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OPTIMIZATION OF SUPERCONDUCTING COILS FOR SOLAR COSMIC RAYS PROTECTION DURING INTERPLANETARY MISSIONS

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Abstract

During manned interplanetary missions, it is necessary to protect the crewmembers from the high energetic solar cosmic rays, mainly protons. A feasible solution consists of an active shield by means of a superconducting magnet. This magnetic lens is able to deflect the almost unidirectional solar cosmic rays away from the zone that can be occupied by crewmembers. Our study indicates that an air core toroid with inner diameter of 0.5 m and outer diameter of 3.5 m and a peak field of 2.80 T is suitable for astronaut protection. In this paper the detailed magnetic, mechanical and thermal design is presented, and different configurations for the superconducting coils are compared in order to find the most efficient and convenient solution in such a complex environment.

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1. INTRODUCTION

In the human exploration of the Solar System by manned missions, the problem of the protection of the astronauts from the cosmic ionizing radiation must be solved. The advantage of using a magnetic active shielding for the protection from the solar cosmic ray (SCR) components has been advanced and discussed in previous papers [1],[2].

A solution composed by a superconducting magnet that produces a toroidal field has been presented elsewhere [3]; the main characteristics of this system are summarized in the following items:

1. The coils are “D” shaped in order to optimise the mechanical stress of the coils and reduce the mechanical structure necessary to withstand the magnetic forces.
2. The superconductor can be either in NbTi or in Nb_3Sn. The mechanical and magnetic design of the magnet doesn’t vary in these two cases. The thermal analysis is slightly different because NbSn allows an operating temperature about 3 K higher than NbTi.
3. The cold mass is cooled indirectly by a cryogen-free system. In this way the problem and the risk of storage (and possible lost!) of large quantity of LHe are avoided.
4. The cold mass of the magnet is protected by the external thermal radiation with two thermal shields: the inner one is actively cooled, whereas the external shield (the “radiation shield”) is a passive system.

In the following paragraphs the magnetic and thermal design of the magnet is discussed in detail with special emphasis in the design optimisation in order to minimize the cooling power and the total mass of the whole system

2. MAGNETIC DESIGN

A toroid is certainly the most efficient configuration for the deflection of SCR; in fact when protons are coming along the toroid axis, the deflection force, is always very effective,. Moreover the field inside the toroid decreases vs. the increasing of the distance from the toroid axis ($B \div 1/R$); consequently the protons at lower radii are more deflected than the protons at higher radii, exactly as it is required. The zone that needs to be shielded is assumed to be a cylinder 4.5 m long and with a diameter of 2 m, and it is centered respect the central axis of the toroid.

Some preliminary studies [1],[2] have considered a toroidal field which can be produced by a magnet with 4 coils with race-track and circular shape. This type of magnet presents the advantage of making construction simple, but on the other hand it requires a mechanical structure to withstand the magnetic forces that tends to deform the coils. Moreover the toroid with circular shape has poor deflection efficiency at low radii, because the path in the magnetic field of the protons is short at low radii. The Table I reports the main parameter of this type of toroid with circular shape.

Fig. 1 is a representation of the trajectories of protons with the action of the toroidal field. The zone with $R<Rmin$ is assumed to be protected by passive absorber (instrumentation for fast electron detection) positioned in the central hole of the toroid.

In order to increase the protection efficiency, it is necessary to increase either the maximum magnetic field and/or the radius of curvature of the coils, with a consequent increasing of the external diameter and mass of the magnet.

TAB. 1: Main parameters of toroid with circular cross section

Parameter	Value
Rmin	0.25 m
Rmax	2.0 m
ρ=(Rmax – Rmin)/2	0.875 m
NI	2.4E6 At
Bmax	1.92 T

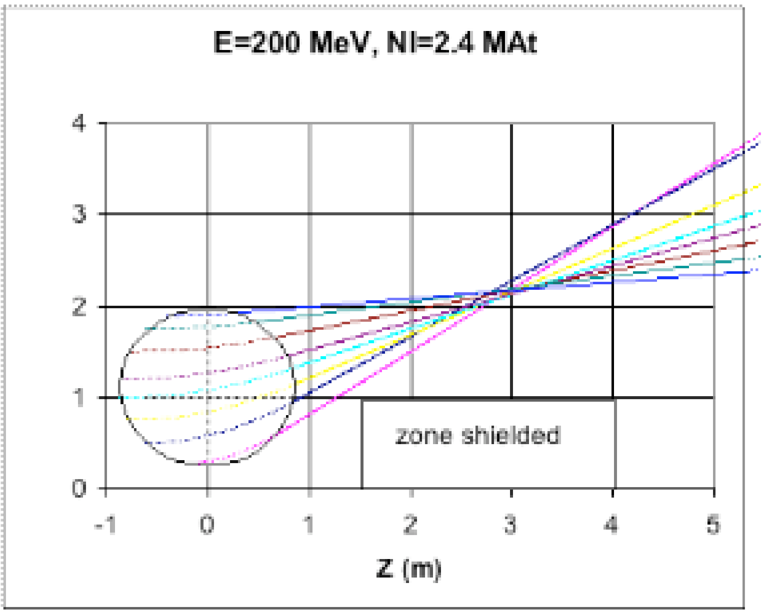

FIG. 1: Trajectories of monodirectional protons in toroidal field.

The magnetic pressure in the toroidal magnet can be countereacted by the simple tension of 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 [4]:

$$T = B \cdot NI \cdot \rho = \text{constant} \qquad (1)$$

where *B* is the magnetic field on the coil, *NI* the total current and r the curvature radius of the coil. Because *B* is not constant in the toroid, necessarily r has to vary too, and it assumes higher values when the distance from the toroid axis decreases; in this way the coils assume a " D " shape. In case of ideal toroid, the magnetic field varies like 1/R, where R is the distance from the toroid axis, and the following analytical relation can express *T*:

$$T = \frac{\mu_0}{4\pi}(NI)^2 Ln\left(\frac{R_{max}}{R_{min}}\right) \tag{2}$$

The choice of *Rmax* is given by the condition to intercept the trajectories of the protons in the zone that has to be protected. If we assume that the angular distribution of the proton trajectories is ±10° [2], the value of *Rmax* is 1.71 m.

The solution of an ideal toroid would require a continuous coil, all along the whole azimuth, with larger thermal loads for power radiation and larger mass for the magnet. For this reason a solution with a discrete and limited number of coils is preferable. In this paper we present a solution composed by 4 coils, symmetrically positioned at 90 deg. one respect the other. Again the curvature radius *R* of the coils has been chosen in order to fulfil the condition (1). In this case, the magnetic field on the conductor doesn't vary anymore like 1/R, like for an ideal toroid, but it changes more slowly: it can be estimated that the variation of B on the conductor is described by the relation:

$$B(R) = B_0 \frac{R_0^{\alpha}}{R^{\alpha}} \tag{3}$$

where the exponent a is a number between 0 and 1 that can be found with a best fit on the calculated values of B for the real case. With this assumption, the shape of the coil in the plane *Z – R* can be determined by the following differential equation:

$$\left(\frac{dR}{dZ}\right)^2 = \left[\frac{k(1-\alpha)}{R_0^{1-\alpha}}\right]^2 \left[\left(\frac{R}{R_0}\right)^{1-\alpha} - 1\right]^{-2} - 1 \tag{4}$$

where *k* is a parameter correlated to the tension *T* of the coil, which can be determined by *Rmin* and *Rmax* with the relation:

$$k = \frac{T}{B_0 R_0^{\alpha} NI} = \frac{R_{max}^{1-\alpha} - R_{min}^{1-\alpha}}{2(1-\alpha)} \tag{5}$$

The equation (4) has been solved numerically, and again the shape of the coil obtained has been used to re-calculate the exponent for a new best fit of the field with relation (3). By iterating this procedure it is possible to compute the shape of the coils that fulfils condition (1). The Fig. 2 reports the shape of the coil after three iterations, with a final best fit for *a*=0.60. In the same picture the shape of the ideal toroid with *a*=1 is reported for comparison. As it was expected, the dimension of the coil in the *Z* direction is sensitively reduced in the configuration with 4 coils, because the variation of the field on the coil is lower than in the case of ideal toroid.

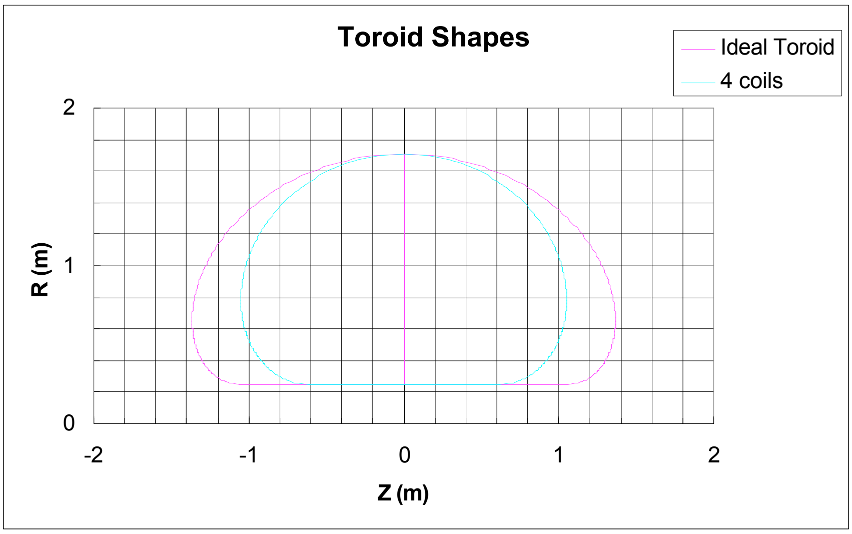

FIG. 2: Shape of D configuration for 4 coils and comparision of D configuration for ideal toroid.

The relation (4) has been deduced in the case of coils with cross section infinitely thin, whereas the real coils have a finite dimension. However we can expect that, if we choose for the central line of the coil the ideal profile calculated by integrating eq. (4), the transversal stresses of the other elements of the coil are limited and can be withstood by the stiffness of the coil itself.

The Fig.3 represents the protons trajectories in the worst situation, i.e. in the plane at 45 deg. between the median plane of two coils (where the field assumes the lowest values) and with the protons coming with an angle of –10 deg. The total current is 2.0 MAt.

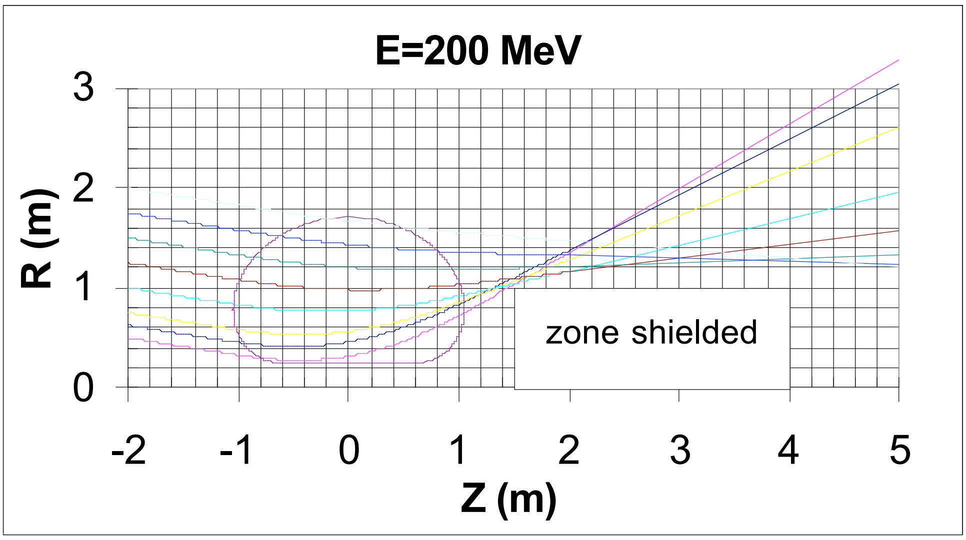

FIG. 3: Trajectories of protons in the plane between two coils, with an initial angle of –10°. NI=2.0 MAt in total. The coil profile is represented as reference.

In Table 2 the main geometrical and electrical parameters of the coils are reported.

TAB. 2: Main geometrical and electrical parameters of the coils.

Conductor cross section (w/o insulation)	2 mm × 2 mm
Conductor cross section (with insulation)	2.5 mm × 2.5 mm
Coil cross section	157.5 mm × 50 mm
Turn number	63 × 20
Max radius of coil cross section center	1.71 m
Min radius of coil cross section center	0.25 m
Average hoop stress on conductor	23.4 MPa
Current	397 A
Magnetic energy	2.3 MJ
Total conductor mass (w/o insulation)	280 kg

Two thin aluminium plates (5 mm thick) are glued on both the large surfaces of the coil: the function of these plates is to reduce the temperature gradient inside the coil, to induce back quench in the coils during a quench, and to have the mechanical connection of the structure necessary to the withstanding the magnetic forces and the weight of the coils before and during the launch.

3. THERMAL LOSS EVALUATION

The main sources of thermal losses are due to thermal radiation, thermal conduction through supports and suspensions and thermal conduction through the current leads. The temperature of the cold mass is 5.8 K or 9.0 K, depending by the choice of superconductor type (NbTi or Nb_3Sn). This point is still open because it doesn't affect sensibly the thermal evaluation and the magnetic design.

3.1 Mechanics of the suspensions and thermal design

We assume that the temperature in the space is 3 K, in a zone completely protected by the solar radiation. However the magnet will be partially exposed to the radiation coming from the sun, which can be estimated to be 1350 W/m2 [5]. In order to intercept this radiation, two thermal shields are foreseen: an inner thermal shield at 40-60 K actively cooled and an outer radiation shield not actively cooled. This last is also the outer since no vacuum chamber is necessary.

In Table 3 the main parameters necessary to the calculations are reported. They have to be considered as reference values, with an accuracy of 10%.

The dimensions of the two shields have been chosen in order to have a comfortable clearance of 7-8 cm between the cold mass and the thermal shield and between the thermal shield and the vacuum chamber.

TAB. 3: Values of the parameters necessary for thermal calculation. The values are referred for each coil.

Description	Symbol	Value
Emissivity of surfaces	ε	0.02
Cold mass surface	*Sc*	2.340 m^2
Thermal shield surface	*Ss*	5.391 m^2
Radiation shield surface	*Sv*	10.864 m^2

3.2 Thermal conduction through suspensions

The number, the shape and the material type of supports and suspensions in the cold mass and in the shields are determined by their mechanical functions; Two types of magnetic forces are present in the coils: a radial force that tends to collapse the coils towards the toroid axis; and the azimuthal forces due to a non perfect symmetry of the toroid.

Fortunately in the “D” configuration of the coil, the radial magnetic forces, that are about 2 orders of magnitude greater than the azimuthal forces, are present only in the straight part of the coils. Moreover, because the distance between two opposite coils is small (about 345 mm), it is possible to include all the 4 straight parts of the 4 coils in a single can, which will separate in a branch for each coil at the beginning of the bending. Consequently the suspensions necessary to react the radial force can connect directly the straight part of a coil with the straight part of the opposite coil, without cold-warm transition, with a great reduction of the thermal power introduced in the cold mass.

After some investigation we found out convenient using a “cold” structure also for the azimuthal forces in the coils. In this way the transition cold-warm of the support can be avoid, and the support can be completely made in aluminium alloy. Despite the fact that each one of these supports has to be surrounded by its own double shield, the thermal balance is very favorable for this support configuration.

One point that has to be remarked is that since we are in high vacuum (space helps, to this respect) and since there is no liquid, the inner can do not necessitate being vacuum tight with a great advantage for all construction, reliability and safety.

The connection of the cold mass with the external radiation shield is realized in the central zone of the toroid, by means of 4 tie rods per coil. These tie rods are about 650 mm long and made of carbon unidirectional fiber straps. The great vantage of the tie rods in the central zone of the magnet with respect to having the support in the bended zone of the coils, is that near the center of the magnet the movement of the structure due to the thermal contraction during the cool down, is much reduced respect the same movement in the outer radii of the magnet: in fact the fixed point for the whole system will be at the center of the magnet. Moreover the inclination and position of the tie-rods can be chosen in order to have the same tension of each tie-road at the ambient temperature and at the operation temperature. By taking in account the thermal contraction in the radial direction and in the Z direction (the direction of the axis of the toroid), it can be calculated that the optimal inclination is about 37° respect the normal of the toroid axis. The cross section of each strap is 16 mm^2, and the thermal and mechanical properties have been desumed by [6]. The Fig. 4 presents a cross view of the magnet, with thermal shield and radiation shield. The Fig. 5 represents an enlargement of the central zone of the magnet.

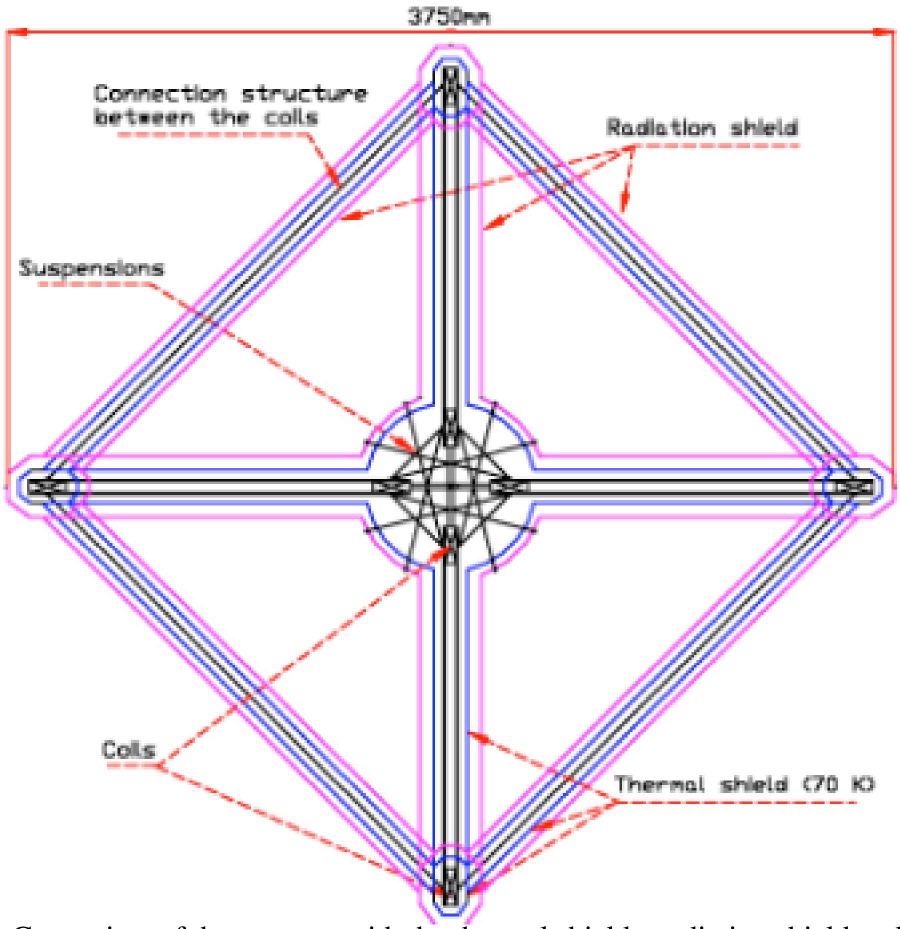

FIG. 4: Cross view of the magnet, with the thermal shields, radiation shield and suspensions.

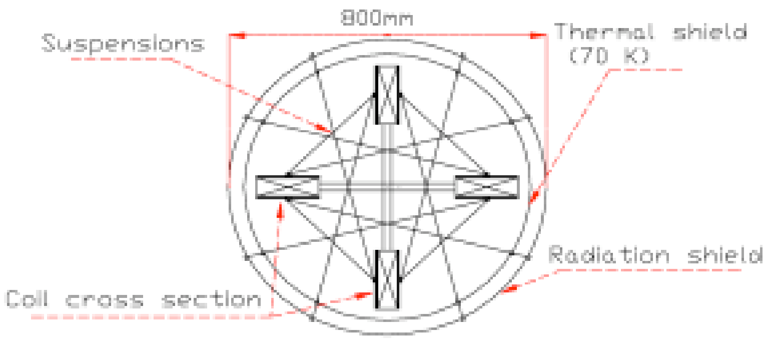

FIG. 5: Cross section of the central zone of the magnet, with the thermal shields, radiation shield and suspensions.

3.3 Thermal conduction through current adductors

In order to minimize the thermal load in the cold mass due to current adductors, high temperature superconducting adductors have been foreseen. The warm side of a HTS adductor is thermally linked at 60-70 K, and the value of power introduced in the cold mass is about 0.11 W/kA. The section between the thermal shield at 70 K and 308 K is normal conductive, and the "optimum length" design has been chosen [4]. During the normal working of the magnet the thermal contact of the adductors with the cold mass and with the external radiation shield will be removed, in order to eliminate the this thermal load after the charge of the magnet.

The total thermal power is reported in Table 4; different values are reported in case of the contribution of the current adductors (during the charge of the magnet) or without the contribution of the current adductors (steady state operation). Eddy current and other transient effect have been neglected at this stage, both because they can be kept smaller than the other and because the ramp can be very smooth, ~ 0.2 T/minute

TAB. 4: Summary of thermal load

Thermal load type	4 coils (steady state)	4 coils (During the charge)
Cold mass	(W)	(W)
Radiation	0.193	0.193
Supports	0.013	0.013
Current leads	0	0.09
TOTAL COLD MASS	0.21	0.30
Thermal shield (70 K)	(W)	(W)
Radiation	15.6	15.6
Supports	0.84	0.84
Current leads	0	36
TOTAL TH. SHIELD	16.4	52.4

5. POWER CONSUMPTION

Even if the thermal power consumption presented in Table 4 is very limited, there are not experimental values of efficiency and power consumption of cryocooling system suitable for space application with such requirements for the thermal loads. However we can expect efficiency similar to real system working on "the earth". The Table 5 reports the value of electrical power consumption, as obtained by actual cooling system [7]. The consumption at the plug are acceptable for important components of a space ship. Some 2 kW in the 15-30 minutes of the charge and 1 kW in steady state are well inside the capacity in spacecraft, although the removal of such power will deserve a study by its own.

TAB. 5: Summary of electrical power consumption (at plug).

Temperature (K)	Input power (W) (normal working)	Input power (W) (during the charge)
5.8 (NbTi)	480	690
9.0 (Nb_3Sn)	210	300
70 (Thermal shield)	340	1100

6. CONCLUSION

This study demonstrates the feasibility of an active system for the protection from SCRs, with relatively simply and state-of-art technique. The values of magnetic field and the operation temperatures allow the use of both NbTi and Nb_3Sn based conductor and the temperature range allows the use of a cryocooling system.

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