Electronics reliability of future power fusion machines: numerical investigations at silicon level

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Abstract

The interactions of high energy neutrons produced in D-D and D-T nuclear fusion reactions with natural silicon have been investigated through direct calculation using nuclear cross section libraries, MCNP6 and Geant4 numerical simulations. We provide a detailed analysis of all interactions per type of reacting silicon isotope and an exhaustive classification of all neutron-induced secondary products. Implications for reliability of the electronics in future power fusion machines are discussed on the basis of these first evaluations.

1. Introduction

Deuterium-tritium (D-T) and deuterium-deuterium (D-D) nuclear fusion reactions are the most interesting and important reactions for magnetic and inertial confinement approaches envisaged to develop future carbon-free source of energy based on the same principle that powers the stars [1]. In both cases, an extremely high level of energetic neutrons will be produced during power fusion operation, creating a residual neutron irradiation field outside the reaction chamber. Of course, the radiation conditions will be very different for D-D and D-T plasma operations, the latter being the most challenging for electronics, with the production of primary 14.1 MeV neutrons against 2.45 MeV neutrons in the D-D plasma operation. Because all future fusion reactors will contain a large amount of electronics part for command and diagnostic operations of such complex large systems, many of these parts will be exposed to nuclear radiation and negatively affected by this environment condition. Nuclear radiation can damage or destroy electronic devices or sensors, corrupt signals in analogue or digital circuits, corrupt data in memories, etc. In fusion machines, these effects can appear progressively, due to accumulated ionization or accumulated atomic displacements, or instantaneously, due to single neutron interactions inducing the so-called Single Event Effects (SEE) [2]. In this work, such neutrons interactions at the origin of SEEs in fusion experiments have been explored. In a first approach, monoenergetic D-D (2.45 MeV) and D-T (14.1 MeV) neutrons reactions with silicon material have been investigated through direct calculation using nuclear cross section libraries and performing numerical simulations with two different radiation transport codes, MCNP6 [3-4] and Geant4 [5-6]. Details about these different approaches are given in section 2. From these systematic simulations of a large amount of neutrons incident on a natural silicon bulk target, we provide in section 3 a detailed analysis of all interactions per type of reacting silicon isotope and an exhaustive classification of all neutron-induced secondary products. Finally, implications for reliability electronics in future power fusion installations are discussed in section 4 on the basis of these first evaluations.

2. Simulation details

In the following, we consider a thin silicon layer with an area of S=1 cm^2 and a thickness of e=20 µm corresponding to the order of magnitude of the sensitive volume of a typical microelectronics integrated circuit in bulk architecture. The composition of this target corresponds to natural silicon: it contains 92.20% of isotope ^{28}Si, 4.70% of ^{29}Si and 3.10% of ^{30}Si with a total atomic density equal to N=5×10^{22} at./cm^3, which corresponds to a material density of 2.32 g/cm^3.

The susceptibility of this layer to neutron irradiation in the fusion machine context, as discussed below in section 4, can be roughly evaluated via the calculation of the number of neutron-silicon interactions when it is subjected to 2.45 or 14.1 MeV monoenergetic neutrons. Such a calculation can be performed following two approaches: i) a direct analytical calculation using neutron cross section

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library data or ii) a numerical estimation using a Monte Carlo radiation transport code. In this latter case, in addition to the amount of interactions, a simulation run can provide more detailed information when the code is able to track secondary particles, as it is possible to do with Geant4 for example.

In this work, the ENDF/B-VII.1 evaluated neutron library [7] has been considered for a direct calculation of neutron interactions in the defined target. From these data (extracted from [8]), the number of interactions in the target at a given neutron energy E is simply given by:

$$R(E) = \sum_i f_i \sigma_i(E) \times 10^{-24} \times Ne \times M$$

where σi is the value at energy E of the cross section for isotope i (in barn), fi is the fraction of isotope i in the target isotopic composition, e is the target thickness, N is the number of atoms per unit volume and M is the number of incident monoenergetic neutrons, in this work fixed to the arbitrary value $M = 5\times10^8$ for standardization purpose (fixed in other studies [9-11], M corresponds to the number of high energy atmospheric neutrons – above 1 MeV – impacting a surface of 1 cm^2 at sea level exposed to natural radiation during 25×10^6 h).

As mentioned above, an alternative to the direct calculation is numerical simulation using a Monte Carlo radiation transport code. In the present work, both MCNP6 and Geant4 were used. Geant4 version 4.9.4 patch 01 was used for these simulations following a methodology used in previous works [9-11]. In particular, the list of physical processes employed was based on the standard package of physics lists QGSP_BIC_HP [12]. Other simulation details can be found in Ref. [10].

3. Simulation results

Tables 1 and 2 report the number of elastic, inelastic and nonelastic events (see [13-14] for a definition of these categories) produced in the 1 cm^2 × 20 µm natural silicon target subjected to 5×10^8 monoenergetic neutrons of 2.45 MeV and 14.1 MeV and evaluated using direct calculation and numerical simulation. These results show a good agreement between the three estimations in terms of global number of events for the different types of interactions and for the three isotopes of silicon.

The numerical differences are within uncertainty margins inherent to Monte Carlo methods and to the extraction of the cross section values from library data (extrapolation from discrete values at 2.45 MeV and at 14.1 MeV).

Table 1. Elastic and inelastic reactions in a natural silicon target (1cm^2 × 20 µm, 5×10^8 n) with 2.45 MeV and 14 MeV neutrons estimated from TENDL-2019 direct calculations, Geant4 and MCNP6 numerical simulations.

Isotope of natural silicon	Reaction	Threshold (MeV)	Number of reactions (1cm^2 × 20 µm, 5×10^8 n)					
			ENDFB-VII.1		Geant4		MCNP6	
			2.45 MeV	14 MeV	2.45 MeV	14 MeV	2.45 MeV	14 MeV
^{28}Si (92.22%)	$^{28}Si(n,n)^{28}Si$ (Elastic)	~ 0	86,207	33,653	85,710	32,812	86,100	30,798
	$^{28}Si(n,n)^{28}Si^*$ (Inelastic)	1.78	29,042	23,972	28,754	24,042	28,677	24,161
^{29}Si (4.68%)	$^{29}Si(n,n)^{29}Si$ (Elastic)	~ 0	4,513	1,880	4,335	1,705	4,467	1,648
	$^{29}Si(n,n)^{29}Si^*$ (Inelastic)	1.8	1,433	1,504	1,397	1,910	1,441	1,823
^{30}Si (3.09%)	$^{30}Si(n,n)^{30}Si$ (Elastic)	,,~0	3,565	1,132	3,475	1,113	3,531	1,043
	$^{30}Si(n,n)^{30}Si^*$ (Inelastic)	1.8	1,131	961	294	893	312	1,598
TOTAL			125,891	62,783	123,965	62,475	124,528	61,071

Table 2. Nonelastic reactions in a natural silicon target (1cm^2 × 20 µm, 5×10^8 n) with 14 MeV neutrons estimated from ENDFB-VII.1 direct calculation, Geant4 and MCNP6 numerical simulations.

Isotope of natural silicon	Nonelastic reaction	Threshold (MeV)	Number of reactions – 14 MeV (1cm^2 × 20 µm, 5×10^8 n)			
			Geant4		MCNP6	ENDFB-VII.1
^{28}Si (92.2%)	$^{28}Si(n,p)^{28}Al$	4.00	12,623	26,383	26,398 (no detail about reactions)	26,738
	$^{28}Si(n,\alpha)^{25}Mg$	2.75	8,195			
	$^{28}Si(n,np)^{27}Al$	12.00	3,798			
	$^{28}Si(n,d)^{27}Al$	9.70	904			
	$^{28}Si(n,n\alpha)^{24}Mg$	10.34	863			
^{29}Si (4.7%)	$^{29}Si(n,\alpha)^{26}Mg$	0.035	379	729	708	846
	$^{29}Si(n,p)^{29}Al$	3.00	350			
^{30}Si (3.1%)	$^{30}Si(n,\alpha)^{27}Mg$	4.34	137	207	170	496
	$^{30}Si(n,p)^{30}Al$	8.00	70			
			TOTAL	27,319	27,276	28,080

The quantitative comparison between Geant4 and MCNP results shows that the two codes produce the same results in quasi all cases (within less than a few percents). The only notable difference is observed for the small amount of nonelastic events in the case of ^{30}Si for which important fluctuations are observed between the three evaluations without explanation at this level. Results of Table 1 and 2 also show that the same number of incident neutrons on a natural silicon target produce two time more interactions at 2.45 MeV than at 14 MeV, respectively about 124 k against 62 k events. For a normalized incident neutron flux of 10 n/cm^2/s (see section 4), this corresponds to an interaction rate of 2.48×10^{-3} s^{-1} (≈ 9 h^{-1}) at 2.45 MeV and of 1.24×10^{-3} s^{-1} (≈ 4.5 h^{-1}) at 14 MeV for the considered target. But the nature distributions of these interactions are profoundly different for these two energies. Figure 1 illustrates this aspect by cumulating the contributions of the different silicon isotopes for each category of interactions: results show that natural silicon subjected to 14 MeV neutrons produces 40% of elastic events, 30% of inelastic and 30% of nonelastic events. At 2.45 MeV, no nonelastic event is produced; elastic events dominate the neutron silicon response with 75% of events against about 25% of events for inelastic interactions.

In addition to the above results, the final paper will include the complete analysis and discussion of product histograms in terms of energy, initial linear energy transfer (LET) and range in silicon which cannot be included in this abstract for lack of space.

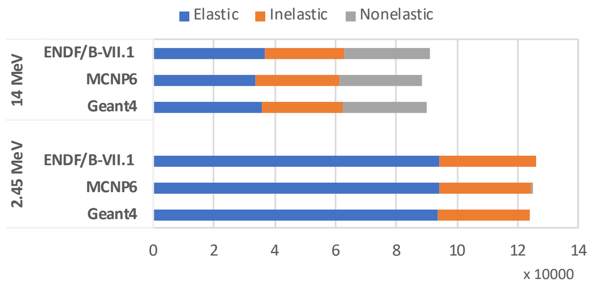

Figure 1. Comparisons between Geant4 and MCNP6 numerical simulations and direct calculations using EDNF/B-VII.1 nuclear data library.

4. Implications for reliability electronics of future power fusion machines

Future power fusion reactors, like ITER or DEMO, will be very large machines characterized by a very large number of electronic equipment's for all operations of control commands, safety diagnosis and information management [15]. Dispersed in the reactor building, around the reactor chamber, these equipment's will be subjected to a machine-induced radiation environment. For these future machines and in order to reduce the cost of electronics, the most plausible design strategy for electronics will be (1) to drastically limit the need of radiation-hardened electronics installed in the severe environment close to the tokamak chamber by deporting and installing electronics in radiation protected area (RPA) and (2) to standardize as much as possible the radiation-hardened electronics needed in the severe environment close to the tokamak chamber. In these RPAs, the radiation conditions are expected to be compatible with the level of electronics reliability requested for machine operation. A large fusion machine such as a tokamak has many auxiliary systems, each of which requires complex instrumentation with many I&C electronic cabinets. For instance, a recent rough engineering estimation for the ITER Project shows that the reactor building will house more than five hundred I&C electronic cabinets [16] containing various types of semiconductor devices (analogue devices, digital devices, optoelectronic devices, power devices, switching devices,…), and that modern I&C electronics cabinet such as those to be used in ITER can typically house up to 30,000 to 40,000 semiconductor devices [16]. Considering conservatively only 300 cabinets and applying a conservative 50% fill factor results in about five million semiconductor devices. This conservative rough estimate can be considered as representative of modern fusion machines. Although a very large proportion of these devices will be installed in RPAs, the radiation shielding of these later risk, for technical and cost reasons, to be not sufficient to totally screen the "high energy" (E > 1 MeV) neutron flux produced in the tokamak plasma (the problematic of low energy and thermal neutrons is considered to be solved by properly shielding the RPAs with appropriate materials and thicknesses).

In the following and in order to illustrate this point, we choose a very plausible value of 10 n/cm^2/s as the maximal residual total neutron flux (E > 1 MeV) tolerated in RPAs. This value will necessarily result from a compromise between the reduction of the radiation level, the size, the weight and the financial cost of the neutron shielding structures. For machines like ITER or DEMO, such a residual value corresponds to a fantastic shielding reduction factor, around 10^{12} to 10^{13}, in the total neutron flux generated in the fusion plasma. But compared to the natural comic-ray induced neutron flux at sea level which is equal to 20 n/cm^2/h (E> 1 MeV) [13], i.e. 5×10^{-3} n/cm^2/s; it represents 2,000 times the terrestrial neutron flux but with an energy distribution of neutrons, of course, very different. At this stage, without an accurate knowledge of the neutron flux energy distributions in RPAs for machine operation with D-D or D-T plasmas, a limit case can be envisaged as a "worst case" to roughly estimate the impact of machine-induced neutrons on electronics: that of considering this residual flux of 10 n/cm^2/s inside RPAs is composed only of 2.45 or 14 MeV neutrons. From simulation results reported in section 2, we estimated under this flux a global interaction rate of 2.48×10^{-3} s^{-1} (≈ 9 h^{-1}) at 2.45 MeV and of 1.24×10^{-3} s^{-1} (≈ 4.5 h^{-1}) at 14 MeV for the considered target. These values represent an "upper limit" for the interactions potentially responsible of SEEs at semiconductor device level in electronics. On this basis, the following estimations can be easily derived: for five million chips on board with a typical silicon surface of 10 mm^2 per chip, we obtain a total of 4.48×10^6 interactions per hour at 2.45 MeV and 2.23×10^6 at 14 MeV susceptible, for a fraction of them, to induce problematic SEEs at semiconductor device level (the impact at system level, which depends on the system architecture, is outside the scope of the present study). For modern digital electronics, if in addition we consider that: i) 2.45 MeV n-Si interactions (exclusively composed of elastic and nonelastic events characterized by very short ranges, see the additional results – range histograms – reported in the final paper) are approximately 4 times less efficient than 14 MeV n-Si interactions (one third are nonelastic events with more energetic and "long range" products as protons and alpha which represent much more dangerous particles in terms of SEE's occurrence and magnitude) to induce SEEs as evidenced in [17] ; ii) only a very small fraction of 0.1% of these events cannot be corrected by error correcting codes (EEC) in logic devices and potentially conduct to "problematic" SEEs (high performance EEC can recover more than 99% of the errors [18], we consider here an efficiency value of 99.9%) ; then this trivial calculation shows that, for five million semiconductor devices estimated in the reactor building of a fusion machine, the magnitude of the failure rate at semiconductor device level should be in the order of 0.3 SEE/s at 2.45 MeV and 0.65 SEE/s at 14 MeV. This typically represents, for a tokamak plasma pulse duration of 10 minutes (600 s), a maximum of 180 potentially « problematic » SEEs in D-D plasma operation, and around 375 SEEs in D-T plasma operation. We would like immediately insist on the roughly character of these first worst case estimations, due to an extreme simplification of the inputs and on the calculation hypothesis: 1) neutrons will not be monoenergetic and their energy will be degraded when a fraction of them will penetrate in RPAs, 2) electronics will not be fully digital and a part of the five million of devices will be analogue, optoelectronics or power components characterized by other neutron sensitivity mechanisms, 3) the fraction of "problematic" events is difficult to generalize and to evaluate for all future components and circuits of electronic equipment of large fusion machines. All these precautions being said, the fact remains that the calculated orders of magnitude is certainly realistic and have the merit of showing that a residual flux of neutrons in the RPAs, as low as 10 n/cm^2/s, will inevitably lead to potentially problematic SEE neutron events in the electronics at device level during machine operation, with both D-D and D-T plasmas.

The next steps of this exploration study will be to use the Geant4 databases computed in this work to more accurately estimate the occurrence of SEEs in a series of generic devices representative of tokamak electronics and also to refine all the calculations by considering neutron spectral distributions in the RPAs when such data will be available. The refined estimates of the occurrence of SEE at the device level, which should be provided by this next stage of study, could then be used as input to estimate the impact of SEEs on the reliability of the various auxiliary systems of a fusion machine.

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