Acta Astronautica 68 (2011) 1430–1439

Contents lists available at ScienceDirect

Acta Astronautica

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

Superconducting magnets and mission strategies for protection from ionizing radiation in interplanetary manned missions and interplanetary habitats

Piero Spillantini *

INFN Branch and Physics Department of the Firenze University, Via Sansone 1, I-50019 Sesto Fiorentino, Firenze, Italy

ARTICLE INFO

Article history:
Received 23 September 2009
Received in revised form
29 July 2010
Accepted 29 July 2010
Available online 15 September 2010

Keywords:
Cosmic rays
Radiation shielding
Superconducting magnets
Manned mission

ABSTRACT

First order evaluations for active shielding based on superconducting magnetic lenses were made in the past in ESA supported studies. The present increasing interest of permanent space complexes, to be considered in the far future as 'bases' rather than 'stations', located in 'deep' space (as it has been proposed for the L1 libration's point between Earth and Moon, or for Stations in orbit around Mars), requires that this preliminary activity continues, envisaging the problem of the protection from cosmic ray (CR) action at a scale allowing long permanence in 'deep' space, not only for a relatively small number of dedicated astronauts but also to citizens conducting there 'normal' activities.

Part of the personnel of such a 'deep space base' should stay and work there for a long period of time. It is proposed that the activities and life of these personnel will be concentrated in a sector protected from Galactic CR (GCR) during the whole duration of their mission. In the exceptional case of an intense flux of Solar Energetic Protons (SEP), this sector could be of use as a shelter for all the other personnel normally located in other sectors of the Space Base.

The realization of the magnetic protection of the long permanence sector by well-established current materials and techniques is in principle possible, but not workable in practice for the huge required mass of the superconductor, the too low operating temperature (10–15 K) and the corresponding required cooling power and thermal shielding.

However the fast progress in the production of reliable High Temperature Superconducting (HTS) or MgB_2 cables and of cryocoolers suitable for space operation opens the perspective of practicable solutions. In fact these cables, when used at relatively low temperature, but in any case higher than for NbTi and Nb_3Sn, show a thermodynamically much better behavior. Quantitative evaluations for the protection of the sector of the 'Space Base' to be protected from GCRs (and therefore from SEPs also) are presented.

For possible large outer radius solutions it must in the meantime solve the problem of the assembling or deploying in space the conductors for returning the electric current.

1. Introduction

Cosmic radiation has been identified as the main health hazard to crews involved in long-term interplanetary

* Tel.: +39 055 4572261, +39 335 395941; fax: +39 055 4572367.
E-mail address: spillantini@fi.infn.it

0094-5765/$ - see front matter © 2010 Elsevier Ltd. All rights reserved.
doi:10.1016/j.actaastro.2010.07.023

missions. It is mainly constituted by charged particles (cosmic rays—CR) emitted by different sources and accelerated in various regions of the Universe to energies several orders of magnitude higher than those of the most energetic particles emitted by radioactive sources on the Earth.

In free space, far away from the protection of terrestrial magnetic field, the two categories to be considered are the solar cosmic rays (SCR) emitted by Sun in solar particle events (SPE), and the much more energetic galactic cosmic rays (GCR) originated and accelerated in the galaxy and penetrating the solar system from outside.

The phenomena originating SCRs are sporadic, not possible to be forecast, and last for several hours up to a few days. Sometimes they originate a very high flux of energetic particles (mostly protons), still very intense behind a shielding of several cm of aluminium, which can lead to acute effects, including lethal radiation syndromes.

The energy of the GCRs is much higher, at least of an order of magnitude, the intensity of their flux is isotropic and roughly continuous in time, as they are the products of a large number of ubiquitous and very far away violent phenomena. What is dangerous for the human health is the accumulation of their effects on an interval of time of several months or a few years.

On the Earth and in its vicinity human life and health are efficiently protected from the action of SCRs and GCRs by the terrestrial magnetic field, which deflects them before reaching the Earth's vicinity. Far away from the Earth the protection must be assured by artificial means. This is the case when the astronauts travel to distances from the Earth of several tens of terrestrial radii (as it is for missions to the Moon, or to the L1 librating point) or to other planets, the typical example being the manned missions to Mars in the plans of the major space agencies.

Shielding in space is problematic because of the huge mass of the needed absorbers, especially when the energetic GCRs are considered. High-energy radiation is very penetrating: a thin or moderate shielding is generally efficient in reducing the equivalent dose, but as the thickness increases, shield effectiveness drops. This is the result of the production of a large number of secondary particles, including neutrons, caused by nuclear interactions of the GCRs with the shield.

1.1. Passive shielding

Bulk shielding poses obvious weight problems on the spacecraft. A heavy load, added purely for reducing radiation exposure, becomes a substantial mass penalty and may dramatically increase the mission cost.

There is immense work already done in developing passive shielding strategies for human exploration missions (e.g. [1–4]). All calculations and measurements show that light, highly hydrogenated materials (such as polyethylene) are ideal materials for space radiation shielding ([5–7]). More research in this field will be able to ensure the best possible bulk shielding for the next generation of interplanetary spacecraft, as well as for living modules on the extra-terrestrial planets.

Whilst this can be satisfactory for 3–6 months mission to the Moon, passive shielding are unable to solve the radiation problem for long human permanence in free space, such that necessary for the exploration of Mars or other celestial bodies, or for maintaining and operating manned space complexes in free space.

1.2. Active shielding

An attractive alternative to passive, bulk material shielding is the use of electromagnetic fields to deflect the charged particles from the spacecraft target. However, technical limitations in the production of intense magnetic fields in space have been the main hindrance toward the application of magnetic shelters in spacecrafts. Technological progress in the field of high-temperature superconductors may provide a large impact.

In the last decades several studies of active systems were dedicated to the protection from the whole radiation, both solar and galactic. Most of them produced projects to be considered ideas to be developed for a very far away future rather than feasible solutions for the near future. In the more workable approach, the use of magnetic fields produced by superconducting coils, the groundless choice of the field intensity (10 T) hampered feasible solutions because the ponderomotive forces have been enormously put up, bringing to a mass of several hundred tons for protecting a volume of the order of 100 m^3, 90–95% of the mass coming from the construction. A comprehensive listing of nearly all publications until the end of the last century related to active shield of spacecrafts can be found in [8], and a short review was given by Townsend [9].

More handy approaches appeared in the last decade. In USA the realization of the AMS-02 superconducting magnet [10] originated the proposal of a superconducting toroidal coil system that could be conceived for the next Mars mission ([11,12]). The mass of the coils was evaluated to be 9.4 t with the total mass of the system amounting to 30.1 t, which the authors compare with the 1000 t of the needed equivalent aluminium absorber. The protected volume is 5.6 m in diameter and 4.5 m long, surrounded by a magnetic sheath of 28 Tm bending power and 10 m outer diameter, and the reduction of the GCR dose inside amounts to 72–85%.

In Europe ESA supported two studies on this thematic: a Topical Team (‘‘Shielding from the cosmic radiation for interplanetary missions: active and passive methods’’) in the frame of ‘Life and Physical Sciences’ [13,14] and the tender based study ‘‘Radiation exposure and mission strategies for interplanetary manned missions to the Moon and Mars (REMSIM)’’ [15].

In both ESA studies it was concluded that, also if the protection from SCR can rely on the use of passive absorbers, the use of active systems based on magnetic fields produced by superconducting coils could significantly reduce the needed mass.

The protection from GCRs becomes necessary when the duration of the mission outside the terrestrial protection lasts several months or a few years. The criteria for protecting astronauts from SCRs cannot be applied because of the following reasons:

(a) the passive shielding are not effective, either too much thick, or even counterproductive;
(b) the need of protecting the astronauts during the whole long duration mission, requires to protect a large volume habitat where the astronauts could live and work, and not a temporary small volume shelter. In the ESA Topical Team study, the solution of the problem of protecting a larger habitat from GCRs was evaluated for a system of toroidal coils surrounding (as a sheath) the volume to be protected. The obtainable reduction of the GCR dose inside was supplied as a function of its geometry and of the maximum intensity of the magnetic field of the system.

The present level of the techniques allows reasonable guesses, but a technical R&D is needed both for the superconducting cable and for the cooling system for matching the needs of a substantial reduction of the GCR dose inside large volume habitats for the future missions. The lines of these technical developments are clearly outlined in the conclusions of both the above quoted ESA studies, where it is also recommended that the R&D activity begin as soon as possible to incorporate its results in the different scenarios of missions to Moon, Mars or to the L1 libration's point.

2. Permanent presence in space: from space stations (astronauts) to space bases (astronauts, specialized personnel, and common citizens)

The work performed until now on active shielding was reviewed at the last COSPAR in Montreal [16]. It can be regarded as 'pioneer' and must be updated for several reasons:

(a) Several huge volume and huge stored energy superconducting magnets have been realized and operated in the meantime, mainly in CERN, for elementary particle experiments.
(b) Technical developments of the so-called High Temperature Superconductors (HTS) have been remarkable (in particular for the new MgB_2 material [17,18]), as well of the cooling techniques (e.g. the light cryocoolers for the N2 shield of AMS space experiment [19]).
(c) Also the panorama of the possible interplanetary missions evolved. The perspective is now not only the exploration of Mars and other bodies of the solar system. Future missions will more and more involve private investments and will be addressed to the use of space as a 'fourth dimension', such as a collective property for implementing services of economical and social benefits, that will be progressively integrated in the usual dimensions of present human activities, with the space agencies supplying the needed technical competences, guaranties and controls in conformity with the political indications of the respective governments.

The first cases of 'space tourism' and the recent successes of the private SpaceShipTwo spacecraft [20] are in this direction, as well the studies for the use of the Moon for the extraction of useful materials (e.g. the rare He3) and for scientific researches (see the series of 'Moon Base initiative' workshops [21]). The awareness of the advantages of using the Lagrange points for achieving scientific results and for supporting the commercial activities on the Moon surface is increasing [22,23]. The relatively low energy for travelling between these points and toward other space destinations appoints them as ideal locations for transferring infrastructures, means and supporting elements, but also in the USA studies [24], for the location of permanent station of transit, observation or use of military systems for the national security. Since these systems should be long time operative they will need permanent personnel to be supplied, repaired or updated.

3. Active protection of large volume multifunction habitats

Based on the conclusions of the previous pioneering work, it is time to device the problem of the protection from CR action at a scale allowing long permanence in 'deep' space, and not only for a relatively small number of dedicated astronauts but also to citizens conducting there 'normal' activities.

The protection from the radiation rises to a different level, either for the dimensions of the habitats to be protected or for the possible long times of permanence or the new safety rules to comply with.[1] The space complex must be therefore equipped, besides possible shelters against sporadic unpredictable energetic solar events,[2] by one (or more) habitat offering a substantial reduction of GCR dose to the permanent staff and acting as SCR shelter easily and timely reachable by all the afferent personnel of the complex.

The active system protecting the habitat must be continuously operative to allow the reduction of GCR dose during the whole permanence period of the staff personnel. It can be constituted by superconducting coils producing a high intensity magnetic field, protecting, as a sheath, the

[1] Recommended limits for astronauts depend from their gender and age [25]. Nowadays they are given as 'carrier limits' and range from 0.4–1.7 Sv/10year (about 0.16–0.7 Gy/10year) for women and from 0.7 to 3.0 (about 0.3–1.2 Gy/10year) for men, i.e. a factor 10 to 5 less that the yearly exposition to GCR at minimum solar activity.

[2] The maximum period that the shelter should support the people is a few days (during which short exits are possible, for example for toilette or short services, etc.) so that it can be really Spartan and house many persons in a small volume. It could be in principle protected by passive absorbers, for example water that could be promptly pumped in suitable shells. For 'complexes' floating in free space, or during travels, where shelters cannot relay on local materials, active systems allow a substantial saving of the mass to be transported (see fig.10 in [16]).

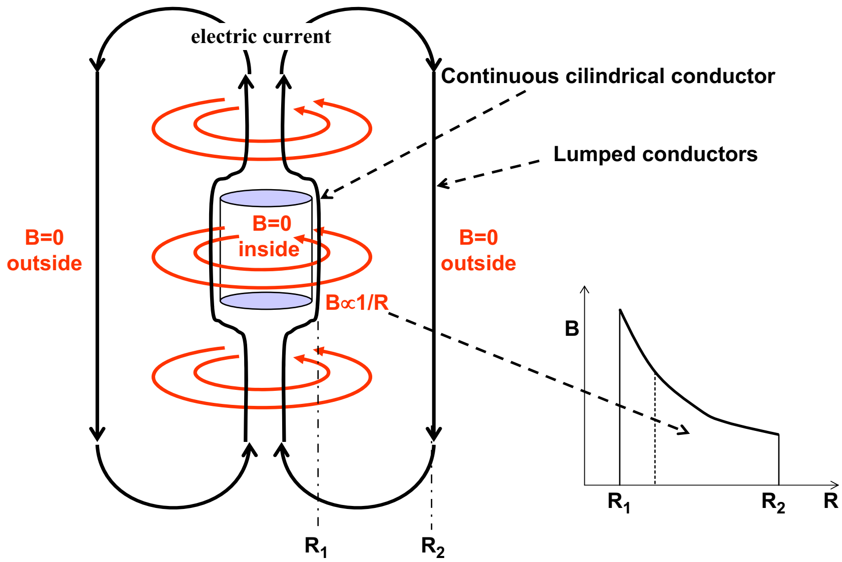

Fig. 1. Toroidal magnetic sheath for protecting a cylindrical volume inside.

habitat. Among the different configurations of the magnetic system that can be imagined, in order to simplify the work of performing quantitative evaluations the most convenient seems to be the toroidal one (see Fig. 1), produced by an electrical current running longitudinally in cylindrical symmetry along an inner conductor. It guarantees the field in the habitat to be zero, produces outside a 'sheath' of magnetic field in cylindrical symmetry whose intensity decreases inversely proportional to the distance from the axis of the system and it is zero outside the external cylindrical conductor returning the electric current running along the inner conductor. If such toroidal configuration has to be adopted in pratice, in order to allow in the habitat normal activities the residual magnetic field inside must be a few gauss at most, three or more order less than that in the surrounding sheath. This is possible in principle if the inner current flows around the cylindrical external wall of the habitat uniformly in a continuous cylindrical surface; however this surface is mechanically unstable due to the buckling pressure of the ponderomotive magnetic forces. Preliminary tests and an accurate engineering are required to guarantee the cancellation of the magnetic field inside in any possible normal or emergency situation. Furthermore recourse can be made to magnetic screen, e.g. superconducting material to close magnetic field draughts penetrating the habitat.

Furthermore the design of the magnetic system must take in account the following points:

- it is advisable that the protection system be integrated with the habitat before its transportation to space;
- therefore its outer dimensions (diameter and length) and its mass must comply with the capability of the transport system;
- the system, also if it could be transported already cooled, must be energized in its final location in space.

For the evaluation conducted in the following of this work for protecting a huge volume habitat the toroidal configuration is specified in the simplified scheme shown in Fig. 2, with the inner cylindrical conductor continuous and the outer one continuous or lumped in many conductors (16 in Fig. 2). The longitudinal section of the magnetic sheath has a rectangular shape, whose radial side is $\Delta R = R_2 - R_1$ (2 m in Fig. 2) and the longitudinal side less defined (L=16–20 m in the figure, assumed L=16 m in the following). As shown in Fig. 2 the inner cylindrical conductor is supposed to be subdivided at the two ends in several cylindrical tubes of smaller diameter, in order to protect down to small angles and meanwhile maintaining the magnetic field intensity not higher than that at $R = R_1$ (this is important, because in a superconducting magnet the strictness of problems strongly depends on the maximum field reached in the system).

The dimensions reported in Fig. 2 are fixed by taking in account the 10 m maximum diameter until now foreseen for transport systems[3]: a habitat of 6 m diameter can be protected by a 'sheath' of magnetic field not thicker than 2 m.

The dose inside the habitat (expressed in gray, the released energy per unit mass) has been calculated due to galactic protons. The results are not reported for a particular choice of the intensity of the magnetic field, but parameterized as a function of its maximum intensity, i.e. the intensity at $R = R_1$. They are summarized in Fig. 3 for two 'thicknesses' $\Delta R = R_2 - R_1$ of the magnetic field sheath (dashed lines): ΔR=2 m as in Fig. 2 and ΔR=1 m considering the maximum diameter of 8 m of the shroud of the transportation systems presently conceivable. In the figure, just as an indication, it is also reported the dose due to all the GCR flux, obtained by multiplying by 5 the dose due to protons. An important result must be

[3] The largest diameter of the payload shroud is 10 m, foreseen for the mammoth Ares V rocket for the next NASA mission to Moon, which should release in Earth orbit the landers and the Earth departure stage to be met by an Orion crew-carrying spacecraft launched on top of the smaller Ares I rocket.

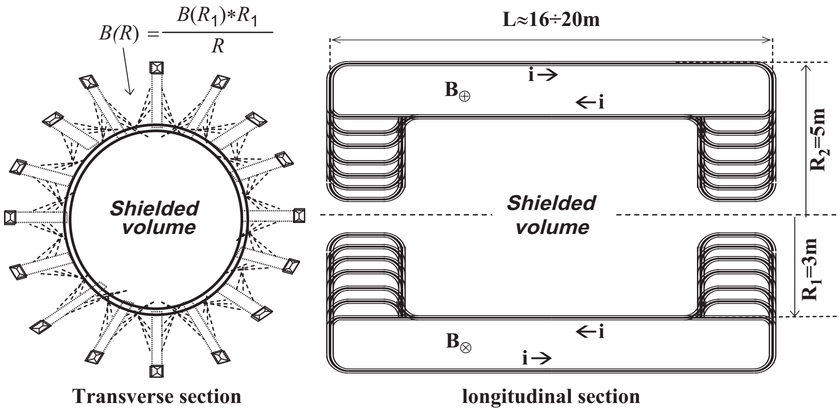

Fig. 2. Configuration assumed to evaluate the protection of a 6 m diameter cylindrical habitat.

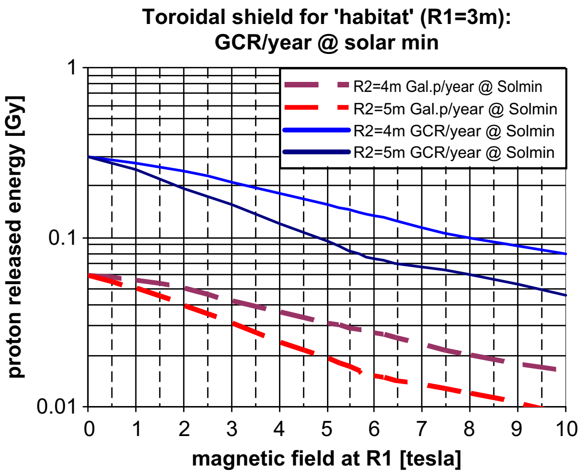

Fig. 3. Reduction of the dose released by galactic protons as a function of the maximum magnetic field for two values of the outer diameter (8 and 10 m) of the system (see Fig. 2). The reduction of the dose released by all the GCRs is reported as indication, obtained by multiplying 5 to the dose released by the protons. For an outer diameter 10 m the reduction is about 70% (80%) for maximum field of 5 T (8 T). For the smaller outer diameter of 8 m the reduction of 70% is obtained with maximum fields of 9 T.

underlined: in order to reduce the GCR dose inside the habitat by a factor about 5 (see below) the maximum magnetic field intensity (that at $R=R_1$) is about 8 T for a magnetic sheath $\Delta R=2$ m, and much more than 10 T for a $\Delta R=1$ m magnetic sheath.[4]

For the assumed geometry of Fig. 2 (diameter of the habitat 6 m, external diameter of the whole system 10 m, 2 m thick magnetic sheath) the energy spectra of the GCR fluxes at solar minimum are reported in Fig. 4; the bottom of Fig. 4 shows (in %) the reduction of the dose for different values of the maximum magnetic field on the superconductor.

In order to evaluate the mass of the needed superconducting cable the following criteria have been adopted:

- the coils are maintained cool by cryocoolers at expenses of electrical power (Cryogen Free Superconducting Magnet concept [26]);
- the superconducting cable is constituted by MgB_2 wires produced by the *in situ* method in a titanium sheath [27,28] stabilized outside in aluminium (see Fig. 5). This choice, proposed by Turin university and Alenia industry ([29]), seems at present the most promising: the cable can work at relatively high temperature(≥ 20 K, a value that can be reached by cryocoolers), with a high current density (1 kA/mm^2 at 2 T, assumed diminishing with the inverse of the field for $B(R_1)>2$ T), its density is low (3 g/cm^3) guaranteying an important mass saving, and it can be produced very thin [30], therefore less serious current and temperature instability and distributing current in the surrounding cables in the case of bad functioning.
- the choice of the MgB_2 superconductor is provisional. In fact the operating temperature is the main guiding parameter for the choice of the superconducting material, in particular for space applications. Other HTS (such as $YBa_2Cu_3O_7$ or $Bi_{1.8}Pb_{0.2}Sr_2Ca_2Cu_3O_{10}$, whose production in ribbons and cables amounts to several hundreds km/year) could result in more convenience in a final project, in spite of the other advantages of the MgB_2 cable.

The resulting superconductor mass is reported in Fig. 6 for the 6 m diameter habitat of Fig. 2, parameterized as a function of the maximum magnetic field of the system for different values of the outer diameter (from 10 to 20 m, corresponding to a sheath thickness from 2 to 7 m) and for 3 values (59%, 82%, and 87%) of the GCR reduction. It must be underlined the strong dependence of the superconductor mass from the outer diameter: for a fixed GCR reduction the required maximum field diminishes on

[4] In Fig. 3 the values of the maximum magnetic field extend up to 10 T; however, it would be not expedient to approach so high values because the stored energy and the ponderomotive forces increase with the square of the field intensity, as well increase the possible instabilities of the superconducting regime of the current, critically depending from the point of higher field in the superconductor.

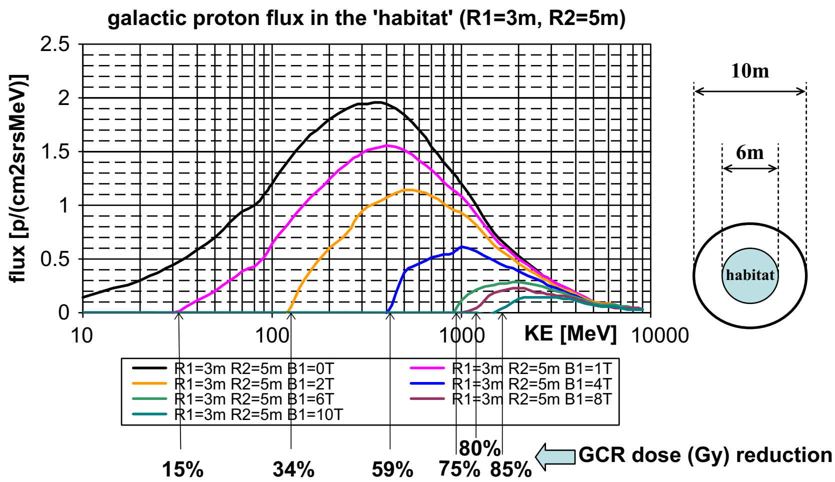

Fig. 4. Reduction of the galactic proton flux inside the habitat. The corresponding reduction of the dose due to GCR flux is reported at the bottom of the figure for different values of the maximum magnetic field (1, 2, 4, 6, 8, and 10 T) of the system.

Characteristic	Value
Averaged density	2.96 g/cm^3
Diameter of the cable	200 μm
Section of MgB2	$6.28 \cdot 10^{-3}$ mm^2
Operation temperature	20 K
Critical current at 2 T	$1.3 \cdot 10^3$ A/mm^2

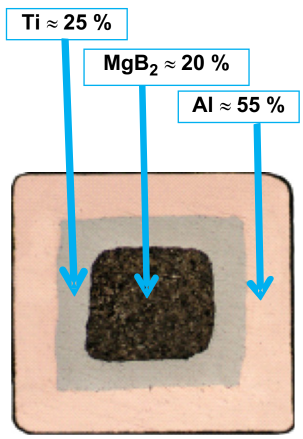

Fig. 5. Characteristics of the sc cable assumed for the evaluation of the superconductor mass of the magnetic system.

increasing the outer radius and the superconductor mass decreases due to the increase of the allowed current density in the superconductor. Furthermore the ratio of the total mass to the superconductor mass (assumed 1.5 in all the previous works[5]) could diminish due to the decreasing of the ponderomotive forces. These results underline the importance of developing systems for deploying or assembling in space the outer conductors returning the electric current running around the external cylindrical surface of the habitat.

For the geometry assumed in Fig. 2 and 8 T maximum field the GCR dose reduction is 82%, a value that, in periods of high solar activity, can be regarded as acceptable by current criteria for permanence in space of more than one year.

This reduction is not enough during periods of minimum solar activity, when the GCR dose increases more than 2 times. To improve the GCR reduction, or also for decreasing the technological risks due to a so high value of the maximum field, two approaches are possible:

a. substantially decrease the diameter of the habitat, but maintaining the 10 m outer diameter, i.e. compatible with the transportation to space of the system habitat+protection as one piece;
b. increase the diameter of the return current of the toroid, by assembling or deploying it in space in its final location; this allows to expand the thickness of the magnetic sheath beyond the 2 m allowed by the transportation system.

The first approach reduces a precious value of the habitat, its volume, and must be compromised with the

[5] An assessment of the total mass is hardly possible without a detailed project, also considering that the mass of the supports strongly depends on the maximum field and the consequent ponderomotive forces. In the ESA TT study [13], taking in account that the system has a cylindrical symmetry, that in free space the vacuum tank (constituting most of the mass in the ground) is not needed and that is not necessary to contrast the gravitation field, it was assumed that the total mass could amount to 1.5 times the superconductor mass.

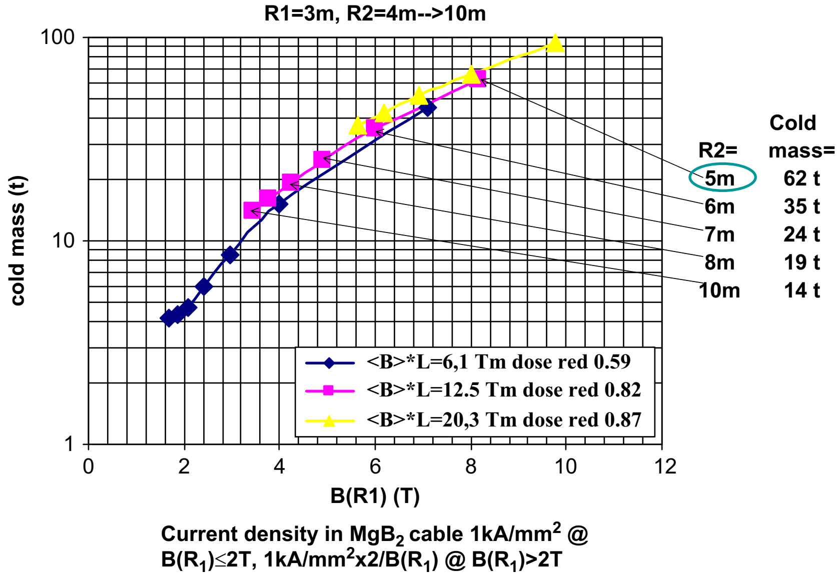

Fig. 6. Superconductor mass of the system realized by MgB_2 sc cable, for the values 6.1, 12.5, and 20.3 Tm of the bending power $\langle B \rangle (R_2 - R_1)$ (corresponding to 0.59, 0.82, and 0.85 reduction of the GCR dose) and several values of the outer diameter as a function of the maximum magnetic field intensity.

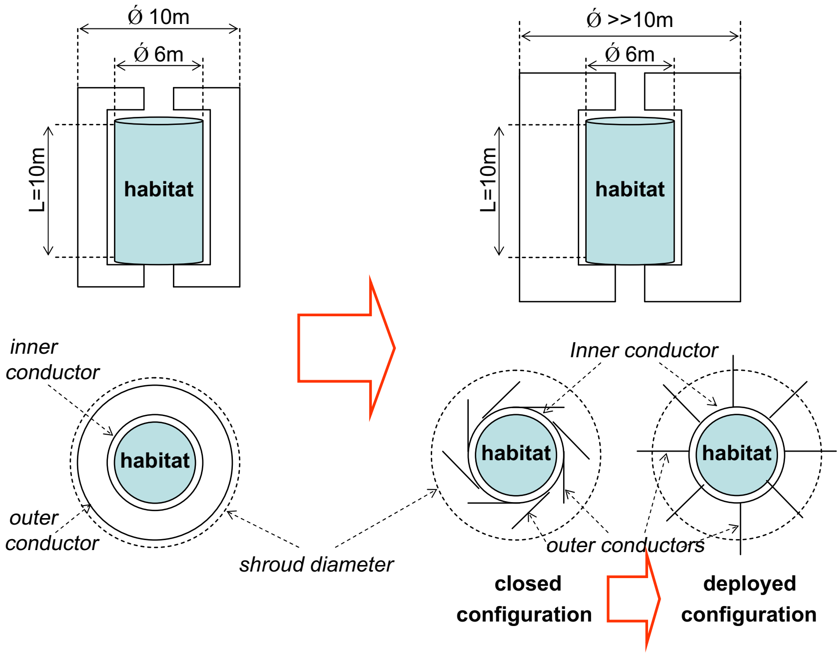

Fig. 7. Schematic of the deployment of rigid outer conductors by their rotation around hinges.

number of persons that could live and conduct inside their activities.

The second approach requires specific preliminary experimentation to be carried out. It could be obtained by several configurations, obviously none simple to be implemented. For example, the outer conductors could be rigid, but could rotate around suitable hinges to increase the external diameter, as schematized in Fig. 7.

If no rigid conductors could be realized, they could be deployed by suitable inflatable elements, or by the push of the electrical current itself, as sketched in Fig. 8.[6] The

[6] An important remark concerns a peculiar characteristic of the toroidal configuration. The shape sketched in Fig. 2 has been used for convenience of computation in the evaluations. However, the most convenient shape of the outer conductor in not a cylinder, but a D shape.

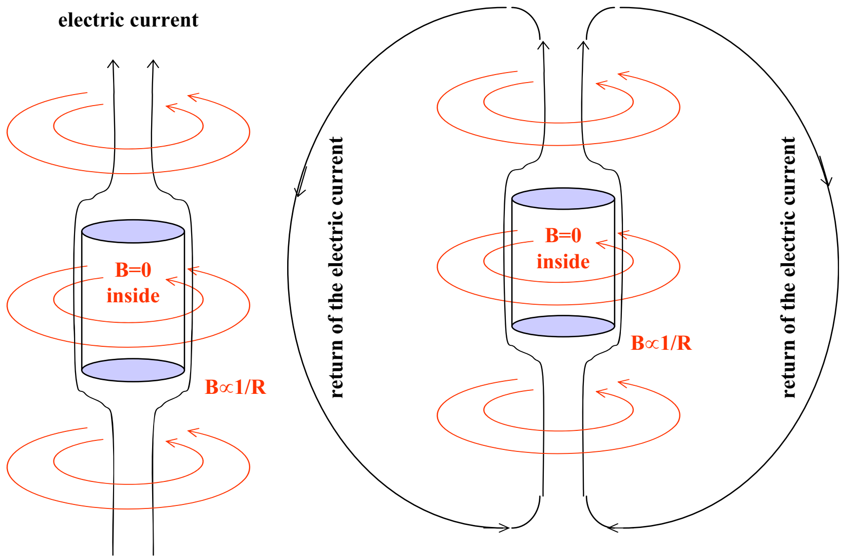

Fig. 8. Schematic of the deployment of non-rigid outer conductors. The field diminishes on increasing the radius, making easier to support the ponderomotive forces. The conductor is prone to assume a D shape where the local magnetic pressure is counteracted by the mechanical tension (see footnote 6 in the text). This condition dodges important mechanical supporting structures for the outer part of the system.

advantage of reaching an external diameter of 12 or more meters in terms of cold mass is well illustrated in Fig. 6: increasing from 10–12 m the outer diameter the maximum needed magnetic field decreases from 8 to 6 T and the superconductor mass is halved. A further halving could be obtained by gigantic 16 m or more external diameters.

4. 'Space complexes' planning and mission strategies

Mission strategies must be elaborated taking into account these new lines of development, either for bases on Moon surface or for other celestial bodies, or for 'floating' complexes such as those foreseen in the L1 libration's point between Earth and Moon. The 'architecture' should foresee one (or more) habitat offering a substantial reduction of the GCR dose to the permanent staff, and possible distributed shelters against the sporadic unpredictable energetic solar events.

The criteria to be adopted for the layout of a permanently inhabited space complex could be as follows:

- all the inhabited modules linked to the protected habitat by easily practicable tunnels;
- protected habitat can be reached by any point of the complex in few minutes;
- habitat fully protected by any conceivable intense and energetic SCR event;
- the habitat guarantees a factor ≥ 5 reduction of the GCR dose inside.

Concerning this last point, duration of the permanence of the personnel should be planned taking into account the 11 yr cycle of the GCR flux with the solar activity (up to a factor 3 less in terms of dose during the years of higher solar activity). In general it must be observed that also the schedule of the needed long duration transfer of men in space must take in account the solar activity cycle and its consequences on the CGR rate.

The volume of the protected habitat should be as large as possible because the staff must not only live but also carry out there their working activities. At the moment we must take in account that in the projects of future transportation systems the shroud diameter will not exceed 10 m. Also it must be considered that in order to avoid complex problems of assembling structures in space it could be advisable to transfer to space the habitat as one piece, complete its magnetic protection system. It is for these reasons that in the above evaluations the diameter of the habitat was assumed not to exceed 6 m (the length has less constraint and was tentatively assumed 10 m). As above commented the efficiency of the magnetic protection, and also the diameter of the habitat, could hopefully be increased by extending the return current elements beyond the diameter of the transport system, or by mechanical deployment or by deployment by inflatable elements.

The layout of a possible space complex is sketched in Fig. 9, constituted by modules of 8–10 m in diameters protected against energetic solar events, linked among them and to the central long permanence module.

(*footnote continued*)
In fact the magnetic pressure in the outer part of the toroidal magnet can be counteracted by the tension on the conductor if the shape of the coil has such a configuration that the tension T on the conductor is constant. This can be expressed by the condition $T=B\times NI\times\rho$=constant, where B is the (local) magnetic field on the coil, NI the total current and ρ the (local) curvature radius. This condition dodges important mechanical supporting structures for the outer part of the system.

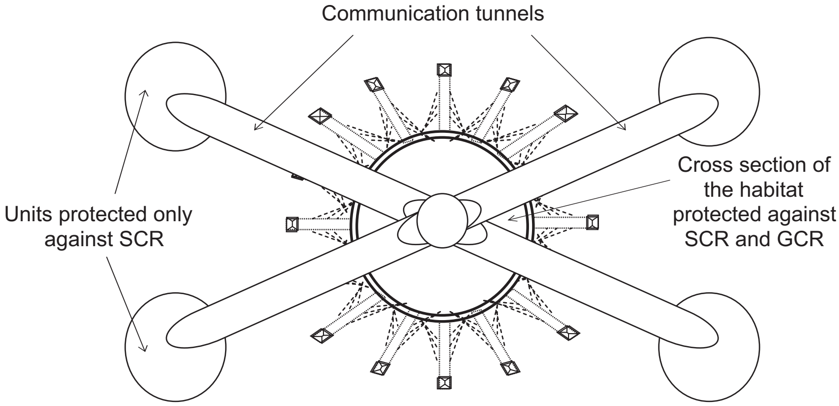

Fig. 9. Possible layout of the 'habitats' of a generic 'space complex'.

On the surface of celestial bodies, in case that manned rover vehicles will be used for far reaching exploration, shelters from SPEs must be provided, which could be reached in short time (10–15 min) from any point of the route.

The architecture of space complexes floating in free space and intended for permanence's longer than one year should possibly be conceived for allowing an artificial gravitation pull in the long permanence habitat.

5. Conclusion

An adequate protection from ionizing radiation of a large human community in space is an unavoidable complex problem, which can be solved in an adequate time provided that a long program of study and R&D will be set up and with the due resources.

It is an urgent professional approach toward the study, project, realization, and test of materials, mechanisms, systems, and finally 'space demonstrators', and their integration in manned exploration programs. This work should proceed by steps, some of them could be: (a) the comparison among different configurations of the magnetic system, taking into account, besides technical progresses in superconductivity and cryogenics, their complexity and their possibility to be integrated in a spaceship or in a deep space station; (b) the evaluation of their effectiveness in reducing the GCR flux inside the habitat computed taking in account all the contributions (such as for example the flux and energies of the neutrons produced in the superconducting material and other massive elements); (c) one (or a few) design of the magnetic system, complete mechanical supports, the cryogenic systems, possible moving elements, and all the needed services; (d) development and realization of samples of the needed superconducting cable, sample of needed parts of the cryogenic system, and samples of specific required mechanisms; (e) development and test of systems for assembling or deploying in space parts of the superconducting coils; (f) realization and mechanical, thermo-vacuum and functional tests of one full scale superconducting turn of the coil of the final system; and (g) realization of a model of the final magnetic system, reduced to a scale suitable for extrapolating to full scale the mechanical, thermo-vacuum and functional tests to whom it should be submitted.

Protection from CR in space is a 'niche', critical for its exploration and exploitation, where the contribution of physicist could be significant. It is also an important occasion of collaboration, where techniques developed for nuclear and elementary particle experiments can be made available to space agencies and industries for their programs. A specific example is a by-product of the above discussion, i.e. the production and use of high intensity magnetic fields for controlling dimensions, direction and divergence of charged particle beams, as it could be the case for propulsion in space, in particular for the MPD propulsion systems. In a somewhat futuristic view superconducting coils could be used for trapping ions in magnetic boxes, where they could interact.

In a more immediate view the development of the cryogenic system needed for the superconducting magnets, which do not require the evaporation of liquid helium as a consumable but operate at expenses of electric power, is in itself interesting for numerous applications in space missions. Improving the performance of cryocoolers and diminishing their mass cryogenics can be introduced in subsystems, either for decreasing noise in transmitters, receivers and other power devices, or for reducing their mass and the mass and heat consumption of the connections.

Acknowledgments

The author wishes to thank Prof. Lucio Rossi for his guidelines in the superconducting magnet techniques and Eng. Silvano Casini for the stimulating discussions on mission strategies.

References

[1] J.W. Wilson, M. Kim, W. Schimmerling, et al., Issues in space radiation protection: Galactic cosmic rays, Health Physics 68 (1995) 50–58.
[2] J.W. Wilson, J. Miller, A. Konradi, F.A. Cucinotta (Eds.), Shielding strategies for human space exploration, NASA CP 3360, 1997.

[3] J.W. Wilson, R.K. Tripathi, G.D. Qualls, et al., Advances in space radiation shielding codes, Journal of Radiation Research 43 (2002) S87–S91.
[4] HUMEX, Study on the survivability and adaptation of human to long-duration exploratory missions, Report ESA SP-1264, 2003.
[5] G.D. Badhwar, F.A. Cucinotta, Depth dependence of absorbed dose, dose equivalent and linear energy transfer spectra of galactic and trapped particles in polyethylene and comparison wih calculations of the models, Radiation Research 149 (1998) 209–218.
[6] M. Durante, K. George, G. Gialanella, G. Grossi, C. La Tessa, L. Manti, J. Miller, M. Pugliese, P. Scampoli, F.A. Cucinotta, Cytogenetic effects of high-energy iron ions: dependence on shielding thickness and material, Radiat. Res. 164 (2005) 571–576.
[7] M.R. Shavers, N. Zapp, R.E. Barber, et al., Implementation of ALARA radiation protection on the ISS through polyethylene shielding augmentation of the service module crew quarters, Advances in Space Research 34 (2004) 1333–1337.
[8] J.C. Sussingham, S.A. Watkins, F.H. Cocks, Forty years of development of active systems for radiation protection of spacecraft, Journal of Astronautical Science 47 (1999) 165.
[9] L.W. Townsend, Overview of active methods for shielding spacecraft from energetic space radiation, Physica Medica, XVII-Supplement 1 (2001) 84.
[10] R., Battiston, for the AMS collaboration, AMS-02: a superconducting spectrometer for the search of dark matter and antimatter on the ISS, in: Proceedings of the XXVII International Cosmic Ray Conference, Hamburg, 2001, p. 2192.
[11] J. Hoffman, P. Fisher, O. Batishchev, Use of superconducting magnet technology for astronauts radiation protection. NIAC phase I final report, 2 May 2005; reported to the American physics society, APS Bulletin 49 (2004) 261.
[12] C.H., Chung, S., Fopp, Th. Kim, et al., AMS on ISS: application of particle physics technology to manned interplanetary flight, AMS Collaboration Internal Report, March 2005, in preparation.
[13] ESA Topical Team, Shielding from the cosmic radiation for interplanetary missions: active and passive methods, in: Proceedings of the 35th COSPAR Scientific Assembly, Paris, July 2004; ESA Topical Team, Topical teams in the life and physical sciences: toward new research application in space, ESA sp-1281 report, October 2005, pp. 184–199.
[14] P. Spillantini, M. Casolino, M. Durante, R. Mueller-Mellin, G. Reitz, L. Rossi, V. Shurshakov, M. Sorbi, Shielding from the cosmic radiation for interplanetary missions: active and passive methods, Radiation Measurements 42 (2007) 14–23.
[15] C. Cougnet, N.B. Crosby, C. Foullon, et al., Radiation exposure and mission strategies for interplanetary manned missions (REMSIM), Earth, Moon and Planets 94 (2005) 279–285.
[16] P. Spillantini, Active shielding for long duration interplanetary manned missions, Advances in Space Research, accepted for publication.
[17] J. Nagamatsu, N. Nakagawa, T. Muranaka, Y. Zenitani, J. Akimitsu, Superconductivity at 39 K in magnesium diboride, Nature 410 (2001).
[18] S.X. Dou, E.W. Collings, A. Shcherbakova, Aluminium stabilized superconductor, Superconductor Science and Technology 19 (2006) 333.
[19] R.G., Ross Jr. R.F. Boyle, P. Kittel, NASA Space cryocooler programs: a 2003 overview, in: Proceedings of the International Workshop on Thermal Detectors for Space Based Planetary, Solar and Earth Space Applications, TDW, 19 June 2003, Washington, DC, USA, 2003.
[20] T. Malik, Virgin Galactic unveils Suborbital Spaceliner Design, 23 January 2008, 〈www.space.com/news/080123-virgingalactic-ss2-design.html〉.
[21] F. Compagnone, E., Perozzi (Eds.), Moon Base—a Challenge for Humanity. Donzelli Editore, Roma, 2007.
[22] S., Casini, A quick look to a European strategy for solar system exploration (the wide vision), in: Proceedings of the Third Workshop on Moon Base: A Challenge for Humanity, Moscow, November 2006.
[23] M.W. Lo, S.D. Ross, The Lunar L1 gateway: portal to the stars and beyond, in: Proceedings of the AIAA Space 2001 Conference, Albuquerque, New Mexico, August 2001.
[24] H.A. Thronson, Logistics in NASA exploration architecture and major science. Goals in space, NASA, Review of the US Human Spaceflight Program Committee, Final Report. NASA, October 2009, The International Society of Logistics 41 (2007) 4.
[25] National Council on Radiation Protection and Measurement (NCRP), Recommendations on dose limits for low Earth orbit, NCRP Report 132, NCRP, Bethesda, MD, 2000.
[26] L. Rossi, CFSM (Cryogen Free Superconducting Magnet), Proposal to ASI for "Methodological Techniques in the Field of Space Systems and Subsystems", Alenia Report SG-PP-Al-0864, ASI Workshop Nazionale 'Utilizzo Scientifico e Tecnologico della ISS', Naples, 17–19 April 2000.
[27] M. Alessandrini, H. Fang, M. Hanna, P. Putman, Y.X. Zhou, K. Salama, High critical current of Ti-sheathed MgB_2 wires for AC and weight-critical applications, Superconductor Science and Technology 19 (2006) 129.
[28] P. Kovac, I. Husek, T. Melisek, T. Holubek, Properties of stabilized MgB_2 composite wire with Ti barrier, Superconductor Science and Technology 20 (2007) 771.
[29] J., Chevallard, Definizione di schermi magnetici per la radioprotezione degli astronauti, Degree Thesis, Turin University, September 2007.
[30] S.I. Schlachter, W. Goldacker, A. Frank, B. Ringsdorf, H. Orshulko, Properties of MgB_2 superconductors with regard to space applications, Cryogenics 46 (2006) 201.