EFDA–JET–PR(07)32

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** See annex of M.L. Watkins et al, "Overview of JET Results ", (Proc. 21 st IAEA Fusion Energy Conference, Chengdu, China (2006)).*

Preprint of Paper to be submitted for publication in
Nuclear Instruments and Methods in Physics Research Section A

ABSTRACT
Since in ITER the radiation field will be much more severe than in present day devices, research programmes are being pursued at JET to develop radiation hard diagnostics and related components. As a preliminary and complementary activity, significant efforts are being devoted to determine the radiation field of both the plasma and the environment with better accuracy. New developments in MCNP calculations and dedicated measurements are providing useful information about the radiation field in the Torus Hall, even during non-operational periods. The effect of Be, which is going to be extensively used in the near future for JET first wall, is being assessed. New materials for activation samples are being considered and tested to improve the calibration of the neutron diagnostics. The long term goal of this work is to obtain spectrometric information by a suitable combination of different materials. Several studies are under way to modify the radiation field using LiH and pure water as neutron filters, to alleviate the problem of the background in the γ-ray measurements. A suite of radiation hard detectors for neutrons, magnetic field and charged particles are being developed.†Super-heated fluid detectors, used for yield and imaging, are being upgraded, in order to provide a broad-band spectrometric capability. Chemical Vapour Deposited diamond diodes are being qualified as counters and as spectrometers. Prototypes of Hall probes made of InSb have already been installed on the machine and have provided some preliminary results, whereas Si-on-insulator detectors for the Neutral Particle Analysers are being tested on the bench. Some attention is being devoted to optical components, fibres and mirrors, and to more radiation hard electronics using reconfigurable Field Programmable Gate Arrays.

1. THE RADIATION PROBLEM FOR ITER DIAGNOSTICS

ITER, the next step machine for the investigation of magnetic confinement fusion as a viable alternative energy source, constitutes a significant step forward in dimensions and plasma parameters. As summarised in table I, the gap between the present best performing Tokamak device, JET, and ITER is striking for parameters, ranging from the input power and energy content to the discharge length. The increase in these parameters, necessary to reach the required fusion rate according to the present scaling laws, will pose some significant technical problems, such as the severity of the plasma wall interactions, with the consequent stress on the first wall materials. Another serious concern is certainly the radiation load, since the rise in the neutron emission will be quite high in ITER compared to present day devices. Indeed ITER is expected to produce a total neutron flux of ~ 2.5 10^{14} n/s/cm^2 and a maximum flux of DT† neutrons at the First Wall of 4.4 10^{13} n/s/cm^2 [1]. JET had the highest neutron yield during DTE1 campaign in 1997 with Yn ~ 5.0 10^{18} n/shot (mMax n rate was about 5.5$10^{18}$ n/s DD + DT neutrons: Record yield: 5.7$10^{18}$ n/s in Pulse No: 42976). Then, as the neutron flux at the first wall at JET, according to MCNP calculations for DT neutron spectra, is ~ 7.0 10^{-6} n/scm^2/JET neutron, the TOTAL (DD+DT+scattered n) neutron flux at JET first wall was ~ 3.8 10^{13} n/s/cm^2, whereas the neutron flux of only 14MeV (11MeV<En<16 MeV) neutrons was about ~ 8. 10^{12} n/s/cm^2. On the basis of this data and given its long pulses and high repetition rate, the neutron fluence in ITER is expected to be four orders of magnitude higher than the one in JET during D/T operation.

Given the dramatic step forward in neutron fluxes and yield, significant research activities will have to be undertaken to converge on diagnostic techniques and technologies fully compatible with the ITER environment. With its high neutron yield in both DD and DT operation, JET is the best fusion device for assessing radiation hardness issues in a radiation field similar to the one expected in the next generation of machines. Moreover, the planned change of first wall materials, particularly with the adoption of Be for the main chamber, will increase further the similarity between JET and ITER from the point of view of the radiation environment.

In this framework, in JET a series of activities are underway to profit most from past experience for both the future operation of the device and planning for ITER. The main areas of work at the moment comprise a better determination of the radiation field, both the source and the environment, the refinement of the computational tools to interpret the measurements, the development of new radiation hard detectors and the investigation of various technologies, like neutron filters and reconfigurable Field Programmable Gate Arrays (FPGAs).

With regard to the determination of the radiation field, in JET a series of diagnostics measurements are made of the neutron and γ-ray emission of the plasma and its spatial distribution [2,3]. The calibration of neutron diagnostics remains a significant problem particularly in the ITER context. In JET historically the reference measurements consist of the activation of foils, which then decay emitting γ-ray radiation (or delayed neutrons), from which it is possible do determine the amount of neutrons originally striking the foils (see section 2.1). Fission chambers and Si diodes are then cross calibrated with the activation foil diagnostic for time resolution. A project to improve the activation foil technique by testing new materials is under way. Collaborations with various laboratories experts in γ-ray measurements with low background have also been established. The long term aim would be the ability to provide also energy resolved measurements of the yield. With reference to the environment, given the recent emphasis on high performance discharges, the determination of the radiation field inside JET torus hall is increasingly important for the operation of various systems, particularly delicate diagnostics like video cameras. It is therefore important to develop a strategy to determine experimentally the radiation field around the torus. This is a very important activity, which will allow the assessment of models, support the design of various components to be located close to the machine and also to evaluate the Occupational Radiation Exposure (ORE). Different detectors, Geiger-Mueller and passive thermo luminescent dosimeters, were installed in the Torus Hall to determine the γ-ray field, when the machine in not operating (see section 2.2).

For both the interpretation of the measurements and the assessment of the radiation field in JET environment, neutron transport models are an indispensable tool. To maintain the quality of JET measurements and interpretation, a series of updates of the MCNP calculations [4] is under way and, since in the next years JET will also install and operate with a new wall, the effect of the neutron multiplication due to Be, is also being investigated (section 2.3). Indeed the Be(n,2n) reaction could give rise to significant multiplication effects for plasmas giving neutrons above the 2.5 MeV threshold. This would be significant for some particular DD plasmas, but a general and more important effect for DT plasmas. The neutronic modelling capability and associated efforts needs to be increased at JET to allow detailed calculation of the effect of these physics changes and of important corrections in the calibrations of all the diagnostics. The MCNP code is the

ITER reference tool for performing neutronic analysis and many attempts have been made in the last decades to couple MCNP with an inventory code in order to predict the shutdown dose rate in a 3-D layout [5]. To this end, two computational tools both based upon MCNP-4c and FISPACT have been developed (section 2.2) and these codes are under validation.

Since some front-end diagnostics will be particularly exposed to hard conditions in ITER, a significant programme is being carried out to support the development of **radiation hard detectors** (see section 3). With regard to neutron detectors, new “bubble detectors” (super-heated fluid detectors) are being developed to measure the neutron yield and to perform imaging. Their use will be extended to obtain spectrometric information about the radiation filed (before and after installation of the new Be wall). Artificial polycrystalline diamond detectors, manufactured with the technique of Chemical Vapour Deposition (CVD), can already be considered qualified as counters for ITER since they have a radiation hardness which is at least two orders magnitudes higher than the Si diodes [6,7]. Monocrystalline CVD detectors for neutron spectrometry have also been manufactured and they seem to be able to provide an energy resolution better than three per cent; the application to the same technology to X-ray and UV detection is under development and test. For magnetic sensors, an alternative is being sought since the traditional approach, based on pick-up coils, could have some problems in ITER, because the high neutron radiation is estimated to generate small spurious currents, which can nonetheless have a significant impact when integrated over long steady state pulses. To overcome this issue, a specific project is being devoted to the development of radiation hard Hall probes, based on a first prototype of a three dimensional sensor that is already installed on the JET load assembly. Specific electronics to solve the delicate issue of the periodic recalibration are under development. For the measurements of lost fast particles and the isotopic composition profile, Neutral Particle Analysers are operational on JET and remain good candidates for ITER. On the other hand, one of their weakest points, at least in the JET implementation, is the high sensitivity of the present CsI scintillators to the neutron background. To overcome this difficulty, a new technology of Si on insulator detectors is being explored. New detectors are being designed, with an active thickness of the order of just a few ten of micrometers, on an insulating layer to increase the mechanical strength. The foreseen thickness of these detectors should guarantee a quite high immunity to neutrons while allowing great efficiency in the detection of the ionised neutrals. More recently, to reduce the neutron fluxes on specific detectors, particularly the scintillators for gamma ray measurements, **neutron absorbers** of ^{6}LiH and demineralised water have been designed and tested (see section 4). A ^{6}LiH prototype is also installed in the roof lab and has improved significantly the S/N ratio of one of the gamma ray spectrometers.

The high neutron yield of ITER poses significant problems not only for the detectors but also for a series of other **measurement related technologies**, ranging from optical components to fibre optics (see section 5). JET has historically tested a series of materials, from heated fibres to Sapphire windows to assess their behaviour in an environment dominated by 14.0 MeV neutrons (section 5). A series of samples of stainless steel and polycrystalline molybdenum have been located in various locations inside the vacuum vessel to determine, among other things, how the neutron load can affect the reflectivity of these materials candidate for ITER mirrors. Since some electronic boards, particularly inside video cameras, have failed in the past because of the radiation load near the machine, reconfigurable FPGAs are being investigated to alleviate this problem and to test the viability of the concept for the next generation of devices.

2. DETERMINATION OF THE RADIATION FIELD

The determination of the radiation field is a challenging proposition in a fusion machine. First of all the emission of the source, the plasma, has to be measured quite accurately. This is not a simple task given the problems posed by the toroidal geometry and the variety of materials surrounding the plasma. In big devices with high fluences, the radiation levels outside the vacuum vessel, inside the biological shield, have also to be quantified quite accurately because they have implications for the safety of the operators and the survival of various components. At JET a coherent programme of upgrades is in place to improve the determination of both the plasma emission and the radiation field in the environment.

2.1. THE SOURCE

The primary calibration of JET neutron emission was originally based on three pairs of fission chambers, located in different toroidal positions, which were directly calibrated with respect to a 252Cf source of known emission rate, deployed inside the torus. This is complemented by an activation system, based on a series of foils, which, after exposure near to the plasma, are extracted from the torus hall. The neutron yield is established by monitoring the γ-ray or delayed neutron emission from the exposed foils. The foils are inserted with a pneumatic system in eight positions close to the plasma edge (see fig.1). This diagnostic, originally considered a secondary check, depends upon neutron transport calculations. After some years, the procedure to calibrate the fission chambers became impractical due to continuing changes to the JET structure at the ports and in the torus hall. From 1990 the activation system has been relied on as the main absolute calibration. The internal consistency of the activation technique has been demonstrated by the fact that, for DD yields, the Th foil (delayed neutron) measurements agree with the In foil (gamma decay) measurements. Also the relative deduced neutron yield is independent of which of several different irradiation positions is used. Historically this calibration was demonstrated to be accurate to ± 10%, or better, for both deuterium and tritium plasmas. This historical absolute calibration of the activation foils is supported by the in-vessel dose-rates, where the rates calculated using fission chamber neutron yield values (which are normalised to the ones of the activation foils) are found to agree with those measured directly, at least within the ~30% errors of these health physics measurements (see fig.2). This demonstrates there has been no large unexplained change in calibration over the complete lifetime of JET. Since 1990 steps were taken to better calibrate the neutron profile diagnostic so it could be the second absolute calibration. The neutron profile diagnostic consists of two fan like cameras, looking tat the plasma along 19 lines of sight (see fig.3). For each line of sight the neutrons are measured with NE213 liquid scintillators (for both 2.45 and 14 MeV neutrons) and with Bicron 418 detectors (for the 14 MeV neutrons). Analysis in 1998 showed agreement to 6% between the activation diagnostic and the neutron profile monitor for DT neutron yields during the DTE1 experiments of 1997. However the profile monitor errors were unclear but certainly larger than 6%. The neutron yield values measured by the independent profile monitor were in agreement with the fission chamber data to within 10-15% during 2000-2003. In any case, to improve the calibration of JET neutron diagnostics, it is planned to upgrade the activation foil technique. The main idea consists of investigating additional materials to improve the accuracy and obtain spectroscopic capability. Indeed, this diagnostic could provide much more information if different elemental foils (activators) were exposed simultaneously. To this end, it is a prerequisite to identify nuclear reactions with suitable cross section thresholds covering the energy interval of interest (0.5 – 16 MeV). In the range of threshold energies Ep 0.5 – 3 MeV, the reactions with relatively large cross-sections are: $^{89}Y(n,n')^{89m}Y$, Ep~1.0 MeV, $T_{1/2}$=16 sec; $^{204}Pb(n,n')^{204m}Pb$, Ep~1.0 MeV, $T_{1/2}$=67 min; $^{167}Er(n,n')^{167m}Er$, Ep~0.1 MeV, $T_{1/2}$=2.3 sec. These reactions have not been used so far in JET experiments because their daughter nuclides decay with a very short half-life time ($T_{1/2}$) or their parent nuclides are very low abundance (like ^{204}Pb). Some preliminary positive results have been obtained with samples based on the following nuclear reactions: $^{180}Hf(n,n')^{180m}Hf$, Ep~0.1 MeV, $T_{1/2}$=5.5 h; $^{111}Cd(n,n')^{111m}Cd$, Ep~0.3 MeV, $T_{1/2}$=49 min. Hafnium and Yttrium have also never been used in JET.

The combined use of some of these materials is expected to provide significant spectroscopic capability to the activation diagnostic. This should allow not only to improve of a few percent the accuracy of the neutron yield measurements but also to give data for a much more thorough benchmarking of the MCNP calculations.

2.2. THE ENVIRONMENT

Neutrons produced by DD and DT plasmas induce the activation of tokamak materials and components. The development of reliable methods to assess dose rates is a key issue for maintenance and operation of nuclear machines, in normal and off-normal conditions.

In support of ITER design activity, an innovative computational tool based upon MCNP-4c Monte Carlo code has been developed to predict the dose rate after shutdown: it is called Direct One Step Method (D1S) [8,9]. In the D1S approach the decay γ-rays are coupled to the neutrons as in the prompt case and are transported in a single step in the same run. This method and the so-called

Rigorous 2-step method, which follows a traditional approach [10,11], are both under benchmarking versus dose rate measurements. To check the capability of both methodologies to predict the dose rate in a tokamak and to improve the knowledge of the radiation field in the environment, a dedicated benchmark experiment was proposed for the 2005-2007 experimental campaign of JET (EFDA JET tasks JW5-FT5.20

2- Upper Irradiation end

Two irradiation positions have been selected for the benchmark: one inner position of the activation diagnostic on top of the vessel, called 2-Upper Irradiation End (IE-2), while the second position is just outside a vertical port in an external position (EX). Passive detectors are used for the IE-2 measurements: the high sensitivity Thermo Luminescent Dosimeters (TLDs) GR-200A (natural LiF) (see fig.4). One active detector of Geiger-Muller (GM) type is used for the EX dose rate measurement. The experiment is in progress since JET shut down started from April-5 2007, here the residual background and dose rate due to early phase of JET 2005-2006 campaign are compared with the same quantities calculated using the D1S approach. The preliminary results of the ongoing benchmark can be found in [12] and are summarized in Table II. The comparison between calculation and residual dose rate measurement shows an optimal agreement in the inner position. The calculation overestimates by about 60% the IE-2 dose rate measurement performed in June 2006.

Concerning the EX position, the preliminary calculated quantities underestimate the measurements: the calculated values are about 70% lower with respect to experimental data. The observed discrepancies can mainly be due to an inadequate accuracy in the material compositions of JET-model. One important issue in activation calculation is the impurity content in materials. Especially at long times after the beginning of a shutdown, few isotopes contained as impurities can play a significant role. This has been proven to be true in the case of ^{58}Co or ^{60}Co, which are produced through n reactions with Ni isotopes and with Co impurities. It has been realized that there is some lack of impurities in materials description in the original JET MCNP model. This is reasonable if the impurity content is low and the main objective of the MCNP model is to calculate the neutron flux. In case of activation and transmutation estimates, impurities have to be included.

In order to evaluate the impact of material impurities on the calculated doses, a further simulation was performed adding Cobalt to Stainless Steel and Inconel components of the vacuum vessel. The results of the calculation have shown that small fractions of Cobalt (+0.1% wt on Inconel-600 and +0.05% wt on Stainless Steel) cause an increment of a factor 2 on the external doses, as a result of the reaction Co-59(n,g)Co-60. This analysis emphasises the necessity to modify the materials compositions of JET-MCNP model. Similar considerations can be invoked to explain the overestimates observed in the inner position. In this case small variations for example on Ni amount in the surrounding structures can have a great impact on the Co-58 production and therefore on doses.

Moreover other reasons can explain the observed discrepancies as the uncertainties on the nuclear activation data and/or on the geometrical description as well as the effect of detectors response at low photon energy.

The work presented in this paper represents a preliminary analysis of the problem. A more complete analysis of the D1S method will be possible after the experiment will be completed and dose rates will be measured for several months after the end of the JET 2005-2007 experimental campaign. The optimisation of the JET model in terms of geometric details and materials impurities modifications as well as the update of the nuclear data are still in progress.

2.3. THE RADIATION FIELD WITH THE PRESENT AND THE FUTURE WALL

To prepare for ITER, JET is in the design phase of a new first wall. The JET main chamber will be completely covered with beryllium (Be) and the divertor with tungsten (W). As far as the radiation field is concerned, the main problems posed by Be include an increased reflectivity and a significant multiplication effect due to the Be(n,2n) reaction. This would be not relevant for D,D plasmas, but is a significant effect for D,T plasmas. At 14 MeV, (n.2n) reactions in present vessel gives 1.2 n/source neutron. With the Be wall the first estimates indicate that increased moderation and neutron multiplication will lead to a (global) neutron yield per source neutron of about 1.3. Moreover, it must be kept in mind that after DTE1, the measured activation Gamma Dose Rate was 40% greater behind antenna (Be, no C) than elsewhere (C). This indicates that particular locations/LoS/diagnostics will see potentially significantly larger changes. Accurate calculations are therefore required to predict effects of the new materials on the radiation field and the consequent impact on the response of the diagnostics. The neutronic modelling capability and associated effort need to be upgraded at JET to allow detailed calculations of the effects of these physics changes and of important corrections in the calibrations of all the diagnostics. This applies in particular to the important neutron yield measurements, where JET relies solely on the activation measurements for a calibrated result (as explained in the previous section).

In order to evaluate the entity of this issue, some preliminary simulations of the reflection from the inner wall have been performed. A simplified model of the wall (see fig.5) was used in a MCNP calculation to assess the effect of the neutron reflectivity of the various materials. This property of the first wall can have a significant impact on the measurements of the neutron cameras, particularly the lateral channels, which can detect a quite low number of neutrons coming directly from the source since they look at a peripheral cold region of the plasma column. In the model the tiles in front of the neutron cameras have been modelled with a stainless steel support covered by a layer of either C, Be or W. the ratio of the forward versus the backscattered neutrons has been calculated for various thicknesses. The most influential material is of course Be, being the one of lowest atomic number. The increase in the reflectivity is more pronounced in the case of the 2.45 MeV neutrons (see table III) but it could become relevant also for the 14 MeV neutrons at higher thicknesses. A more systematic analysis of this issue is of course required to obtain the final quantitative estimates of the effect but these preliminary calculations already show that the material mix can have a significant impact on the neutron measurements already in JET and that therefore the situations must be studied in even great detail in ITER.

3. DEVELOPMENT OF RADIATION HARD DETECTORS

With its radiation field very similar to ITER's, JET is the most suitable place to develop and test detectors in a reactor relevant environment. In the last years, some significant efforts were devoted to investigating radiation hard components for neutron and charged particle detectors. Moreover, also the issue of developing Hall probe capable of working properly in ITER is being addressed.

3.1. SUPER-HEATED FLUID DETECTORS (SHFD'S)

Super-heated fluid detectors (also known as "bubble detectors") are suspensions of metastable droplets which readily vaporise into bubbles when they are nucleated by radiation interactions. The active detecting medium (see fig.6) is in the form of microscopic (20-50^{o}m) droplets suspended within an elastic polymer [13]. 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 bubbles generated in the detector are counted by various means: eye counting for up to a few tens of bubbles per detector, automatic counting through processing of the detector image, acoustical detection of the bubble formation. The number of bubbles generated within a given volume of the detector is simply and directly related to the neutron fluence (neutrons per unit area).

The bubble detectors have been very successfully developed as neutron dose meters due to the following particular characteristics: immediate, visible response; high neutron efficiency (about 3%); (practically) zero gamma sensitivity; lightweight, rugged and compact; broad energy range spectrometric capability.

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 0.3-10 MeV. Using detectors with different energy thresholds, a bubble detector spectrometer (BDS[(*)]) is obtained. The BDS covers a broad energy range (0.01 – 20 MeV) and provides six energy thresholds in that range.

Standard bubble detector of the BD-PND[(*)] type have been used on the JET tokamak for neutron fluence measurements, while high sensitivity DEFENDER[(*)]-type detectors have been used for neutron beam imaging. All measurements have been done at the end of the KM11 diagnostics line-of-sight, above the TOFOR neutron time-of-flight spectrometer (Figure 7). The SHFD detectors have been placed in front of the vertical NaI(Tl) gamma-ray spectrometer. By using high sensitivity DEFENDER[(*)] detectors the profile of the neutron beam propagating along the collimated vertical line-of-sight of the KM11 diagnostics was obtained (Figure 7). The radial distribution of the neutron fluence in the neutron beam at a distance of about 3 m from the exit of the 40 mm diameter KM11 collimator was obtained with a spatial resolution of less than one centimetre. As an immediate effect of this measurement a better alignment of the vertical NaI(Tl) gamma-ray spectrometer was obtained. Figure 8 shows the one-dimensional neutron beam profile for JET Pulse No: 68447. It can be seen that the FWHM of the beam profile is approximately 40 mm, i.e. equal to the diameter of the floor collimator hole.

3.2. CVD DIAMOND DETECTORS

Electronic grade single crystal diamond devices are used for several purposes from UV detection to X-ray and charged particle spectroscopy. Since it is well known that Carbon reacts mainly with high energy neutrons via the (n,α) reaction, one very promising application is the development of neutron detectors for the next thermonuclear experimental reactors. For this reason some artificial diamond detectors are successfully tested at JET since 2003. This study is a collaboration between the Fusion Department of ENEA Frascati and the Mechanical Engeneering Department of Rome "Tor Vergata" University. Several studies on radiation damage have been already carried out on natural and synthetic diamond detectors [14-17]. However the high radiation tolerance to neutrons of natural diamond (up to 3×10^{16} n/cm^2), was not confirmed by the synthetic diamond detectors since a large degradation of the spectroscopic properties was found for fluence greater than 5.5×10^{13} n/cm^2. However, when comparing the different data and results, one problem is represented by the differences in the experimental conditions: neutron spectra (usually fission reactors or spallation sources) and fluence rate. Up to now just one single irradiation was performed with 14 MeV neutrons for one polycrystalline diamond detector [16] substantially confirming that this kind of diamond can withstand neutron fluences up to 5.0E+14 n/cm^2.

High grade Single Crystal diamonds films are now routinely produced at Rome "Tor Vergata" University and the detectors produced with them show high performances in term of charge collection (100%), time dependent stability and energy resolution, which render these devices already mature for several applications. It is thus necessary to study their radiation tolerance.

A synthetic single crystal diamond neutron detector, was irradiated with 14.8MeV neutrons at the Frascati Neutron Generator (REF Angelone-7) up to a fluence of 1.50×10^{14} neutrons/cm^2.

The detector was obtained adopting a layered structure for the device fabrication [18]. The device was characterized, in term of charge collection efficiency and energy resolution. The performances of the electronics were verified measuring the a emission spectrum of mixed nuclides under vacuum with a partially depleted Si detector. The FWHM resolution for the 5485keV of ^{241}Am peak was 0.6% (see fig.9). The SCD detector shows excellent resolution not far from that of a silicon diode. It is worth noting that satellite peaks typical of the used three alphas source are clearly visible in the PHA spectrum.

The neutron irradiation was performed in several steps during a period lasting three months.

Before and after each neutron irradiation the detector was irradiated both with a three peaks alpha source (Pu-239-Am-241-Cm-244) and with 14 MeV neutrons in order to study the effect of the neutron fluence delivered by each irradiation on the spectrometric performances of the detector. In the second case the goal was to study the degradation of the typical peak due to (n,α) reaction in Carbon; this is of direct interest to fusion application. The results so far obtained are summarized in figures 10 and 11. The data so far collected seems to indicate a good stability of the detector performances up to a 14 MeV neutron fluence of about 1.5E+14 n/cm^2. The irradiation is still in progress, since the goal is to reach the fluence level above which the detector performances are degraded so much that the operation with the diamond detector is no longer acceptable.

3.2. HALL PROBES

In a Tokamak, the accurate determination of the magnetic fields is essential for the operation of the device and the interpretation of the other diagnostic signals. In present day machines, the measurements of the magnetic topology are performed mainly with pick-up coils, a technology quite consolidated and reliable. On the other hand, the next generation of devices will constitute a quite hostile environment for these sensors. The most severe aspects for this diagnostic in a machine like ITER will be the necessity to perform accurate magnetic field measurements at steady state (up to 3600 s) and the considerable level of penetrating radiation. These requirements are very problematic for the traditional inductive methods based on pick–up coils and integrators, since the high neutron yield can produce small spurious signals that integrated over long times can significantly reduce the final accuracy of the measurements.

One of the alternatives considered to overcome these problems consists of developing galvanomagnetic transducers, namely transducers based on the Hall effect, which are inherently capable of measuring steady state fields. On the route to qualify these new detectors for operation in a reactor relevant Tokamak environment, the main aspect to be addressed is the stability over time of the measurements. The present strategy in this respect consists of developing solid state materials with sufficiently high stability to operate in harsh environments like ITER.

If the materials are sufficiently stable, the unavoidable drifts of these detectors, over years of operation, can be corrected by periodic in-situ recalibration of the Hall sensor parameters.

With regard to the materials, the problem with semiconductors is that radiation induces defects of both donor and acceptor types, and that one of these defects' types might prevail in certain semiconductor materials. If under irradiation, in a material of electron-type conductivity mostly acceptor defects are induced, they change the Fermi level modifying the electrical properties of the detector. The approach adopted to overcome this problem consists of doping the crystal with impurities, which create getters for radiation defects and also compensate the radiation defects of acceptor type with additional donors generated by nuclear transmutation of basic lattice atoms (for example In in InSb) into the donor impurity (Sn). This solution has already been tested in fission reactor with positive results [19].

These materials are used to build integrated magnetometric transducers, which can be periodically recalibrated to eliminate the effect of the long term drifts. These detectors comprise two elements for each spatial direction: a Hall Transducer (HT) and a small-size solenoid with a coil's diameter of 1˜2 mm, which is wound around the Hall sensor and acts as known source of magnetic field (see fig.12). The test field, which is generated in the coils, is the reference for the self-calibration. This method of in-situ calibration is being refined for the three-dimensional magnetometric transducer already installed on JET. The detector is located on top of the machine near one of the poloidal field coils. The measurements of the three components of the magnetic field have been simulated with a electromagnetic code. The results of the Hall probe are in good agreement with simulations as shown in fig.13.

3.4. SI ON INSULATORS DETECTORS FOR NEUTRAL PARTICLE ANALYSIS

JET is equipped with two Neutral Particle Analysers (NPAs) of ITER relevance. One is meant to measure the isotopic composition profiles and the other the losses of high energy neutral particles [20]. They both convert the neutral particles escaping the plasma into charged ions using suitable Carbon foils. The energy and mass of the ions are then discriminated using a combination of electric and magnetic fields. The detectors in both neutral particle analysers consist of thin CsI(Tl) scintillators coupled to PhotoMultiplier Tubes (PMTs). Unfortunately, in addition to the ions, the detectors are also sensitive to the background caused by neutrons and X-rays. The background can be separated from the ions by the use of pulse-height analysis, however, the process is not ideal as background and signal counts can overlap. Problems do occur particularly at high neutron rates and low ion energies. Furthermore, the count rate capability is limited by the long scintillation time (1-3 ºs) of CsI(Tl). The present detectors have also issues with particle identification, as it is not possible to separate deuterons (energy *E*) from ± particles (energy 2*E*). Especially in DT experiments, it would be extremely important to be able to identify these particles.

In order to improve the signal to noise ratio of these diagnostics, new silicon detectors, similar to those in use in High Energy Physics (HEP), are being developed. The proposed solution consists of ultra thin silicon 2D detectors to be optimized for the use in JET NPAs. Achieving good background rejection in ion detection requires matching the thickness of the detector active layer to the ion range in the material. Presently, Si detectors have typically a thickness of the order of 200-300ºm, which is unecessarly thick for the NPA ions. Therefore new thin detectors, with an active area of a few micrometers thickness and based on silicon-on-insulator technology, are being designed for JET. In such thinned sensors, ions will have close to 100% detection efficiency but the background radiation will deposit much less energy per event to the detector than ions. Pulse height analysis will be used to discriminate ion events from the background signals. This is anticipated to be easier than with the present detectors because detector response is proportional to the deposited energy while scintillators are 2-10 times more sensitive to energy deposited by electrons and X-rays than ions. Silicon detectors are expected to have superior energy resolution compared to scintillators, which will also facilitate ion identification and background suppression. However, this has to be demonstrated as this is a novel application. The signal time constant is anticipated to be ~50 ns, nearly two orders of magnitude improvement over the present CsI(Tl) scintillator detectors (~3^{o}s). The structure of the detectors is illustrated in fig15. In the reference design the detectors present a 7×10 mm^2 active area, covered by 64 strips (110μm pitch).

The detectors will be directly bonded to readout chips comprising the acquisition electronics. The concept of compact Si detectors is inherently quite robust against electrical noise due to the close integration. Radiation hardness of detectors has been of utmost concern in high energy physics for a long time and it has posed some problems in the past even at JET. Presently, Si detectors have proven to behave satisfactorily up to 10^{15} *p*/cm2 [21], and better tolerance is expected for thin devices. Even with no shielding, at some 10 m away from the plasma, this would correspond to a yield of >1022 DT neutrons at JET, well exceeding what is planned in future experiments.

4. MODIFYING THE RADIATION FIELD: NEUTRON ABSORBERS

The measurements of the gamma-rays at JET are affected by a strong neutron background. It was therefore decided to test the performance of ^{6}LiH filters for gamma-ray background reduction by means of neutron flux suppression. Preliminary tests were carried out during JET experiments with deuterium (*dd*) plasmas. A neutron filter, (Δ30mm×300 mm) developed and manufactured by the Ioffe Institute, was installed in the 2-m vertical line-of-sight collimator used for fusion gamma-ray spectrometry (see fig.15). Gamma-ray spectra, recorded with *BGO*- and *NaI(Tl)*-detectors, were acquired in similar deuterium plasma discharges with neutral beam injection heating to compare the spectra recorded with ^{6}LiH-attenuator and without it. The analysis showed that there are two main sources of the gamma-ray background given by neutrons due radiation capture, (n,g) and inelastic-scattering reactions, (n,n'γ) in both tokamak construction materials and the detector themselves. Only the last source of the background could be reduced with ^{6}LiH-attenuator plugged in the collimator. Assessments of the reduction obtained from changes in gamma-lines intensity give a factor 100. It is found that that type of gamma background lies in the energy range below 3MeV. A small reduction (factor 2) of the gamma-ray flux was found in the energy range above 3MeV, which is due to the limited transparency of the ^{6}LiH-attenuator in that energy range. The fusion gammas and gammas, which are induced by neutrons in tokamak structure materials, are responsible for this part of the spectrum. JET experiments with ^{6}LiH show that the attenuator is very effective in reduction of gamma-ray background caused by *dd*-fusion neutrons, and results are consistent with neutron-generator measurements. Further tests in deuterium-tritium discharges are needed to prove the capability of ^{6}LiH-attenuators as an indispensable component of the gamma-diagnostic system in ITER.

The positive results, obtained with the previously described neutron filter, motivated the investigation of alternatives to improve the gamma-ray imaging. A relevant design activity has been therefore undertaken to assess the potential of various materials and solutions. For JET neutron cameras pure water is considered adequate for DD operation. A series of Monte Carlo calculations has been performed to estimate the influence of the proposed neutron attenuators on the neutron field, namely on the attenuation of the neutron and gammas, the induced gammas and the inscattering of the neutrons from the attenuator in the parking position. The Monte Carlo code MCNP5 was used, which is a well tested MCNP model, developed on JET. It was of course modified in accordance with the needs of the calculation, i.e. a neutron attenuator was inserted (in blue color in the figure 17). None of the listed tasks could be achieved through a straight-forward Monte Carlo method due to the severe degradation of the neutron flux from the plasma to the detector region, which is of the order of 10^{-10}, and the consequent low statistical accuracy of the results. Calculations were performed for neutrons with DD energy (peak at 2.45MeV) and a monodirectional neutron flux below the filter, oriented parallel to the flight tube. The results are presented in table IV for filters, filled with water and heavy water as the ratio of transmitted neutrons per one incident neutron.

The majority of the gamma-rays, induced in the attenuators, originate from thermal neutron capture on either H or D. The transitivity of the “plasma” gamma-rays varies with gamma energy and amounts to approximately 20% at 2MeV to some 60% at 10MeV, being slightly higher for a D_2O than a H_2O filled attenuator.

In the future additional calculations should be performed also for other approximations of the incident neutron beam. On the other hand, a point which was carefully addressed is the amount of the scattering of neutrons into the detector region from the attenuator, when this is placed in the parking position (to perform imaging of the neutron emission not the gamma-rays). The problem was addressed in an an indirect way and the ratio was not calculated directly but it was rather compared to the value of inscattering from the attenuator in the parking position possibly amounts to is less than 3% of the overall inscattering into the detectors from the shield. Through the installation of the attenuator, thus, the neutron background is raised for less than 3%.

5. OTHER DIAGNOSTIC RELATED COMPONENTS AND ELECTRONICS

In fusion devices, such as tokamaks, the diagnostics make use of a series of ancillary systems, among which the ones more susceptible to radiation damage are optical components and electronics. Mirrors, lenses, fibres and windows are important for imaging, spectroscopy and laser supported techniques [22]. Electronic equipments are vital to practically all modern measurement systems. All these component and technologies have been conceived for different environments and are therefore intrinsically vulnerable to radiation damage. The aspects where more experience was gathered at JET and in which some activities are under way are fibres and electronics.

5.1 OPTICAL COMPONENTS: FIBRES

Multimode step-index optical fibres of “large” core diameter, 300 - 1000mm, are routinely used to relay light emitted by the plasma to analysers and detectors located remotely, outside the machine enclosure. The deployment of such fibres offers a number of advantages: 1) immunity from electrical and magnetic interference, and reduced influence by ionising radiation, 2) simple collection optics can be used with no need to maintain alignment of relay optics over long paths, 3) the space occupied by the apparatus in the vicinity of the machine is small, reducing crowding, and 4) access to the analysers and detectors is unrestricted, even during machine operation, which obviates the need for complex remote-control systems. There are two principal disadvantages. Firstly, compared with a close-coupled system, the etendue, dΩ.a, is significantly smaller (a factor of 5 - 20 less) due to the restricted diameter of the fibre core and small numerical aperture of the fibre. Secondly, below ~ 400 nm the light is severely attenuated due to a combination of high absorption, ~ 60 - 200 dB/km, and the long lengths of fibre used, typically 50 to 200m. The operation of tokamaks with a mixture of deuterium and tritium, instead of deuterium only, results in a much-enhanced neutron yield and increased neutron energy. The DT neutrons can interact directly with the silicon in an optical fibre through the Si(n,p)Al reaction, creating energetic protons in the silica lattice. In addition, the neutrons produce intense gamma-rays, through (n,γ) reactions in the machine structure. As a consequence of the radiation, the performance of the fibre is degraded through two processes: 1) induced absorption which, due to its time-dependent nature, can significantly reduce the accuracy of absolute intensity measurements, and 2) radio-luminescence, which contributes a stray light background to the collected plasma light. When optical fibre waveguides are exposed to nuclear radiation, the incident energy can be dissipated through the formation of electron-hole pairs or free radicals. While most of these pairs undergo recombination, a small number of electrons and holes become trapped on defects to form additional absorption bands called colour centres. These reduce the light transmission by resonant absorption followed by isotropic re-radiation. The defects either existed in the amorphous network of the glass prior to irradiation or were created by the exposure itself.

Radiation damage is a dynamic process; concurrent with the production of colour centres by irradiation is recovery due to emptying of electrons or holes out of these centres. In general, the radiation-induced attenuation comprises a permanent component, that persists years after the initial exposure or grows in during steady state irradiation at a very low dose rate (< 0.1 Gy / day), and a metastable component. Some of the optically absorbing species produced by irradiation may remain in the lattice for extended periods of time, usually many days. This is termed “permanent absorption”, for practical purposes, although in reality thermal de-trapping processes continue indefinitely. The metastable component consists of both a transient part, which exhibits decay times of < 1s after a radiation pulse, and a component which recovers on a time-scale > 10 s and is measured during and after steady-state exposures of 0.1 to 100 Gy / min. Transient absorption is typically a few orders of magnitude larger than permanent absorption. The nature and extent of the transient and steady-state recovery processes depend strongly on the composition, fabrication process and previous irradiation of the fibre.

It is difficult to compensate for the effects of induced absorption as it depends on many factors, eg the accumulated dose, the dose rate and the irradiation history of the fibre. In addition, the absorption can depend on the level of any optical signal that might be carried by the fibre. The transmitted light can reduce the absorption by photo-bleaching, but the effect varies strongly with wavelength and intensity. Consequently, the best approach to dealing with absorption is to attempt to eliminate the effect altogether, or to reduce it to an insignificant level, eg by operating at elevated temperatures.

The irradiation of a fibre with X-rays, gamma-rays or neutrons generates luminescence by several mechanisms. Electron-hole pairs created by the radiation or by secondary high-energy electrons may recombine immediately to give luminescence. Alternatively, transient or permanent defects may be produced by the radiation and subsequently serve as recombination sites for mobile electrons and holes. In addition, light may be produced by the photon-emitting decay of trapped electrons, which are raised to excited states by the radiation. Finally, there is Cerenkov radiation whereby secondary high-energy electrons exceed the velocity of light in the silica and emit their excess energy as electro-magnetic radiation. The electrons are produced by the gamma-rays, either photo-electrically or by Compton scattering. Luminescence is only observed during irradiation. However, the component of luminescence arising from Cerenkov radiation is not dependent on the fibre temperature.

In principle it is not difficult to circumvent this problem of luminescence: an extra blind fibre is run along the same route as the signal fibre. A subtraction technique then permits the plasma signal to be recovered, provided the luminescence signal is not very much greater than the plasma signal, as illustrated in fig.18. The solid line shows the time-varying Z_{eff} signal obtained from an absolute measurement of the JET plasma continuum signal at 523.5 nm, using a PCS optical fibre to relay the collected light to a narrow-band filter / photomultiplier combination. However, the continuum signal has been augmented by luminescence induced in the fibre by a 14 MeV neutron pulse, during operation with a DT mixture, leading to an over-estimate of Z_{eff}. The luminescence component was measured by running a second identical fibre along the same path as that used to measure the continuum, to the same combination of filter and photomultiplier. However, the second fibre was blind – so did not measure the plasma continuum, only the luminescence. Subtracting the luminescence signal from the combined signal yields the corrected Z_{eff} trace, as shown.

5.2. OPTICAL COMPONENTS: MIRRORS

Several diagnostics in ITER will make use of mirrors located inside the vacuum vessel. The reflectivity of these components could be degraded by various effects, among which the most relevant are the neutrons, the gamma-rays and the energetic plasma ions. Moreover, material eroded from the first wall can also form codeposited layers on these mirror surfaces, potentially causing strong degradation of their optical properties. In JET some of the candidate materials for ITER mirrors are being tested inside the vacuum vessel [23]. Thirty two samples, made of stainless steel 316L and polycristalline Molybdenum, remained inside the vessel for the last set of campaigns and are about to be removed for the optical tests. They were located in four poloidal position, three in the divertor and one in the equatorial plane. It is planned to repeat the same tests with the new wall, to assess the effects of a different mix of materials on the degradation of the optical properties of these components.

5.3 ELECTRONICS

A field of investigation so far neglected at JET is the one of radiation hard electronics. On the other hand some failures of electronic components located in JET Torus Hall have occurred during the last high power campaigns. Particularly vulnerable are the video cameras (visible and infrared), some of which contain quite sophisticated circuits, which can be affected by neutron and gamma-ray radiation. Since in some occasions the damage was not permanent and the proper functionality of the circuits was recovered after re-installation of the software, Single Event Upsets (SEU) seem to be a problem worth considering with a certain attention. SEU are soft errors which take place due to either the deposition or the depletion of charge, induced by ions generated by the incoming radiation, at a circuit node, causing a change of state in a memory cell. This type of event causes no permanent damage, since the effect are mainly bit flips, changes in state that causes a momentary glitch in the device output and corruption of the data in a storage element. The device can therefore be reprogrammed after such an event has occurred but if this failure mode was avoided, the benefits would be significant since accessibility to JET cameras is quite complicated and their unavailability can disrupt the scientific programme. Reconfigurable FPGAs are considered to eliminate or at least limit the frequency of these failures. The architecture of the FPGAs and their programme can be organised in such a way that the circuits can perform different functions depending on the situation [24]. This implicitly improves the radiation hardness of the components because fewer components are necessary, reducing the exposed area. More activate strategy can consist for example of the triple voting methods for the memories. Three copies of the data are stored in the dynamic memories and their content periodically compared. If a memory's content is not aligned with the other two, the different one is considered victim of a SEU. Its proper configuration can then be refreshed while the system keeps operating properly on the basis of the information of the two other components still intact.

CONCLUSIONS AND OUTLOOK

In JET the developments of diagnostics for the fusion products is constantly pursued in all its various aspects, from neutron counting to neutron and gamma-ray spectrometry, from imaging to calibration. Particular attention is devoted to radiation hard detectors, also for the measurement of other quantities like the magnetic field. In the last years, in preparation of both the new wall and ITER, the modelling of the field in the Torus Hall has been improved and more measurements are being made to benchmark the MNCP calculations. This additional knowledge is expected to have a significant impact in the determination of the dose rate and possibly in the design of electronics and other components to be installed close to the machine. First very positive results have been achieved in the use of neutron filters to alter the radiation field and make it more compatible with gamma-ray measurements. Some tests are being carried out also to test optical components, particularly mirrors, in conditions as close as possible to ITER. In the near future, a lot of attention will have to be devoted to the change of materials for the first wall, since tungsten and beryllium can have a significant impact on various measurements. Innovative techniques, like the use of samples activated by escaping fast ions [], will also be further pursued.

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(Footnotes)

(*) All detectors used in this work were manufactured by Bubble Technology Industries, Chalk River, Canada

	PULSE LENGTH (S)	STORED ENERGY (MJ)	INPUT ENERGY/ SHOT/(MJ)	DIVERTOR PARTICLE FLUENCE/ SHOT
JET	10^1 range	10-20	10^2 range	1 x 10^{24}
ITER	10^3 range	350	10^5 range	4 x 10^{27}
	x 100	x20	x100-1000	x4000

Table I: Comparison of ITER target parameters with JET performances achieved so far. In red the factors JET performances have to be multiplied in order to obtain the ITER expected values.

Position (Detector Type)	Residual Dose Rate (μGy/h)	Calculation (μGy/h)	C/E	Dose Rate (June 2006) (μGy/h)	Calculation (μGy/h)	C/E
IE-2 (TLD)	50.0 ± 5.0	44. 7 ± 4.4	0.89 ± 0.13	75.4 ± 6.0	123±10	1.63±0.15
EX (G.M.)	0.89 ± 0.36	0.13±0.03	0.15±0.07	1.47 ± 0.17	0.47±0.04	0.32±0.05

Table II: Comparison between experimental and calculated results

Neutrons at 2.45 Mev

Thickness (mm)	2	5	10
C	1	1	1
Be	0.946	0.878	0.801
W	1.056	1.129	1.265

Neutrons at 14.6 Mev

Thickness (mm)	2	5	10
C	1	1	1
Be	0.972	0.930	0.864
W	1.012	1.028	1.052

Table III: Ratio of the forward scattered neutrons divioded by the back scattered neutrons for C, Be W layers of different thicknesses. Top results for the 2.45MeV neutrons, bottom for the 14MeV neutrons.

Attenuation factors for neutrons:			
	Transmitted (ratio)	Scattered into the detector (ratio)	Total
H_2O:	8.41E-03	3.94E-04	8.81E-03
D_2O:	1.20E-02	3.91E-04	1.23E-02

Table IV

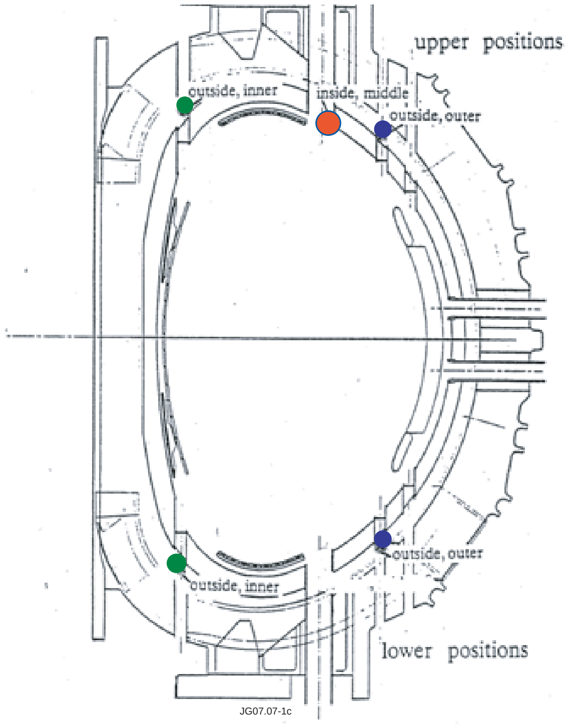

Figure 1: Localisation of the radiation ends of JET activation foil diagnostic in the poloidal cross-section. Eight radiation ends are located in four octants.

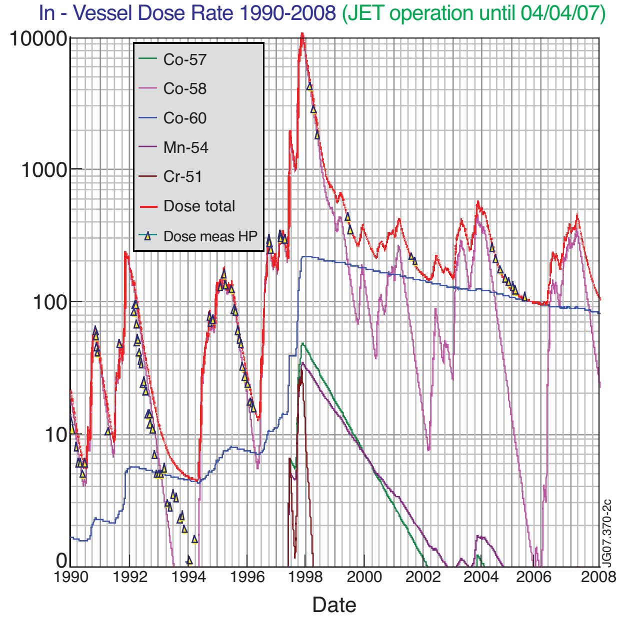

Figure 2: Comparison of the activation expected by the measurements of the activation foil diagnostic (red line) and the measurements performed by Health Physics inside the vessel with thermo luminescent foils (triangles).

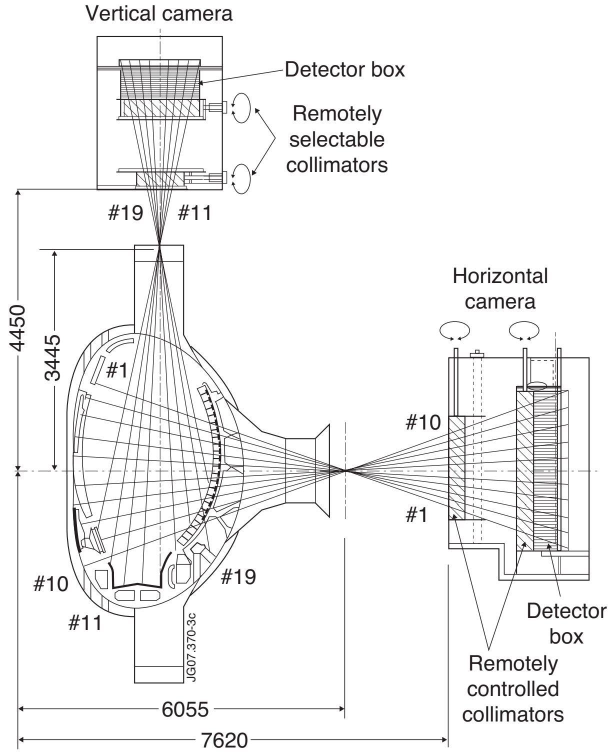

Figure 3: Neutron profile diagnostic.

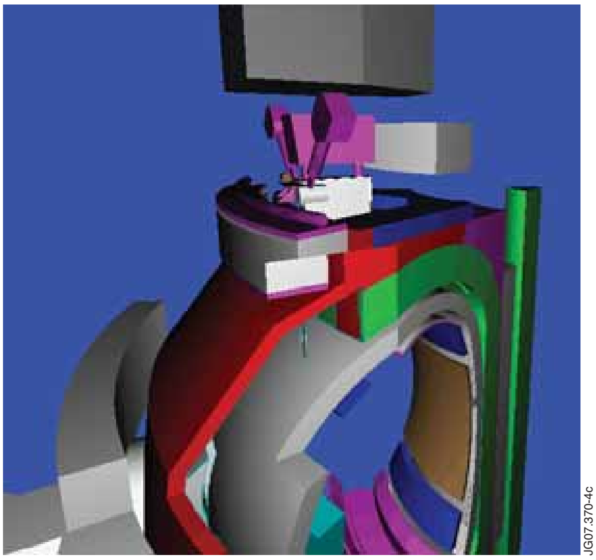

Figure 4: 3-D plot of the updated MCNP model of Octant 1. GM tube has been located below the KN3 diagnostic system on the main vertical port of Octant 1. The TLDs are located in the 2-upper irradiation end closer to the vessel.

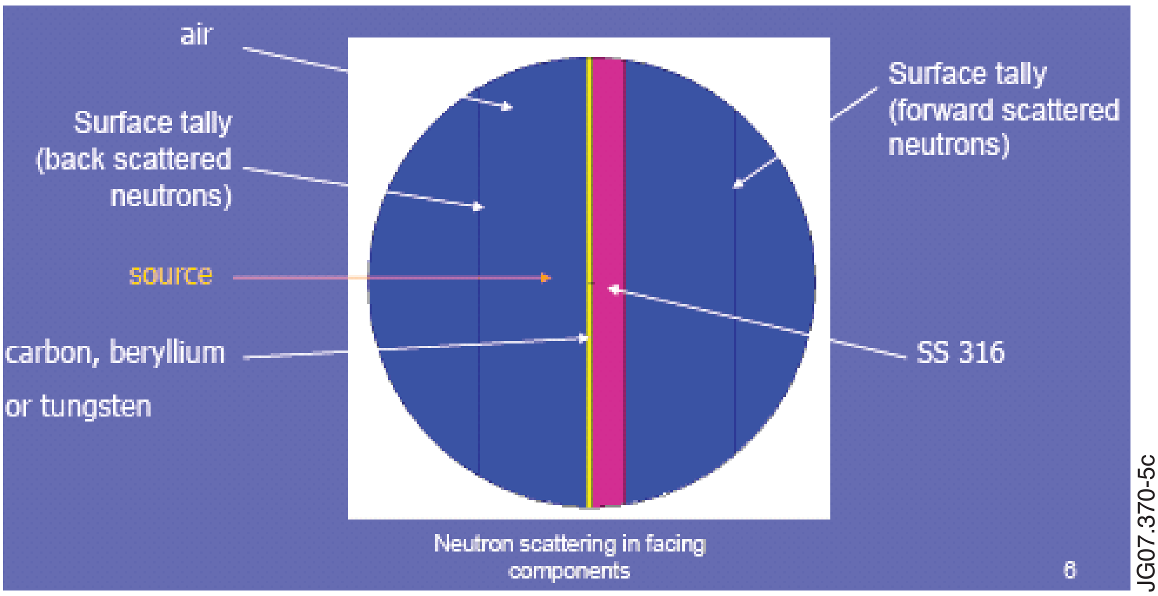

Figure 5: Schematic of the MCNP model used to investigate the effect of various materials on the reflection of neutrons. In red the stainless steel support and in yellow the layer of C, Be or W.

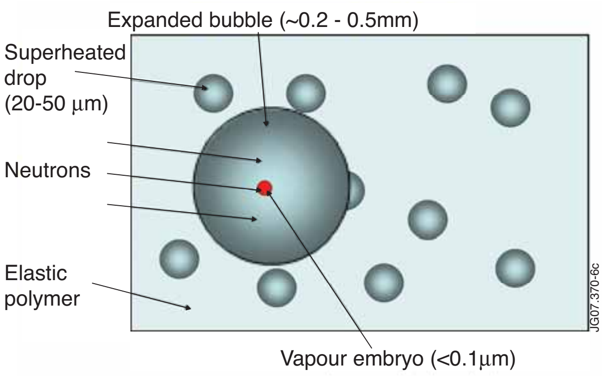

Figure 6: The basic operation of a Super-Heated Fluid Detector

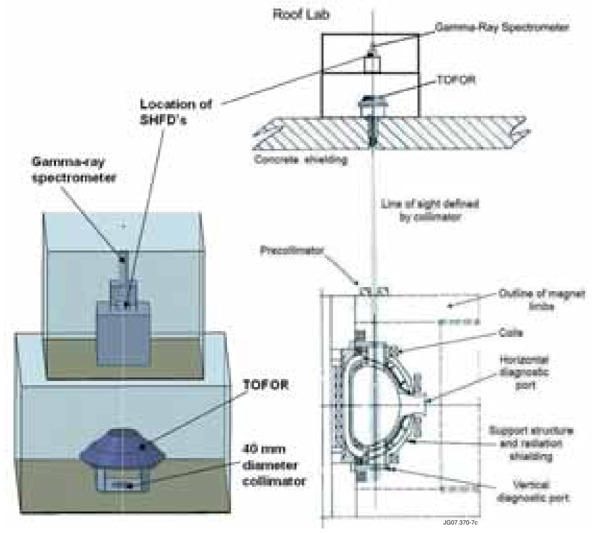

Figure 7: Experimental setup for SHFD neutron measurements along the JET KM11 line.

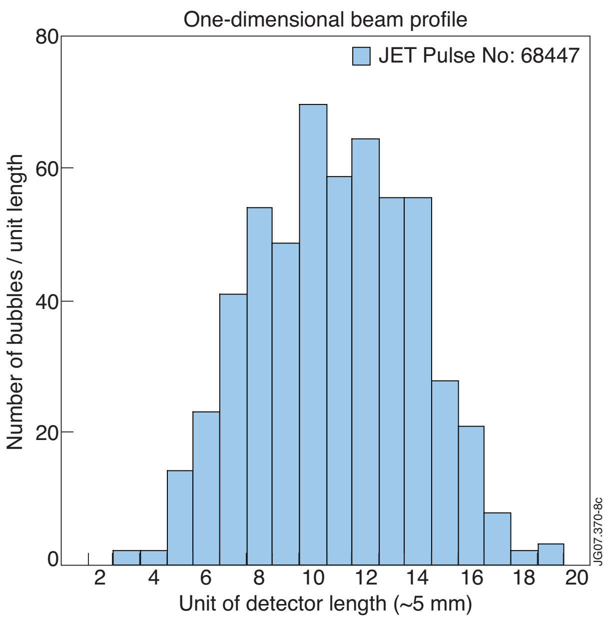

Figure 8: One-dimensional beam profile for JET Pulse No: 68447

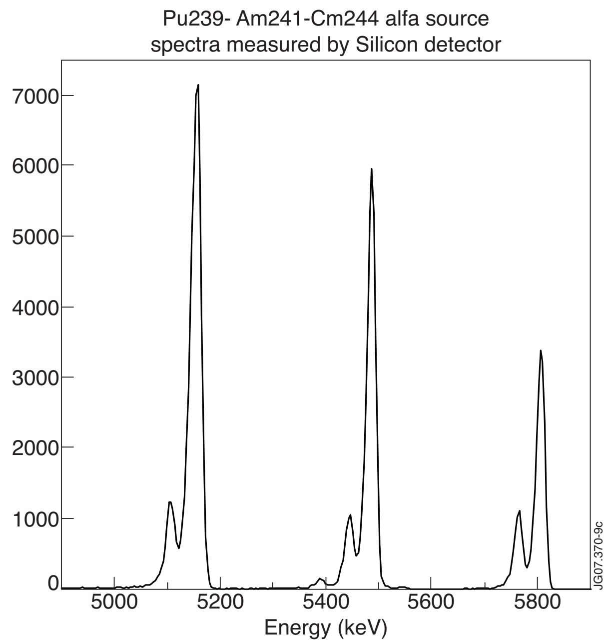

Figure 9: Energy spectrum of a Pu-239-Am-241-Cm-244 Alpha source recorded with our SCD detector. The FWHM of the peaks is 0.6%.

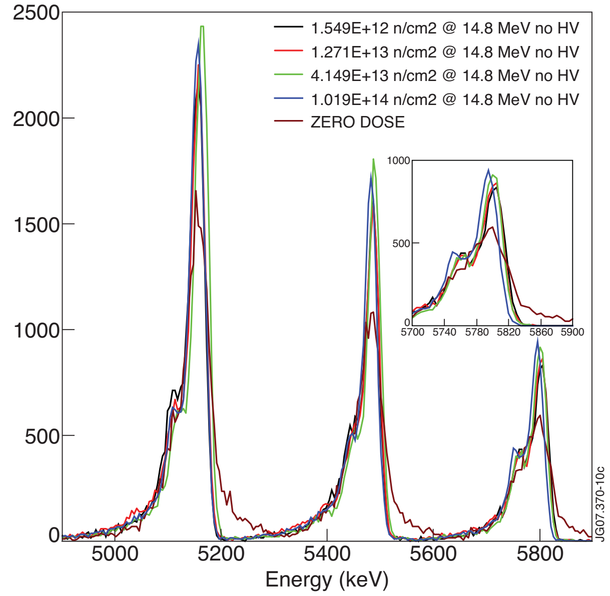

Figure 10 The alphas source spectrum recorded by our SCD at several 14MeV neutron fluences. The inset shows details due to the high resolution (0.6%).

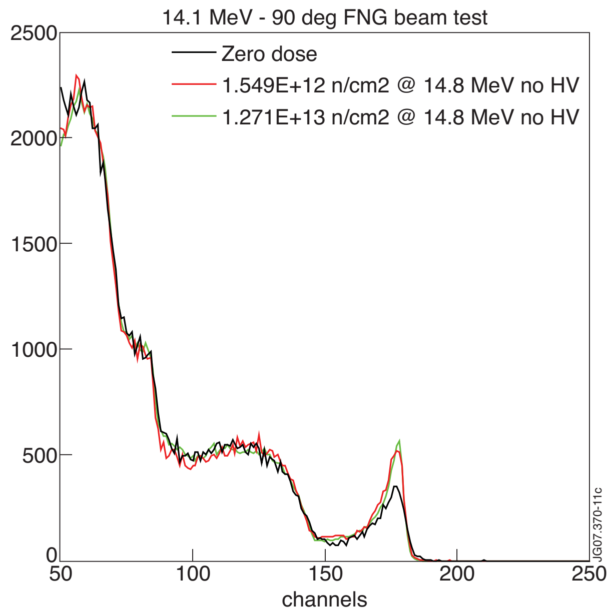

Figure11: Behaviour of the (n, α) peak produced by 14Mev neutrons detected by our Diamond detector as function of the 14 MeV neutron fluence.

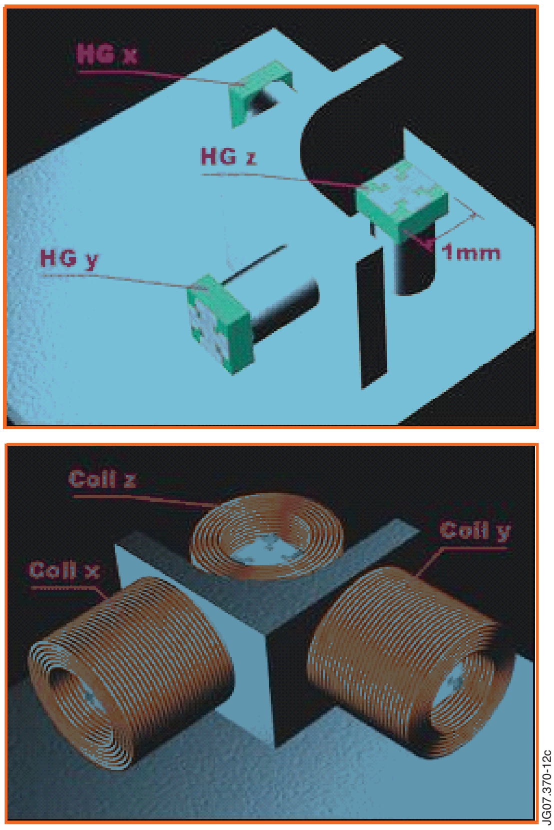

Figure 12; The schematic view of the prototypical 3-D Hall probe installed on JET. Top: the three hall sensors. Bottom: the three calibration coils.

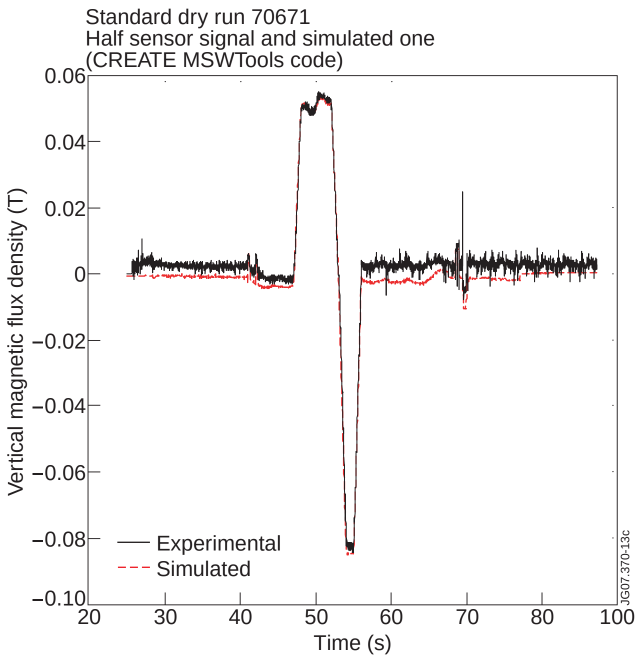

Figure 13: Comparison between the vertical magnetic field as measure by the radiation hard hall probe and a simulation.

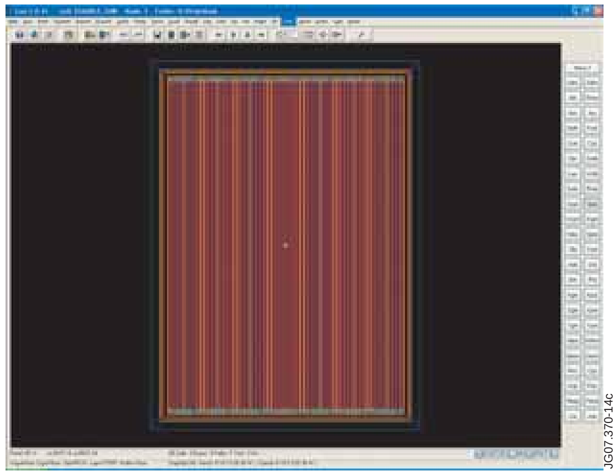

Figure14: The topology of the strip detector under development.

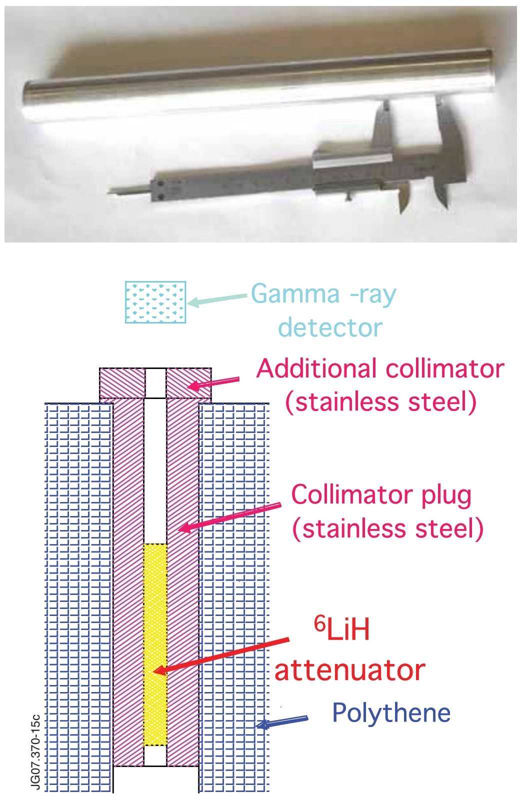

Figure 15: Top: the metal container of the 6LiH. Bottom: th location of the filter inside the collimator plug of a rooflab penetration.

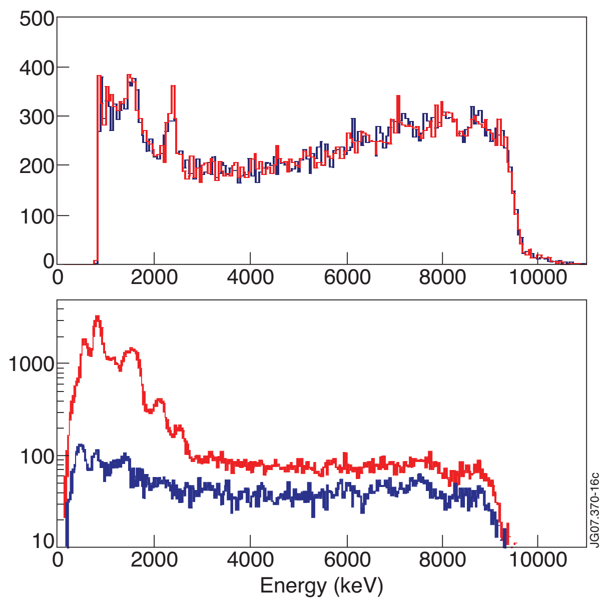

Figure 16: Top: the γ-ray field in two discharges measured with the same detector to show their similarity. Bottom: comparison between the spectrum with (blue line) and without the neutron filter (red curve)

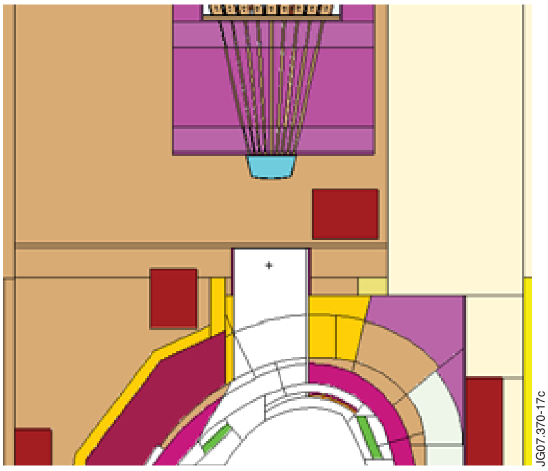

Figure 17: Upper portion of the JET tokamak with the neutron camera system (above in the picture) and the neutron attenuator (in blue colour)

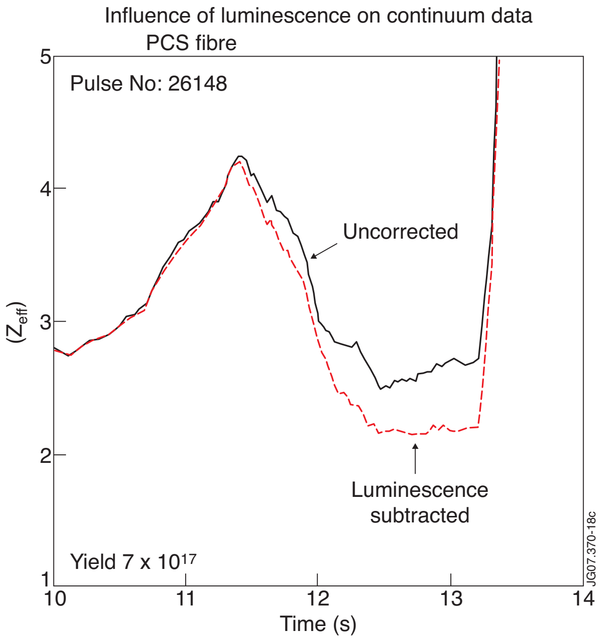

Figure 18: Effect of luminescence on continuum measurements. The correction was performed by subtracting the signal of blind fibres.