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Toroidal magnetic fields for protecting astronauts from ionizing radiation in long duration deep space missions

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ABSTRACT

Among the configurations of superconducting magnet structures proposed for protecting manned spaceships or manned deep space bases from ionizing radiation, toroidal ones are the most appealing for the efficient use of the magnetic field, being most of the incoming particle directions perpendicular to the induction lines of the field. The parameters of the toroid configuration essentially depend from the shape and volume of the habitat to be protected and the level of protection to be guaranteed. Two options are considered: (1) the magnetic system forming with the habitat a unique complex (compact toroid) to be launched as one piece; (2) the magnetic system to be launched separately from the habitat and assembled around it in space (large toroid).

In first option the system habitat + toroid is assumed to have a cylindrical shape, with the toroid surrounding a cylindrical habitat, and launched with its axis on the axis of the launching system. The outer diameter is limited by the diameter of the shroud, which for present and foreseeable launching systems cannot be more than 9 m. The habitat is assumed to be 10 m long and have a 4 m diameter, leaving about 2 m all around for the protecting magnetic field. The volume of the habitat results about 100 m^3, barely sufficient to a somewhat small crew (4–5 members) for a long duration ($\cong 2$ years) mission. Technological problems and the huge magnetic pressure exerted on the inner cylindrical conductor of the toroid limit to not more than 4 T the maximum intensity of the magnetic field. With these parameters the mitigation of the dose inside the habitat due to the galactic cosmic rays (GCRs) is about 70% at minimum solar activity, while also most intense solar events cannot significantly contribute to the dose. The toroidal magnetic field can be produced by a large number of windings of the superconducting cable, arranged in cylindrical symmetry around the habitat to form continuous inner and outer cylindrical surfaces (‘continuous’ winding).

In the option of separated launches for the habitat and the magnetic system, the volume of the habitat can be much larger, up to ≈ 300 m^3, i.e. a volume to be considered for a permanently manned space basis rather than for a spaceship. The toroidal field can occupy a larger volume around it, and indeed be less intense ($B < 3$ T) for obtaining the same mitigation of the radiation dose inside the habitat. Also for the separate launches option several structural arrangements can be foreseen, depending from the considered number of windings. The limit of only two huge windings is the most attractive, as it minimizes the material and could be mechanically more stable, but it could be the most difficult to be assembled in space.

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Main parameters for the different configurations are reported, and the plan for the development of solutions and techniques is presented.

1. Introduction

For defending by magnetic fields a habitat from GCRs in deep space the most appealing configuration is a toroidal magnet (or ‘magnetic torus’) surrounding the habitat. The main reason is the efficient use of the produced magnetic field, being most of the incoming particle directions perpendicular to the induction lines of the field. The parameters of the ‘torus’ essentially depend from shape and volume of the habitat and the level of protection to be guaranteed.

The toroidal field can be produced by a number of lumped coils radially arranged around the habitat to be protected [Fig. 1-(a)], or by a cylindrical current uniformly distributed in azimuth running longitudinally around the habitat and closed in lumped conductors outside [Fig. 1-(b)], or by cylindrical current uniformly distributed in azimuth running longitudinally around the habitat and closed outside in a cylindrical conductor also uniformly distributed in azimuth [Fig. 1-(c)].

This last configuration will be called ‘continuous’ toroid and discussed in this report.

2. Continuous toroid

The magnetic field configurations can be classified in two classes depending from their global geometry: (1) the coil forms a unique complex with the habitat, to be launched to space as one piece by one launch (compact toroid); (2) the habitat is launched separately to space, and the coil is separately launched by one or more launches and assembled around the habitat in space (large toroid).

In Fig. 2 both these classes are represented for the case of a toroidal field surrounding a cylindrical habitat, and also, as an example, some typical parameters are reported.

Referring to Fig. 2-(a) (compact toroid: habitat + toroid launched as one piece) the system must match the cylindrical shape of the shroud of the rocket and be contained in its inner diameter. Presently all available or in program launchers foresee shroud not larger than 9 m. Assuming for the habitat a module similar to the International Space Station (ISS) modules (about 4 m in diameter) and considering some tolerance around, the magnetic field sheath cannot be thicker than about 2 m. In such a scenario the volume of the habitat would be 12 m^3/1 m length. Assuming 20 m^3 the minimum volume/astronaut necessary for long duration missions and a number of 4–5 astronauts, the length of the habitat should not be less than 10 m, considering also that effective volume can be diminished by insulation and other limitations. Technological boundaries, such as the density of the current in the superconducting cable (which determines the mass of the needed superconducting material) and the magnetic pressure to be supported limit the maximum field intensity in the superconducting material.

In all subsequent evaluations we assume MgB_2 for the superconducting material, which is nowadays widely used besides the Low Temperature Superconductors (LTS: NbTi and NbSn), and has characteristic parameters suitable for its use in superconducting magnets in space.

First, it can be operated at a temperature much higher than the LTS materials, up to 20 K, with a high current density in high magnetic field. This feature is extremely important for using superconducting magnets in space, because they can be maintained cool by cryocoolers or coolant recirculation at expenses of electric power, without relying on supplies of expendable coolants. As already pointed out in the Topical Team study organized by ESA in 2002–2004 [1] and in the ESA supported industrial study “REMSIM” [2], for large superconducting magnetic systems operated in space it is necessary to implement the Cryogen Free Superconducting Magnets (CFSM) concept [3], based on new superconducting materials operating at temperatures higher than LTS and cryocoolers or coolant recirculation powered by electricity. It is a simple concept, not easy to be implemented, potentially a bottleneck for using superconducting magnets in space.

Second, MgB_2 is thermodynamically more stable than LTS, what can guaranty a high margin of safety against quenching

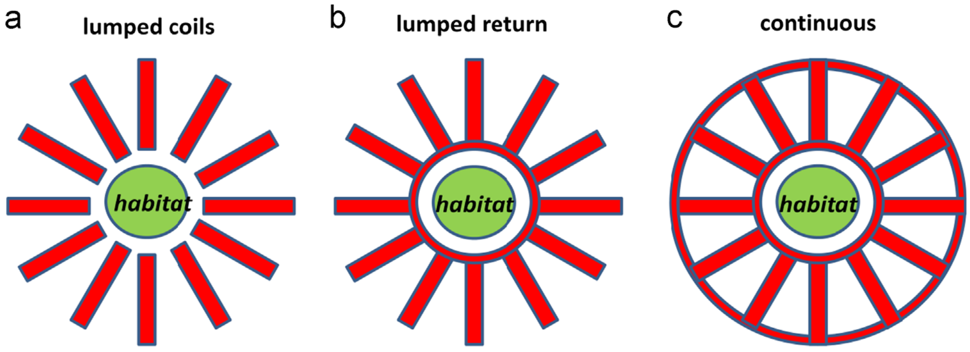

Fig. 1. Configurations of coils producing a toroidal field.