Radiation Shielding Using Magnetic Fields

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Abstract. Radiation shielding is essential to future space exploration missions with longer exposure to space radiation. High Atomic Number and Energy particles (HZE) in Galactic Cosmic Radiation (GCR) presents one of the most difficult types of radiation to shield. We propose a combination of active and passive shielding to maximize deflection of radiation and minimize production of secondary radiation, while creating a possibility of usable power. The focus of this paper is on the 7687 kg wire design and the 0.57 T magnetic field created, with less than 2 G in the crew area, and its ability to deflect a 2800 GeV iron ion. Estimates of trapped plasma reducing the iron ion to 140 GeV, as well as thrust production of 34 N are presented.

Keywords: Space Travel, Galactic Radiation Shielding
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INTRODUCTION

Radiation shielding is essential for all future space exploration. Interplanetary space is full of ionizing radiation that can interfere with sensors, on-board computers, and cause severe harm to astronauts.[1] It is imperative that a method be developed to limit all types of ionizing radiation. Many ideas have been proposed using passive shielding, wire loops, and plasma, but none have been demonstrated to adequately shield against high energy Galactic Cosmic Radiation (GCR) on their own while accounting for secondary effects.[2-5]

We propose a method for radiation shielding using a combination of confined magnetic fields, unconfined magnetic fields, and passive shielding to protect against radiation.

SR2S Project

The SR2S project began in 2013 by a team of seven European organizations. The program reevaluated active shielding based on the fact that space is not a vacuum as all previously proposed concepts assumed it was, but rather a diffuse plasma of charged particles. This can increase the effectiveness of active shielding due to trapped plasma, which induces another magnetic field and can deflect charged radiation with Coulomb interactions.

The SR2S project released several articles including an analysis on superconducting material, the effectiveness of unconfined magnetic fields in space, and a sun-shield to keep a superconductor below its critical temperature. One SR2S experiment showed that a B-field in space will induce a plasma, and predicts how the results enhance the active shield.[6]

Materials and Methods

To create large magnetic fields, superconductors must be used. The SR2S project analyzed the effectiveness of Ti-MgB_2 superconductors, which is easily produced and has a critical temperature of 39 K. A 360 m spool of Ti-MgB_2 superconducting wire has a weight of 4000 kg/m^3, a current density of 80 A/mm^2, and operates well in a 1 T field at 29 K.[7]

The most dangerous ionizing radiation particle is not the highest energy particle ever recorded, but rather a high energy particle with a significant flux through space. Schimmerling describes recent data of the kinetic energy and flux of GCR radiation which enters the solar system.[8] From these values of GCR particles our target particle is an iron ion, Fe^{+26}, moving at 0.9998*c*, having a relativistic energy of 2800 GeV with an atomic mass of 55.85 u or 52024 MeV/c^2 and a charge of +26 *e*.[8]

Proposed Method

No one method of shielding appears to be sufficient in the literature, and hence we propose a combination of active magnetic and passive mass shielding. The design, shown in Figure 1, consists of a large deployable 100 m radius wire loop (in blue), a smaller loop with current opposite that of the larger loop in black of 15 m radius, and a split toroid in blue with an inner radius of 10 m, outer radius of 15 m, and a height of 10 m. The structural components (ship habitat) design has mass shielding of Boron Nitrogen Nanotubes (BNNT), which is a promising material for reducing secondary radiation, however, BNNTs are still being studied.

The split toroid design is advantageous due to the configuration of the magnetic fields. Since two *B*-fields of opposite direction are produced, small amounts of thrust can be generated and focused in one direction.

The key to this method's shielding ability is the large deployable loop. The SR2S project demonstrated that a magnetic field in a diffuse plasma will trap charged particles, creating an induced plasma and an induced magnetic field.[6] In our method, the outer loop will create a magnetic field that will induce radiation belts to surround the ship and decrease the kinetic energy of radiation particles that pass through. One potential problem is that the magnetic poles tend to direct particles into a spiral down the magnetic field lines similar to Earth's magnetic poles. This collection of radiation particles at the magnetic poles can be redirected by adjustable magnetic field caps as seen in Figure 2.

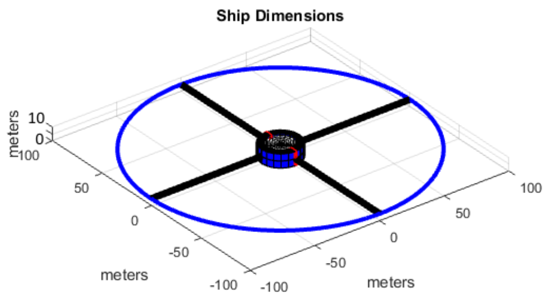

FIGURE 1. Proposed Shielding Structure

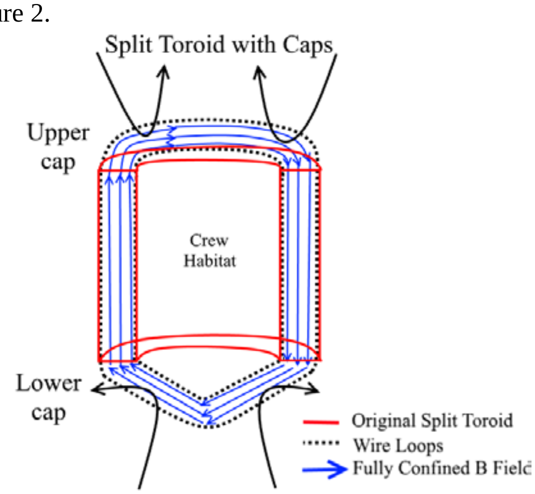

FIGURE 2. Particle deflection at top and bottom of design (Toroidal caps)

To control how much thrust is produced at any time, the toroid caps must be adjustable by some mechanism which can bend the orientation of the toroidal cap wire loops. Since our proposed method produces electromagnetic radiation (bremsstrahlung and synchrotron), there is a potential for power production using silicon solar cells. A recent experiment by Hirota, Tarusawa, Kudo, and Uchida demonstrated that power can be produced from incident X-rays and gamma rays using amorphous silicon.[10] The ability to create power from a shielding method would be extremely useful for many applications in future space flights.

Calculations

The SR2S project has shown that a magnetic field in space will induce a plasma. The calculations to find how much shielding ability this plasma creates are so complex and variable that the SR2S project did not develop an equation to use. They explain the equations they provide should only be used as a guide for a rough estimate as the plasma effect has so many variables.[11] Calculating the additional shielding effect exactly is not done here; however, we know that any additions from the plasma will be positive additions to the shielding ability.

We do a rough estimate of the plasma effect using knowledge of the Van Allen belts which provide substantial shielding from GCR. One example where shielding is known is for the ISS that orbits below the Van Allen belts, but above the atmosphere. We assume that a wire loop creating a *B*-field of the same magnitude of Earth's will create radiation belts that shield as much as Earth's Van Allen belts. If this assumption is false, our method can be easily altered to create stronger or more spread-out fields. To calculate how much current is required, we assume Earth's outer core acts as a wire loop and scale the radiation belts and *B*-field to a 100 m radius wire loop. Using the National Centers for Environmental Information on the NOAA website,[12] we calculate a current loop of 100 m radius to require 7.14×10^4 A with a standard deviation of 2.26×10^4 A using the Biot-Savart law. The reasonably large uncertainty is due to the Earth not being a perfect magnetic dipole. In our calculations, we assumed the high end of this current range and propose a needed current of 7.14×10^4 A. Since one Ti-MgB_2 superconducting wire can carry 8000 A, 9 wires are needed for the outer loop to produce the magnetic field.

Strong *B*-fields can cause health risks to a crew over long missions. Therefore, we calculate the small wire loop's current to be -10800 A, creating a maximum *B*-field no greater than 1.14 Gauss in the crew habitat.

A NASA presentation from the Space Radiation Analysis Group presents collected data from low Earth orbit.[13] The average proton kinetic energy is 8.4 to 27 MeV. According to Schimmerling, GCR protons with the highest flux have an energy level of around 3.33×10^2 MeV.[9] If we take the middle of the average energy range of the low Earth orbit data (17.7 MeV) and compare it to the average kinetic energy from Schimmerling's GCR data, we find that radiation particles in low Earth orbit are about 5% of the average GCR proton. This means if energy is reasonably accounted for within the belts, the Van Allen belts decrease the incident radiation to approximately 5% their initial kinetic energy. Our qualitative ballpark estimate of shielding effectiveness of an induced plasma in a similar magnetic field to Earth's is a decrease in kinetic energy of about 20 times the initial kinetic energy. If our target particle (Fe^{+26}) enters this induced plasma at 2800 GeV, it will slow down to an energy of 140 GeV.

A 3D simulation of the field with an outer loop of 9 wires, an inner loop of 2 wires, and a partially confined split toroid of 60 wires per meter created a *B*-field of about 0.57 T inside the split toroid and a maximum *B*-field of about 2 Gauss inside the crew area. This can be seen in Figure 3. The approximate weight of the wires is 7687 kg. Assuming this is implemented on a ship the size of the space shuttle, this is a total weight of 82,500 kg. This weight includes the weight of a method to keep the superconductors cool such as liquid helium or a sun shield.[14] Assuming the induced plasma can be redirected at the poles, we calculated a maximum thrust of 34.4 N, creating a constant acceleration of 4.17×10^{-4} m/s^2.

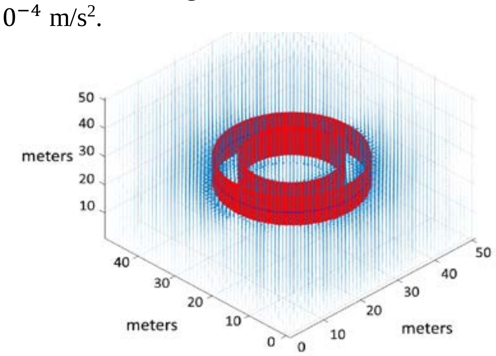

FIGURE 3. Simulation of ***B***-field in blue created by wire configuration. The walls of the toroid are in red.

Our proposed method has produced the *B*-field strengths and characteristics we expected, however, they should not be used as exact specifications for a working design, but rather an explanation of a proposed shielding method. More analysis on the proposed design is required. We are currently working on a simulation sending in relativistic particles of varied energies from various directions. Initial findings look promising even without plasma effects considered, however we have not yet included secondary radiation effects. Our next step will be to include the synchrotron radiation produced and calculations of the minimum effect the plasma must have to fully shield the crew area from our test particle. More research must be done to find the full range of BNNT shielding capabilities. The implications of this concept could decrease the travel time to Mars and open greater possibilities for space exploration due to the constant thrust.

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