Executive Summary:
The future, long duration missions in deep space will expose astronauts to harmful radiations which increase the probability of developing serious diseases, even with fatal outcome. The Moon, Earth-Moon Lagrangian points (EMLP), Near Earth Asteroids and finally Mars are our next space frontiers, and the whole Solar System represents the ultimate space challenge. While in low terrestrial orbit astronauts are partially protected by the combined effect of the geomagnetic field and of the planet shadow, an effective radiation protection becomes an enabling factor for safely transporting and keeping astronauts in deep space. The main sources of space radiation are the Solar Particle Events (SPE) and the Galactic Cosmic Rays (GCR). The former are very intense, short bursts of low energy particles, while the latter are a continuous flow of protons and ions having a wide energy spectrum with the maximum flux around 1 GeV for protons and 500 to 600 MeV/nucleons for ions. Shielding strategies do exist for the SPE, involving alarm systems and passively shielded shelters. On the contrary, it is difficult to design an effective shield for GCR (the dominant source of radiation dose for a long duration mission) mainly due to the high energy
component of their spectrum and to the large dimension of the volume to be shielded. The EU Project Space Radiation Superconductive Shield (SR2S) worked to devise a solution for and active radiation shield involving superconducting magnets. Active shielding exploits the energy of electric or magnetic fields to deflect particles changing their trajectory and they are the main focus of the present work. The passive shielding instead is based on the selection of the best materials able to modify in an appropriate way the radiation field through energy loss, when the radiation gets through the material itself. A superconducting radiation shield would in principle enable astronauts to withstand longer periods of time in space and thereby conduct longer space missions.

This project aimed to demonstrate the feasibility of an active magnetic shielding technology to protect astronauts from radiation in the space environment by using superconductive technology. This is vital for missions that require a long-term stay in space for a minimum of 18 months. The SR2S project succeeded in proving the technological concept and demonstrated the potential of key technologies needed for the development of the active, space born, magnetic shield. The project developed detailed design specifications, and for the key technologies implemented and validated them through hardware prototypes. Such a study has not been performed in the past. The existing literature presents only a limited number of simplified simulations suggesting that a toroidal configuration would be able to reduce the yearly absorbed dose by nearly an order of magnitude, by using intense magnetic fields. For the first time, SR2S has performed a comprehensive analysis, using state of the art simulation tools, including 3D tracking, material simulations as well as rather detailed magnetic configuration, structural, safety, thermal and mission scenarios analyses.

The results of these analyses have shown

a) The complexity of the interaction between active shielding methods based on particle deflection based on magnetic fields and passive shielding methods based on particle absorption through material thickness;
b) The importance of developing very transparent magnetic systems, in order to avoid excessive generation of secondary neutrons; this makes continuous toroidal magnetic systems, considered in the past literature, unsuited for active shielding. A new shielding structure has been studied, based on a set of autonomous, self-supporting toroids located around the habitat module in a non-axial configuration ("pumpkin" configuration). This configuration is promising, since it could provide a factor two in reduction of the CR dose with suitable technical developments;
c) The need for TRL developments on a number of key technologies which are needed for such a space based active shield. The SR2S project has focused on a number of these developments, most notably: cryogenic thermal control (Pulsed Heat Pipes), lighter superconducting cables operating at intermediate temperatures, quench protection of large high temperature superconducting systems, reliable Monte Carlo simulations.

At the end of the SR2S project, the need for the development of an active radiation shield system for interplanetary mission has been confirmed. Further steps of technical and conceptual development have been identified which could be addressed in more detail by a potential continuation of these studies. SR2S represent a major step beyond previous study results for the development of future Active Radiation Shielding Systems and provided a roadmap for future technical progresses needed to develop the active shield technologies.

The SR2s project reached a Technology Readiness Level (TRL) of 3 (experimental proof of concept), while some of the key technologies, superconducting cable and pulsating heat pipes, increased the TRL to 4 (technology validated in lab).
Project Context and Objectives:

The context

After the completion of the International Space Station (ISS), exploration missions beyond low Earth orbit (LEO), to Moon, Mars or Near Earth Asteroids (NEA) are considered as the next step of human space exploration. These missions would inevitably last much longer than the long duration missions on the ISS, traveling on deep space orbits, posing severe challenges in several areas of life sciences like, in particular, radiation health, as discussed in the 2003 HUMEX study by ESA.

The most challenging part of these exploration missions will certainly be a human mission to Mars. Presently, human permanence in space is quite short. The maximum duration in space for the crew on the ISS is six months before they have to return to earth, even though the vehicle is partially protected by the Earth’s shadow and magnetic field.

In order to reach distant planets, long-term human permanence in space is required. Beyond Low Earth Orbit, the magnetosphere is too weak and a radiation shield for spacecrafts has to be put in place. The most difficult problem to solve, in order to ensure the future of space travel, is to protect the crew for such a long time.

Moreover, as it currently operates, astronauts are chosen on the basis of their body’s ability to withstand radiation. Young individuals are exposed to higher risk than elders and women are more sensitive to radiation than males. Improving the radiation shielding, with the consequent reduction of the adsorbed dose, means also smoothing the gender and age differences, allowing humans to take part in deep space missions.

During SR2S project, the team validated and increased the Technology Readiness Level (TRL) of some critical technologies related to a magnetic shielding system for protecting astronauts’ lives during long duration space missions, reaching TRL 3 for the whole system and 4 for some of its components.

The SR2S foundation technology is the superconducting magnet. Although superconductivity is used in many scientific and applied fields since the sixties, there is limited experience on the technologies needed to build and operate a superconducting magnet in space. The SR2S magnet is based on a titanium clad MgB2 wire that guarantees lightness, reliability and simple cryogenics.

The shield design involves detailed understanding of the thermal and magnetic conditions settings in space as well as of the effects of ionizing radiation on the human body over as sustained period of time. Before SR2S, most of the effort in this research field was spent on the analysis of the effect of the sole magnetic field. In SR2S we studied the various aspects of the superconducting magnet including the mechanical structure.

In order to consider SR2S not just a ground-breaking idea, the key technologies needed for the development of the active, space born, magnetic shield had been assessed and partially validated. Building upon those technologies, the SR2S project will paved the way for a practical solution to this complex problem and provides a roadmap for future technical progresses needed to develop the active shield technologies. SR2S should be the foundation to develop the necessary protection for future human space exploration.

Main Objectives

The mission of the SR2S project is to demonstrate the feasibility of an active magnetic shielding technology to protect astronauts from radiation in the space environment by using superconductive technology.
The mission of SR2S project translates into the following scientific and technical objectives:

• OB1: Defining Space Exploration Mission / System Requirements, including the definition of the complete space radiation environment experienced during the deep space travel and the staying on the exploration target planets.

Space Exploration Mission has been defined together with the possible human mission scenarios to which an active shielding system technology may be applied, with particular attention on long-term missions beyond LEO, where the contribution of radiation shielding from Earth's magnetosphere drastically reduces or becomes null.

The radiation shielding requirements have been defined to drive the design phase.

The radiation environment for the SR2S reference mission has been defined, as one of the fundamental input to Monte Carlo radiation analysis to determine the dose and dose reduction within the spacecraft.

• OB2: Identifying criteria for determining the effectiveness of shielding the human body from radiation effects that are recognised as valid by radiation protection community, based on risks to the crew.

Space Radiation Dose Simulations used the ICRP123 guidelines to provide results on the effective dose using both ICPR and NASA quality factors.

• OB3: Implementing the use of the most up to date Space Radiation Dose Simulation Tools that can effectively support trade-off analyses for selecting the preferred radiation shielding concepts and the following design phase.

Implementation of the most up to date Space Radiation Dose Simulation Tools through the use of GEANT4 and GRAS, as well as other interface software like MCIPY. Such instruments had a fundamental role in the iterative process of the design of the active shielding configuration.

Extensive effort was devoted into the implementation in Monte Carlo simulations of the complete space radiation environment experienced during the deep space travel. Several models have been checked (CREME96, CRÈME86, ISO-15390, NYMMIK) to see if there was any relevant difference into dose reduction calculation. As a result, ISO-15390 was chosen as model to be used in the simulations for the CGR environment at minimum (resulting therefore in a worst case scenario).

• OB4: Design a radiation protection system based on the provision of a Magnetic Shield and identify the critical technologies involved.

A complete conceptual design have been realized for two different kind of toroidal configuration (axial and non axial) using an iterative process which involves as first the magnetic and preliminary mechanical design, then the radiation dose simulation and finally the mechanical design. In such process, involved critical technologies were identified. In particular, the superconducting cable, the winding process, the thermal system and the cryogenic system.

Among the critical technologies, two of them (superconducting cable and pulsating heat pipes) were deeply studied and their TRLs were increased from 2 to 4.

• OB5: Develop a set of Technology Validation Units for validating these critical technologies and upgrading their TRL.

A set of technology validation units has been developed:

o A racetrack coil and a pancake winding of the superconducting cable have been build and tested: both windings are superconductive even if the maximum measured current values were low compared to the critical current of cable short samples. The test results showed that the choice of the winding technique and of the bending radius were correct,

o PHP (Pulsating Heat Pipe) experiment realization and verification: PHPs are almost 4 m long and are cooled by a 175 W nitrogen cryocooler. The cryostat used for this experiment is about 6 m long and has a heat shield.
1 m inner diameter. The PHPS have been tested at the nitrogen temperature but the experimental conditions did not allow to maintain a permanent heat transfer so far but the first results we obtained make us optimistic about the issue of the experimental session o LHP (Loop Heat Pipe) verification, using LHPs from the AMS-02 experiment: LHPs work in the expected regime
Tests have been performed at CERN, CEA, CGS and INFN-Genova facilities, with positive results
• OB6 Define a Roadmap for the further development of such technologies up to their full suitability to be employed in a space mission.
A Roadmap for further development of such technologies up to their full suitability to be employed in a space mission have been implemented and provided. The main milestones, for the active shield, are a further optimization in shape, dimensions and materials an activity of research and development in order to improve the performances. As regards the cryogenic and thermal system, a deep study of integration with the active shield is foreseen.
• OB7 Implement a set of effective Dissemination & Exploitation activities, to increase the impact of the project results.
Facebook, Youtube, Twitter are used as social medias, while the project website (www.sr2s.eu) is constantly updated. Medias, like posters, pictures and videos have been made or filmed with partners collaborations. Exploitation activities have been identified and two of them have already started as INFN projects for future scientific missions: at feasibility level, one consists in using the SR2S technology and the gained expertise for a magnetic diverter to be installed on the Athena telescope, the other in designing a new particle spectrometer to be sent to space for studying antimatter and dark matter.

Project Results:
Main S&T results/foregrounds
Overview
The SR2S project achieved successfully all the objectives, providing a complete conceptual design of a superconductive active shield for space manned missions and identifying the environment it has to operate in. The Space Exploration Missions have been defined, including the definition of the complete space radiation environment, as well as the system requirements.
Criteria for determining the effectiveness of the shielding for the human body from radiation effects have been implemented using the state-of-the-art ICRP123 guidelines. Such criteria have been used to test the conceptual design with the most up to date Space Radiation Dose Simulation Tools (GEANT4 and GRAS), simulating for the first time complex magnetic field and detailed geometrical structures. The simulation results drove the structural design.
The structural analysis was performed on the most promising configurations pointed out by Monte Carlo analysis. In order to consider SR2S not just a ground-breaking idea, but a concrete future solution, the design of realistic magnetic shields have been studied. The shield design involved also a detailed understanding of the thermal conditions. A cryogenic system was studied, able to intercept heat flux coming from the Sun (and eventually planets) and from the human habitat (HAB). Due to the complexity of the project and its high degree of innovation, the SR2S feasibility was evaluated also in terms of safety, that could be one of the main showstoppers for the magnetic shielding.
Many efforts were dedicated to develop a set of Technology Validation Units. The lightest superconducting cable has been designed and produced at industrial length and with good properties in terms of critical current. Two coils have been build and tested: results shows the feasibility of using such cable for
A new, long PHP (Pulsating Heat Pipe) has been designed and built and can be used for cryogenic apparatus. The LHP (Loop Heat Pipe) technology had been validated in the SR2S context, using LHPs from the AMS-02 experiment. Disseminations and exploitation activities reached a vast audience, with more than 2,000 people following the SR2S activities on social networks and project presentations.

Potential Impact:
The SR2S innovative active shield configuration
The future human exploration of Solar System depends on many technological challenges. Cosmic rays biological effects are one of the main showstoppers and the SR2S project aims to assess the feasibility of a space radiation superconducting magnetic shield.

During the project, different magnetic configurations were examined and compared. Monte Carlo simulations were used to assess their effective shield capability. After a trade-off analysis, it was decided to focus on a toroidal shield: a large toroid is placed around the spacecraft habitat and the endcaps shielded passively or with a proper smaller toroid.

In SR2S simulations, the team applied a new approach considering the combined effects of the magnetic field and of the materials composing the system (magnet, spacecraft and supporting structures). The analysis of simulation results led the team to reach one of the main SR2S scientific achievements, about the contribution of the secondary particles on the adsorbed dose. Monte Carlo simulations have shown that both high energy heavy ions and protons coming from galactic sources interact with the materials of the active shield generating showers of secondary particles, including neutrons which are not deflected by the magnetic field. The effect of these particles on the dose is not negligible and affects the effectiveness of the shield respect to the high energy region of the spectrum.

As results analysing the scientific literature, the effect of the secondary particles was never taken into account in previous works and consequently the effectiveness of the magnetic shields was overestimated. After this observation was confirmed, it was clear that the radiation dose does not depend only on the shielding power (i.e. magnetic field time magnetic length), but also on the active shield design choices. Simulations were therefore necessary in order to have a continuous feedback on the design.

The first attempt to deal with this discovery was to decrease the total structures mass \( B_1 \), but it has been shown that this was again not sufficient to drastically improve the magnetic shielding efficiency. The same conclusion was reached even when increasing the shielding power from 7.9 Tm to 11.9 Tm \( B_2 \). Realistic simulations revealed that the increase of shielding power is useless if it is not coupled with an appropriate choice of the materials and their geometrical distribution in order to limit, as much as possible, secondary particle production.

The SR2S project subsequent step was design new magnetic configurations. The new configuration developed in the second period of the project, is still based on toroidal coils but arranged in non-axial geometry (the toroid axes are perpendicular to the spacecraft axis). It is called pumpkin configuration and provides a quite “transparent” and light magnetic systems, avoiding excessive generation of secondary neutrons. Differently from the previous configuration (large toroid surrounding the habitat, co-axial with the spacecraft) it does not require a huge inner mechanical structure to support the inward magnetic pressure.

Two different pumpkin structures were studied, the former with three (MT3) and the latter with four toroids (MT4), located around the habitat module. This configuration is very promising, and the simulations results shown an increase of the shielding efficiency for both MT3 and MT4.
In order to evaluate the efficiency of each configuration (B1, B2, M13 and M14), it was important to distinguish between the contributions to the dose reduction due to the magnetic field and the one due to the mass distribution.

A first realistic study
It can be said that SR2S represents a first realistic study where active shielding were considered from an engineering point of view.

In the first period of the project, the team focused the analysis on axial toroidal configuration (Figure 1(a)), where the axis of the toroidal magnet is the same axis of the habitat. The result of the Monte Carlo simulations in the second period, led to focus the project effort the non-axial toroidal configuration (nicknamed “pumpkin configuration”), where the axis of the toroidal magnet is perpendicular to the axis of the habitat (Figure 1(b)).

On the base of the Monte Carlo results, the team developed detailed specifications and designs of a realistic configuration, able to operate continuously and reliably in space. It was clear that the effect of the interaction between galactic cosmic rays and matter had to be careful taken into account. Weight, size and modularity became essential aspects in SR2S. The mass had a great role in the system design, not only for the limit of the payload, but also because of the interaction of the galactic cosmic rays with the materials: limiting the mass means limiting the secondary particles with a positive effect on the dose (lower dose).

A possible solution, which has still many margins of optimization, has been finally identified as a non-axial toroidal configuration (named pumpkin configuration for the shape of the magnetic field it generates). Such configuration, allowing the magnetic field being unconfined outside the spacecraft (and null inside), is very transparent to radiation, avoiding the massive production of neutrons as secondary particles and increasing the effectiveness of the shielding by the magnetic field.

Considering the mass budget, the highest mass of the coils toroidal structure is due to the conductor (30 tons), while the covering structure results very lightweight thanks to the used of the honeycomb. Also the main structure results in a relative lightweight component. The mass of the whole system composed by four toroidal magnets and the main structure is around 50 tons. This represents a great improvement with respect to the other configurations studied in the project. This result can be considered as a starting point for the future developments, where the mass could be cut down even further, using new and innovative materials.

The structural concepts for a system which requires assembly operations in orbit were studied and defined on the pumpkin configuration. Due to the large volume of the whole structure, the choice is to launch the four magnets into space in two launches, depending on the future launcher.

Given the size and mass of the SR2S system it is necessary to perform in orbit its integration to the
vehicle. A possible scenario has been outlined, under the assumption of using a large launch vehicle, the SLS Block 1. This vehicle could accommodate under its fairing 2 of the 4 SR2S toroids already in the deployed 3 coils configuration, avoiding complex in-orbit assembly of each single coil. The two modules will be installed one above the other. Dedicated structural adapter will be necessary to carry the upper module and the lower module. It is assumed that the spaceship is already in LEO and it is habitable so that a crew for the integration of the SR2S can be hosted for some time (not necessarily the same crew which has to perform the final mission).

Moreover by the safety point of view, in the pumpkin configuration the magnets don’t act loads towards the habitat, providing a safer configuration. A failure on the superconductivity state has an impact only in the reduction of the protection and not on the habitat structure. The safety and FMECA analysis was performed and it had identified hazardous conditions associated with the SR2S subsystems, that might damage equipment and/or cause injury to personnel. All precautions to be respected to mitigate the risks of occurrence had been defined.

4.1.3.4 Key enabling technologies

In order to consider SR2S a concrete future solution, the key technologies needed for the development of the active magnetic shield had been assessed and validated.

A light, reliable conductor based on MgB2 embedded in a titanium matrix was developed. Long length prototype Ti-MgB2 tapes (100 m and 360 m long) were produced. A procedure to produce the conductor (Ti-MgB2 tape + Al strip) was defined. A demonstration unit of the racetrack coil has been realized, using an innovative conductor suitable for active shield applications.

Other fundamental key technologies are related to the thermal control system. A new, extra-long PHP suitable for space cryogenics was also demonstrated, and the use of LHPs was consolidated and validated.

In particular a fundamental SR2S technological achievement regards to the development of the conductor, that led to the production of about 360 m long titanium clad MgB2 tape, which is the base for manufacturing of the cable breadboard unit. The performances measured on short samples of this conductor are very good and encouraging.

FIGURES IN THE PDF DOC

The thermal control system is another key technology, fundamental for the functioning of the active magnetic shield. The superconductive coils need a very cold environment in order to offer almost no resistance to the passage of electrical current and maintain a strong magnetic field around the spacecraft: this is achieved by a dedicated cryogenic thermal control system (TCS), able to keep the magnet at 10 K. For that purpose, a cryogenic system was proposed, able to intercept heat flux coming from two sources: the Sun and eventually planets and the human habitat (HAB). An innovative solution was carried on during SR2S, involving passive solution using long cryogenic pulsed heat pipes (PHP). These devices are two-phase heat transfer devices that rely on the oscillatory flow of liquid slugs and vapor plugs in a long miniature tube bent into many turns.

In order to evaluate the thermal performance of the PHP cooling system, a conceptual design of cryogenic fluid recirculation technology validation had been performed, including the construction of an experimental facility. The results were very promising and encouraging.

FIGURE IN THE PDF DOC
The results were very promising and encouraging since we have measured that a 3.6 m long PHP made of 36 tubes of 1.5 mm in diameter can exhibit an equivalent thermal conductivity of 105 W/m.K in stable oscillating operation over 1 hour. This PHP is the longest ever tested whether the working fluid is cryogenic or not (cf. figure 6).

FIGURE IN THE PDF DOC

A thermal control system is needed also for the cryogenic system, in order to to keep the cryocoolers helium compressors within their operational temperature range, transporting and rejecting the high dissipated power to the ultimate sink, the deep Space. Many solutions had been studied for transporting and rejecting high waste heat. Analysing performances and the advantages of a purely passive device, the Loop Heat Pipe (LHP) had been selected and validated, in order to assess of the Loop Heat Pipe (LHP) capability and flexibility in the framework of SR2S project.

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Building upon those technologies, the SR2S project will pave the way for a practical solution to this complex problem and will provided a roadmap for future technical progresses needed to develop the active shield technologies. If successful, SR2S will be the foundation to develop the necessary protection for future human space exploration.

Addressing the challenge embodied by the magnetic shield will also open the opportunity to provide technology for superconducting magnet that could have an important impact for example in the sanitary field and in electric energy production as well as in scientific payloads and satellites.

The roadmap
While we have found a new approach to the active protection with respect to the existing literature, we do not consider MT4 as the ultimate, optimized result. A systematic exploration could be carried on various kinds of “not fully confined” magnetic field configurations and geometrical coil layouts, which could deliver a similar or better result. The fractional contribution to the dose reduction due to the magnetic field suggests that there are “gaps” in the magnetic coverage, therefore the number of pumpkin coils can be increased/optimized. The mass of the coils could be further reduced by refining the optimization of the coil geometries and by applying advanced structural materials, whose cryogenic properties are not yet known. Further steps of technical and conceptual developments have been identified and collected in the following SR2S roadmap:
- Increasing the TRL of the conductor (the SR2S prototype production allowed identifying the main issues);
- Optimization of the Active Shield configuration :
  • improving the pumpkin configuration in terms of number, shape, dimension and total current of coils as well as of their distance from the habitat
  • studying new and innovative “not fully confined” magnetic field configurations and geometrical coil layouts, which could deliver a similar or better result;
- Deepen the knowledge of light structural materials. Within SR2S we proposed the use of many advanced materials but the cryogenic properties of most of them are not well known;
- Further development of the magnet cryogenics including enhancing of PHP THL;
- Explore new solutions for quench detection and protections (non-insulated winding);
- Study of ancillary equipments like power supply or flux pump;
- More detailed studies of the shield assembling in orbit.

List of Websites:
http://www.sr2s.eu/

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