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Monte Carlo simulations for the space radiation superconducting shield project (SR2S)

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ABSTRACT

Astronauts on deep-space long-duration missions will be exposed for long time to galactic cosmic rays (GCR) and Solar Particle Events (SPE). The exposure to space radiation could lead to both acute and late effects in the crew members and well defined countermeasures do not exist nowadays. The simplest solution given by optimized passive shielding is not able to reduce the dose deposited by GCRs below the actual dose limits, therefore other solutions, such as active shielding employing superconducting magnetic fields, are under study. In the framework of the EU FP7 SR2S Project – Space Radiation Superconducting Shield – a toroidal magnetic system based on MgB_2 superconductors has been analyzed through detailed Monte Carlo simulations using Geant4 interface GRAS. Spacecraft and magnets were modeled together with a simplified mechanical structure supporting the coils. Radiation transport through magnetic fields and materials was simulated for a deep-space mission scenario, considering for the first time the effect of secondary particles produced in the passage of space radiation through the active shielding and spacecraft structures. When modeling the structures supporting the active shielding systems and the habitat, the radiation protection efficiency of the magnetic field is severely decreasing compared to the one reported in previous studies, when only the magnetic field was modeled around the crew. This is due to the large production of secondary radiation taking place in the material surrounding the habitat.

1. Introduction

Future manned missions to Mars and lunar outposts will require the evolution of technology and quite fascinating engineering challenges. Among the technical problems to deal with, one of the most troubling is related to ionizing radiation (Durante and Cucinotta, 2011; Cucinotta, 2013; Zeitlin et al., 2013). Reducing the health risks associated with space radiation is a fundamental prerogative to allow the execution of long duration manned interplanetary missions. The solutions studied until today involve the use of passive and active shielding (ECSS E-10-04; Spillantini, 2011). The first is based on the loss of energy due to the interactions of particles with the materials. The latter exploits magnetic fields to deflect particles.

The space radiation environment to be counteracted is mainly produced by two different components: Solar Particle Events (SPE) and Galactic Cosmic Rays (GCR).

SPE are occasional events, with possible high fluence concentrated in short periods (hours or days). Due to their relative low energy particles, they can be stopped by a passive shielded shelter (Cucinotta, 2013).

On the other hand GCR are very high energy particles arriving isotropically from outside the solar system. The GCRs, if not shielded, produce the largest contribution to the total effective dose (>500 mSv/y) in a long-duration interplanetary mission and shielding from GCR is still an open challenge due to their capability to produce secondary particles when interacting with matter. For this reason other options than the passive shielding have been investigated during the years and, among those, the use of magnetic fields to deflect radiation is one of the most interesting ones.

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The use of large superconducting magnets to generate a shielding field around the spacecraft dates back to 1960 and was subsequently proposed in several configurations (Wilson et al., 1997; Braun, 1969). However, previous works considered only the ability of the magnetic field in deflecting particles neglecting in this way the outcomes of the interaction of the charged particles with the magnetic materials necessary to generate the field (Braun, 1969; Townsend et al., 1990; Hoffman et al., 2005).

This paper describes a toroidal magnetic system studied in the framework of EU FP7 SR2S Project (Space Radiation Superconducting Shielding). Monte Carlo simulations have been used to evaluate the effective shield capability considering the combined effects of the magnetic field and materials composing the magnet, the spacecrafts and a realistic supporting structure.

The aim of the work is not to provide the values cumulated by astronauts, but to compare the dose reductions with respect to free space for several realistic shielding structures.

2. Toroidal magnetic shield

2.1. Motion of charged particles in a toroidal magnetic field

An initial trade-off between different possible active shielding structures led to the adoption of a toroidal magnetic configuration (Battiston et al., 2013; Musenich et al., 2014). The toroidal field has in fact many advantages, including an isotropic protection around the habitat and a very low fringe field inside the internal module. Clearly a toroid surrounding the spacecraft leaves the endcaps of the habitat module free of the field (and therefore protection), so eventual solutions including smaller end cap toroids could be considered to shield the side of the habitat not attached to other modules. Alternatively, passive or a combination of active and passive end cap can be used. However the treatment of this issue is beyond the scope of this work.

A scheme of the basic idea behind a toroidal shield is shown in Fig. 1. In the case of a charged particle moving radially, i.e. having zero angular velocity, the motion equation in an infinite toroidal magnetic field can be analytically solved. It can also be demonstrated that a particle with zero angular speed $\dot{\theta} = 0$ is the most penetrating one and therefore, as shown in Battiston et al. (2013) the shielding power of the toroid can be written as:

$$\Xi = \int_{R_i}^{R_e} B_\vartheta \, dR = \frac{\mu_0 I}{2\pi} \ln \frac{R_e}{R_i} \tag{1}$$

where I is the total current flowing in the toroid, R_e the outer radius and R_i the inner radius. The shielding power can be written also as a function of the particle properties:

$$\Xi = \frac{m_0}{q} c \sqrt{\gamma^2 - 1}(1 - \sin\varphi) \tag{2}$$

where m_0, q and γ are the particle rest mass, charge and Lorentz factor respectively. φ is the angle of incidence shown in Fig. 1.

Using (2) it is straightforward to calculate the maximum kinetic energy K_η of the particle that can be deflected by the toroidal field (Hoffman et al., 2005):

$$K_\eta = -\frac{m_0 c^2}{\eta}\left(1 - \sqrt{\left(\frac{q}{m_0 c}\frac{\Xi}{(1 - \sin\varphi)}\right)^2 + 1}\right) \tag{3}$$

where η is the number of nucleons, q the charge. If the angle of incidence φ is set to −90° (corresponding to a direction of a particle entering perpendicularly in the magnetic field of the toroid, being the magnetic field clockwise oriented as shown in Fig. 1) the latter equation defines the shield cut-off energy. Under the previous hypothesis the ideal toroidal magnetic field with bending power Ξ is able to deflect all the particles having kinetic energy less than K_η defined in (3).

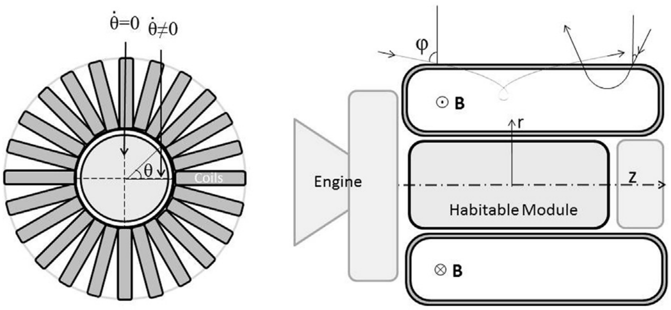

Fig. 1. Schematic view of a toroidal Space Radiation Superconducting Shield. The trajectories of two particles with different angle of incidence φ are shown.

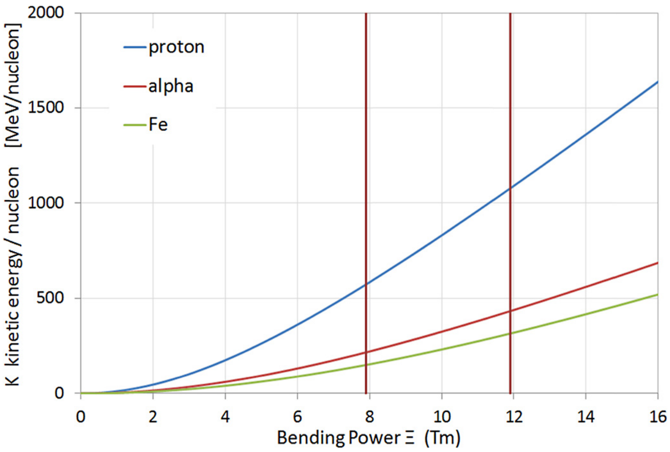

Fig. 2. Ideal "cut off" kinetic energy K_n given as a function of the bending power for protons, alpha and iron nuclei.

This formula can be useful to perform a first check on the magnetic field reproduced in the simulation code, while, however, the actual capability to protect the crew must be evaluated including the interaction of the cosmic rays with the materials surrounding the astronauts.

In Fig. 2 the ideal "cut off" kinetic energy K_n is given as a function of the Bending Power, for protons, He and Fe ions.

2.2. Magnet winding and mechanical structure

The SR2S superconducting magnet was thought as composed by several racetrack coils supported by a mechanical structure, whose goal is to withstand the magnetic force.

In a toroidal magnet, it is necessary to support both intra-coil forces, which tend to enlarge each coil, and the radial, inward forces resulting from the interaction of all the coils. As a consequence, the toroid needs one mechanical structure to support the intra-coil forces, and an inner one for the inward forces. In principle, under the hypothesis of perfect system symmetry, the magnet would not need any mechanical structure between the coils as no torque would be experienced by the coils. However, small mispositioning is possible in a real magnet therefore metal foam or light honeycomb will be present too to space out the coils.

Different requirements with respect to an Earth based magnet have been identified in the initial phase of the project. In particular, the mass density of the conductor and of all the materials composing the active shielding has to be minimized and the