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Technical preparations for the in-vessel 14 MeV neutron calibration at JET

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Technical preparations for the in-vessel 14 MeV neutron calibration at JET

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Abstract

The power output of fusion devices is measured from their neutron yields which relate directly to the fusion yield. In this paper we describe the devices and methods that have been prepared to perform a new in situ 14 MeV neutron calibration at JET in view of the new DT campaign planned at JET in the next years. The target accuracy of this calibration is ±10% as required for ITER, where a precise neutron yield measurement is important, e.g., for tritium accountancy. In this paper, the constraints and early decisions which defined the main calibration approach are discussed, e.g., the choice of 14 MeV neutron source and the deployment method. The physics preparations, source issues, safety and engineering aspects required to calibrate directly the JET neutron detectors are also discussed. The existing JET remote-handling system will be used to deploy the neutron source inside the JET vessel. For this purpose, compatible tooling and systems necessary to ensure safe and efficient deployment have been developed. The scientific programme of the preparatory phase is devoted to fully characterizing the selected 14 MeV neutron generator to be used as the calibrating source, obtain a better understanding of the limitations of the calibration, optimise the measurements and other provisions, and to provide corrections for perturbing factors (e.g., anisotropy of the neutron generator, neutron energy spectrum dependence on emission angle). Much of this work has been based on an extensive programme of Monte-Carlo calculations which provide support and guidance in developing the calibration strategy.

1. Introduction

JET is an experimental device aiming to develop nuclear fusion as an energy source for civil applications. JET can obtain the required physical conditions in which nuclei of hydrogen isotopes fuse into helium nuclei releasing a large amount of energy. In this process, 2.5 MeV and 14 MeV neutrons are generated when Deuterium or Deuterium – Tritium mixtures, respectively are used to fuel the plasma. The fusion power output is measured from the neutron yields which relate directly to the fusion yield. The JET neutron source spans a range of ten decades of intensity ($\approx 10^8$ n/s in Hydrogen and Deuterium ohmic operations to nearly 10^{19} n/s in D-T operations). JET is equipped with several types of neutron detectors - ^{235}U/ ^{238}U fission chambers (KN1) and the in-vessel activation system (KN2) - to measure the absolute neutron emission rate from the JET source (Fig.1) [1]. The fission chambers are mounted in moderator packages at mid-plane locations close to the transformer magnet limbs in Octants 2, 6 and 8. The activation system pneumatically delivers and retrieves capsules to/from locations inside the torus structure, e.g., to the edge of the vacuum vessel. There are 8 such 'Irradiation Ends' (IE), located in 5 octants. Capsules are

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delivered before and retrieved after the pulse for counting of the induced gamma radioactivity. Both KN1 and KN2 need to be calibrated as accurately as possible to provide a reliable measurement of the fusion energy produced and determine the efficiency of the underlying physical processes. An accurate calibration at 2.5 MeV neutron energy of the JET neutron detectors was performed in 2013 [1] and a new calibration at 14 MeV neutron energy is now needed to allow accurate measurements of the fusion power and of plasma ion parameters as a new Deuterium-Tritium campaign is planned in 2019 [2]. The target accuracy of this calibration is ±10%, just as in the earlier JET calibration and as required for ITER, where a precise neutron yield measurement is important, e.g., for tritium accountancy [3].

This paper presents the technical requirements for a 14 MeV neutron generator (NG) to be used for calibrating the neutron detectors installed on the JET device as well as providing a description of the functional requirements and of the design constraints in the JET environment. The paper describes the solutions developed to meet these function requirements within JET. Factors that have been taken into account include personnel safety requirements, maintaining the cleanliness within the machine, RH compatibility and the limited space available, resistance to failure, the ability to recover from failure and the ability to perform the calibration in a restricted time window. In addition, physics issues must be considered to better understand the limitations of the calibration, to optimize the measurements, and to provide corrections for NG source versus plasma source differences and for perturbing factors (e.g. presence of the remote-handling boom and other non-standard torus conditions).The paper describes the methodology planned to be used to perform the JET calibration.

2. Requirements for in-vessel calibration

The neutron calibration consists of the deployment of a neutron source of known intensity and energy spectrum at different toroidal/poloidal locations inside the JET vacuum vessel at accurately defined positions, to simulate the volume plasma source, and in recording the resulting signals in the JET neutron detectors located inside (KN2) and outside (KN1) the machine. For the 2.5 MeV neutron calibration, a ^{252}Cf source, which emits neutrons with a mean energy of 2.1 MeV, was placed at about 80 different positions, covering the whole JET in-vessel space. At 14 MeV, however, there are no naturally occurring neutron sources that could be conveniently employed, and therefore a neutron generator (NG) has to be used. In a neutron generator, a D^+/T^+ beam is accelerated at energies typically in the range 80-120 keV onto a titanium target containing T/D inside a sealed tube thus producing beam-target fusion reactions. The operation time required in vessel for the neutron generator in each position will vary in the range 0.3 - 4 hours, hence the ability to operate stably over these timescales is important as is the ability to operate stably over the longer timescales covering the complete calibration.

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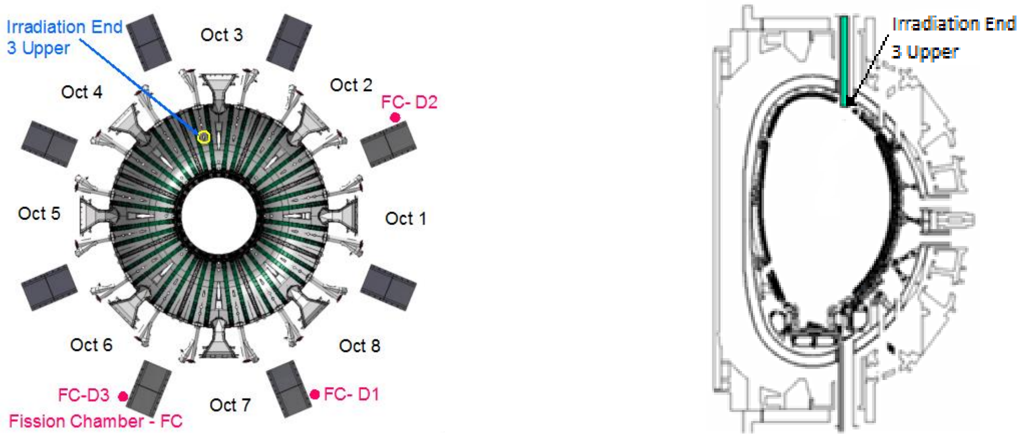

Fig.1 Left: Top view of JET machine showing the position of Fission Chambers (KN1) close to the magnetic limbs, and of the 3-Upper Irradiation End (KN2). Right: Cross section of JET showing the 3-Upper Irradiation End (KN2)

A NG can be deployed by remote handling (RH) inside the JET vessel, mounted on one of the two existing RH booms and its 'MASCOT'(MAnipulator Servo COntrollato Transistorizzato) robotic arms (Fig.2). This system can access a wide range of source positions over the whole vessel and is compatible with contamination conditions (Be, T). The MASCOT is equipped with integrated 10 A, 600 V cables installed close to the neutral axis of the boom joints to minimise their degree of bending. In total the cables are routed through a series of cable deployment configurations which include a 364 degree rotational articulation, a 164 degree vertical articulation, a 244 degree horizontal articulation, followed by 5, 238 degree horizontal articulations and finally a 7.4m linear translation. The wires are internally connected with a series of 5 DPX type connectors to allow the boom to be disassembled and maintained.

However, the use of the RH booms requires intensive planning and preparations from Physics, RH and Engineering teams to design the attachment system of the NG to the MASCOT, design a position check system as location accuracy is limited to ~1 cm (especially important for KN2), minimise neutron scattering and radiation damage to RH cameras, and design safe NG uploading/ recovery and operation methods. The MASCOT robotic arms can bear a maximum weight of 10 kg. A NG, together with associated tooling, with this or lesser weight is therefore required. Power supply cables (mains and VHV cables), as well as signal cables linked to a control unit have to be provided. The RH boom used can access the JET torus vessel inner volume through a lateral port and from there can move by about 20 meters to either side. Separate umbilical cables, provided by the NG manufacturer with sufficient length are therefore required through another port. The preferred solution, however, is to avoid umbilical cables and to deliver the power supply to the NG through the cables integrated in the RH boom. In fact, for safety reasons, and in order to protect the integrity of the machine, it is not desirable to draw VHV cables inside the vessel. Therefore, it is strongly desirable to have the VHV converter unit attached close to the neutron emitting tube, so that no long cables are to be drawn inside the vessel during the boom movements. The "cable through the boom" solution, with the VHV unit integrated in the neutron tube, was finally adopted mainly for safety reasons.

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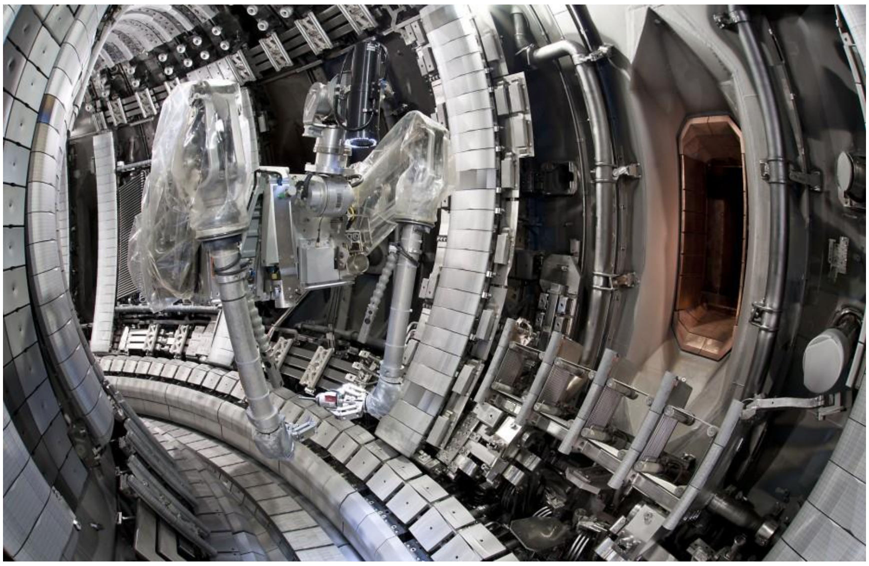

Fig. 2 Remote Handling MASCOT inside the JET vacuum vessel

As a calibration source, the NG must also have adequate characteristics such as: sufficient neutron source intensity, stability, lifetime and simplicity of configuration to obtain the target accuracy in the JET neutron monitor calibration. In order to meet these challenging objectives, the following have to be considered.

- NG operation must provide sufficient neutrons in order to obtain enough response in the neutron detectors. As it is preferred to use a non-actively cooled NG so as not to introduce complexity and weight, the heating of the target during operation may represent a limit.
- A NG intensity ≈10^8 n/s can be obtained without active cooling and is considered sufficient if the target accuracy is set at ≤±10% for both KN1 and KN2 systems, and provided there is sufficient NG operation and life time.
- The possibility to operate continuously (up to about 20 minutes @10^8n/s) is required. This option would reduce the irradiation time, at given total neutron yield, required to complete the planned measurements with the desired statistical uncertainties both for KN1 and KN2.
- It is estimated that the calibration time would be of the order of 100 hours in total. Neutron emission intensity in NGs is subject to time decay due to the Tritium consumption in the target. Therefore a sufficiently long NG lifetime > 300 hrs is required.
- The NG intensity can be subject to fluctuations due to variations in the voltage/current or target heating. Although NGs are now equipped with digital controls incorporating advanced diagnostic routines, achieving stability of emission down to a few percent level is still very challenging in present NG technology. Therefore, during the in-vessel calibration the neutron emission intensity, or the NG total neutron yield, needs to be monitored by compact detectors mounted close to the NG in suitable positions.
- The NG beam energy, typically 80 - 120 keV, introduces an energy-angle dependence and anisotropy of the neutron emission. The latter, being of the order of a few percent in the forward/backward directions for typical accelerating voltages, cannot be neglected. The tube components introduce further anisotropy, as the source neutrons interact with materials surrounding the target. The tube anisotropy has therefore to be measured.
- The uncertainty in the intensity of neutron yield directly propagates in the uncertainty in the calibration of the neutron detectors; hence it should be as low as a few percent. Measuring the

absolute NG neutron emission intensity is a challenging task that can only be achieved with redundant and independent measurements/techniques.

3. Selected 14 MeV neutron generator

The 14 MeV neutron generator type ING-17 (Fig.3) provided by VNIIA [4] was identified as a suitable source and complies with the requirements described above. The neutron generator system consists of a Power Supply and Control Unit (PSCU) and a Neutron Emitting Unit (NEU), connected by a power supply cable. The VHV unit is enclosed within the NEU, together with the sealed tube containing Tritium/Deuterium. One PSCU and two NEUs were purchased because of the need to avoid delays in the JET programme in the case of a NEU failure. The main parameters of the ING-17 are given in Table 1.

The NG was delivered in October 2015. The NG has an operating system using a simple graphic interface which sets the beam energy and the time duration and monitors the target temperature; switching off the power if it exceeds a pre-set threshold. The characteristics given in Table 1 were checked and, in particular, it was verified that the nominal neutron emission rate was produced with a beam energy of 100 keV. Moreover, the NG could work in continuous mode for more than 20 min with the target temperature steady at around 30°C.

Fig.3 Left: The Power Supply and Control Unit. Right: The two Neutron Emitting Units

Table 1 – Main Characteristics of ING-17 neutron generator

Characteristic	**Requirement**
Max neutron emission rate	2×10^8 n/s
Dimensions / Weight: Neutron Emitting Unit Power Supply & Control Unit	 ∅70 mm x 459 mm / 2.8 kg 356 mm x 315 mm x 110 mm / 4.6 kg
Operation mode	Continuous
Continuous operation time	> 20 min
Target temperature limit	60°C
Recovery time after switch off	< 0.5 hours
Beam Energy	Should not affect or limit the operation
Power supply	220 VAC, 50 Hz
Power consumption	< 150 W
Main Cable length	> 30 m, flexible
Tritium content	< 370 GBq

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Lifetime: Neutron Emitting Unit Power Supply & Control Unit	 300 hours > 5000 hours

4. Physics preparation

The use of the 14 MeV NG as a calibrating source requires that it is accurately characterized in a laboratory prior to the in-vessel calibration; measurements of the neutron source intensity in 4π, the angle - energy distribution, and the neutron emission rate vs angle are needed. Moreover, extensive neutronics analyses are required to derive the calibration factors related to the plasma neutron source from those measured by deploying the NG inside the vessel, and to take into account the many particular circumstances such as the presence of the RH system. For these reasons, a detailed and validated neutronics model of the NEU and source routine are needed.

The strategy adopted is the following:

- Develop a MCNP model of the NEU using the information on the configuration and material composition provided by the manufacturer.
- Provide the NEU with “monitoring detectors” in fixed and well defined positions to monitor the neutron yield during the in-vessel calibration – use multiple monitoring detectors, both active and passive (activation foils), providing redundant measurements.
- Characterize/calibrate the NEU at a standard neutron facility using multiple “characterization detectors” to measure:
  - The total neutron emission in 4π (<±5%)
  - The angle – energy distribution of emitted neutrons
  - The neutron emission as a function of angle (anisotropy profile)
- Calibrate the “monitoring detectors” during the characterization / calibration campaign at a standard neutron facility. Monitoring detectors will be used at the defined positions both at the facility and inside JET using a dedicated mechanical support.
- Use the calibration/characterization measurements to validate the MCNP model of the NEU.
- Perform the in-vessel calibration and derive the experimental “NG calibration factors” for both KN1 and KN2.
- Perform extensive neutronics analyses to correct the “NG calibration factors” for the presence of the RH MASCOT body, for the non-standard machine configuration during calibration (open ports, diagnostic/heating systems in maintenance, etc.), for the characteristics of the NEU source vs the plasma source (energy, anisotropy, spatial extension) etc., and finally derive the “plasma calibration factors”.

4.1 Neutronics model

The MCNP model of the NEU is shown in Fig. 4 (left), with the calculated map of the neutron flux in Fig. 4 (right). Fig.5 (left) shows the neutron energy spectra of neutrons emitted at different angles with respect to the beam direction. The shown spectra are calculated for a 100keV-D^+ beam impinging on a tritiated Ti target. In reality, there may be different components in the neutron spectra due to the presence of mixed T/D and of molecular species both in the beam and in the target. A source routine has been developed to be used in MCNP calculations to account for mixed

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D/T beams, and for atomic and molecular species in the beam which result in different effective energies on the target [5,6].

Fig. 5 (right) shows the emission rate at different angles with respect to the beam direction. The bare source presents a slightly higher emission rate in the forward direction due to the D→T reaction kinematics. However, the distribution of scattering/absorbing masses around the T/D-Ti target is responsible for a much larger anisotropy profile, with sharp features, that have to be accurately measured and taken fully into account in the calibration analyses.

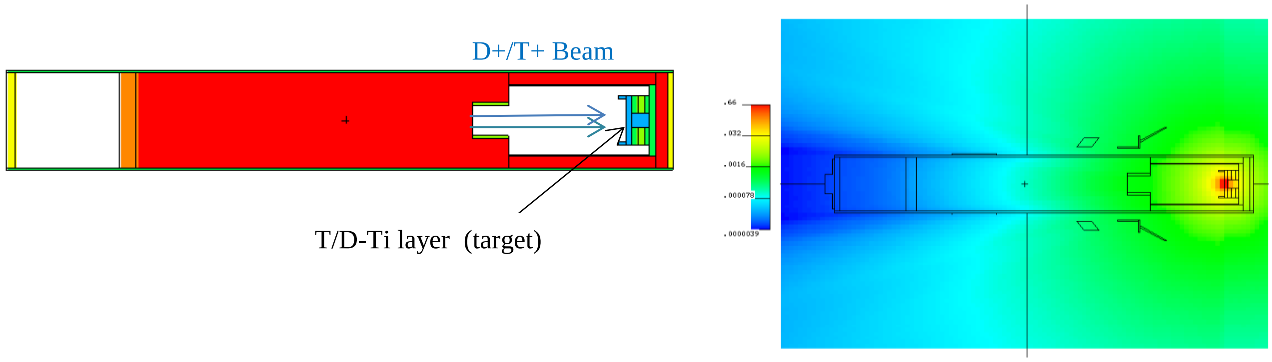

Fig. 4 – Left: MCNP model of the Neutron Emitting Unit (Green: 94% Al, 6% Mg; Light green: Pr 17%, Nd 16%, Fe 58%, Co 4%, Dy 3%, B 1%; Yellow: 94% Al, 2% Mg, 4% Cu; Blue: Cu; Orange: Fe 70%, Cr 18%, Ni 10%, Mn 2%: Red: Oil). Right: Map of the neutron flux around the NEU

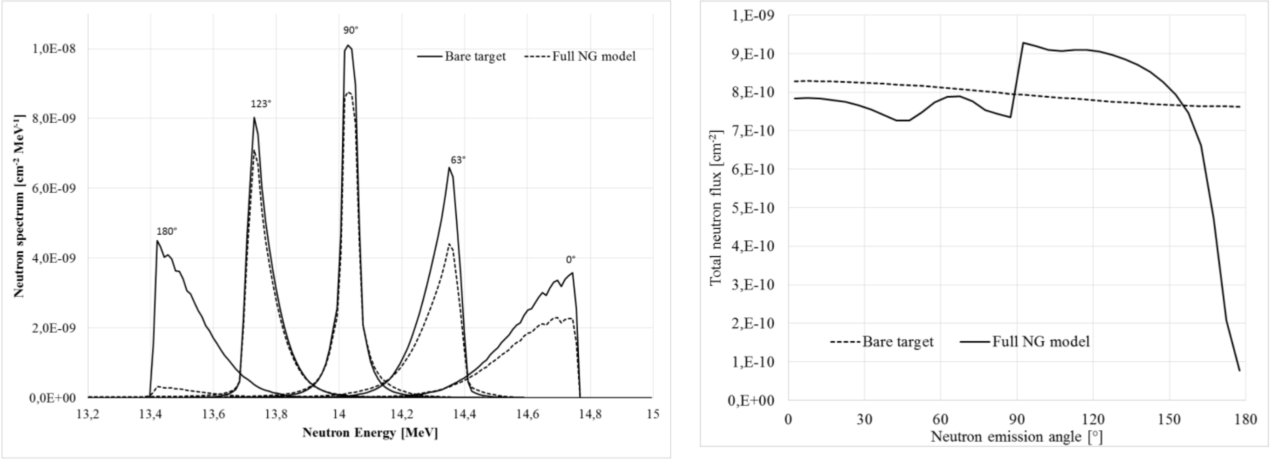

Fig.5 Left: Neutron energy spectra of neutron emitted at different angles to the beam direction, due to the D^+*@100 keV→ T component. Right: Neutron emission rates at different angles with respect to the beam direction in the case of bare source (full line) and of full NEU configuration (dotted line)*

4.2 Monitoring detectors

When inside the JET vessel, the absolute neutron yield produced by the NEU can only be obtained by the calibrated "monitoring detectors". Multiple detectors will be used: two active detectors (2 CVD diamond detectors, or a CVD diamond plus a Si-diode), and a set of activation foils. Given the intensity of the NEU and the available irradiation time, the activation reactions given in Table 2

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were chosen which can provide sufficient activity at the end of every day of operation, when at least ten 20 minute shots are expected.

Table 2 Dosimetry reactions selected for the "monitoring" activation measurements

Reaction	**Energy threshold (MeV)**	**Isotopic abundance**	**Half-life**	**Gamma energy (keV)**	**Intensity gamma**
^{27}Al(n,p)^{27}Mg	3.2	1	9.458 min	843.8	0.718
^{56}Fe(n,p)^{56}Mn	1.9	0.918	2.577 h	846.7	0.989
^{27}Al(n,α)^{24}Na	3.0	1	15.03 h	1369	0.999
^{93}Nb(n,2n)^{92m}Nb	9.0	0.6827	36.08 h	1377.6	0.817

These detectors have to be attached to the NEU in well-defined and fixed positions both during the calibration\characterization campaign and during the in-vessel calibration. In this way, the active monitoring detectors can be "absolutely calibrated" in their operating conditions, i.e. their absolute response in the operating position can be derived.

However, the monitoring detectors will experience a different neutron spectrum during the in-vessel calibration with respect to that occurring in the calibration campaign due to the presence of neutrons scattered by the vacuum vessel itself. This effect is minimized by the fact that the detectors are very close to the NEU, and by the choice of high energy threshold reactions (the ^{93}Nb(n,2n)^{92m}Nb activation reaction and, for the CVD diamond detector, the ^{12}C(n,α)^{9}Be reaction with a threshold at 5.7 MeV). Nonetheless, the effect will have to be taken into account by neutronics simulations to correct for the different operating conditions.

4.3 Mechanical support

In order to install the monitoring detectors on the NEU at fixed and well defined positions, an *ad hoc* mechanical support has been designed and realized (Fig. 6). This also provides attachment points to allow the MASCOT arms to grip the NEU, the housing of a pre-amplifier for the active detectors, and two lasers to be used whenever precise positioning of the NEU at well-defined locations inside the vessel is required. The mechanical support is made of predominately aluminium to minimize its weight (about 500g including all monitoring detectors, cables and pre-amplifier), activation and its impact on the neutron flux and energy spectrum of neutron emitted by the NEU. To minimise the torque on the MASCOT arms and grips, the grip attachment points were positioned at the centre of gravity of the NEU and tooling. In addition the tooling was designed to allow the NEU to be replaced in the tooling. However, due to the accuracy requirements on replacement, it was decided to procure a second set of tooling and calibrate the two NEU/tooling pairs separately.

The two active detectors are located at nominally symmetrical positions with respect to the target. The "horseshoe" component surrounding the target can hold 8 activation foils, each 1-mm thick, and 18 mm in diameter, two for each type of the four reactions shown in Table 2. It is designed in such a way that the horseshoe can be removed at the end of the day of NG operation from the vacuum vessel to the Octant 1 boom tent were the foils can be easily replaced. The activated foils will then be measured at a remote counter and the horseshoe with fresh foils returned to the vacuum vessel ready for the next NG operation period.

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A very detailed MCNP model of the mechanical support has also been developed based on the CAD model (Fig. 7). The full MCNP model (NEU with mechanical support and monitoring detectors) is used to accurately simulate the neutron field around the neutron source, the neutron fluence and spectrum at the monitoring detectors, and finally, to predict the activation of all components after operation as a function of irradiation time and cooling time. After obtaining neutron flux and spectra, the MCR2Sv2, two step activation and decay code [7] is then used in order to calculate the shutdown gamma dose rate that will be expected after running the generator. During this calculation step the 175 group neutron spectrum is used to calculate an inventory at any given time, post irradiation in each voxel of the problem, using the FISPACT II activation code [8]. A decay gamma source is thus created. An example of a dose rate map around the whole assembly is shown in Fig. 8. It has been obtained using MCR2Sv2 / Fispact II codes assuming the following irradiation scenario: 7 cycles, each with 2 min on at $2{\cdot}10^8$ n/s and 2 min off, followed by 1 min cooling time. The calculation predicts for this case a dose rate of 350 µSv/hr on the blue contour on Fig.8 (in part coincident with the NG tube surface). The statistical uncertainty in the calculation is <1%. This is in good agreement with measured dose rate of 350 ± 80 µSv/hr at a distance of 2 mm from the NG front end, at 1 minute cooling time after 7 cycles with 2 min on and 2min off at a nominal flux of $2.06{\cdot}10^8$ n/s.

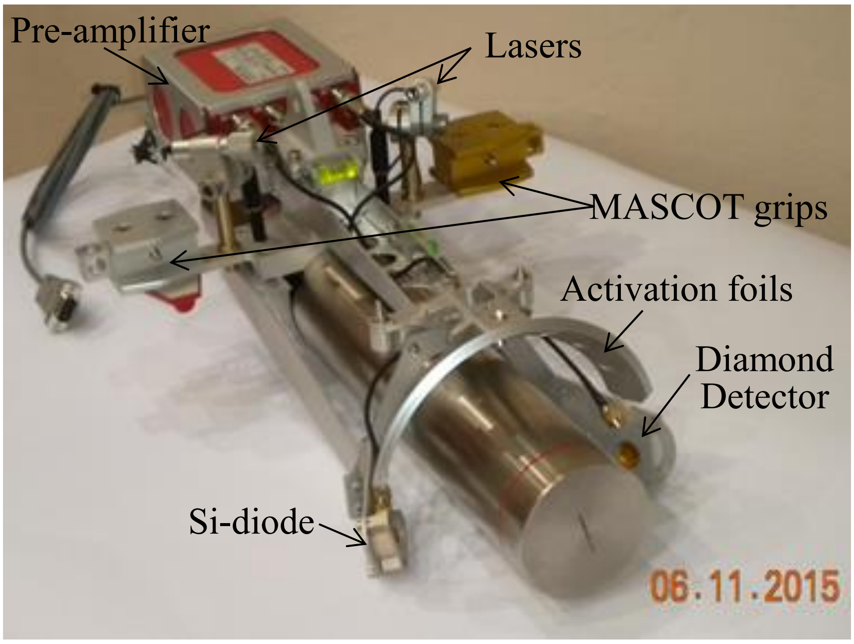

Fig.6 Neutron Emitting Unit with the mechanical support needed for MASCOT gripping and to support the "monitoring detectors" and pre-amplifier (red box at the back).

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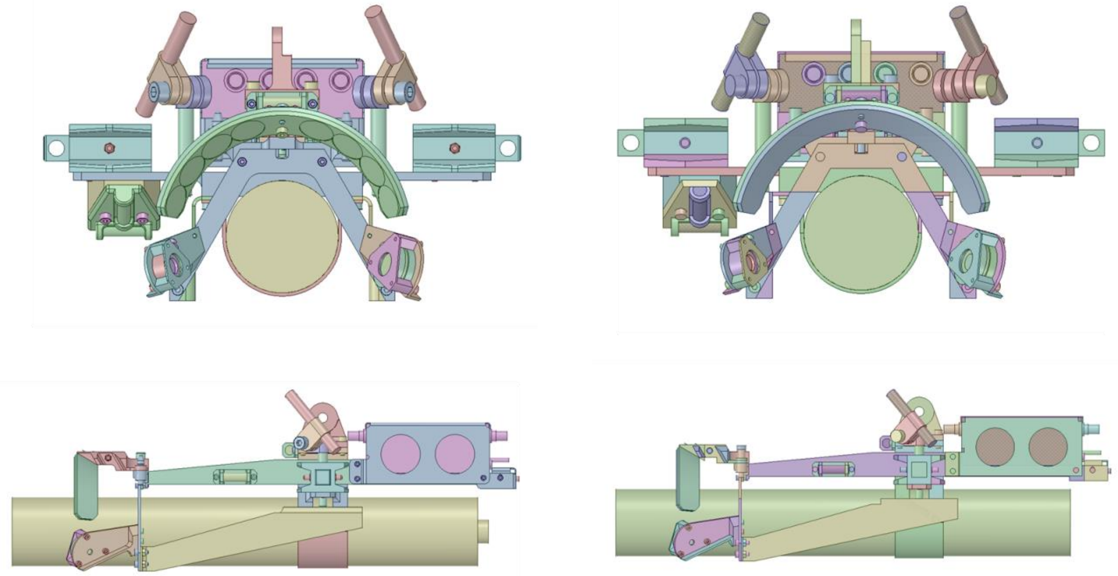

Fig. 7 Left : Original CAD model of NEU and of mechanical support, including the monitoring detectors, and, Right: the resulting MCNP model

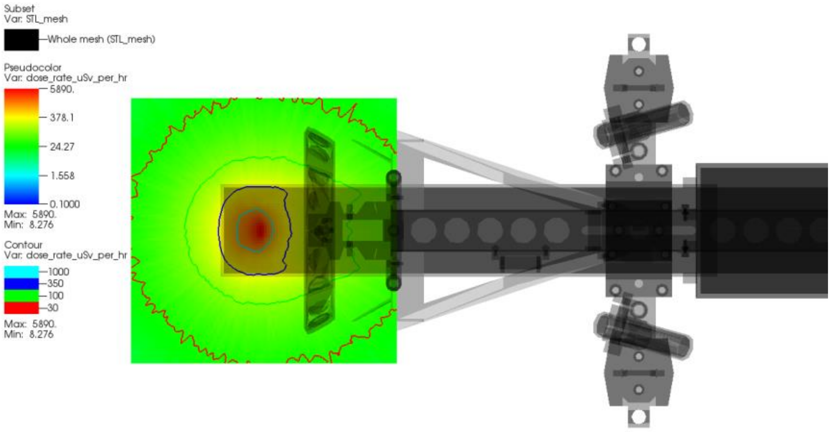

Fig. 8 Dose rate map around the NEU assembly calculated assuming the following irradiation scenario: 7 cycles with 2 min on at 2·10^{8} n/s, 2 min off, and 1 min cooling time.

5. Layout of in-vessel calibration

The NG deployment environment is shown in Fig. 9. The JET torus is shown in cross-section with the robotic boom and MASCOT entering JET Octant 5 from its Boom Tent (protected environment) on the right. On the left, the second boom enters from its Boom Tent in JET Octant 1. These booms are substantial objects spanning the 11 m port to port distance across JET.

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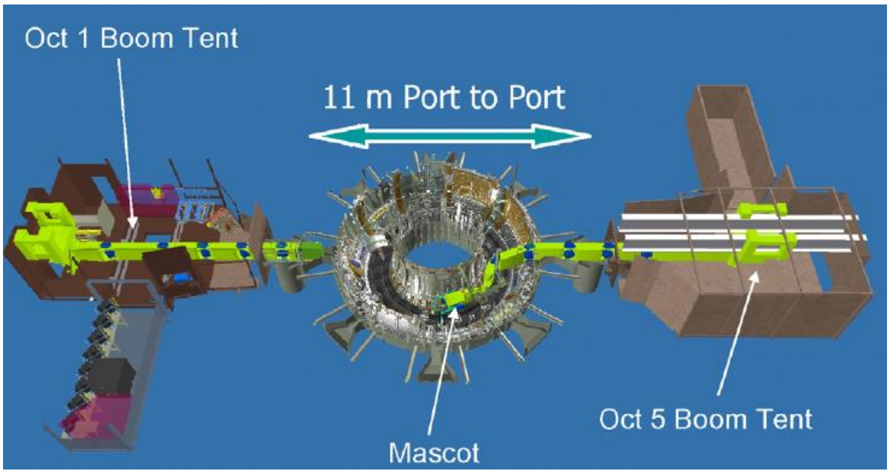

Fig. 9 Deployment environment for JET neutron calibrations. The JET torus and accompanying boom tents are shown in cross-section.

All of the electrical supplies for the NG and measured signals come through the Octant 5 boom and are available for connection at an electrical connector on the MASCOT body. Due to the size of the PSCU it cannot be externally mounted on the MASCOT and then brought into the vacuum vessel.

The NEU and PSCU, together with the monitoring detectors, form a complete instrumentation package which has to be integrated into an assembly suitable for Remote Handling. In addition, a laser based system, calibrated in laboratory, has been designed to ensure that the MASCOT can accurately position the NEU at the desired distance from the in-vessel KN2 position by observing the convergence of the two laser beams on the Irradiation End lower surface (Fig.6). The schematic of the instrumentation package is shown in Fig. 10. The individual components are essentially commercial devices, packaged for use in a laboratory environment, so the design challenge is to ensure that the complete construction meets the following requirements for use 'in vessel':

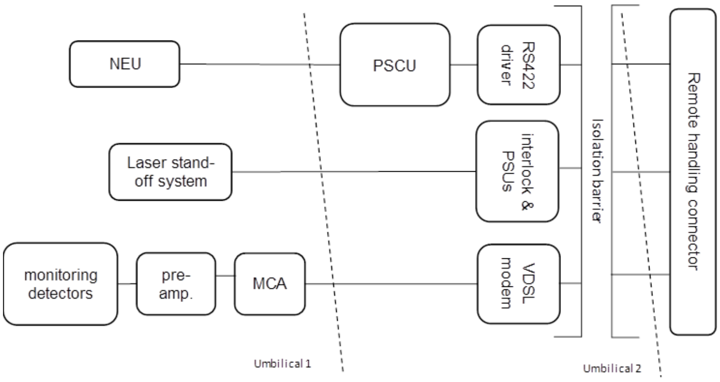

Fig. 10 Schematic of Instrumentation package showing Umbilical grouping and Electrical Isolation barrier

- Interconnections of individual units and umbilical cables have to be highly reliable and designed so as not to impede the manipulation of the NEU by MASCOT

- Power to the instrumentation package has to be supplied through the existing Boom wiring, as described. To avoid voltage drop problems, local isolated power supplies have been used to ensure dependable supplies to the monitoring detector's pre-amplifier and Multi-Channel Analyser (MCA)

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- Data connections to the PSCU and MCA, for command and monitoring, are made with an isolated RS422 driver and VDSL modems. These ensure robust electromagnetic compatibly margins and secure operation through the available boom wiring, which consists of aircraft type twisted pair ribbon cables

- All circuits and control to the NEU, including the interlock circuit, are electrically isolated from the boom wiring and Remote Handling control system

- Containment of parts – material lost or dislodged may contaminate the Torus vacuum. ‘Gaitoring’, by wrapping with vacuum compatible material is necessary

- The design has to permit rapid and convenient fault repair. Any break downs have to be rectified with the equipment still in the Torus Boom tent environment, where restricting personal protective equipment has to be worn

A design solution was therefore developed, where the PSCU and NEU are electrically connected together, with all of the necessary detectors and electronics, and then brought into the vessel on a tray via Octant 1 boom and physically mounted, by the MASCOT arms, onto the MASCOT on the Octant 5 boom inside the vessel, see Fig.11. One electrical connector is then implemented to connect the PSCU and associated electronics to the MASCOT chest connector. This activity is then only necessary at the start of the calibration and reversed at the end to remove the components. This ensures that these complicated electrical connections are made only once during the whole calibration, maximising their reliability and saving time.

At the end of every day’s operation the NEU will be returned to the tray where the horseshoe with activation foils can be removed and replaced with a fresh one. Due to the series of complex RH operations planned mock-ups of all the main components have been produced and the whole sequence of RH operations are to be rehearsed and tested in the In-Vessel-Training Facility (IVTF) prior to the actual calibration.

An electrical assembly of the relevant components, with representative wiring looms, has been incrementally tested during the preparatory work. Further proving will be carried out during mock-up handling trials before final deployment in the vessel.

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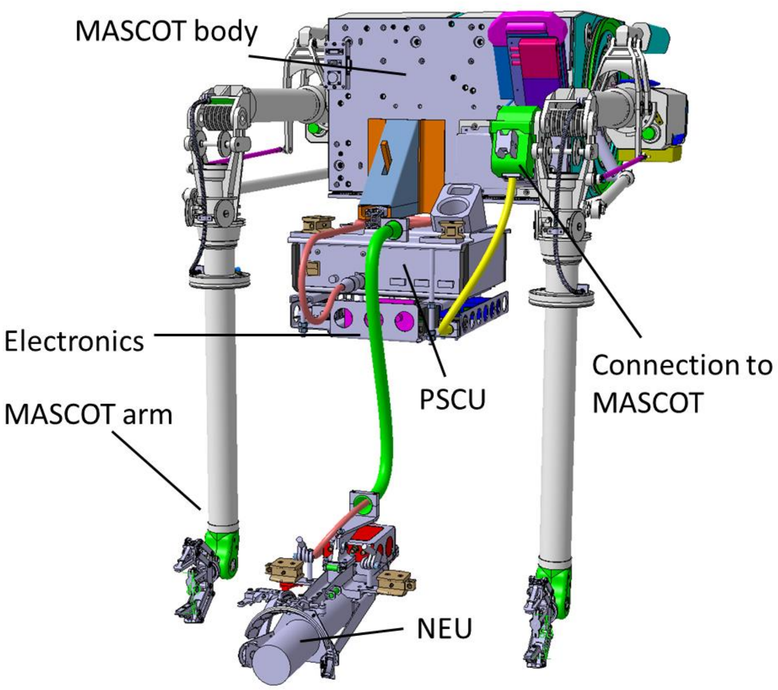

Fig. 11 Model of the NEU, PSCU and electronics mounted on MASCOT showing electrical connections

The personnel hazards associated with the in-vessel calibration using the NG consist of, in the first place, the exposure to high levels of neutron radiation emitted from the NG itself. Safe operation is ensured predominantly by controlling personnel access to the NG at all times when it is switched on. The NG operation will be controlled by isolating and padlocking off the power supply before allowing access to the Torus Hall (J1T). The keys to allow the power supply to be switched on will not be available until a search has been performed of J1T and access to JIT closed off. A procedure will be produced to manage this control. Dose-rates around the neutron generator due to self-activation will be monitored by Health Physics and portable neutron monitors will be used during the set-up and removal of the generator.

6. Conclusions and future activities

The strategy for 14 MeV neutron calibration of the JET neutron monitors is driven as much by the requirements imposed by the Remote Handling and Safety limitations as by those imposed by physics considerations. In selecting a suitable NG, a detailed assessment was needed of the handling capabilities of the MASCOT arms and of other design constraints imposed by the specific tokamak in-vessel environment. Notwithstanding the challenging requirements, it has been possible to identify a neutron generator suitable for the purpose, to design the mechanical and electrical components needed to allow the NG to be used in the JET vessel and to develop a safe and reliable procedure for its deployment and operation inside the JET vessel.

Given the characteristics of the identified neutron generator and its associated tooling, a strategy has been elaborated for its full calibration and characterization. The numerical tools required in support of this activity, a beam-target neutron source routine and the MCNP model of the neutron emitting unit, have been developed. The calibration strategy includes the adoption of multiple monitoring

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*See the Appendix of F. Romanelli et al., Proceedings of the 25th IAEA Fusion Energy Conference 2014, Saint Petersburg, Russia

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detectors that will monitor the NEU neutron yield during the in-vessel calibration, attached to the NEU by means of a dedicated and optimised mechanical support.

The next step of the 14 MeV calibration project is the full calibration/characterization of the NG in a standard neutron laboratory as well as of the monitoring detectors using multiple, well calibrated neutron detectors. This activity is now in progress and will be reported later.

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