MT25
25th International Conference on Magnet Technology

INFN

The Limits of Space Radiation Magnetic Shielding: an Updated Analysis

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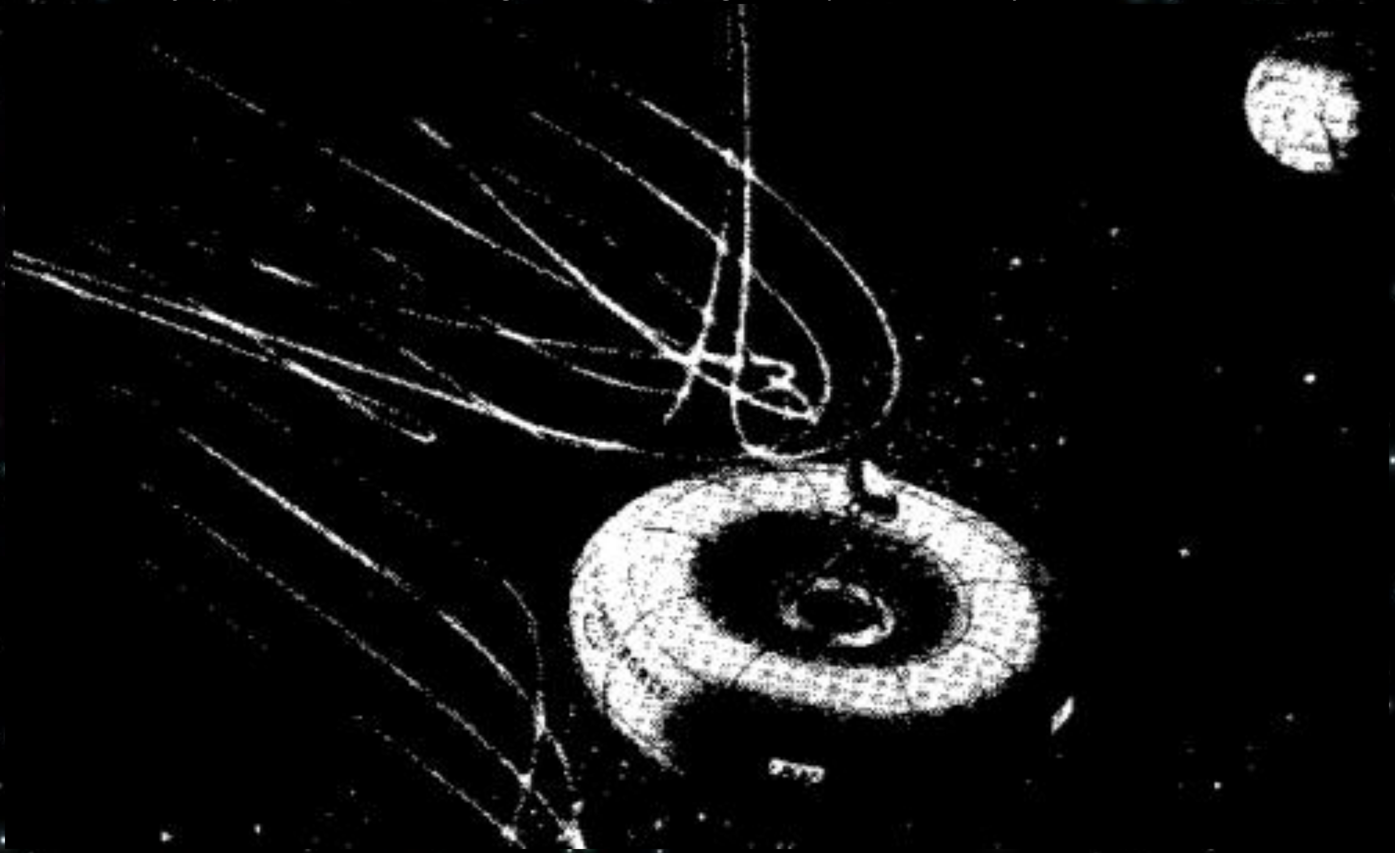
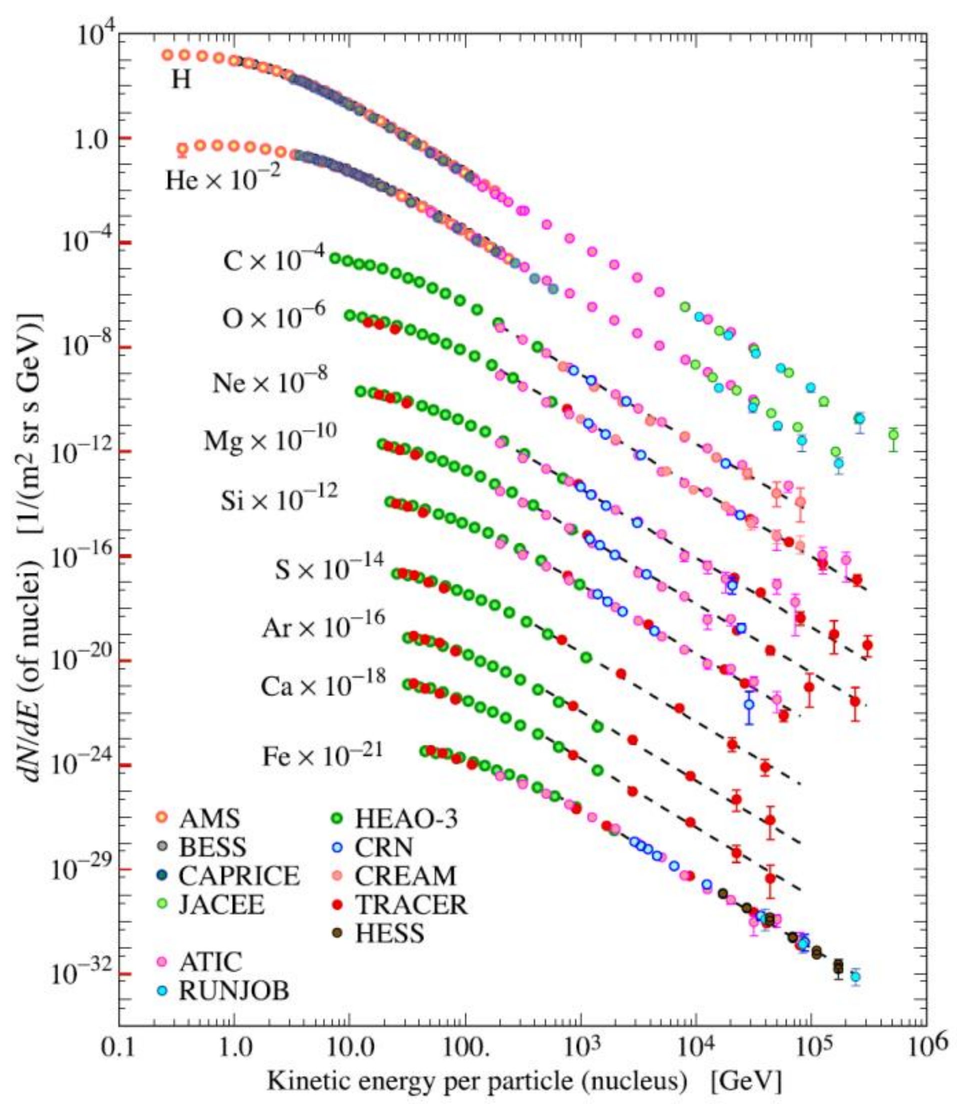
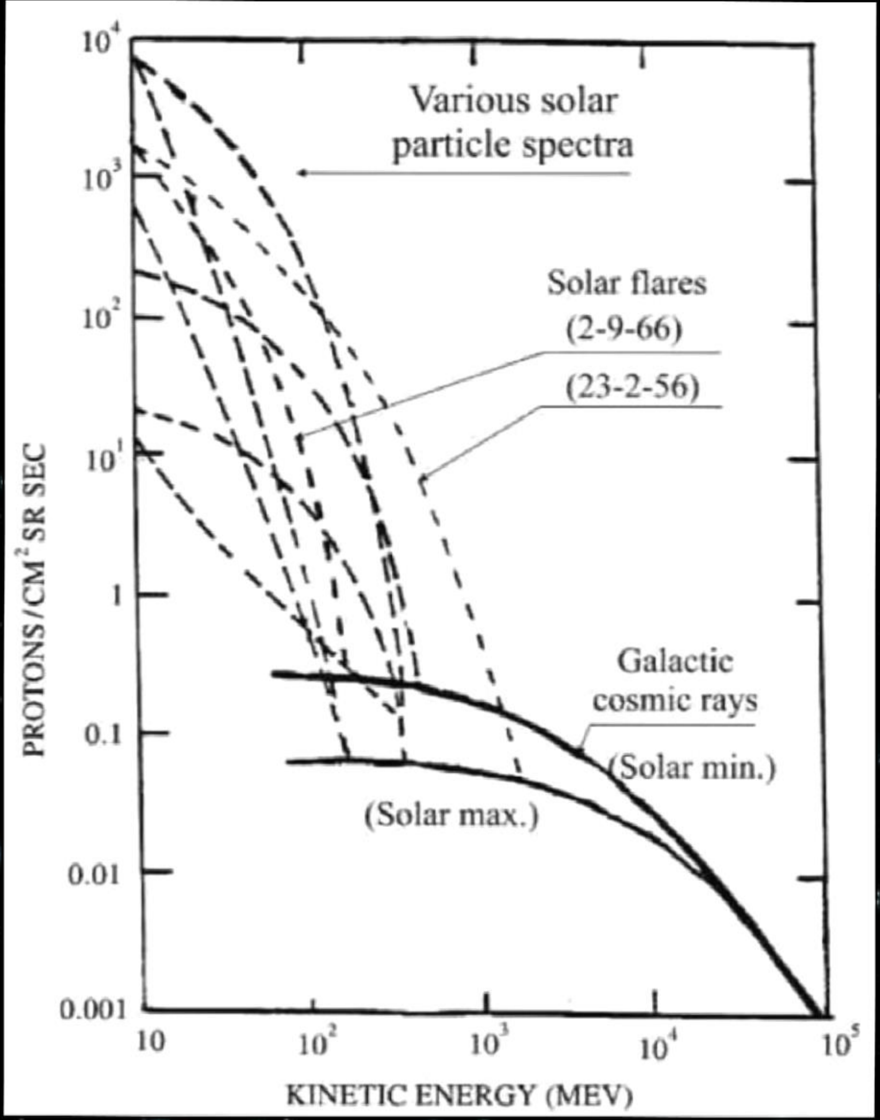
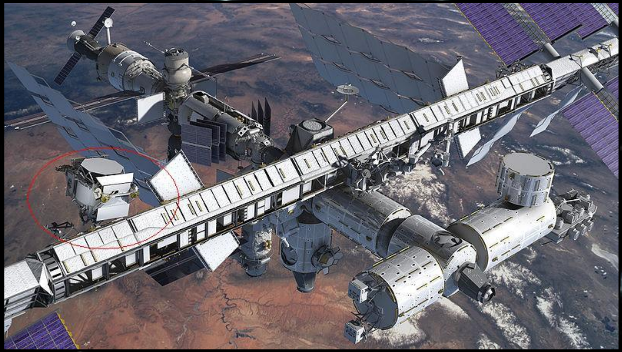


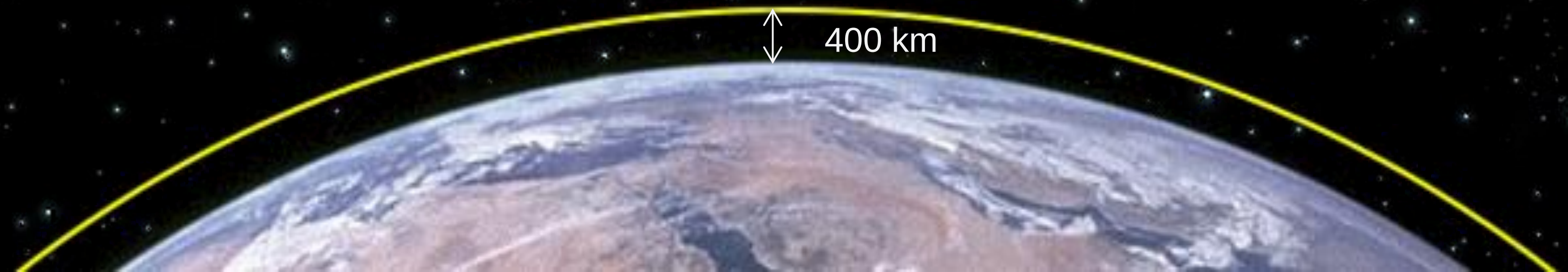
«Applying the strange phenomenon of «superconductivity» in space flights promises shields against deadly radiation, gyros without friction and other innovations in travels beyond the Earth.»

Werner von Braun
«Will Mighty Magnets Protect Voyagers to Planets?»
Popular Science 1969


H
He × 10^{-2}
C × 10^{-4}
O × 10^{-6}
Ne × 10^{-8}
Mg × 10^{-10}
Si × 10^{-12}
S × 10^{-14}
Ar × 10^{-16}
Ca × 10^{-18}
Fe × 10^{-21}
AMS
BESS
CAPRICE
JACEE
ATIC
RUNJOB
HEAO-3
CRN
CREAM
TRACER
HESS
dN/dE (of nuclei) [1/(m² sr s GeV)]
10^4
1.0
10^{-4}
10^{-8}
10^{-12}
10^{-16}
10^{-20}
10^{-24}
10^{-29}
10^{-32}
0.1
1.0
10.0
100.
10^3
10^4
10^5
10^6
Kinetic energy per particle (nucleus) [GeV]


Various solar particle spectra
Solar flares
(2-9-66)
(23-2-56)
Galactic cosmic rays
(Solar min.)
(Solar max.)
PROTONS/CM² SR SEC
10^4
10^3
10^2
10^1
1
0.1
0.01
0.001
10
10^2
10^3
10^4
10^5
KINETIC ENERGY (MEV)




400 km

shielding strategies

passive

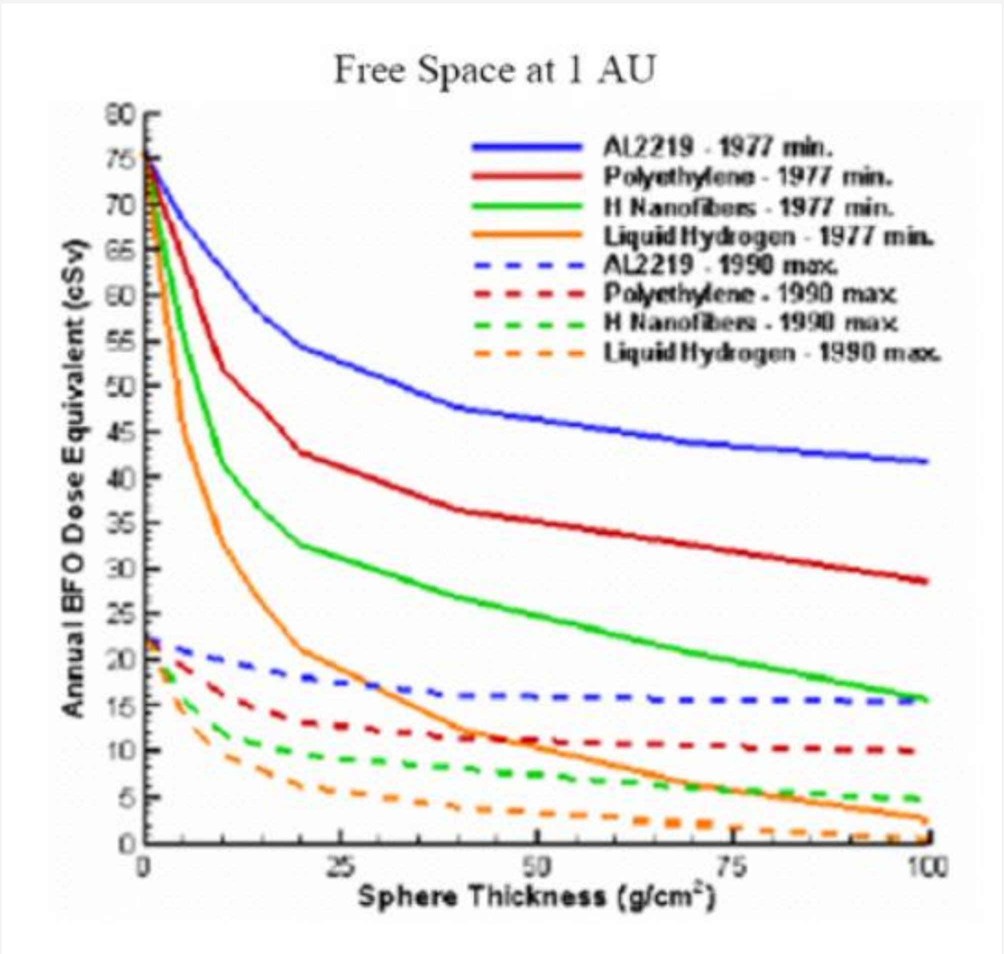
based on the ionization losses in materials of sufficiently depth to stop the incident particles

active

electrostatic

magnetostatic

large superconducting magnets surrounding the spacecraft cabin



M. Durante,
“Space radiation protection: Destination Mars”
Life Sciences in Space Research 1, 2014

½ dose with HDPE
100 m^3 habitat
↓
>80 tons

Mass impacts on

Launch cost

Maximum speed

$$v = v_e ln\left(\frac{m_i}{m_f}\right)$$

Magnetic shielding

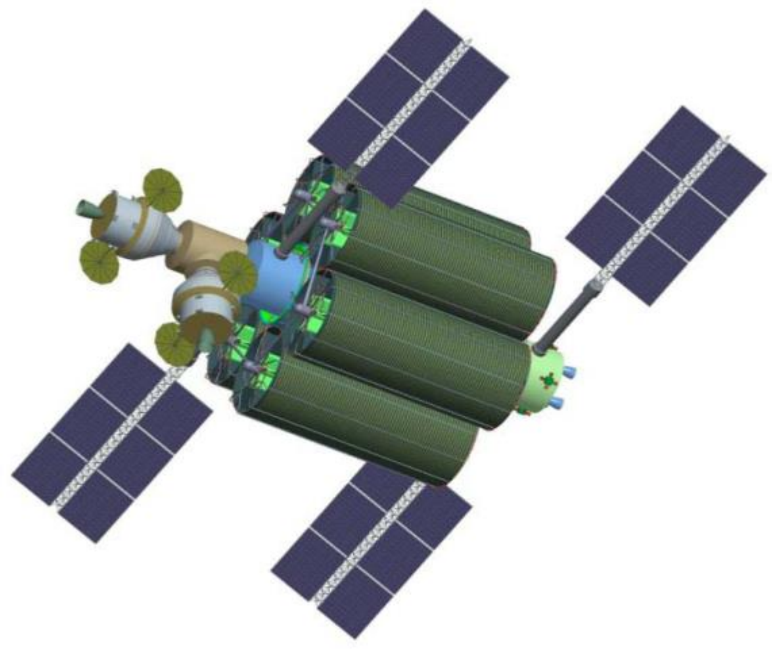
1961 - 2007 conceptual studies on magnetic shielding

Between 2010 and 2015, for the first time, technological investigations were carried out to verify the feasibility of superconducting magnets for cosmic radiation shielding.

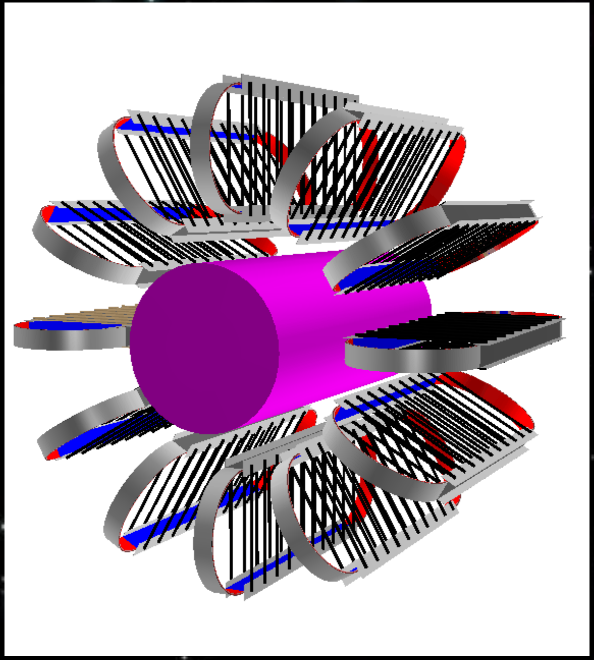
ARSSEM	2010	partially funded by ESA
MAARS	2012-2014	funded by NIAC
SR2S	2013-2015	partially funded by the European Union

Magnetic shielding

solenoids



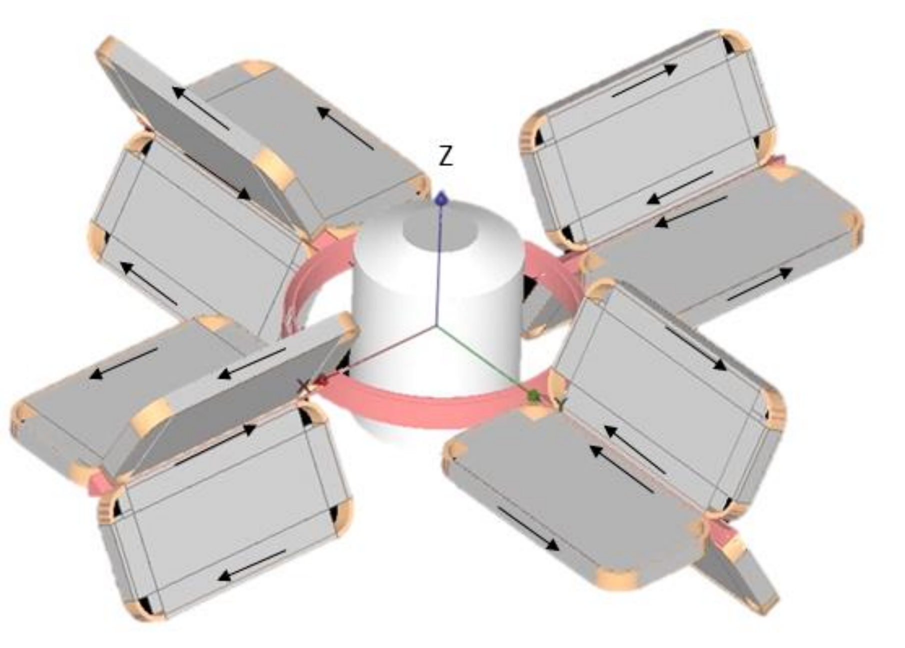
toroids



problem

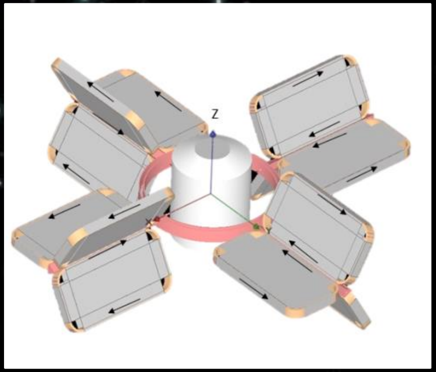
Materials composing the shield provide partial passive shielding but generate <u>secondary particles</u>

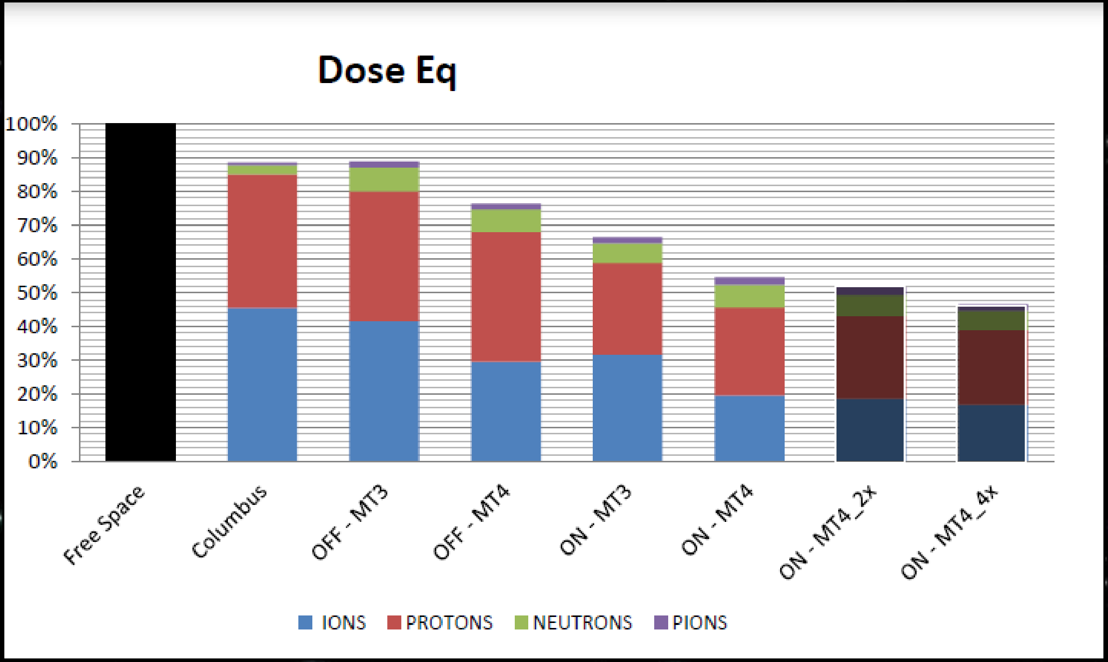
Secondary particles limit the effectiveness of magnetic shields



«pumpkin» configuration

V.Calvelli, R.Musenich, F.Tunesi, R.Battiston
A Novel Configuration for Superconducting Space Radiation Shields
IEEE Trans. on Appl. Supercond. **27** (4), Art. No. 0500604, 2017


z


Dose Eq
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
Free Space
Columbus
OFF - MT3
OFF - MT4
ON - MT3
ON - MT4
ON - MT4_2x
ON - MT4_4x
IONS
PROTONS
NEUTRONS
PIONS

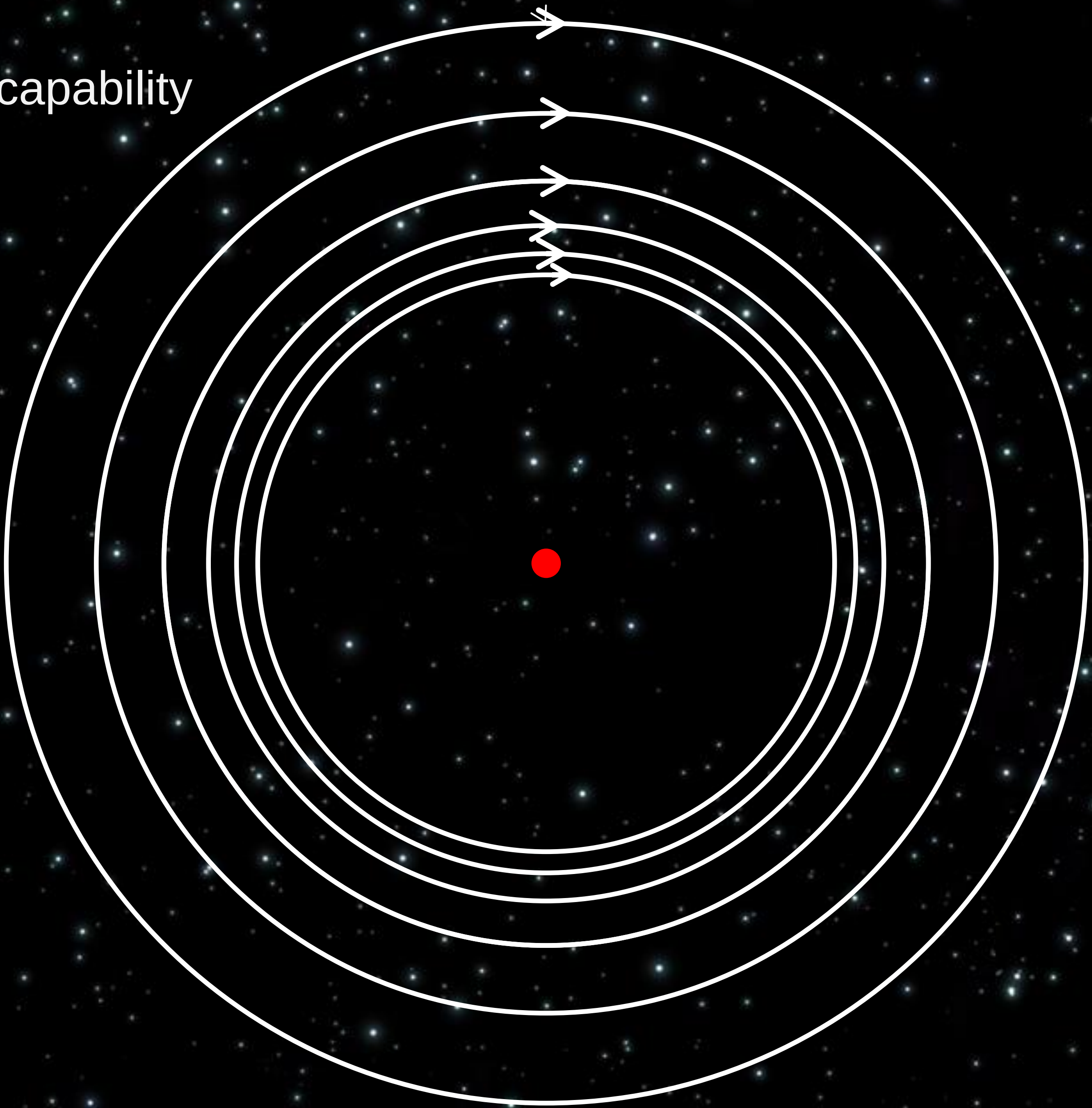
Evaluation of shielding capability of a toroidal field

Isotropic GCR flux

No matter

Infinitely long toroid

Punctual astronauts

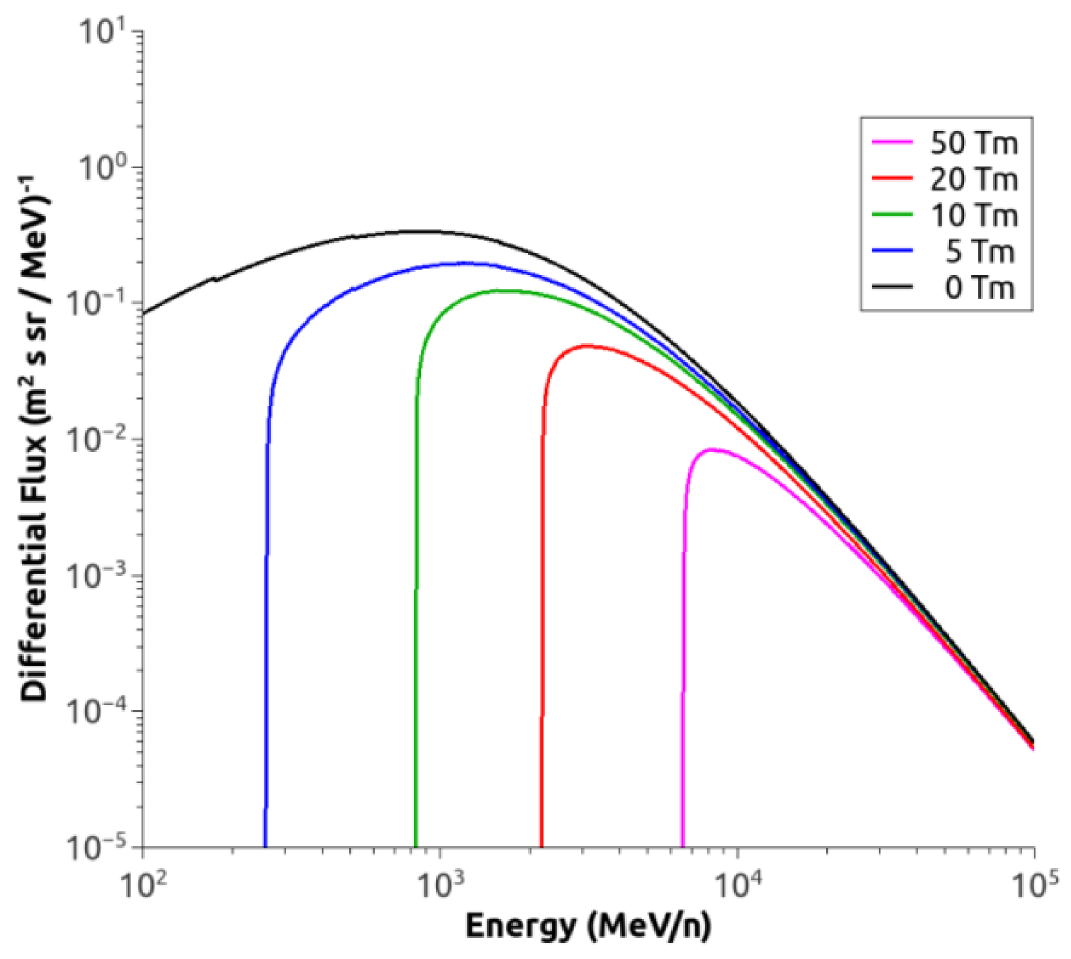


Cut-off energy:

$$K(\Xi,\varphi) = \frac{m_0c^2}{\eta}\left(\sqrt{1+\left(\frac{q}{m_0c}\frac{\Xi}{(\alpha(r)-\sin\varphi)}\right)^2}-1\right)$$

Shielding power: $\Xi = \int_{r_i}^{r_e} B dr$

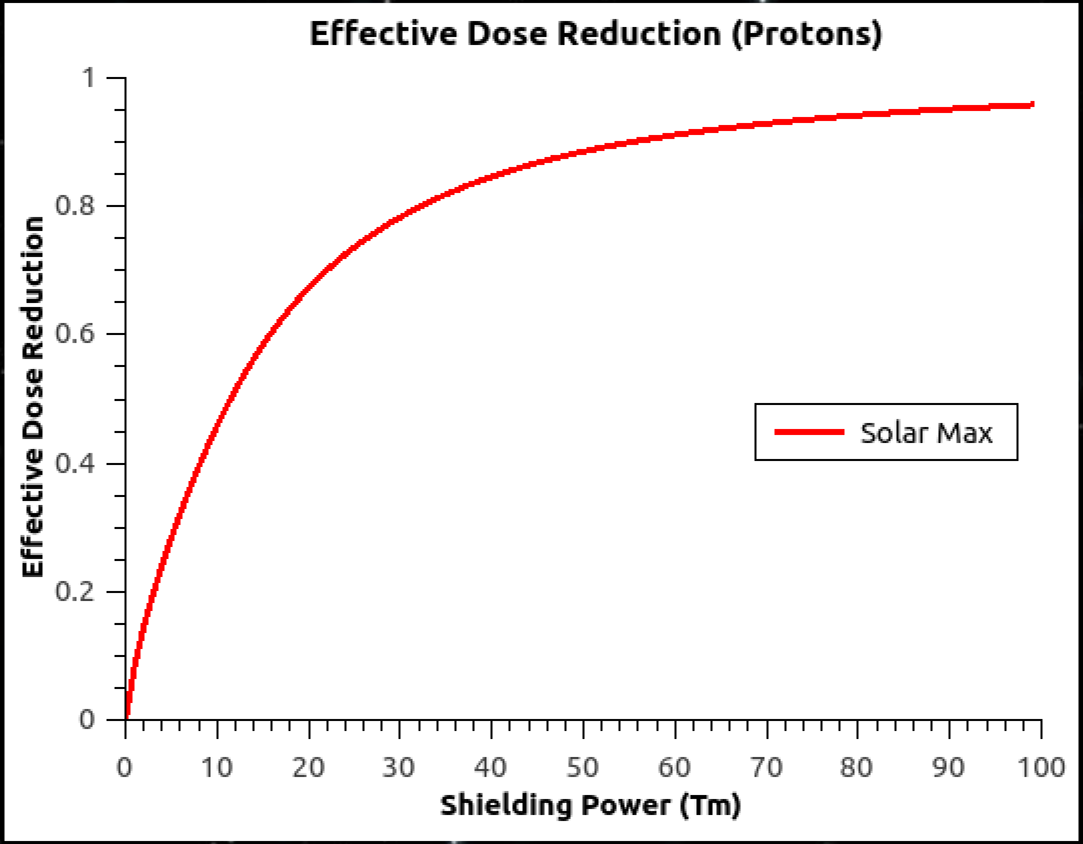
$$\alpha(r) = \sqrt{1-\frac{r^2\dot{\vartheta}^2}{c^2(\gamma^2-1)}}$$

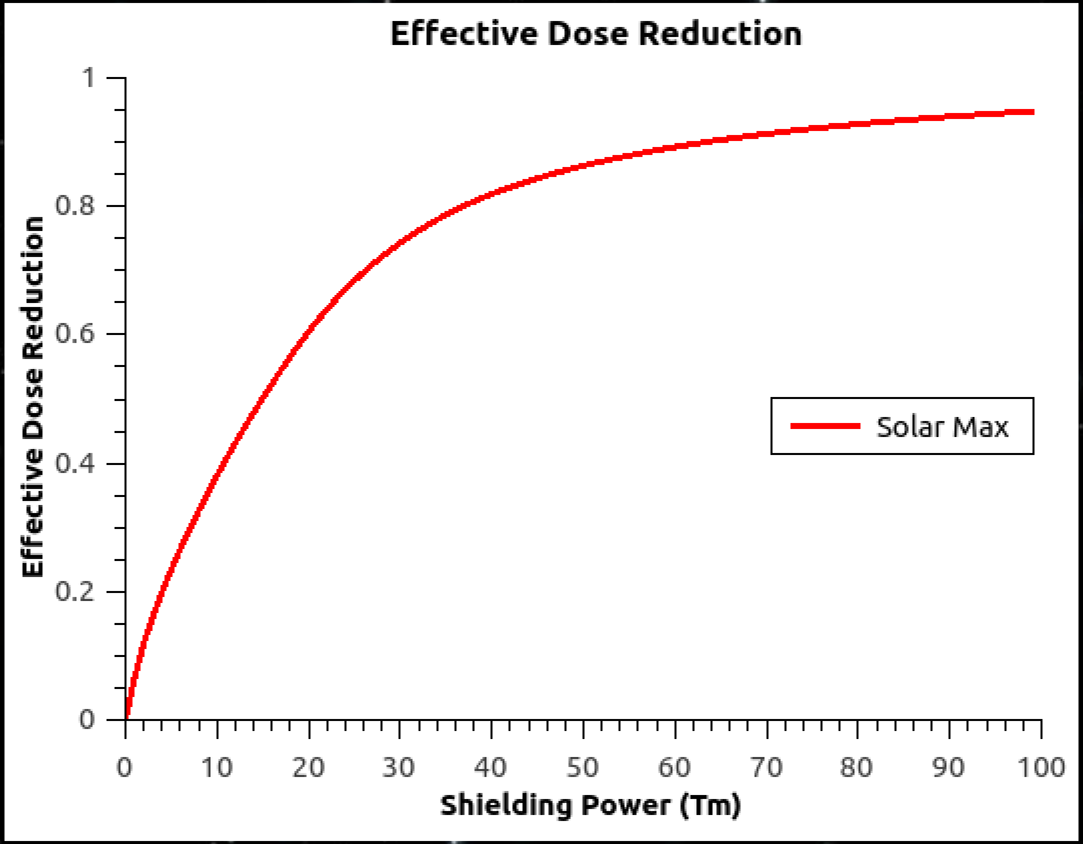

Differential Flux (m^2 s sr / MeV)$^{-1}$
Energy (MeV/n)
10^1
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^2
10^3
10^4
10^5
50 Tm
20 Tm
10 Tm
5 Tm
0 Tm

$$D_Z(\Xi) = \frac{1}{\pi}\int_{-\frac{\pi}{2}}^{\frac{\pi}{2}} d\varphi \int_{0}^{\epsilon_f} w_Z\,(\epsilon) Q_Z(\epsilon)\,\frac{\partial \Phi_Z(\epsilon)}{\partial \epsilon}\,\Theta(K_Z(\Xi,\varphi))d\epsilon$$

$$\Theta(K_Z(\Xi,\varphi)) = \begin{cases} 0, & \epsilon < K_Z(\Xi,\varphi) \\ 1, & \epsilon \geq K_Z(\Xi,\varphi) \end{cases}$$

$$\mathrm{DR}(\Xi) = 1 - \frac{\mathrm{D_{unsh}} - \sum_{\mathrm{Z}} \mathrm{D_Z}(\Xi)}{\mathrm{D_{unsh}}}$$


Effective Dose Reduction (Protons)
Effective Dose Reduction
1
0.8
0.6
0.4
0.2
0
0
10
20
30
40
50
60
70
80
90
100
Shielding Power (Tm)
Solar Max


Effective Dose Reduction
Effective Dose Reduction
Shielding Power (Tm)
0
0.2
0.4
0.6
0.8
1
0
10
20
30
40
50
60
70
80
90
100
Solar Max

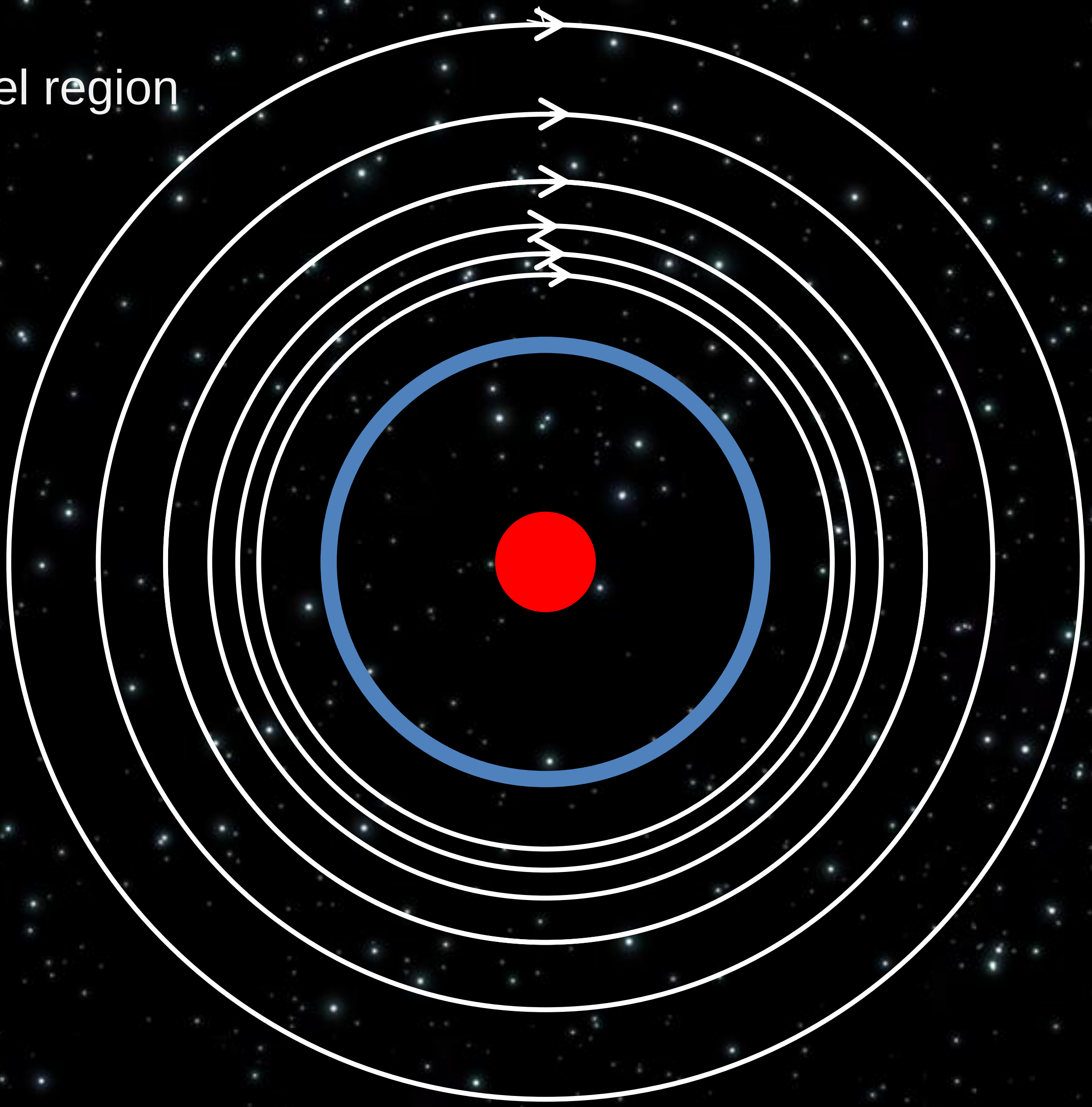
Monte Carlo simulations (ideal model)

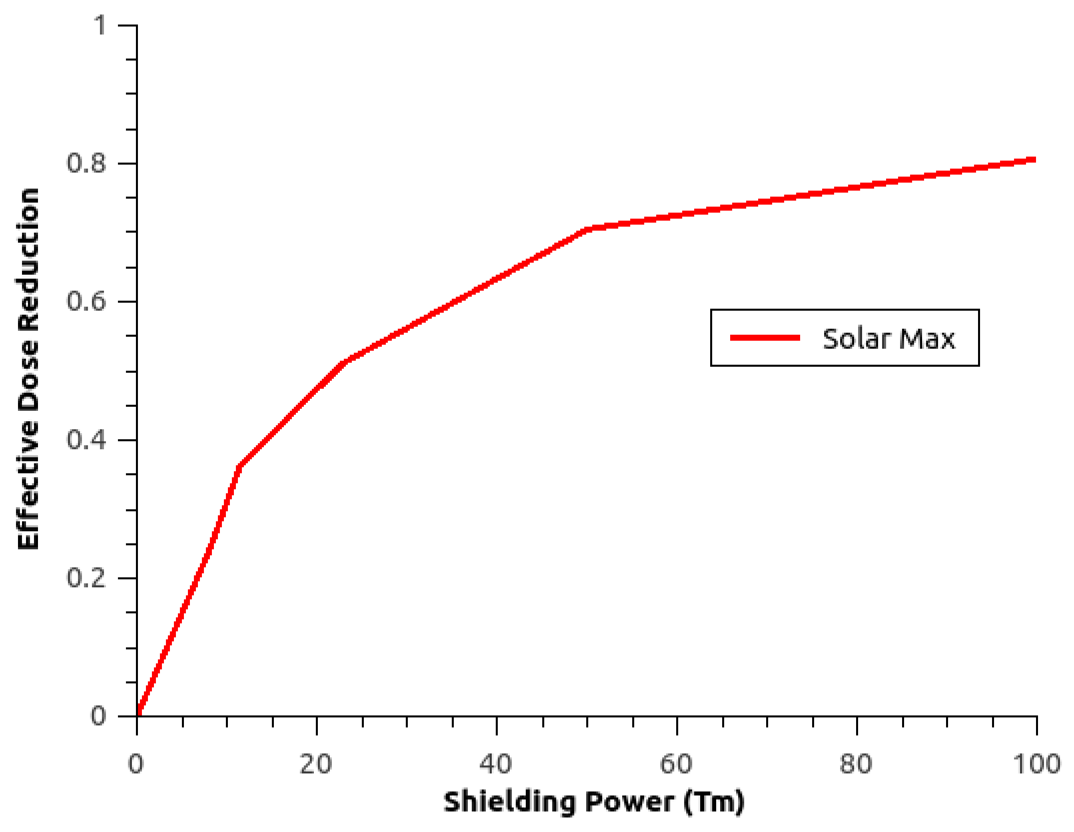
GCR flux limited to the barrel region

Immaterial magnet

Al spacecraft wall

Spheric astronauts




1
0.8
0.6
0.4
0.2
0
Effective Dose Reduction
0
20
40
60
80
100
Shielding Power (Tm)
Solar Max

Conclusions

- A superconducting toroid having 8 T·m shielding power could completely eliminate the risk due to SPE and can provide a partial protection to GCR.
- A 20 T·m shield could reduce the GCR adsorbed dose enough to make acceptable the risk of developing long term diseases after a return trip to Mars.
- Unconventional magnetic shielding configurations, like the “pumpkin” design, provide better shielding than a traditional toroidal magnet of the same weight.
- Magnetic shielding, as sole countermeasure to the space radiation problem, cannot be a final solution.
- Longer permanence in deep space or trips farther in the Solar System, probably require appropriate coupling of passive and active shields.