EFDA–JET–PR(11)11

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** See annex of F. Romanelli et al, "Overview of JET Results",*
(23rd IAEA Fusion Energy Conference, Daejon, Republic of Korea (2010)).

Preprint of Paper to be submitted for publication in
Nuclear Engineering and Design

ABSTRACT

The power output of fusion experiments and fusion reactor-like devices is measured in terms of the neutron emission rates which relate directly to the fusion yield rate. The largest fusion power produced in magnetically confined experiments so far was at JET in 1997, when a peak value of 16MW was achieved. Determination of such parameters requires a set of absolutely calibrated neutron detectors. At JET, the Fission Chamber neutron detectors were originally calibrated some 20 years ago by performing a set of in-situ calibrations using neutron sources and the absolute calibration has been maintained since then by cross calibrations against activation system measurements. After this elapsed time and a succession of changes to the internal and external JET structures, the JET Neutron yield calibration needs re-measurement.

A new, more detailed, calibration is being provided by means of an engineering programme of development of the robotic tools which will allow safe and accurate deployment of a strong ^{252}Cf source for the measurements. It is led by a scientific programme which seeks to better understand the limitations of the calibration, to optimise the measurements and other provisions, to provide corrections for perturbing factors and to ensure personnel safety and safe working conditions. Much of this work is based on an extensive programme of Monte-Carlo calculations. These include the updating of previous JET models to provide continuity of comparison with previous understanding, the provision of fast models for side effect estimation and the development of a new more detailed JET model which will allow comparisons with the older more homogeneous model while coping with the demands of the new calibration.

1. INTRODUCTION

Nuclear fusion is one of the few technologies with the potential to provide power for the future in a sustainable way. The energy comes from fusion reactions between isotopes of hydrogen and the provision of significant output power requires high densities of high temperature ions to be contained for appreciable times. The provision of these temperatures and densities and the containment of the ions have been best attained and developed over recent decades in the magnetic containment devices, primarily in the TOKAMAK variants. Indeed, nuclear fusion devices have advanced a long way since early short pulse, low energy output experiments, to the point where the present world-leading machine, JET has produced a peak fusion power output of 16MW and a 2MW output over 4 seconds [13]. This 16MW represents a fusion power gain of $Q \sim 0.65$ and is the closest approach so far to 'break-even' ($Q = 1$) when the power out would equal that in.

Unsurprisingly, the design of the successor machine, ITER (see ITER web site, 'ITER.org') which is now being built in the south of France, has depended much on the design features, innovations and outputs of JET and other recent fusion devices. ITER will be linearly larger by factor of ~2, with other parameters also scaling up to make an output power of up to 500MW available for up to 1000 Seconds. However some design questions remain and JET is well placed to answer these because of its many existing ITER-like features (e.g. tritium fuel operation, beryllium conditioning) and the upgrades which are being installed during the current major shutdown. JET is an ongoing and changing Experiment, not a reactor prototype. It has been a successful and flexible machine, with ~ 25 years operation in different configurations. A strong feature of JET is the comprehensive set of diagnostics installed on the machine. Notable are the neutron diagnostics, especially those whose yield rate measurements crucially maintain the most direct measurement of the fusion output. A yield recalibration is planned for these diagnostics after the installation of the current major changes in JET and this is the subject of this paper.

2. JET YIELD CALIBRATIONS

2.1 CURRENT METHODS AND CALIBRATION STATUS

At JET the Fission Chambers and the Activation System methods have maintained the neutron measurement capability since 1984. Accuracies of 8-10% have been achieved. The Fission Chamber (FC) neutron monitors comprise 3 pairs of moderated ion chambers containing ^{235}U and ^{238}U respectively, mounted in moderator packages at locations on the transformer magnet limbs and on the vertical mid plane of the torus [17].

These operate in both pulse counting and current modes. In particular, the ^{235}U Fission Chambers are insensitive to neutron energy and cover the neutron emission rate range from 10^{10} to 10^{17} neutrons per second. They were calibrated directly with respect to a standardised ^{252}Cf fission source inside the torus vessel in 1984/9 and that calibration has been maintained over the years by cross-calibration to the in-vessel Activation System [10, 5, 6].

The Activation System pneumatically delivers and retrieves capsules to/from locations inside the torus structure, i.e. the edge of the vacuum vessel. There are 8 such ‘Irradiation Ends’, located in 5 octants. Capsules are delivered before and retrieved after the pulse for counting of the induced radioactivity by gamma spectroscopy or by delayed neutron counting, depending on the sample type placed within the capsule [7].

The original calibration methods and results were described by [10]. This first in situ absolute calibration of Fission Chambers used a standards laboratory calibrated ^{252}Cf source of 2.0×10^8 n/s. The sensitivity to the neutron energy spectrum was also demonstrated using a ^{241}Am-Be source and a 14MeV neutron generator. The data comprised direct measurements of the Fission Chambers’ Calibration Factor for ^{252}Cf versus Toroidal Position, plus indications of its dependence on Source Radius & Height. They were also used to define parameters of a 3-dimensional model of the plasma and to help model the response for each FC detector. Monte Carlo and analytic calculations were used: a) to help understand the data, b) to correct the results, and c) to relate point source yields to modelled plasma yields.

After 25 years, many changes to the JET device have ensued and it is necessary to renew this calibration work. Indeed it is now possible to make a more comprehensive experiment and a more detailed calculational analysis. These will be the main subject of this paper, but for now we summarise the early measurements and their results and consider the current extent of knowledge of the calibration.

The measurement conditions, data and neutronics calculations of [10] are summarised in figures 1a and 1b. Note that the calibration has also been confirmed at different times and in different conditions by other independent neutron diagnostics, for example the Neutron Profile Monitor [11] and more recently the Magnetic Proton Recoil spectrometer [15].

Laundy and Jarvis note a significant change in the calibration value between 1984 and 1989. This arose because of the installation of many new large systems in the torus hall outside the JET vacuum vessel which in this case, reduced the fission chambers' response per ^{252}Cf neutron. This changing calibration situation was set to continue and so, after some time cross-calibrating against the fission chambers, the internal Activation System was used to carry forward the absolute calibration and has done so thereafter. The fission chambers are now cross-calibrated to the activation system in plasmas with particular conditions and which provide well-understood neutron emissions of adequate rates. The Activation system is essentially unaltered by changes in the major devices outside the JET vacuum vessel, but not necessarily by major changes inside the vessel, as we see later in section 2.7.1.

Scientifically we need to check the direct calibration after all this time and it is now possible to improve on both the early data and the calculations. After JET operations restart in 2011, there will an extended period of learning on operational issues related to the new ITERlike (beryllium) wall and this will restrict the use of the high power neutral beam-driven plasmas which would normally be used for our cross-calibration and indeed to give adequate statistical precision on the Activation System measurements. Therefore it is necessary after the wall changes to independently confirm the Fission Chambers' absolute calibration.

2.2 PROPOSED MEASUREMENTS & MODELS FOR THE JET IN-VESSEL NEUTRON SOURCE CALIBRATIONS PROJECT

It is intended to make updated JET neutron yield calibrations as soon as operationally possible after the 2010 wall changes. This project includes physics, engineering and safety work to ensure safe and accurate deployment of a strong neutron source in the JET vessel, plus updating of the relevant JET neutronics models used to understand, correct and use the measurements for plasma yield predictions. Specifically, we will

1. Confirm previous measurements for the Fission Chambers, i.e. make a ring scan in-torus, plus a simple vertical scan and a simple horizontal scan at one port. Also we will update previous models with major JET changes (C, Be Walls, Antennae) to give continuity of comparison with previous data & models;
2. Extend previous measurements for the Fission Chambers, i.e. make an extended 'basket scan' (Fig.2) as a better 3D plasma proxy. Since the previous (1-sector) neutronics models do not cope accurately, we will develop 3D neutronics models which do;

3. First Direct Calibration Measurements of the Activation System. This requires firstly the use of a stronger source to give enough activation events. Secondly we must develop a new 3D JET neutronics model, to cope with the local detail required, and to relate point source measurements to ring and plasma sources.

Figure 2 gives an impression of the draft in-vessel scan pattern. A week of working in-vessel is required for the measurements (covering both the Fission Chambers and the Activation System), using robotic deployment of a strong ^{252}Cf source, with an emission rate up to 1×10^9 n/s.

As this source can give a substantial fraction of the annual dose limit to a person at 1m in just one hour, the calibration project requires appropriate precautions to ensure careful separation of people and source at all times. The calibration project is therefore structured with components on Physics Preparations, Neutron Source Issues, Health Physics & Safety Issues plus Engineering and Remote Handling (RH) developments. In fact, activities within these four work threads interact iteratively all through the project design, development and execution.

2.3 DEPLOYMENT ENVIRONMENT

The earlier source deployment for calibrations had been done in a relatively pristine JET machine, which had a clean all-metal inside wall, no divertor and relatively easy man access. The recent JET is very different. It has Carbon tiles and a divertor floor inside the vessel, and its atmosphere is contaminated by tritium and beryllium from previous campaigns. Delicate beryllium & tungsten tiles will be in place after the current shutdown activities. Man access is now difficult and is undertaken wearing an air suit with external air supply. While building a scaffold and laying a tube toroidally round inside the machine was relatively straightforward in the JET of the late 1980's, the interior environment and difficult access now make it very difficult. After a more detailed analysis, it was decided to make use of the existing JET robotics arms [18] to effect the neutron source deployment.

The deployment environment is shown in Figure. 3. The torus is shown in crosssection with the robotic boom and MASCOT robot entering JET octant 5 from its Boom Tent (protected environment) on the right. On the left, the second boom enters from its Boom Tent environment into JET Octant 1. This boom is used only for dealing with contingencies in our case, while on the other boom, the MASCOT will carry the ^{252}Cf neutron source for all normal measurement operations. These booms are substantial objects spanning the 11m port to port distance across JET. Their normal task is to change tiles and other inside equipment during JET shutdowns, by Remote-Handling.

2.4 SEPARATION OF SOURCE AND MASCOT ROBOT

The Mascot Robot head is massive, so the calibration project has produced tools which help to minimise the effect on the measurements by separating the neutron source from it and which meet the several other requirements below. The key tool is the 'Source Baton' within which resides the source. It allows remote handling pickup of the neutron source on JET site, and is taken up by the MASCOT, using a tool called the 'Mascot Baton'. The combined 2-baton length provides the required separation. This allows us to satisfy the main requirements, which are: minimal neutron scattering distortion of measurements by the presence of the Mascot Robot and its Boom, negligible radiation damage to cameras on the robot & loading bay approaches, failsafe source pickup and deposit with a remote handling compatible connection, a safe source transfer method into JET from the delivery transport flask and a plan to deal with major contingencies (see section 2.6).

2.5. NORMAL OPERATIONAL DEPLOYMENT OF THE 252CF NEUTRON SOURCE WITHIN THE JETENVIRONMENT

In the JET facility, the source is received within its 'Source Baton' within its 1 Tonne Transport Flask and transferred to the Octant 5 Boom Tent in the torus hall. After people are withdrawn from the torus hall, the MASCOT Robot, uses its Mascot Baton to connect to and withdraw the Source Baton containing the ^{252}Cf neutron source. [Fig.4] The boom takes the source and MASCOT into the torus via the Octant 5 entry port. Within the torus, the source is deployed at the end of the combined baton at the end of the MASCOT robotic arm, so it is some distance (~ 1-2m) from the MASCOT head (Fig.5). Movements of boom joints allow deployments more than half way round the torus (in either direction) and at a range of heights and radii within the vessel. This provides the complete range of normal deployments. The source can be withdrawn back to its transport flask for return at the end of the measurement series, by movements exactly as for entry, but in the opposite sense.

2.6 CONTINGENCY ARRANGEMENTS

A detailed Fault Susceptibility Analysis [14] has shown that the main risk of potential faults in the deployment sequence come from particular movements of either Oct 5 or Oct 1 boom. These faults are still very unlikely, but in such an eventuality, the neutron source must be retrievable to a Safe Shield Point, i.e. its Transport Flask (TF), or to a separate mobile shield, to allow safe torus hall entry to effect manual repair actions. The key contingency provision is this mobile shield, ie the 'Operational Shield' (OS) which is a rectangular polythene shield of size limited by port entry and carried on the Octant 1 Boom. The boom can present the OS more than 160 degrees round the torus and can deposit the OS in a safe store outside the torus. [See Figure 3] The OS reduces the emitted dose rates from the Source and would be used when there might be a fault on either boom.

2.7 NEUTRONICS CALCULATIONS TO SUPPORT THE JET NEUTRON CALIBRATIONS

As in the original calibrations, neutronics calculations are required to support the physics, safety and engineering efforts. These cover 3 main requirements as given below with typical examples:

1. Validity of Calibration & Planning, e.g. rates, statistics, position & energy dependencies and JET model updates for both FC and Activation System (AS) methods are required.
2. Corrections, e.g. scattering from source encapsulation, holder, or robot and otherneighbouring items or edge and 'real world' effects such as open octants, items outside torus)

3. Safety, e.g. dose rate estimates for various operating conditions, shields etc to help decide which operations are manual or remotely handled.

The models used have to be adequate in complexity to meet the required accuracy, but able to run in a finite time. [10] used a JET model of simplified geometry to predict and understand the dependence of the response of the external FC's with angle from the nearest port. The absolute FC rate values were adjusted to fit the measured yields in order to obtain the agreement seen in Fig.1b. Over 1995-2000, M Loughlin developed the MCNP [1, 19] model most used to describe the JET features necessary for calibration purposes. We call this the 'JET Homogenised Model' [11]. The version with a JET interior wall geometry and composition relevant to the real JET of about year 2000 is referred to as 'JET C Wall 2000'. This extensively Homogenised 1-Sector Model, gave reasonable results for the then current values of the Activation Coefficients [activations produced per target atom per source neutron] for the (AS) samples [11]. The external FC's are not covered by these calculations, which were restricted to predictions of in-vessel responses for ring-type plasma sources.

Since 1995 computer power has gone up by more than a factor of 1000, so a more complete and detailed model is now possible which could potentially calculate JET Activation System and external FC responses on a simultaneous basis.

2.7.1 Choices of models

We now have developed 3 types of MCNP model which have been useful in different aspects of the calibration preparations.

1. The first type is an updated version of M Loughlin's homogenised 1-sector model 'JET C Wall 2000', to allow comparison with the earlier Activation System results in a consistent way for the newer JET conditions. The updated models were made by I Lengar, between 2008 and 2010, to reflect the more recent configurations of JET geometry and materials, ie the more recent Carbon wall (2005-2009) and the new ITER-like 'Be wall' which is now being installed (2011). In fact this wall has a complex geometric distribution of tiles of different materials & types (mainly Be, W, C) but we do not discuss that further in this paper.

   Only the changes in major internal items were updated, see Figures 6a, 6b. The models are now called: JET C Wall 2000, JET C Wall 2009 and JET Be Wall 2011 [8]. Output from running these models has allowed assessment of the effect of JET major internal changes on the neutron calibration on a consistent modelling basis. For example, the addition of the ~10 Tonne Lower Hybrid Antenna in Octant 3 and the RF antenna in Octant 3 inside the JET torus is shown to have a combined effect of just +3% on the Activation Coefficient value. The Be wall itself and its modelling are more complex, but the basic JET structure is unchanged. The transition to the ITER-like wall has an opposite effect and in fact, reduces the activation coefficient by ~10%.

2. The second type of model is a simplified but quick-running 3 dimensional model of the JET torus in its torus hall, with a torus of rectangular cross-section [16] which is similar to the original model used by [10]. This new model has allowed the rapid evaluation of particular calibration issues, e.g. the prediction of the toroidal dependence of the Fission Chambers response with source position in the torus (Fig.7) plus the use of flagging to show that the response comes mainly via the ports, and their relative importance. The optimisation of the source baton design for low neutron scattering and the prediction of corrections for such effects is another example [16].
3. The final type of model is a new & more-detailed 3 dimensional model of the JET torus in its torus hall [2, 3]. This model is necessary to properly calculate the Activation System Response for the new direct point source calibrations and to deal with the wider range of scan information for FC and AS systems which will be provided by the new calibration data set. An early version of this model was used for the important task of estimating dose rates from the source in various shields and in the torus, for the purpose of evaluating the limitations to man access in various operational situations. An example is shown in Fig.7. This shows colour-coded 'contour maps' of dose rate, calculated from the Neutron Source in its Operational Shield (OS) in the torus versus position & versus orientation – the particular position is with a vertical OS, orientated at 0 degrees to the port.

These calculations helped us conclude that when the neutron source is in the OS & in the torus, we can allow man access to the torus hall for most Mascot & Oct 5 Boom repairs, ie that the OS is a valid safe source storage situation. This occurs mainly because the OS cuts the TOTAL emission of radiation by a factor of 33.

3. SUMMARY

Fusion is a potential source for future power plants. Fusion science and technology have seen dramatic development over the last few decades, culminating in JET, which is the present world-leading fusion device. Fusion yields are measured most directly by neutron yields. In this regard, the JET neutron yield calibration has been known for 20 years – but needs re-measurement in what is now a radically different JET. The planned In-Vessel Neutron Source Calibrations will both confirm and improve upon the previous calibration. An extensive set of accompanying Neutronics Calculations are required and are ongoing. Both measurement methods and calculations have been described in this paper. The actual JET Calibration Exercise will be carried out within the JET schedule of operations after the 2011 wall changes.

The next machine, i.e. the ITER, is beginning its final design and build phase. JET will test many ITER-like features in the next few years, both from its established position as the key ITER test bed and from its 2010 installation programme of an ITER-like first wall. The neutron calibration exercise at JET will be a valuable guide to planning the more extensive calibrations on ITER. Subsequent calibration work on JET will be linked to a return to Tritium plasmas, to be run about 2015.

ACKNOWLEDGMENTS

This work was supported by EURATOM and carried out within the framework of the European Fusion Development Agreement. The views and opinions expressed herein do not necessarily reflect those of the European Commission. M Loughlin is acknowledged for communication of his homogenised 1-sector MCNP models of JET in 2007.

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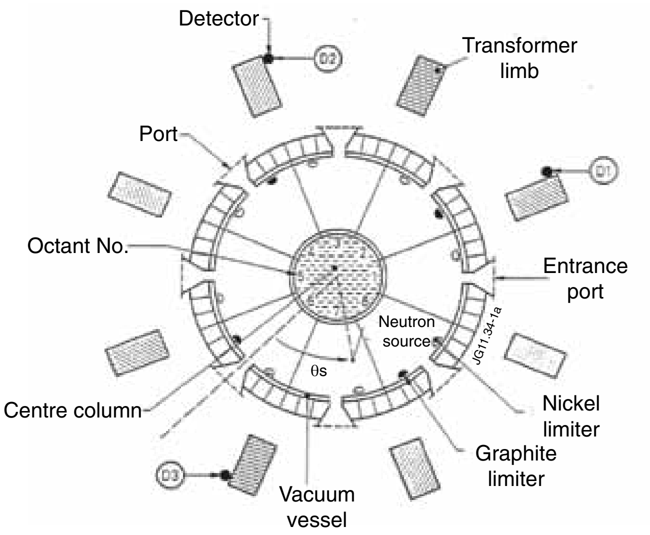

Figure 1: (a) JET torus schematic, showing Fission Chamber Detectors on the transformer limbs & trajectory of source positions round the torus torus, from the nearest port.

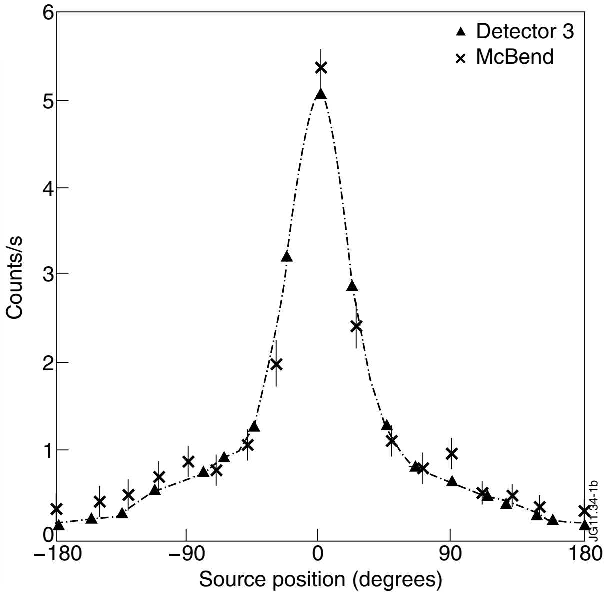

Figure 1: (b) FC 3 counting rate versus angle of source round & trajectory of source positions round the torus torus, from the nearest port.

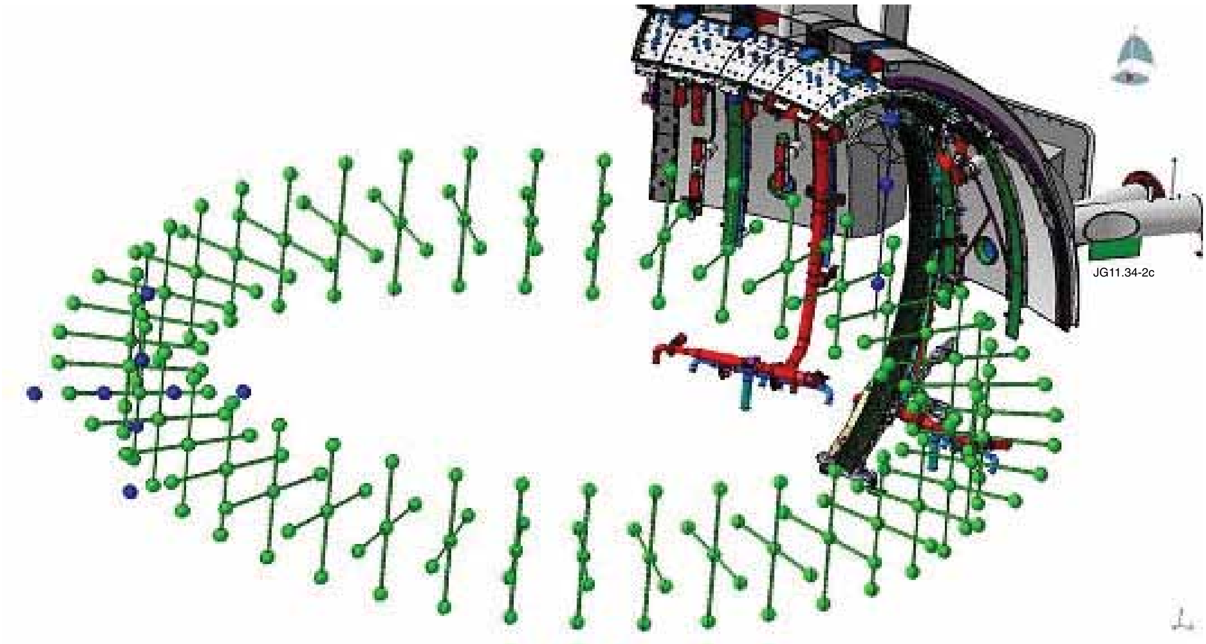

Figure 2: Draft in-vessel scan pattern. Only part of the JET structure is shown.

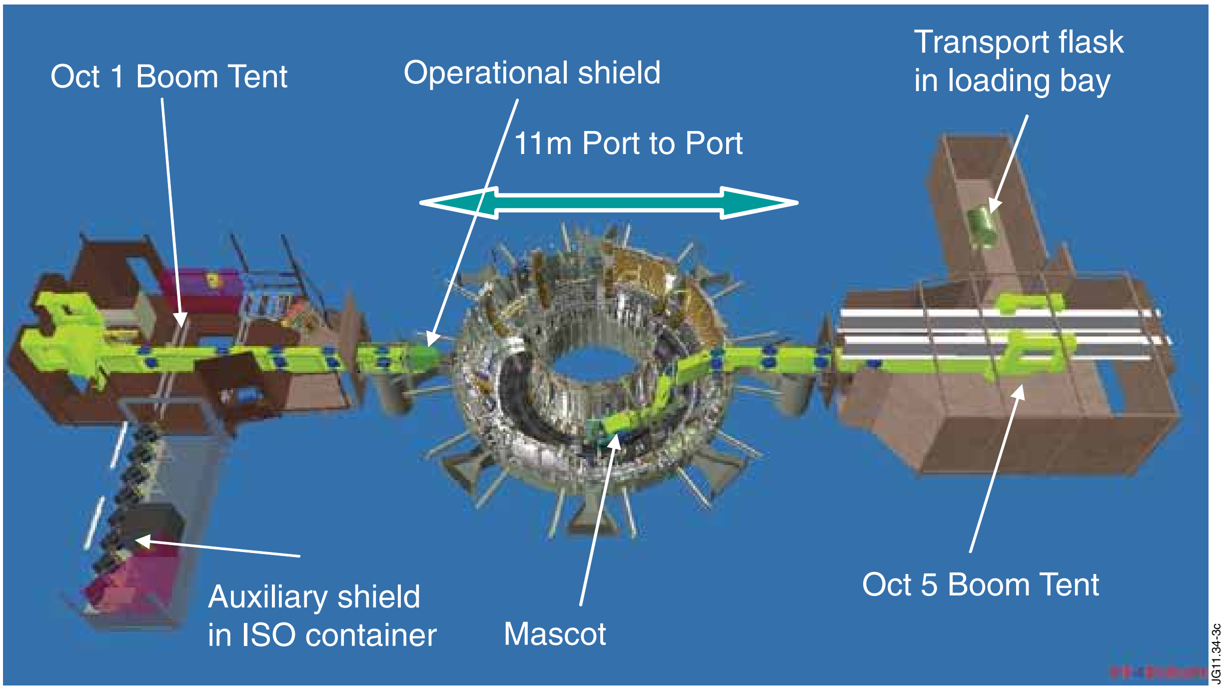

Figure 3: Deployment Environment for JET Neutron Source calibrations. Equipment and items on the right are for normal source deployment operations. Equipment and items on the left are used in contingencies. The JET torus and accompanying boom tents are shown in cross-section.

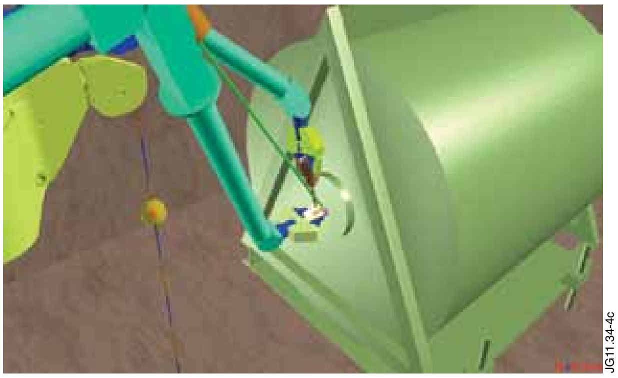

Figure 4: Transport flask schematic, with the MASCOT robot arms connecting to the neutron source baton (inside the flask).

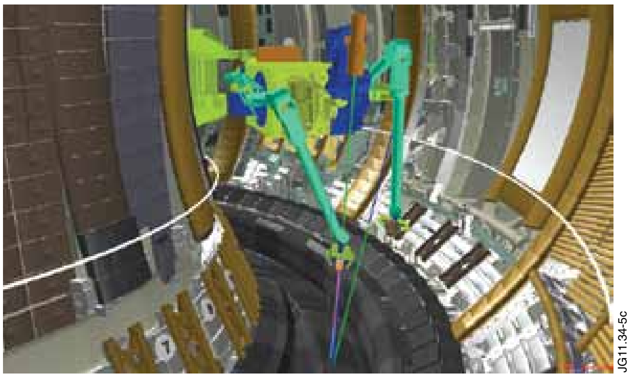

Figure 5: JET torus schematic, showing MASCOT the MASCOT robot arms connecting to Robot deploying neutron source baton round the interior of the JET torus.

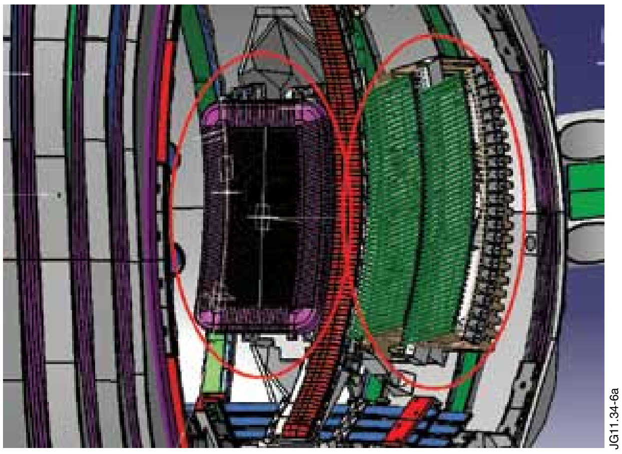

Figure 6: (a) JET torus schematic, showing the Lower Hybrid (LH) and RF Antennas in the interior of the, vacuum front vessel. The RF antennas are on the right of the Oct 3 port.

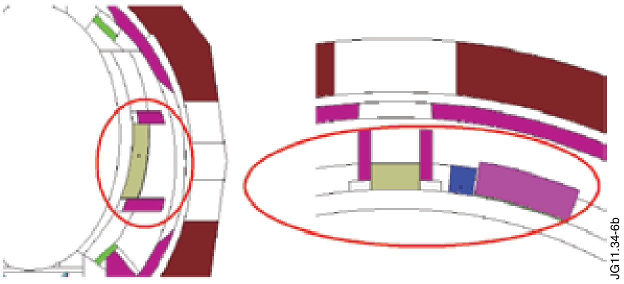

Figure 6b: MCNP model of the JET interior showing the block representation of the two Antennas shown in Fig 6a. The LH Antenna is on the left and the RF Antennas are on the right.

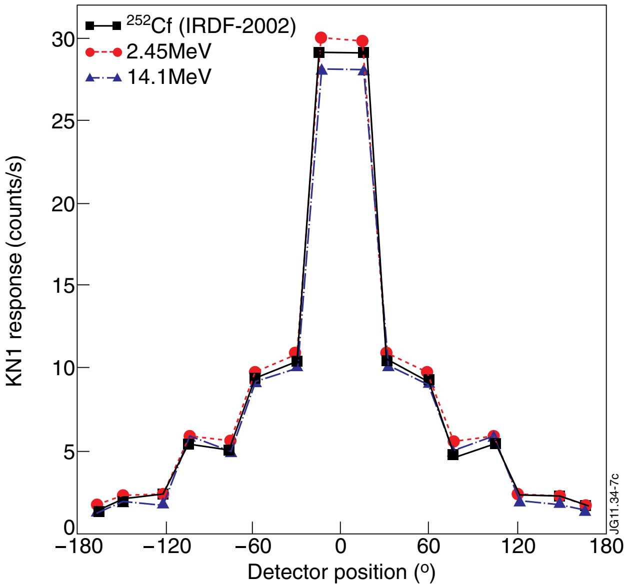

Figure 7: JET Fission Chamber response at different azimuthal positions, with respect to a point source located in the plasma centre and in front of a particular port, ie at 0^o.

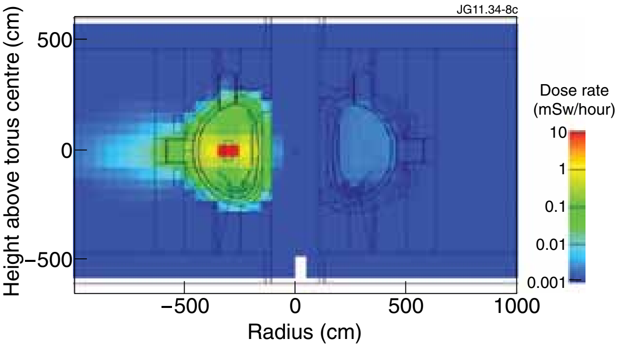

Figure 8: Dose rate 'contour map' and key for the neutron source in the source baton, in the OS, in the torus. Radiation levels outside the torus walls are less than 10uSv/h.