Executive Summary

Superconductive Magnet for Radiation Shielding of Human Spacecraft

After the completion of the International Space Station *(ISS)*, missions beyond low Earth orbit *(LEO)*, to Moon, Mars or Near Earth Asteroids *(NEA)* are considered as the next step of manned, peaceful, space exploration. These missions would inevitably last much longer than the long duration missions on the *ISS* (Expeditions), posing severe challenges in several areas of life sciences like, in particular, radiation health.

Space radiation environment represents a serious challenge for long duration mission. On *LEO* the shadow of the Earth and the effect of the magnetosphere, reduces by a factor *4/5* the dose absorbed by astronauts. During a long duration exploration mission, the dose could easily reach and exceed the current dose yearly limits.

For this reason, during the last four decades, means to actively shield the Galactic Cosmic Ray *(GCR)* component have been considered in particular using superconducting magnets creating a toroidal field around the habitable module. Theses studies indicated that magnetic shielding with up to a factor of *10* of reduction of the *GCR* dose could, in principle, be developed.

Europe has a significant amount of experience in this area thanks to previous human missions in *LEO* (*Spacelab, MIR* and *ISS*), related programs (e.g. *HUMEX, AMS-02*) and *Topical Teams* activities: this background represent a solid starting point for further progress in this area.

Due to recent and significant progress in superconducting magnet technology both in ground laboratory (*ITS* – Intermediate Temperature Superconductors - and *HTS* - High Temperature Superconductors) and on the preparation of space experiments (development of the space qualified *AMS-02* superconducting magnet), it is interesting to re-evaluate active shielding concepts as potentially viable solutions to crew protection from exposure to high energy cosmic radiation.

Past active radiation shielding concepts yielded architectures that are significantly massive and too costly to be launched and assembled in space. This is largely due to the magnet size and field strength required to shield Galactic Cosmic Radiation (*GCR*) and Solar Proton Events (*SPE*) for meaningful level of crew protection from radiation in space.

Since then, state-of-the-art superconducting magnet technology has made significant progress in performance including higher temperature superconductivity (*ITS* and *HTS*) and new mechanical solutions better suited to deal with the Lorentz forces created by the strong magnetic fields. In addition, ten years of design, research and development, construction and testing of the *AMS-02* magnet, the only space qualified superconducting magnet built so far, provides an heritage of European based experience which motivates further developments of this technology for space applications.

Use of *ITS* or *HTS* allows for simpler magnet cooling systems using liquid hydrogen, gaseous helium or even liquid nitrogen as cryogens instead of the more complex liquid helium systems required for Low Temperature (*LTS*) superconducting magnets like *AMS-02*. Due to the large energy margin of *ITS* and *HTS* conductors, significantly lighter support structures are possible for the superconducting coils providing for more creative ways to shield from radiation a crew in space.

We compared *15* different magnets geometries producing toroidal field, both from the point of view of their mechanical properties (coil mass, structural mass) as well as from the point of view of their shielding properties. For the purpose of the study we analyzed magnetic configurations which would be possible to build *"today",* using state of the art technologies: the identification of the most promising solutions would then provide the starting basis for *R&D* and future design studies. For this we have considered relatively low bending power/shielding power configurations, assuming that future improvements in the technology would allow to increase their shielding capabilities. The structural design of two coil configurations having magnetic bending power of *4-5 Tm* were analyzed more in detail, to determine their structural mass and material budget: the classical *"racetrack"* toroid magnet design and a new multi-coil geometry based on a technology called "*Double Helix" (DH)*. The radiation shielding efficiency of these two solutions have been evaluated and compared using an advanced *3D* simulation tool developed in the frame of the AMS Collaboration, able to simulate Cosmic Rays interaction with the magnet structure, including secondary particle production, and their *3D* propagation in the magnetic field.

The accuracy of the simulation tools we developed and used for this study allow for a better understanding of the interplay among different elements concurring to the definition of the dose absorbed by the different parts of the body of the astronauts during a long duration mission like: shielding effect of the structural mass versus shielding effect of the magnetic field, the dependence of these effects on the ion charge *Z* and on their energy.

The result of the study shows that the two coil configurations analyzed have similar performances in terms of shielding capability, in particular for the low BdL configurations which we have studied in detail. At *4-5 Tm* the combined effect of passive and active shielding would provide a *40%* reduction of the dose due to *GCR* with respect to empty space, reducing it to a value *30%* below the currently recommended yearly dose limit of *50 rem*. These configuration would also ensure a good shielding against the sudden radiation spikes due to *SPE*. Increasing the magnetic bending power (higher field and/or larger magnetized volumes) would increase the active shielding efficiency, provided that the amount of the material crossed by the *GCR* is kept to a minimum, which one of the key technological challenges.

The *DH* design looks promising from the point of view of the weight and complexity of the supporting structure, transportation to orbit and modularity of the multi coil designs, since a good fraction of the resulting Lorentz forces are distributed within the coil windings, requiring less additional supporting structures. Extrapolation to high value of *BdL* should make the situation even more favorable for the *DH* design. In addition *DH* design has more flexibility both in terms of magnetic as well as of mechanic design, including the possibility of designing coils with complex field configurations matching the needs of the shield application or of *"game changing"* new technologies based on *"magnetically inflatable"* self supporting coils.

Following the main idea behind this study, namely to identify designs based on state of the art but existing technologies, which could be developed within a decade or so with a high degree of confidence, we defined a *Radiation Protection System Roadmap*, identifying *Ten Critical Technologies* needed to develop within the next ten years a realistic *DH* active magnetic shield, identifying the corresponding Technology Tree as well as the technological *R&D* and development of demonstrators which are needed over a period of ten years to bring these technologies from the current status to the *TRL* needed to test such a system in space.

The ten critical technologies which have been identified are:

#1 High performances *ITS* and *HTS* cables (MgB_2, *YBCCO*)

#2 *Double Helix* coil

#3 Cryogenic stable, light mechanics

#4 Gas based recirculating cryogenic systems

#5 Cryocoolers operating a low temperature

#6 Magnetic field flux charging devices

#7 Quench protection for *ITS* and *HTC* coils

#8 Large cryogenic cases for space operation

#9 Superinsulation, Radiation Shielding, Heat Removal

#10 Inflatable *SC* Coils

Most of these critical technologies are within the background of the European industry and top research laboratories. As a recommendation of this study, a European led effort to develop them to the level of ground based and space based active shield demonstrators should be supported. We present in the study a *Radiation Protection System Planning*, taking as reference the latest version (2011) of the *"The Global Exploration Roadmap"* developed by *ISECG* (International Space Exploration Coordination Group). A first step toward a final objective of human Mars exploration could be a mission to *NEA* (Near Earth Asteroids), the so-called *"deep space first"* as an alternative to a *"moon-first"* approach. Such a mission would require as well a Radiation Protection System for the crew as the mission duration could be in the range of *400* days, so that radiation protection becomes an issue. A reference mission with *4* astronauts has been considered, as well as an extension to an *8* crew mission.

The development plan is in principle divided in four main sequential phases:

1. Technology development, in which the critical and/or not yet mature technologies are brought to *TRL5*.

2. Ground Demonstrators, aiming at integrating, with different steps, the required different technologies in one system, allowing to validate the capability of the system in providing the expected functions and performance.

3. In-space Demonstration, where a representative Radiation Shield model is flown in *LEO* (maybe as a free-flying item in proximity of the *ISS*).

4. Deep Space Habitat (*DSH*) Radiation Shielding System; this is the operational system for the *DSH*.

This report summarizes - as the Final Report of the " *Superconductive Magnet for Radiation Shielding of Human Spacecraft* " - the findings presented in details in four Technical Notes (ESTEC/Contract N° 4200023087/10/NL/AF):

TN1 - Data Collection and Requirements Generation

TN2 - Radiation Protection System Concept Report

TN3 - Radiation Protection System Preliminary System Engineering Plan

TN4 - Results of Active Shielding Round Table Discussions

The study has been led by University of Perugia (I) with the cooperation of INFN (I), CGS (I), SCL (UK), AML (USA).