TOKAMAK NEUTRON DIAGNOSTICS BASED ON THE SUPER-HEATED FLUID DETECTOR (SHFD)

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1. Introduction

Super-heated fluid detectors, SHFFD's (also known as "bubble detectors") are suspensions of metastable droplets which readily vaporise into bubbles when they are nucleated by radiation interactions [1-2]. The active detecting medium is in the form of microscopic (20-50 μm) droplets suspended within an elastic polymer. The phenomenon of neutron detection by a SHFD is a mixture of nuclear interactions (neutron collisions with nuclei of the active medium), thermodynamic behaviour of the detecting medium (the super-heated fluid), and the mechanical response of the elastic polymer. If sufficient energy is transferred from the colliding neutron to the nucleus of one of the elements in the composition of the active medium, the recoil nucleus will initiate the generation of a vapour embryo of sub-micron dimensions. Under proper conditions (that depend on the thermodynamics of the active medium) the vapour embryo will lead to the vaporisation of the super-heated droplet with the subsequent expansion into a macroscopic (0.2 – 0.5 mm) bubble.

The SHFD's have a threshold-type energy response with the threshold energy depending on droplet composition, detector operating temperature, detector operating pressure. For a standard bubble detector like the BD-PND(*) type, the energy response is approximately flat within the range 0.3-15 MeV. Using detectors with different energy thresholds, a bubble detector spectrometer (BDS(*)) is obtained.

The main aim of the project for 2009 was the determination of the neutron field characteristics in high performance discharges (experiment code D-1.5.2 within the JET Work Programme) during the JET experimental campaign C26 using techniques based on the bubble detectors, indium activation and time of flight [3]. The D-1.5.2 experiments have been scheduled to be carried out as parasitic experiments during the JET campaign C26. The main (host) experiment was chosen that on "Steady-state scenarios at high beta normalised" [4] which employs high neutral beam powers (~20MW) and produces neutron yields in the range (3-5) x10^{16} neutrons. Some other high neutron yield experiments have also been used as the main experiment.

This paper is a report on the data processing and analysis of the neutron energy distribution measurements carried out by means of bubble detectors spectrometers.

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1. (*) All detectors used in this work were manufactured and calibrated by Bubble Technology Industries, Chalk River, Canada
2.

2. Neutron energy distribution measurements

A series of neutron measurements have been done by means of the super-heated fluid detectors during campaign C26 (January - April 2009) within the D-1.5.2 experiment. These included measurements on neutron fluence, neutron energy distribution and time-resolved neutron fluence spatial distribution [5]. The bubble detector measurements have been done simultaneously with other two independent techniques: indium activation and time of flight. Only neutron energy distributions measured by means of the bubble detectors will be reported here.

The neutron measurements have been done at the end of the KM11 neutron diagnostics line-of-sight, above the TOFOR neutron time-of-flight spectrometer (Figure 1). The distance from the SHFD location to the TOFOR first (start) detector is approximately 3.5m and the distance to the torus mid-plane is approximately 20m. The SHFD's have been positioned to cover the "neutron spot" determined in the previous measurements using (high sensitivity) DEFENDER(*)-type bubble detectors [6].

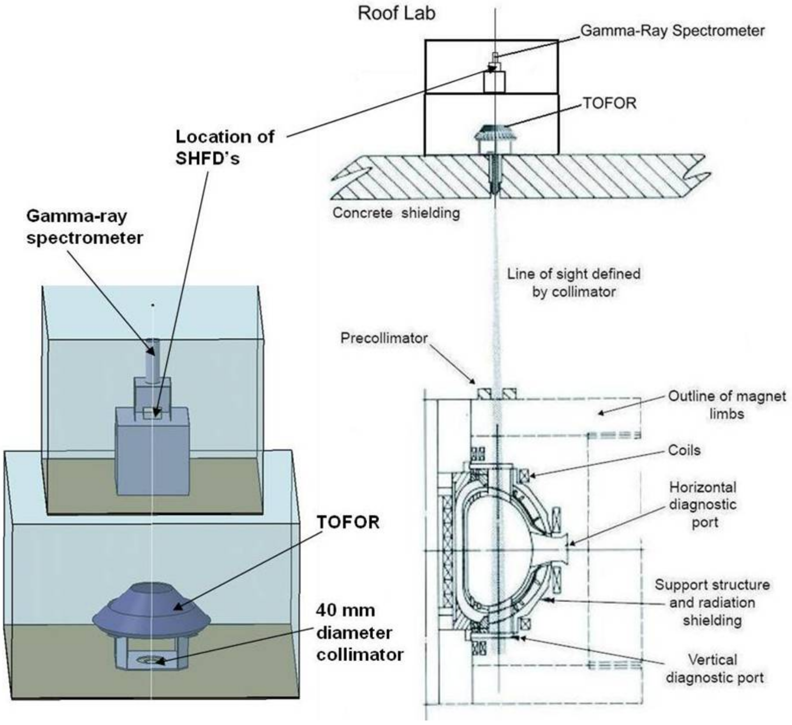

Figure 1. Experimental setup for SHFD neutron measurements along the JET KM11 Line-of-Sight.

The BDS bubble detector spectrometer consists of 36 neutron bubble detectors to cover a broad energy range (0.01 – 20 MeV) and provides six energy thresholds in that range. Six detectors are used for each of the following energy thresholds: 0.01, 0.1, 0.6, 1.0, 2.5, 10.0 MeV. The neutron energy response is represented in Figure 2. The energy thresholds define six energy bins as follows: 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; E6: 10.0-20.0 MeV.

Five different spectrometric sets (BDS type) have been used for neutron energy distribution measurements on forty-one JET pulses.

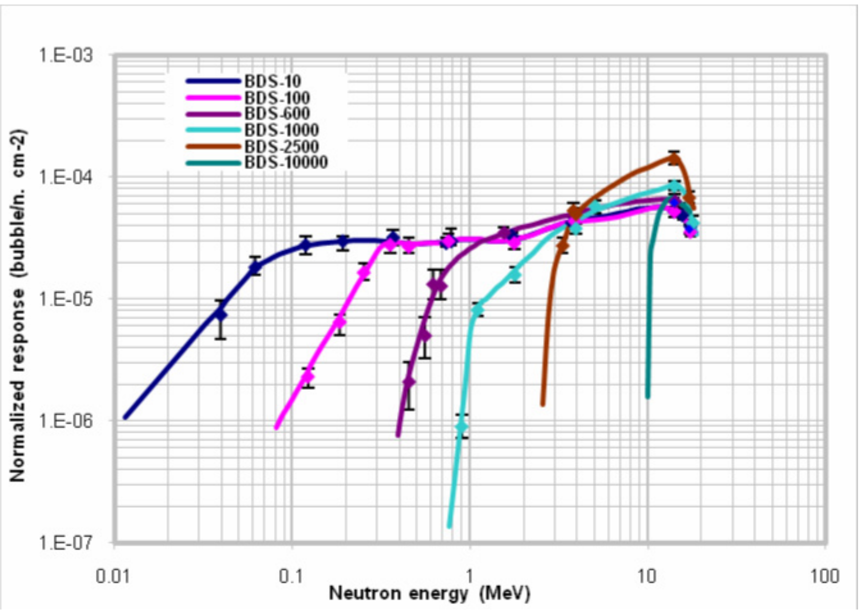

Figure 2. Bubble Detector Spectrometer (BDS) neutron energy response.

3. Neutron energy distribution data processing and analysis

Three different techniques of increasing complexity have been used for the processing of the neutron energy distribution data obtained by means of the bubble detector spectrometer.

A first method ("uniform response") is based on the following assumptions:

- All detectors have a constant identical energy response;

- All detectors have equal sensitivities.

This method allows for a fast qualitative comparison between different measurements.

A second method is based on the "spectral stripping" technique for the de-convolution of the energy distribution. The energy distribution is obtained as a six energy bin histogram. The main assumption is that the fluence per unit energy is constant within one energy bin. The method leads to error accumulation as the "stripping" proceeds from high to low energies.

A third method is based on the "expected energy distribution". The "expected distribution" refers to the energy distribution expected to be obtained for the neutrons produced by a thermal deuterium 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 bin E4 (defined by detectors BDS1000) sees the full TOFOR energy 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.

In the analysis of the energy distribution experimental data a “control parameter (CP)” is defined in terms of the number of neutrons in energy bins E4 and E5, as follows: CP = N5/(N4+N5). For a purely Gaussian distribution CP=0.5. A value lower than 0.5 shows the presence of scattered neutrons in the energy distribution. A value higher than 0.5 can be obtained either by a shift of the mean energy distribution to values higher than 2.45 MeV, or by the presence of neutrons generated by other processes than the DD fusion.

Figure 3 shows the “uniform response” distributions for measurements done with three BDS spectrometric sets.

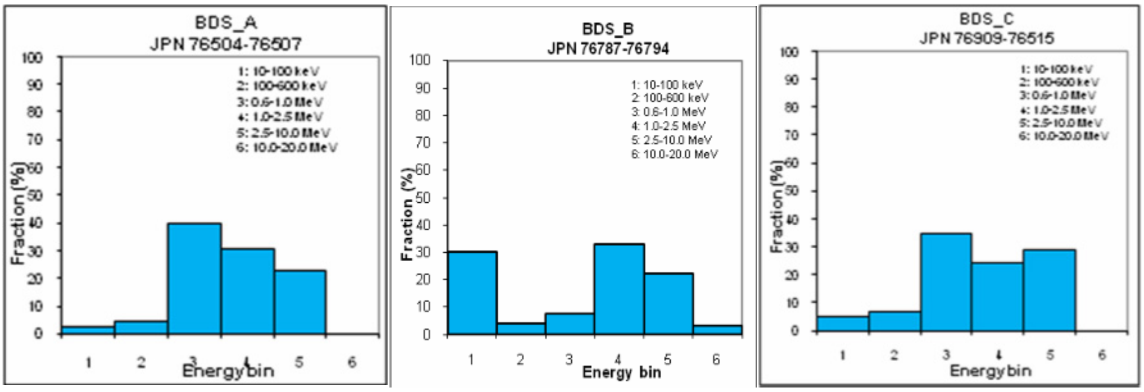

Figure 3. “Uniform response” energy distributions

The control parameter for the three “uniform response” distributions is: 0.42, 0.41 and 0.54, respectively. The distribution measured by the BDS_B spectrometer 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 JET discharges. This is also independently confirmed by the Si diode neutron detectors (KM7 14 MeV neutron yield monitors) [7].

For the same measurements the large number of neutrons 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 in one of the measured JET pulses (JPN 76794).

The energy distributions obtained by the “spectral stripping” method are shown in Figure 4.

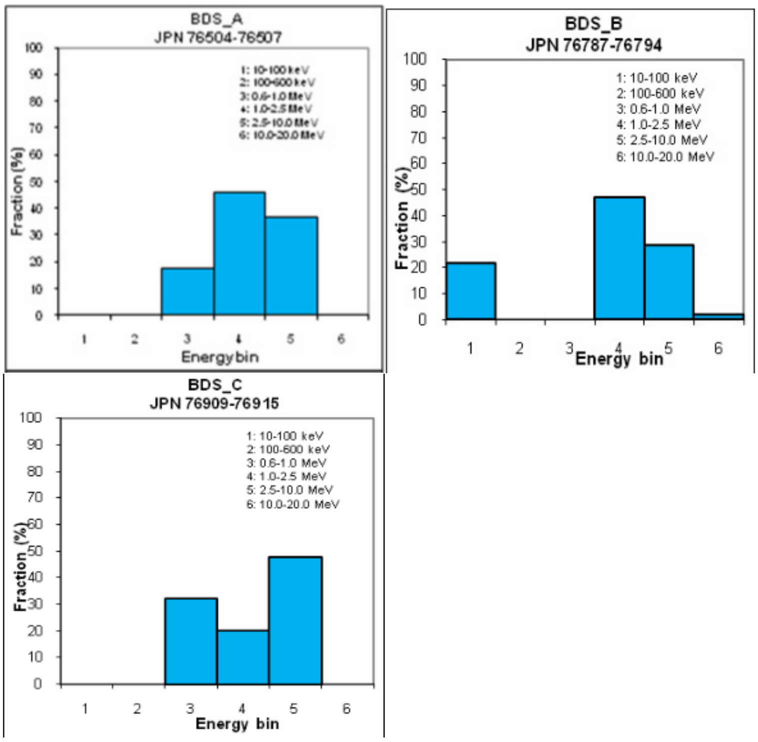

Figure 4. "Spectral stripping" energy distributions

The control parameters for the "spectral stripping" distributions are: 0.44, 0.38 and 0.71, respectively. The interpretation of the measurements based on the "uniform response" procedure remains valid.

The measurement made by means of the BDS_A spectrometer has been processed also by means of the "expected energy distribution" method.

The Gaussian fit to the time-of-flight (TOFOR spectrometer) spectrum integrated over three JET pulses [8] is shown in Figure 5. The Gaussian distribution parameters were: Eo=2.5 MeV and FWHM=0.455 MeV.

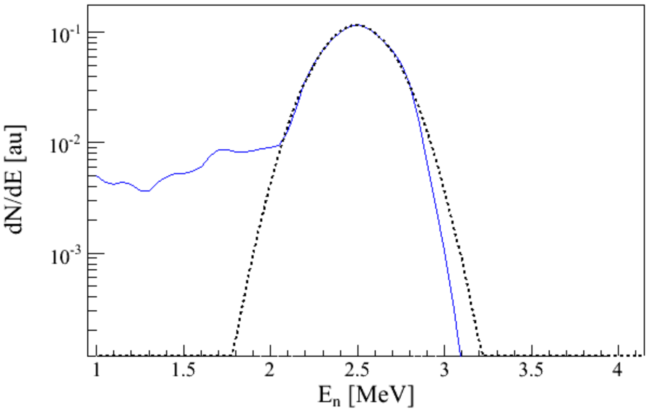

Figure 5. Gaussian fit to the TOFOR neutron spectrum integrated over shots JPN76504, 76506 and 76507. (Solid blue curve: TOFOR neutron spectrum; Dashed curve: Gaussian fit)

The energy distribution obtained from the BDS_A spectrometer measurement using the "expected energy distribution" is shown in Figure 6.

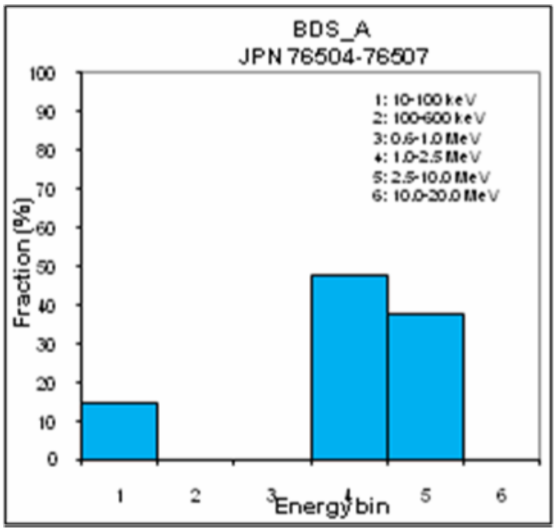

Figure 6. Neutron energy distribution obtained by the "expected (Gaussian) distribution" method.

The control parameter for the "expected (Gaussian) energy distribution" shown in Figure 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 [8]. The 15% neutrons seen by the BDS spectrometer at low energies cannot be accounted for by the TOFOR spectrometer.

4. Conclusion

Three different techniques of increasing complexity have been used for the processing of the neutron energy distribution data obtained by means of the bubble detector spectrometer: "uniform response", "spectral stripping" and "expected energy distribution". Using these methods the following main results have been obtained:

- The presence of neutrons emitted from a deuterium plasma with an energy above 10 MeV was clearly shown. This confirms the emission of triton burn neutrons (energy 14 MeV) in high performance JET deuterium discharges.

- The fraction of low energy neutrons is in some discharges higher than that which could be explained by scattering processes. This could be explained by other neutron emitting reactions from the tokamak machine (such as photonuclear reactions, triggered by high energy electrons generated in a plasma disruption).

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[7] **S. Popovichev,** private communication.

[8] **M. Gatu Johnson,** private communication.