Spacecraft Scale Magnetospheric Protection from Galactic Cosmic Radiation

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The Radiation Hazard

Legal Limits based on annual exposure (radiation workers)
–5 REM/year in USA with guideline of <10 REM/5 years

- **Epidemiological studies cannot track risk at <5 REM (acute) or <10 REM (lifetime)**

Actual Doses:

-Sea Level Background Exposure	0.005 rad/year (.05 in brick houses)
-Airplane Cross-Country Trip	0.004 rem
-Chest X-ray	0.01 rem
-Typical Shuttle Flight	5.0 rem
-Living in Denver ("Mile-High City")	0.2 rem/year
-Dental X-ray	0.009 rem
-Apollo Moon Landings	0.2-1.1 rem
-Skylab (3 months)	7.4 rem
-ISS~	(0.1 rem)/day
-Estimated Mars trip (no solar flares)	100-150 rem

Rem is unit of radiation dosage applied to humans that causes the same biological injury as one rad of X rays or gamma rays.

SI units: the gray (Gy) [1 J/kg], where 1 gray = 100 rad.

Deep Space Radiation Environments

- Galactic cosmic rays (GCR)
  - Originate in supernovae remnants outside the galaxy
  - Includes everything on the periodic table (fully ionized)
  - Highly energetic, approaching the speed of light
  - Continuous, omnipresent background radiation in space

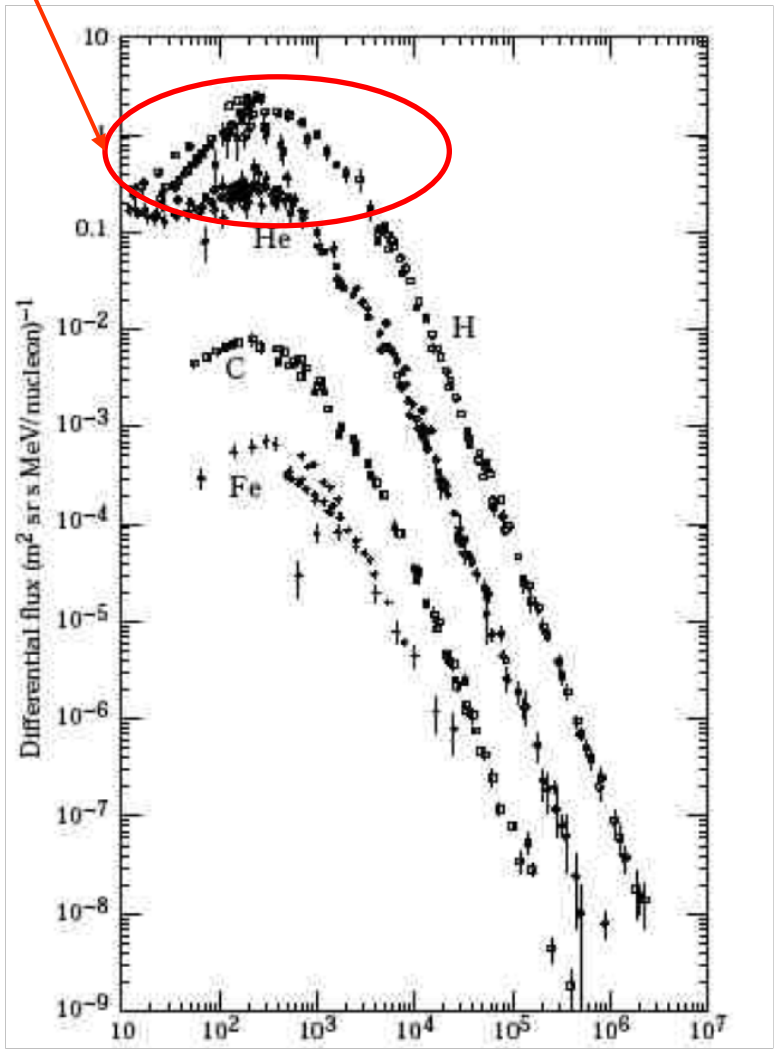
GCR are the main biological risk for human exploration missions

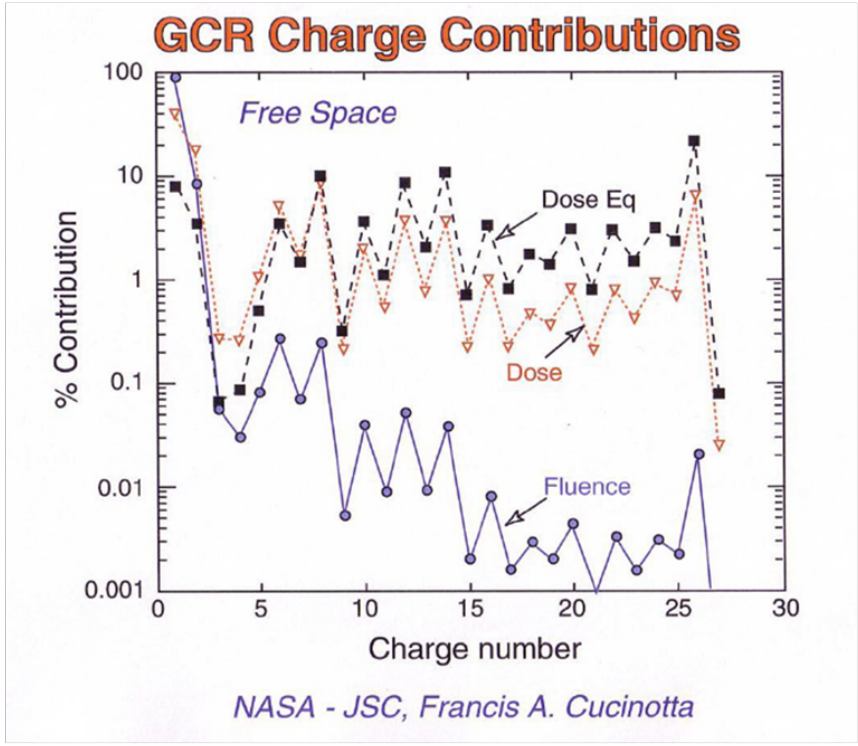


Slide from “The Space Radiation Environment and Ground Based Simulations” – Tony C. Slaba

Problem is primarily GCR GeV/nucleon particles

These are the particles That need to be stopped

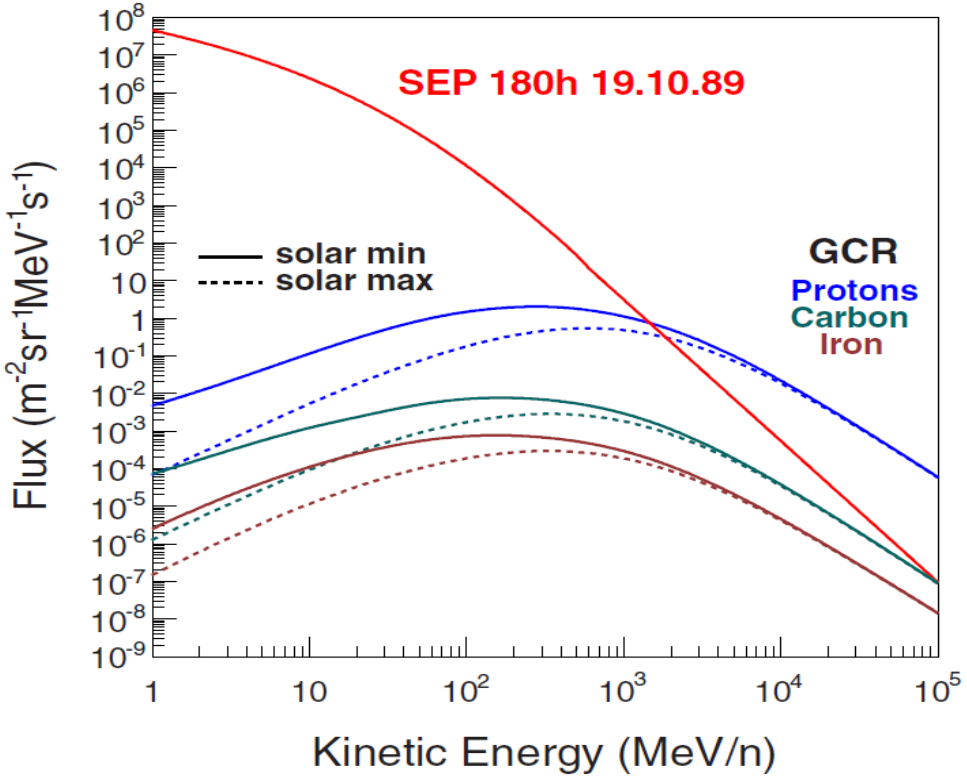




Unlike material shielding, magnetic Shielding has the same deflection effect on particles with the same charge to mass which is essentially a constant for all GCR nucleons

Radiation Environment in Space

Evidence of the Effectiveness of Magnetic Shielding

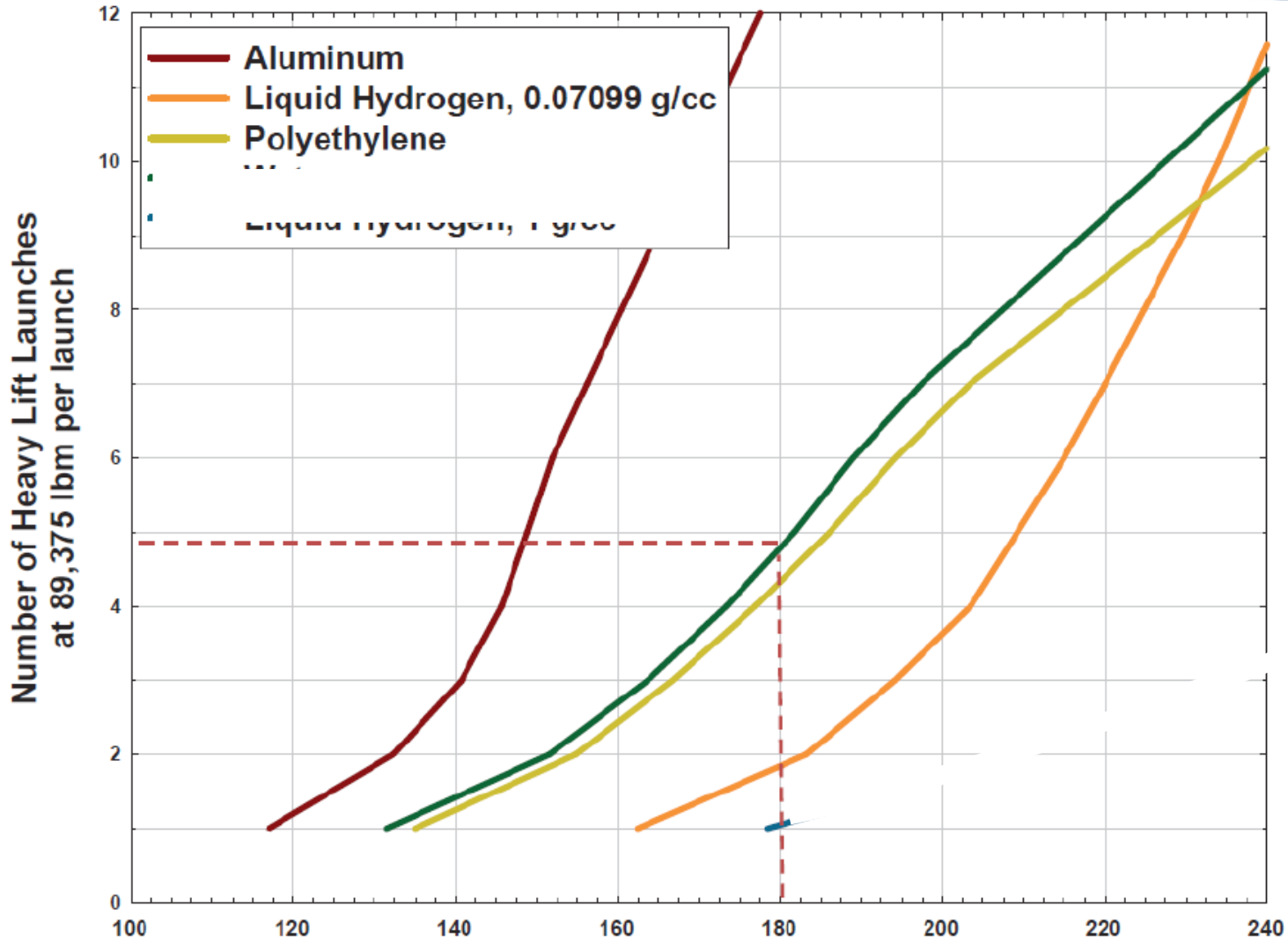


Intensification of the magnetosphere (B field) reduces exposure to GCR
(Low energies a lot
Higher energies a little)

The proton flux of a 10-day SEP event in 1989, and the GCR proton, carbon, and iron nuclei fluxes for solar minimum and maximum periods

Passive Shields





Per LaRC/R. Singleterry

Magnetic Field Requirements

Unlike the electric force, the magnetic force is a non-central force (induced motion NOT in the same direction as the force) ⇒

You can't slow or stop GCR with a magnetic field – you can only deflect it.

In order for a magnetic field to deflect a charged particle, the scale length of the magnetic field within the magnetic shield has to be comparable to the gyro-radius of the particle,

$$r_L = \frac{m v_\perp}{qB} \cong \frac{mc}{qB}$$

$$\mathbb{V}_{\perp,\mathrm{deflect}} \leq \frac{q}{m} \int \boldsymbol{B}_\perp \mathrm{d}r$$

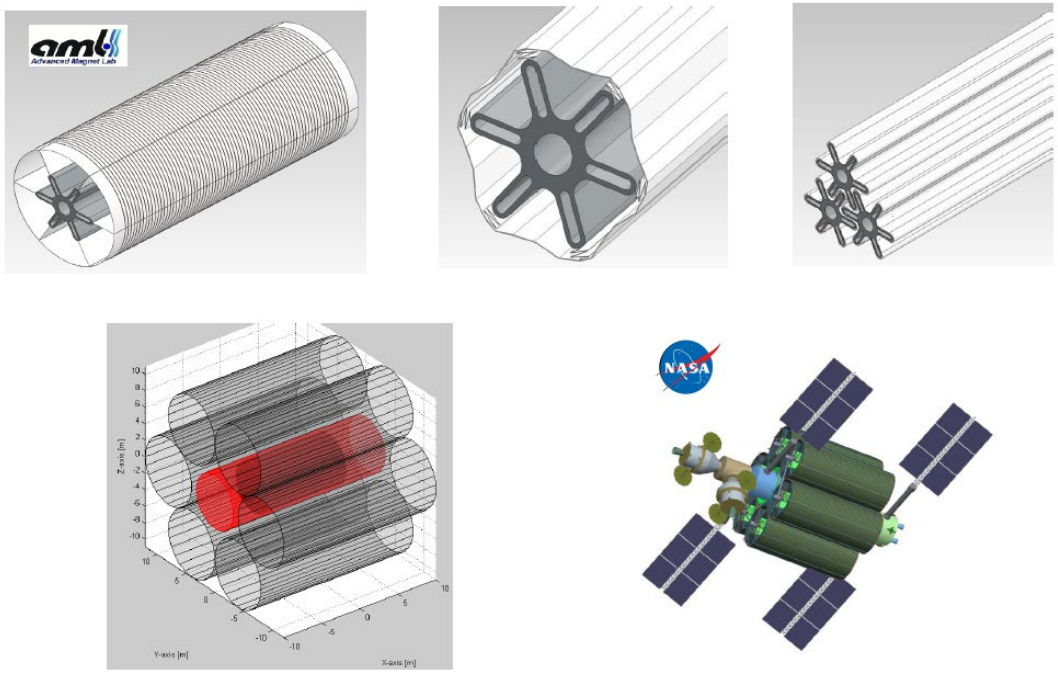
Deflection of GeV/nucleon particle would then require

$\int \boldsymbol{B}_\perp dr$ to be **~ 10 T-m**

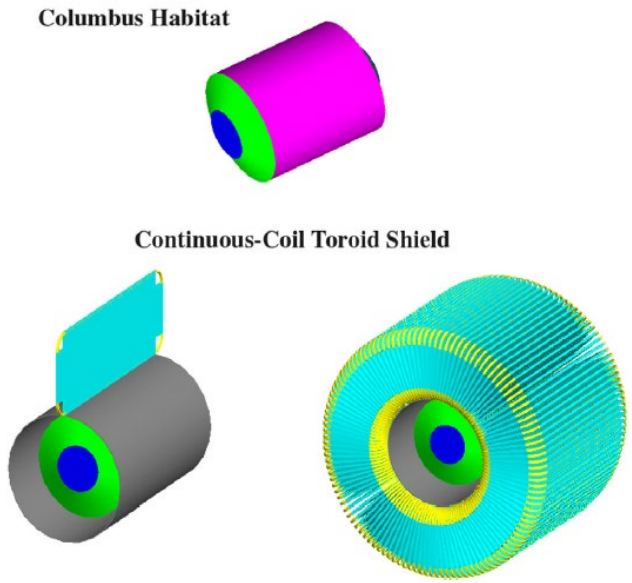
while solar wind particles would require only - 0.001 T-m.

Previous Major Concept Studies for Magnetic Shielding

(a) 6+1 Expandable Solenoid Coil Shield

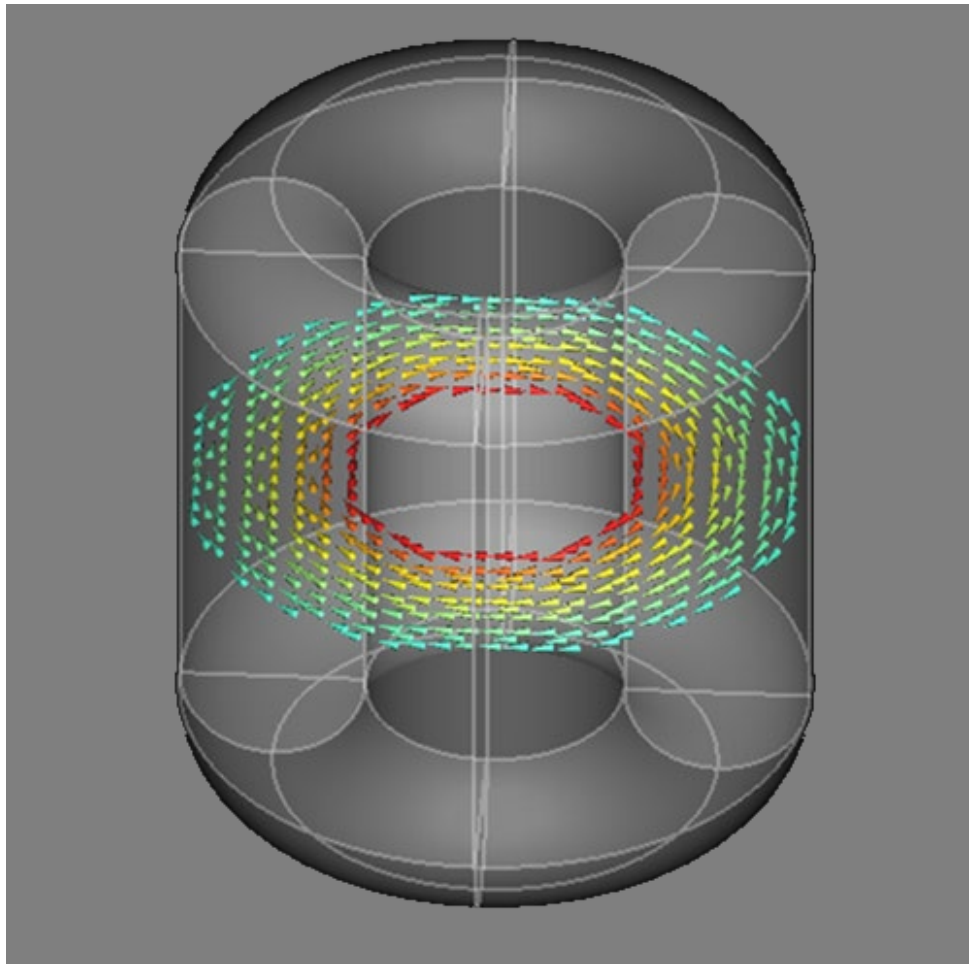


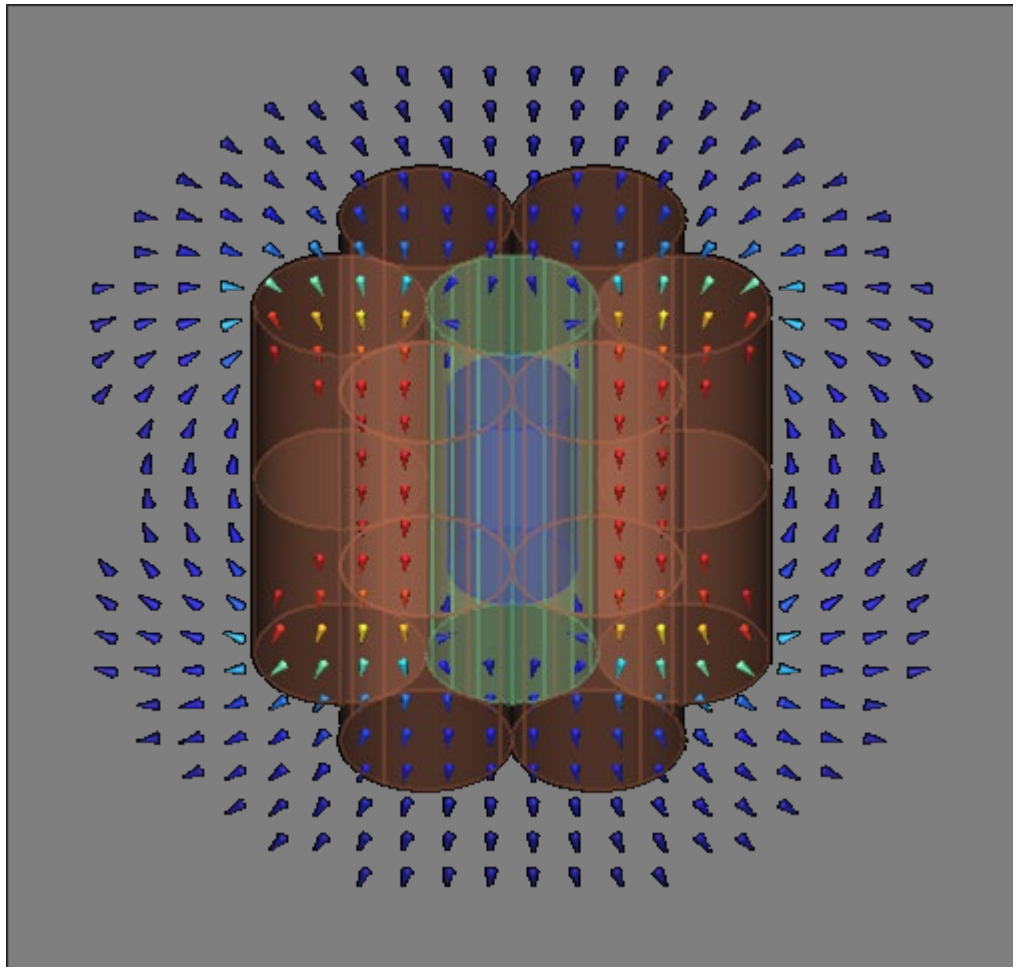
(b)



HTSC Magnet designs from (a) NIAC 6-1 Solenoid study, and (b) ESA Toroid study.

2-D B vector plots for ESA toroid (midplane) and 6-1 solenoids

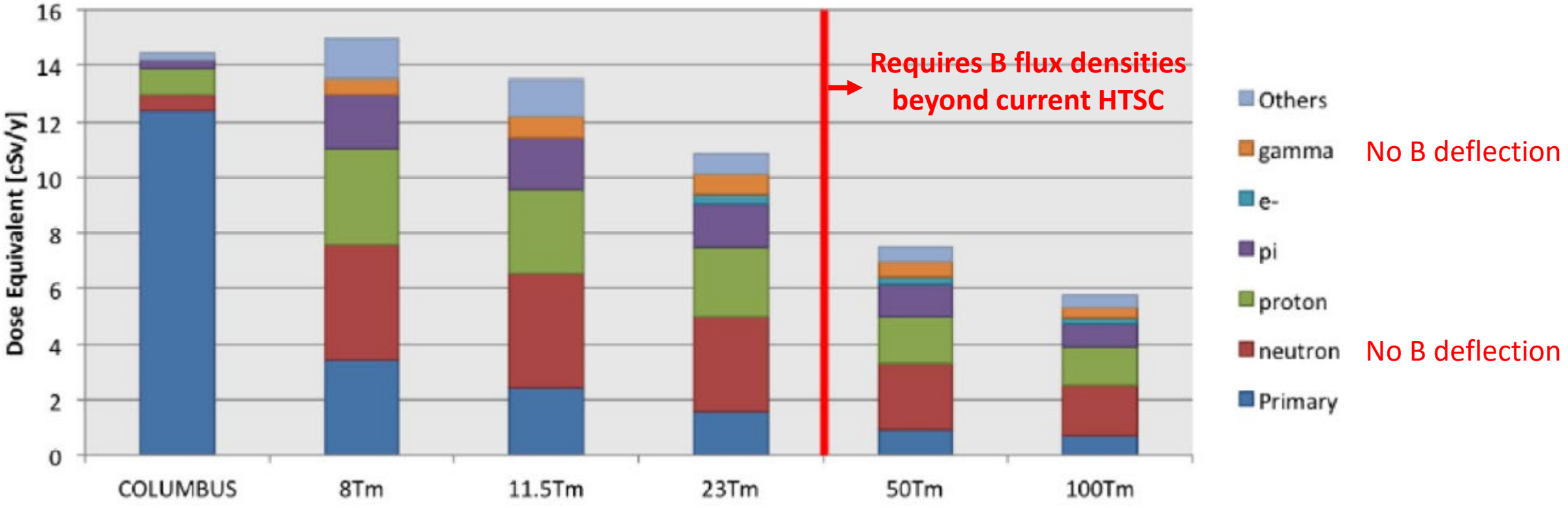




- The vectors are color coded red to blue indicating magnitude of the field. The plots range from the maximum field down to 5% of the maximum.
- The ESA toroid had no external fields larger han 1% of the maximum outside of the torus.

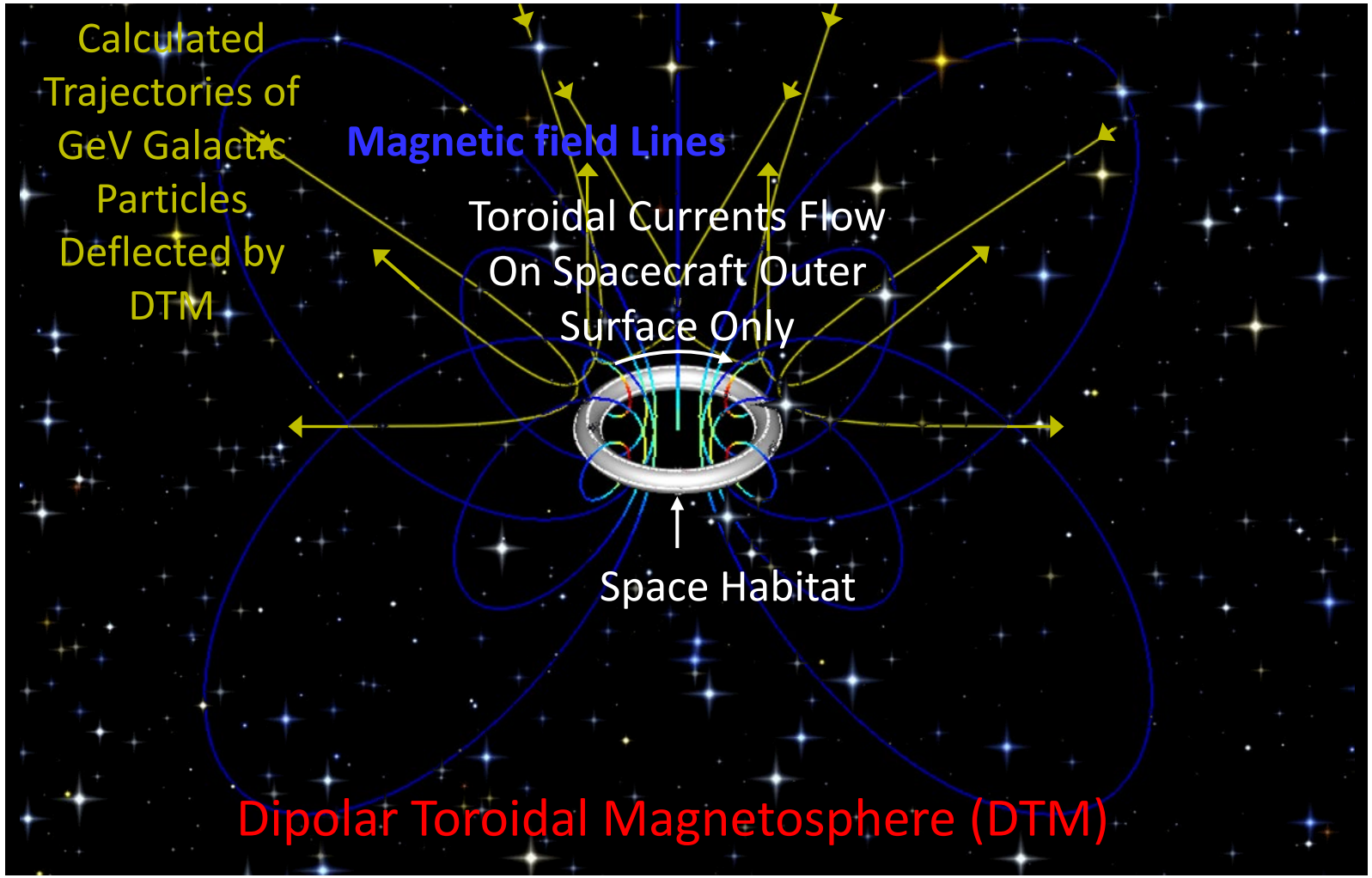
Big Problems with Previous Shielding Concepts

- **Neither the ESA toroid nor the 6-1 solenoids have significant B field in the spaceward direction**
- **These systems are essentially vulnerable to ALL GCR – even from the lowest energy ones that would be deflected by the shield**



The annual body dose equivalent of the primary GCR proton and He nuclei, with a breakdown of the contribution of each of the principal secondary particles.

Shielding Solution: Dipolar Toroidal Magnetosphere (DTM)

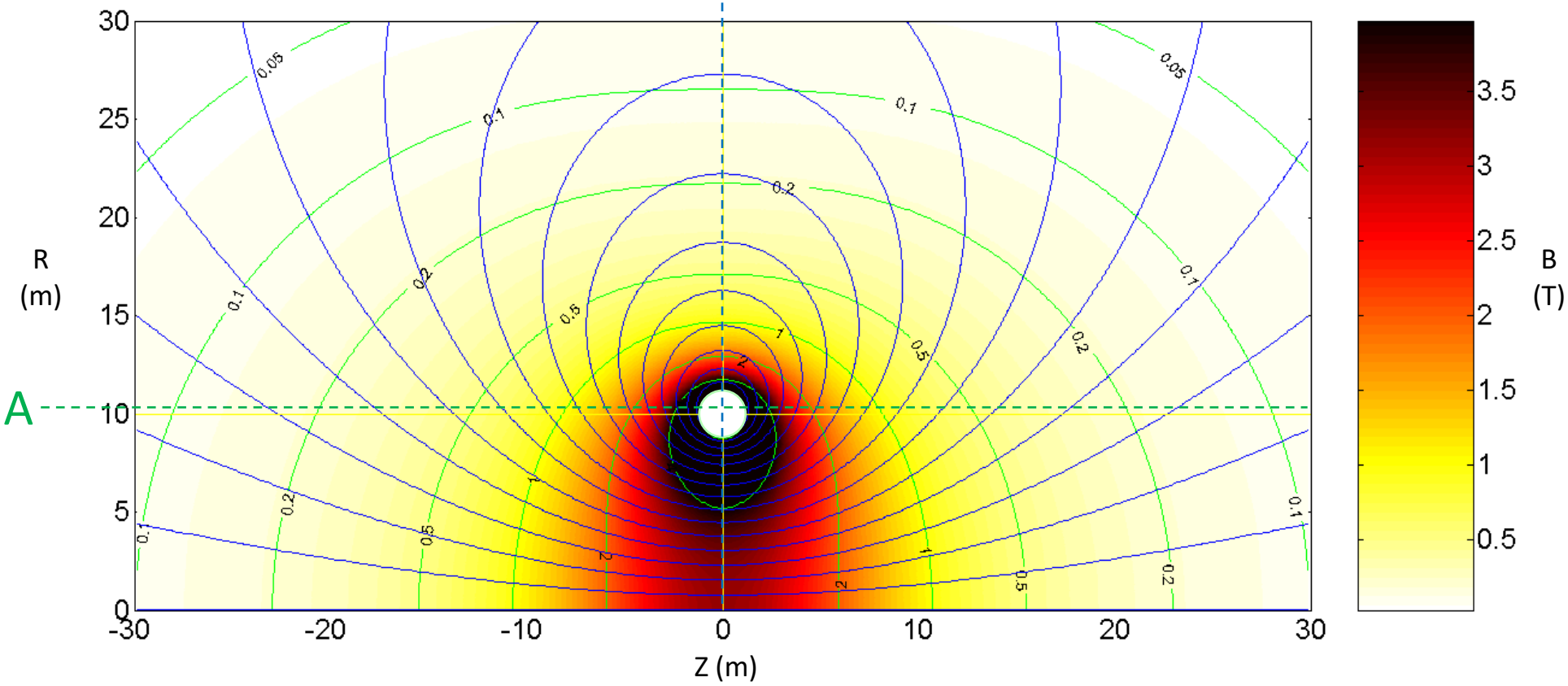


Dipolar magnetospheric shielding provided by toroidal currents Ic. The HTSC magnet (sliver colored shell) is placed external to the toroidally shaped space habitat. The magnet would fully surround the habitat to assure cancelation of all magnetic field inside the habitat.

Flux Lines and Magnetic Contours for a Dipole Torus at Spacecraft Scale Used for Initial GCR Shielding Calculations

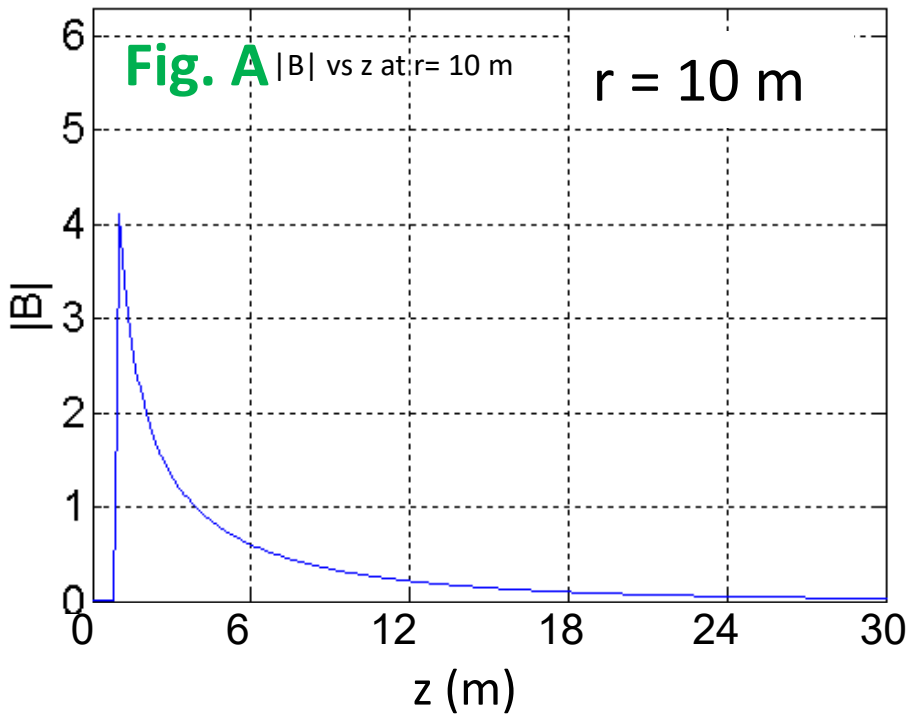
Fig. B

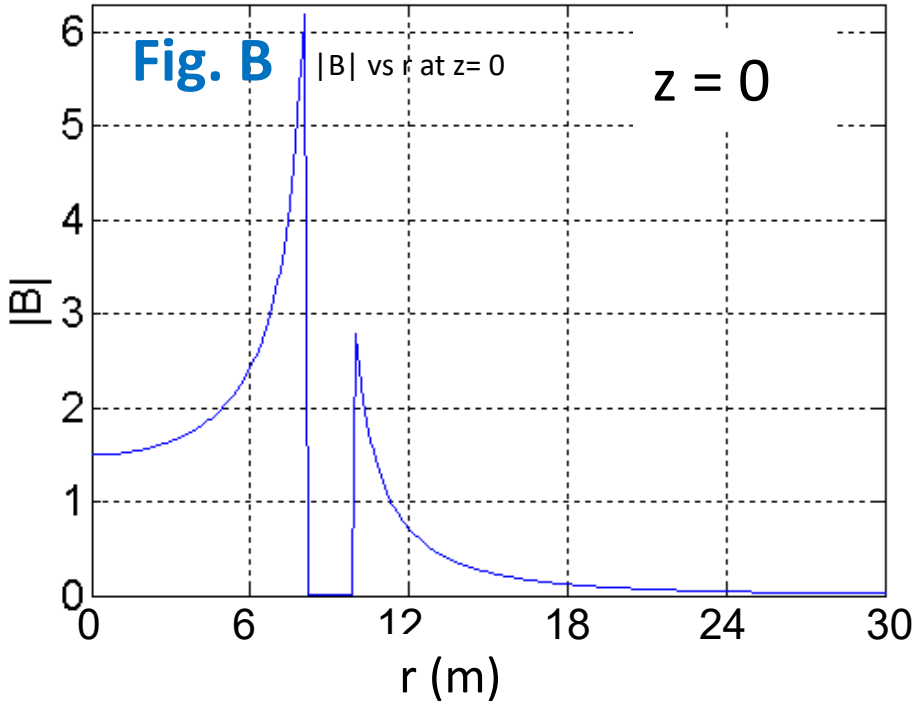
Fig. A



Here the current flows only at the toroid surface such that the magnetic field vanishingly small inside.

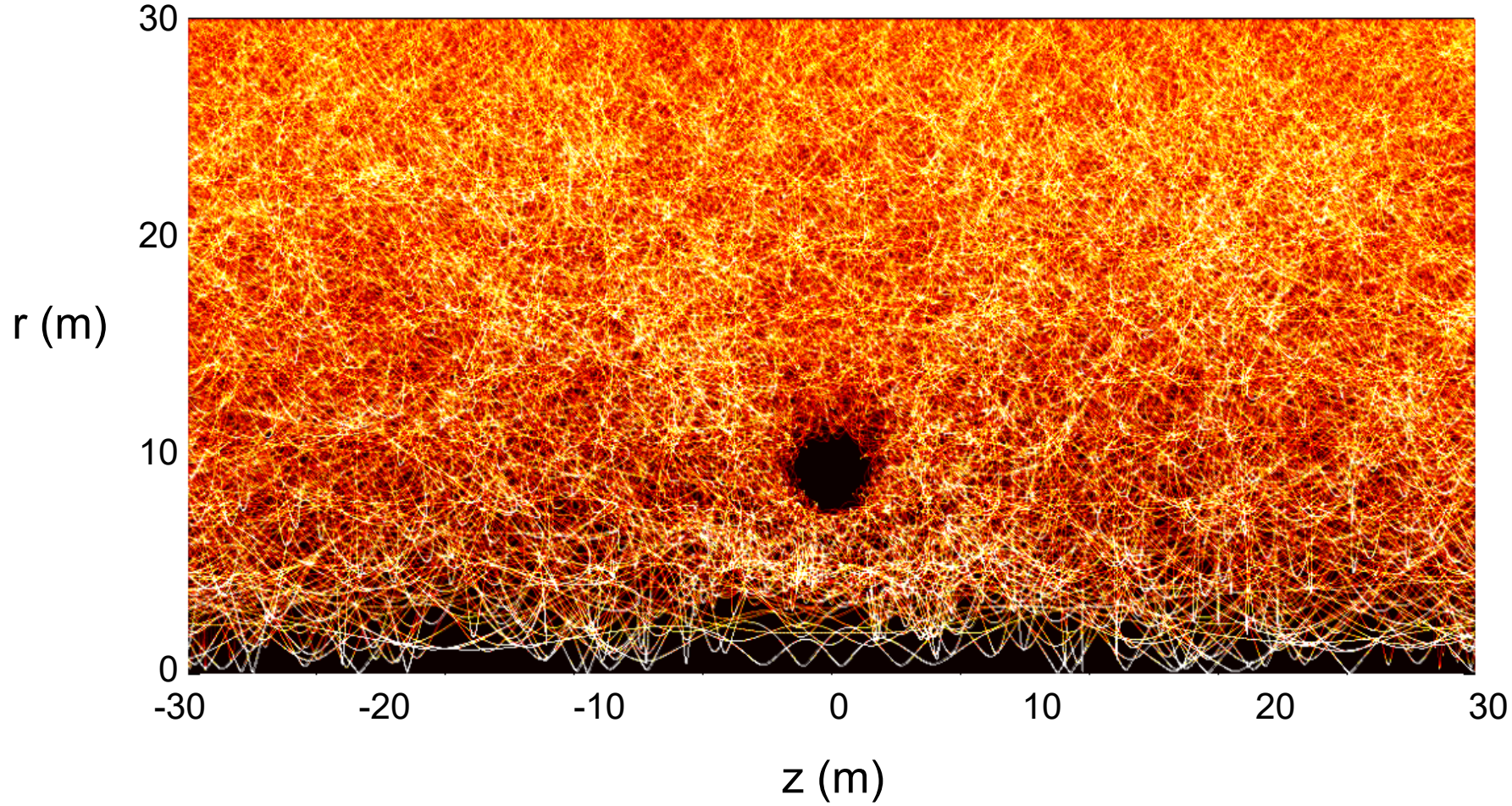
Magnitude of the Magnetic Field as a Function of Z on Axis and at the Dipolar Toroid Large Radius R





- **Currents must be arranged as above to produce ϕ = 0 surface at the toroid (habitat) boundary.**
- **Only for torii at very large aspect ratio (torus diameter/habitat diameter = α) does it approach uniformity poloidally.**
- **For a typical aspect ratio α ~ 10, a larger current must flow on the inner wall of the torus to produce the ϕ = 0 boundary shown.**

3D Particle Trajectory Calculations



Trajectories of 1500 isotropic 1 GeV particles on to dipole ring.

Apparent shielding at small R reflects the volume reduction as r ⇒ 0.

Comparison of prior proposed magnetic shielding geometries to the DTM

Four main criteria which will be used to evaluate the three most developed concepts

1) **Effectiveness of the magnetic shielding – Determined based on Ω parameter:**

$$\Omega = \frac{\sum_{n} I_n \cdot L_n}{\frac{1}{Vol_{Hab}}}$$

I_n – current in conductor n

L_n – length of conductor n

2) **Issues with secondaries - daughter particle generation from primary GCR**

3) **Launch and space assembly – The amount of mass, scale of structures, and complexity of assembly**

4) **Advantages and other uses for the shield outside GCR protection.**

Dipolar Toroidal Magnetosphere (DTM) Field Characterization

The shielding effectiveness can be characterized by the B_z field on axis at the center of the toroid (B_{00}), and the far-field dipole magnetic field $B_z(r)$:

$$B_{00} = \frac{\mu_0 I}{2R} \quad \text{and} \quad B_z(r) = gB_{00}\frac{R^3}{r^3}$$

where it was found that g = 0.5. B_{00} is typically less than the field strength at the torus boundary but serves the purpose of relating the field strength to the shielding effectiveness. If one assumes that an incoming particle penetration distance must be less than a characteristic deflection distance (shown on previous slide), one has:

$$\int_{l_1}^{l_2} \frac{dl}{r_L} \geq 1 \quad \rightarrow \quad \int_{r_0}^{\infty} B \cdot dr \geq \frac{m}{q}\gamma v$$

where the relativistic nature of the GCR particle is explicitly expressed. Integrating using expressions above one obtains:

$$B_{00} \geq \frac{m}{q}\frac{4\gamma v r_0^2}{R^3} \sim \frac{m}{q}\frac{4\gamma v}{R}$$

Magnetic coil surfaces and habitats assumed in the ESA-Toroid, NIAC 6-1 Solenoids, and DTM studies.

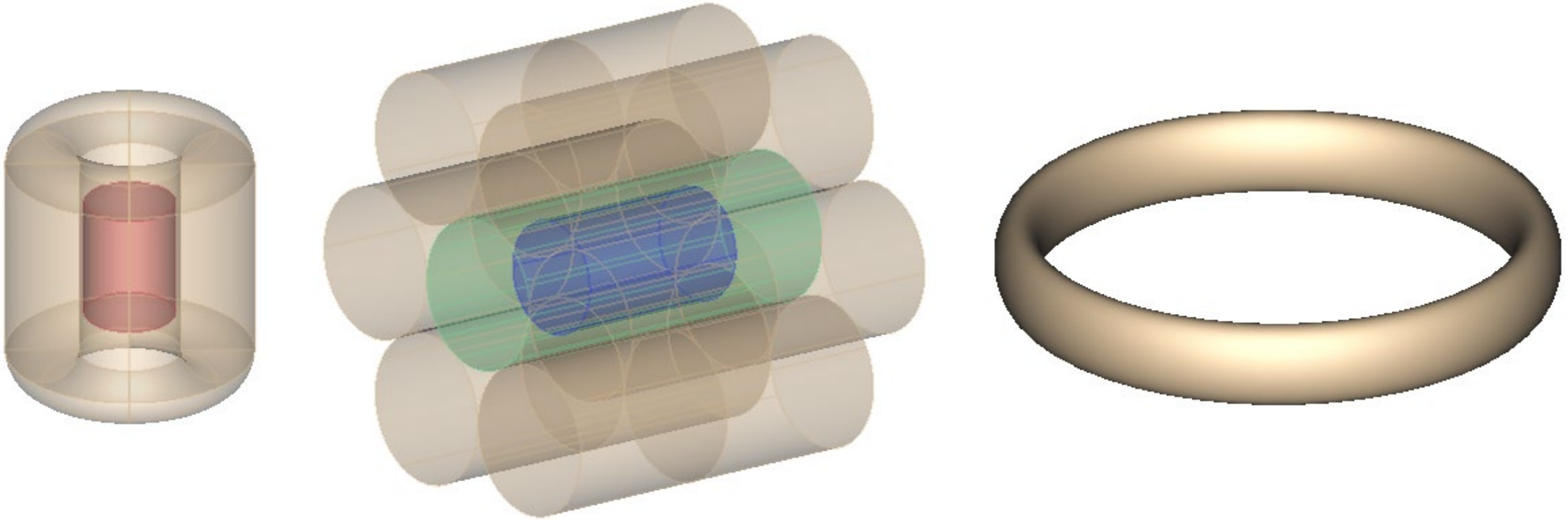
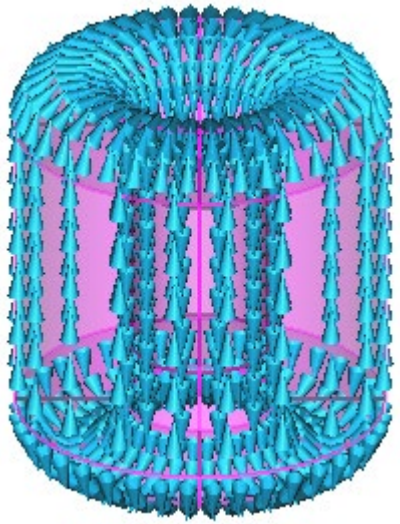
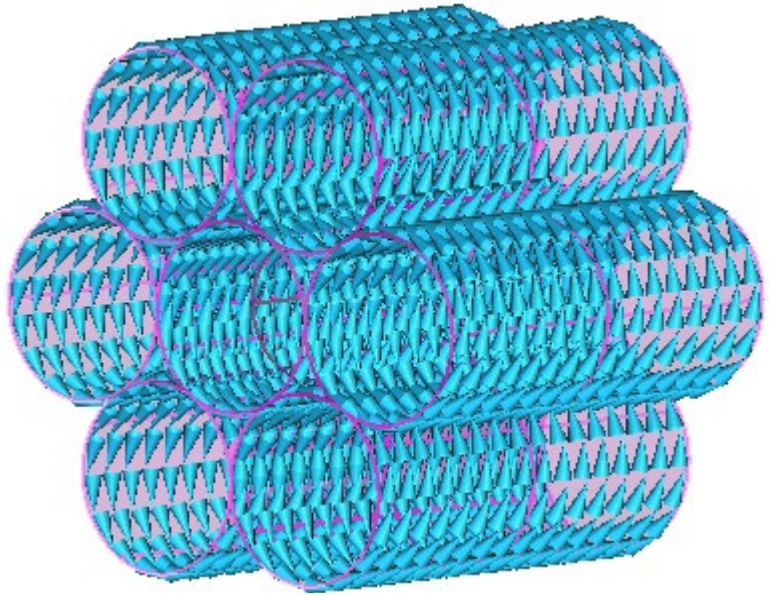
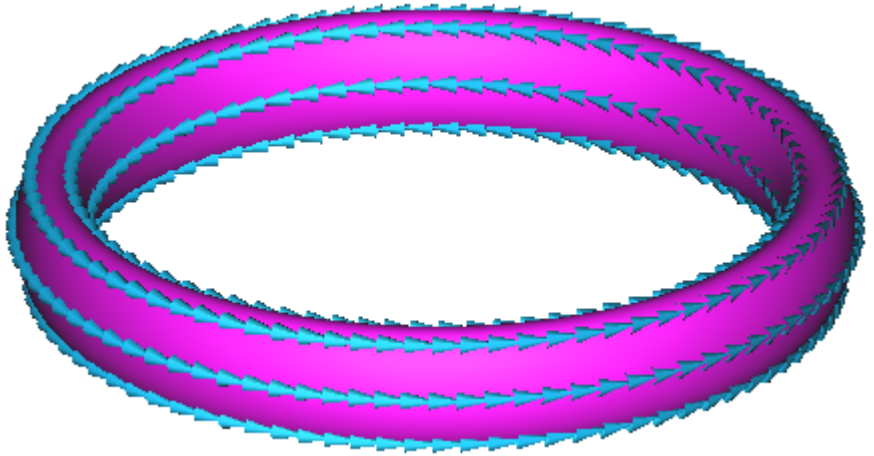


Figure 8. Left: ESA-toroid (length – 13.6 m, width at midplane – 3.6 m, bore – 3 m) with Columbus habitat inside (4.5 m diameter, 6 m long). Center: NASA 6-1 solenoids with 6 outer solenoids with inner solenoid carrying reverse current (8 m diameter, 20 m length). Cylindrical habitat is 3 m diameter and 10 m in length. Right: DTM with a toroid major radius of 12 m and a 4 m by 2.2 m elliptical cross-section. As the current coils are supported by the spacecraft habitat wall, the coil surface and habitat cannot be distinguished

Current Flow for the Three Candidate Shielding Concepts

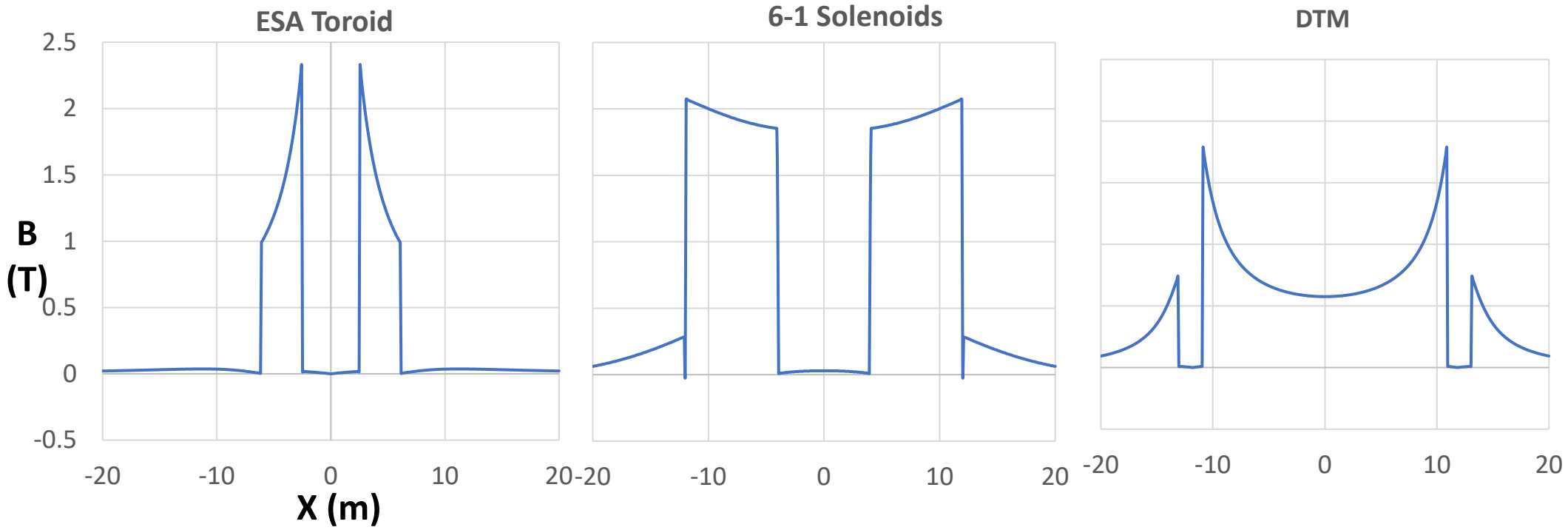






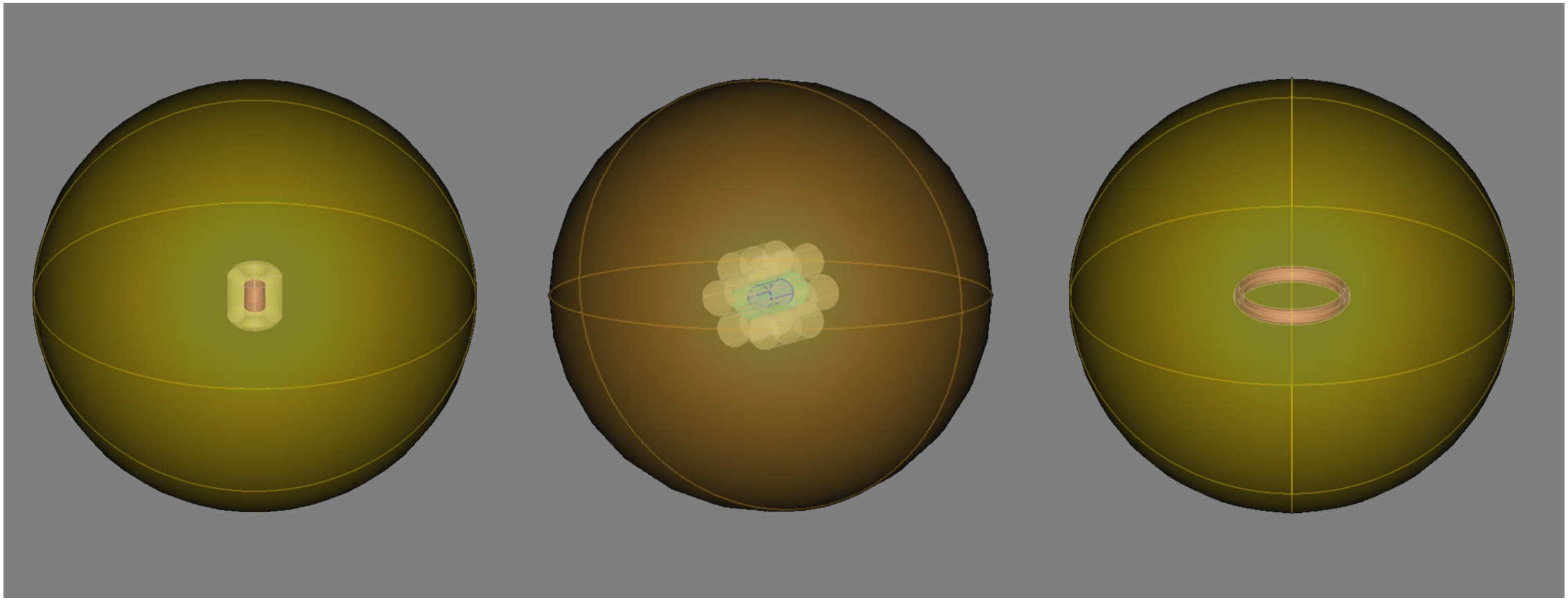
All currents are surface currents. The magnitude of the current is uniform around the toroidal direction for the ESA toroid, but varies in the poloidal direction as the surface cross-section changes from inside to outside. The azimuthal currents in the 6-1 solenoids are also uniform along the Z-axis for each solenoid, and is equal in magnitude for the outer six solenoids. The toroidal belt currents in the DTM vary in strength poloidally from the inner side to the outer side so as to maintain the magnetic flux inside the ellipsoidal toroid near zero, i.e. a null magnetic field

Magnitude of the Magnetic Field for the Three Candidate Shielding Concepts



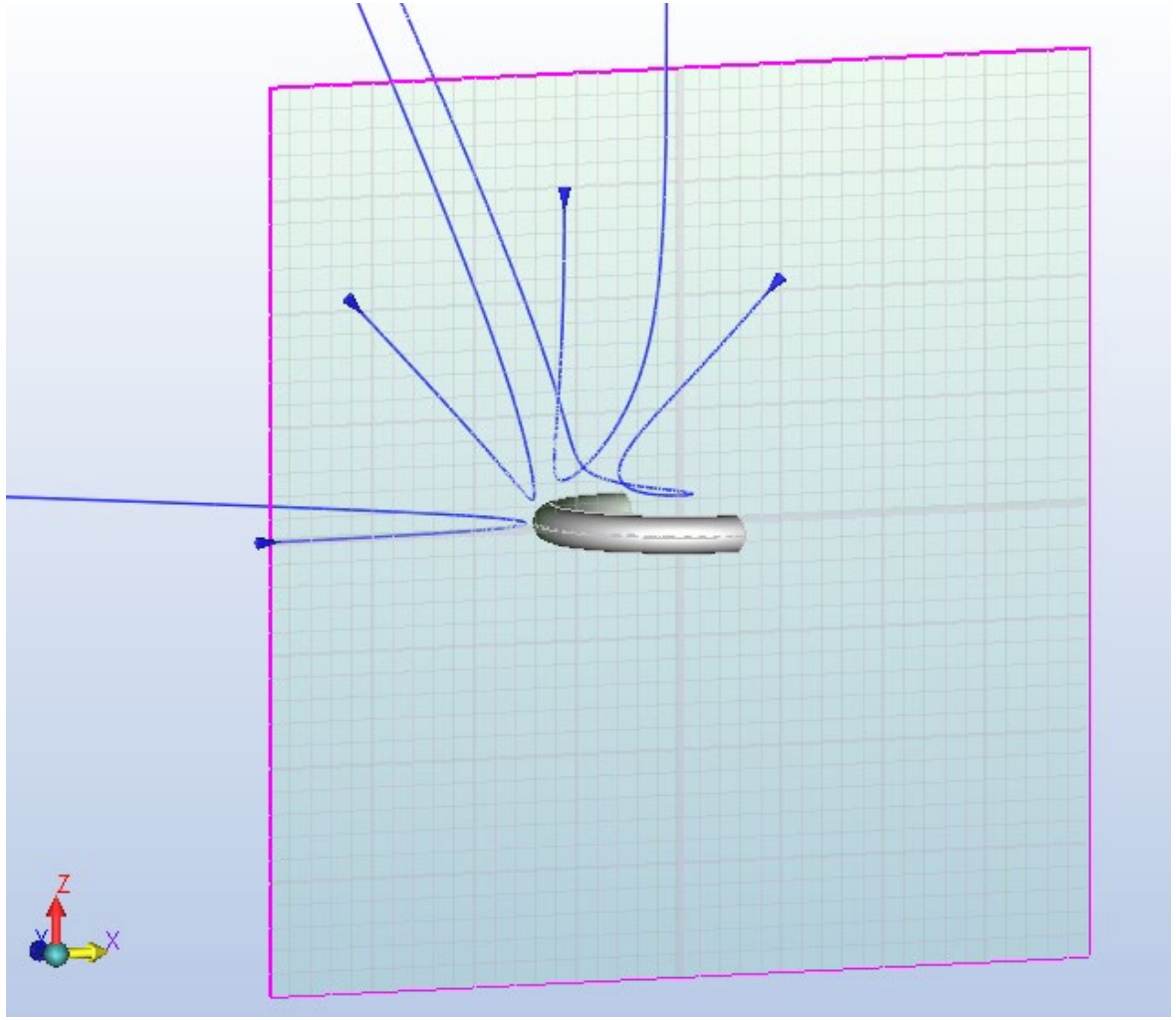
Modulus B along the X-axis. The X-axis was chosen to lie in the plane of mirror symmetry for each configuration and along the direction that was perpendicular to the magnetic field direction thereby reflecting the maximum magnetic field strength. This X-axis can be chosen to be in any direction in this plane for the ESA Toroid and the DTM due to azimuthal symmetry. It was oriented to pass through the central axis (Z-axis) of three of the 6-1 Solenoids (two outer and the one central).

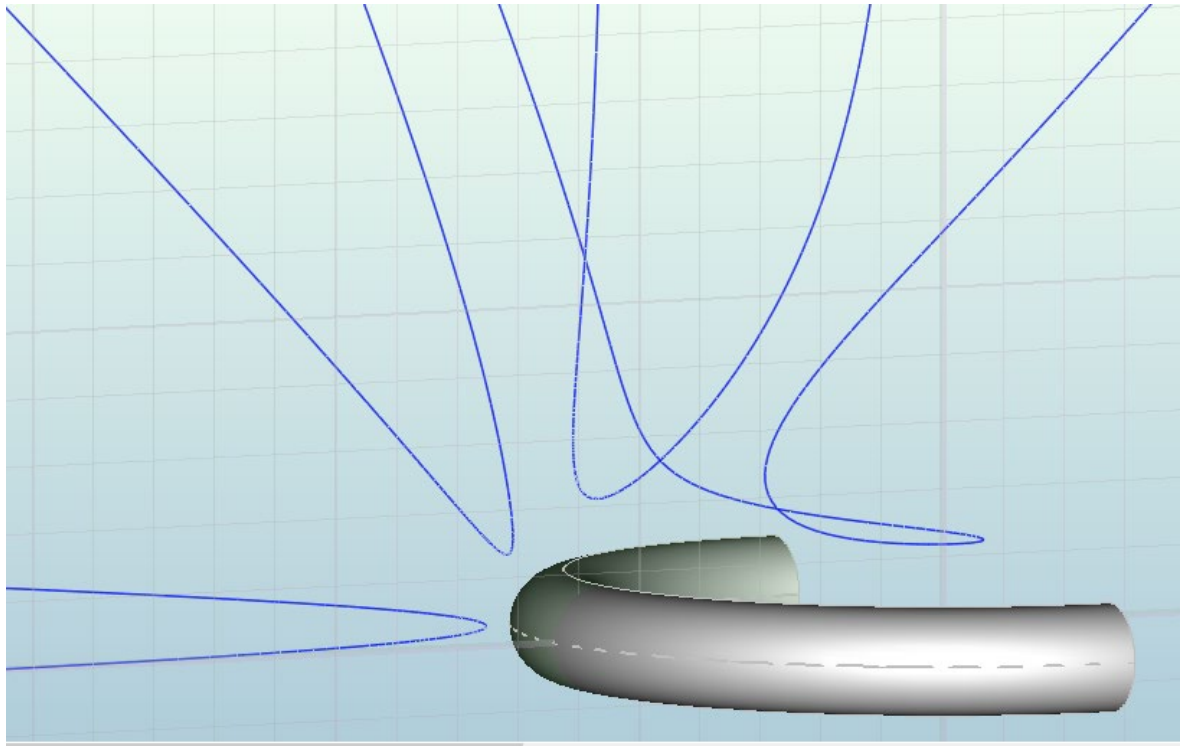
Spherical Surfaces for the Random Launch of GCR Test Particles for Isotropic Bombardment of the 3 Shield Configurations



The magnetic coils are shown as semi-transparent with the habitat incased within as described for the three concepts. The meridian lines are for showing position of spherical surface and had no significance with regard to the calculations

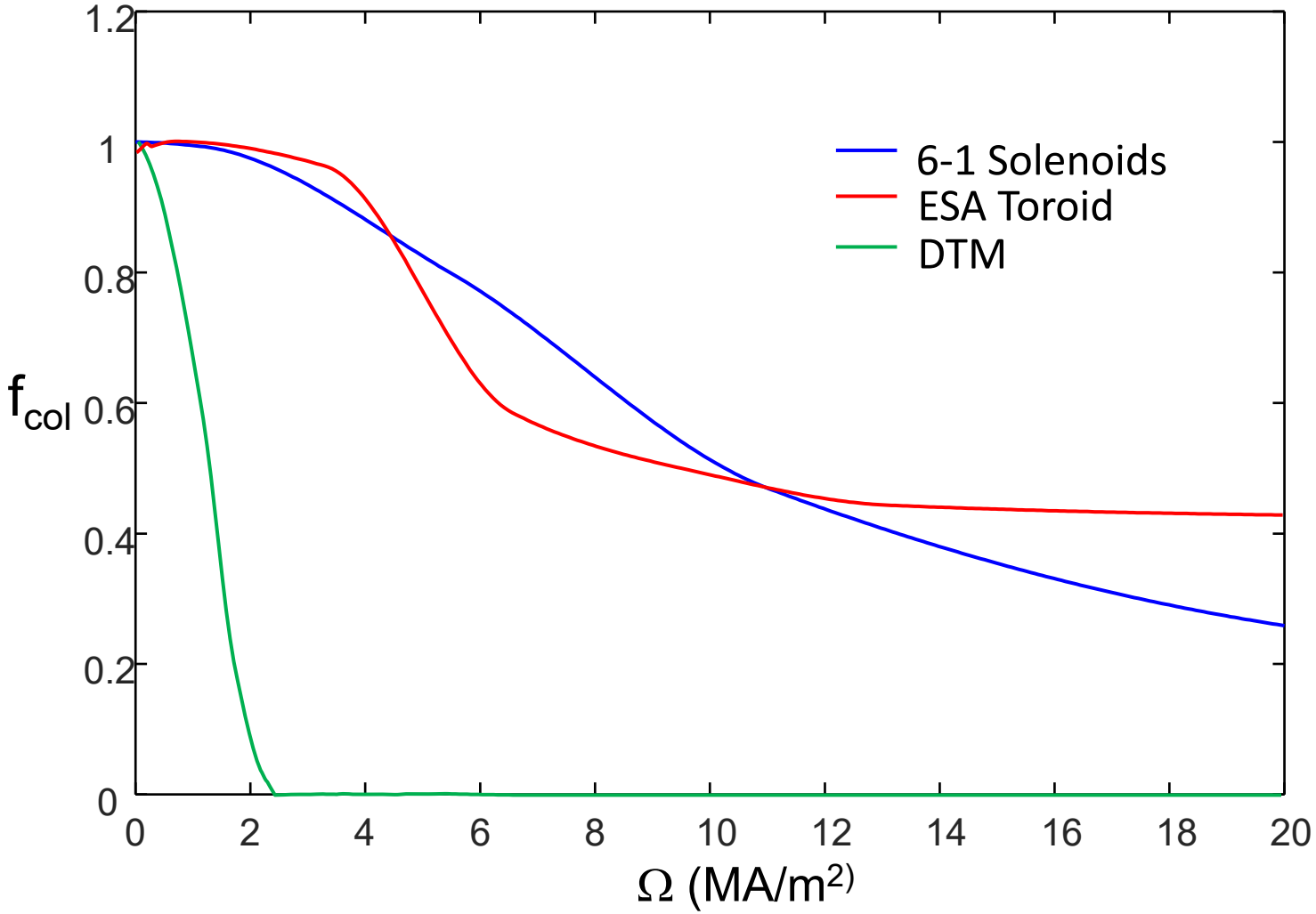
LORENTZ 3D® Trajectory Calculations with the Subscale Dipolar Toroidal Magnet





(Left) Trajectories of four protons directed towards a specific point on the torus midplane.
(Right) Close-up near DTM. All protons have the same directional energy (500 eV)

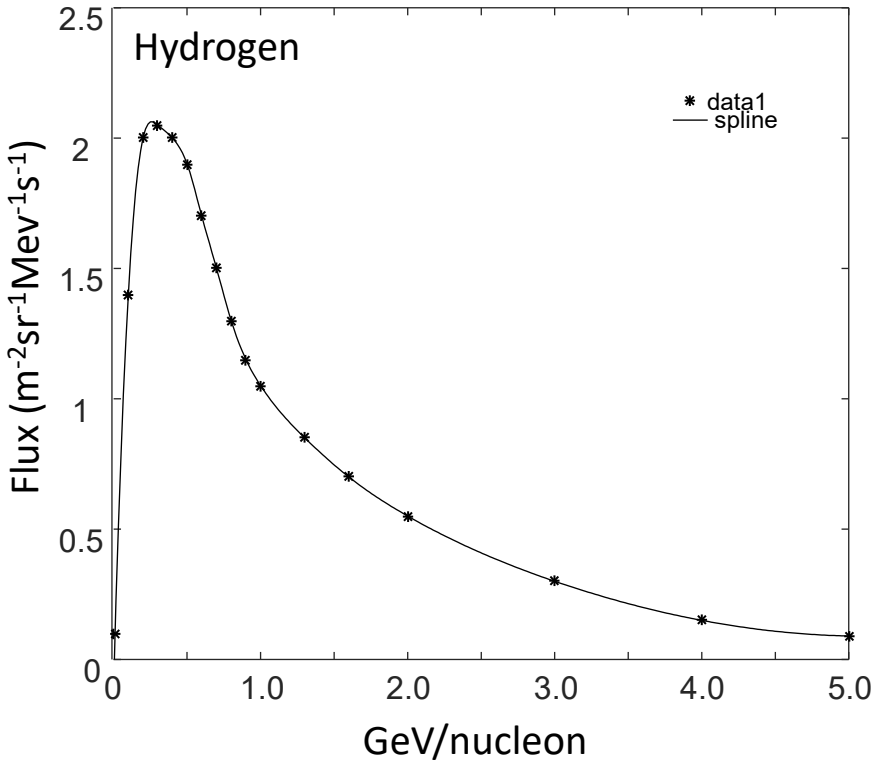
Fraction of 500 MeV Protons Reaching the Habitat of the Various Concepts as a Function of the Efficiency Parameter .

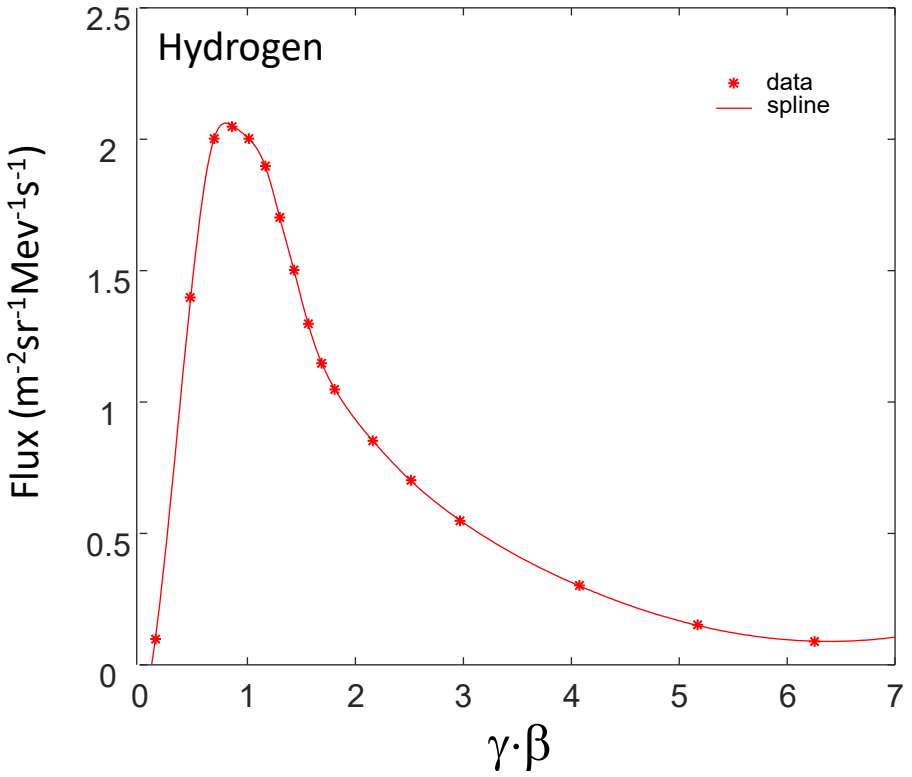


$$\Omega = \frac{\sum_{1}^{n} I_n \cdot L_n}{Vol_{Hab}}$$

The efficacy is measured by the total HTSC mass per unit volume of habitat where the sum is over all the current elements times the length of that current element

Linear Plot of GCR in Relevant Parameters for Magnetic Shielding





Recall condition for full deflection in DTM: $B_{00} \geq C_B \frac{m_0}{qR} \gamma\beta c$

(where c_B is a constant depending on toroid geometry)

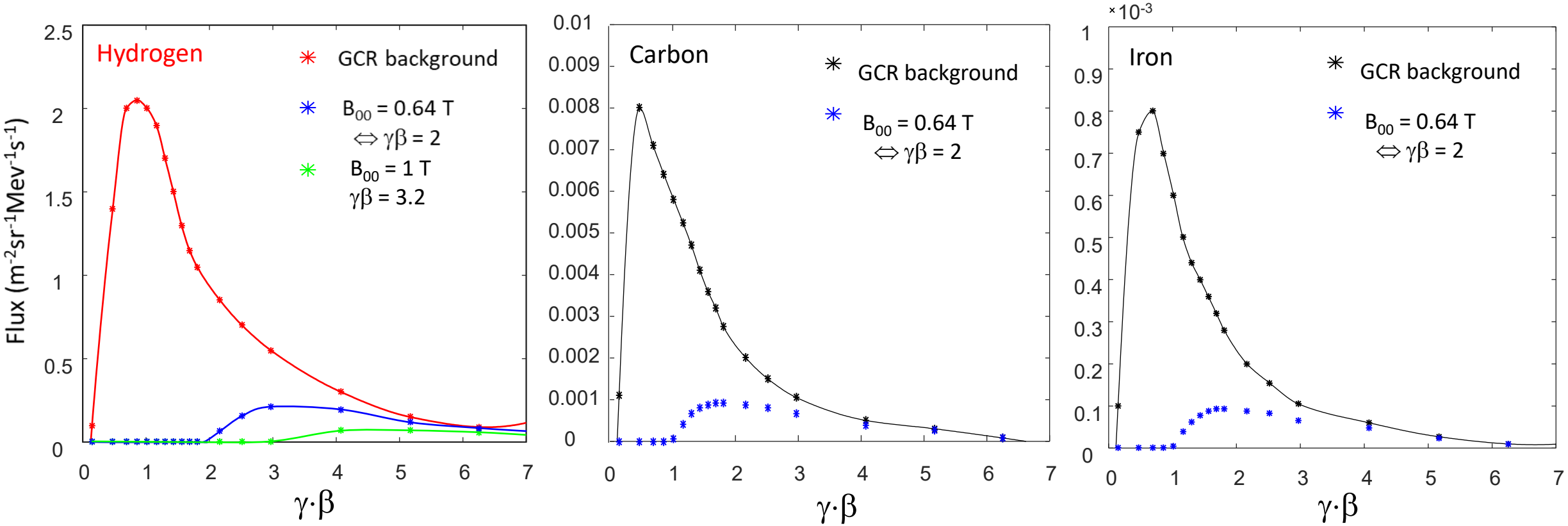
From calculations and experimental results: $C_B \approx 1$

Note: $\gamma = \frac{E_{tot}}{m_0 c^2} = \frac{E_k + E_0}{m_0 c^2} = \frac{E_k}{m_0 c^2} + 1$

$\beta = \sqrt{1 - \frac{1}{\gamma^2}}$

For nucleon: $m_0c^2 = 0.94$ GeV

Predicted Attenuation of the GCR Spectrum from Dipolar Toroidal Magnetosphere (DTM)

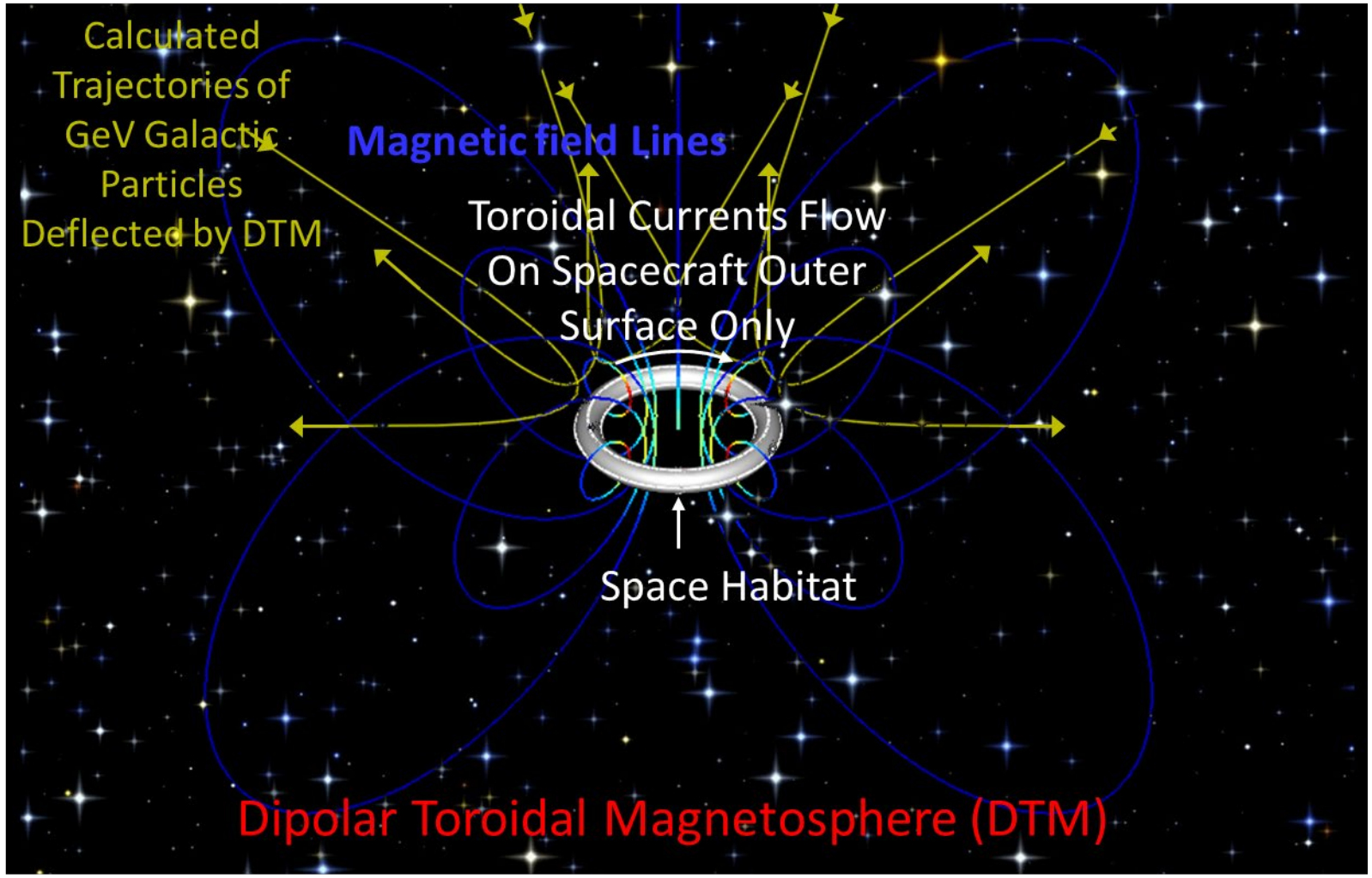


DTM radius R = 10 m,

$$B_{00} \geq \frac{m_0}{qR}\gamma\beta c$$

The Dipolar Toroidal Magnetosphere (DTM) Solution

- **Discovered a magnetic shielding configuration referred to as a Dipolar Toroidal Magnetosphere (DTM) that can deflect the vast majority of the GCR including HZE ions**
- **DTM shields *both* habitat and magnetic coils significantly reducing secondary particle irradiation hazard**
- **DTM magnetic shielding can be mounted on spacecraft reducing structural mass and complexity.**



- **Low cost method for testing shielding on Earth was realized with a subscale DTM using surrogate ion beam in a large vacuum chamber**