NEUTRON FLUX AND ACTIVATION CALCULATIONS FOR A HIGH CURRENT DEUTERON ACCELERATOR

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Abstract

Neutron analysis of the first Neutral Beam (NB) for the International Thermonuclear Experimental Reactor (ITER) was performed to provide the basis for the study of personnel safety during normal operation and maintenance. The first ITER NB is a 1 MeV negative deuterium ions accelerator. The daily average beam current is 13.3 A. To assess neutron transport in the ITER NB structure a mathematical model of the components geometry was implemented into MCNP (Monte Carlo N-Particle transport code system) computer code. The neutron source definition was outlined considering both D-D and T-D neutron production. FISPACT code was used to assess neutron activation in the material of the system components. Radioactive inventory and contact dose rate were assessed considering the potential operative scenarios.

ACCELERATOR MODEL SPECIFICATIONS

The work is mainly aimed to provide data and tools useful to support the licensing and decommissioning phases for the first ITER NB. According to this, the following points have been developed: source term analysis, neutron fluxes, component activation and dose rates. The device is composed by five separated sections: ions source, acceleration section, neutraliser, residual ions dump and calorimeter; they are all inside a vacuum vessel (VV). The source produces 1 MeV deuterium ions which are accelerated, neutralised and stopped on a calorimeter. Ions neutralization takes place in a gaseous environment and residual ions capture is obtained with an electrostatic deflection system. The calorimeter is composed by copper tubes with cooling water inside. Neutral beam is intercepted by the calorimeter, that acts as a copper-water beam-dump. Deuterons have a beam pulse with a charge of 48000 C/h and are mainly responsible of two different reactions, D-D and T-D reactions. A deuterons fraction is suitable to be caught by the copper target and to be hit by the rest of the deuteron beam, producing the following reactions:

$$^{2}H + ^{2}H \Rightarrow \quad ^{3}He{+}n + 3.27\ MeV$$

$$^{2}H + ^{2}H \Rightarrow \quad ^{3}H{+}^{1}H + 4.03\ MeV$$

These reactions provide neutrons with energy in the range 2-4 MeV and tritium in the range 0.5-1.5 MeV. A fraction of these energetic tritons produced in the D-D reactions is involved in the secondary T-D reaction:

$$^{2}H + ^{3}H \Rightarrow ^{4}He{+}n + 17.6\ MeV$$

This reaction yields neutrons with energy in the range 12,5-16,5 MeV that are likely to activate many materials. Neutrons and tritium production due to deuteron acceleration in the ITER NB was not assessed and data were taken from an independent specific work [2]. The calorimeter represents the neutron source in the MCNP model.

Mathematical Model: Geometry and Materials

To assess neutron transport in the ITER NB structure a mathematical model of the components geometry was implemented into MCNP computer code [1]. In this preliminary study, simple geometrical forms (see figg. 2-3 for details) have been defined for beam source, neutraliser, residual ion dump, calorimeter, cryo-pump and vacuum vessel (VV). The VV is replicated with two cylinders, that simulate the beam source vessel (BSV) and the beam line vessel (BLV). The ion source and the accelerator model are situated into the BSV. No detailed structure of these components was replicated, only a copper void cylinder whose external dimensions are equal to the maximum dimensions of the real source was used. The VV has been segmented into eight parts using seven planes located at different distances from the calorimeter in order to obtain separate results according to their position. In the following, the parts that have been simulated are described in order of distance from the ion source into the BLV:

the *neutraliser model*, composed by nine rectangular parallelepipeds. Five of them delimitate four void channels; the rest represent the lateral faces of a box that has no frontal and rear faces. Cooling tubes inside the neutraliser panels are represented by parallelepipeds that have the same water volume as the real one contained in the channel walls. The *RID* is composed by five vertical parallelepipeds that replicate the dump panels. The five panels produce four channels. The RID water content is replicated by internal parallelepipeds that have a volume equal to that of the real system. The *calorimeter* is composed by two multi-slab parallelepipeds and a total of eleven cylinders representing the dump panels, the cooling manifolds and main tubes. The two panels are placed so that their main planes form an angle of 9,6°. Each parallelepiped is composed by an internal water slab and two lateral slabs made of CuCrZr-alloy. The *cryo-pump*, completely located inside the BLV model, is composed by two concentric cylinders and two inclined planes which cut longitudinally the cylinders conferring them an horse shoe shape (with an angle of 250°). The NBI has a total length of 13,3 m and total wide 3,6 m.

The materials considered in the simulation are: CuCrZr, SS316, Cu, H2O and Air. CuCrZr-alloy is used for the main panels of Calorimeter and RID; its elemental

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composition by weight is as follows: Cu = 99.3%; Cr = 0.65%; Zr = 0.05%. SS AISI 316 is the material of the VV, of the cooling tube walls, of the supporting structures and of the cryo-pump. The elemental composition is the following: B = 0.00308%; C = 0.03%; N = 0.0365%; Si = 0.296%; S = 0.0034%; Ti = 0.101%; Co = 0.0538%; Cr = 17.2%; Mn = 1.74%; Fe = 65.3%; Ni = 13.2%; Cu = 0.1%; Nb =0.00 329%; Mo = 1.89%.

Neutron Source Assessment

Both D-D and T-D neutron production have been considered. The saturation density of deuterium implanted in copper calorimeter is known from literature [2] to be between 10% and 20% of deuterium atoms per copper atoms. With the above hypotheses, the reference work prediction [2] of neutron production from D-D beam-target reactions expressed per Coulomb of incident D particle is $3.78\ 10^{12}\ C^{-1}$ while the secondary neutrons production is manly associated to the T-D reaction (D-T reaction is negligible) with a production rate of 5.2×10^{7} C^{-1}. Neutrons from D-D and T-D fusion reactions are energy-angle dependent vs. the beam energy (see fig. 1,2).

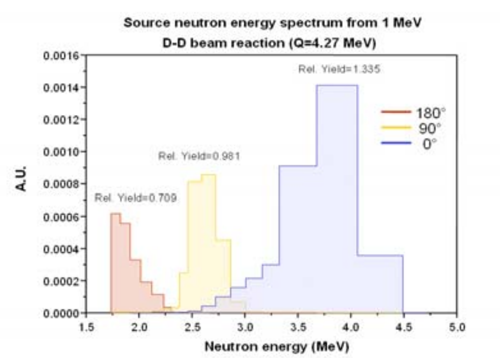

Fig. 1: D-D neutron spectrum.

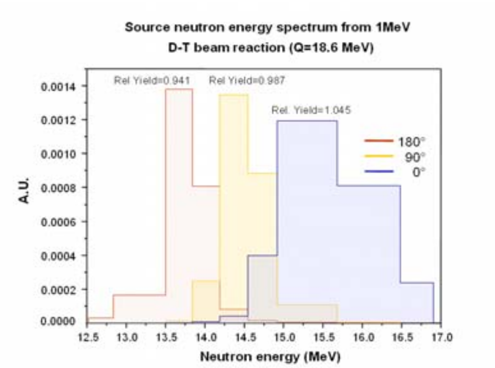

Fig. 2: D-T neutron spectrum.

A detailed source subroutine was implemented for MCNP calculation using a mathematical model already developed for the FNG (Frascati Neutron Generator) facility [3]. This model assume a center of mass isotropic distribution of the D-D or T-D fusion reactions and also consider the deuterons slowing down and atomic scattering in the target. According to our present model, neutron source anisotropy reaches a factor 1.33 in the forward direction for 1 MeV D-D beam reaction (about 1.05 for T-D neutrons) This anisotropy is taken into account in our MCNP calculation.

NEUTRON TRANSPORT

Neutron transport starting from the calorimeter plates was simulated with MCNP code [1]. MCNP is a general-purpose Monte Carlo N–Particle code that can be used for neutron, photon and electron or coupled neutron/photon/electron transport. The code treats an arbitrary three-dimensional configuration of materials in geometric cells bounded by surfaces. Pointwise cross-section data are used. For neutrons, all reactions given in a particular cross-section evaluation (such as ENDF/B-VI) are accounted for. In our MCNP simulation the neutron source has been uniformly distributed on the calorimeter surfaces. The 3D scheme is reported in figure 3.

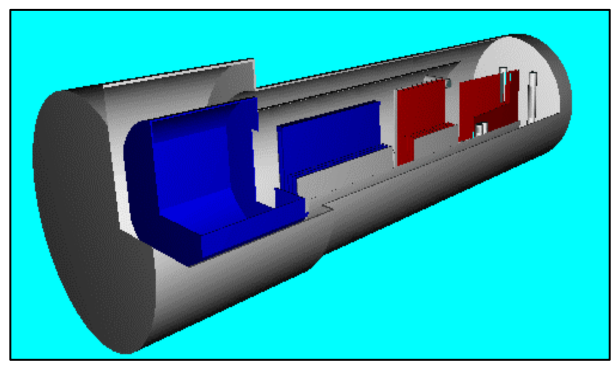

Fig. 3: 3D model of the MCNP geometry.

The following main technical solutions were adopted in the MCNP calculations: no variance reduction techniques were used, up to 67 geometry cells were defined, 175 groups energy bins were selected, typical running time was 7 hours, about 10^{9} neutron stories were generated in each run, statistical uncertainties are lower than 1%.

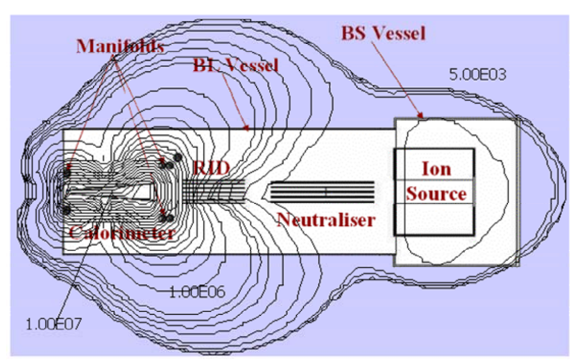

Fig. 4: Neutron flux (n/cm^2s) for an average current of 1 A.

Two main results were calculated with MCNP code: the neutron flux in each geometry cell and the dose rate at different distance from the NB vacuum vessel. In fig. 4

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qualitative iso flux contours due to 1 A deuteron current for the NB model are shown.

Reference Operational Scenario

The ITER NB system is designed to generate 40 A of negative deuterium ions accelerated up to 1 MeV with a five-stage electrostatic accelerator. In order to assess the potential components activation in a severe situation an extreme operational scenario was defined for the interim campaign, considering 20 s pulses of 40 A each and assuming 100 days campaign with 100 pulses per day. The testing period is completed with a 14 days final test during which long pulses of 3600 s each are repeated each 4 hours (6 pulses per day) giving a total of 84 pulses. Assuming a annual campaign composed by the interim campaign and a final test, the average annual current will be:

$$(100x0.93+14x10)/365 = 0.64 \text{ A}$$

In table 1 the annual average of the dose rate due to three interim campaigns and one final test is reported. The results were assessed considering the operational scenario described in the next section.

Table 1: Annual Average of the Dose Rate Due to 3 Interim Campaigns + 1 Final Test

(Dose rates in Sv/h)	100 cm	500 cm
From the VESSEL (highest value)	5.41	0.89
From the front end	7.38	1.21
From the rear end	0.28	0.026

NEUTRON ACTIVATION

Activation and Dose Rates

FISPACT code [4] was used to assess neutron activation in the material of the system components. It is an inventory code that has been developed for neutron induced activation calculations for materials in fusion devices. Seven main components of the NB were considered in the calculation: the solid plates of the calorimeter, the beam source vacuum vessel wall, the calorimeter manifolds, the cryo-pump, the residual ion dump, the neutraliser. For the above components dominant nuclides and contact dose rate were assessed considering two potential operative scenarios, the first one represented by the interim campaign and the second one composed by the interim and a sequential final campaign. As already pointed out, seven planes were located at different position in order to have different results for the VV segments as a function of the distance from the source term. The planes ranges from S1 to S8; in the geometry assessment planes enumeration begins with the plane closer to the calorimeter (S1).

The plane number increases progressively as one gets far from the calorimeter. Table 2 shows the dominant nuclides after 10 years of cooling time, following D-D neutrons activation of the VV segment 8.

Table 2: Dominant Nuclides after 10 Years of Cooling Time

NUCLIDE	ACTIVITY (Bq)	PERCENT ACTIVITY	PRODUCTION PATHWAYS
Fe 55	1.0E+07	49.59E+00	Fe54(n,γ)Fe55
			Fe54(n,γ)Fe55
Co 60	8.3E+06	39.81E+00	Co59(n,γ)Co60
			Co59(n,γ) Co60
Ni 63	2.0E+06	94.81E-01	Ni62(n,γ)Ni63
			Cu63(n,p)Ni63
Mn 54	2.0E+05	96.62E-02	Fe54(n,p)Mn54

Contact dose rates after neutron activation have been assessed as well, considering separately D-D and T-D neutrons. Figure 5 shows the contact dose rates on the VV segments due to D-D and T-D neutrons after a reference campaign and the final test.

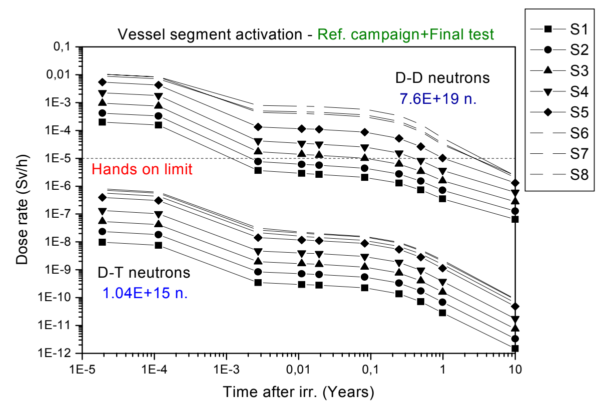

Fig. 5: V segments activation.

D-D neutrons show a contribution about 10^4 times higher than that due to the T-D neutrons. The ratio between the two contributions is almost equal to the ratio between the respective neutron yields, showing that the different nuclear reactions at the different energies do not affect the activation result.

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