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Neutron induced activation in the EVEDA accelerator materials: Implications for the accelerator maintenance

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ABSTRACT

The Engineering Validation and Engineering Design Activities (EVEDA) phase of the International Fusion Materials Irradiation Facility project should result in an accelerator prototype for which the analysis of the dose rates evolution during the beam-off phase is a necessary task for radioprotection and maintenance feasibility purposes. Important aspects of the computational methodology to address this problem are discussed, and dose rates for workers inside the accelerator vault are assessed and found to be not negligible.

1. Introduction

Deuteron beam losses along the EVEDA accelerator collides with the surrounding materials, resulting in a source of secondary neutrons produced by deuteron interaction with (i) copper hosting atoms, and (ii) deuterium implanted in the copper lattice.

This neutron source is the main responsible of structural materials activation and subsequent dose rates during beam-off phases of the EVEDA accelerator. This paper, within the framework of the IFMIF Design Integration EFDA task, addresses this problem. A comprehensive computational methodology has been defined for reasonably predictions, and a detailed description can be found in [1].

In a first step, neutrons produced from d–d and d-target reactions should be determined, and secondly these source neutrons should be transported to compute the neutron flux. Computational tools selected and results regarding this phase are presented in Section 2. In the second step, the radioactive inventory and the corresponding decay photon source are calculated, then transport of the emitted gamma rays is performed and the dose rates are evaluated. Also dose rates from deuteron activation are computed for comparison purposes. Section 3 is devoted to this phase.

2. Neutron source and flux evaluation

Geometrical model used for the EVEDA accelerator components, Radio Frequency Quadrupole (RFQ), Matching Section (MS), and Drift Tube Linac (DTL), is that agreed in [2]. In particular for the RFQ, the model consists of the following concentric cylindrical-shaped materials from inner to outer radius: copper (1 cm), copper plus vacuum (20 cm), copper (1 cm), stainless steel SS316 LN IG (3 cm), water (1 cm), vacuum (10 cm) and stainless steel SS316 LN IG (5 cm).

The deuteron losses estimations are (i) those from IAP/Frankfurt (2006) for the RFQ [3], (ii) those from CEA (2003) for the MS (unaccelerated particles from RFQ) [4], and (iii) 1.25 nA/m for the DTL.

As can be seen in the Table 1, EVEDA accelerator is divided in several sections. No energy increase is considered for each section. The maximum energy value at the output of each section is attributed for each one. For the sections 11, 12 and 13, deuteron losses come into contact with the materials perpendicularly, whereas for the remainder sections an angle of 85° respect the normal is assumed.

In evaluating the neutron source produced by d–d and d-Cu interactions, one of the problems is that no secondary neutrons are produced by Monte Carlo transport codes, such as MCNPX [5], up to around 6 MeV. The proposed solution to address the issue [1] makes use for d–d nuclear interactions of the cross section data provided by the DROSG-2000/NEUYIE code [6], and for d-Cu interactions the cross sections are taken from European Activation File Library EAF-2007 [7]. Consequently, for incident deuterons with energy below 6 MeV, we compute first the neutron source, and then, this is input to MCNPX in order to carry out neutron transport and flux calculations.

In determining the d–d neutron source other important issue is to predict the density profiles of the deuterium content within the implantation zone of the copper-target material. This is performed by a coupling use of the SRIM [8] and TMAP7 [9] codes. The empiric parameter describing the state of the surface plays a major role in

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Table 1
Deuteron beam losses for each section.

Section	Energy (MeV)	Device	Losses (mA)
1	0.1	RFQ	6.24
2	0.15	RFQ	3.12
3	0.2	RFQ	0.78
4	0.4	RFQ	0.16
5	1	RFQ	0.08
6	1.7	RFQ	0.23
7	2.3	RFQ	0.23
8	3	RFQ	0.23
9	4	RFQ	0.16
10	5	RFQ	0.16
11	0.095	MS	0.22
12	7	DTL	2.89×10^{-6}
13	9	DTL	2.89×10^{-6}
		Total	11.53

the kinetics of surface recombination of the implanted deuterium. This parameter, known as sticking factor (σ), can vary from $\sigma = 1$ in a pure crystalline perfect clean surface, to $\sigma = 10^{-5}$ in a roughly oxidized surface. For our problem, $\sigma = 1$ is assumed to be reasonable.

Spatial distribution and temporal evolution of the density profiles of the deuterium implanted in the copper lattice exhibits a very similar shape for all accelerator sections of concern (RFQ and MS). Fig. 1 shows the deuterium profile evolution for section 10 (irradiation from 1 day to 1 year, and 125 mA- full power current). Beyond few days of irradiation, density profiles of the deuterium implanted in the copper lattice keeps almost stationary. They show a uniform density with depth up to around 2 mm, followed by a sharp fall. This constant value depends on the deuteron flux properties for each section (energy and angle of incidence). The maximum density is 3.85×10^{25} at/m^3, corresponding to the MS, and for the other sections of the RFQ this value is of the order of 10^{24}. It is worthwhile mentioning that for a conservative sticking factor of 0.01, the density (and consequently the neutron source) increases one order of magnitude, and that the maximum deuterium saturation density in copper at room temperature, 1.7×10^{28} at/m^3, traditionally used in this type of calculations, is 4 orders of magnitude higher.

Fig. 2 shows the neutron source due to d–d and d-Cu reactions at one year irradiation time. The highest value of the neutron source is reached at section 10 of the accelerator and is due to the d-Cu neutron source. In the inner zone of this section, the neutron flux is 1.5×10^8 n/cm^{2}s.

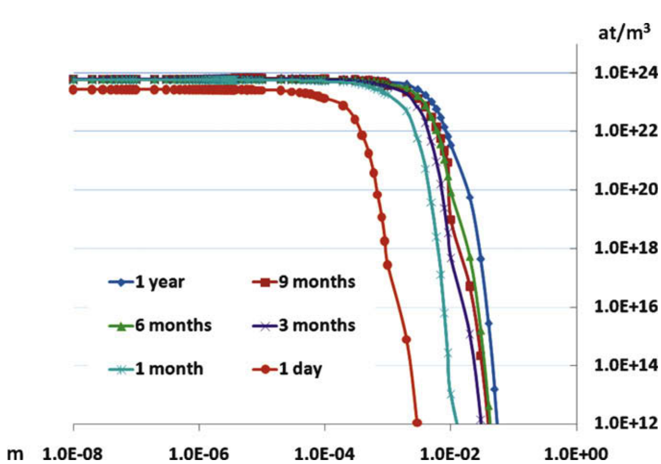

Fig. 1. Evolution of the deuterium concentration profile for the section 10 (RFQ).

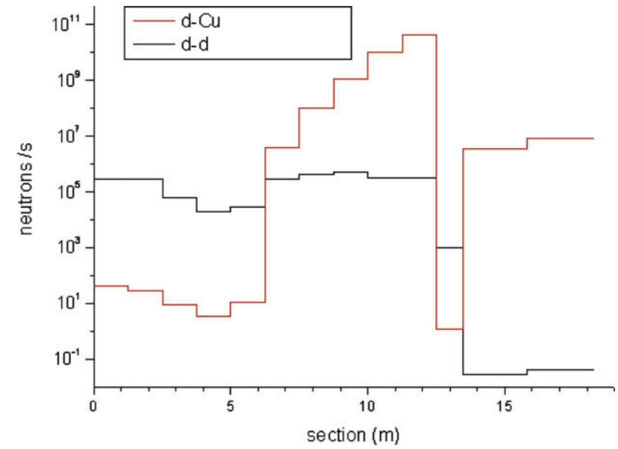

Fig. 2. Neutron source rate due to d–d and d-Cu reactions for 1-year irradiation and sticking factor equal to 1.

Table 2
Decay gamma dose rate evolution in section 10 (RFQ).

Cooling time	Gamma dose (μSv/h)	
	At external surface	At 1 m from surface
Shutdown	72.98	13.82
1 Hour	28.43	5.09
1 Day	26.01	4.67
1 Week	23.96	4.28
1 Month	19.34	3.45
3 Month	16.15	2.87
6 Month	7.00	1.24

3. Activation and dose rates

Decay gamma dose rates at various distances from the external surface of the cylindrical-shaped accelerator, have been evaluated. The irradiation scenario corresponds to one-year irradiation and 125 mA full power current. Dose rates are due to the neutron activation induced in all the layers of the accelerator.

The radioactive inventory and the corresponding decay photon source are calculated with the ACAB [10] activation code, and the nuclear data from EAF-2007 System [7,11]. Transport of the emitted gamma rays is performed with the MCNPX code using the Photon Library MCPLIB02 [12], and the dose rates are evaluated using the gamma fluence to dose conversion factors from NIST data base [13].

The d–d reaction effect dominates the dose rates only in the sections where d-Cu reactions do not take place, that is, in the RFQ up to 6 m length. However, the maximum decay gamma dose rate level, that from section 2 of the RFQ at shutdown and at surface, is only 2.24×10^{-4} μSv/h. On the contrary, the d-Cu reaction has a relevant effect on dose rates levels. Maximum values are obtained in the section with the greater neutron source, i.e. in section 10. Table 2 shows decay gamma dose rate evolution for this section at surface and at 1 m distance. As can be seen, the level corresponding to the dose rate limit for workers (10 μSv/h) is reached at surface after a cooling period of around 5 months.

Dose rate from deuteron activation has been also computed. Maximum values, those in section 10 at shutdown and at the external surface are 3.50×10^{-2} μSv/h, i.e. more than three orders of magnitude lower than that resulting from neutron activation.

4. Conclusions

In the framework of the EVEDA phase, neutron source, neutron flux and the corresponding dose rates on beam-off phase has been calculated. A comprehensive methodology to deal with the problem has been proposed.

The d–d neutron source obtained using density profiles for the implanted deuterium computed with the proposed tools has been found very different than that obtained using the traditional deuterium saturation density in copper at room temperature. And above all, the effect of considering d-Cu interactions at energies below 6 MeV has been found critical in assessing the neutron source relevance for dose rates evaluations.

The d–d neutron source is negligible in terms of dose rate production when compared to the workers dose rate limit. Dose rate from deuteron activation has found also to be irrelevant. On the contrary, the d-Cu neutron source has a very significant effect. It is responsible of the dose rates at the end of the RFQ and in the DTL. Maximum decay gamma dose rate is observed at the end of the RFQ, where the deuteron energies are in the range between 4 and 5 MeV. At the external surface and after a few months of cooling, dose rate levels are higher than the dose rate limit for workers.

As d-Cu reactions in the 4–5 MeV range have been found the most relevant in regards to neutron source (and dose rates) evaluations, an additional quality assessment of the cross sections data used for this range, EAF-2007, would be very useful.

Acknowledgments

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