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Other sources of error in the system are as follows: 1) fluctuations in coupling factors with frequency both at the output coupler used for power leveling and at the input coupler to the LNA; 2) variation of antenna gain with frequency.

Since both of these effects are broadband in nature, the systematic errors incurred over the relatively small sweep bandwidth are likely to be extremely small ( $<0.1$  dB). These effects can usually be ignored, but may be accounted for if necessary when maximum accuracy is required by prior measurement during the installation phase of an Earth station. The data obtained can then be used in software correction of the measured response. For Earth stations already in operation, practical and economic considerations will determine whether these systematic errors are to be calibrated out.

### Conclusions

Results from tests made with the OTS satellite indicate that the technique described for the determination of a satellite repeater amplitude-frequency response gives improved accuracy and reliability as compared with standard procedures. This arises from three factors: pilot injection for receive chain measurement, reference carrier transmission in a neighboring channel, and automatic system calibration in the receive chain. Advantages claimed for the technique described are as follows:

- 1) The effects of propagation are largely eliminated.
- 2) The effects of satellite motion are largely eliminated.
- 3) The measurements are repeatable and precise.
- 4) A high degree of automation is achievable, resulting in rapid measurement.
- 5) No prior knowledge of transponder operating point is required.

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## HZE Particle Shielding Using Confined Magnetic Fields

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### Introduction

IN future, long-duration, manned space missions, chronic exposure of flight crews to the high-energy heavy-ion (HZE) component of galactic cosmic radiation appears to be

potentially hazardous.<sup>1,2</sup> For galactic heavy ions with energies above 100 MeV/nucleon, typical daily fluences in interplanetary space are approximately 100 nuclei/cm<sup>2</sup>. Although not large when compared to proton or electron fluences, their unique damage mechanisms and cumulative adverse effects on nonregenerative tissues (e.g., eyes and the central nervous system) are important considerations for longer missions.<sup>2</sup> Since these particles are charged, shielding may be accomplished either by ionization and nuclear fragmentation (breakup) in passive bulk material shields<sup>3-5</sup> or by active means such as deflection of the incident nuclei by electromagnetic fields. Proposed concepts for the latter include the use of electrostatic fields,<sup>6</sup> plasma,<sup>7</sup> and confined<sup>8,9</sup> or unconfined<sup>10,11</sup> static magnetic fields.

The primary focus of each of these proposed active methods has been to shield against space protons and electrons, especially during periods of intense solar activity. Except for the unconfined magnetic field configuration of Ref. 10, none of the analyses considered HZE particles. For the unconfined field configuration, magnetic shielding offers substantial weight savings over passive shielding for large permanent habitats (colonies), but not for the smaller vehicles likely to be utilized for near-term exploration.<sup>10</sup> Since the HZE particle kinetic energies of interest are on the order of 1 GeV/nucleon, electrostatic shielding can be immediately dismissed as an alternative since the required potentials are in the range of tens of gigavolts. Shielding by plasma will not be considered here since the required potentials and plasma densities are too large to be attainable in the foreseeable future. In this work, attention is focused on examining the suitability of confined magnetic field designs as HZE particle shields. Particular attention will be given to the potential utility of the Mars class design,<sup>9</sup> which displayed substantial weight advantages for shielding against solar protons when compared to equivalent bulk material shields.

### HZE Particle Analysis

For a charged particle moving under the influence of a constant magnetic field, the rigidity (momentum per unit charge) is given by<sup>12</sup>

$$R = pc / Ze \quad (1)$$

where  $p$  is the particle's momentum,  $Ze$  its charge, and  $c$  the velocity of light. The rigidity is also related to the radius of curvature (Larmor radius)  $r$  and magnetic field intensity through the relation

$$R = 0.003 Br \quad (2)$$

where  $B$  is the component of the magnetic field intensity,  $T$ , which is perpendicular to the particle's momentum. The rigidities in Eqs. (1) and (2) are given in gigavolts (GV). From Fig. 1, the most critical trajectory for shielding is grazing incidence. If the "thickness" of the confined magnetic field  $\Delta$  is greater than or equal to the Larmor diameter ( $\Delta > 2r$ ), the particle trajectory will not intersect the shielded volume. Since HZE particle motion is usually described in terms of its kinetic energy per nucleon (rather than its total momentum), Eq. (1) can be rewritten as

$$R = A (T^2 + 2m_0c^2 T)^{1/2} / Ze \quad (3)$$

where  $T$  is the kinetic energy per nucleon (GeV/nucleon),  $A$  the number of nucleons (mass number), and  $m_0$  the nucleon rest mass ( $m_0c^2 = 0.939$  GeV). Equation (3) is general in that it is valid for any nuclear species ( $Z, A$ ) at any incident kinetic energy. For simplicity, we now restrict the analysis to iron nuclei ( $Z=26, A=56$ ), which are among the dominant radiobiologically damaging species in space.<sup>2</sup> For a typical kinetic energy of interest ( $T \approx 1$  GeV/nucleon), Eq. (3) yields a rigidity of  $R = 3.654$  GV. Present state-of-the-art in continuous magnetic field generation<sup>13</sup> is approximately 25 T.

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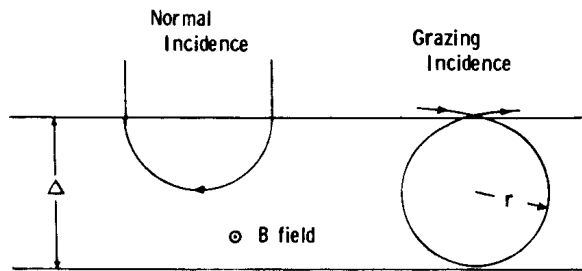


Fig. 1 Charged particle trajectories in a confined magnetic field for normal and grazing incidence.

Hence, from Eq. (2), the Larmor radius in this field is  $r = 48.7$  m. Thus, the required shield thickness is nearly 100 m. Since magnetic fields of 25 T exceed critical field strengths for superconducting coils, they are generated by resistive magnets that are extremely bulky and require vast quantities of power<sup>13</sup> ( $\approx 10$  MW for a laboratory version). For superconductors, the limiting field intensity is  $\approx 12$  T, which yields a required shield thickness of 203 m. As will become apparent in the following section, these dimensions imply a shield mass increase of several orders of magnitude.

### Mars Class Shield Analysis

The design of the Mars class shield<sup>9</sup> was based upon a typical Mars class mission of 2-3 yr with a crew of 10 astronauts. Total solar flare exposure time for the mission was assumed to be no more than 5% of the total trip, with a maximum duration of 7 days for any particular flare. Within these constraints, a spacecraft consisting of two concentric spheres (radii of 2 and 3 m) was designed. The shielded inner sphere (30 m<sup>3</sup> volume) housed the astronauts. The magnetic field, confined to the annular region between the spheres, was generated by a set of nested toroidal superconducting coils that were cryogenically cooled. A simple sketch of the shield configuration is shown in Fig. 2. The optimum magnetic field strength, for shielding against protons at energies up to 170 MeV, was 4 T. Thus, for grazing incidence, the Mars class shield design rigidity from Eq. (2) is  $R = 0.006$  GV. Since this rigidity is orders of magnitude smaller than the iron nucleus rigidity of 3.654 GV, the design Mars class shield is clearly ineffective as an HZE shield. For the design configuration, the Mars class shield is effective only for those iron nuclei whose kinetic energies are less than 5 keV/nucleon. Retaining the design dimensions, the magnetic field intensity required to shield against iron nuclei is  $B = 2436$  T from Eq. (2). This is two orders of magnitude greater than present state-of-the-art. Increasing the radius of the outer sphere to 205 m yields a more realistic 12 T for the magnetic field intensity. The increase in shield mass  $M_s$  can be estimated using the relation<sup>8</sup>

$$M_s \propto B\rho^2 \quad (4)$$

where  $\rho$  is the radius of the outer sphere. For the design Mars class shield:  $\rho = 3$  m,  $B = 4$  T, and  $M_s = 10^4$  kg. For use as a shield against iron,  $B = 10$  T and  $\rho = 205$  m yields a new shield mass of  $M_s \approx 10^8$  kg, an increase of four orders of magnitude. Whether such a magnetic shield would retain its weight advantage over a comparable bulk material shield cannot at present be determined since the HZE reaction and transport theories are not sufficiently well developed to enable accurate bulk material shield analyses to be performed. It seems unlikely that it would, since the confined field shield mass is now comparable to that required to shield much larger permanent habitats with unconfined fields.<sup>10</sup> Using the nuclear absorption mean free path

$$\lambda \approx (N\sigma)^{-1} \quad (5)$$

a very crude estimate of the required bulk shield mass can be made. For iron nuclei at 1 GeV/nucleon colliding with an aluminum shield, the nuclear absorption cross section<sup>14</sup> is

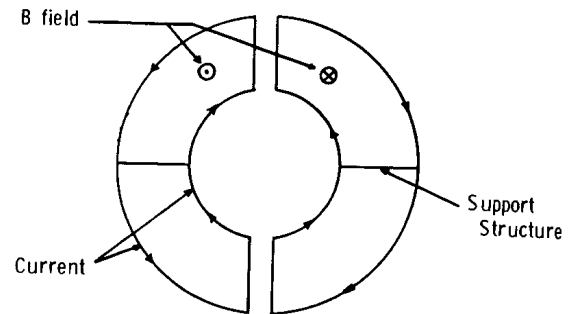


Fig. 2 Simplified sketch of hybrid torus magnetic field configuration.

$\sigma \approx 2.1 \times 10^{-24}$  cm<sup>2</sup>. For aluminum, the number density is  $N \approx 6 \times 10^{22}$  cm<sup>-3</sup>. From Eq. (5) the mean free path is approximately 8 cm. Choosing the shield thickness to be twice this value yields, for the Mars class design, an estimated bulk shield mass of  $\approx 2.5 \times 10^4$  kg. Note that this is several orders of magnitude smaller than the estimated mass of  $10^8$  kg for the confined magnetic field configuration.

### Conclusion

The very large rigidities of HZE particles appear to preclude the near-term use of confined magnetic fields of reasonable physical dimensions and strengths for shielding of small spacecraft. In particular, these results have demonstrated that the design Mars class shield, although effective as a solar-proton shield, is effectively useless as an HZE shield unless the mass and size of the shield are increased by several orders of magnitude, resulting in a shield mass comparable to that required for a much larger permanent space habitat.

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