EFDA–JET–PR(12)01

L. Snoj, I. Lengar, A. Čufar, B. Syme, S. Popovichev, S. Conroy, L. Meredith
and JET EFDA contributors

Calculations to Support JET Neutron Yield Calibration: Modelling of the JET Remote Handling System

Calculations to Support JET Neutron Yield Calibration: Modelling of the JET Remote Handling System

L. Snoj[1], I. Lengar[1], A. Čufar[1], B. Syme[2], S. Popovichev[2], S. Conroy[3], L. Meredith[2] and JET EFDA contributors*

JET-EFDA, Culham Science Centre, OX14 3DB, Abingdon, UK

[1]EURATOM-MHEST Association, Reactor Physics Division, Jožef Stefan Institute, Jamova cesta 39, SI-1000 Ljubljana, Slovenia
[2]EURATOM-CCFE Fusion Association, Culham Science Centre, OX14 3DB, Abingdon, OXON, UK
[3]EURATOM-VR Association, Department of Physics and Astronomy, Uppsala University, Box 516, SE-75120 Uppsala, Sweden
** 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

After the coated CFC wall to ITER-Like Wall (Beryllium/Tungsten/Carbon) transition in 2010-11, confirmation of the neutron yield calibration will be ensured by direct measurements using a calibrated ^{252}Cf neutron source deployed by the in-vessel remote handling boom and Mascot manipulator inside the JET vacuum vessel. Neutronic calculations are required to calculate the effects of the JET Remote Handling (RH) system on the neutron monitors. We developed a simplified geometrical computational model of the JET remote handling system in MCNP. In parallel we developed a script that translates the RH movement data to transformations of individual geometrical parts of the RH model in MCNP. After that a benchmarking of the model was performed to verify and validate the accordance of the target positions of source and RH system with the ones from our model. In the last phase we placed the JET RH system in the simplified MCNP model of the JET tokamak and studied its effect on neutron monitor response for some example source positions and boom configurations.

As the correction factors due to presence of the JET RH system can potentially be significant in cases when the boom is blocking a port close to the detector under investigation, we have chosen boom configurations so that this is avoided in the vast majority of the source locations. Examples are given.

1. INTRODUCTION

Neutron yield measurements are the basis for the determination of the absolute fusion reaction rate and the operational monitoring with respect to the neutron budget during any campaign for the Joint European Torus (JET).

After the Carbon wall to ITER-Like Wall (Beryllium/Tungsten/Carbon) transition in 2010-11, confirmation of the neutron yield calibration will be ensured by direct measurements using a calibrated ^{252}Cf Neutron Source (NS) deployed by the in-vessel Remote Handling (RH) boom and mascot manipulator inside the JET vacuum vessel [1].

This calibration will allow direct confirmation of the external Fission Chambers (FC) calibration which was the original JET standard [2] and provide the first direct calibration of the JET activation system inside the torus. The objective of the calibration is to achieve at least 10 % accuracy in absolute calibration of the JET external neutron monitors.

In total more than 200 locations of the NS inside the tokamak will be used for neutron monitor calibrations. The locations of all NS calibration points inside the torus are schematically presented in Figure 1. There are 40 locations in the toroidal direction round the torus, each location having 5 positions: one is Centrally located (C) in the plasma centre 30 cm above the tokamak midplane and 4 positions are offset from this central one by 0.5 m in the Upper (U), Lower (L), Inner (I) and Outer (O) directions. These point source measurements simulate 5 rings round the torus; a central ring plus up, down, in and out.

These desired locations and the preferred source-baton orientations for physics needs were given to the RH group who produced the required Virtual Reality (VR) files of the RH dispositions of the mascot and the boom by using special software named VR4 Robot (Figure 2). These files contain the orientation information for all joints in the boom/mascot and enable the movements between successive locations.

Preparation of all RH movement files and simulating all RH movements in advance is needed in order to ensure that the boom + mascot move within strictly approved safety limits, e.g. away from the vessel edge.

Note that the RH system is normally driven by direct operator control (master-slave system) when it gets near the point of work within the torus. The operator uses visual and touch feedback at that point e.g. for the common tasks of replacing tiles & components. But, for our purposes we essentially require the VR system to place the end of the mascot baton on a point within the torus under VR control, although there may be operator guidance during the final fine positioning stage. In order to safely handle the neutron source, it will be placed inside and at one end of a specially designed tube (the 'source baton') which is small enough to be carried within a shielded transport flask. At JET, the neutron source will be deployed into the JET vessel via the octant 5 'mascot' manipulator. The source baton can be picked up by and locked on to a specific RH tool called the 'mascot baton' which is borne by the mascot. The 2-baton combination provides remote source handling, while ensuring adequate separation of the neutron source from the mascot body. That separation is required in order to reduce neutron scattering from the mascot manipulator, to reduce activation of the manipulator and to limit the dose on the manipulator cameras [4].

As in all such calibrations, neutronic calculations are required to support the physics, safety and engineering efforts. Many are based on Monte Carlo modelling using the advanced Monte Carlo transport codes, such as MCNP [5].

The JET RH system contains some substantial objects, which will be inside the vacuum vessel during the calibration, hence it is expected that these objects will significantly affect the neutron transport from the NS to the neutron monitors.

The purpose of this paper is to provide guidance on how to asses the effect of the RH system on the neutron transport, how to model the remote handling tool in MCNP or any other code that uses similar syntax and how to verify the code that transfers remote handling data to MCNP. In addition the paper serves as an introduction to the studies of the effects of major components of the JET RH system on neutron monitor response.

Firstly we developed a simplified geometrical computational model of the JET RH system in MCNP based on the engineering drawings. In parallel we developed a script that translates the RH movement data to transformations of individual geometrical parts of the RH model (boom + mascot) in MCNP. Secondly we performed a benchmarking of the model to confirm accordance of the target source and RH system positions from our model with the originals. In the last phase we placed the RH system model in the simplified MCNP model of the JET tokamak [3] and studied its effect on the neutron monitor response for some characteristic deployment configurations. In the paper the above activities are described and preliminary results are presented.

2. JET REMOTE HANDLING SYSTEM

The JET RH system has evolved over decades of learning and is currently the most accomplished RH system of any fusion device in the world [6]. It comprises two articulated Booms that access the vessel through diametrically opposite ports, see Figures 2 and 3.

The first boom is called the Octant 5 Boom after the number of the octant through which it enters the tokamak. It transports and positions the dexterous, force-reflecting master-slave servo-manipulator (called the Mascot) [8]. A second articulated Boom (the Octant 1 Boom) works in parallel with the first. Its role is to transfer components and tools between storage facilities outside the torus and the workplace within the torus. Both Booms are hyper-redundant multi-joint devices to allow them to "snake" their way through the narrow ports and around the torus. In the continuation of this paper we will talk only about the first boom, which will be used to deploy the mascot manipulator carrying the neutron source around inside the vessel.

The boom includes several joints and has 9 degrees of freedom, one translation and 8 rotations. The mascot manipulator has 6 degrees of freedom for each arm, all of them being rotations. Any configuration of the JET RH system is defined by 21 coordinates, 9 defining one translation and 8 rotations of the boom sections and 6 defining the rotations of the joints on each of the two arms. Coordinates of any joint on the JET RH systems can thus be reconstructed by knowing the lengths of the links between the joints and knowing the JET RH coordinates.

3. NEUTRONIC MODELLING OF THE JET REMOTE HANDLING SYTEM

This section provides guidance on how to model a remote handling tool in MCNP and how to verify the code that transfers remote handling data to MCNP. Moreover the guidelines are applicable in any other code using similar cell definitions syntax as MCNP, e.g. TRIPOLI [11].

3.1 GEOMETRICAL MODEL IN MCNP

In MCNP the geometry of the system under investigation is defined by objects called cells, which are each filled with a designated material and bounded by surfaces. The surfaces can be transformed in space by using the so called transformation card. The latter feature was used to transform the components of the JET RH system within the tokamak in such way to correspond to the actual situation.

Simple shapes, such as boxes and cylinders were used to explicitly model the casing of the RH system components which contain most of the mass. The interior however, is more complicated as it contains cables, electromotors and other small and geometrically complicated components. As we are dealing mostly with neutrons of relatively high energies, (i.e. $E > 100$keV), which are not sensitive to the fine details, we modelled the interior components as a homogenous mixture of materials, such as Al, Fe and Cu, representing the electromotors, stainless steel presenting wires, cables, W for balance weights, etc. Voids in components were taken into account by adjusting their densities. More details on the modelling are presented in Table 1.

It is important to note that due to lack of accurate information on the exact material details, the material composition and the density of the homogeneous mixture at this stage is estimated based on the photos of the interior of the components, visual inspection of accessible components, private communications with people from the JET Remote handling group and the JET Drawing office. A more complete investigation of the compositions and layout of materials is now in process and the results will be included in the final calculations, which are out of scope of this paper. As the purpose of this study is to investigate the size of the effects and to understand the corrections of the neutron monitor response due to the JET RH system, it is believed that the present modelling is adequate at this stage. The neutron source baton assembly containing the Cf neutron source is modelled in every detail, as already presented in [4].

The individual JET RH components are then transformed in the system e.g. the tokamak, by using the transformations (i.e. translations and rotations) in such way that they represent the actual arrangement for individual calibration points. The calculations of the transformations are thoroughly described in the following section.

The 3D view of the MCNP model of the JET RH system holding the neutron source holder in its basic position is presented in Figure 4.

3.2 COUPLING OF MCNP AND JET RH SYSTEM COORDINATES DATA

As mentioned earlier the purpose of our work is to be able to calculate the neutron monitor response correction factors for every calibration point, i.e. for every JET RH system configuration. Hence we have to prepare MCNP input for every source point, each featuring a different arrangement of the JET RH system components. In order to do this we wrote a script named RH2MCNP (in Fortran 77) that reads the JET RH coordinates and calculates the transformations of each RH system component in the MCNP model and computes the location of the neutron source.

In section 2 it was mentioned that coordinates of any joint on the JET RH systems can be reconstructed by knowing the lengths of the links between the joints and knowing the JET RH coordinates. The latter can be easily extracted from the VR4 Robot software, which is used to plan and simulate the JET RH movement.

A section A_i in the MCNP model of the JET RH system is represented by the body featuring the primary axis in direction $\vec{A}_i$, where $|\vec{A}_i|$ is the length of the link between the joints connecting the sections. Hence a radius vector of joint T_{i+1} connecting the sections A_i and A_{i+1} can be calculated in the following way:

$$\vec{T}_{i+1} = \vec{T}_i + R_i \vec{S}_i, \quad (1)$$

where R_i is the rotation matrix of the section A_i, defined as

$$R_i = R_{A,i} R_{i-1} \quad (2)$$

and $R_{A,i}$ is the rotation matrix of the section A_i around joint T_i.

This is then done for all joints and sections and the output of the script is a list of translations $\vec{T}_i$ and corresponding rotation matrices R_i. By knowing the geometry of the neutron source holder [4], we can also reconstruct the neutron source position which is the key input for the MCNP calculations. Additional scripts and batch procedures in DOS are then used to couple the RH VR files containing all RH coordinates with the RH2MCNP script and then take the script output (translations, rotation matrices, NS positions) to prepare the MCNP input files run them and extract the necessary data (various neutron monitor responses) from the MCNP output. For easier understanding a simple flowchart of the process is presented in Figure 5.

3.3 VERIFICATION AND VALIDATION OF THE COUPLING SCRIPT

Verification and validation of the coupling script (RH2MCNP) was done by making a series of tests. In the first test, called the rail test, we calculated the boom rail, i.e. the virtual rail inside the tokamak which is a circle with radius 270 cm, along which the joints of the boom are moving. The script successfully passed the rail test.

In the second test (determinant test) we calculated the determinants of all rotation matrices. As they are all orthogonal, their determinants are all equal to unity within the numerical accuracy of the script. The script successfully passed the determinant test.

The third test was called the visual test, as we visually compared the 3D views of the JET RH system from the VR4 Robot software and from the MCNP model (Figure 7). The latter test is not very accurate but it could reveal any major errors either in the script or in the MCNP model.

In the fourth test (link length test) we compared the distance of links distances between the joints. The script successfully passed the link length test as all distances were within the uncertainties, which arise mostly from numerical rounding of numbers.

The final test, called the Point Comparison Test (PCT) is the most accurate and reliable as we compared the coordinates of the NS calibration points, i.e. the target ones with the ones calculated with our script. This script passed the PCT satisfactory as the differences between the target and calculated positions were no more than 1.19 cm on average with standard deviation of 0.6 cm (Figure 7). Maximum difference is 3.5 cm and 90 % of all points lie within 2 cm from the target value.
The possible sources of discrepancies were the following: uncertainties in dimensions of some RH components, uncertainties in absolute positioning of the “virtual “RH system. In order to provide the physics-preferred source baton orientations, the VR positions were generated by positioning the neutron source (on a baton incorporated in the VR model) in ‘the centre of’ a 2 cm diameter sphere around the target location (Figure 2). Hence discrepancies of this order are anticipated.

4. CORRECTION FACTORS

Estimation of the effect of the major components of the JET RH system (the mascot manipulator and the boom) on the JET neutron monitor response (from the external fission chambers on the transformer limbs inside the vacuum vessel) was performed in the following way. Firstly we calculated the undistorted neutron monitor response versus NS position for every calibration point, i.e. a response without the JET RH system in the vessel. Secondly we did the same calculation with the exception that the JET RH system consisting of the boom and the mascot manipulator holding the NS holder was modelled inside the tokamak in a particular configuration. Then we calculated the RH correction factor for the i-th detector and the j-th NS position, $C_{RH}^{i,j}$, as the ratio between the distorted neutron monitor response, Φ_0^{ij} and the undistorted response, $\Phi_{RH}^{i,j}$:

$$C_{RH}^{i,j} = \frac{\Phi_{RH}^{i,j}}{\Phi_0^{i,j}}$$

$$\begin{aligned} \Phi_0^{i,j} &= \text{undistorted neutron monitor response} \\ \Phi_{RH}^{i,j} &= \text{distorted neutron monitor response} \\ i &= \text{detector index (i = 1,16)} \\ j &= \text{NS position (j = 1,200)} \end{aligned} \tag{3}$$

The computational model of the JET tokamak featuring the JET RH system is depicted in Figure 8. In order to understand the effects of the JET RH system on the external neutron monitor response, the calculations of the correction factors were performed for all the 16 notional fission chambers in the model. However special attention was paid to the three fission chambers, denoted by D1, D2 and D3 in Figure 88, which are located at the positions of the real fission chambers at JET tokamak. Presenting final RH correction factors for all calibration points is out of scope of this paper. Hence the RH correction factors are presented only for D1, D2 and D3 and for one representative NS position. In these studies we focused on the positions of the real FCs, i.e. D1, D2 and D3. Firstly we calculated the undistorted KN1 detector response for the central NS position (Figure 9 above). It can be seen that the results are in agreement with [3], i.e. the neutron monitor response is the highest, when the NS is closest to the detector, except for the position, which is approx. 30 ° from the detector. The peak at the latter position is due to a line of sight effect. Hence the location, shape and height of the peak strongly depend on the shape of the port and the neutron detector in the computational model. Secondly we calculated the RH correction factor (as defined in Eq. 3) for the NS at the central position and for the FCs at D1, D2 and D3 positions (Figure 9 below). It can be observed that FC response at location D3 is the most affected by the JET RH system as it is closest to the RH entrance port in Octant 5, which is blocked by the boom. Moreover the FC response for D1 and D2 positions is the most affected by the JET RH system when the NS is located in Octant 5. It is interesting to note that when the NS is located in the octant close to the FC position, the FC response is only slightly affected by the JET RH system, i.e. the RH correction factor is slightly larger than unity, mainly due to increased back-scattering from the mascot robot body. All these findings are in agreement with our previous studies showing that the highest contribution to a certain FC is via the closest port and the second highest contribution is via the port closest to the neutron source [3]. The effects of the JET RH system depend on the RH configuration and on the neutron monitor location. The response can be decreased by the boom blocking a port or increased by favourable scattering.

The JET RH correction factors are required for each of the 200 measurement positions. In order to obtain the plasma (volumetric neutron source) relevant response these should then be convoluted with the fission chambers position-dependent response (importance function [3]) to generate the integrated ring responses for each detector. The integrated RH correction factors for the central

NS position are presented in Table 2. For D1 and D2 positions the integral correction factor is 2%, which is mainly due to neutrons back-scattered from the mascot body. In D3 position however the integral correction factor is -5 %, mainly due to the boom blocking the port in Octant 5, which is relatively close to the D3 position in Octant 6.

The effect of the boom mascot and baton is just one of the many correction factors that will have to be calculated for the measurements of monitor responses to the Cf point sources. Others include e.g. the effect of any equipment missing compared to normal operating conditions and the effect of the second boom, located within the Oct 1 port.

From the fully-corrected 5-ring point source data, we will later have to derive the monitor responses for equivalent plasma shaped volumetric sources (for ^{252}Cf neutron spectra) and calculate the responses for the interesting neutron spectra from DD or DT fusion neutrons. That will be the subject of future publications.

CONCLUSIONS

Performing absolute calibration of the JET external neutron monitors with an accuracy of below 10 % is a very difficult task due to complex geometry and to numerous geometrical and material uncertainties. Hence it is essential to use an advanced neutron transport code, such as MCNP to computationally support the experiment by calculation of experimental corrections, uncertainties and, determination of biases. In this paper an approach on how to estimate the effect of the remote handling system on neutron transport was presented. We had to convert the RH movement instructions via a script to input files for the neutron transport code, which was in our case MCNP. This was followed by a rigorous verification and validation process. Only then could we commence calculation of the correction factors due to major components of the RH system.

The major findings are the following: D2 and D1 are the least affected FCs as they are furthest from the RH entrance port in Octant 5, D3 is the most affected FC as it is closest to the RH entrance port in Oct 5 that is blocked by the boom. However the RH effect is not significant, i.e. less than 5 %, when taking into account NS importance function

Although the correction factors due to presence of the JET RH system can potentially be significant in cases when the boom is blocking a port close to the detector under investigation, we have chosen boom configurations so that this is avoided or minimised in the vast majority of the source locations. This is shown by the examples we have given. The results of great interest for any RH application involving manipulation of strong neutron sources, e.g. neutron monitor calibration in ITER or DEMO.

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.

REFERENCES

[1]. Syme D.B. et al., Fusion Yield Measurements on JET and their Calibration, Nuclear Engineering Design, article in press,

[2]. Laundy B.J., Jarvis O.N., Numerical study of the calibration factors for the neutron counters in use at the Joint European Torus, , Fusion Technology, vol.**24**, pages 150-160, September 1993.

[3]. Snoj L. et al., Calculations to support JET neutron yield calibration: contributions to the external neutron monitor responses, Nuclear Engineering Design, article in press, doi:10.1016/j.nucengdes.2011.07.011

[4]. Snoj L. et al., Calculations to support JET neutron yield calibration: neutron scattering in source holder, Proc. Int. Conf. Nuclear Energy for New Europe 2010, Portorož, Slovenia, September 6-9, Nuclear Society of Slovenia, 2010,

[5]. X-5 Monte Carlo Team, MCNP - A general Monte Carlo N-particle Transport code, Version 5, LA-UR-03-1987, April 24, 2003 (revised June 30 2004).

[6]. Mindham, T.J., et al., Developments in remote metrology at JET. Fusion Engineering and Design. In Press, Corrected Proof.

[7]. Haist, B., S. Mills, and A. Loving, Remote handling preparations for JET EP2 shutdown. Fusion Engineering and Design, 2009. **84**(2-6): p. 875-879.

[8]. http://www.jet.efda.org/remote-handling/how/ (August, 2011)

[9]. Murcutt P. et al.,High level integration of remote handling control systems at JET, Fusion Engineering and Design, In press, doi:10.1016/j.fusengdes.2011.03.072

[10]. J. P. Both, A. Mazzolo, O. Petit, Y. Peneliau, B. Roesslinger: User Manual for version 4.3 of the TRIPOLI-4 Monte Carlo method particle transport computer code, CEA-Report : CEA-R-6044, DTI, CEA/Saclay, France, 2003

[11]. TRIPOLI code available from OECD-NEA Databank, http://www.oecd-nea.org/tools/abstract/detail/nea-1716

Component		Shape	Material composition (wt. %)	Density (g/cm^3)
Boom section	casing	rectangular box	Stainless Steel	8.0
	interior		50 % Fe, 50 % Cu	0.8
Boom links joint - electro-motor		cylinder	50 % Fe, 50 % Cu	5.6
Mascot body	casing	rectangular box	Al	2.7
	interior		40 % Fe, 40 % Cu, 20 % Al	5.6
Mascot arm components	casing	cylinder	Al	2.7
	interior		Stainless Steel	0.4

Table 1: Modelling of the main components of the JET RH system.

Neutron monitor	D1	D2	D3
Integral RH correction factor	2 %	2 %	-5 %

Table 2: Integral RH correction factors for D1, D2 and D3 neutron monitors.

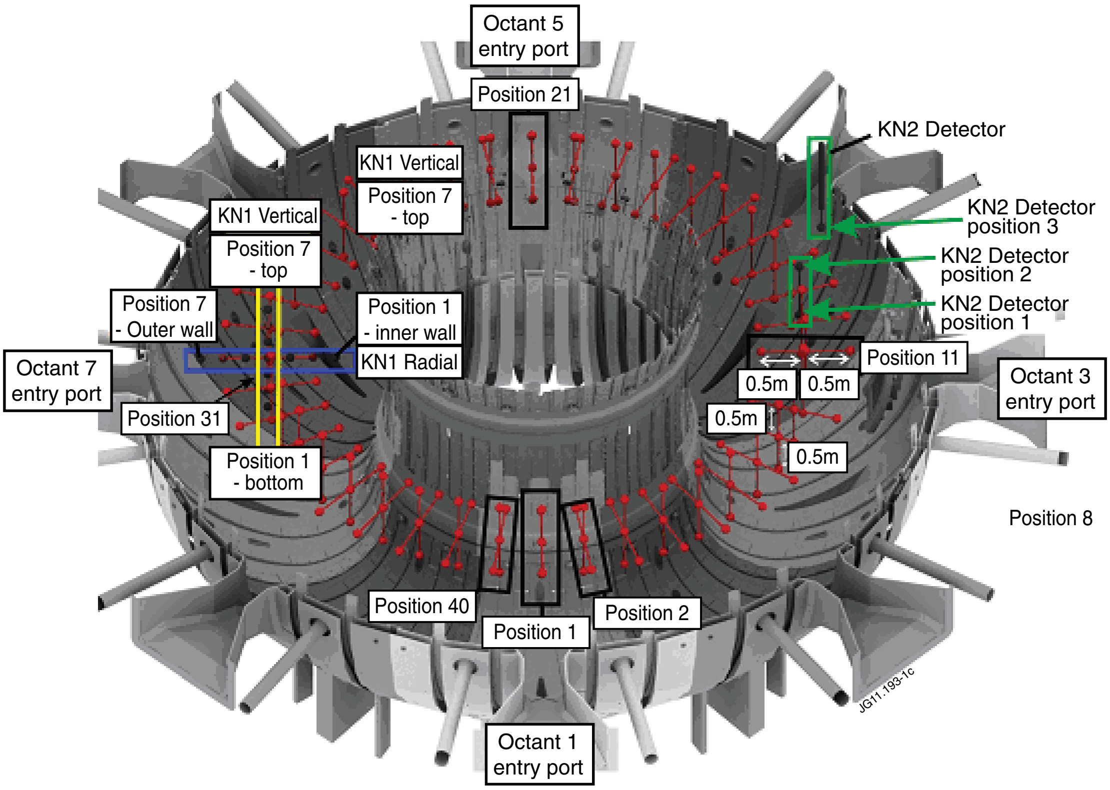

Figure 1: Draft of in-vessel scan pattern. There are 5 points at each toroidal location round the vessel, i.e. 5 rings of points, plus some subsidiary points at other particular locations. Only part of the JET structure is shown. KN1 denotes external neutron monitors and KN2 denotes the JET activation neutron monitoring system.

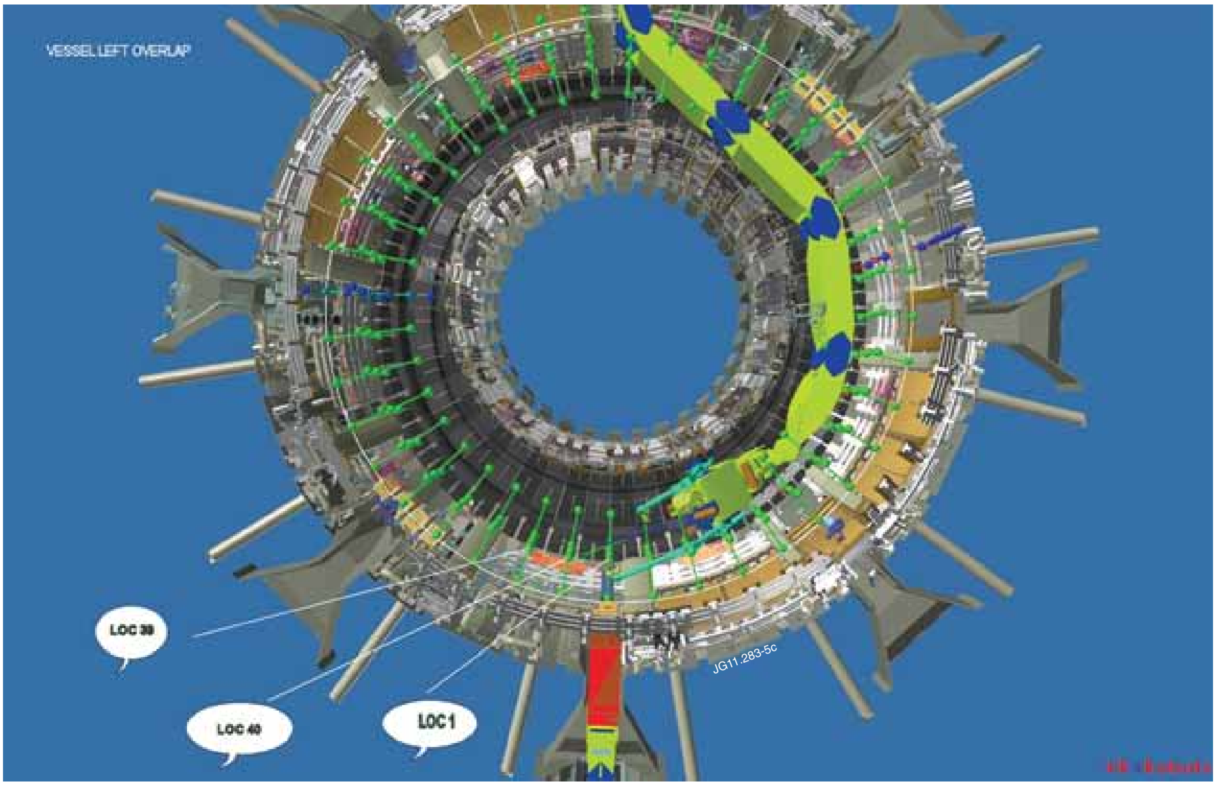

Figure 2: Draft of in-vessel scan pattern and the JET RH system inside the vacuum vessel visualized by the VR4 Robot software. Calibration points 1, 40 and 39 are denoted by callouts.

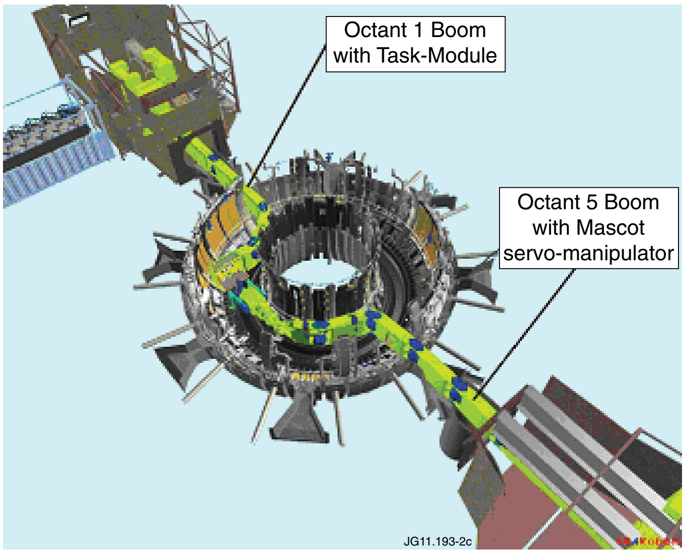

Figure 3: The first and the second boom inside the vessel [7].

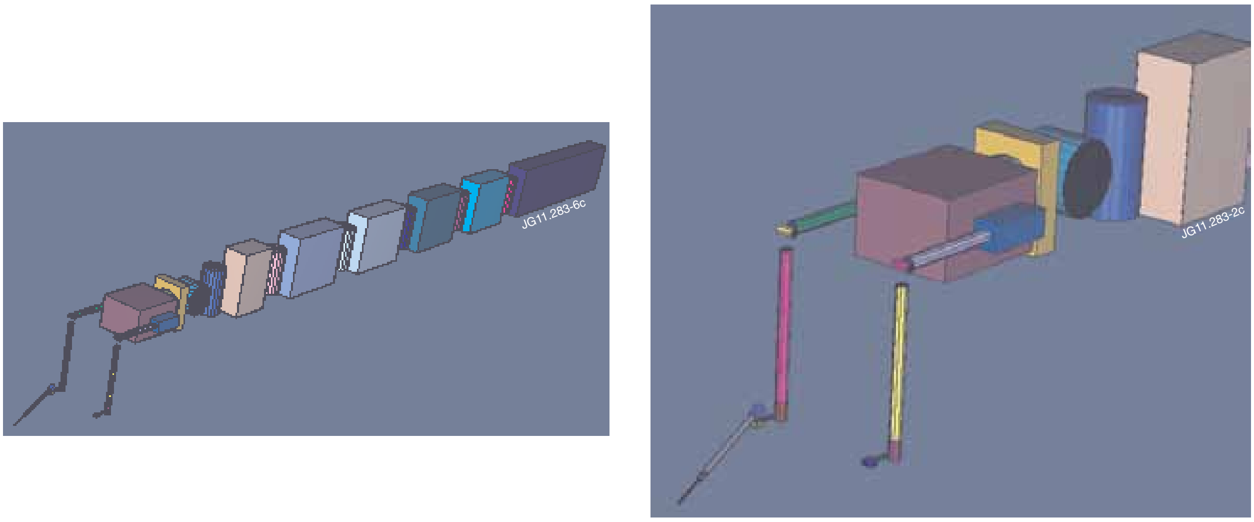

Figure 4: The 3D view of the MCNP model of the JET RH system in basic position (left) and close up of the Mascot manipulator end, (right). It is important to note that the colour of the structures does not indicate anything, it is just the colouring system used by the MCNP Visual editor.

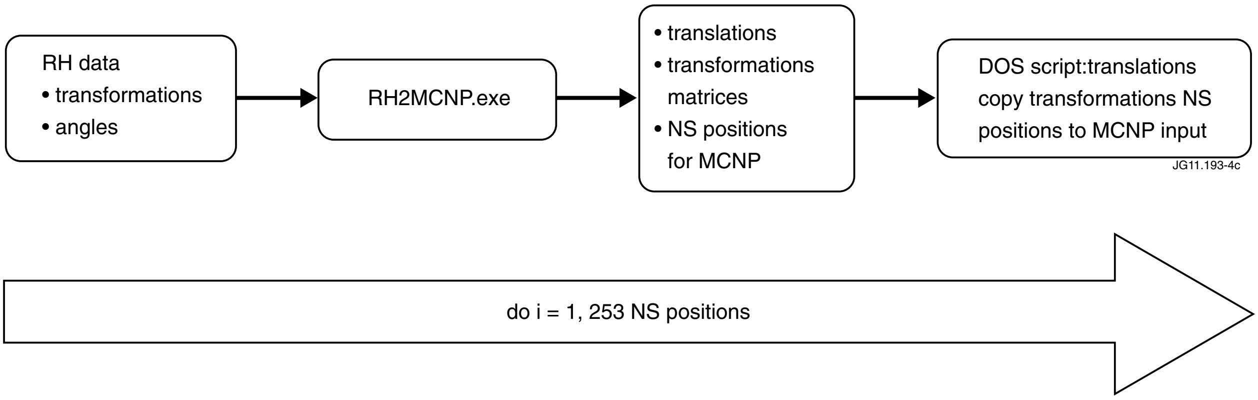

Figure 5: Flowchart of the procedures to model the JET RH system in MCNP.

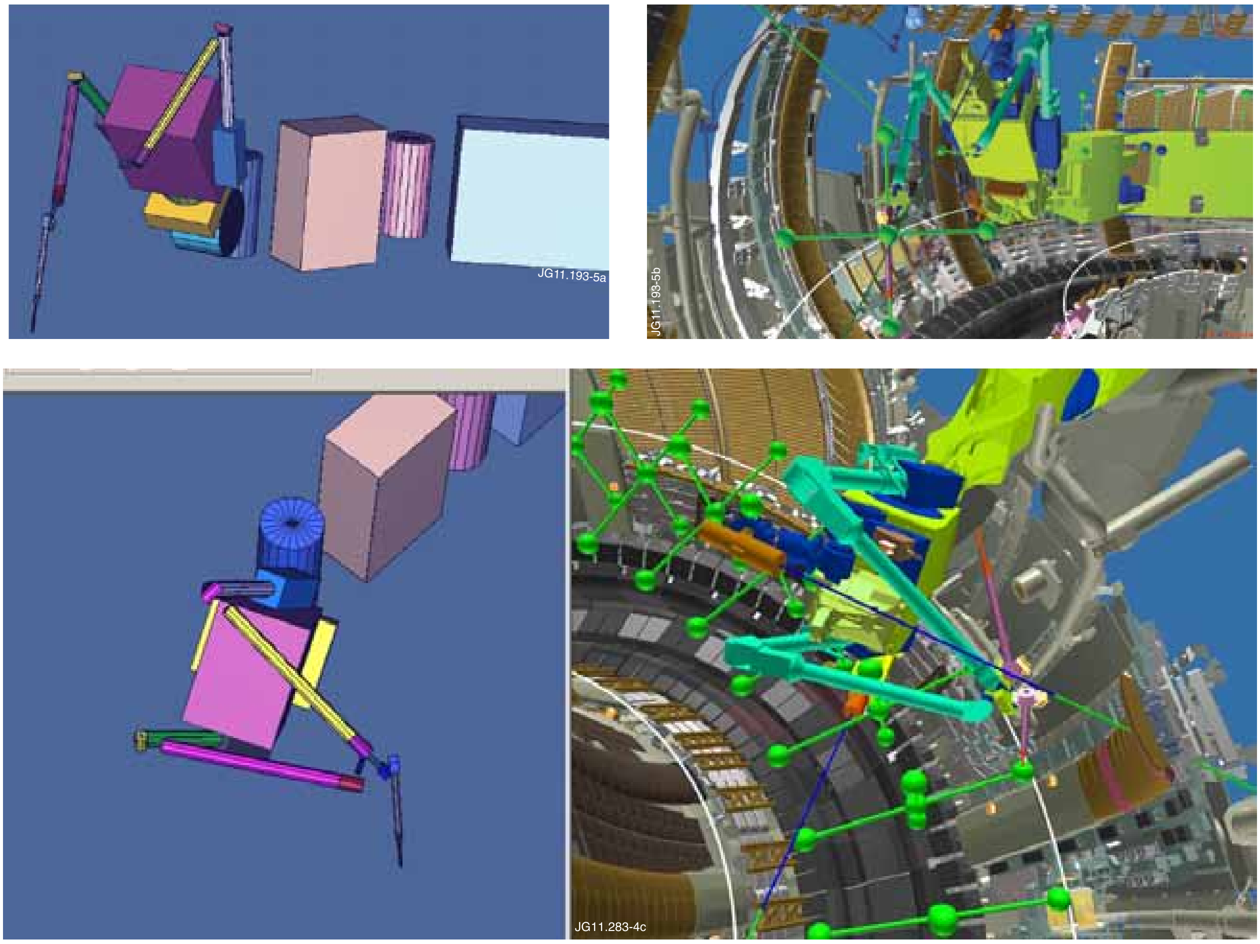

Figure 6: Visual comparison of the 3D views of the JET RH system from the MCNP model (left) and from the VR4 Robot software (right).

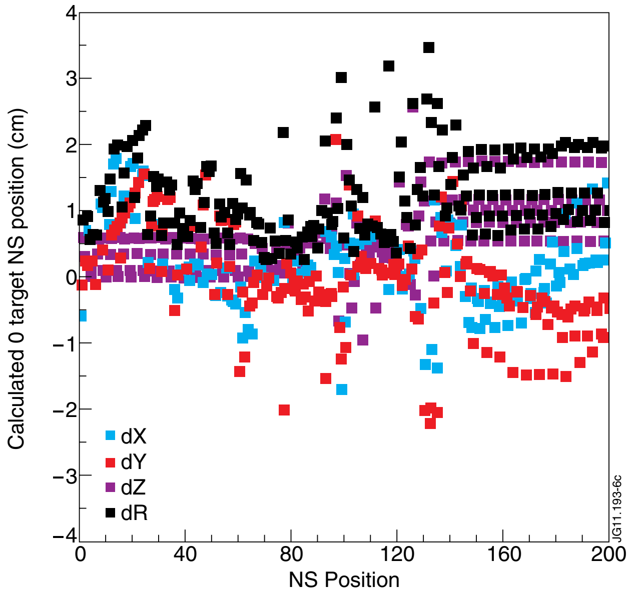

Figure 7: Comparison of target and calculated calibration points' coordinates. dX,dY,dZ denote differences in x, y and z coordinate , respectively. dR denotes difference in the total distance between target and calculated points. Note that each of the 40 neutron source (NS) locations has 5 positions, central (C), inner (I), outer (O), upper (U) and lower (L), in total making 200 NS positions. For example positions 1–5 correspond to C, I, O, U and L positions at NS location 1.

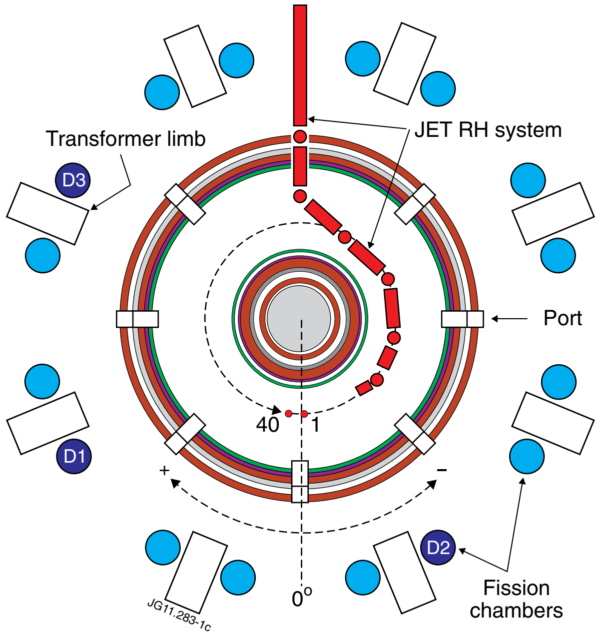

Figure 8: Top view of the MCNP JET geometrical model with the JET RH system deploying the source at location 1 C. The section is made at the tokamak midplane (z=0). As the mascot manipulator is tilted relative to the XY plane only the boom is visible. The positions of the JET external neutron monitors are denoted by D1, D2 and D3.

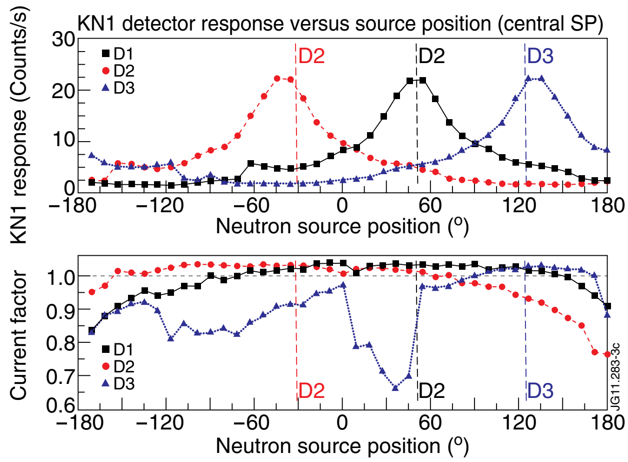

Figure 9: KN1 response versus NS position for D1, D2 and D3 FCs (above). Remote handling correction factor versus NS position for D1, D2 and D3 FCs (below). NS is located on the central ring.