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Spacecraft Radiation Shielding Using Ultralightweight Superconducting Magnets

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This work examines the performance and feasibility of a novel inflatable lightweight spacecraft radiation shielding system employing superconducting magnet technology. In the proposed approach a set of lightweight toroid-shaped coils surround a spacecraft creating strong shielding fields, which are wholly contained within the volume of the coils, leaving the spaceship free of magnetic fields. A numerical model and Monte Carlo optimization tool were developed to simulate the interaction of ionizing particles with various confined magnetic field configurations and geometries. Using an isotropic distribution of protons with kinetic energies ranging from 0.1 to 2 GeV, the model was used to explore a wide parametric space of potential spacecraft shielding options and to assess which parameters are most responsible for determining shielding effectiveness. For a candidate spacecraft, it was found that more than 90% of incident particles with a 1-GeV kinetic energy could be deflected away from the spacecraft using a 5-T toroid-shaped shield.

Nomenclature

a = radius of the wire loop, m
B = magnetic field intensity, T
B_r = radial component of the magnetic field, T
B_z = axial component of the magnetic field, T
c = speed of light, 299,792,458, m/s
E_k = kinetic energy of particles, eV
E_0 = energy of particles at rest, eV
F = Lorentz force, N
I = current in conductors, A
m = relativistic mass, kg
m_0 = rest mass, kg
N = number of conductor turns
N_{OFF} = number of particles that hit the spacecraft when there is no shield
N_{ON} = number of particles that hit the spacecraft when the shield is active
p = particle momentum, GeV/c
q = charge of particle, C
r = radial distance from the center of the toroid, m
V = velocity of particle, m/s
η = efficiency
μ_0 = vacuum permeability, $4\pi \times 10^{-7}$, V T m/A
ρ = radius, m
φ = azimuthal direction

I. Introduction

SPACECRAFT carrying human missions to Mars will be exposed to ionizing radiation for extended periods of time. Exposure of the crew and instrumentation to such radiation must be minimized. Hazardous radiation may originate from the sun in the form of solar wind or flare-ups, or may be in the form of high-energy galactic radiation which pervades the solar system. Althogh low-energy particles may be absorbed by spaceship walls, higher momentum particles (>100 MeV/c) require heavy shielding with thicknesses of up to several centimeters for absorption [1–4]. Alternative low-mass shielding methods would benefit space missions by reducing the gross liftoff weight. Recent advances in high-temperature superconductors and magnet technology suggest the possibility of using high-strength magnetic fields to repel charged particles over a wide energy range. In the proposed approach a set of lightweight toroid-shaped coils surround a spacecraft creating strong shielding fields, which are wholly contained within the volume of the coils, leaving the spaceship free of magnetic fields. A mathematical model was developed to predict the ability of the shield to repel high kinetic energy particles away from the spacecraft. The tool was then used to optimize the design of a radiation shielding system for a spacecraft approximately sized for a human mission to Mars. Protecting the spacecraft using the proposed system would improve safety while minimizing the considerable mass penalty associated with an equally effective passive shielding approach.

II. Superconducting Magnetic Shield Concept

This section presents an overview of the superconducting magnetic shielding concept, as well as basic design parameters and operation of the shielding system in a space environment.

A. Lorentz Force and Toroidal Magnetic Fields

In the same way that prisms and lenses are used to bend, focus, or defocus light rays, charged particle trajectories are affected by magnetic fields due to the Lorentz force which is mutually perpendicular to the direction of particle motion and the magnetic field, as shown in Eq. (1):

$$\mathbf{F} = q \cdot (\mathbf{V} \times \mathbf{B}) \tag{1}$$

Because the particle energy, charge, and velocity are not altered by static magnetic fields they are independent of the shielding design. To deflect particles away from the spacecraft, forces must be large and are set by the magnetic field intensity B according to Eq. (1). For example, if a charged particle moves in a constant magnetic field, its

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