Acta Astronautica 129 (2016) 154–160

Contents lists available at ScienceDirect

Acta Astronautica

journal homepage: www.elsevier.com/locate/aa

Review Article

Galactic cosmic rays dose mitigation inside a spacecraft by a superconductor “compact” toroid: A FLUKA Monte Carlo study

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ARTICLE INFO

Keywords:
SR2S
Magnetic shielding
Galactic Cosmic Rays
Monte Carlo
FLUKA

ABSTRACT

Galactic Cosmic Rays and Solar Cosmic Rays are responsible for a significant absorbed dose by the astronauts that increases their risk and the probability of health problems. The mitigation of this dose is crucial for planning future missions, beginning from those to Mars. Different strategies have been designed to protect the crew during the mission. In this work it is considered the shielding of cosmic rays using a superconductor magnet enough compact for the launch. A Monte Carlo study is carried out. The simulations are made by modelling the structures with Monte Carlo FLUKA code, dividing cosmic rays into 5 ionic groups.

1. Introduction

The deep-space exploration represents a hazard for astronauts due to the exposure to Galactic Cosmic Rays (GCR) and Solar Cosmic Rays (SCR). Over-exposure to such radiations causes a significant increase of the probability in development of cancer. To this came the needs of adequately shield the astronauts from the ionizing radiation in order to realistically plan for exploration missions to Mars.

The emission of SCR is sporadical but their fluence can be so high to be lethal to an unprotected crew. The radiation and proton fluxes increase the most (by several order of magnitude) during flares and are predictable monitoring X-ray and extreme UV solar emission dozens of minutes up to some hours early [1]. SCR have relatively low energy and allows their absorption in passive shields varying the spaceship orientation [2].

GCR have higher mean energy with respect to SCR, are emitted continuously and their fluence is predictable with models [3] and in this work it is afforded a study for mitigating their dose released to astronauts.

The radiation risk can be defined through the maximum number of days with 95% confidence level to be below the 3% limit probability of contracting a cancer or circulation disease for an astronaut shielded with 20 g/cm^2 of aluminum. In periods of minimum solar activity the limit is ~220 days, reaching ~330 days in periods of maximum solar activity [4]. The variation with sex and age of astronauts is ± 25% and the effect of the shielding accounts for ≈10%. To take into account all these variations for a typical 1.5 years duration of the travel of a Mars mission, the required mitigation of the body dose must be not less than 3 with respect to the free space body dose.

Toroidal magnets, with a bending power sufficient to deflect out a relevant fraction of ionizing radiation, are a promising solution for protecting astronauts from GCR.

The transport of large masses in space is a big problem and can require several rocket launches. In the EU supported Space Radiation Superconducting Shield (SR2S) study [5] it was considered in detail the dose mitigation for several configurations of large toroids brought to orbit by several SLS class launches and assembled in space [6]. To completion it is worthwhile to consider here the dose mitigation obtained with a toroid enough small and light for the shroud of a SLS class rocket for the launch. This solution has strict mass and shape restrictions but promise a lower complexity of the mission.

As reference configuration it is considered here the continuous “compact” toroid described in Sections 2.1 and 2.2 of Ref. [7]. This study intends to estimate the mitigation of the radiation dose released on an astronaut at the center of the toroid by (a) pushing to a very high intensity the magnetic field by increasing the total current in the toroid and also (b) deploying in orbit the outer part of the toroid to increase its magnetic volume.

In approach (a) the dose mitigation is evaluated for reference configuration run with 40 MA electric current (Section 2.2). The same configuration is also considered run with higher currents in two hypotheses: increasing the current density in the cable without increasing the mass of the superconductor (SC) cable (Section 2.3); increasing the mass of the SC cable without increasing the current density in the cable (Section 2.4). In approach (b) the dose mitigation is evaluated in case that the outer part of the toroid could be deployed in space for extending the magnetic volume without increasing the maximum magnetic field intensity and by maintaining the azimuthal

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http://dx.doi.org/10.1016/j.actaastro.2016.09.010
Received 1 July 2016; Accepted 7 September 2016

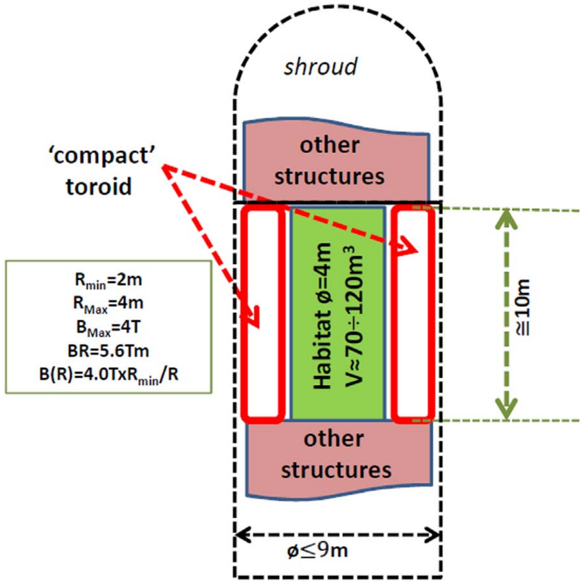

Fig. 1. Reference configuration of "compact" toroid inside the shroud of a SLS class rocket (adapted from Fig. 1 of Ref. [7]).

symmetry of returning the current at the outer diameter.

The dose mitigation of the different configurations is summarized and discussed in Section 3. Few considerations concerning the dimensions of the habitat in the center of the toroid, the central tube supporting the magnetic pressure of the system and the subdivision of the current running in the toroid in several sub-toroids are reported in Section 4.

2. Materials and methods

2.1. FLUKA settings

The evaluations of the dose to an astronaut inside the crew habitat are made with FLUKA [8,9] Monte Carlo (MC) code. It is considered only the galactic component (GCR) as modelled in ISO15390 averaged over one year as reported by SPENVIS [10]. Primary particles are generated on a sphere centered on the axis of the toroid whose radius contains the system. The detector (simulating an astronaut) is a water cylinder 180 cm long and with radius of 24 cm (mass 81.5 kg). The habitat is modelled as an aluminum cylinder of 10 m of length, 4 m of diameter, 1.5 cm thick in barrel region (lateral surface of cylinder) and 3 cm thick in end-cap regions. The water cylinder is placed at the center of the habitat in coaxial orientation. The emission of cosmic rays is made to obtain an isotropic field in all the points inside the sphere. The results of the calculations are expressed in % of the body dose (the mean dose released in the water cylinder) related to the body dose in free space evaluated in centi-sievert per year (cSv/y) using the FLUKA estimator DOSEQLET. Two perfect absorber cylinders in end-cap regions (other structures area of the spaceship, see Fig. 1) are always present in simulations. The relative percent body dose with respect to free space within the habitat is $87.5 \pm 3\%$, the same as calculated in Ref. [6] Table 2 (Columbus at 0 T m). The dose is the sum of contributions from primary particles belonging to 5 ionic groups in the atomic number Z intervals ($Z = 1$, $Z = 2$, $Z = 3 - 10$, $Z = 11 - 20$, $Z = 21 - 28$). The materials of the SC coils and of their supporting structures are modelled as concentric cylinders coaxial to the habitat and to the detector. The structure for supporting the magnetic pressure is modelled as a tube coaxial to the system made by aluminum honeycomb.

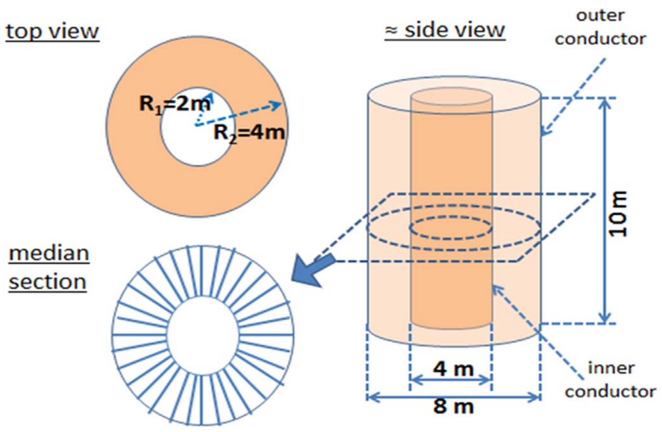

Fig. 2. Geometry for the continuous "compact" toroid.

2.2. Reference configuration

The "compact" toroid assumed as reference configuration is described in Ref. [7], with the details of the supporting mechanics in Section 2.2 of the same reference. For the sake of clearness and convenience the characteristics of the "compact" toroid are reproduced below. The reference configuration concept is outlined in Fig. 1, adapted from Fig. 2 of Ref. [7]. Main parameters are inner radius $r_i = 2$ m, outer radius $r_e = 4$ m, length $L = 10$ m. The considered total current is $I_{tot} = 40$ MA to produce a maximum magnetic field $B_{max} = 4$ T at $r = r_i$. For the SC cable it is assumed that used in Ref. [6], composed of Al (57.4%), MgB_2 (8.6%), Ti (23%) and SiO_2 (11%) with mean density of 2.93 g/cm^3. The current density in the SC cable is assumed J=120 A/mm^2 at 10 K. This value is scaled from the value of J=117 A/mm^2 at B=5.15 T and 10 K assumed in Ref. [11]. Other structures of the spaceship at the two ends of toroid and habitat are supposed to entirely absorb particles. The toroid is modelled as composed of a large number of sectors (Fig. 2, from Fig. 4 of Ref. [7]). For the simulations each sector is modelled by the SC cable winding held in shape by an aluminum cladding running outside the winding perimeter (Fig. 3) simplified as a rectangle and enclosed in external faces (Fig. 4) by a bandage in Kevlar. The cladding and the bandage allow to discharge the magnetic force of the outer segment of the winding on the inner segment, halving the magnetic pressure on the central tube of the system.

The large number of sectors (256) allows to model the toroid by continuous surfaces: the inner cylinder 10 m long of radius r_i=2 m, carrying the total current of 40 MA evenly distributed in the angular azimuth around the axis of the cylinder; the outer cylinder 10 m long of radius r_e=4 m for returning the current also evenly distributed in azimuth; two annuli fitting the cylinders at their ends. The continuous cylindrical surfaces are supposed to be realized by assembling the 256 sectors in cylindrical symmetry around the axis of the toroid. The sectors are assumed to be mechanically independent and self-supporting, each covering one angular sector (360/256)°=1.406° in azimuth, exerting their magnetic pressure toward the central axis of the system. If the 256 sectors, also if assembled together and rigidly packed, are supposed not contributing to the rigidity of the whole system, then a central tube must be foreseen to support their pressure in order to avoid to collapse on the habitat. The main parameters of the "compact" toroid and the masses of the SC windings and of their mechanical structure are summarized in Table 1 for $I_{tot} = 40$ MA ($B_{max} = 4\,T$ at r_i=2 m). The body dose in the center of the system in % of the free space body dose is reported in Fig. 5, with the contribution due to the different components of the GCR spectrum put in evidence, with the magnetic field OFF (third column) and ON (fourth column).

It must be highlighted that the contribution of the interactions in