Radiation Shielding Using Magnetic Fields

M.W. Sailer* and H.M. Doss
Department of Physics and Engineering, Point Loma Nazarene University
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Radiation shielding is essential to future missions of space exploration due to increased time of exposure to harmful radiation. One of the most damaging and difficult types of radiation to stop is High Atomic Number and Energy (HZE) particles in Galactic Cosmic Radiation (GCR). These particles are fully ionized and travel at near light speeds. The most dangerous of these are iron nuclei. Many shielding options have been proposed in both active and passive categories of shielding. This research explores several previously proposed methods of both active and passive shielding and proposes a method using a combination of active and passive shielding in an attempt to maximize the deflection of radiation, minimize the production of secondary radiation, create a net thrust from the redirected particles, create useable power with captured synchrotron and Bremsstrahlung radiation, and account for space being a diffuse plasma.

I. INTRODUCTION

Radiation shielding is essential for all future space exploration. As rocket technology advances, more probes and human explorers will be sent outside the protection of Earth's magnetic field. Interplanetary space is full of harmful radiation that can interfere with sensors, on-board computers, and cause severe harm to astronauts. With both NASA and SpaceX announcing the goal of landing an astronaut on Mars in the near future [1], it is imperative that a method be developed to limit ionizing and dangerous radiation exposure to a manageable level. Although there are many approaches for radiation shielding, the final result will not be one specific implementation, but rather a combination of methods to best shield future explorers. We propose a method for radiation shielding using a combination of confined magnetic fields, unconfined magnetic fields, and passive shielding to protect against radiation. The proposed magnetic field configuration also produces thrust from redirected particles and produces usable electrical power from captured synchrotron and bremsstrahlung radiation.

OVERVIEW

This paper will analyze and discuss the following sections:

- Radiation Shielding and Background Information
- Shielding Methods: Passive and Active
- Previously Proposed Ideas
- SR2S Project
- Materials and Methods
- Proposed Method
- Plasma Effect Approximation
- Calculations
- Simulations
- Analysis and Future Research
- Implications

II. RADIATION BACKGROUND INFORMATION

Galactic Cosmic Radiation is the generic term for all particle radiation in space. It exists everywhere in interplanetary space, but is deflected by strong enough planetary magnetic fields and atmospheres. Additionally, GCR is isotropic. This means that at any point in deep space, GCR is passing through equally from all directions. It is composed of mostly protons and electrons, but also contains a small percentage of heavier ions. These particles interact with matter primarily with Coulomb interactions. R.A. Mewaldt [2] states that about 89% of positively charged GCR radiation is made up of ionized hydrogen, 10% of ionized helium, and 1% of ionized heavier elements. Surprisingly, only about 1% of all GCR radiation is made up of electrons, and the reason for this has yet to be discovered. Most GCR radiation in the Milky Way is confined to the galaxy due to its net magnetic field.

Radiation can be classified into different groups based on origin, location, and composition. We classify Galactic Cosmic Radiation (GCR) into three different categories: Solar Energetic Particles (SEP), High atomic number energetic particles (HZE), and the Van Allen belts.

High atomic number energetic particle radiation is a type of GCR radiation, but is limited to the heavier ions. It makes up about 1% of GCR, and consists of

* mwsailer12@gmail.com

fully ionized nuclei of elements with 6 or more protons. Mewaldt [2] states that HZE kinetic energy is typically on the order of a few GeV to as great as 3×10^8 TeV (Tera Electron Volts), making it the most difficult radiation to stop. For comparison, a proton with 1 GeV of kinetic energy is traveling at a velocity of 0.712c or over 215 million meters per second. These particles originate from the most violent events in space such as supernovae and collisions between gravitationally compact objects such as neutron stars and black holes. The energy released during these events is more than the total energy released by our Sun during its entire predicted 10 billion year life. During these events heavy elements are created and particles are ejected at insane speeds. Mewaldt states that one of the highest energy particles ever recorded had a kinetic energy of 10^{20} eV. This is similar to the kinetic energy of a baseball being thrown at 100 mph [2]. Although this doesn't sound too harmful, since catchers consistently catch baseballs at speeds similar to this, it is extremely harmful. A baseball transfers its kinetic energy over a large area to whatever it comes into contact with, however, the nucleus of an atom has an incredibly smaller surface area, with a diameter as small as 10^{-15}m, and contains a charge making it wreak havoc throughout the material it is colliding with.

Solar Energetic Particles are particles of radiation in a solar system sent out from its star. The sun sends out radiation in two ways: solar wind and solar flares. The Solar Wind is a generally uniform bombardment of protons and electrons traveling radially away from the sun. The intensity of SEP decreases the further you are away from the sun. Earth's magnetic field and atmosphere give ample protection for life to survive on Earth. Solar flares are violent events which send out a concentrated burst of SEP radiation which can be deadly if unprotected. Earth's magnetic field protects us from this too, however, astronauts on the ISS must take precautions by going into a storm shelter made of thick walls that help shield in the event of a solar flare. Solar flares begin with a burst of electrons which will bombard a spaceship about ten minutes prior to the harmful proton radiation providing advanced warning to some degree. Additionally, solar flares will momentarily block all GCR radiation originating from outside the solar system since the accelerated particles produce a magnetic field. Radiation will tend to decrease for astronauts aboard the ISS during solar flares [3]. This is called the "Forbush decrease." The incoming radiation is a dense plasma of charged particles moving with high velocities which induce magnetic fields. Levels of radiation tend to drop around 30% providing extra protection from radiation, however, it only lasts a few hours making it still necessary for a shielded shelter.

The Van Allen belts are layers of radiation over Earth. Galactic Cosmic Rays interact with Earth's magnetic field and get trapped forming two layers as seen in FIG. 1. The outer layer is composed mostly of electrons on the less than 10 MeV and extends from around 13,000-60,000 km. The inner is composed of lower energy electrons on the order of keV and high energy protons on the order of MeV. The inner belt stays between around 1000-6000 km. Radiation levels within the Van Allen Belts are often measured in terms of "roentgem equivalent man" or rem. This is a measurement of radiation representing the effects on biological material of ionized radiation. On average the outer belt has a radiation dosage of 24 rem per hour while the inner belt has a dosage of around 200 rem per hour. For comparison, 500 rem in a short period of time is typically lethal to a human. Most of the radiation will be received while passing through the inner belt. The radiation belts are most prominent around the equator and taper off as you reach Earth's magnetic poles [4].

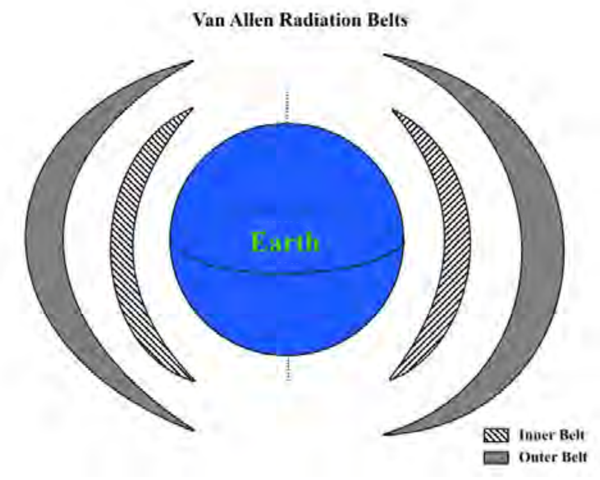

FIG. 1. Van Allen Belts

III. SHIELDING METHODS: PASSIVE SHIELDING

There are two methods of shielding radiation: Passive and Active. Passive Shielding uses material to absorb and stop the radiation from penetrating a spacecraft. This method relies on the massiveness of the material to fully stop all the damaging effects of ionized particles from making it through. The advantages to passive shielding are its simplicity and its lack of required electrical power. The disadvantages, however, are severe. While a layer of extra material can stop low energy radiation, particles such as HZE radiation require enormous amounts of material to be stopped. Furthermore, passive shielding produces large amounts of secondary radiation due to the collisions with the atoms making up the material of the ship. This secondary radiation can often times be as harmful as the initial radiation. According to Mewaldt, secondary radiation produced from GCR radiation hitting our atmosphere consists of pions, muons, neutrinos, and gamma rays [2]. They can also produce neutrons which are very difficult to stop since they have no charge.

According to R.H. Levy, carbon and water are typically the proposed materials for passive shielding [5]. Calculations have shown that for a 100 MeV proton, 85 $\frac{\mathrm{kg}}{\mathrm{m}^2}$ of carbon or 76 $\frac{\mathrm{kg}}{\mathrm{m}^2}$ of water is needed to stop the particle. For a 0.5 GeV proton, 3578 $\frac{\mathrm{kg}}{\mathrm{m}^2}$ of carbon or 3215 $\frac{\mathrm{kg}}{\mathrm{m}^2}$ of water is needed to stop the particle. For comparison, a 2017 Tesla Model S electric car weighs roughly 2000 kg [6]. So for every square meter on the surface of a spacecraft, there would need to be about 1.5 Tesla Model S's weight of shielding material dedicated to radiation shielding. To get an idea how thick this is, given the density of water is $1000\frac{\mathrm{kg}}{\mathrm{m}^3}$, if liquid water was used as a shielding material over 1 cubic meter of a spaceship, a block of water with dimensions, 1 m $\times$ 1 m $\times$ 3.215 m would be needed at a weight of 3,215 kg. If we tried to shield just the solar panels in the ISS, given its solar panel surface area is 3567 m^2, we would need 1.14×10^7 kg of water which is highly impractical. These numbers do not take into consideration secondary radiation, so much more material would be needed.

Levy also cites an article by D.H. Robey which states a careful approximation of neutrons produced by secondary radiation from copper per proton is given by:

$$\frac{E^2}{9 \times 10^4} \tag{1}$$

This was estimated based on protons having energies, E, ranging from 10-1000 MeV. However, in a solar flare and within the Van Allen belts, the numerator changes to E^{-a} where a is typically between 2 and 5 giving the surprising result that lower energy protons tend to produce more neutron secondary radiation.

Solar flares can vary in intensity which will affect the shielding ability of materials. Levy explains that in some of the more powerful solar flares (such as the one in February of 1956) will produce so much secondary radiation, if only using 1000 $\frac{\mathrm{kg}}{\mathrm{m}^2}$, that the neutrons produced will be more intense and dangerous than the initial radiation[5].

SHIELDING METHODS: ACTIVE SHIELDING

Active shielding tends to be broken down into three types: Plasma, Electric fields, and Magnetic fields. Artificial plasma shielding requires that a plasma of ionized particles be distributed around the outside of the ship using magnetic and electric fields to form a

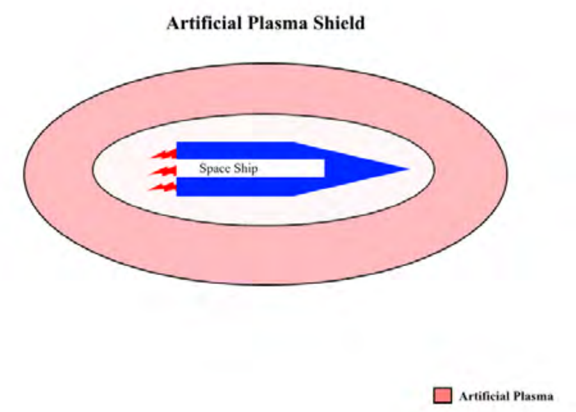

FIG. 2. A plasma field surrounding a ship

barrier of charged particles which slow down or stop any galactic cosmic rays passing through using Coulomb interactions. R.H. Levy describes a concept using this design in his paper "Plasma Radiation Shielding" [7]. FIG. 2 shows a rough diagram of what this looks like. There are three serious issues with creating an artificial plasma around a ship. First, significant power is required to keep plasma around a ship using electromagnetic fields for extended periods of time. Additionally, a ship would need to supply its own particles to form a confined artificial plasma surrounding it. Finally, there would need to be a continual addition of particles to maintain the artificial plasma as galactic cosmic rays bombard and interact with it.

Electric field shielding uses electric fields surrounding a ship to repel the more harmful radiation particles. This can be done either with a capacitor along the walls of a ship, or by maintaining a voltage on the outer shell of a ship. This shielding method works by repelling ionized radiation particles using Coulomb interactions as seen in FIG. 3. There are two disadvantages to this method. First, although the positively charged particles are repelled due to the ship's Voltage, the negatively charged particles are accelerated forward causing more damage than they normally would. The second disadvantage is that extremely high power is required to maintain the needed electric potential on the walls of the ship. Current technology would not be able to create the scale of capacitors required here on Earth let alone in space [8].

Magnetic field shielding redirects particles using artificial magnetic field configurations. While most shielding methods slow down GCR particles, magnetic fields change the direction opening up the possibility of creating thrust. Large currents are required to create strong magnetic fields rather than specifically large

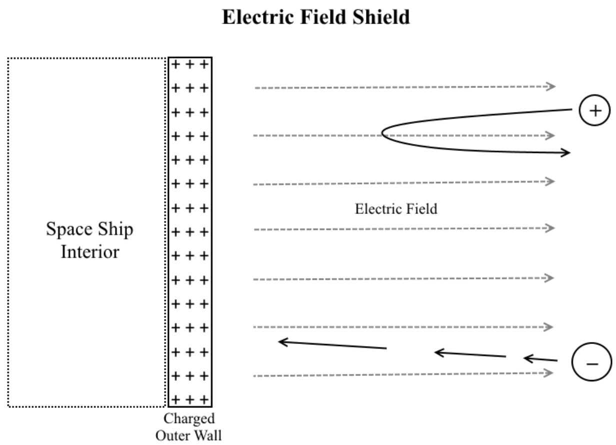

FIG. 3. Electric potential method

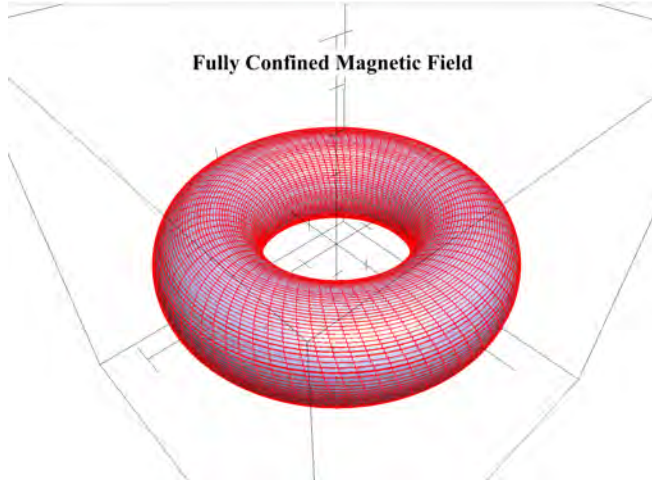

FIG. 4. Fully confined magnetic - toroid

voltage in electric fields. One of the advantages to exploring this method is the constant advancement of superconductors. Every superconductor has a critical point in its temperature which causes electrical resistance to drop to exactly zero. Superconducting material reduces the need for incredible amounts of sustainable power since it has no electrical resistance, but its temperature needs to stay below its critical point to maintain its superconductive properties using a cooling system. Magnetic fields can be fully confined, partially confined, or unconfined. A fully confined field is made in a toroid created by wire loops as seen in FIG. 4 and has the magnetic field fully confined within the wire loops. A partially confined magnetic field is a long solenoid where the magnetic field is strong and essentially uniform inside and weak in its outer surroundings. Wire solenoids have magnetic poles as seen in FIG. 5. An unconfined magnetic field can be created by a wire loop with a non-uniform field everywhere as seen in FIG. 6. This drastically increases the amount of possible configurations and opens the doors to many creative solutions. One disadvantage to note is the creation of synchrotron radiation which is produced when a charged particle travels through a magnetic field. Synchrotron radiation is electromagnetic radiation produced when a charged particle undergoes centripetal acceleration. The power of the produced radiation can be found with the following equation:

$$P = \frac{2Ke^2\gamma^4v^4}{3c^3r^2} \tag{2}$$

In this equation, P is power, K is Coulomb's constant, e is the charge of an electron, γ is the lorenz factor, v is velocity, c is the speed of light, and r is the radius which the particle follows as it travels through a magnetic field. The power ends up being in terms of Watts/electron with electrons losing 10^{13} times more energy than a proton of the same energy [9]. Any

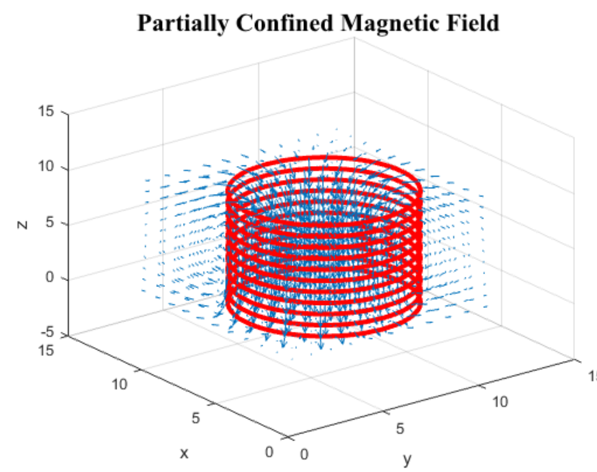

FIG. 5. Partially confined magnetic field - solenoid

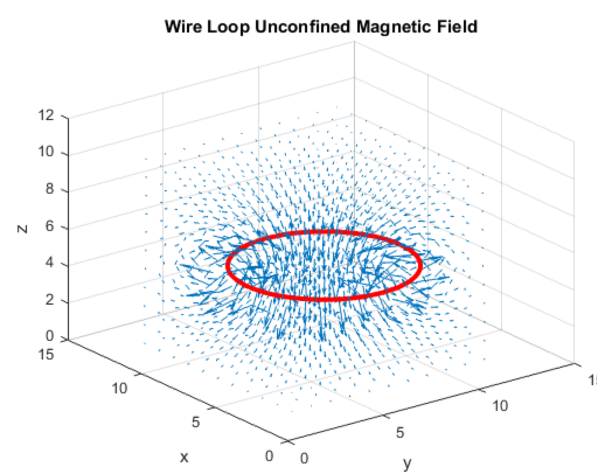

FIG. 6. Unconfined magnetic field - magnetic dipole

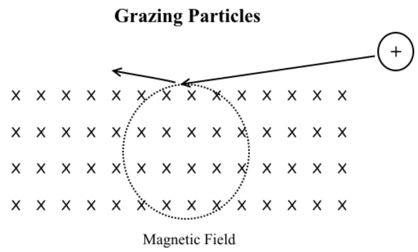

FIG. 7. Grazing particle in a uniform B field

shielding method which uses magnetic fields will need to take into consideration the produced gamma rays which have potential to bombard the ship.

IV. PREVIOUSLY PROPOSED IDEAS

A number of ideas have been proposed as to stop some or all of the radiation. Townsend brings up a point that many proposed ideas only consider SEP particles and neglect the harmful HZE particles in GCR radiation [8]. So a proposal will not be adequate unless it considers the following conditions:

- The entire radiation spectrum
- The effects of relativity
- Grazing particles

If a particle enters a confined magnetic field at a small angle (such that it is just grazing across its surface), it will roughly follow a circular path with a radius double that of a particle entering perpendicular. In other words, as a particle grazes the edge of a magnetic field, it will be pulled into the field, depending on its orientation, and make a complete loop entirely inside the field. This is called a grazing particle and is visualized in FIG. 7. L.W. Townsend discusses and visualizes this concept in his paper [10]. The final concept for radiation shielding will consider these conditions.

Three ideas that have been proposed are Boron Nitride Nano Tubes (BNNT) as a passive shield, deployable unconfined magnetic fields as active shielding, and a toroid as a confined magnetic field active shield.

BORON NITRIDE NANO TUBES

Boron Nitride Nanotubes (BNNT) are a method of passive shielding proposed by the NASA Langley Research Center [11]. BNNTs are similar to carbon nanotubes but made with Boron and Nitrogen. They are also strong and durable and can withstand heat of 800°C in air making them a potentially viable building material. The nanotubes are hydrogen attractive and can be incorporated into high-hydrogen polymers. BNNTs have great potential in being a passive shield for radiation because of their composition. Boron is the highest neutron absorber of any element, and hence can prevent harmful neutrons from causing secondary radiation. The nanotube structure gives the design incredible strength and resistance to fluctuations in temperature and hostile environments. Hydrogen is the best element to shield ionized radiation.

This method of passive shielding is still in development but has great potential as a passive shield. Even though this appears to be a great method on its own, huge amounts of this material would still be needed to stop the higher momentum particles. A potential danger in this method is the strength of the BNNTs may be compromised over time if the ionized radiation particles break the bonds of the nanotubes. Radiation will break down the bonds between any material, but since BNNT are made out of nanotubes, there is a greater potential for compromised strength if the bonds break. This is not certain, however, as BNNTs are still being tested. Another unresolved issue is that the weight of BNNT material needed to create adequate protection on its own is enormous. It will only be a matter of time until this technology is tested, available, and have the ability to be mass produced. Overall, this seems to be the most efficient and effective passive shielding method.

DEPLOYABLE UNCONFINED MAGNETIC FIELD

A deployable unconfined magnetic field is typically created by a single wire loop with a large radius like in FIG. 6. This creates a concentrated field in the center of the loop, and a decreasing field as the outside distance from the loop increases. The resulting field is a lot like Earth's magnetic field. One advantage to this method is for a particle to make it to the center of the field, it would need to travel through a large distance of increasing magnetic field giving it plenty of distance to be affected by the magnetic field. One disadvantage is that particles traveling down through the magnetic poles would be unaffected by the magnetic field since they would be running parallel with the magnetic field lines. Another disadvantage is to create a strong enough field, either a lot of current is needed, or a large radius in needed. Additionally, the larger the radius, the more of an engineering challenge it would be to keep the wire circular and cooled to the correct temperature if superconductors are used.

F. H. Cocks explained a method of radiation shielding using unconfined magnetic fields [12]. The basic physics behind the ability of a magnetic field to redirect radiation is from a combination of the equations $F = \frac{mv^2}{r}$ and $\vec{F} = q\vec{v} \times \vec{B}$. F is the centripetal force produced from an object following a circular path with radius r, mass m and velocity $\vec{v}$. $\vec{F}$ is also the force vector produced when a particle moves through a magnetic field $\vec{B}$ with a velocity $\vec{v}$ and a charge q. Since both of these equations describe the same motion of a particle traveling through a magnetic field, they can be set equal to each other:

$$r = \frac{mv}{qB} \tag{3}$$

where r is the radius a charged particle will follow in a magnetic field. If the particle is traveling at relativistic speeds, it will have a γ term attached to it making it:

$$r = \gamma \frac{mv}{qB} \tag{4}$$

where γ is $\frac{1}{\sqrt{1-\frac{v^2}{c^2}}}$. These equations work well for magnetic fields that are uniform over an area, but the equations are more complex for a non-uniform magnetic field such as a wire loop. F. H. Cocks describes the concept of a Störmer Radius which is a radius of a forbidden zone for particles of specific momentum. According to Störmer, a good approximation for this radius is

$$R_{st} = \sqrt{\frac{q\mu_0 M}{4\pi P}} \tag{5}$$

where q is the charge of the particle, μ_0 is the permeability of free space, M is the magnetic moment, and P is the relativistic momentum γmv. The shape of this protected area depends on the design of the wire loop, but it has been shown from detailed analysis that the actual fully protected area is about 40% of this radius. This means the real radius of the fully protected area is:

$$R_{st} = \frac{2}{5}\sqrt{\frac{q\mu_0 M}{4\pi P}} \tag{6}$$

For a single wire loop, this fully protected area is a circle around the wire's cross section or a toroid with the wire at its center. FIG. 8 shows a cross section of a wire loop and a representation of its fully protected toroidal volume.

For a wire loop by itself to work in deflecting particles, a large magnetic moment is needed. The magnetic

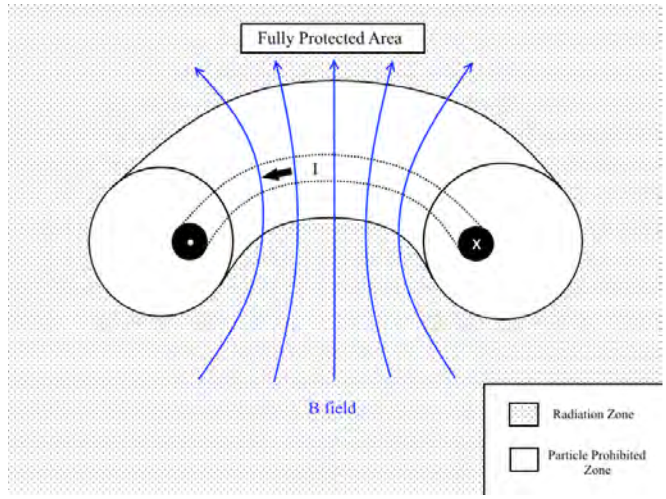

FIG. 8. Fully protected area of a wire loop

moment for a wire loop is calculated $M = nIA$ where n is the number of wires, I is the current, and A is the area. S. G. Shepherd and B. T. Kress show that a wire loop alone will do almost nothing for deflecting shielding against ionized iron particles with a charge of +1 and a kinetic energy of 1 GeV [13]. However, they show a toroidal magnetic field will have a particle free area if it has a magnetic moment of $M = 1.1 \times 10^{13}$ A m^2. This large magnetic moment means either it has to have a strong B field on the order of Tesla or a large radius on the order of kilometers to stop a 1 GeV iron atom, and a much higher value to stop the more energetic particles. In order to get an idea on what these values are, Shepherd and Kress include a table listing what values of the B field and radius must be. These values can be found in Table I.

r (m)	B (T)	I (A)
5	17592	8.0×10^8
10	2199	2.0×10^8
15	651	8.9×10^7
25	140.7	3.2×10^7
50	17.6	8.0×10^6
100	2.2	2.0×10^6
500	0.017	8.0×10^4
1000	0.0022	2.0×10^4

TABLE I. Magnetic Moment $M = 1.1 \times 10^{13}$ A $\times$ m^2

F. H. Cocks proposes a concept for a "Deployable High Temperature Superconducting Coil" (DHTSC)[12]. His design uses 2 large wire loops in a figure-eight configuration attached to a rocket with extended arms holding the crew quarters as visualized in FIG. 9. The advantages to this design is that the ship can spin to

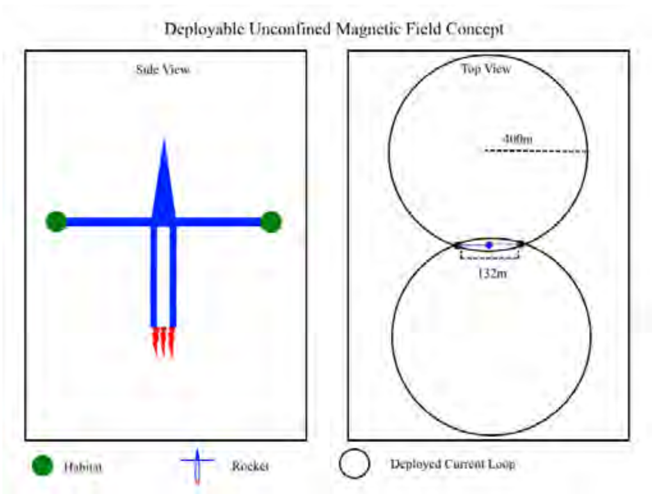

FIG. 9. DHTSC concept

help keep the coils deployed and to provide artificial gravity in the crew habitat using centripetal acceleration. Cocks calculates how much current and mass is required, and how much stored energy it requires. This configuration, if the radius of the coil is 564 m, requires 732 loops of wire to carry a current of 22,700 A and a mass of 650 kg for the coils. He calculates that the stored energy would be on the order of a few million joules making this configuration able to be powered on and off several times instead of one burst of stored energy as in other methods. This way the configuration can be used when needed throughout the mission. This method could be possible, however, Cocks brings up the point that when this ship is near a planet's magnetic field, the fields could interact and affect its navigation. Furthermore, this concept does not take into account the added mass of keeping the superconducting wires cool, the high magnetic field in the crew habitat from the high current wires, the structural supports required to keep the loops deployed as the ship accelerates, and the potential for space debris to hit the loops spread over a large area.

V. SR2S PROJECT

The problem of radiation shielding has been around since before man has stepped on the Moon. Many active shielding methods, including the one above, were proposed, but dismissed due to the problems they still have to overcome. Research generally shifted to passive shielding methods until the Space Radiation Superconductive Shield (SR2S) project began in January 2013 by a team of seven European organizations [14]. The program lasted 3 years and reevaluated the effectiveness of active shielding based on the realization that space is not a vacuum as all previously proposed concepts assumed it was. Instead, space is a diffuse plasma of charged particles. This means that a magnetic field in space will build up charged particles and form a plasma just as Earth's magnetic field does. This increases the effectiveness of active shielding due to the trapped plasma inducing another magnetic field and deflecting radiation with coulomb interactions.

The SR2S project released several articles pertinent to magnetic field shielding. These articles included 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. This new realization of space being a diffuse plasma opens the door to many new configurations for magnetic field shielding.

VI. MATERIALS AND METHODS

This section will discuss what materials are advantageous to create a magnetic field and what types of particles a shielding method should be able to stop.

SUPERCONDUCTORS

To get a strong enough magnetic field, superconductors must be used to induce a strong enough field. The SR2S project analyzed the effectiveness of Ti-MgB_2 superconductors which has a critical temperature of 39 K [15]. Although there are more efficient superconductors, Ti-MgB_2 is easily produced. The article shows a picture of a 360 m spool of Ti-MgB_2 superconducting wire with a weight of 4000 $\frac{\text{kg}}{\text{m}^3}$ and a current density of 80 $\frac{\text{A}}{\text{mm}^2}$. In other words one wire can carry 8000 A. The article explains the current is limited to 80 $\frac{\text{A}}{\text{mm}^2}$ since it was designed for the project's shielding concept which subjected the superconductor to up to a 4 T magnetic field and operates best at 10 K in these conditions. This means a concept that uses Ti-MgB_2 superconductors does not need to decrease the temperature to 10 K if the magnetic field it creates is less than 4 T, but can be cooled to a higher final temperature. The article included a graph showing what some of the values are which can be seen with approximate values in Table II.

Our proposed method of shielding will not create a magnetic field greater than 1 Tesla, so the Ti-MgB_2 will not need to be cooled to 10 T. Although more than 80 $\frac{\text{A}}{\text{mm}^2}$ could be produced in our method, that will be the current density we will use in favor of a higher critical

B (T)	T (K)
3.5	15
4	13
4.5	10
4.8	8.5
5	7

TABLE II. Temperature needed for current density of 80 $\frac{A}{mm^2}$ in different B fields

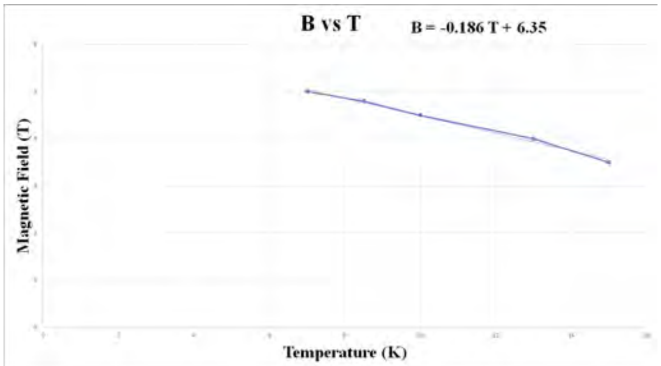

FIG. 10. Magnetic Field vs Temperature plot for Ti-MgB_2

temperature. The article doesn't list what that temperature will be, however, we can estimate it by graphing these values and finding what it is projected to be. This graph along with its trend line can be seen in FIG. 10.

Assuming an approximately linear relationship in this region, we can plug in 1 T as the magnetic field to find the new temperature 29 K. From this article, our shielding method should require the superconductors to be at around 29 K.

TEST PARTICLE

In developing a solution to radiation shielding, it is essential that a target particle is defined which a shielding method should be able to shield. The highest energy particle ever recorded, which was mentioned earlier, had a kinetic energy on the order of 10^{20} eV, however, it was only found once. Since the flux of high kinetic energy particles decreases the more kinetic energy a particle has, the target particle must be the highest energy, and most damaging, particle we can find that still has a dangerous flux. Schimmerling describes recent data of the kinetic energy and flux of GCR radiation which enters the solar system [16]. In his paper, he shows a graph of differential flux vs kinetic energy per nucleon of different ionized particles. The approximate values of the data can be seen in Table III where m is meters, sr is steradians, s is seconds, and MeV is Mega Electron Volts.

Ion	charge	Max KE	Differential Flux
H	+1	5×10^7 MeV	5×10^{-8} $m^2 \cdot sr \cdot s \cdot MeV$
He	+2	4×10^6 MeV	2×10^{-8} $m^2 \cdot sr \cdot s \cdot MeV$
C	+6	1.1×10^7 MeV	6×10^{-9} $m^2 \cdot sr \cdot s \cdot MeV$
Fe	+26	2.8×10^6 MeV	2.8×10^{-5} $m^2 \cdot sr \cdot s \cdot MeV$

TABLE III. GCR KE and Differential Flux

From these value of GCR particles, an Fe ion should be the target particle. Although the maximum kinetic energy of carbon is greater than iron, the iron ion has a smaller mass to charge ratio and a greater differential flux making it the most harmful and most difficult particle to stop. Because of this, our target particle will be a 2.8×10^6 MeV (2800 GeV) particle with an atomic mass of 56 and a charge of +26.

VII. PROPOSED METHOD

So far, this paper has described and analyzed many different methods to solve this problem of radiation shielding. The goal of this paper is to propose a reasonable method which will fully shield a region from an Fe ion of 2800 GeV with any incident direction. We propose the best method of shielding radiation is a combination of two wire loops with opposite current, a split toroid, and structural components made of BNNT. The split toroid of 15 m outer radius and 10 m inner radius surrounds the center of the ship which holds the crew habitat and instruments. A large deployable wire loop with a radius of 100 m surrounds the toroid generating an Earth-like magnetic field. A small wire loop of opposite current and 15 m radius surrounds the outside of the toroid canceling the large B-field produced by the deployable loop inside the crew habitat. This design can be seen in FIG. 11 where the deployable ring is the large blue ring and the small wire loop is the small black ring surrounding the blue split toroid.

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. FIG. 12 shows a top down view of the split toroid and how thrust can be created.

As positively charged ions enter the magnetic field from each direction, they will be repelled by the magnetic field and sent out the same direction. The change in momentum of the particles will be equal and opposite to the change in momentum of the ship causing the ship to move forward. This thrust will be very small and potentially able to make minor adjustments in the ships

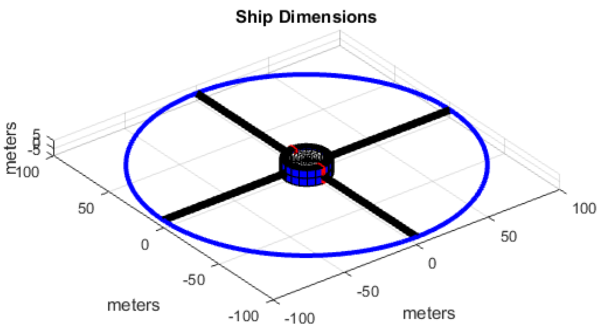

FIG. 11. Proposed Concept

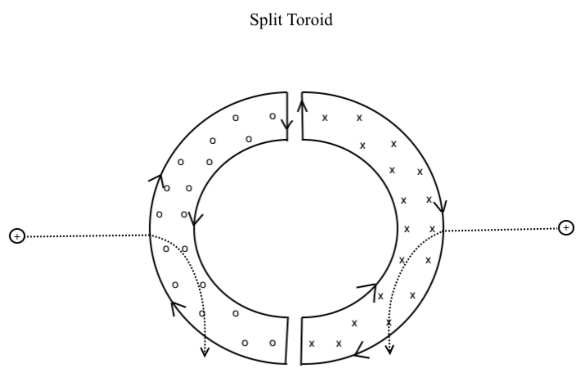

FIG. 12. Top Down View of the Split Toroid

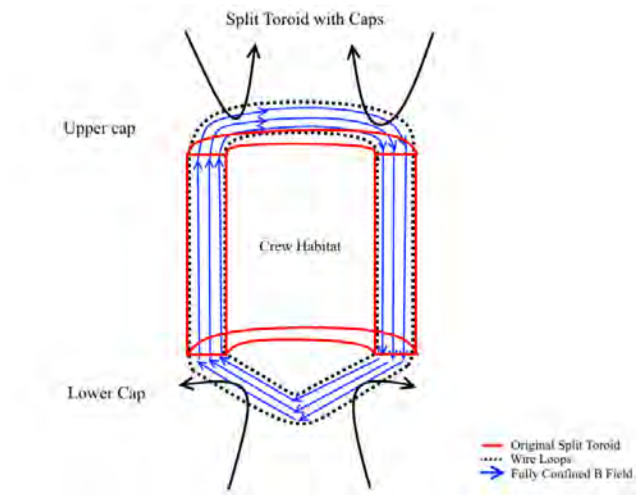

FIG. 13. Magnetic Pole Particle Deflection

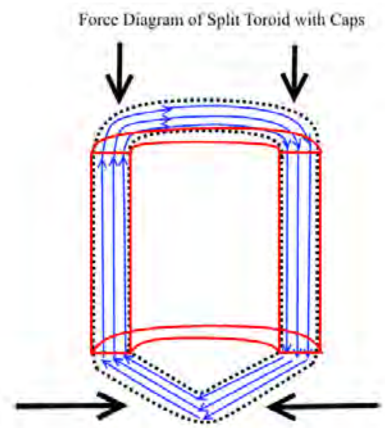

FIG. 14. Force Diagram of Net Thrust Produced

path, but is controllable with a change in the direction of current of each side.

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 [14]. In a wire loop, the induced plasma will be similar to the Van Allen Belts around Earth under the right conditions. 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. This is exactly what happens at Earth's magnetic poles. Charged particles from the Van Allen belt spiral down the magnetic field lines and bombard Earth's atmosphere creating the Northern and Southern lights or auroras. The same thing will happen with a B field created by a wire loop in space sending energetic particles directly into the center of the loop and into the crew's habitat if unshielded. This collection of radiation particles at the magnetic poles is both a good and a bad thing. It must be deflected, but it can be deflected in a way that potentially produces significant thrust. Since this effect is happening at both ends of the ship, adjustable magnetic field caps can be added to deflect particles 180° on one end of the ship and 90° the other creating a net thrust from the redirected particles. This process can be seen in FIG. 13 and a force diagram showing the net thrust can be seen in FIG. 14.

In order to adjust 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 wire loops. This can be seen in FIG. 15.

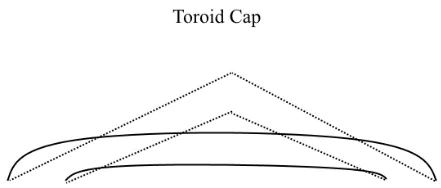

FIG. 15. Adjustable Toroid Cap

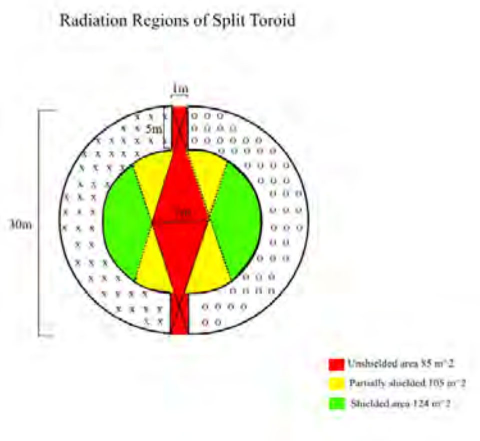

FIG. 16. Shielded Regions of Toroid

A split toroid design does pose a challenge with the unshielded region in the "split" between the magnetic fields. To solve this, the gap can be filled with passive shielding in order to limit the radiation dose that comes through, and regions can be designed to have different levels of radiation. This can be seen in FIG. 16 which shows unshielded, partially shielded, and shielded areas of the ship. These areas can have a limit to how long a crew can spend in them. Since some particles will make it into the crew habitat, an electric potential can be created on the top of the crew habitat, using a capacitor, to periodically flush out any trapped particles to prevent a buildup.

Another issue that must be addressed is produced electromagnetic radiation. Any active shielding method is going to produce radiation from accelerating charged particles. In the case of magnetic fields, it will produce bremsstrahlung and synchroton radiation. Bremsstrahlung radiation is produced by charged particle collisions sending out gamma rays or X-rays [17]. Synchrotron radiation is produced by centripetal acceleration which all charged particles undergo in a magnetic field [9]. Because these GCR particles are charged and accelerating, the crew habitat will be bombarded with gamma rays and X-rays in addition to neutrons from particle collisions in any of the material. BNNT's have great potential to protect against all of this radiation.

According to the BNNT website, BNNTs have a lot of potential for future applications [18]. One major application listed on the website is radiation shielding.

> "BNNT can be the basis for neutron shielding composites for use in radiation shielding applications due to the presence of boron with its unique high efficiency for absorbing thermal neutrons. BNNT can also be used for ultra violet (UV) shielding applications."

Unfortunately, BNNTs are still being tested to find its full capabilities, they are a promising, reliable, and resilient material. For this reason, our proposed concept uses BNNTs for any major structural components to shield the crew habitat from neutrons and electromagnetic produced radiation from bremsstrahlung and synchrotron radiation.

Given the fact that an active shielding design will produce electromagnetic radiation, 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 [19]. The experiment used a square of about 6 cm by 4 cm of amorphous silicon, and used a 10 cm by 10 cm by 436 μm intensifying screen composed of Gd_2O_2S:Tb. A maximum power of 125 mW was able to be produced in standard conditions of sunlight (100 mW/cm^2). It produced an operating voltage of 3.3 V and an operating current of 36 mA. The goal of this article is stated as:

> "to determine the feasibility of generating electric power from X-rays and gamma rays emitted by nuclear waste..."

We believe this means of power production can be used to produce power in space. The silicon was demonstrated to have an efficiency of 1.4%. Given the amount of gamma rays readily available in space, and the produced gamma rays from synchrotron radiation, a substantial amount of energy can be harvested. Our proposed design includes a 10 m radius crew habitat which can be lined with amorphous silicon. The crew habitat's side has a surface area of 628 m^2. The amorphous silicon can produce a power up to 125 mW for a 1.25×10^{-3} m^2 square section. A maximum power of 262 W can be produced. The produced electromagnetic radiation may be of too high intensity for the amorphous silicon, but the amorphous silicon can be surrounded by BNNTs to decrease the intensity of the incident gamma rays. The ability to create power from a shielding method would be extremely useful for many applications in future space flights.

For clarity, a short outline of the components of our proposed method can be seen below.

- Deployable wire loop with radius of 100 m (FIG. 11)
- Small wire loop of opposite current to cancel out B-field in crew habitat with radius of 15 m (FIG. 11)
- Split toroid of radius 10-15 m surrounding crew habitat (FIG. 12)
- Adjustable toroid caps to create controllable thrust (FIG. 13 and 14)
- Structural material composed of BNNT to shield neutrons and gamma rays
- Amorphous silicon to create power from gamma radiation

VIII. CALCULATIONS

Our calculations rely heavily on the effects of plasma produced by the magnetic fields. From the SR2S project, we know that a magnetic field in space will induce a plasma surrounding the ship. In order to carry out any calculations, we must first make an approximation of the shielding capacity of induced plasma. The issue is this is nearly impossible. The SR2S project worked on some approximations and explained that rough approximations are the best a calculation can do. The following quotes are from one of the articles from the SR2S project [20].

> "The actual physics of the interaction is immensely complex and largely non-deterministic analytically due to non-linearities. Thus these are 'rules of thumb', intended only as a guide. A fully detailed analysis will require the use of complex plasma physics and simulation codes. Due to the resources needed this would best be conducted on a specific case for which as much verifiable data as possible is available."

> "Since an analytical approach is not available as a guide, we can take an observational example from comets, and in particular, the AMPTE comet."

> "The equations provided above, can only give approximate values as the complexity of the interaction is highly variable, with multiple parameters interdependent in both time and orientation. This is a typical description of a non-linear system. We know that mini-magnetospheres work because of the example of the Moon. We know that the same principles used here occur for both natural and artificial comets."

The SR2S project mentions the AMPTE comet experiment that was conducted in space by the AMPTE (Active Magnetospheric Particle Tracer Explorers) satellite. This experiment injected a cloud of barium ions into the solar wind and demonstrated that the solar wind has a substantial effect in a plasma cloud [21]. In the experiment, the plasma cloud was pushed several hundred kilometers in a short time and formed a head and a tail just as a regular comet. The Barium, however, quickly dissipated since there was no magnetic field. One of the important things this experiment demonstrated was the strength of the solar wind. The SR2S project states that we know effects such as this happen from observing comets and experiments such as the AMPTE experiment, but these are incredibly difficult to simulate. Because of this, we cannot make an adequate calculation to estimate the effects of plasma. We can, however, make a qualitative ballpark estimate based on a larger magnetosphere; the Earth.

PLASMA EFFECT APPROXIMATION

Earth is significantly smaller than a comet and produces a large magnetic field which induces plasma in a region known as the Van Allen Belts. The Earth's magnetic field is believed to originate from the circulating currents through the liquid metal of the outer core [22]. This electrical current can be represented by an imaginative wire loop in the center of the outer core. Earth's magnetic field takes roughly the same shape as one produced by a wire loop.

The major assumption of this paper's calculations is that we can scale down the Earth's magnetic field spatial dimensions and assume the same shielding ability of the induced plasma. We know this will not likely be the case, however, there are a few differences which work to our advantage and cause a greater shielding ability of our design than Earth's B-field.

First, on Earth, we are shielded mostly by the magnetic field of Earth and the Van Allen Belts. This can be seen from data on board the International Space Station (ISS). The international Space Station orbits in a low Earth orbit between the Atmosphere and the Van Allen Belts. The ISS uses a layer of aluminum to help shield the low energy radiation that makes it through the Van Allen Belts and the magnetic field as opposed to the $3000\frac{kg}{m^2}$ of shielding material required in unprotected space. Earth's magnetic field is not very strong which

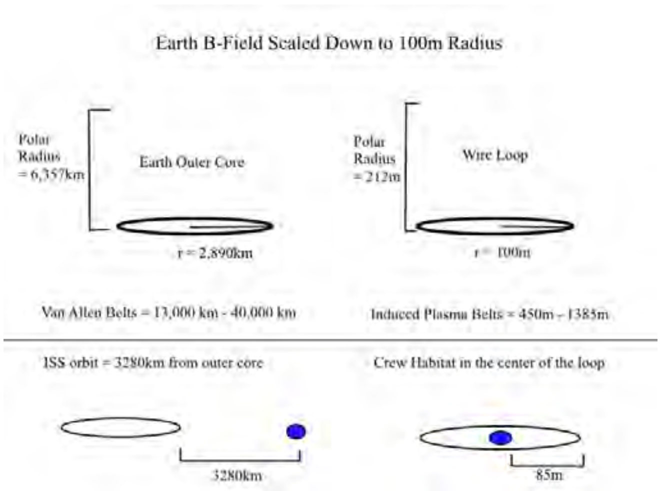

FIG. 17. Location of ISS as compared to location of crew habitat in proposed concept

means the trapped plasma causes most of the shielding. Above Earth's surface, even in low Earth orbit, the ISS is shielded substantially, and yet the ISS is 3280 km from the center of Earth's outer core. In other words, there is substantial shielding 3280 km away from the wire loop creating the magnetic field. Our proposed concept puts the crew habitat at the center of the wire loop causing a significantly longer distance the radiation particles must travel in order to reach the crew. This can be seen in FIG. 17.

Second, this extra distance will be filled with radiation particles which made it through the induced plasma creating a diffuse plasma with increasing density as the radial distance decreases. This provides more coulomb interactions which further slows down particles.

Third, we calculate the shielding ability of the magnetic fields assuming the particles do not lose any energy due to bremsstrahlung and synchrotron radiation. Although the particles will lose energy due to this, the calculation is highly dependent on the magnetic field it travels through and the coulomb interactions it undergoes as it travels through the ship's magnetic field. This decrease in kinetic energy is ignored in our calculations of shielding effectiveness.

Given these three differences between the Earth's magnetic field and our proposed concept we made a qualitative assumption that the shielding ability of an equal magnitude magnetic field is similar. If this turns out to not be the case, we can assume substantially more wires and increase the radius to adjust for the difference. This is because our proposed method does not use many wires as we will demonstrate in a later section.

For now we will assume the same shielding effect will be produced with a similar magnetic field strength as Earth for the reasons stated above. Because Earth's magnetic field is tilted, the easiest way to analyze the strength of Earth's B-field is to look at its magnitude at altitudes above one of Earth's magnetic poles. The National Centers for Environmental Information on the NOAA website (National Oceanic and Atmospheric Administration) provides a calculator to find the components and magnitude of Earth's B-field given a coordinate and an altitude [23]. Earth's magnetic south was projected to be at 86.5°N and 110.8°W in 2017 according to a Wikipedia article [24]. We collected data from the B-field calculator in February which can be seen in Table IV. The calculator only gave data up to 7931 km in altitude for that coordinate, so we collected data up to and including that altitude.

Altitude (km)	$\lvert B \rvert$ (nT)	Equivalent Altitude (m)
0	56947.2	0
10	56705.9	0.346
55	55752.6	1.73
100	54587.7	3.46
200	52344.2	6.92
500	46255.8	17.3
1000	37941.9	34.6
4000	14010.2	138.4
7931	5371	274.4

TABLE IV. Earth B-field by Altitude

Scaling down to the equivalent altitude of a 100 m wire loop, with the ratio $\frac{WireLoopRadius}{Earth'sOuterCoreRadius}$ which yields $\frac{1}{28900}$. We used this ratio to get the equivalent altitudes for those values of the magnetic field. The current can be found with the equation for the magnetic field on the axis of a wire loop:

$$B_z = \frac{\mu_0}{4\pi} \frac{2\pi R^2 I}{(Z^2 + R^2)^{\frac{3}{2}}} \tag{7}$$

where R is the radius of the wire loop and Z is the distance from the center of the loop. Our altitudes are measurements above the polar radius. The scaled polar radius of Earth is calculated to be 219.9 m, so we set:

$$Z = 219.7m + EquivalentAltitude \tag{8}$$

Our calculated current required to produce this magnetic field is 4.88×10^4 A with a standard deviation of 2.26×10^4 A. The reasonably large uncertainty is due to the fact that Earth is not a perfect magnetic dipole, and the parameters we input into the B-field calculator had uncertainty, so we took the addition of the current and the uncertainty to use for our current; 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.

Magnetic fields can cause potential danger and health risks to a crew over long missions. Therefore, a cancellation of the B-field in the crew habitat is essential. A smaller wire loop can be added with nearly the same radius as the crew habitat (15 m) with an opposite current to cancel out the majority of the magnetic field. This can be calculated with equation 7, and different values of R:

$$\frac{\mu_0}{4\pi}\frac{2\pi(100)^2(7.14\times10^7)}{(Z^2+(100)^2)^{\frac{3}{2}}}=-\frac{\mu_0}{4\pi}\frac{2\pi(15)^2 I}{(Z^2+(15)^2)^{\frac{3}{2}}} \quad (9)$$

From this formula, we get a value of -10800 A needed in the smaller wire loop to fully cancel out the field at the center. The crew habitat, however, extends 5 m in each direction meaning there will be a small B-field at the top and bottom of the crew habitat. We calculate this to be 1.14 gauss (1 Gauss is 10^{-4} T) which is an acceptable maximum B field value given that Earth's B field is around 0.5 Gauss.

If we assume a 100 m current loop of 7.14×10^4 A creates a similar induced plasma with a similar shielding ability, we can calculate the shielding ability from the average kinetic energy of protons in low Earth orbit. A NASA presentation from the Space Radiation Analysis Group presents collected data from low Earth orbit [25]. The values are on the order of 10 MeV with the average proton kinetic energy being 8.4 - 27 MeV using data collected on the STS-84 space mission at an average altitude of 341 km in May of 1991. According to Schimmerling, GCR protons with the highest flux have an energy level of around 3.33×10^2 MeV [16]. 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 meaning, if energy is reasonably conserved within the belts, that the Van Allen Belts decrease the incident radiation to approximately 5% their initial kinetic energy.

So, our qualitative ballpark estimate of shielding effectiveness of an induced plasma in a magnetic field with the same strength as Earth's magnetic field 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. In other words, the iron ion will go from $0.9998c$ to $0.614c$ which is significantly easier to stop.

TOROID SPECIFICATIONS

The toroid surrounding the crew habitat must be able to shield against our target particle's new kinetic energy of 140 GeV from any incident direction. Our split toroid design uses Ti-MgB_2 superconducting wire wrapped around creating a magnetic field with a depth of 5 m. With the addition of the toroid caps, the B-field will be fully confined and essentially uniform. The split toroid's approximate magnetic field is calculated with the same equation as a solenoid's magnetic field because it is essentially a solenoid within a solenoid:

$$B=\mu NI \quad (10)$$

where μ is $\mu_0\cdot k$, k is the relative permeability of the core (which is space is 1), I is the current, and N is the number of loops per length of the solenoid. The distance a particle enters into a uniform magnetic field with perpendicular velocity is calculated from EQU. 4. If the particle grazes the magnetic field, then the particle will enter a maximum depth of $2r$:

$$r=2\gamma\frac{mv}{qB} \quad (11)$$

Our target particle has a kinetic energy of 140 GeV. This is a speed of $0.614c$ and a γ of 1.27. With these equations, the maximum depth our target particle of 140 GeV can enter is calculated to be 4.63 m with a wire density N of 60 wires/m. This is caused by a generated B-field of 0.6032 T.

WEIGHT AND THRUST CALCULATION

To generate this B-field, our toroid has a wire density of 60 wires/m or a total lumber of 600 wire loops spread across its 10 m height. Given the dimensions described previously and the weight of Ti-MgB_2 superconducting wire, the weight of the wires is calculated to be 7.687×10^3 kg. The ship design will require the basic structure of the crew habitat, a sun shield to keep the wires cooled to below their critical temperature, and arms to deploy the large wire loop. Assuming all of the extra mass is the same mass of the space shuttle, the mass is calculated to be 8.25×10^4 kg [26].

The thrust which is produced at the magnetic poles can be calculated using our same approximation from the Van Allen Belts. Although again this may not be the case, a ballpark estimate can be calculated based on data from the Van Allen Belts. The Van Allen Belts protons have an average kinetic energy of 200 MeV and an average flux of 10^8 particles per square meter at the magnetic poles. The particles from the Van Allen Belts spiral down Earth's magnetic field lines and contact Earth's atmosphere creating the Northern Lights. The area of the Northern lights is approximately 1.96×10^{13} m^2. If this area is scaled down to the area of the crew habitat, and assuming all of the particles are directed down onto that area, a maximum thrust is calculated to be 34.4 N. Although this does not sound like a lot of force, it is continuous and free. The force translates to a constant acceleration of $4.17\times10^{-4}\ \frac{m}{s^2}$.

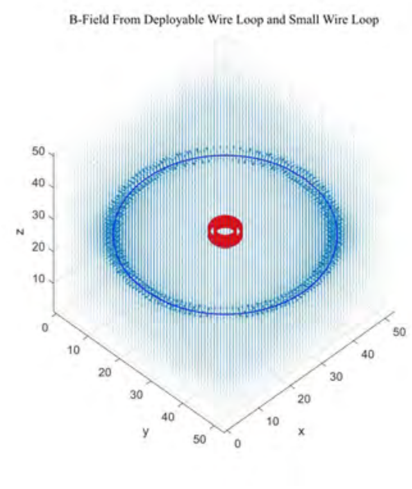

FIG. 18. B-Field from wire loops

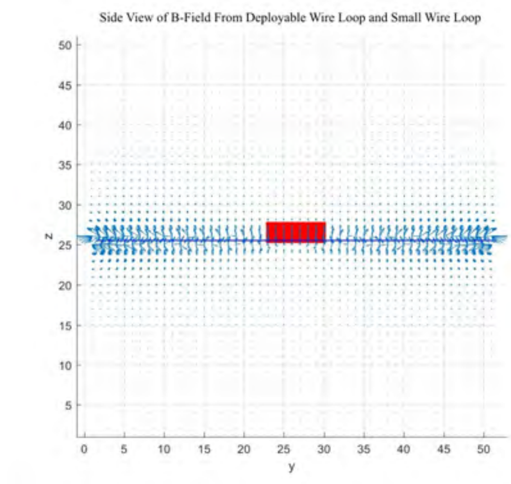

FIG. 19. Side view B-Field from wire loops

If a ship were to undergo this acceleration, and given the fact that the average distance to Mars is 225 million km, it would take 380 days to get to Mars. If the total mass can be cut down to twice the mass of the wires, the acceleration is calculated to be 0.00225 $\frac{m}{s^2}$. The time to Mars is only 164 days or about about 5.5 months. With the addition of a small rocket, the time can be decreased even more.

IX. SIMULATIONS

We used Matlab to create a model of the magnetic fields produced from our proposed wire configurations. Using the Biot-Savart Law:

$$\vec{B} = \frac{\mu_0 I}{4\pi} \int \frac{\mathrm{d}\vec{l} \times \vec{\mathscr{r}}}{\mathscr{r}^2} \tag{12}$$

we plotted a 3-D vector field of the large deployable loop and the small loop of opposite current direction. We used the previously calculated currents of 72,000 A for the large deployable loop and -10,800 A for the smaller loop. The plots can be seen in FIG. 18-20 with 1 unit on the axis representing 20 m.

We can assume an analysis of this B field, excluding the inside of the toroid, will yield the same results as a complete analysis including the toroid since the toroidal field is fully confined. When analyzing the data, the magnitude of the B-field is 0.462 G in the center. In reality, the very center is exactly zero, but our calculations set the z axis center at 25.5 making the value at $z = 26$ and $z = 25$ 0.462 G. Given the scale of the plot, the top and bottom of the toroid should be at $z = 26.75$ and $z = 24.25$ with a magnitude of 1.14 G. Since our plot has one vector at each point, we should expect to see a magnitude above 1.14 G at $z = 27$ and $z = 25$. The calculated values are 3.5 G making our

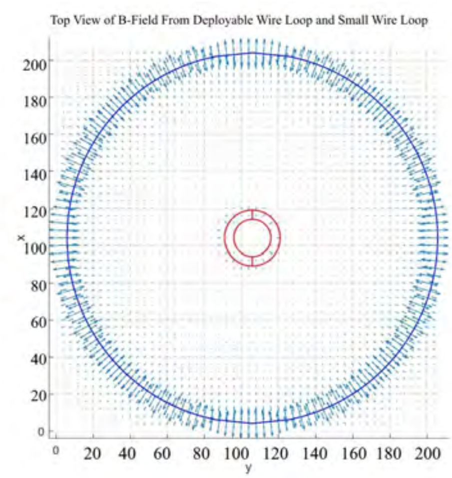

FIG. 20. Top down view B-Field from wire loops

predictions correct and demonstrating our calculations are accurate.

We also plotted a 3D vector field of the magnetic field produced from a split toroid without the toroid caps. Our maximum B-field vector had a magnitude of 0.5753 T which is very close to our calculated 0.6032 T. This is a difference of 4.6% which is expected since we assumed the toroid followed the same equations as a solenoid. The inclusion of the caps should increase the magnetic field slightly because the caps will make it a fully confined field. These plots can be seen in FIG. 21-23.

We made one last simulation of the magnetic field of the wire loops from a zoomed out view. This simulation shows the 3D vector field of the wire loops far away from the wires. The vectors follow a similar path to Earth's magnetic field. These simulations can be seen in FIG. 24-26.

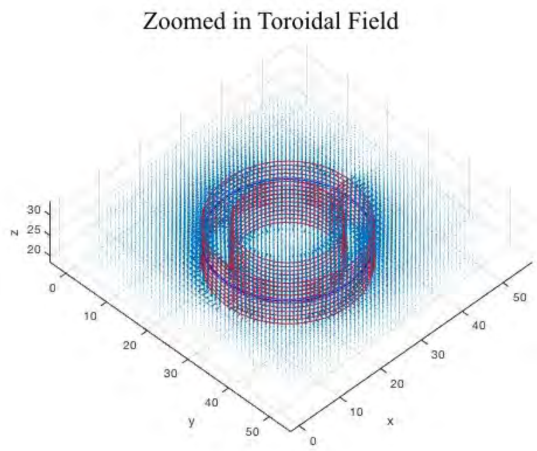

FIG. 21. B-Field from split toroid without caps

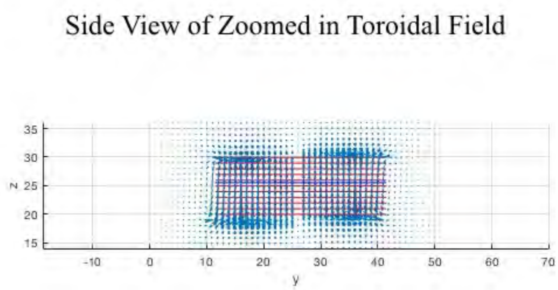

FIG. 22. Side view B-Field from split toroid without caps

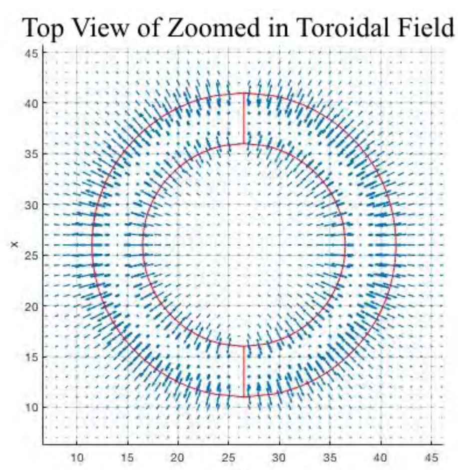

FIG. 23. Top down view B-Field from split toroid without caps

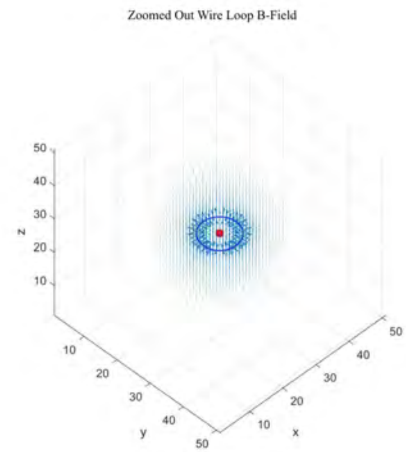

FIG. 24. B-Field from wire loops

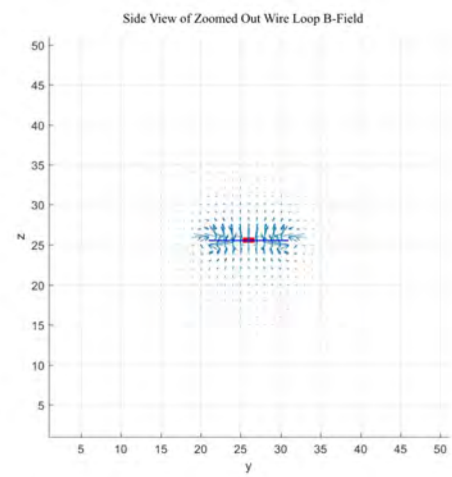

FIG. 25. Side view B-Field from wire loops

The values of the simulated B field at different heights above the polar radius can be seen in Table V. The altitude of simulation values are in multiples of 20 m starting at 8 m since the equivalent polar radius of the wire loop is 212 m.

If we graph both the magnetic field values and their altitudes, we can see the fields are very similar. They will not be equal because the simulated B field includes the smaller loop with opposite current. Even with this extra loop, the values of the B field are very similar since the small loops radius is significantly smaller than the deployable loop's radius. This graph can be seen in FIG.27.

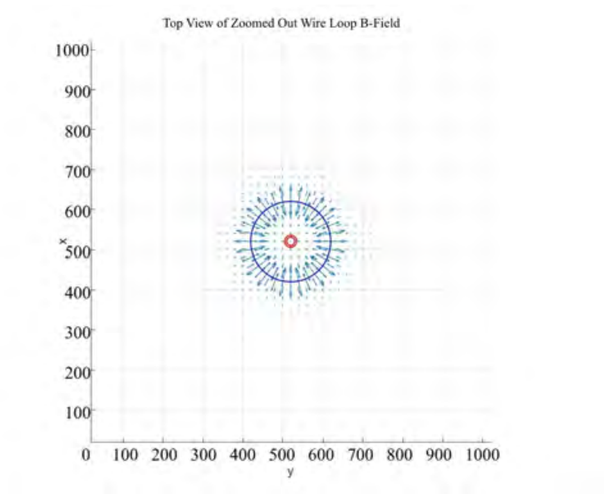

FIG. 26. Top down view B-Field from wire loops

Simulated $\lvert B\rvert$ (nT)	Altitude of simulation (m)	Earth's $\lvert B\rvert$ (nT)	Equivalent Altitude (m)
57105	8	56947.2	0
46154	28	56705.9	0.346
37752	48	55752.6	1.73
31220	68	54587.7	3.46
26078	88	52344.2	6.92
21984	108	46255.8	17.3
18688	128	37941.9	34.6
13812	168	14010.2	138.4
6423	288	5371	274.4

TABLE V. B field of simulation vs expected B field values

All of the simulated B-Fields align closely with what we expected. They demonstrate the crew habitat is safe from intense magnetic fields and that the magnetic field magnitudes are what we expected. This project did not have enough time to simulate a particle interacting with our B fields due to the time constraint of one year. We were also not able to simulate a magnetic field of the toroid with caps. We were able to simulate the magnetic field of an uncapped split toroid, but we know

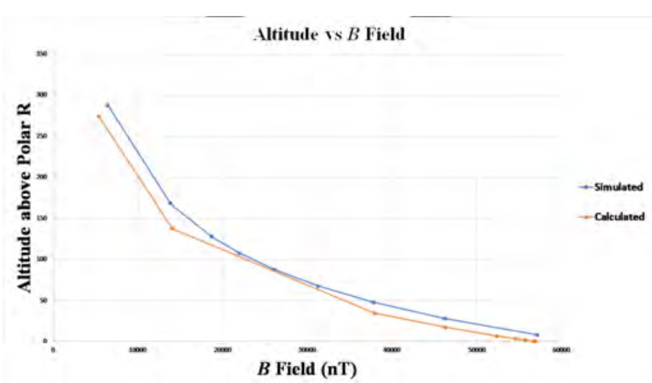

FIG. 27. Top down view B-Field from wire loops

our calculations should be correct based on the fact that the toroid will hold a uniform B field in theory.

X. ANALYSIS AND FUTURE RESEARCH

As stated previously, the assumption that the induced plasma will have the same shielding effectiveness may not be accurate. Our proposed design, however, is adjustable in the number of wire loops and the radius used. This paper is not meant to be an exact specification of a ship design, but to demonstrate the shielding concept to be plausible and reasonable. Before this concept is fully confirmed or rejected, more research must be done.

Research must be done in space just as the AMPTE comet experiment was conducted. An accurate model for the plasma effects and characteristics on an induced plasma must be tested in space while subject to the solar wind. This would not be a complicated experiment, but simply expensive to get a wire loop and some sensors into space outside of Earth's magnetic field. With Space X's reusable rockets, the price of sending mass to space is continuing to drop making this experiment cheaper to do as time goes on. A simulation on Earth in a lab can only do so much as GCR radiation is coming from all direction and all energies which cannot be accurately simulated in a lab setting.

Research must also be done to calculate exactly how much synchrotron and bremsstrahlung radiation is produced from the induced plasma and the magnetic fields. The magnitude of this radiation is dependent on the effects of plasma and the acceleration that the radiation particles undergo.

The shielding effectiveness of BNNTs must be further studied as well. The space environment will subject it to radiation extremes and the limits of this material must be analyzed.

A method of keeping the Ti-MgB_2 superconducting wire must be kept at a low temperature to ensure it does not rise above its critical temperature of 39 K. The SR2S project explored a design for a sunshield to keep the wires at a low temperature using V-groove shields [27]. If a sunshield can adequately keep the superconducting wires cool, it would dramatically decrease the weight and cost of the ship as liquid helium cooling system would not be required.

Once the above concepts are understood, an accurate method of simulating the full shielding ability of the design must be used to determine the shielding effectiveness, produced power, and produced thrust.

Finally, the engineering feasibility must be researched.

Although this concept does not require more challenging engineering than previously proposed concepts, research will be needed to determine how easily this concept can be constructed, what it would cost, how structurally sound it is, and its durability.

XI. IMPLICATIONS

The implications of this concept are huge. The travel time to Mars is potentially faster. If reasonable thrust can be produced from the magnetic fields, this could decrease the need for chemical propulsion on future space missions. Astronauts could spend much longer times in space for missions opening up greater possibilities of exploration.

Because this concept relies on an induced plasma, it may take some time for the radiation to be captured. This means it might be beneficial to have this ship unmanned and orbiting Earth until a solar flare erupts and floods the magnetic field with radiation. If this is the case, it would be more beneficial to have this concept as a mobile space station which does not land on a planet, but sends up and down a small vehicle from a planet, similar to the ISS. This smaller vehicle would need to pass through the magnetic poles of the wire loop when approaching the ship as to not subject the astronauts to high levels of radiation.

XII. CONCLUSION

In conclusion, this paper is by no means a final design or adequate proof of this concept, but a description of a proposed concept to solve the problem of radiation shielding. Our concept uses several methods of shielding working together to produce a design using confined and unconfined magnetic fields and passive shielding that adequately shields astronauts from radiation, produces thrust from redirected particles, and produces usable power from captured synchrotron and bremsstrahlung radiation. This concept relies entirely on the plasma effects and specifications of an induced plasma from a magnetic field in space. More research must be done in order to demonstrate this concept as plausible.

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