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May 26th, 7:30 AM

Spacecraft Radiation Shielding by a Dispersed Array of Superconducting Magnets

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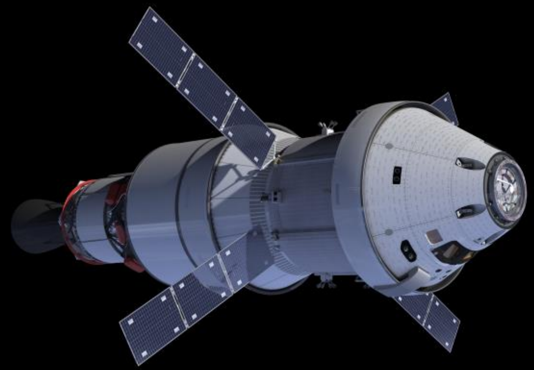

Spacecraft Radiation Shielding by a Dispersed Array of Superconducting Magnets

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[1]Florida Institute of Technology

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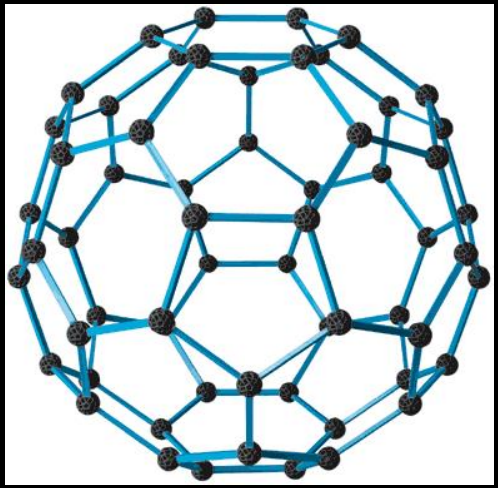
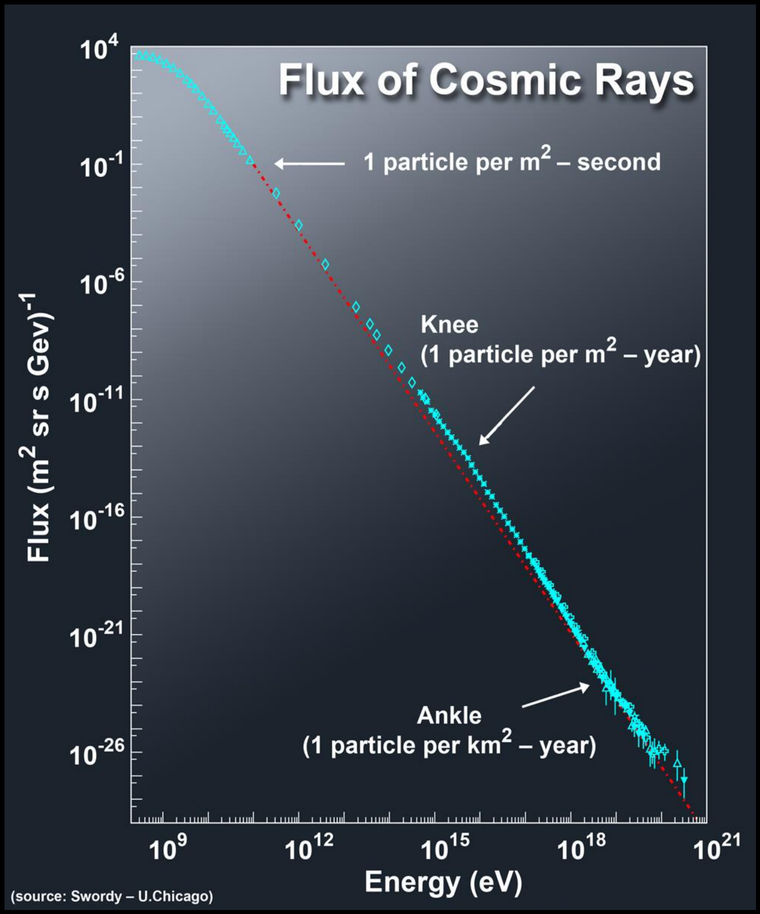
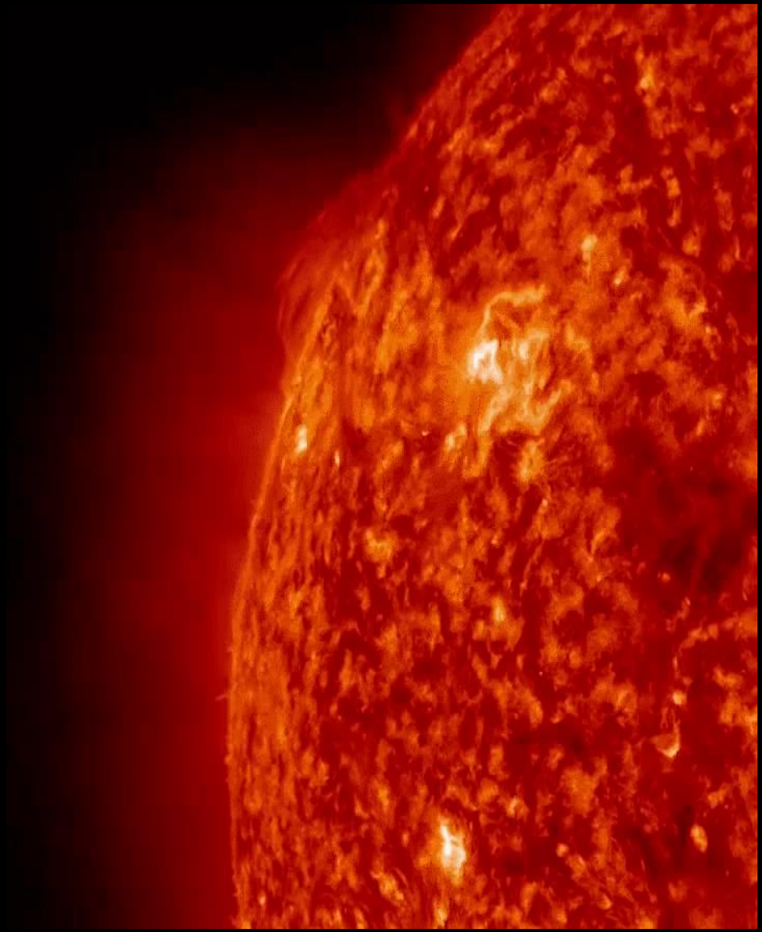


Interplanetary Radiation Environment





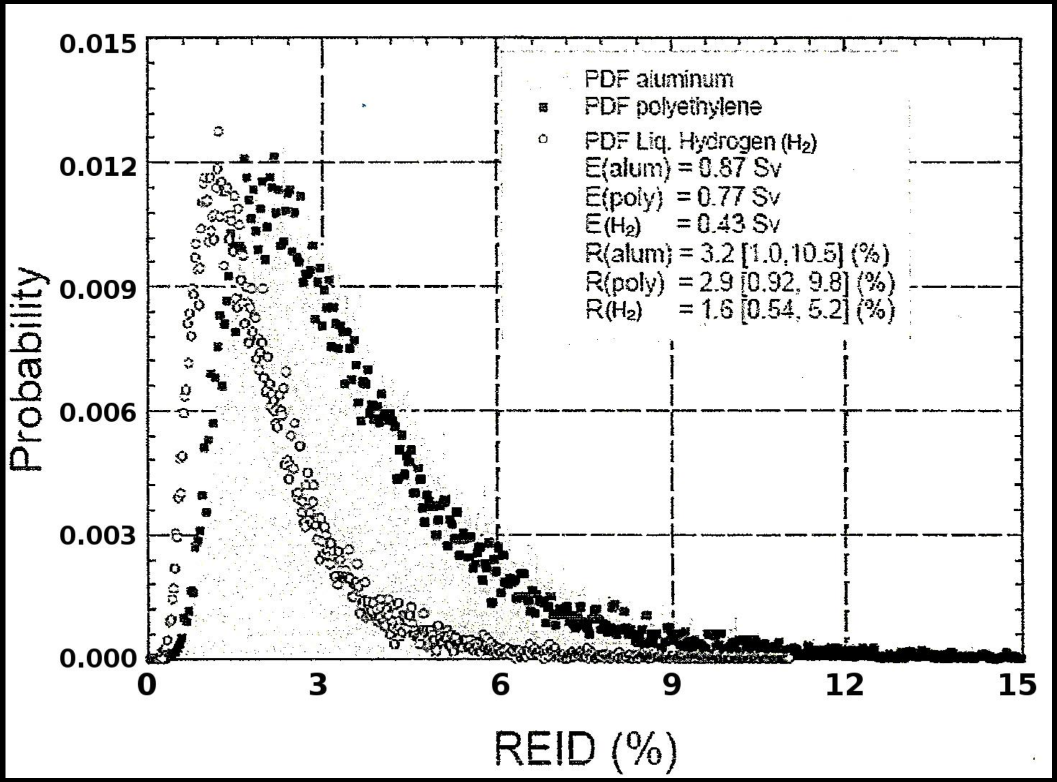
Galactic Cosmic Rays (GCRs)

Isotropic
1—1000 GeV particles
protons, H, He, C, O, Ne, Fe
Z = 1, 2, 6, 8, 10, 26

Solar Particle Events (SPEs)

Uni-directional
1—1000 MeV particles
protons, H, He, C, Si, Fe
Z = 1, 2, 6, 14, 26

Radiation Threat



Equivalent Dose (Sv)

$$H_T = \sum_R W_R \cdot D_{T,R}$$

Radiation (*R*) Weighing Factor

protons $W_R = 2$
heavy nuclei $W_R = 20$

Absorbed Dose in Tissue (*T*) by Radiation (*R*)

Measured in Gray (Gy)

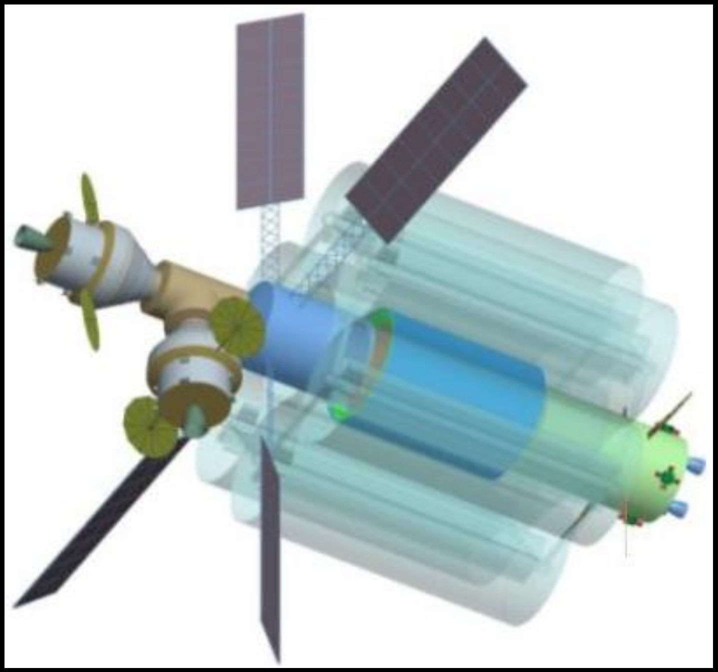
1 Gy is the absorption of 1 J/kg

Radiation Exposure Induced Death (REID)

NASA Standard of **<3%** increase (95% confidence)

Mean REID = 3.2%
95% Confidence Level = 10.5%
REID Probability = 10.5%

Previously Proposed Safeguards



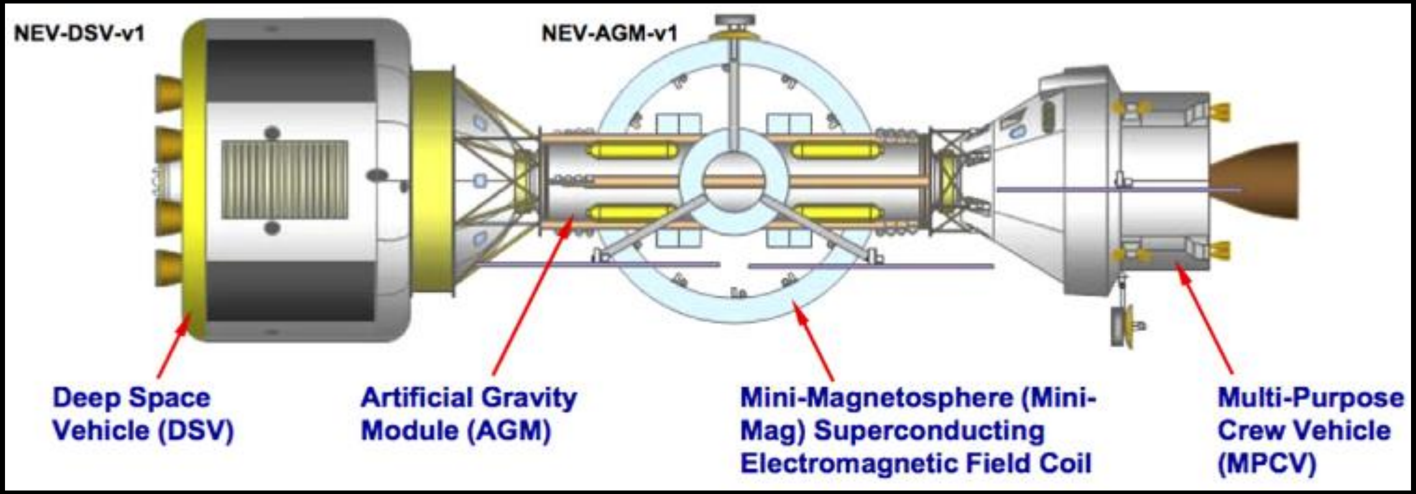
Kervendal, E., Kirk, D., Meinke, R. (2006)

Superconducting magnets attached directly to spacecraft

Shielding efficiencies: 90% for 1 GeV
57% for 2 GeV

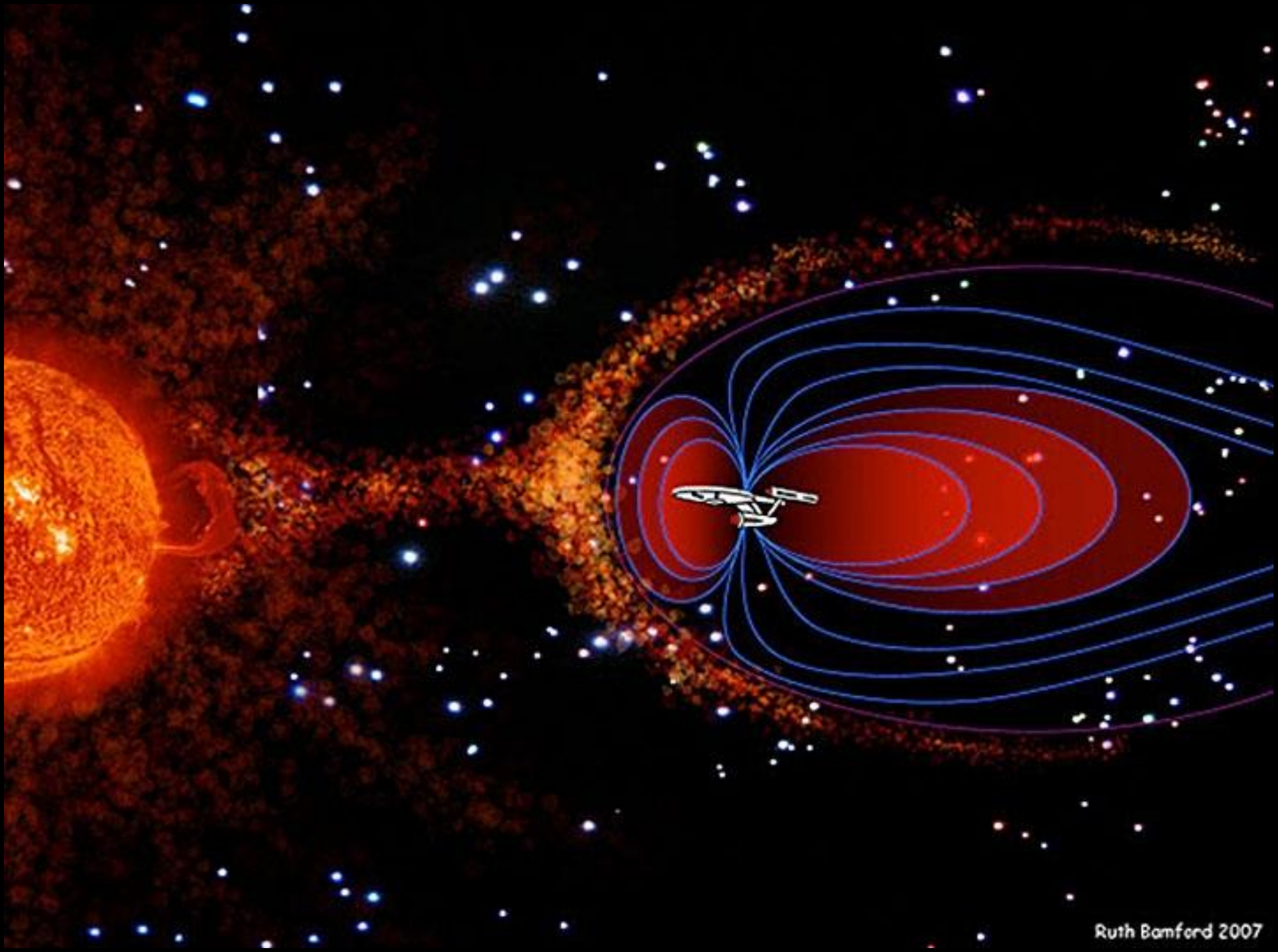
Drawbacks

- Screen interior from field
- Thermal management
- Hinders EVAs
- Re-designing Orion



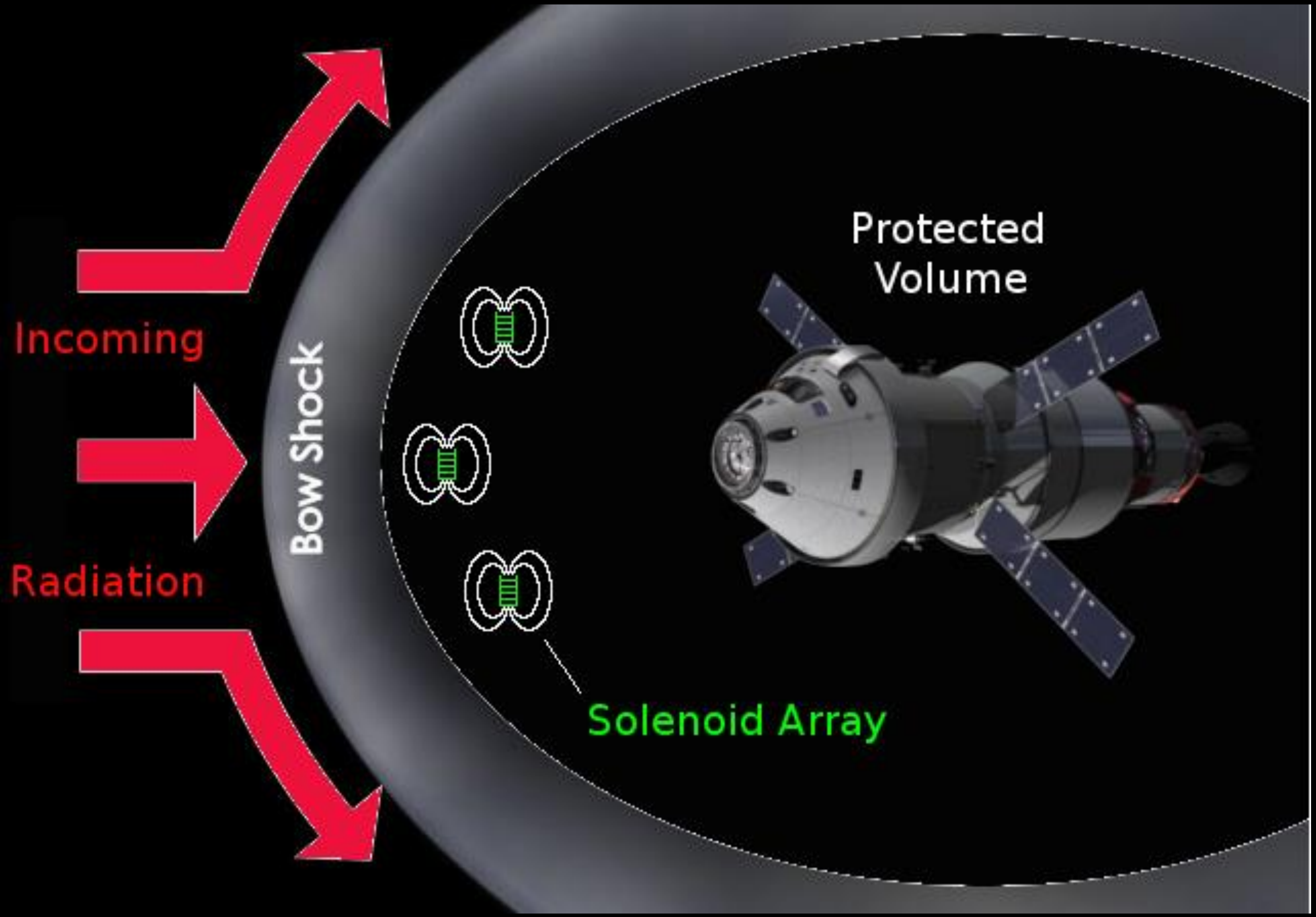
Bamford, R. A., et al. (2014)

Magnetic Shielding



New Concept

Dispersed Array of Superconducting Magnetic Satellites



Exploit the Integral Field Parameter

$$\int \vec{B} \times d\vec{l}$$

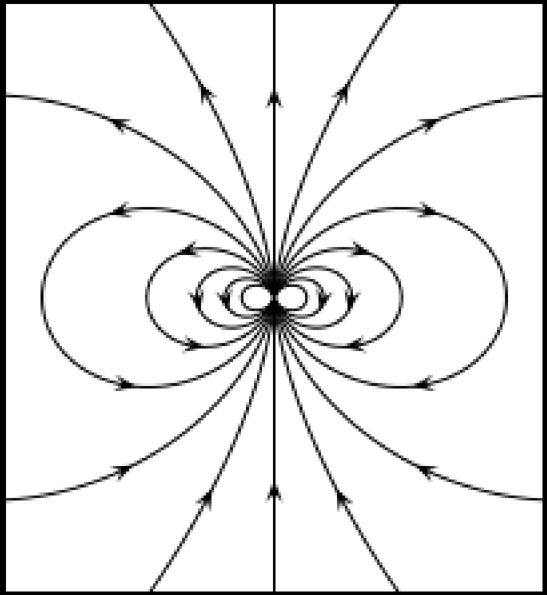
Small vs large deflections

Code Formulation

Magnetic Dipole

$$\vec{B}_{dipole} = \frac{\mu_0}{4\pi}\left(\frac{3\vec{r}(\vec{r}\cdot\vec{m})}{|\vec{r}|^5} - \frac{\vec{m}}{|\vec{r}|^3}\right)$$

Throw away regions of divergence



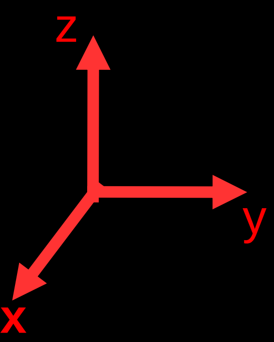
Translation, Rotation, and Superposition

Equation of Motion

$$\frac{d\vec{u}}{dt} = \frac{300}{E_n[\mathrm{MeV}]}\frac{Z}{A}(\vec{u}\times\vec{B}[T])$$

$$u[n+1] = u[n] + a\cdot dt$$

$$r[n+1] = r[n] + u[n+1]\cdot dt$$



Plane of Solar System

***y* towards spacecraft**

Effective Shields

Momentum "Maps"

Limit for small deflections

$$\Delta\vec{p}\left[\frac{\mathrm{MeV}}{\mathrm{c}}\right] = \frac{300Z}{A}\int \vec{B}\times d\vec{l}$$

$$\Delta p_x = 300\,\frac{Z}{A}\int (B_y dz - B_z dy)$$

$$\Delta p_y = 300\,\frac{Z}{A}\int (B_z dx - B_x dz)$$

$$\Delta p_z = 300\,\frac{Z}{A}\int (B_x dy - B_y dx)$$

For +y velocity charged particles in a magnetic field

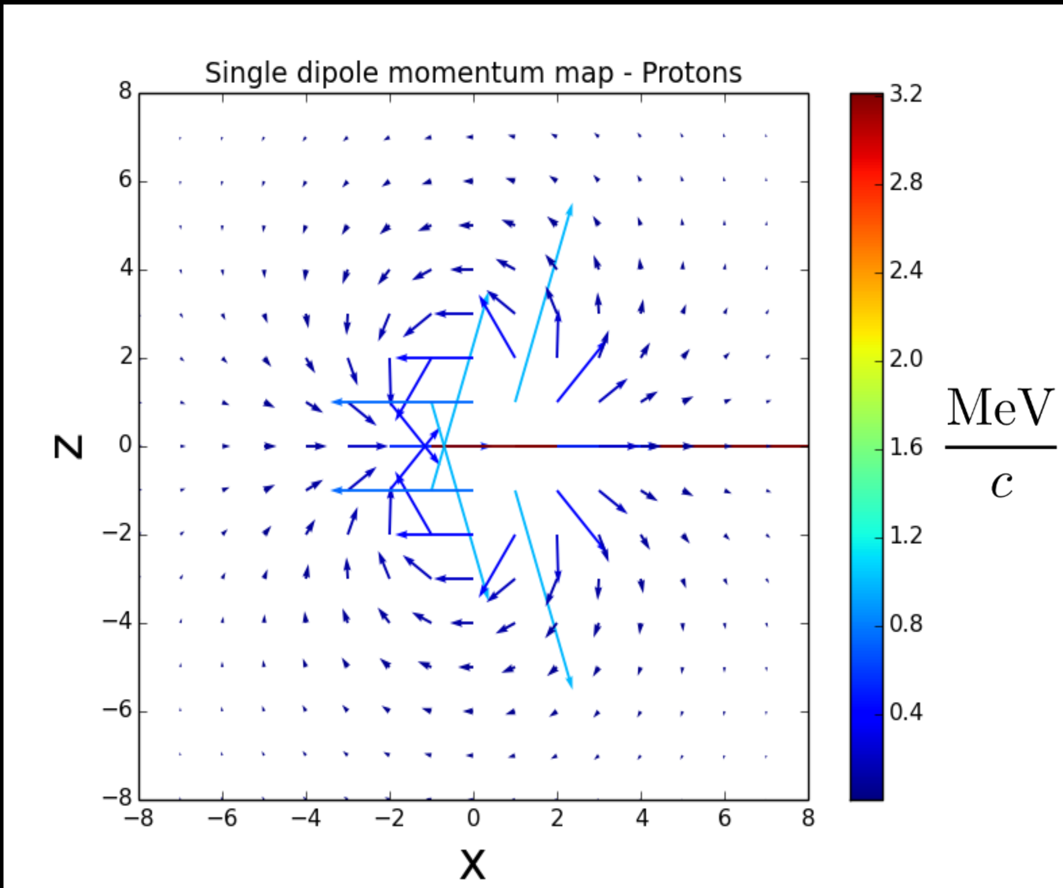
$$\Delta p_x = -300\,\frac{Z}{A}\int B_z dy$$

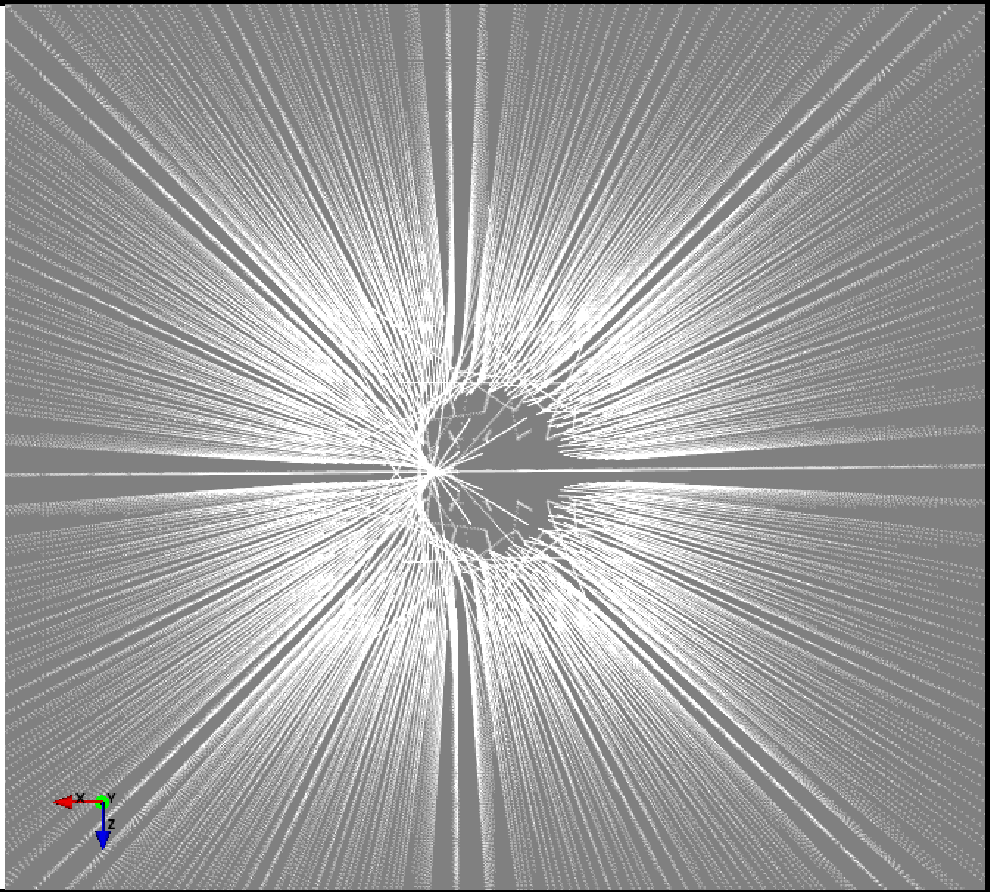
$$\Delta p_z = 300\,\frac{Z}{A}\int B_x dy$$

How do different magnetic dipole configurations affect particle momenta?

Momentum Map

Single Dipole

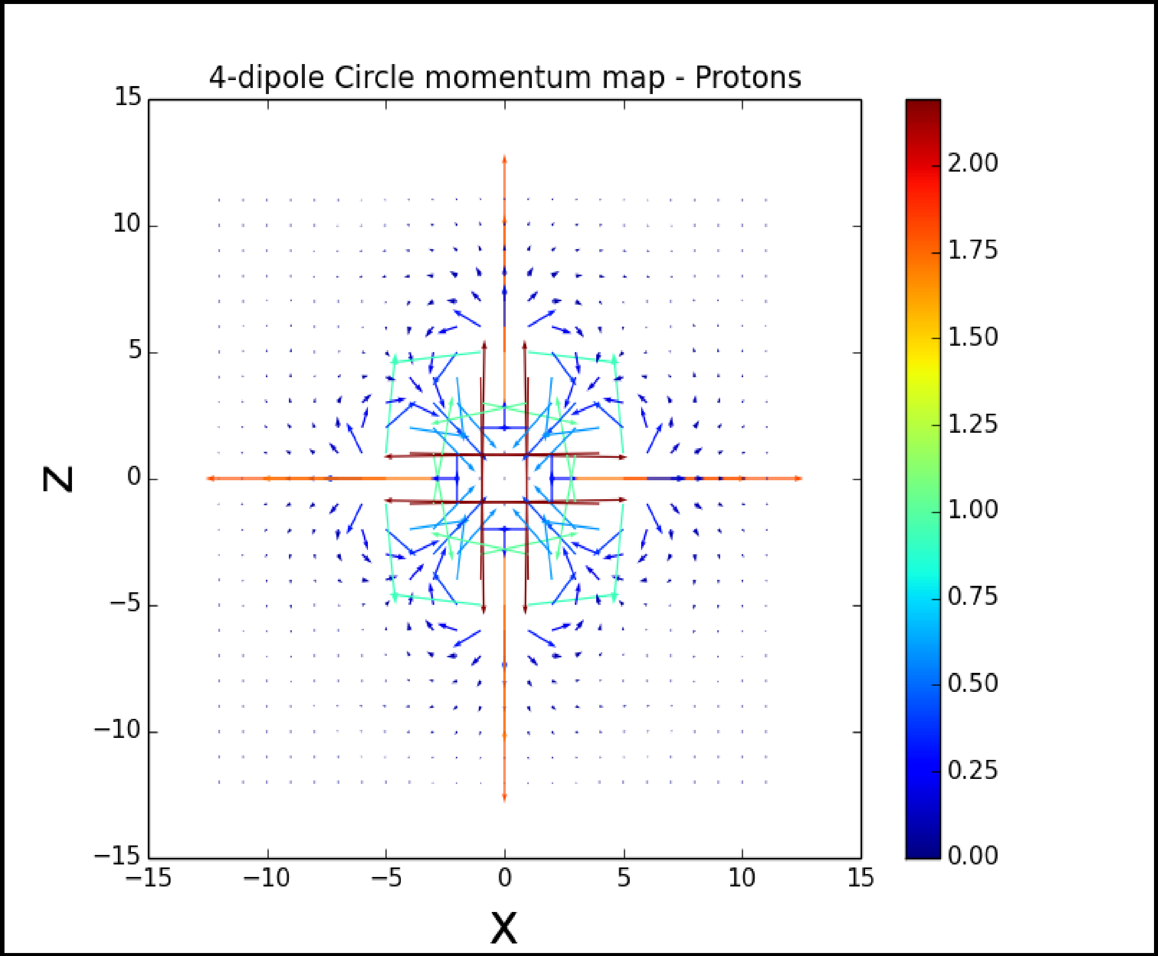


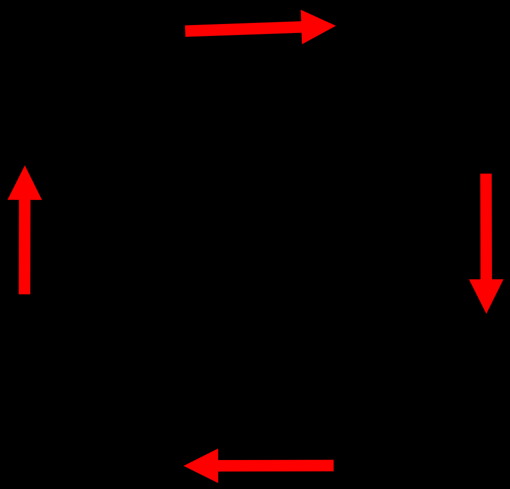


E_n = 1 MeV
m = πx10^4 A m^2

Momentum Map

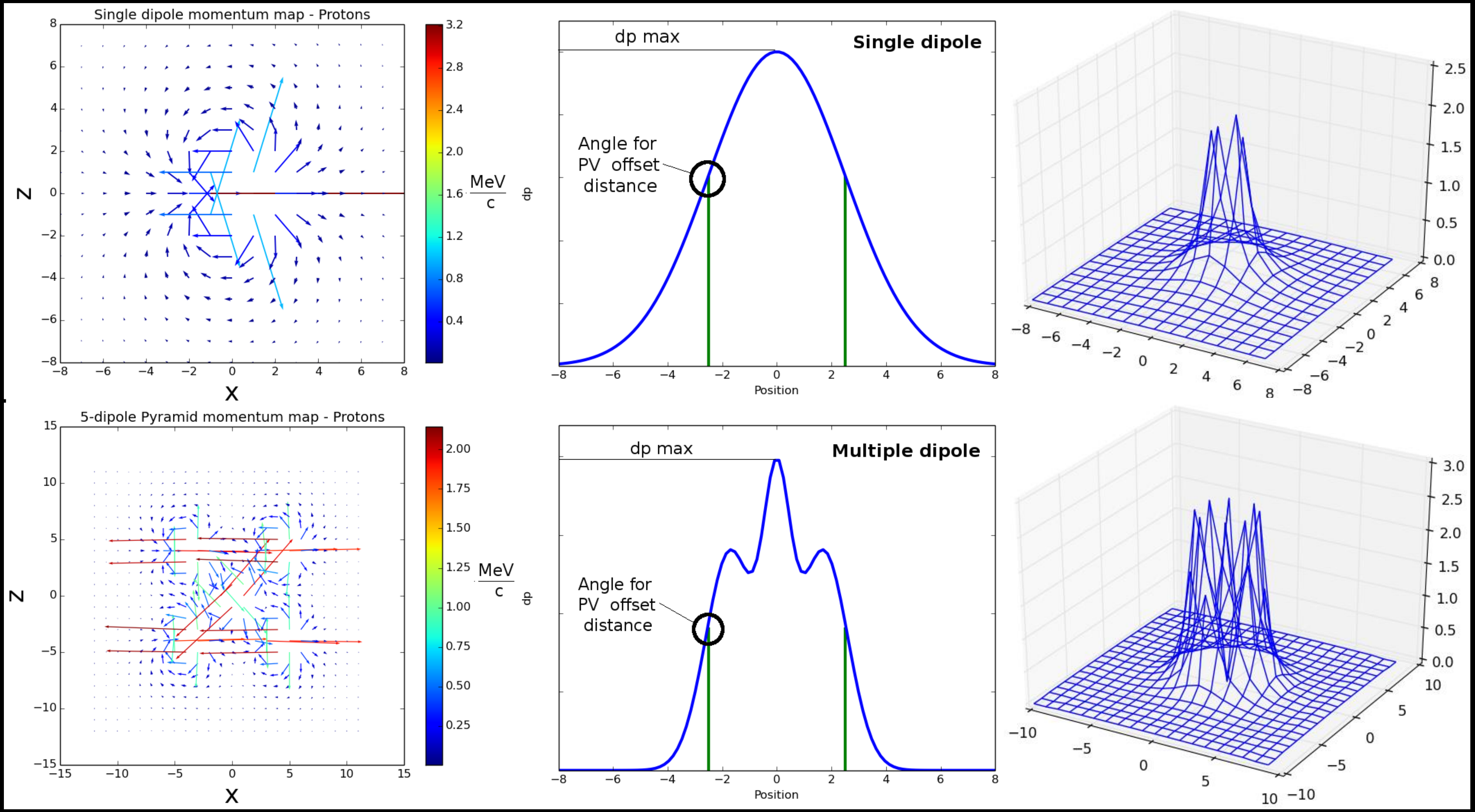
4-dipole circle





Shield Optimization

2D Gaussian fits



Superconducting Magnets

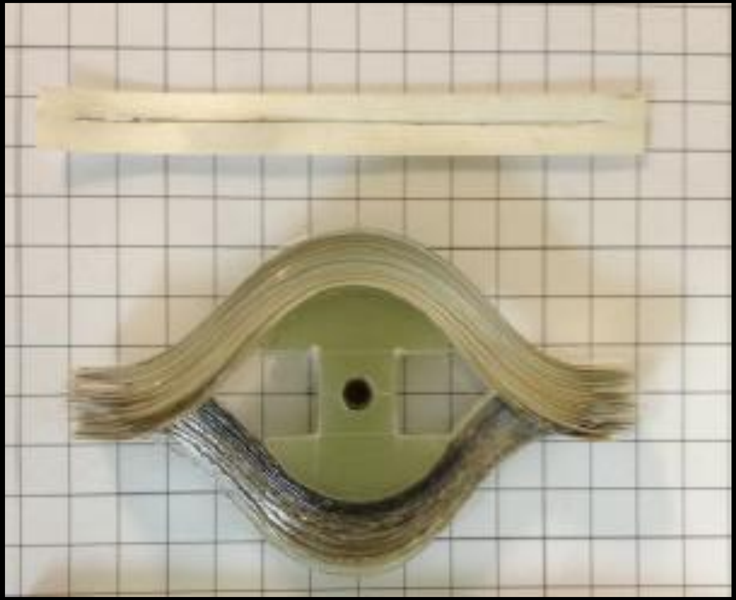
For $m = \pi x 10^4$ Am^2 (20 cm radius loop) – 5.6 kg

High-temperature superconducting wires (YBCO coated conductors)

Critical temperature 90 K - operating temperature 40-50 K, maintained using sunshield, similar to JWST, or “Solar White” coating

Magnets operate in persistent mode.

A closed loop made out of coated conductor.



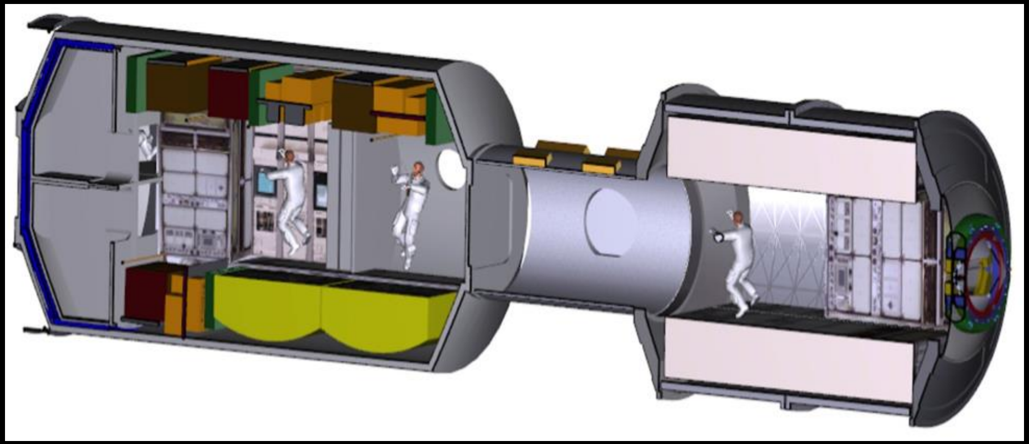
An assembly of 100 loops.

Protected Volumes

Orion Multi-Purpose Crew Vehicle

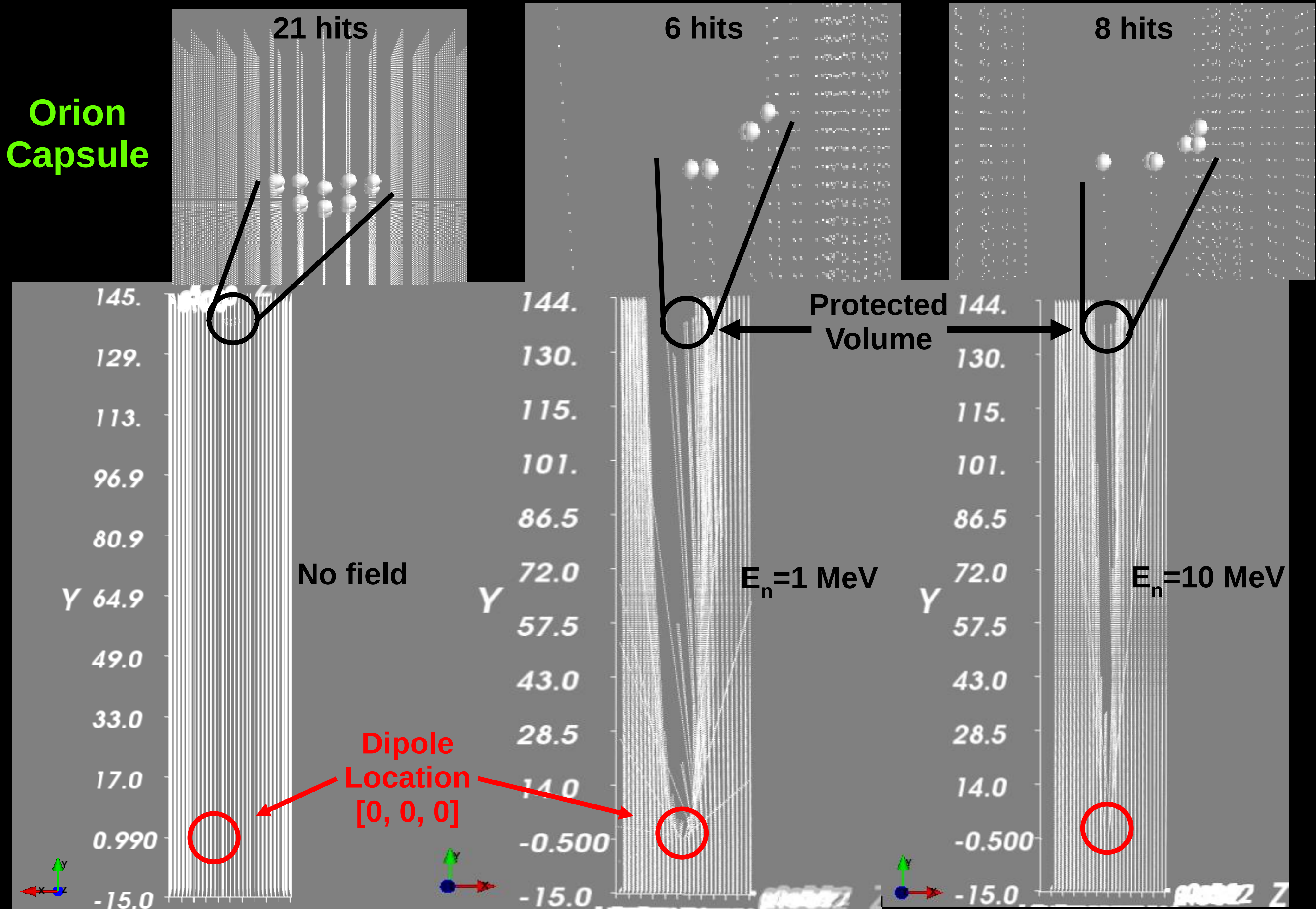
Sphere of 5 m diameter

Deep-Space Habitat



Cylinder of 5 m diameter and 15 m length

Simulation – Single Dipole (m=πx10^4 Am^2)



$$\% \text{ Reduction} = \frac{\text{No field hits} - \#\text{hits}}{\text{No field hits}}$$

1x resolution (21 hits) Velocity Errors: 1.000±0.006, 1.000±0.005, 1.001±0.02

E_n (MeV)	1	10	30	60	100	150	200	1000
$\pi x10^3$ A m^2	61.9	4.8	4.8	4.8	4.8	4.8	4.8	4.8
$\pi x10^4$ A m^2	71.4	61.9	47.6	23.8	4.8	4.8	4.8	4.8
$\pi x10^5$ A m^2	85.7	71.4	61.9	66.7	61.9	52.4	61.9	4.8

2x resolution (81 no field hits) Velocity Errors: 1.000±0.003, 1.000±0.006, 1.001±0.02

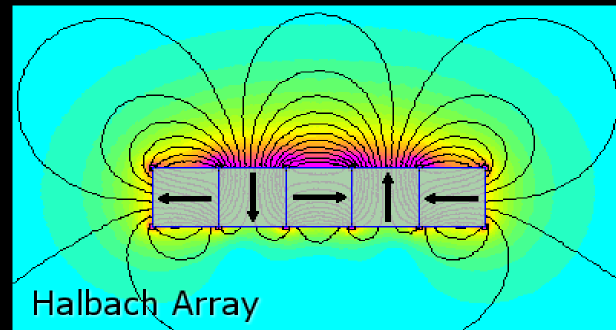
E_n (MeV)	1	10	30	60	100	150	200	1000
$\pi x10^3$ A m^2	60.5	14.8	7.4	9.9	9.9	9.9	9.9	9.9
$\pi x10^4$ A m^2	65.4	60.5	51.9	24.7	14.8	12.3	11.1	9.9
$\pi x10^5$ A m^2	71.6	65.4	65.4	64.2	60.5	59.3	58.0	14.8

3x resolution (177 no field hits) Velocity Errors: 1.000±0.002, 1.000±0.006, 1.001±0.02

E_n (MeV)	1	10	30	60	100	150	200	1000
$\pi x10^3$ A m^2	58.8	10.2	1.7	1.7	0.6	0.6	0.6	0.6
$\pi x10^4$ A m^2	66.7	58.8	45.2	22.6	10.2	6.8	5.1	0.6
$\pi x10^5$ A m^2	70.1	66.7	63.3	62.1	58.8	55.4	51.4	10.2

Simulation – Halbach Array

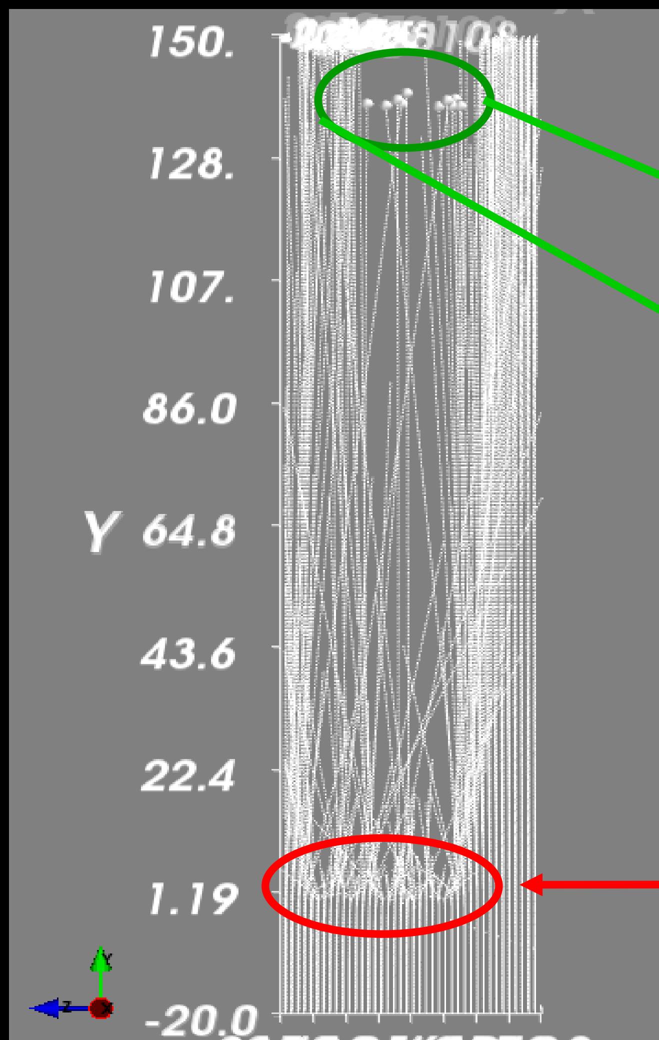
Deep Space Habitat

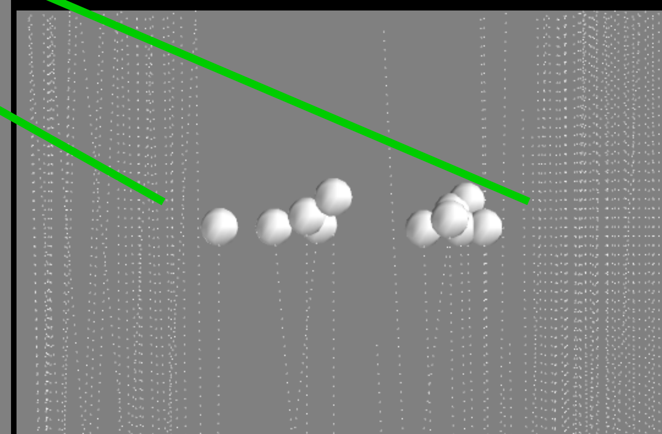


Increased B energy

Decreased B energy

E_n=10 MeV





11 hits

Halbach 5-dipole location

Simulation Results – Halbach Array

$$\%\,\text{Reduction} = \frac{\text{No field hits} - \#\text{hits}}{\text{No field hits}}$$

1x resolution (75 hits)

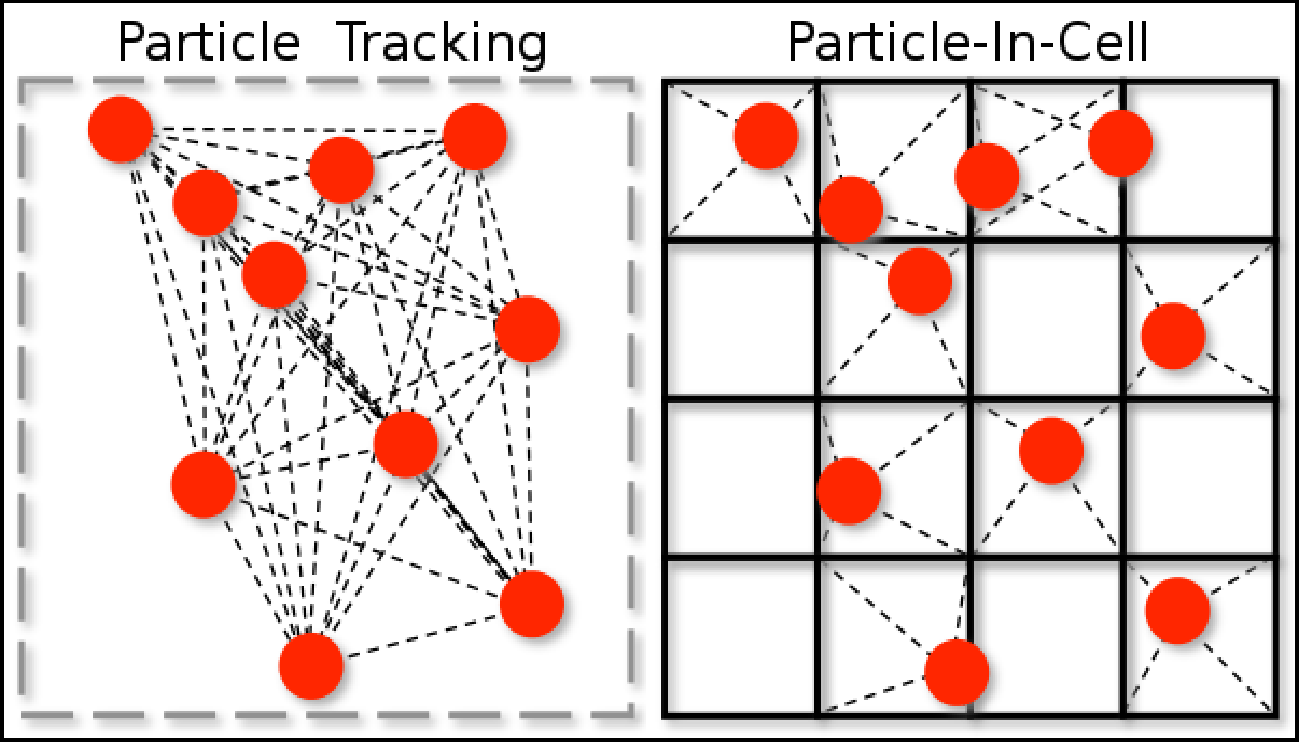
E_n (MeV)	1	10	30	60	100	150	200	1000
πx10^3 A m^2	64.0	5.3	4.0	4.0	4.0	4.0	4.0	4.0
πx10^4 A m^2	85.3	64.0	34.7	17.3	5.3	4.0	4.0	4.0
πx10^5 A m^2	94.6	85.3	77.3	66.7	64.0	50.7	46.7	5.3

Velocity Errors: 1.002±0.020, 1.013±0.032, 1.052±0.078

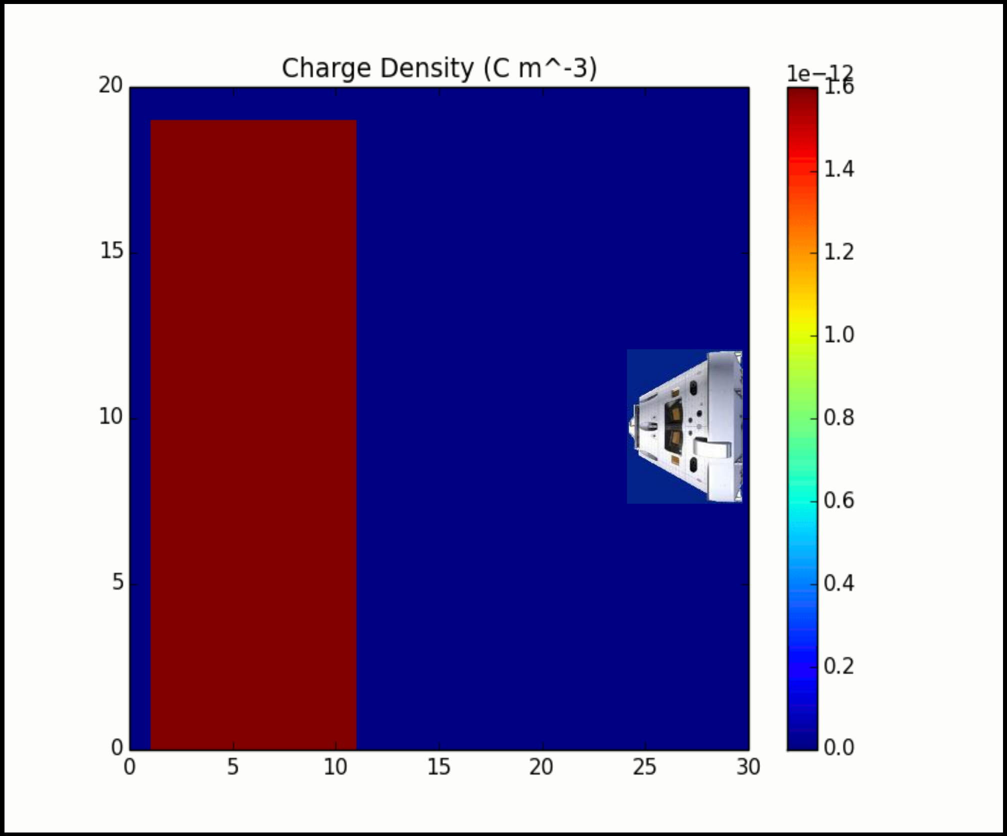
Robust Simulations

<u>Plasma</u> – an electrically neutral collection of a large number of positively and negatively charged particles

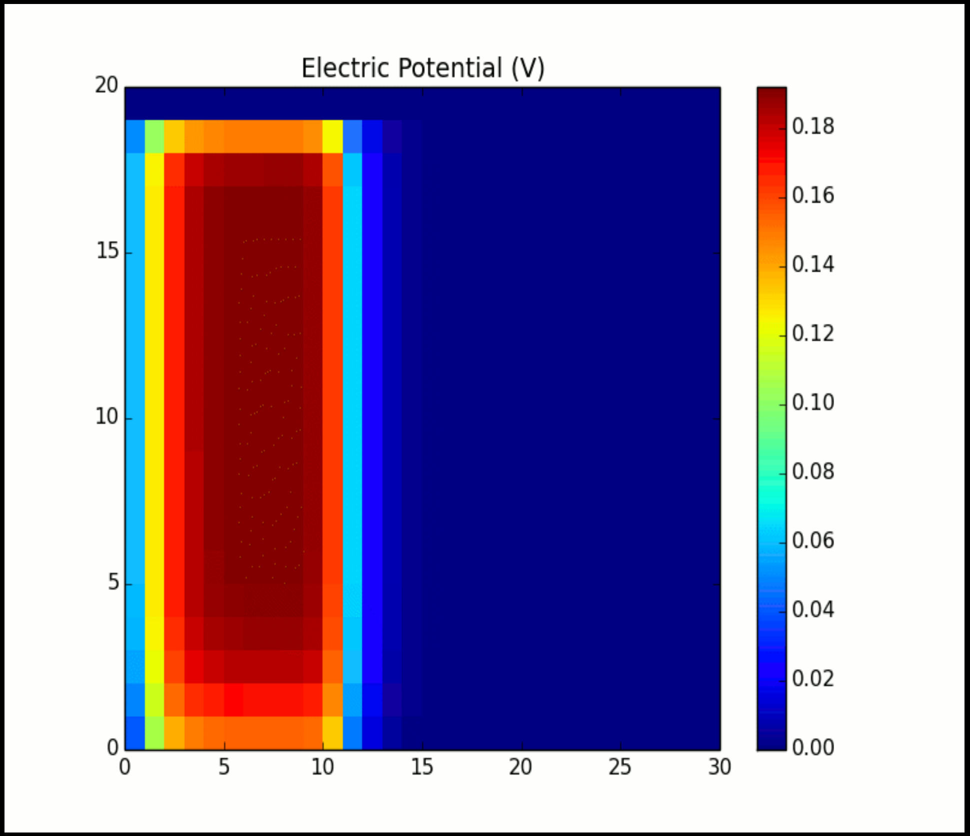
For accurate description of shields, we must account for BOTH ions and electrons



Particle-in-cell Method



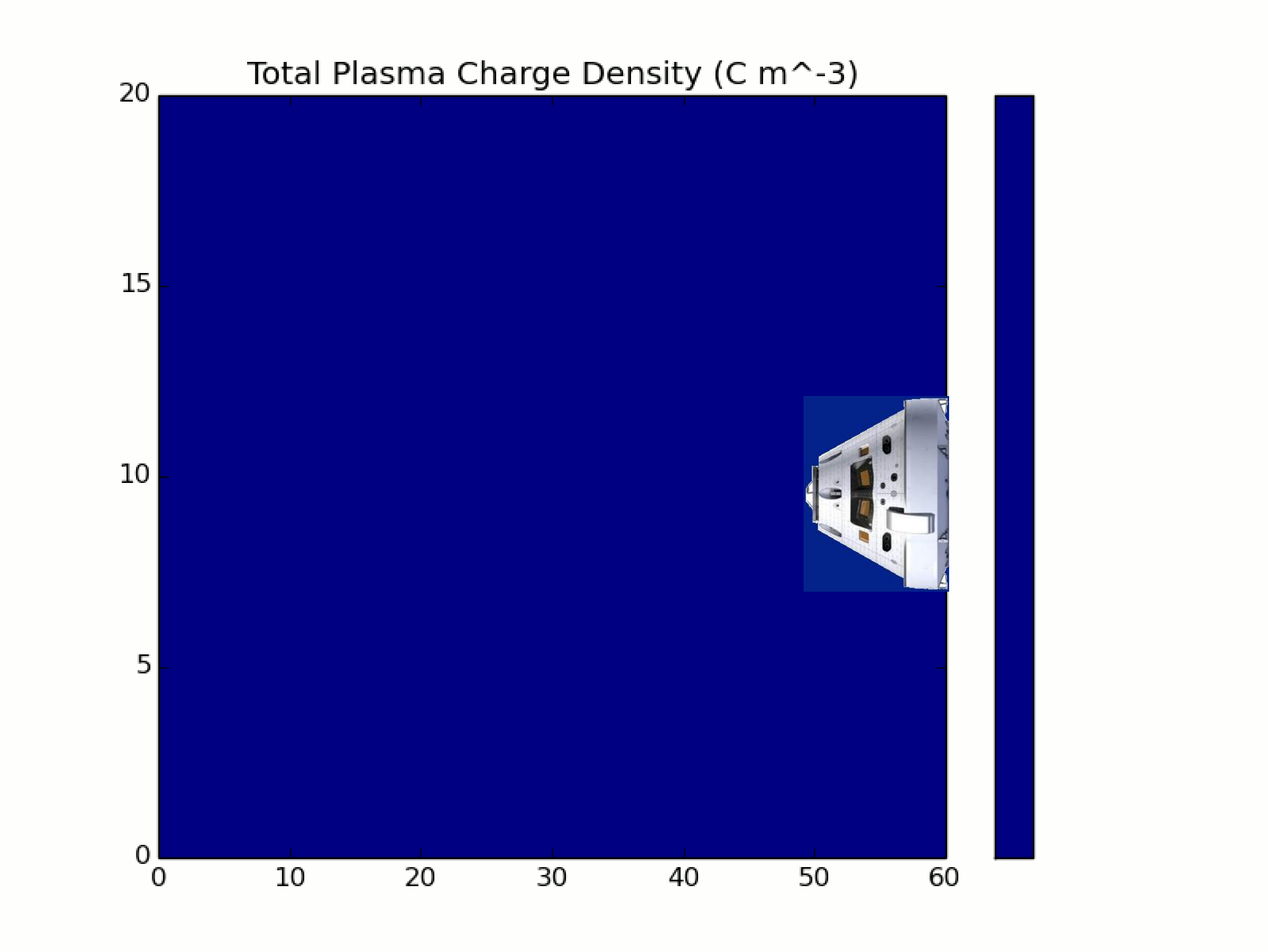
Ion charge density (C m^{-3})



Ion electric potential (V)

$$\vec{F} = q(\vec{E} + \vec{v} \times \vec{B})$$

Particle-in-cell Method



From Idea to Mission

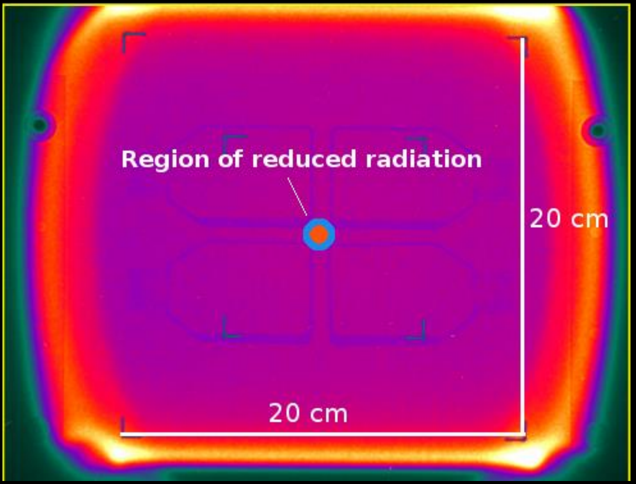
Increase **Technology Readiness Level (TRL)**

- Superconductors in Space
- Technology Demonstration
- On-board Control in Deep-space

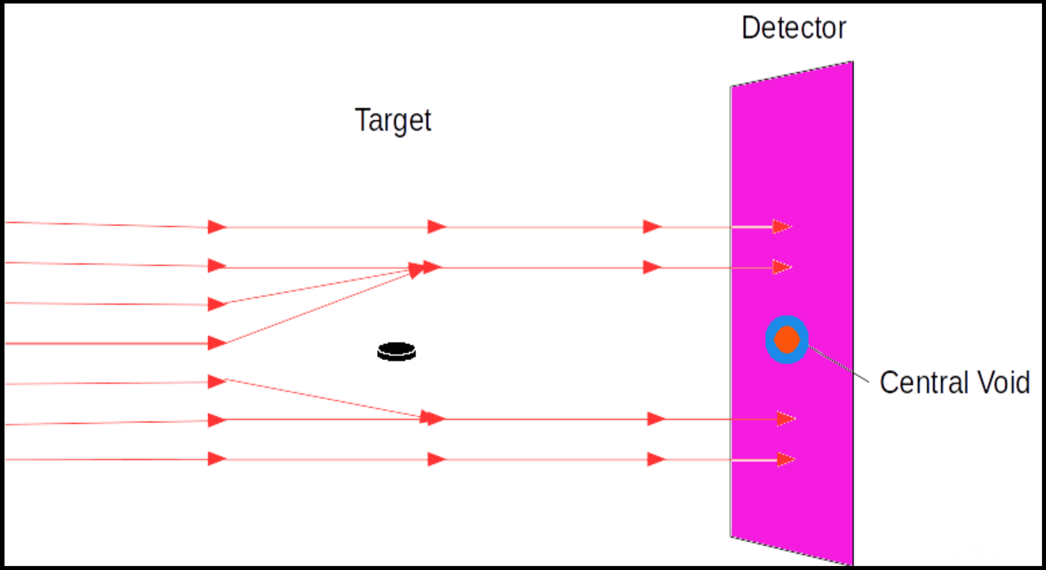
Increase TRL

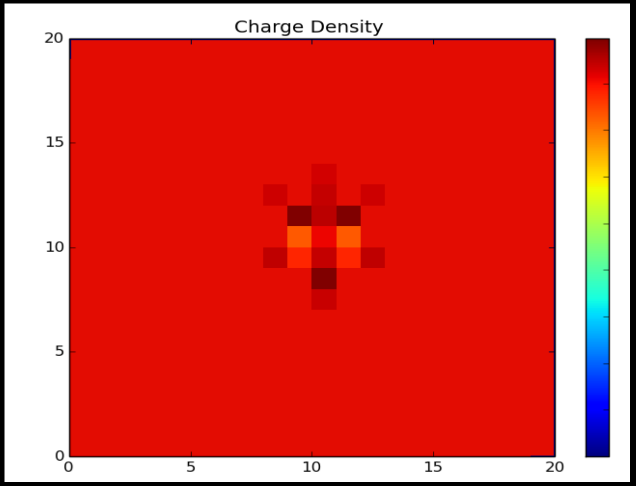
BROOKHAVEN
NATIONAL LABORATORY

NASA Space Radiation Laboratory



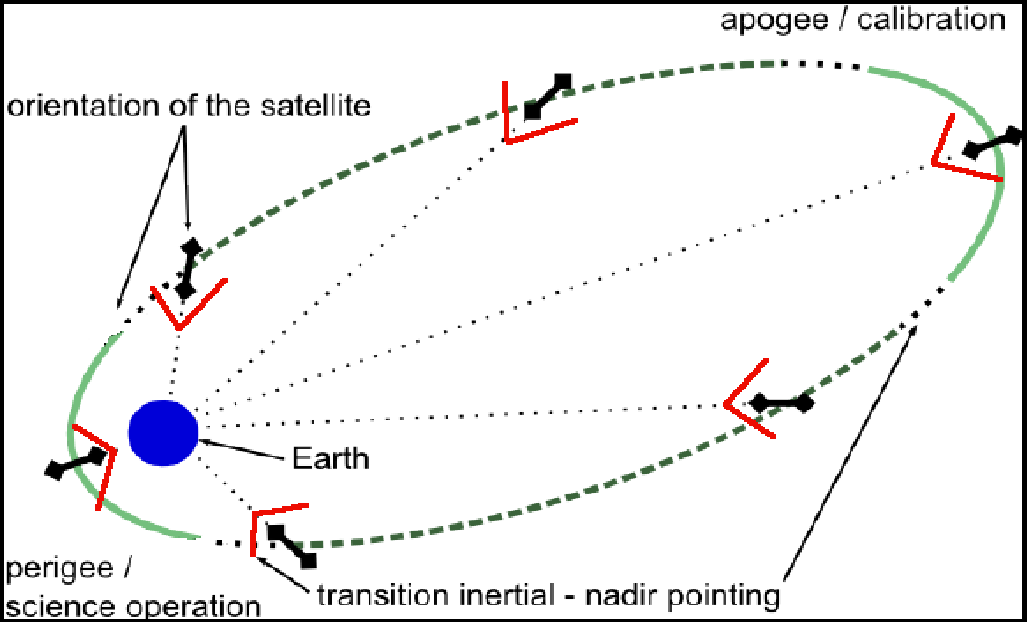
Digital Beam Imager

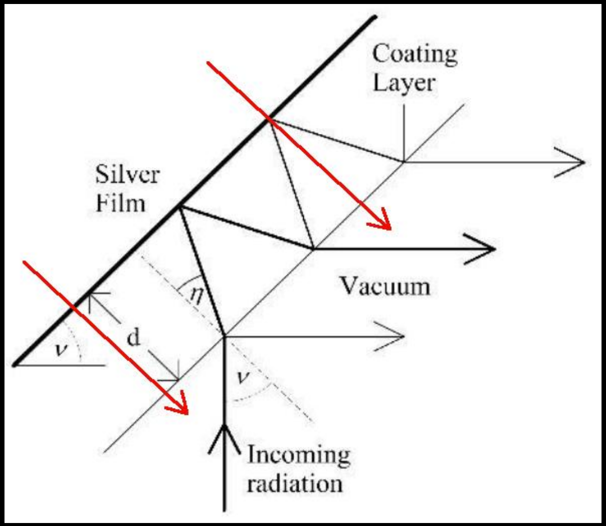


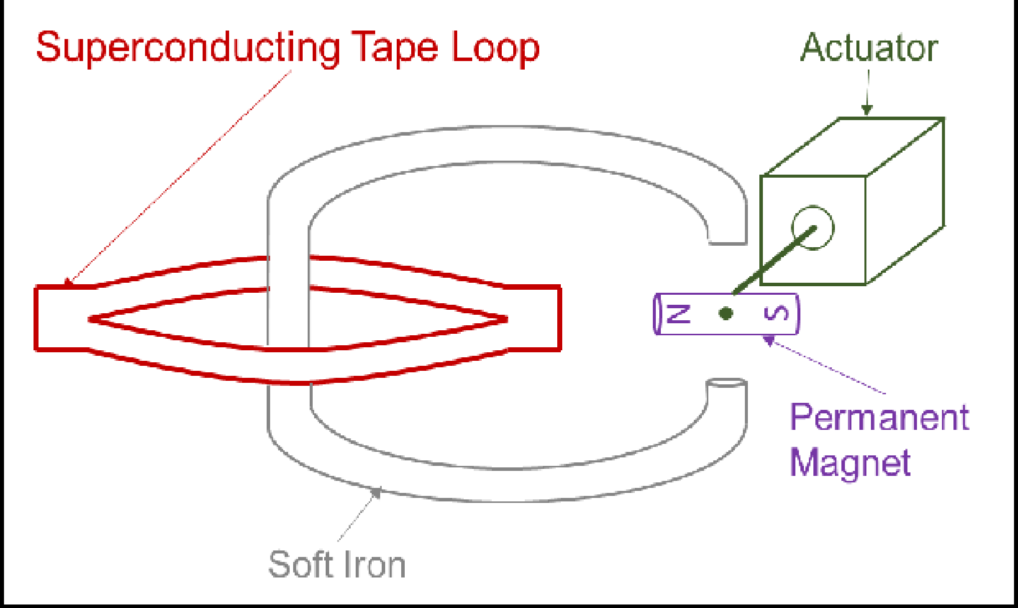


PIC prediction

Superconductors in Space







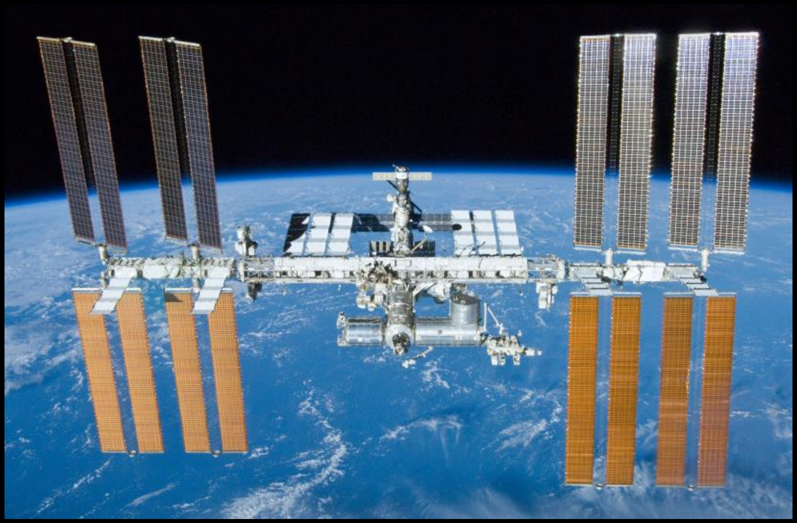
Cryogenic Select Surfaces

Reflects 99.9% solar irradiance

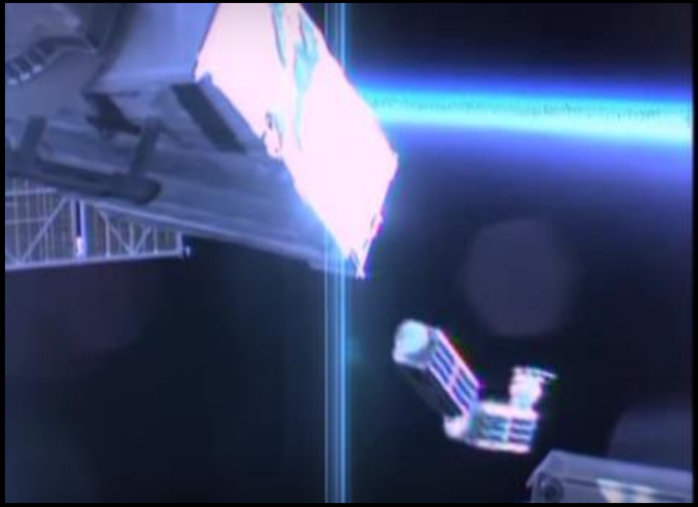
Transmits long infrared radiation from interior

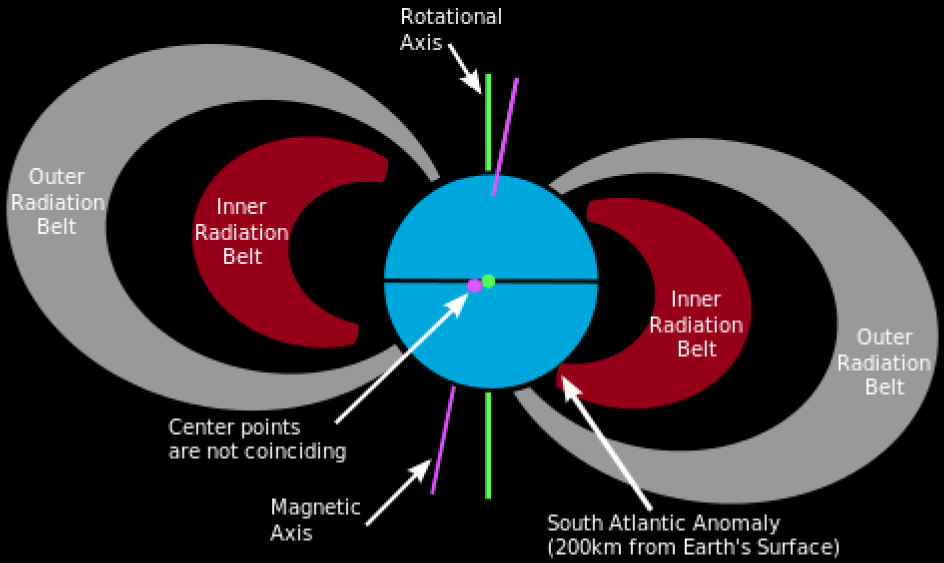
Result: Cryogenic temperatures below 50K

Technology Demonstration

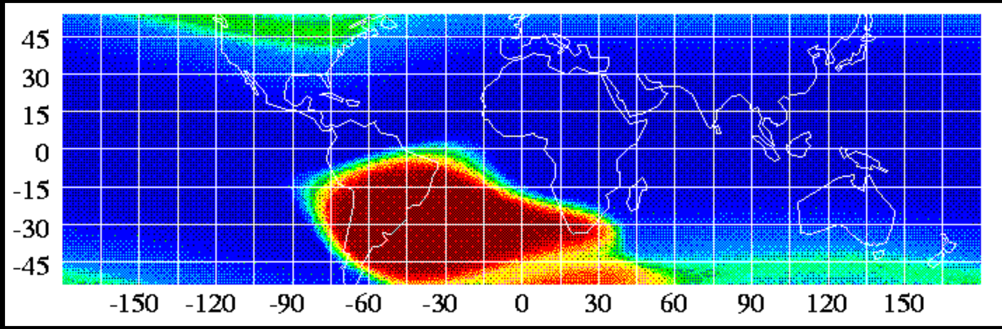


Nanoracks CubeSat deployment



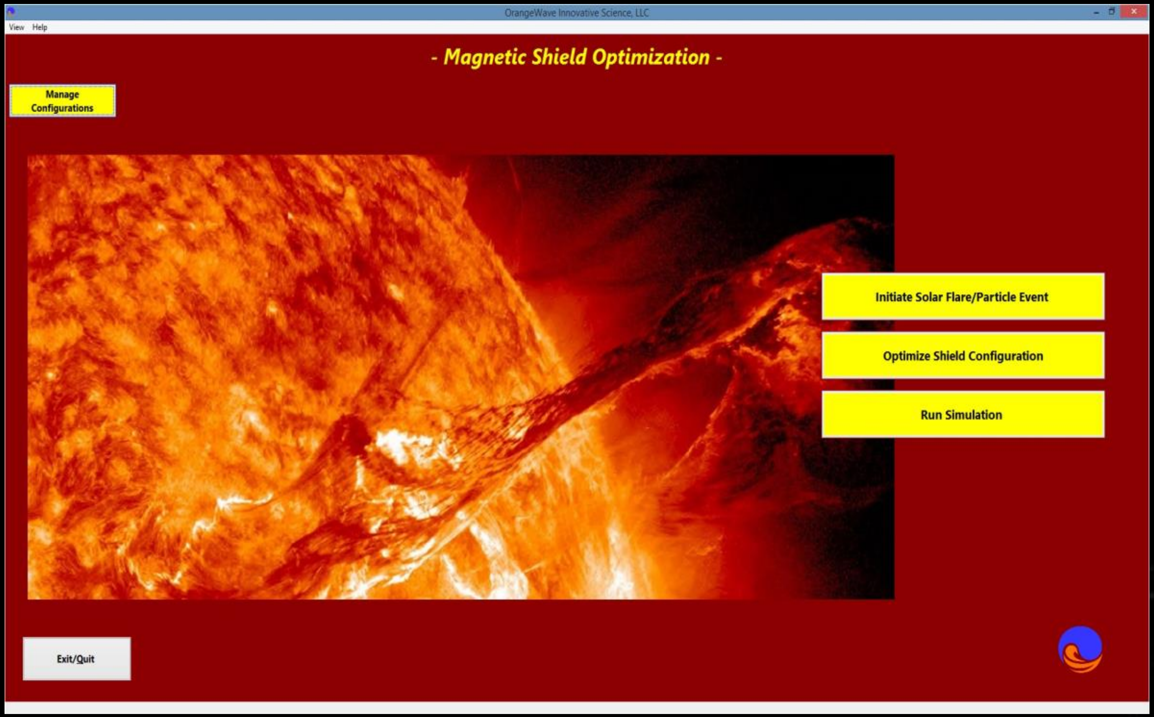


South Atlantic Anomaly

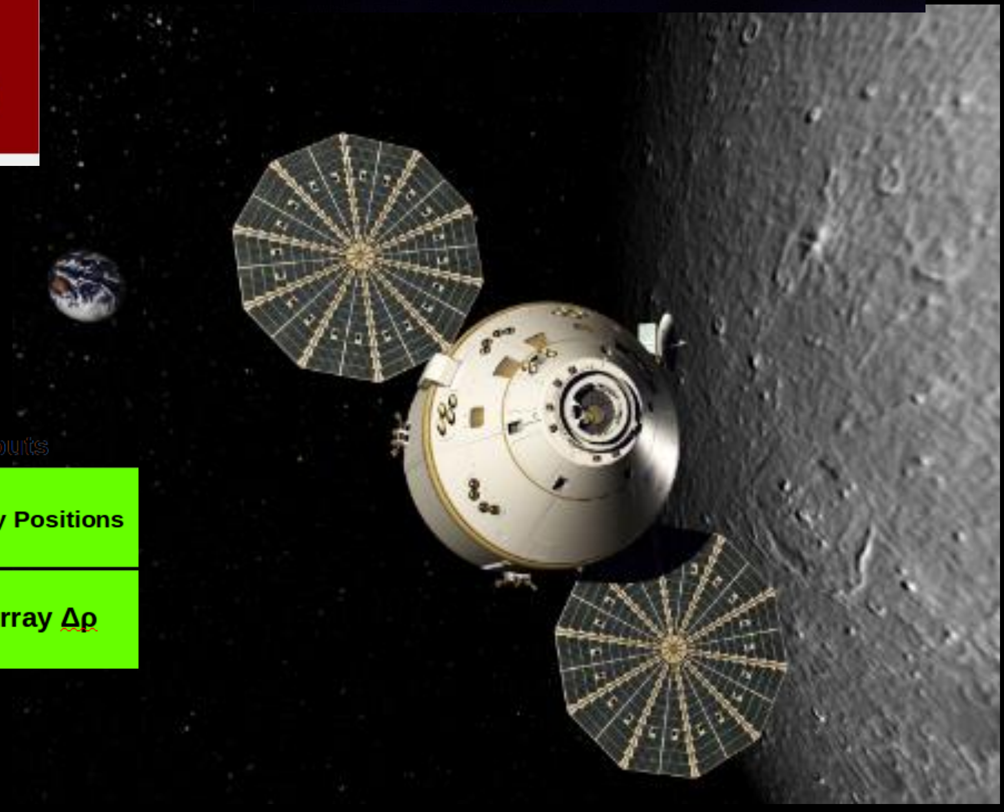


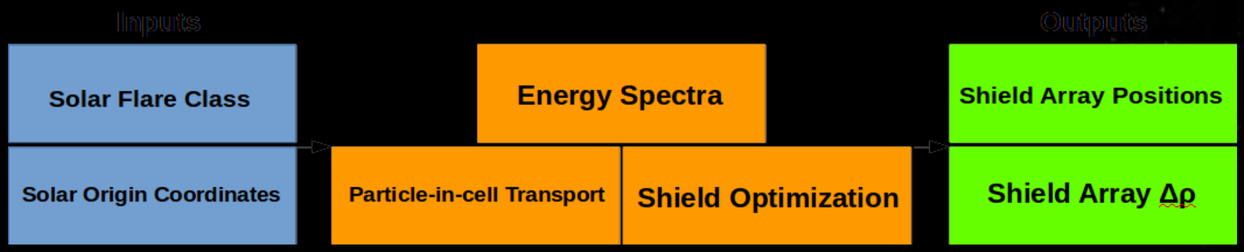
0.04 – 10 MeV inner Van Allen Belt particles

On-board, Deep-space Control




Heliospheric current sheet





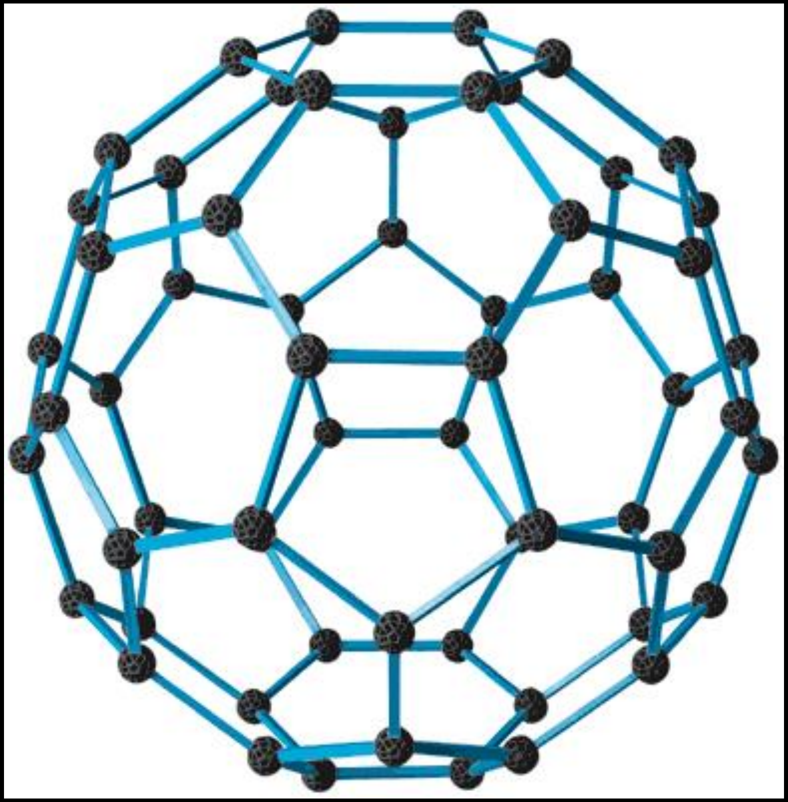
GCR Defense

For an isotropic distribution $f(\vec{r}, \vec{p})$ in a magnetic field,

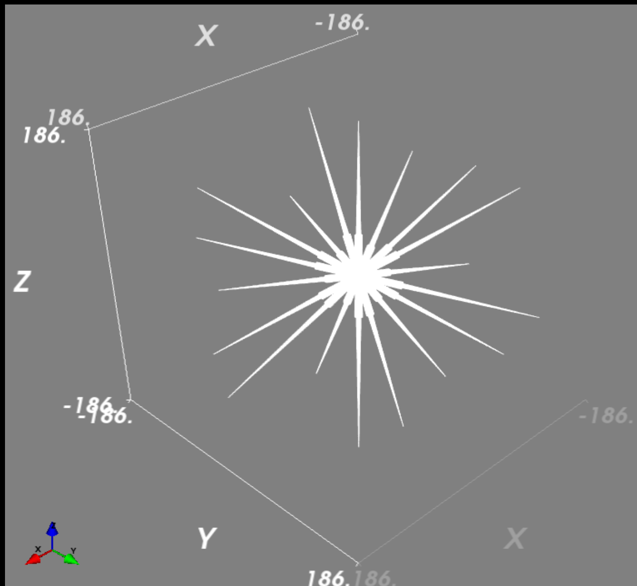
a first-order perturbation $f = f_0 + \sigma$ gives $\vec{v} \cdot \frac{\partial \sigma}{\partial \vec{r}} = -(\vec{F} \cdot \vec{p}) \frac{\partial f_0}{\partial |\vec{p}|} \frac{1}{|\vec{p}|} = 0$

Evenly spherical distribution of dipoles

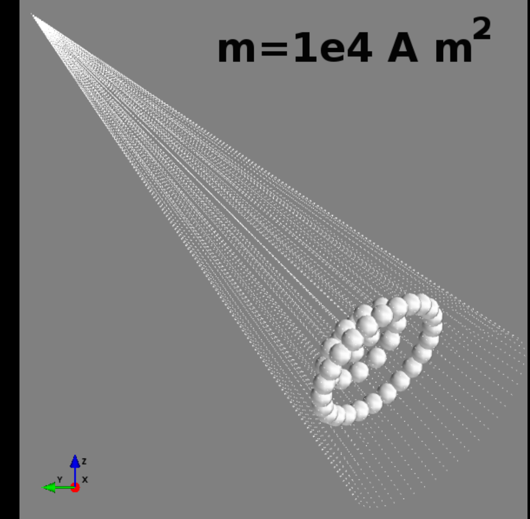
Create isotropic distribution

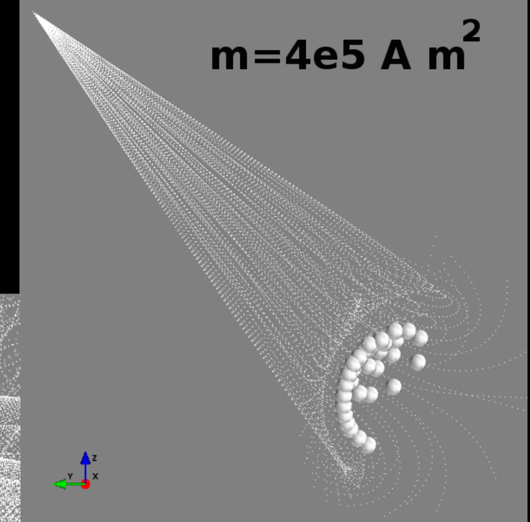


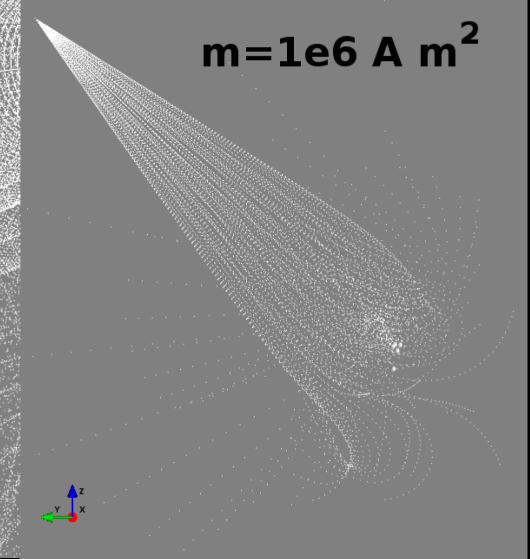
20-pt Buckyball Simulation

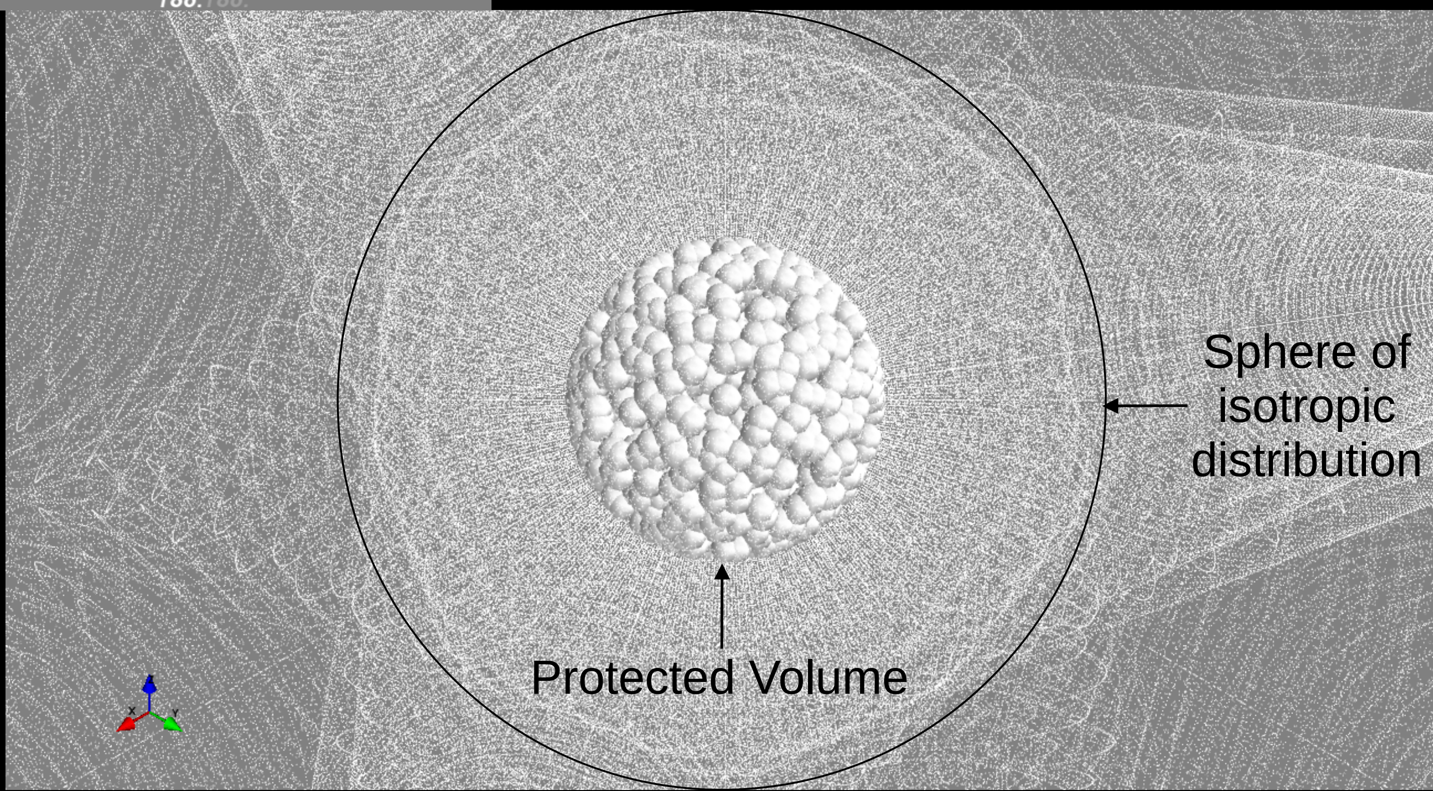


- Arbitrary number of particles per injection
- Arbitrarily narrow beam

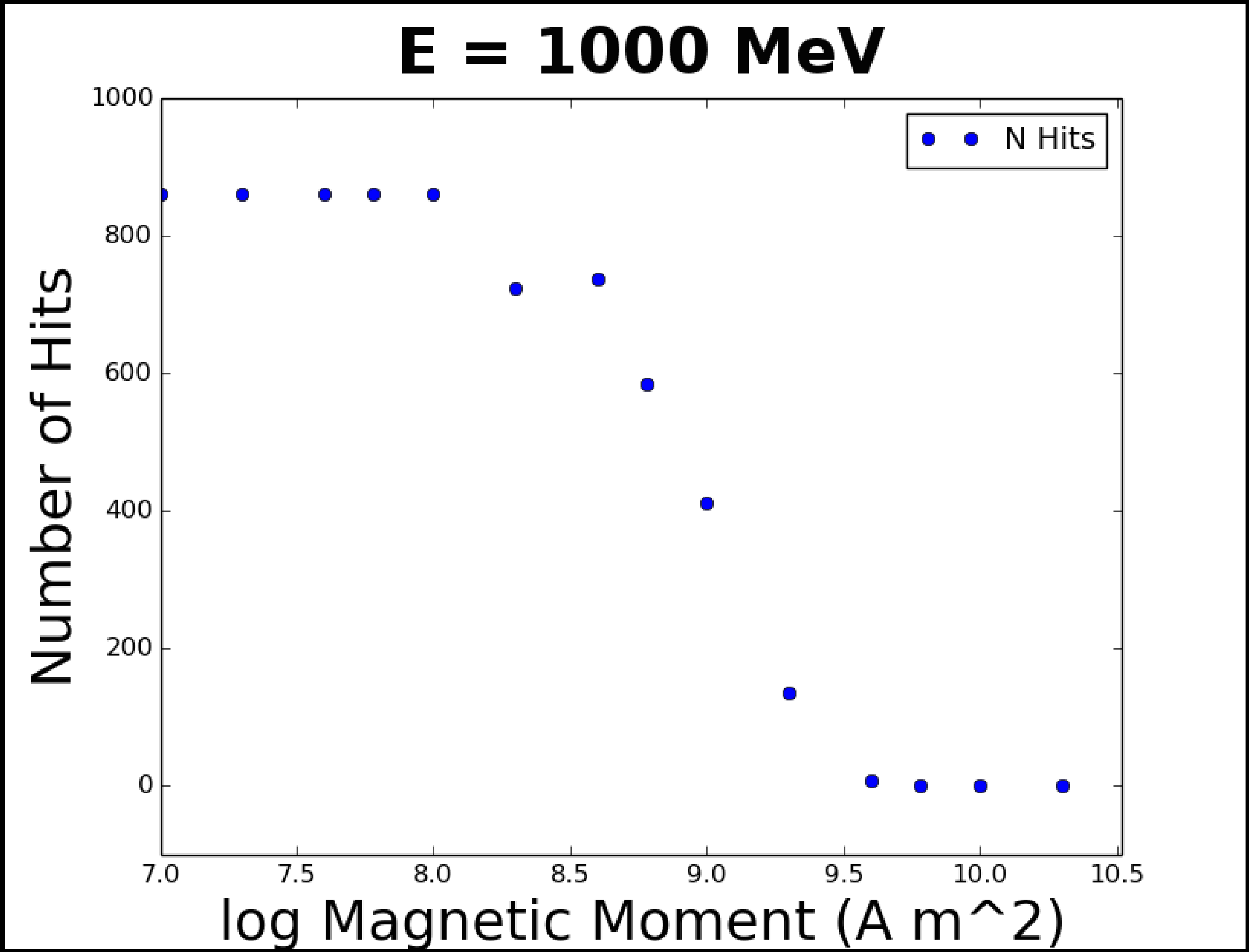






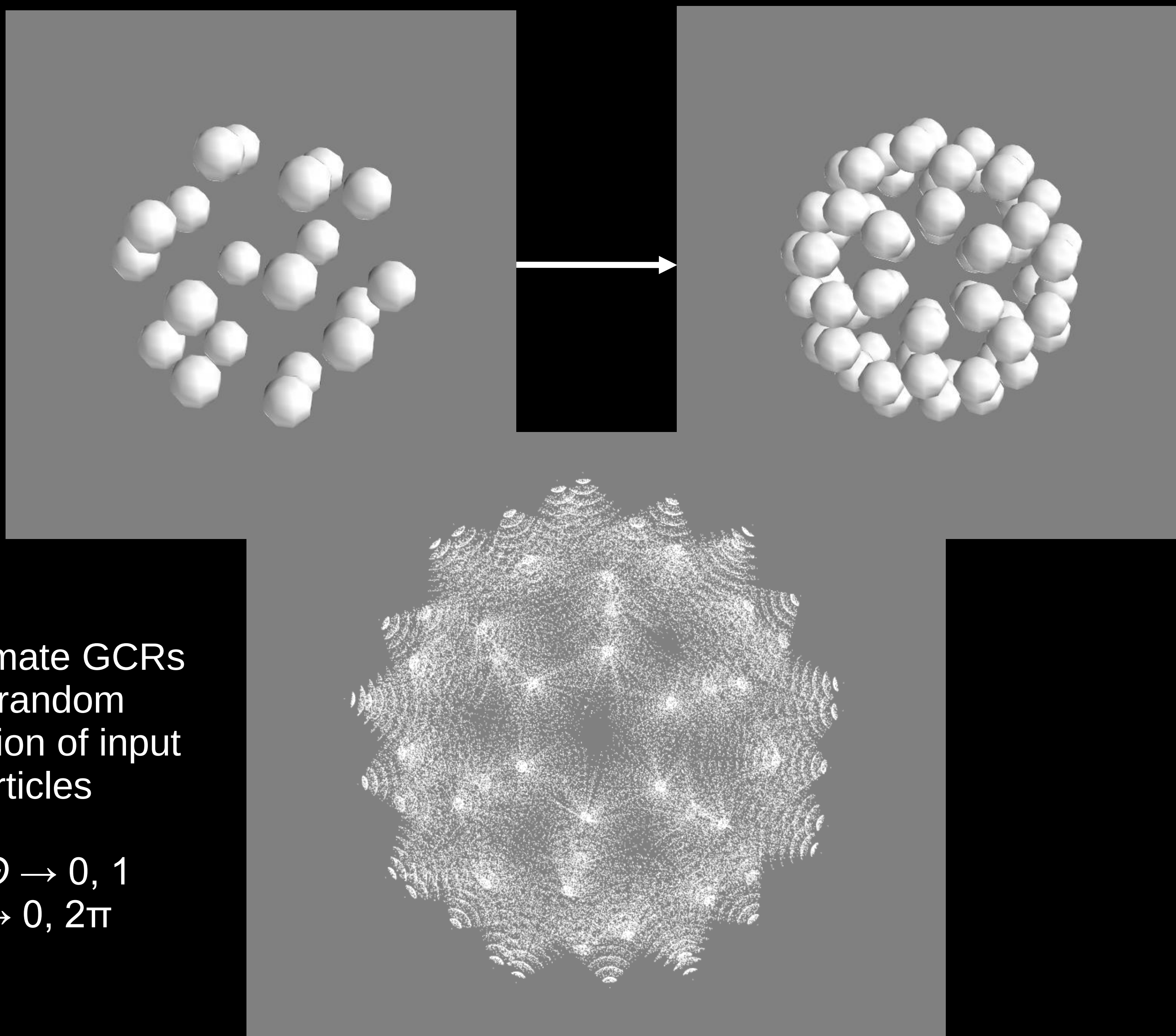


GCR Deflection



Code validation run

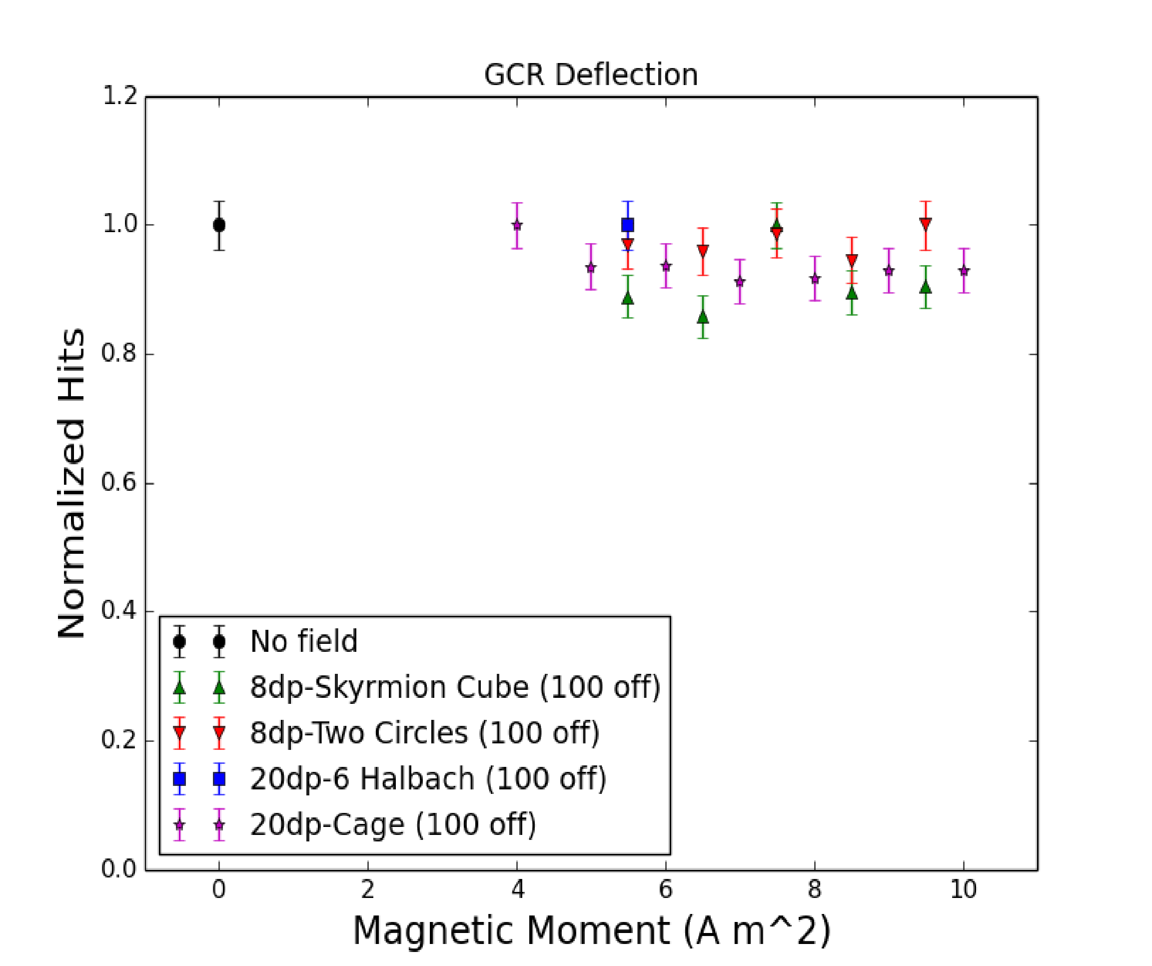
Robust Simulations

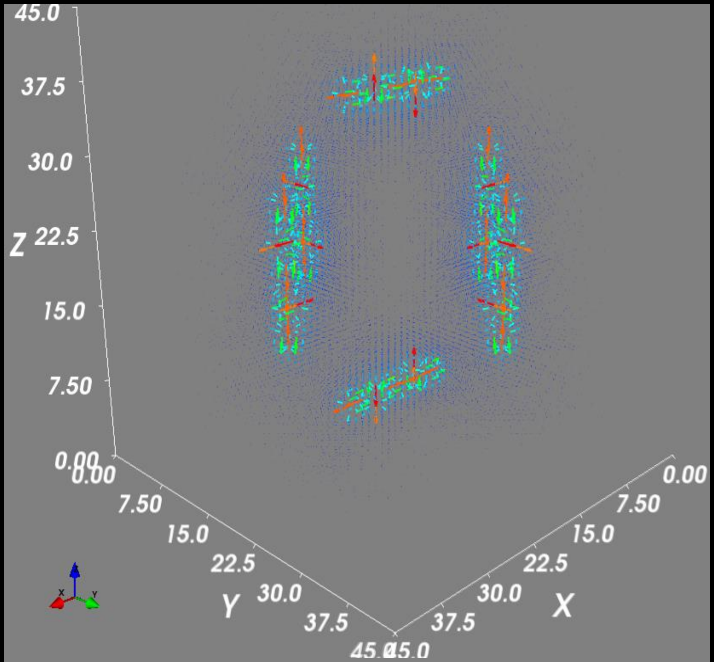


Approximate GCRs
with random
distribution of input
particles

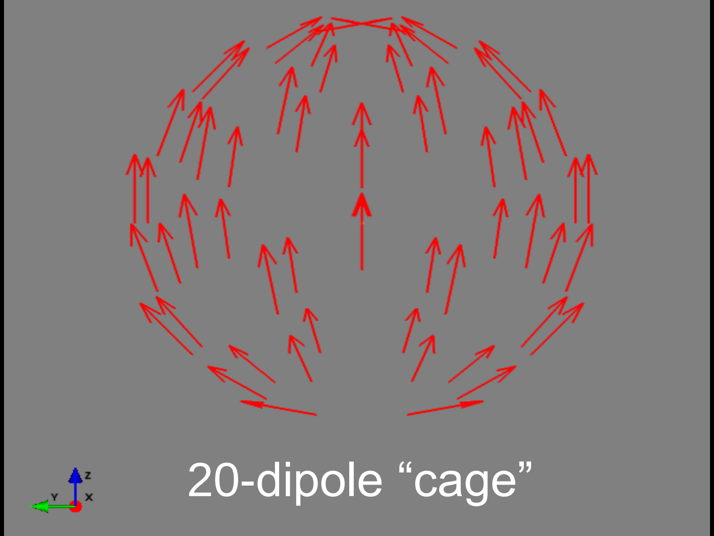
Cos$\Theta \rightarrow 0, 1$
$\Phi \rightarrow 0, 2\pi$

Results





6-Halbach "cage"



20-dipole "cage"

Thank You

Percent reductions in SPE radiation show **feasibility**

Existing technology shows **viability**

Equivalent Dose

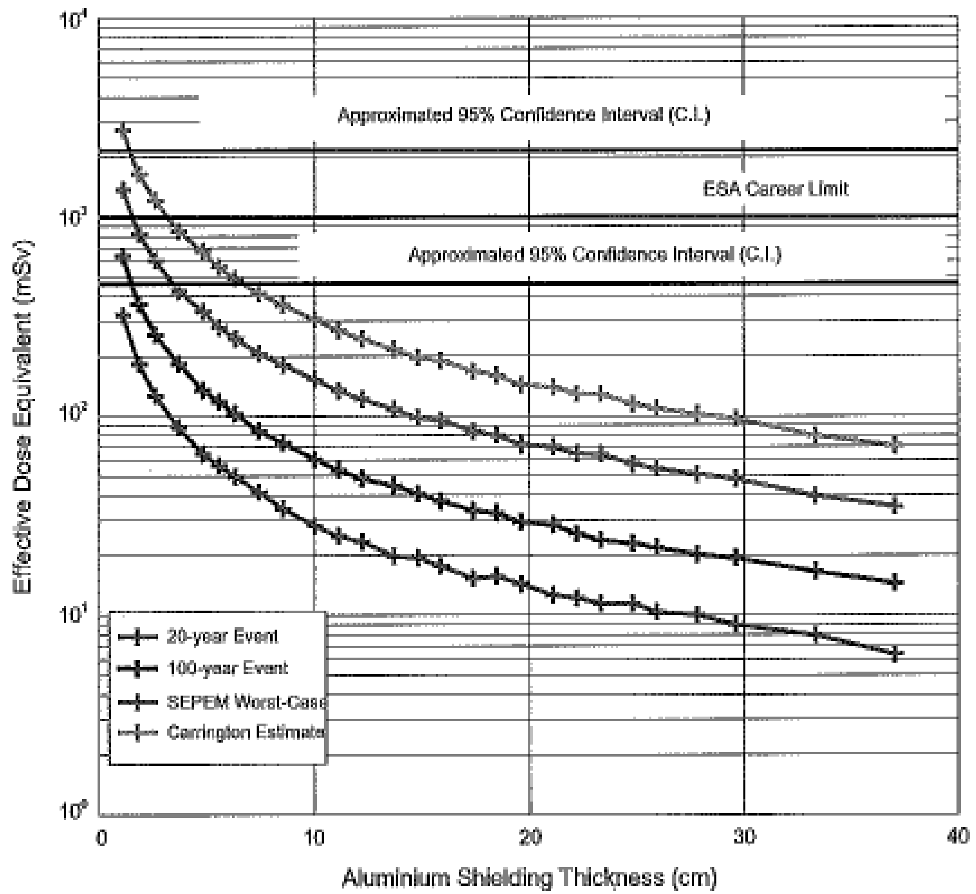


Fig. 13. Effective Dose Equivalent (milli-sieverts) in an astronaut as a result of extreme SPEs compared to the recommended ESA career limit for the four SPEs shown in Figure 9.

Jiggens, P., et al. (2014)

Enabling Technology

Consider 12 mm wide and 50 μm thick (no stabilizer) coated conductor.

Critical current at 77 K is 300 A. Lift factor at 50 K in 2 T field is about 2.

Then the critical current at 50 K is about 600 A.

We can take persistent current to be 50% of the critical.

Then, the engineering current density of persistent current is approximately
J = 50 kA/cm2

Consider a loop of 20 cm radius creating a dipole moment d=πx10 ^4 Am^2.

This required current of 250 kA or 5 cm^2 cross-section of the loop.

Enabling Technology

Mass density of Hastelloy (the substrate) is about 9 g/cm^3.

The total volume of a torus 20 cm in radius and 5 cm^2 cross-section is 630 cm^3.

The mass of the superconducting material then is 5.6 kg.

For greater or smaller dipole of the same size the mass is scaled proportionally.

Increasing the size of the loop decreases the required current and the amount of the superconducting material inversely proportional to the radius.

These estimates do not take into account the support structure, power supply, electronics, sunscreen, etc.