TOKAMAK NEUTRON DIAGNOSTICS BASED ON THE SUPERHEATED FLUID DETECTOR (SHFD)

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1. Introduction

Neutron diagnostic techniques based on a new type of detector (the superheated fluid detector –SHFD) have been evaluated and found to be of particular interest for the characterisation of the neutron emission from the European tokamak machines (JET, in particular, but it could be applied to other machines, e.g., FTU). The proposal for the development of SHFD technique for tokamak devices followed from the successful application of this technique on pulsed plasma devices [1-3].

One detection configuration that uses the SHFD in a spectrometer mode is able to measure the neutron fluxes and spectra over a broad energy range (0.01-15 MeV) thus allowing the study of the various sources of the observed neutron emission (besides those due to DD and DT fusion). This is particularly of importance for JET during ICRF heating scenarios when the nuclear reactions between the accelerated light ions and bulk fuel ions (e.g. $T(p,n)^3He$ fusion reaction) main or plasma impurities (e.g. ^9Be, ^{12}C) could give a strong contribution to the neutron yield. For the proposed full tritium experiments (FTE) on JET, carried out either with a C (FTE1) or a Be (FTE2) wall, the neutron yield would be dominated by such processes. In addition, the non-fusion (photoneutron) neutron emission arising from runaway electron generation during plasma disruption can be also successfully addressed.

Another SHFD detection configuration, the Threshold SHFD Stack (TSS), can be used in a manually (FTU) or pneumatically (JET) operated capsule arrangement; this provides a unique procedure for cross-calibration with the foil activation method.

An advanced SHFD Detection Unit (SHFD-DU), based on customer designed, very high sensitivity detection elements should be able to provide neutron fluxes and spectra with millisecond time resolution. An adequate number of multi-threshold SHFD-DU's installed on the JET neutron cameras could represent a highly versatile neutron diagnostics set-up installed on a tokamak, at a cost that should be at least one order of magnitude lower than any feasible extrapolation of the existing techniques. Such a diagnostics could provide energy-resolved neutron emission profiles on a millisecond time scale.

In its simplest form (e.g., commercially available bubble detectors) the SHFD technique is able to measure directly the neutron dose around the machine, while still providing valuable scientific data on neutron fluence and spectrum. No other single neutron detection technique is capable of providing such a broad range of physical information on the fusion plasma neutron field.

2. Development of the SHFD technique for tokamak neutron diagnostics

2.1 Tests of the high sensitivity bubble detectors on a pulsed plasma neutron generator

A new type of bubble detector (a superheated fluid detector), the DEFENDER™, was tested within a neutron diagnostics experimental setup on a pulsed plasma neutron source, the NX2 plasma focus device at the Nanyang Technological University (NTU), Singapore. This was done within the international collaboration agreement between the National Institute for Laser, Plasma and Radiation Physics, Bucharest and the NTU, Singapore. The DEFENDER™ detector was recently developed and commercialised by BTI, Canada [4], and it is characterised by a very high sensitivity (a factor of about 30 higher than the standard detectors) to fast neutrons (energy above 100 keV). Together with its particular energy response this high sensitivity allows for the development of improved neutron diagnostics for tokamak plasmas.

The SHFD neutron diagnostics experiments carried out on the NX2 neutron source involved a set of four DEFENDER™ detectors and included the following measurements [5, 6]:

1. Relative calibration of the four detectors. The detectors were irradiated simultaneously, in identical conditions, by plasma emitted neutron pulses and their neutron responses were compared. The experiments pointed out differences in the relative detector response with respect to the absolutely calibrated values provided by the manufacturer. However, it was concluded that better controlled measurements (e.g., use of a collimated configuration and better statistics) were needed for a definite assessment of the SHFD behaviour.

2. Angular distribution of the neutron fluence (obtained on a single shot basis). The distribution of the neutron fluence was measured at four angles with respect to the neutron source axis: 0^o, 30^o, 60^o and 90^o. The experimental results have proved the advantage of the increased sensitivity by allowing a better source-detector geometry.

3. Reproducibility of the neutron yield at high repetition rate operation. The plasma neutron generator was operated at 1 Hz repetition rate.

4. Bubble detector response time. The response time of the DEFENDER™ detector was tested by using the short plasma emitted neutron pulses and a high-speed video camera. It was found that the bubble growth time (and thus the corresponding detector response time) was shorter than 5 ms (the maximum time resolution of the video camera).

A better designed test experiment for the study of the SHFD parameters was prepared to be performed on the IPF-2/20 pulsed plasma neutron source at NILPRP. The experiment could not be performed until the end of 2005 due to the delay in funding for the acquisition of deuterium, and it is now planned for the second half of 2006. A new set of SHFD's has also been purchased meanwhile.

2.2 Calculation of the neutron response of a SHFD placed inside a shielding container

In order to design a collimated experiment for testing the response of shielded SHFD detectors to a point-like plasma neutron source a Monte Carlo transport calculation was performed. The calculations were done for an AmBe neutron source having a known spectrum (Figure 1a). The AmBe spectrum was discretised at 17 energy values (Figure 1b). The energy response of the SHFD (type BD-PND bubble detector) was taken as given by the manufacturer (Figure 2).

The material of the shielding was considered to be paraffin in two forms: pressed paraffin powder (simple manufacture of the shield) and solid paraffin (powder molten and solidified, a complicated manufacturing procedure). For the two cases the density of the paraffin was taken as 0.60 g/cm^3, and 0.93 g/cm^3, respectively.

The proposed experimental setup is presented schematically in Figure 3, with the two cases calculated: detector inside (Figure 3a) and outside (Figure 3b) the paraffin shield.

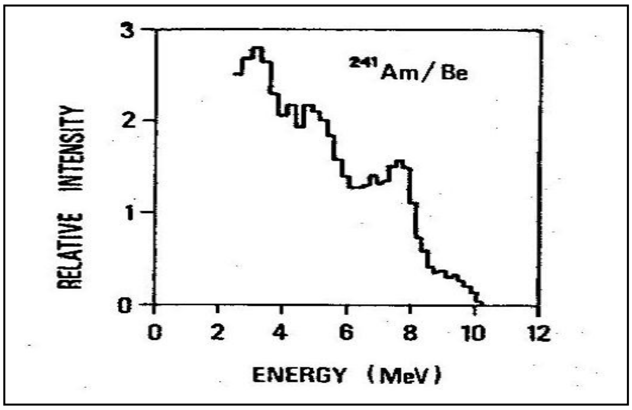


Figure 1a. AmBe neutron source spectrum

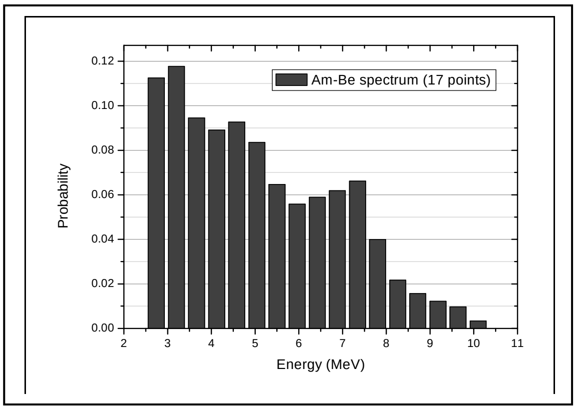


Figure 1b. Am-Be spectrum (discretised in 17 points)

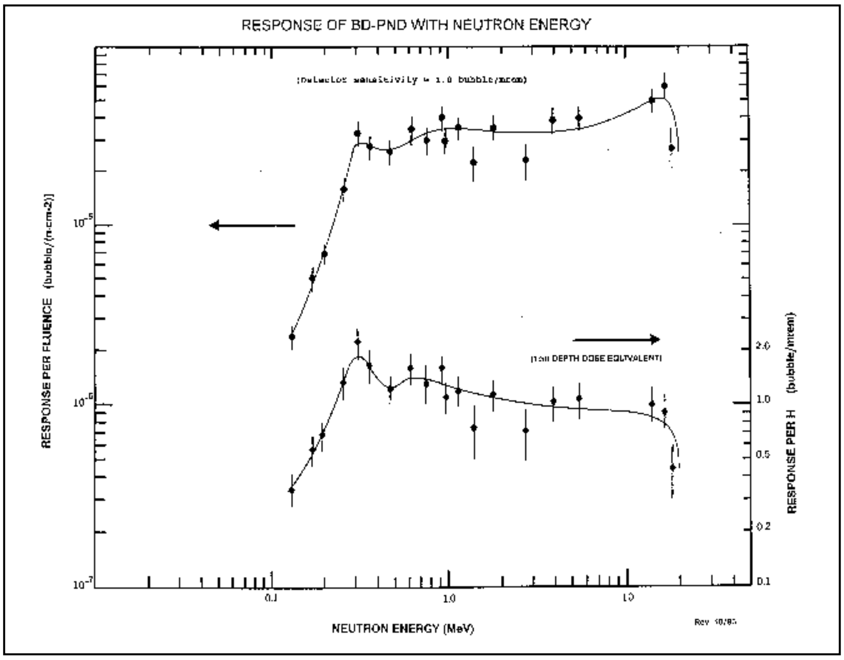
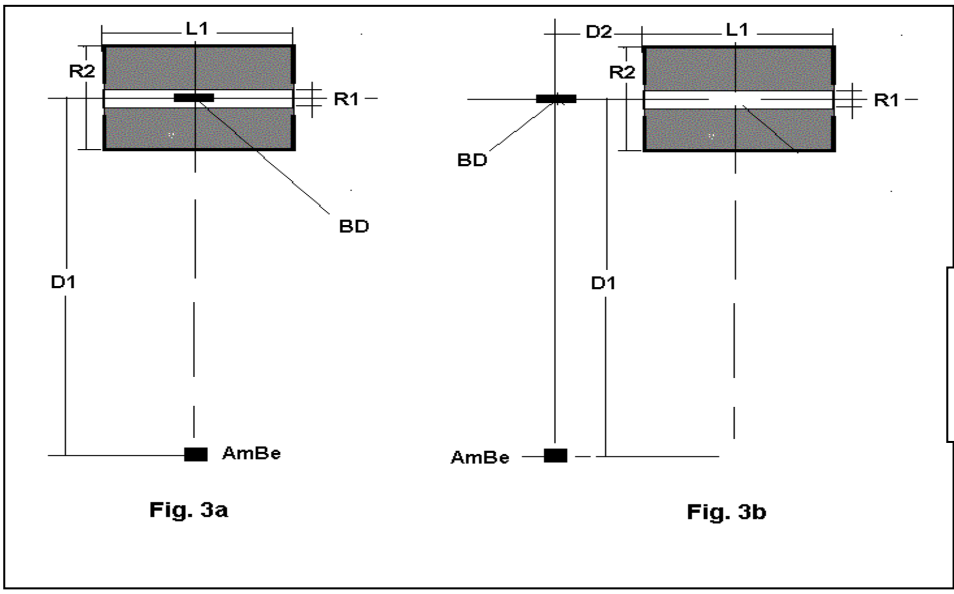


Figure 2. SHFD (type BD-PND) energy response



L1 =500
R2 =500
R1 =20
D1 = 3000
D2 =250

Figure 3a. SHFD (BD) inside the shield

Figure 3b. SHFD (BD) outside the shield

The neutron transport calculations have shown that a pressed powder paraffin shield will produce an attenuation of only 3.8×10^{-2}. A molten and solidified paraffin shield would produce an attenuation of 3.3×10^{-3}.

Based on the results of these calculations a set of paraffin neutron collimators were constructed.

Paraffin density 0.93

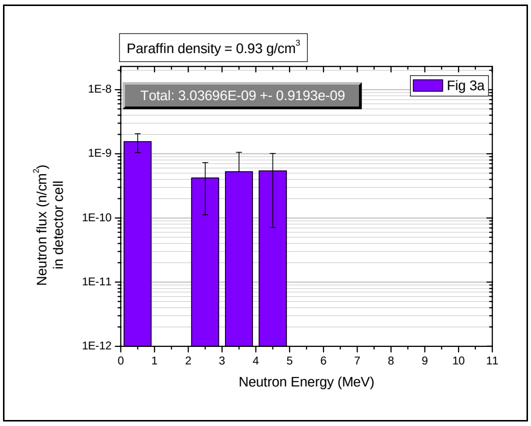


Figure 3a. Total: $(3.03696 \pm 0.9193)10^{-09}$

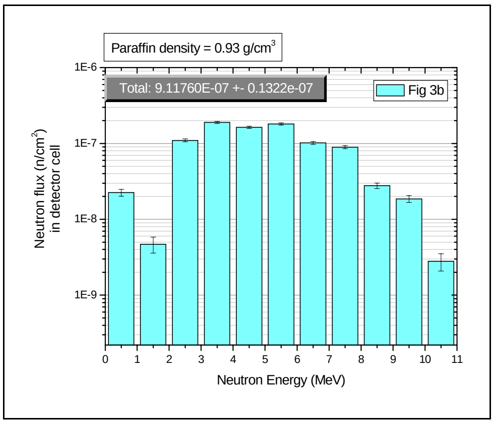


Figure 3b. Total: $(9.11760 \pm 0.1322)10^{-07}$

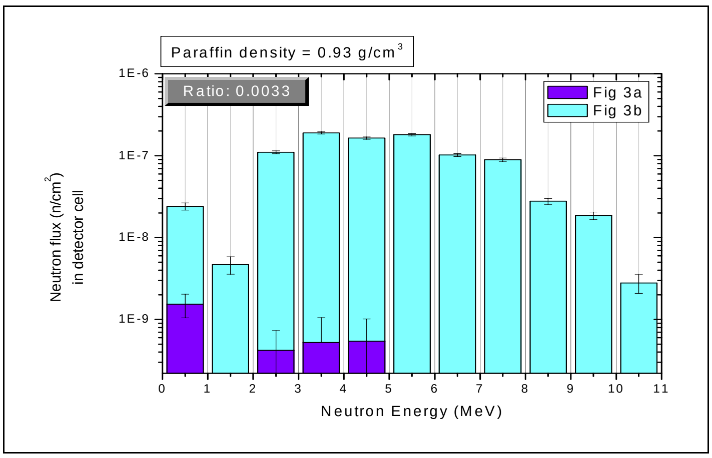


Fig 3a + 3b

$$\text{Ratio}=\frac{Fig3a}{Fig3b}=0.0033$$

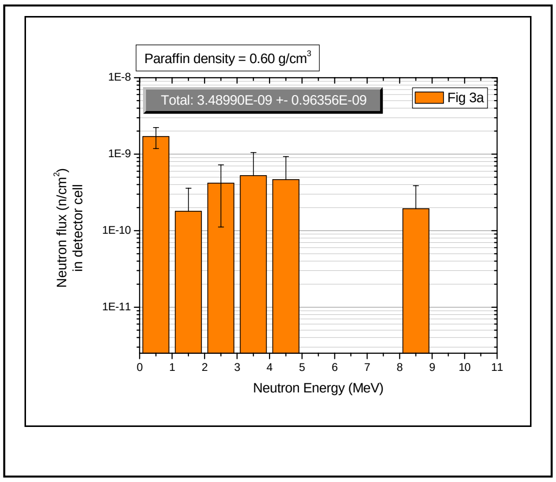


Figure 3a. Total: (3.48990 ± 0.96356)10^{-09}

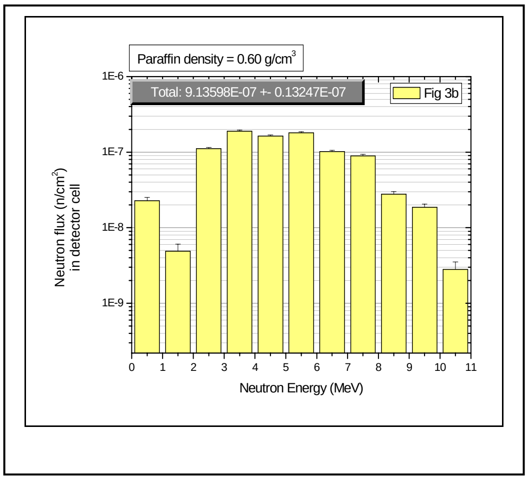


Figure 3b. Total: (9.13598E-07 ± 0.13247)10^{-07}

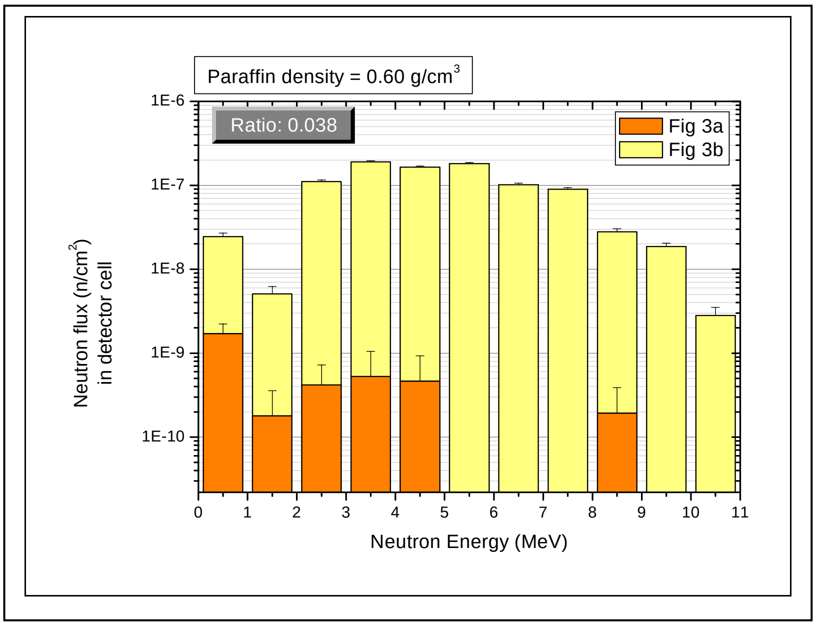


Fig 3a + 3b

$$\text{Ratio}=\frac{Fig3a}{Fig3b}=0.038$$

2.3 Conceptual design of a SHFD Detection Unit

The main components of the SHFD Detection Unit (SHFD-DU) are presented in the bloc diagramme of Figure 4.

The collimated neutrons are detected by the energy threshold superheated fluid detector (SHFD). The SHFD image is projected on an image capture device (a CCD or CMOS chip) whose data is acquired and (temporarily) stored locally. The image data is transferred by a high-speed data line to a remote, high capacity, image processing and analysis computer system. From the processed SHFD image the energy resolved neutron flux is determined with a time resolution limited by the SHFD response.

A simpler structure, similar to that presented in Figure 4, is proposed to be used as neutron flux monitors both on FTU, and possibly on JET. A commercially available high-speed (1 kHz image acquisition rate) CMOS digital camera will be used to capture and store the images of the SHFD's in the neutron flux monitors. The time-resolved neutron flux will be obtained by processing off-line the SHFD images. The neutron spectrum could be obtained on a shot-by-shot basis using SHFD's of different energy thresholds. A rather expensive system could also be considered in order to obtain time resolved spectra on a single discharge using only commercially available components: a number of fast CMOS digital cameras coupled to SHFD's having energy thresholds covering the energy spectrum of interest.

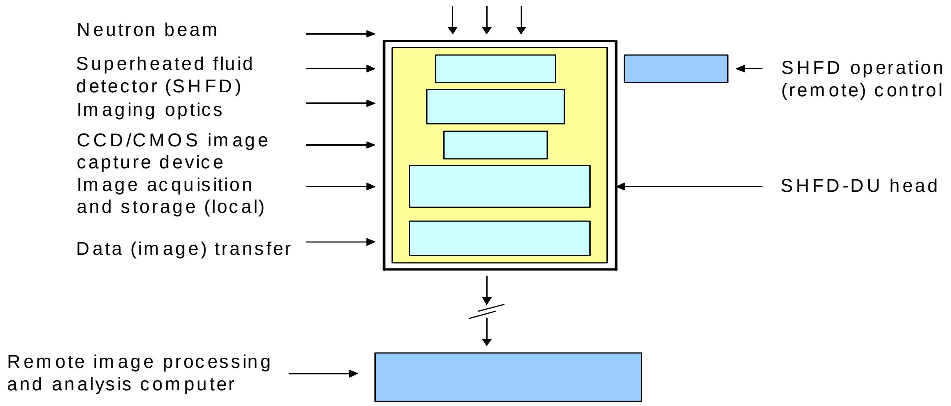


Figure 4. The structure of a SHFD Detection Unit (SHFD-DU) (one energy threshold channel, millisecond time resolution)

3. Proposals for the application of the SHFD neutron measurement technique

3.1. Proposal for neutron measurements by means of the SHFD technique on the FTU tokamak

The possibility of using the SHFD technique for the diagnostics of tokamak plasmas was analised and agreed upon with the ENEA-Frascati Association.

As a first step, neutron fluence measurements at a specific location on FTU were proposed. One such location was proposed to be at the place of the neutron activation detector. The SHFD measurements would provide the time-integrated (over one FTU shot), energy-integrated (above the detector threshold) value of the neutron fluence (n/cm^2) at that location. These measurements would allow a comparison of the two methods based on very different neutron interaction processes. It could have as a scientific result an improvement in the accuracy of the measurement of the neutron yield per discharge.

A second step would be aimed at the determination of the spatial distribution of the neutron fluence around the FTU tokamak. To this end, a set of SHFD's would be irradiated simultaneously, on one discharge, at various locations around the FTU machine. The results of the measurements could be used for various purposes: from the evaluation of the neutron dose around FTU to the analysis of the effects of non-thermal components of the reacting deuteron population in the FTU plasma. A set of four detectors (the new high sensitivity, DEFENDER type detectors recently introduced by BTI, Canada) is proposed to be used.

A further step in the measurements to be done on FTU would use would be to have the four detectors along the same irradiation channel, i.e. radially, at different distances away from the plasma. Such a measurement could be done in relation to the validation of neutron transport calculations.

The first step in these proposals for diagnostics on the FTU tokamak it was agreed to be done during the first half of November 2005. Unfortunately this was not possible due to the delay in funding. The set of four detectors used at the beginning of 2005 (purchased in November 2004 using non-EURATOM funding) would have been nearing their guaranteed life-time. A new set of SHFD's have been purchased at the end of 2005 and beginning of 2006.

3.2 Proposal for neutron measurements by means of the SHFD technique on the JET tokamak

Rationale

Neutron diagnostics techniques based on a new type of detector (the superheated fluid detector –SHFD) have been evaluated and found to be of particular interest for the characterisation of the neutron emission from the JET tokamak machine. The ability to measure the neutron fluxes and spectra over a broad energy range (0.01-15 MeV) allows studying the different sources of the observed neutron emission. This is particularly of importance during ICRF-only heating scenarios when the nuclear reactions between the accelerated light ions and bulk fuel ions (e.g. $T(p,n)^3He$ fusion reaction) or plasma impurities (e.g. ^9Be, ^{12}C) may contribute to the neutron yield significantly. SHFD detectors can make spectrally resolved measurements also at low energies where none of the existing JET neutron spectrometers are useful.

General Proposal

It was proposed to:

- Perform neutron spectrum measurements in the range 10 keV –10 MeV using a commercially available spectrometric set of SHFD's having six energy thresholds on JET during Campaign C16. This additional diagnostic capability is of particular interest for the experiment H/S2-4.2 Anomalous neutron production reactions in ICRH minority heated plasmas.

It was proposed to install a bundle of SHFD's before a JET shot(s) at the end of the KH2 beamline in J1D diagnostic hall. The detectors will be removed during an inter-shot time interval and another bundle of SHFD's will be installed for the subsequent JET shot(s). The exposed detector bundle would be analysed and reset at a remote location.

The spectrometric SHFD has been developed by the MEdC Association (NILPRP) for these JET experiments. As far as the preparation of the experiment is concerned, this small neutron diagnostics enhancement could be finalised with no negative influence on the existing JET diagnostics.

Acceptance criteria

The proposal was considered by the JET Task Force Diagnostics (TFD) as being of high scientific importance since it could provide presently nonexistent capability to analyse the spectral characteristics of the JET neutron flux over a broad energy range, starting from low energies (0.01-10 MeV). The spectrometric SHFD set represents a stand-alone equipment that can be implemented on JET with no interference with other machine components.

Detailed Proposal

- A commercially available spectrometric set of SHFD's manufactured by Bubble Technology Industries, Chalk River, Ontario, Canada has been adapted for neutron measurements on JET.

The spectrometric SHFD set contains 36 detectors, with 6x6 detectors having the following six energy thresholds: 10 keV, 100 keV, 600 keV, 1MeV, 2.5 MeV, 10 MeV. The overall dimensions of one SHFD bundle (6 detectors) are approximately 70 mm diameter and 200 mm length.

- The spectrometric SHFD set will be installed at JET in the diagnostic hall at the end of the KH2 beamline with a well-collimated tangential view of the plasma through Octant 6 port. As the location is outside the Torus Hall, and the detectors are completely passive devices it would cause no other interference with JET operations apart from the needed inter-shot access to KH2 room.

- Work plan:

The following work plan was agreed with JET TFD and carried out as specified below:

(i) Launching of the purchasing order for the spectrometric SHFD set: October 2005

(ii) Purchase of the spectrometric SHFD set: December 2005

(iii) Development of data acquisition and processing technique for the spectrometric SHFD set: December 2005. It is under development.

(iv) Neutron spectrum measurements on JET using the spectrometric SHFD set: campaign C16: January 2006.

(v) Analysis and interpretation of the spectrometric SHFD set data: February 2006.

For items (iii) – (v) new deadlines will be set depending on the new schedule of the JET Campaigns C15-C17 and on the decision to install the diagnostics on JET.

3.3. Other proposals made for the use of the SHFD technique

The use of the SHFD measurement technique was discussed with JET Task Force Fusion Technology in relation to the validation of neutron transport calculations carried out at JET for the estimation of the shut-down radiation dose. It was concluded that the method should be included in a future technology task.

4. Conclusions

In spite of the fact that the SHFD neutron diagnostics technique has obvious potential for providing new or better characterised experimental data, no significant progress in its application to tokamak plasmas could be made during the year 2005. Plans for possible developments during 2006 would be difficult to make at this moment. A first preliminary test of the method (neutron fluence measurements) was proposed to be done during one of the campaigns C15-C17. One the other hand, most of the human resources involved in the development of the SHFD neutron diagnostics technique have already been engaged in a new complex tokamak diagnostics project: the EP2 JET "Gamma-Ray Cameras –Neutron Attenuators" diagnostics upgrade project.

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