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STUDY OF THE DISPLACEMENT PER ATOM IN THE n-ALPHA REACTION ON MgB_2

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Abstract

In the frame of the High-Luminosity LHC[*)] project (Working Package 6.4, dedicated to the energy deposition and material studies), the effects of the energy deposition from the 7+7 TeV p-p debris on the High Temperature Superconducting Links (made of MgB_2) is evaluated. This paper is focused on the effect of the n-alpha reaction on MgB_2 and the determination of the induced Displacement per Atom (DPA).

The contribution of the single component of the reaction i.e. neutrons, alpha particles and lithium atoms on the DPA is evaluated.

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1 INTRODUCTION

In the frame of the High Luminosity LHC (HL-LHC) project aimed to increase the machine luminosity many improvement on the machine are foreseen.

Among them the removal of the power converter, feeding the magnets, from the tunnel and their location on surface. The delivery of about 150kA to the magnets will be done through Superconducting Links (SCL) in MgB_2. The Links will be exposed to the radiation field of the debris from the Interaction Point (IP) and to the secondary generated particles. Among them neutrons are the main component (about 71% of the total).

The high cross section of ^{10}B (^{10}B natural abundance is about 20% of the natural Boron composition) for the neutron capture reaction need a careful analysis of the effects of this interaction, in order to guarantee a safe operation of the SC Links during the lifetime of the machine. The parameter indicating the radiation damage is the Displacement Per Atom (DPA). The effect of the boron capture reaction (releasing a Lithium nucleus and an alpha particle) on the SC Links and the induced DPA are presented.

Then simulation of irradiation test have been done, in order to evidence the relative contribution by the alpha particles and Lithium ions to the total DPA. The data of the simulation are then compared with the results of irradiation tests.

2 THE HI-LUMI-LHC PROJECT AND THE COLD POWERING TASK

The LHC will remain the most powerful accelerator in the world for at least the next two decades. Its full exploitation is the highest priority of the European Strategy for particle physics. To extend its discovery potential, LHC will need a major upgrade in the 2020s to increase its luminosity (and thus collision rate) by a factor of five beyond its design value. The integrated luminosity goal is a factor ten times design. The novel machine configuration, the HL-LHC, will rely on a number of key innovative technologies representing exceptional technological challenges. These include among others: cutting-edge 11-12 tesla superconducting magnets; very compact with ultra-precise phase control superconducting cavities for beam rotation; new technology for beam collimation; and long high-power superconducting lines (hereafter called “links”) with zero energy dissipation.

In the present LHC configuration, the electrical feeding of the about 1700 LHC superconducting (SC) circuits requires the transfer of more than 3 MA of current from the power converters to the magnets. Now this is done via conventional copper cables for the room temperature path between power converters and current leads, High Temperature Superconductors (HTS) or resistive currents leads for the transfer to the 4.5 K liquid helium bath. Then, Nb-Ti bus-bars operated in liquid helium at 4.5 K or in superfluid helium at1.9 K provide the connection to the SC magnets. In the present LHC configuration, power converters and current leads are both located in underground areas, the first mainly in alcoves, adjacent to the machine tunnel, and the second in special cryostats that are near the LHC interaction points and in line with the SC magnets. From each of the eight interaction points, power converters and leads feed the magnets occupying half of the two adjacent machine sectors. A number of smaller amperage power converters are placed along the tunnel, underneath the SC magnets. All equipment in the tunnel is exposed to significant levels of radiation.

HL-LHC will require novel superconducting lines are being developed for feeding the magnets from remote distance[1)]. The new electrical layout envisages the location of the power converters and of the current leads either in surface buildings or in underground areas, some hundred meters away from the tunnel. The transmission of the current to the magnets is performed via SC links containing tens of cables feeding different circuits and transferring all together up to about 150 kA. The benefits of this remote powering via SC links are several and can be summarized as follows:

- Access of personnel for maintenance, tests and interventions on power converters, current leads and associate equipment in radiation free areas, in accordance with the principle of radiation protection that optimizes doses to personnel exposed to radiation by keeping them As Low As Reasonably Achievable (ALARA) and making integration easier (the IR regions are quite busy places and would be difficult, if not impossible, to locate all new power converter needed for HL-LHC in the existing alcoves or aside tunnels.

- Removal of the current leads and associated cryostats from the accelerator ring, thus making space available for other accelerator components;

- Location of the LHC power converters in radiation free areas with a definitive solution to the problem associated with the radiation damage of these devices. As already experienced during the first years of LHC operation, events that result stochastically from single interactions between energetic ionizing particles and electronic components - single event effects - at some locations in the tunnel affect the performance of the power converters and induce failures that impact on beam availability for physics.

The Hi-Lumi program was dedicated to the development of SC links to be integrated at the LHC interaction point 1 (P1), point 5 (P5) and point 7 (P7). Further development will not foresee, probably, the location on surface of the power converter.

3 WHAT IS THE DISPLACEMENT PER ATOM (DPA)

The displacement per atom is an indicator of the effects of the radiation damage on irradiated material. It is a displacement damage related to energy transfers to atomic nuclei and can be induced by all particles produced in the hadronic cascade; it is an intensive quantity (like density and dose).

DPA indicates the times an atom is has been removed from its site in the lattice, so N DPA means that every atom in the considered solid has been moved N times.

DPA can be calculated from the formula:

$$DPA = \frac{1}{\rho} \sum_i N_i N_F^i \tag{1}$$

where : ρ is the atomic density (atoms/cm^3)
N_i is the number of particles per interaction channel
N_F^i is the number of Frenkel pairs per channel

An equivalent way of expressing DPA is:

$$DPA = \frac{1}{\delta} \frac{A}{N_A} N_F \tag{2}$$

where : δ is the material density (g/ cm^3)
A is the mass number of the material
N_F^i is the number of Frenkel pairs
N_A is the Avogadro's number

A detailed description of the atomic radiation induced damages can be found in[2] while the DPA implementation in the FLUKA[3) 4)] code is described in[5)] .

4 PARTICLE FLUENCE, NUCLEAR REACTIONS, DPA

The particles coming from the 7+7 TeV proton-proton interaction interact with the beam pipe, the low-beta quadrupoles and all the ancillaries, then hit the SC links.

4.1 Particle Fluence

In the conservative hypothesis of placing the SCL one meter above Q1 (about 23 m from the IP (actually the final configuration foresees the link terminating about 80 m from the IP going in a connection module, where the cables of the links connects to the corresponding loads), the amount of the particles escaping from Q1, as from FLUKA simulations, is shown in Fig.1(black bars), together with the particles entering the SCL (red bars). The neutrons going into the SCL are about 67% of the total, while photons are about 33%.

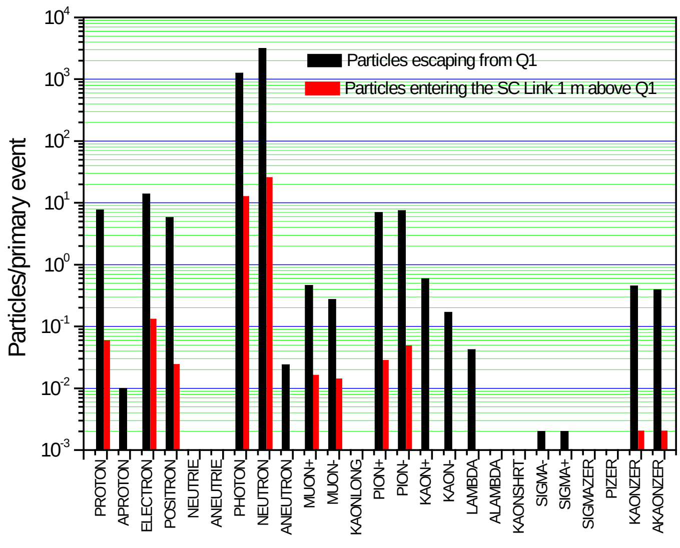


Fig.1: Particles escaping from Q1(black) entering the SCL (red)

In Fig.2 the mean kinetic energy of the particles escaping from Q1(black) and entering the SCL (red) is shown. The energy carried by the neutrons is about 68% of the total entering the SCL, while 14% is carried by the photons.

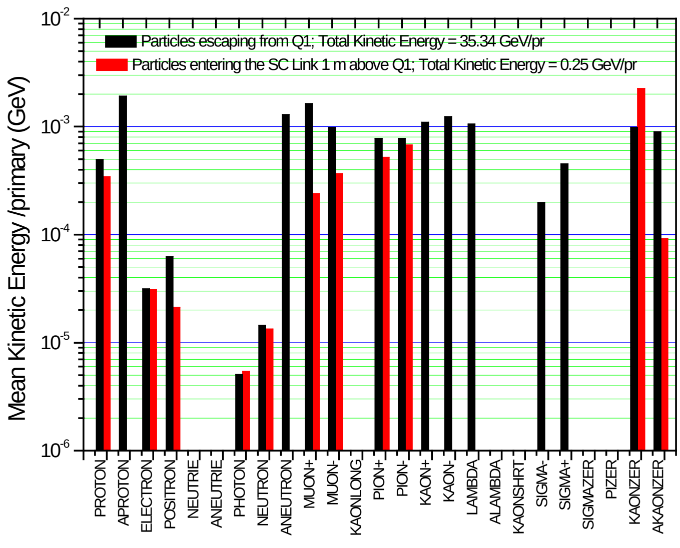


Fig. 2: Kinetic energy of the particles escaping from Q1(black) entering the SCL(red)

The spectrum of the neutrons entering the SCL is shown in Fig.3. About 3 ‰ of the neutrons have energy below 0.025 eV and 2.5% have energy below 1 eV corresponding to a cross section higher than about 600 b (see Fig.4).

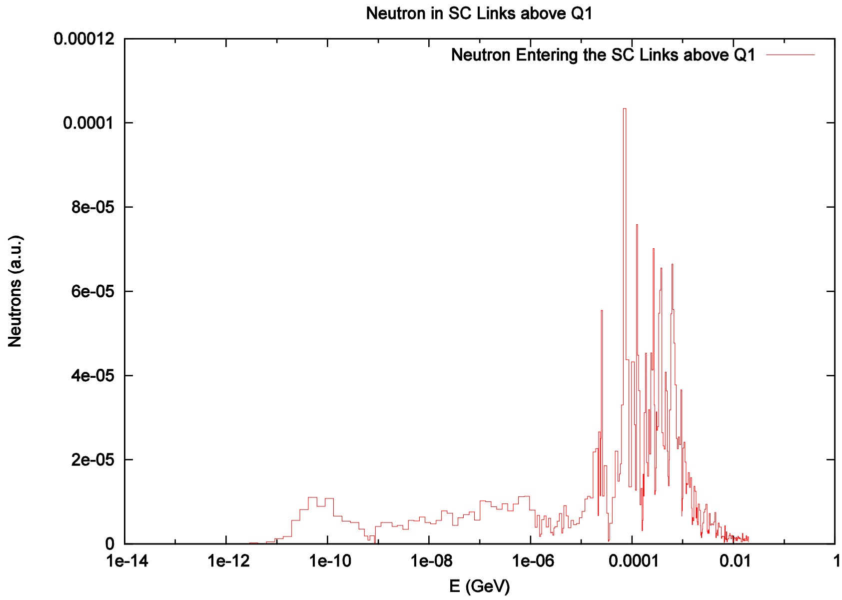


Fig. 3: Spectrum of the neutrons entering the SCL at 1 m above Q1

The most important reaction occurring (in term of cross section) is:

$$n+{}^{10}_{5}B \rightarrow {}^{11}_{5}B^{*} \begin{cases} \xrightarrow{6\%} {}^{7}_{3}Li+\alpha & 1.015\,MeV+1.777\,MeV \\ \xrightarrow{94\%} {}^{7}_{3}Li^{*}+\alpha \rightarrow {}^{7}_{3}Li+\gamma+\alpha & 0.84\,MeV+0.482\,MeV+1.47\,MeV \end{cases} \qquad (3)$$

The visualization scheme and the corresponding cross section are shown in Fig. 4.

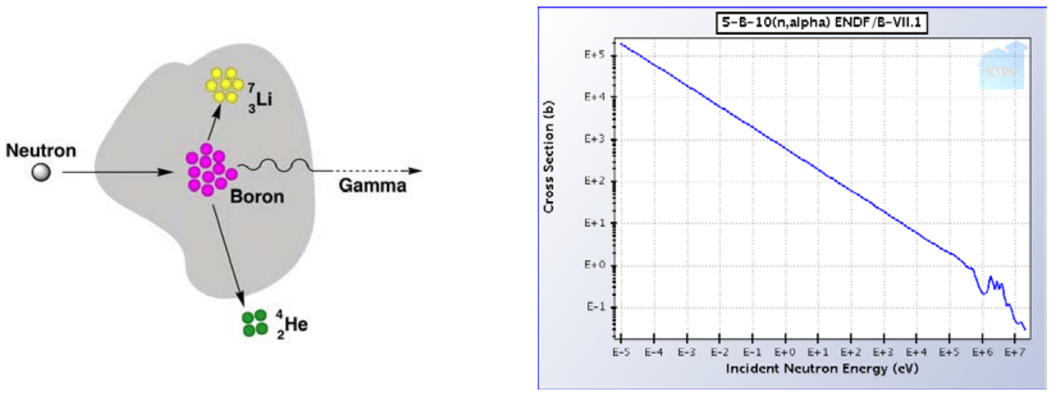


FIG. 4: Cross section for ^{10}B(n,α) reaction

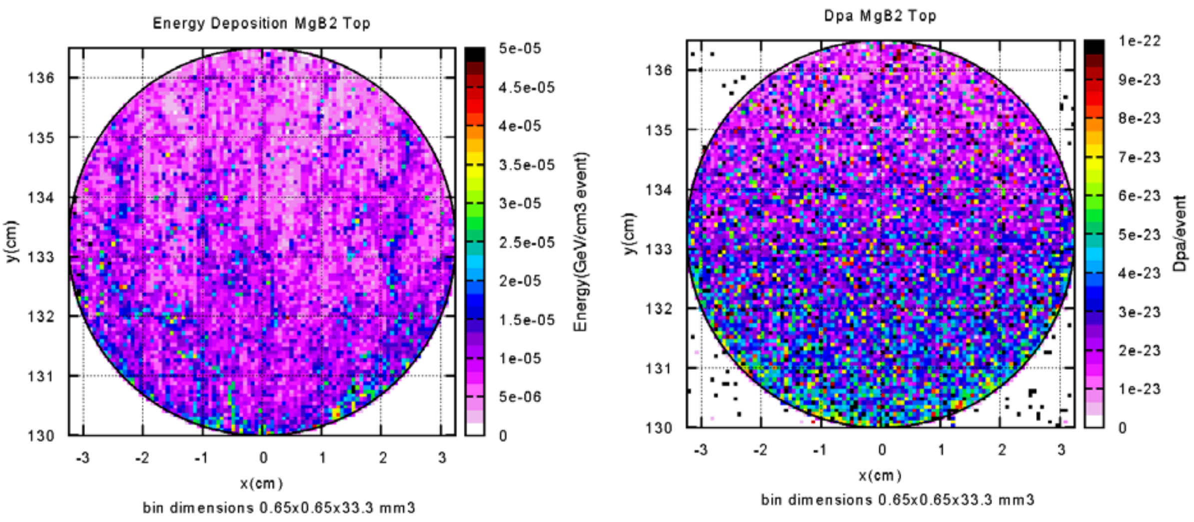
The boron consumption by this reaction is not a concern for the performances of the SC Links. As a matter of fact we have 25 neutrons per event entering the SCL, by normalizing to $3\cdot10^{17}$, i.e. the neutron entering the SCL foreseen for an integrated luminosity of $3000 fb^{-1}$ we can estimate a that $7.5\cdot10^{18}$ neutrons will enter the SCL. Let's remind that this is a conservative hypothesis of locating the SCL 1 m above Q1 and not in the real very far away location.

If all the $7.5\cdot10^{18}$ neutrons in the lifetime of the SCL (3000 fb^{-1}) produce one reaction (3) (this is another very conservative hypothesis, because we are supposing all the neutrons are thermal) we have a consumption of $7.5\cdot10^{18}$, over an amount of 10^{25} nuclei of ^{10}B present in 1m link cable, in a cable configuration as reported in[6]. So the fraction of the modified Boron nuclei is negligible.

A more likely layout of the SCL is the one reported in[7] and the SCL arrive in a Connection Module located after the separation dipole D1. In this case the amount of neutrons entering the SCL is lower (about 3.2 neutrons per event), further diminishing the neutron consumption.

4.2 Energy Deposition and DPA

In Fig. 5 the energy deposition map (a)and the DPA (b) in the SCL cable at 1 m upside the first quadrupole is shown. As we can see the energy deposition and DPA have a very similar distribution.



(a) (b)

FIG. 5: Energy deposition (a) and DPA (b) in the MgB_2 SCL cable placed 1 m above Q1. (Bin dimensions = 0.65x0.65x33.3 mm^3).

The data refer to the energy deposition and DPA per 7 TeV p-p event. They have been obtained with 30 different runs of 500 p-p events. If we scale the dose in the cable at 3000 fb^{-1} we obtain an integrated dose of 15.4 ± 1.0% kGy (being 2.57 g/cm^3 the density of the MgB_2), while the corresponding DPA is $1.0 \cdot 10^{-6}$ ± 0.5%.

If we consider the point of maximum DPA, being the location where the maximum damage occurs, we can guess, assuming the maximum value of Fig. 5b a value of about $3x10^{-5}$ DPA that can be considered safe, according to the irradiation test results and the consideration of section 5.3.

Because of the high cross section of the reaction (3), most of the DPA will be caused by the by alpha particles and Li ions generated.

The question of the weight of the different contribution (neutrons, alpha particles, Li nuclei) to the total DPA arose during a discussion with colleagues that performed irradiation test at Atomic Institute of the Austrian Universities (Wien)[8].

5 IRRADIATION TEST SIMULATIONS

As told before we performed irradiation test simulation for the reaction (3) and for the right term of the reaction, in order to have the single contribution of the reaction products.

5.1 Geometry and Parameters

At first we simulate the irradiation of a cubic sample 2 cm wide by an isotropic slow neutron beam as shown in Fig.6. The simulation were done with the FLUKA Monte Carlo code.

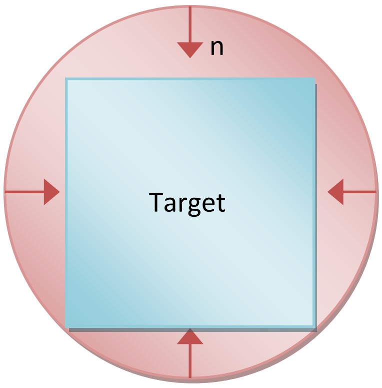


FIG. 6: Geometry of the n irradiation test

The transport cut-off for hadrons was set to 10^{-6} GeV while it was and 10^{-14} GeV for the neutrons:

```
* ..+....1....+....2....+....3....+....4....+....5....+....6....+....7....+....8
PART-THR      -1E-06  4-HELIUM  @LASTPAR        1.        0.0
PART-THR      -1E-14   NEUTRON                            0.0
```

In addition the explicit activation of transport for heavy ions was set, in order to correctly compute the effect of the Lithium

```
* ..+....1....+....2....+....3....+....4....+....5....+....6....+....7....+....8
IONTRANS         -2.
```

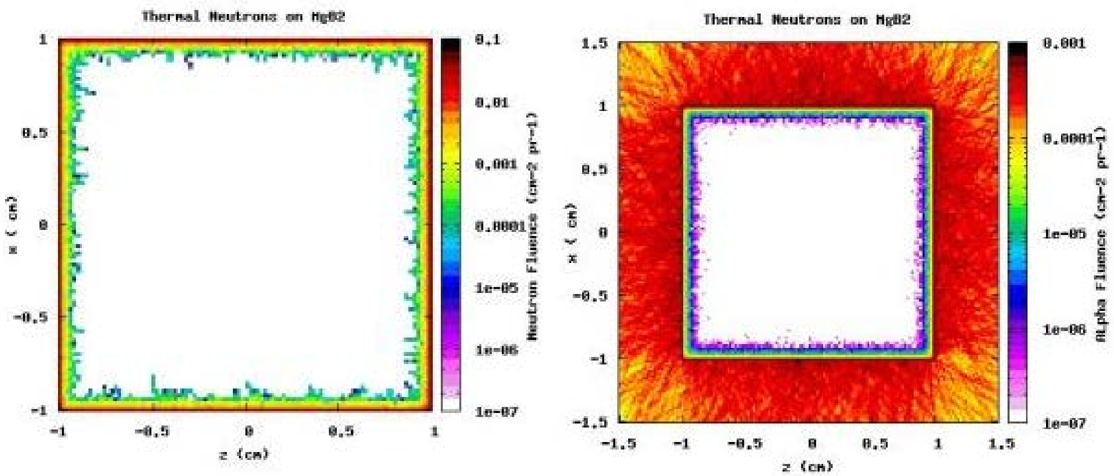
To evaluate the DPA in the material and check the results with irradiation test reported in literature[8)] damage energy threshold was set to 25 eV (the FLUKA default is 30eV)

```
* ..+....1....+....2....+....3....+....4....+....5....+....6....+....7....+....8
MAT-PROP        25.0                                MAGNESIU  MAGNESIU            DPA-ENER
MAT-PROP        25.0                                BORON-10  BORON-10            DPA-ENER
MAT-PROP        25.0                                BORON-11  BORON-11            DPA-ENER
MAT-PROP        25.0                                    MgB2      MgB2            DPA-ENER
```

In Fig 7a (left) the neutron fluence is shown. We can see that the neutrons entering the target are absorbed (by the ^{10}Boron atoms) in a thin slab, where all the energy deposition occurs (self shielding effect).

If the energy of the neutron is higher, the neutron can penetrate deeper into the target, be thermalized and then be captured by the ^{10}B.

In this way the reaction occurs inside the target, depending on the energy of the neutron, and both the alpha particle and the Li ion depose their energy and induce DPA, completely inside the target. Fig. 9b shows the alpha particle fluence around the target.



(a) (b)

FIG. 7: (a) Neutron fluence inside the target. (b)Alpha particles fluence around the target.

It can be seen that a huge amount of the alpha escape from the target, being generated at the surface.

To evaluate the effect of the alpha particle, simulations with internal source were performed.

5.2 Particle contribution simulations

In order to evidence the single contribution from neutron, alpha particles and Lithium nuclei, we simulated the reaction (3). To this aim we put the particle source i.e. thermal neutrons, 1.47 MeV and 1.777 MeV alpha, 0.84 MeV and 1.015 MeV Lithium, inside the MgB_2 target, the photons are neglected because they have no influence on this analysis, as a matter of fact only a small fraction (about 8%) of their energy is deposed inside the sample, and the induced DPA is about 5 order of magnitude less than the alpha or Li one.

The energy deposition and DPA plots for the case of a thermal neutron source internal to a 8 cm^3 MgB_2 cube are shown in Fig. 8.

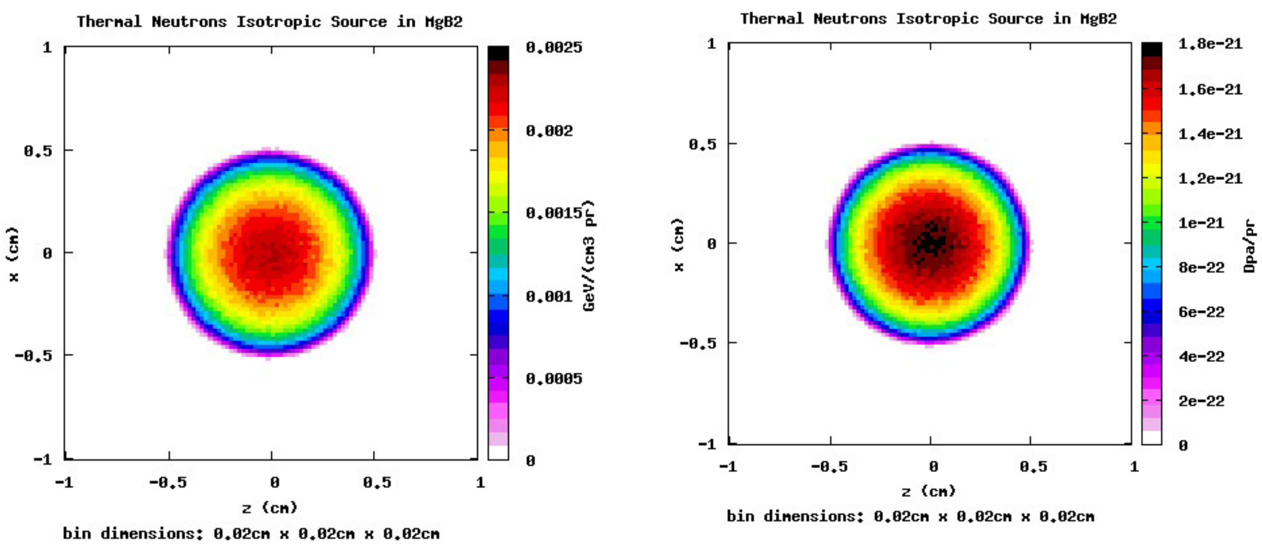


FIG. 8: Energy Deposition (left) and DPA map (right) for an isotropic neutron source inside a MgB_2 target.

For the other different cases studied there are similar plots, showing that all the energy and DPA occur inside the target, meaning that despite the value of the energy and DPA, that is weighted on the target volume, the values obtained are among them coherent.

The plots have not any absolute meaning, they just show that all the energy is deposed inside the sample (and the corresponding DPA is all provided inside them) and so the results can be compared.

The most significant parameter between peak (or maximum) and mean DPA is the peak value, as a matter of fact the mean value of the DPA, as it is defined, indicates that every atom undergoes to the given amount of displacement. It is evident that it does not happen because from Fig. 8 the energy deposition and DPA occur in a limited part of the target, so it is meaningless to attribute a DPA to the whole region. Conversely the peak value gives an indication of the localized radiation damage and this can actually provide an estimation of the effects on the material characteristics.

In Fig, 9 the plot of the maximum DPA in the target is shown

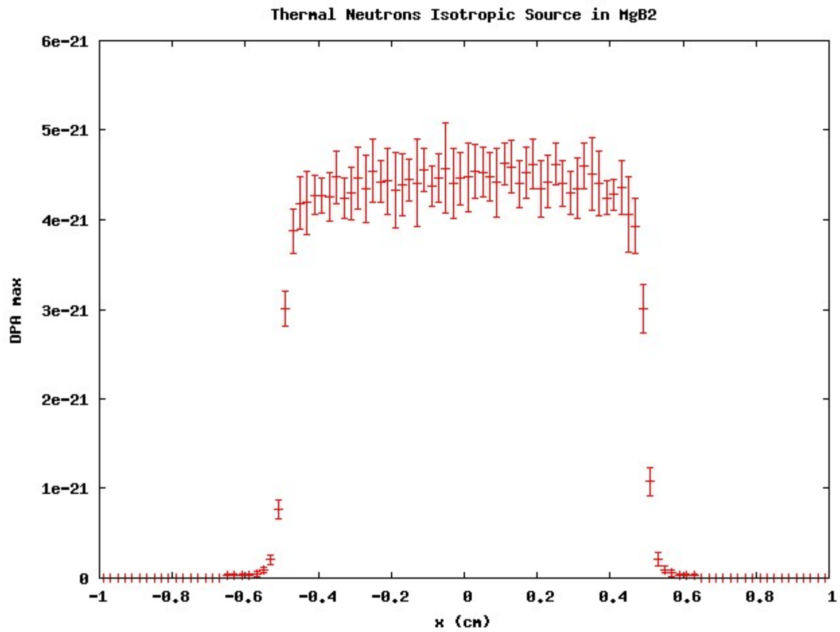


FIG. 9: Maximum DPA for the MgB_2 internal thermal neutron source.

In Tab. 1 the maximum and mean DPA inside the target are summarized.

TAB.1: Maximum and average DPA in the MgB_2 target induced by the reaction products of the Boron capture.

Reaction occurrence		Max DPA [DPA/primary]±Err%	Mean DPA [DPA/primary]±Err%
94%	Alpha (1.47 MeV)	$15.911 \cdot 10^{-22} \pm 7.9$	$6.1633 \cdot 10^{-22} \pm 0.001$
	Lithium (0.84 MeV)	$32.968 \cdot 10^{-22} \pm 6.9$	$11.952 \cdot 10^{-22} \pm 0.001$
	Photon (0.482 MeV)	==	==
6%	Alpha (1.777 MeV)	$16.422 \cdot 10^{-22} \pm 6.3$	$6.3141 \cdot 10^{-22} \pm 0.002$
	Lithium (1.015 MeV)	$31.447 \cdot 10^{-22} \pm 6.6$	$12.240 \cdot 10^{-22} \pm 0.001$

The induced DPA obtained by combining the data of Tab.1 with the corresponding weight are summarized in Tab.2. The data of the thermal neutron internal source are reported too.

TAB.2: Maximum and mean DPA induced by alpha particles, Lithium ions and thermal neutrons

	Max DPA [DPA/primary]±Err%	Mean DPA [DPA/primary]±Err%
Alpha	$15.942 \cdot 10^{-22} \pm 7.8$	$6.1724 \cdot 10^{-22} \pm 0.001$
Lithium	$32.876 \cdot 10^{-22} \pm 6.8$	$11.969 \cdot 10^{-22} \pm 0.001$
Neutron	$46.295 \cdot 10^{-22} \pm 5.0$	$18.345 \cdot 10^{-22} \pm 0.001$

If we sum up the contribution of the alpha particle with the Lithium ones we have:

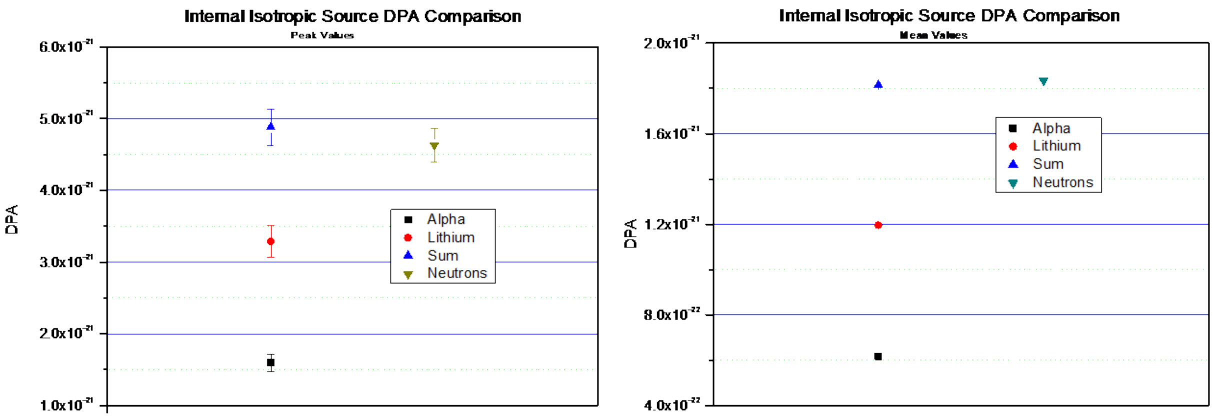
$15.942 \cdot 10^{-22} + 32.876 \cdot 10^{-22} = 48.818 \cdot 10^{-22} \pm 0.257$ for the maximum DPA
$6.1724 \cdot 10^{-22} + 11.969 \cdot 10^{-22} = 18.142 \cdot 10^{-22} \pm 0.001$ for the mean DPA

Internal neutrons
$46.295 \cdot 10^{-22} \pm 2.334 \cdot 10^{-22}$ for the maximum DPA
$18.345 \cdot 10^{-22} \pm 0.001 \cdot 10^{-22}$ for the mean DPA

If we consider the peak values we can see that the DPA calculated by the sum of the alpha and Li contribution are about a factor 6% higher that the values given by the neutrons, as shown in Fig. 10a, because we assume that every neutron reacts with ^{10}B realizing one Li and one alpha particle.

This does not happen for the mean values of the DPA (Fig 10.b) being the DPA calculated by the sum of the alpha and Li contribution about 1% lower that the DPA induced by the neutrons.

This is probably due to the statistics, and anyway this value in our analysis is less important, as explained before.



(a) (b)

FIG. 10: Comparison of the DPA induced in MgB_2 by internal source of neutrons, alpha particles, Lithium ions and neutrons (a: maximum DPA; b mean DPA). The error bar in the mean DPA plot are smaller than the symbol dimensions.

It is worth noting that the Lithium contribution to DPA is higher than the alpha one being about 66-67% of the total, while the contribution of the alpha is about 33-34%, as expected being the Lithium mass higher.

5.3 Comparison with irradiation experiment simulations

Irradiation tests performed on a sample of MgB_2[8)] show that under a fluence of thermal neutron of about $1.6x10^{21}$ nm^{-2}, the resulting DPA is about $2x10^{-4}$. With correction for the self-shielding effect the resulting DPA is about $1.1x10^{-2}$.

In Fig.11, taken from[8)], the effect of such irradiation on the upper critical fields are shown.

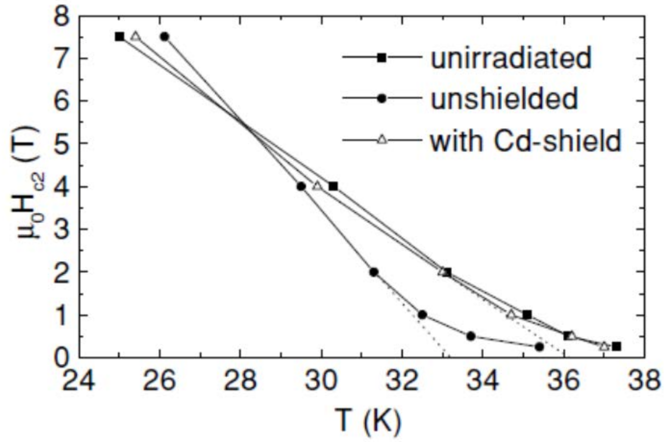


FIG. 11: Effect of the neutron irradiation on the MgB_2 upper critical field (from[8)]).

We can see that below 28 K the Hc2 is higher in the irradiated samples. Conversely this increase in the upper magnetic field has a lowering of the critical temperature (from 38.6 to 36 K). Let' s remind that the irradiation test produce a DPA of $1.1x10^{-2}$ so we can take this figure as a reference. By considering that the working temperature of the SCL will be below 25 K, that the maximum DPA is evaluated, under very conservative hypothesis, to be about $3.5x10^{-5}$, we can expect that no superconducting degradation of the SCL occurs, and be sure of their safe behavior during all the lifetime of LHC.

6 CONCLUSIONS

The energy deposition in the SCL will not endanger the behavior of the links for their whole lifetime. A possible positive effect can be the increase of the upper critical magnetic field, with a decrease of the critical temperature. Taking into account the working temperature of the SCL (about 30-40 K), and the lower particle fluence (respect to an irradiation test) this effect can be neglected.

The investigation on the neutron capture reaction has shown that the Boron consumption is negligible. The detailed study on the DPA induced by the boron capture reaction shows that the Lithium contribution to DPA is higher than the alpha one being about 66-67% of the total, while the contribution of the alpha is about 33-34%, as expected being the Lithium mass higher.

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