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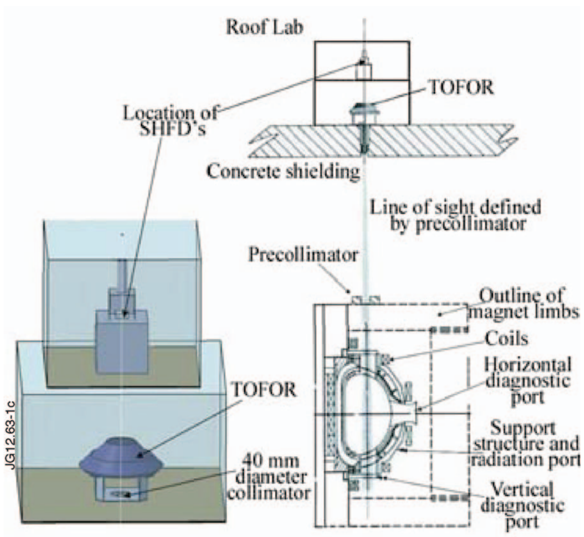

FIG. 1. Experimental setup for SHFDs neutron measurements at JET.

of the JET tokamak. The distance from the bubble detectors location to the entrance of the 40 mm diameter collimator in the concrete shielding is approximately 3.5 m. The distance to the torus mid-plane is a further approximately 17.5 m (Fig. 1).

III. DETERMINATION OF NEUTRON FIELD PARAMETERS

A. Neutron fluence measurements

By using high sensitivity DEFENDER type[2] detectors the spatial distribution of the neutron beam propagating along the collimated vertical line-of-sight of the KM11 diagnostics was obtained. An array of six DEFENDER type detectors was used for the JET pulse number (JPN) 72737. The spatial distribution of the neutron fluence in the detector array plane along the radial and toroidal directions was obtained (Fig. 2). The integrated fluence was compared with the TOFOR neutron flux and a 0.99 correlation factor was found.[4]

The radial distribution of the neutron fluence was also obtained in measurements done on a set of six JET discharges using two-dimensional arrays containing up to 10 BD-PND-type detectors. The individual detector cross-section is approximately 15 × 2 cm^2. The measurements have been done using various openings of the TOFOR pre-collimator: "fully open" (pre-collimator opening ∼100%), ∼60% open and ∼40% open (Fig. 3). The estimated error for the experimental fluence values is 25%. It includes 20% absolute calibration accuracy and an average counting error of 15%. The curves in

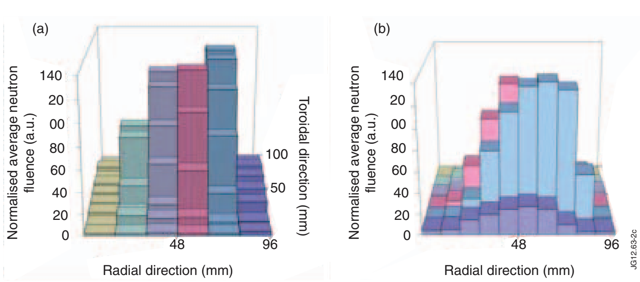

FIG. 2. Spatial distribution of the neutron fluence. (a) Radial distribution; (b) Toroidal distribution.

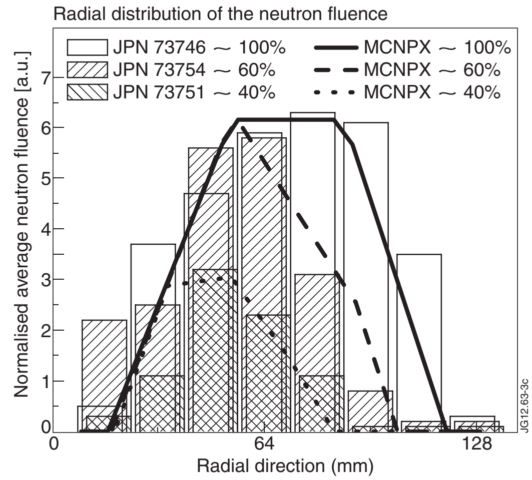

FIG. 3. Radial distribution of the neutron fluence for three different pre-collimator openings.

Fig. 3 represent fluence values resulting from neutron transport calculations done by means of the MCNPX code.[5] A flat neutron emission profile was assumed in the tokamak mid-plane.

B. Neutron energy distribution measurements

Three BDS spectrometric sets with different energy sensitivities have been used for neutron energy distribution measurements on a series of JET pulses.

In the analysis of the energy distribution experimental data a "symmetry parameter (SP)" is defined in terms of the number of neutrons in energy bins E4 and E5, as follows: SP = N5/(N4 + N5). For a purely Gaussian distribution SP = 0.5. A value lower than 0.5 indicates the presence of scattered neutrons in the energy distribution.

As a first step in the processing of the experimental data a "spectral stripping" technique is used for the de-convolution of the energy distribution with the distribution being obtained as a six energy bin histogram. The main assumption is that the fluence per unit energy is constant within one energy bin. The energy distribution obtained from the data of spectrometer BDS_B by the spectral stripping technique is shown in Fig. 4. The symmetry parameter is 0.38 and the distribution shows clearly the presence of neutrons with energy above 10 MeV emitted by a deuterium plasma. This confirms the emission of triton burn neutrons (energy 14 MeV) in these high-performance (high neutron yield) JET discharges. This is also independently confirmed by the Si diode neutron detectors (KM7 14 MeV neutron yield monitors) which measured 14 MeV neutron yields of about 10^{14} neutrons for these discharges.

For these measurements the large number of neutrons (20%) in the energy bin E1 (10–100 keV) could be explained by non-fusion nuclear reactions such as photo-nuclear reactions induced by high energy electrons generated in the disruption which occurred during the JET pulse 76794.

A further analysis of the energy distribution experimental data was done by a method based on the "expected energy distribution." This refers to the energy distribution expected to be obtained for the neutrons produced by a thermal deuterium

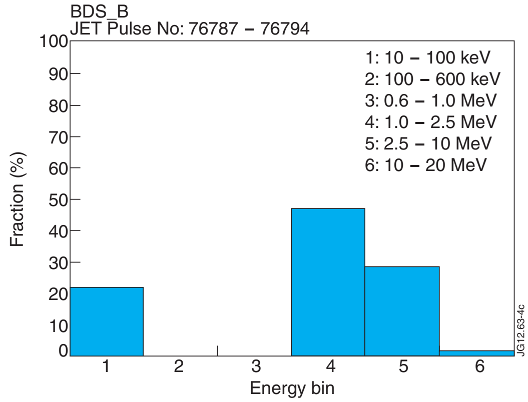

FIG. 4. Neutron energy distribution obtained by the "spectral stripping" method.

plasma. The main assumptions are:

- –The neutrons have a Gaussian distribution around 2.5 MeV (this is experimentally obtained from the time-of-flight spectrometer, TOFOR);
- –The energy bins E4 and E5 see the full TOFOR distribution;
- –There should be no scattered neutrons with energy above those of the 2.5 MeV Gaussian;
- –The scattered neutrons are assumed to be uniformly distributed within lower energy bins.

The measurement made by means of the BDS_A spectrometer has been processed by means of the expected energy distribution method. The Gaussian fit to the time-of-flight (TOFOR spectrometer) spectrum integrated over three JET pulses is shown in Fig. 5. The Gaussian distribution parameters were: Eo = 2.5 MeV and FWHM = 0.455 MeV.

The energy distribution obtained from the BDS_A spectrometer measurement using the expected energy distribution is shown in Fig. 6. The symmetry parameter for the expected (Gaussian) energy distribution shown in Fig. 6 is 0.44. The energy bins 4 and 5 cover the TOFOR neutron spectrum. From the TOFOR energy distribution 88% are fusion neutrons and 12% are scattered neutrons.[5] The 15% neutrons seen by the BDS spectrometer at low energies (bin E1) cannot be accounted for by the TOFOR spectrometer. The explanation proposed above for the BDS_B measurements is no longer valid for these disruption-free JET pulses. The actual origin of these "excess" neutrons is still to be identified.

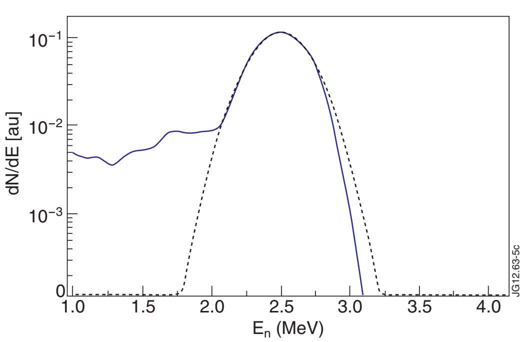

FIG. 5. Gaussian fit to the TOFOR neutron spectrum integrated over JPN76504, 76506, and 76507. (Solid blue curve: TOFOR neutron spectrum; Dashed curve: Gaussian fit).

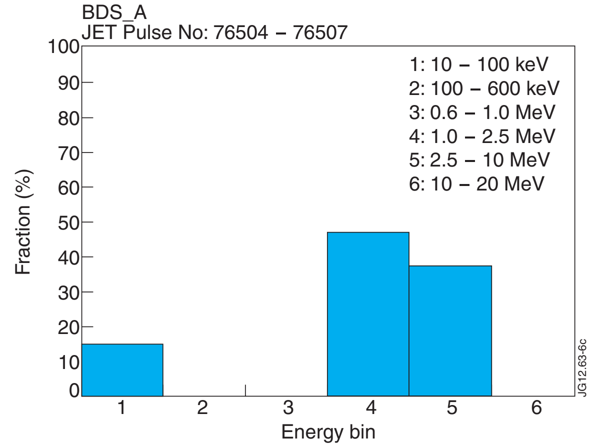

FIG. 6. Neutron energy distribution obtained by the "expected (Gaussian) distribution" method.

IV. CONCLUSIONS

Spatially resolved distributions of the neutron fluence along the radial and toroidal directions have been obtained at the end of the JET KM11 neutron line-of-sight by means of superheated fluid detectors ("bubble detectors"). Neutron fluences from neutron transport calculations done for an assumed flat emission profile show reasonable agreement with the experimental data.

The neutron energy distribution over a wide energy range (10's keV to over 10's MeV) was obtained by means of a set of three bubble detector spectrometers (a total of 108 detectors). The presence of neutrons emitted from a deuterium plasma with an energy above 10 MeV was clearly shown. This confirmed the emission of triton burn neutrons (energy 14 MeV) in high performance JET deuterium discharges. In some measurements the fraction of low energy neutrons was found to be higher than that which could be explained by scattering processes. The origin of these "excess" neutrons is still to be identified.

ACKNOWLEDGMENTS

All detectors used in this work were manufactured and calibrated by Bubble Technology Industries (BTI), Chalk River, Canada. Particular thanks are due to Robert Noulty of BTI for his continuous help and very valuable support. This work, supported by the European Communities under the contract of Association between EURATOM and MEdC, was carried out within the framework of the European Fusion Development Agreement. The views and opinions expressed herein do not necessarily reflect those of the European Commission.

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