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Cryogenic design of a large superconducting magnet for astro-particle shielding on deep space travel missions

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Abstract

The Space Radiation Superconducting Shield (SR2S) European project aims at studying a large superconducting toroid magnet to protect the human habitat from the ionizing radiations coming from Galactic Cosmic Ray during long term missions in deep space. Titanium clad MgB2 conductor is used to afford a bending power greater than 5 T.m at 10 K. A specific cryogenic design is needed to cool down this 10 m long and 12.8 m in diameter magnet. A passive cooling system, using a V-groove sunshield, is considered to reduce the heat flux coming from the Sun or Mars. An active configuration, using pulse tube cryocoolers, will be linked to the 80 K thermal screen intercepting most of the heat fluxes coming from the human habitat. The toroid magnet will be connected also to cryocoolers to absorb the few watts reaching its surface. Two kinds of thermal link are being considered to absorb the heat on the 80 K thermal screen. The first one is active, with a pump circulating helium gas in a network of exchange tubes. The second one is passive using long cryogenic pulse heat pipe (PHP) with the evaporator on the surface of the thermal screen and the condenser attached to the pulse tube.

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Keywords: Space radiation shield; Supercondutor; MGB2; Sunshield; PHP;

1. Introduction

During future long term missions in deep space, the astronauts without protection will receive a large amount of space radiation. The dose received represents a serious health problem. The SR2S project is one of the active shielding strategies, using a large toroid superconducting magnet (10 m long and 12.8 m in diameter), that have been

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proposed to protect the crew during a journey to Mars (Fig. 1) (Musenich 2014). This paper presents the conceptual cryogenic design for the SR2S magnet. This large magnet receives heat flux from the Sun and eventually planets on one hand and from the human habitat on the other hand. These fluxes have to be intercepted to maintain the MgB_2 magnet in its superconducting state at 10 K.

Concerning the thermal interception of the heat flux impacting the external side of the magnet (Sun and planets), a passive cooling technic has been chosen, usually used for space devices like satellites. This system mostly uses the deep space temperature to reduce the thermal fluxes coming from space. We present in this paper one configuration of the sunshield placed around the magnet to intercept the large amount of the heat flux coming from the Sun and Earth/Mars. Moreover, a solution with an 80 K thermal shield linked to pulse tube cryocoolers has been studied to absorb most of the heat flux coming from the human habitat. Two configurations have been studied to absorb the heat flux on the surface of the 80 K thermal screen: one active with a pump moving helium gas and another one using pulsating heat pipe (PHP). This last configuration requires some R&D that is under progress.

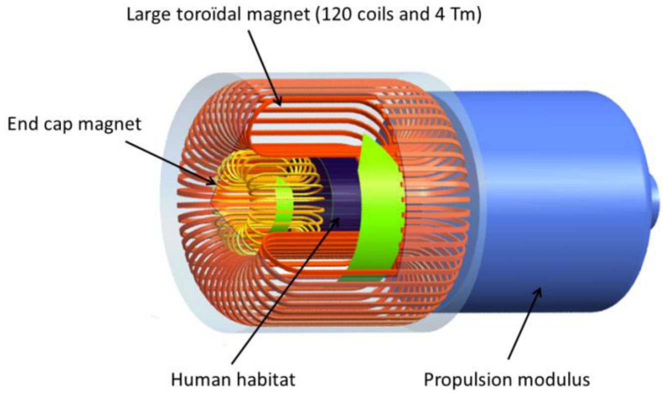

Fig. 1. Design of the SR2S project

2. The passive cooling system: the Sunshield around the magnet

2.1. Flight characteristics and design

During a journey to Mars, the external surface of the magnet receives fluxes coming from the Sun and the Earth or Mars. Without any protection, the magnet would receive about 200 kW with a maximum temperature of about 400 K at its surface.

A sunshield made of V-groove layers is generally used in space applications to reduce the impact of the solar heat fluxes. The V-groove shield is made of different reflective layers oriented with different angles to each other allowing a better extraction of heat radiation at each layer and the deep space temperature helps cooling down the different layers that compose the sunshield. This solution has been used on the Planck and the Webb telescope (Moery 2006). Each layers is made of Kapton® covered with aluminium (emissivity=0.1). The equivalent emissivity for n V-grooves having an emissivity of ε is ε^n (Meseguer 2012) compared to ε/n for Multi-Layer Insulation system (MLI) (Fig 2).

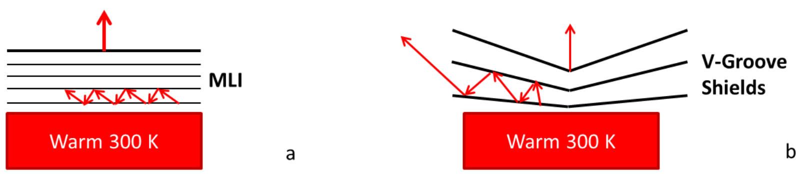

Fig. 2. (a) MLI and (b) V-groove sun shield design

For the Webb telescope, the first layer (the one which directly faces the Sun) is covered with an Optical Solar Reflector (OSR) to reflect most of the heat flux coming from the Sun and Mars (about 90%). A sunshield configuration surrounding the magnet and using multiple V-grooves has been chosen as the passive technique to significantly reduce the amount of heat flux that reaches the surface of the magnet. The conceptual design of the sunshield is depicted in Fig. 3.

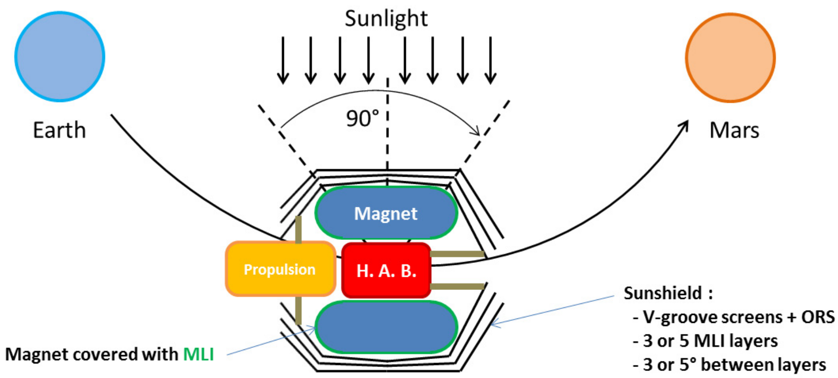

Fig. 3. Scheme of the SR2S V-groove sunshield design during it flight to Mars

2.2. Heat radiation calculations using Fluent®

One calculation has been performed using ANSYS Fluent v15.0 radiative S2S solver to estimate the heat fluxes absorbed by a sunshield made of 3 V-grooves MLI layers (3° angle between layers) with the first one covered with OSR (absorption = 0.1 and emission = 0.86). The temperature of the space environment is considered to be at 7 K and the heat fluxes coming from the Sun is 1371 W/m². The thermal conductivity between each V-groove layer has been neglected. The temperature on the external surface of the sunshield and the total heat fluxes reaching the magnet at 10 K are shown on the Fig. 4.

In this configuration, the heat flux reaching the surface of the entire magnet is about 10 W making it a very efficient passive cooling system. It has been chosen to consider a heat flux 10 times higher for the design of the cryogenic system which is the safety regulation for space devices.

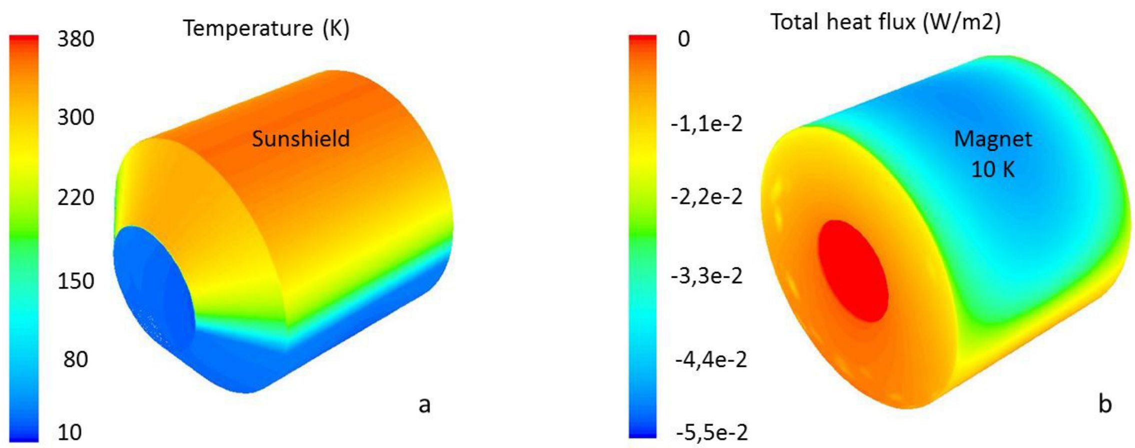

Fig. 4. (a) Temperature at the external surface of the sunshield; (b) Total heat flux at the surface of the 10 K magnet

3. The active cooling system inside the magnet

3.1. The 80 K thermal shield and cryocoolers

An 80 K thermal screen has been placed to intercept a large amount of the heat fluxes coming from the human habitat at 300 K. This thermal screen is made of aluminium panel 2×2 m² wide and 0.01 m thick to minimize the effect of the eddy current during current loading or in case of quench. The entire panel is 7 m long and 4.2 m in diameter (arbitrarily placed in middle between the human habitat Ø=4.1 m and the magnet $Ø_{inside}$=4.3 m) and covered, on its internal side, with MLI (10 layers) to reduce the heat fluxes reaching it. The magnet is also covered on the internal side with MLI. Performance of such MLI is about 1 W/m² from 300 to 80 K and 0.1 W/m² from 80 to 10 K (Barron 1999). With this configuration, the 80 K thermal shield and the entire magnet received respectively about 100 W and 10 W.

Some mechanical supports with low heat conductivity like G-10 glass-fiber/epoxy composite are needed to attach the human habitat to the 80 K thermal screen and to the magnet. The magnet is planned to be assembled in orbit and the maximum acceleration during the flight to Mars is about 0.1g. An acceleration of 1 g has been chosen to maximize the impact of the conductive heat flux reaching the magnet. It represents 9 W on the 80K thermal shield and 0.9 W on the magnet.

These heat loads have to be absorbed by an active cryogenic system. According to references about cryocoolers in space applications (Ross 2006), it's the first time that such a large structure is needed to be cool below 40 K. For this conceptual design, calculations have been performed using the characteristics of pulse tube cryocoolers that are developed for ground applications. These could last longer than Gifford McMahon and are not affected by microgravity. The pulse tube, when developed; should be able to absorb 50 W at 80 K on its 1st stage and 4 W on its 2nd stage at 10 K. Due to the size of the magnet compared with the size of the possible rocket that is supposed to bring it in space, it has to be divided in four parts. Considering this 4 launches configuration, 8 pulse tube cryocoolers will be needed to absorb the 100 W on the 80 K thermal shield and the 20 W on the magnet at 10 K (10 W from the habitat and 10 W from the sun and Earth/Mars). On earth, the compressor associated to the pulse tube cryocooler is usually connected to a water cooling system. In deep space, loop heat pipes, filled with refrigerant gas and connected to radiators, are used and are capable of extracting the 4000 W heat loads using the deep space temperature as a cold source. The Fig. 5 summarizes the cryogenic design of the SR2S magnet.

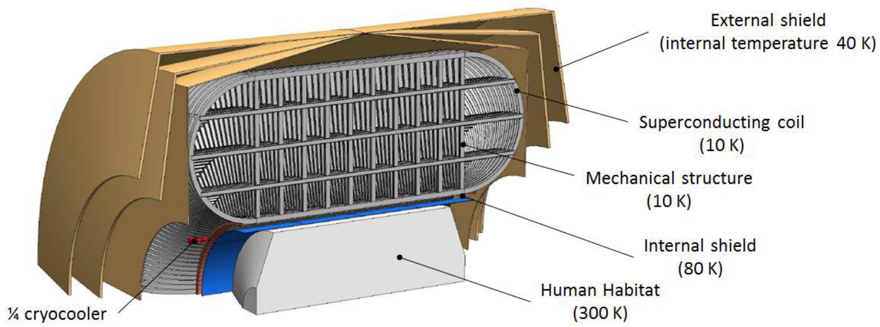

Fig. 5. ¼ of the SR2S magnet with the HAB and the Sunshield

3.2. Thermal links

The cold mass of the magnet will be connected directly to the second stage of the pulse tube cryocoolers. The material used for the mechanical structure surrounding the magnet is still under investigation. Thermal calculations with a Comsol® solver have been performed on one of the 120 coils constituting the SR2S magnet. The cryocooler cold parts working at 9 K are modelled in contact with the lower part of the structure (near the human habitat) on both side of the magnet (cf. Fig. 6. a). The temperature at the surface of the coil are shown on Fig. 6 b. Using pure titanium, the thermal characteristics of the structure of the magnet are sufficient to absorb the 20 W without the help of any specific thermal link (ΔT_{max}<1 K over the structure). With titanium alloy, the maximum ΔT is about 7 K. For the moment, it has been considered that no thermal links are needed to cool down the magnet itself.

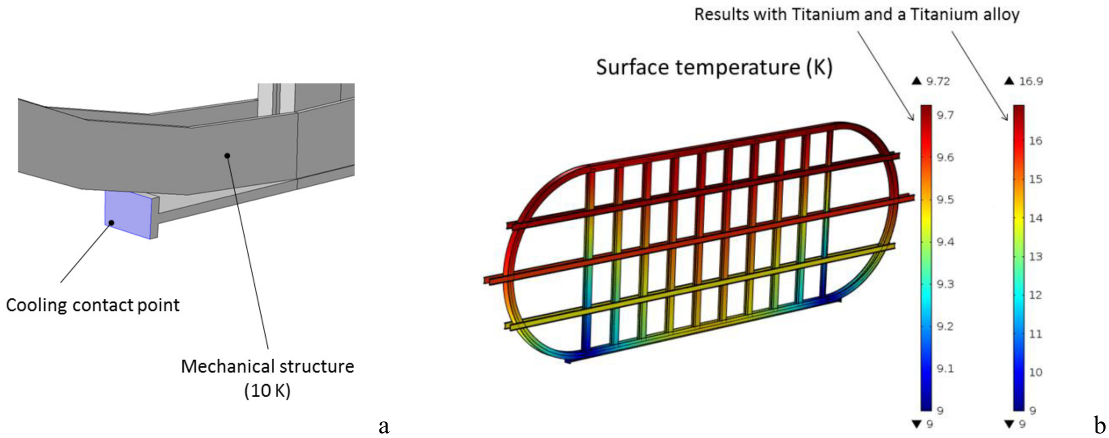

Fig. 6. (a) Position of the thermal contact with the cryocooler; (b) Temperature at the surface of one of the 120 coils of the SR2S magnet

On the contrary, some thermal links are needed to cool down uniformly the 80 K thermal screen. Two kinds of thermal link are being considered.

The first one is active, with a pump circulating helium gas in a network of tubes. The 80 K thermal screen is 7 m long, 4.4 m in diameter and 0.01 m thick cylindrical shell. The temperature difference developed by heat conduction in this shell must remain below a limiting value, around 10 K, to ensure a constant thermal configuration on the entire shield. The heat exchanger attached to the surface of the 80 K thermal screen would be made of multiple tubes in which helium gas will be circulating. The maximal temperature difference between each horizontal tube is chosen to be 5 K. To maximize the exchange between the helium gas and the surface to cool-down, the number of horizontal tubes is 16 for a 4 launches configuration, with cryopumps moving the fluid inside the 0.01 m inner diameter aluminium tube constituting the heat exchanger. The Tube size chosen represents a good balance between the available space, between the thermal screen and the magnet and low pressure drop in the exchanger. To reduce the speed of the flow inside the system and to ensure sufficient mass flow rate to extract the 100 W on the entire panel, the pressure of helium gas has been fixed to 20 bars. According to the logarithm mean temperature difference with a maximum temperature difference of 5 K between the helium circulating at the entrance of the heat exchanger and it surface, the minimum mass flow rate of this system is about 5 10^{-3} kg/s. The mass flow rate chosen is two times more important, about 10^{-2} kg/s for safety reasons. The pressure drop due to friction of the fluid and the pump are 0.4 bars. Only 4 commercial cryopumps are needed in this configuration (one for every part to be launched in space) and the extra heat due to the heat load of the pump (around 10 W) would be absorbed by the 1st stage of the cryocooler. This active thermal link technique is a well-known solution. The main risk of this active thermal link is the use of moving part that can be broken during the long journey to Mars.

The second thermal link option envisaged is a passive solution using long cryogenic pulse 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 our case, the condenser part of the PHP would be fixed to the 1st stage of the pulse tube cryocooler and the evaporator to the 80 K thermal shield (Fig. 7). In cryogenic engineering, only small PHP have been tested (30 mm length for the evaporator and condenser and 100 mm for the adiabatic part) and the equivalent thermal conductivity of this system can reach 44 kW/(m.K) (Jiao 2009) at 80 K using nitrogen. In comparison, the thermal conductivity is 60 W/(m.K) for aluminium 5083 and 500 W/(m.K) for Copper with RRR=100 at 80 K. Furthermore, experiments at ambient temperature show no effect of the gravity when using more than 40 turns (tubes) PHP (horizontal PHP) (Zhang 2008) and, in parabolic flight, pulsating heat pipe shows better performance in reduced gravity than in normal or hypergravity (Gu 2004). An experience has been done on long

PHP (Okazaki 2012) (2 m length for the evaporator and condenser and the adiabatic part) at ambient temperature. The equivalent thermal conductivity is important with 18.7 W/K for 150 W heat input with 16 turns at 300 K and the PHPs have a low sensitivity to the orientation. Even if the results given by these experiments seem promising, a R&D program will be launched to study the thermal efficiency of several meter long PHP as a thermal link for the SR2S project.

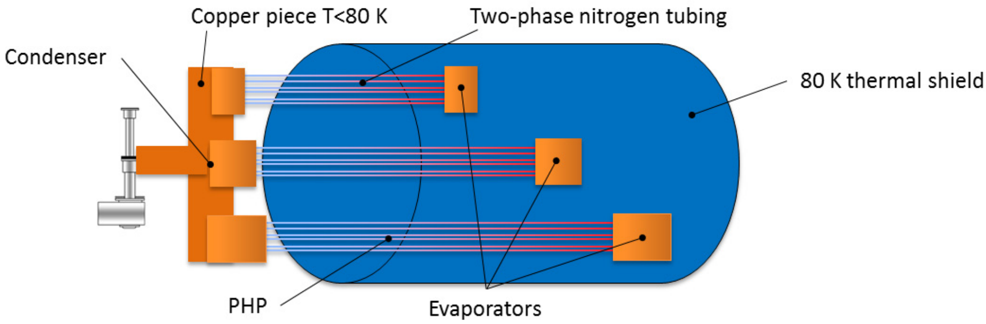

Fig. 7. Scheme of the passive thermal link using PHP on the 80 K thermal shield

4. Conclusion

This paper presents the conceptual cryogenic design for the SR2S toroïdal magnet. Concerning the passive cooling for the external thermal fluxes, one configuration has been numerically studied with a V-groove sunshield placed around the magnet to significantly reduce the solar heat load during the flight to Mars.

Pulse tube cryocoolers attached to an 80 K thermal shield and the magnet intercept the heat fluxes coming from the human habitat. Some thermal links, active using pumps or passive using PHP are studied to absorb uniformly the heat on the surface of the 80K thermal screen.

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