6th IAASS Conference

Session 33 Safety Design

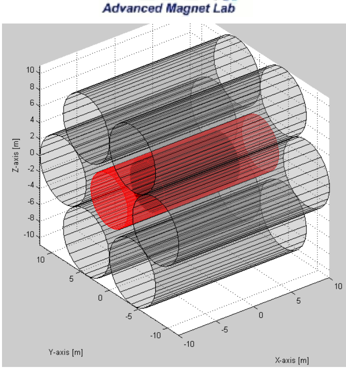
Active Magnetic Shielding for Long Duration Manned Space Missions

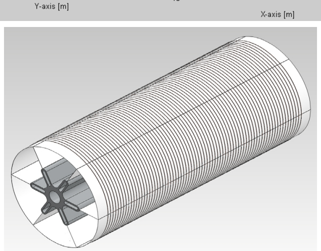
W.J. Burger

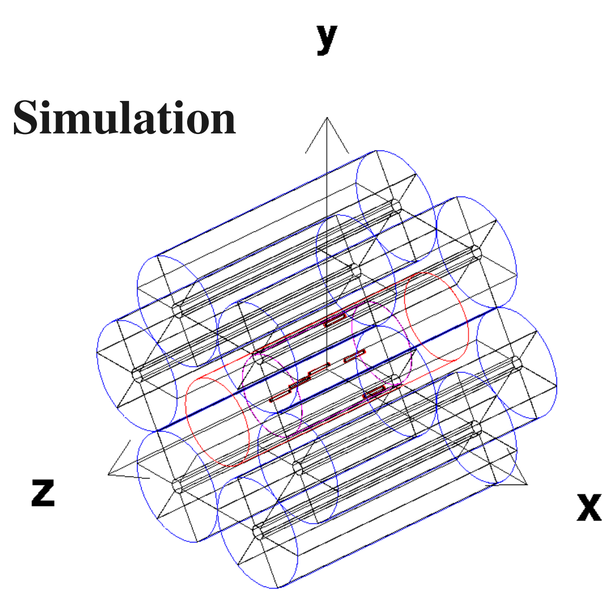
Università degli Studi di Perugia

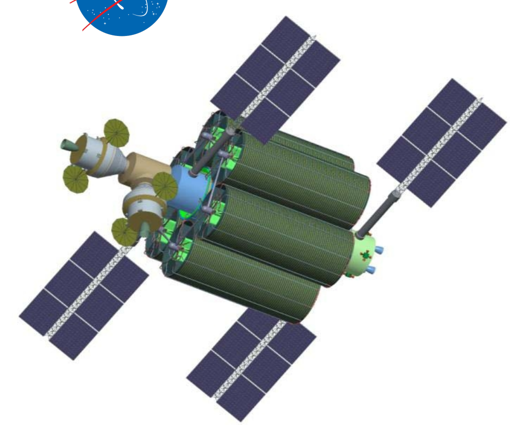
6+1 Expandable Solenoid Coil Configuration

Advanced Magnet Lab









21-23 mai 2013 - Montréal - Canada

Radiation Hazards

ionization losses

$$dE/dx \sim (z^2 / \beta^2)\,(Z / A)$$

z, β particle charge, velocity

Z, A material atomic number, mass

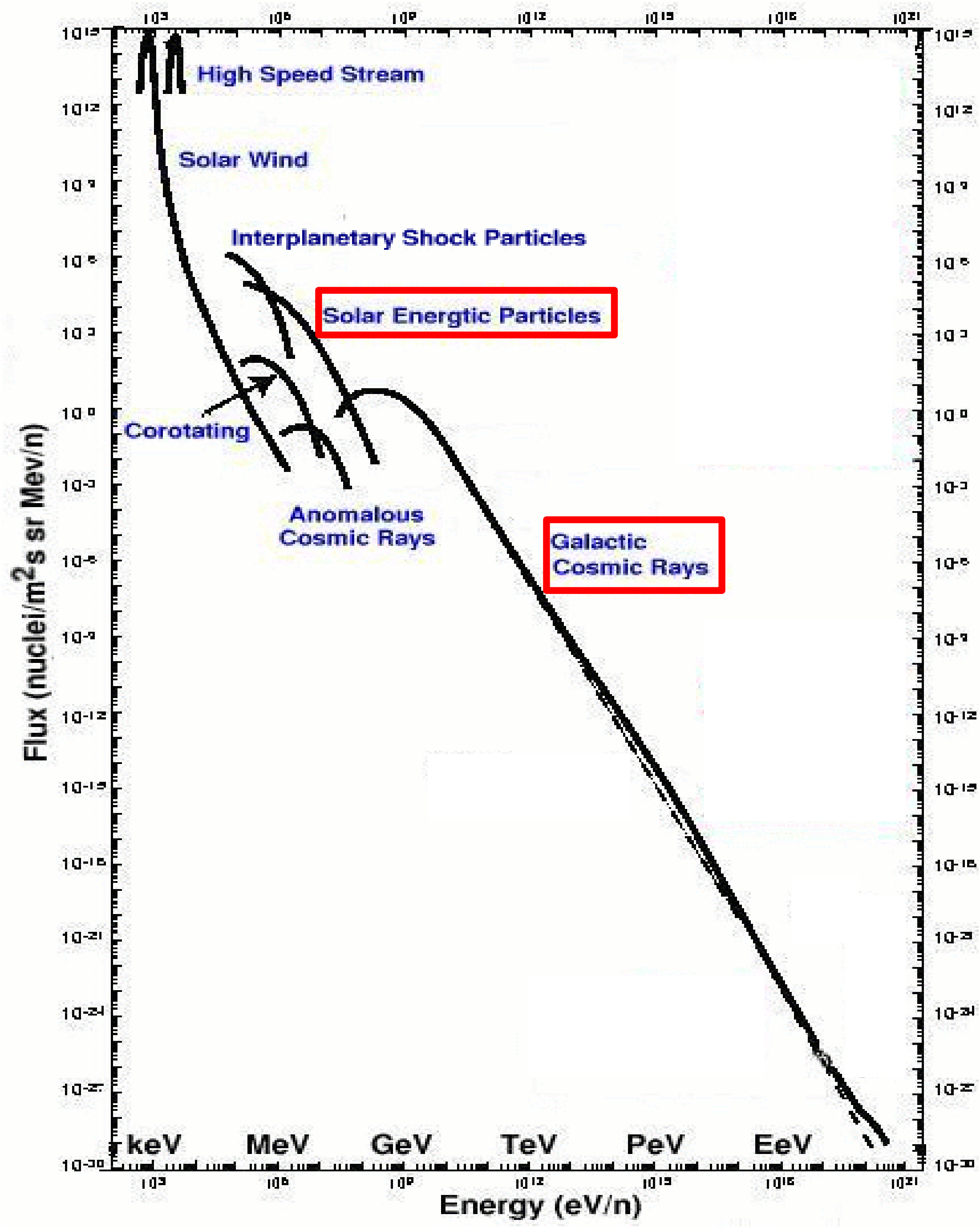
SEP protons (1-500 MeV)

risk of lethal instantaneous dose levels

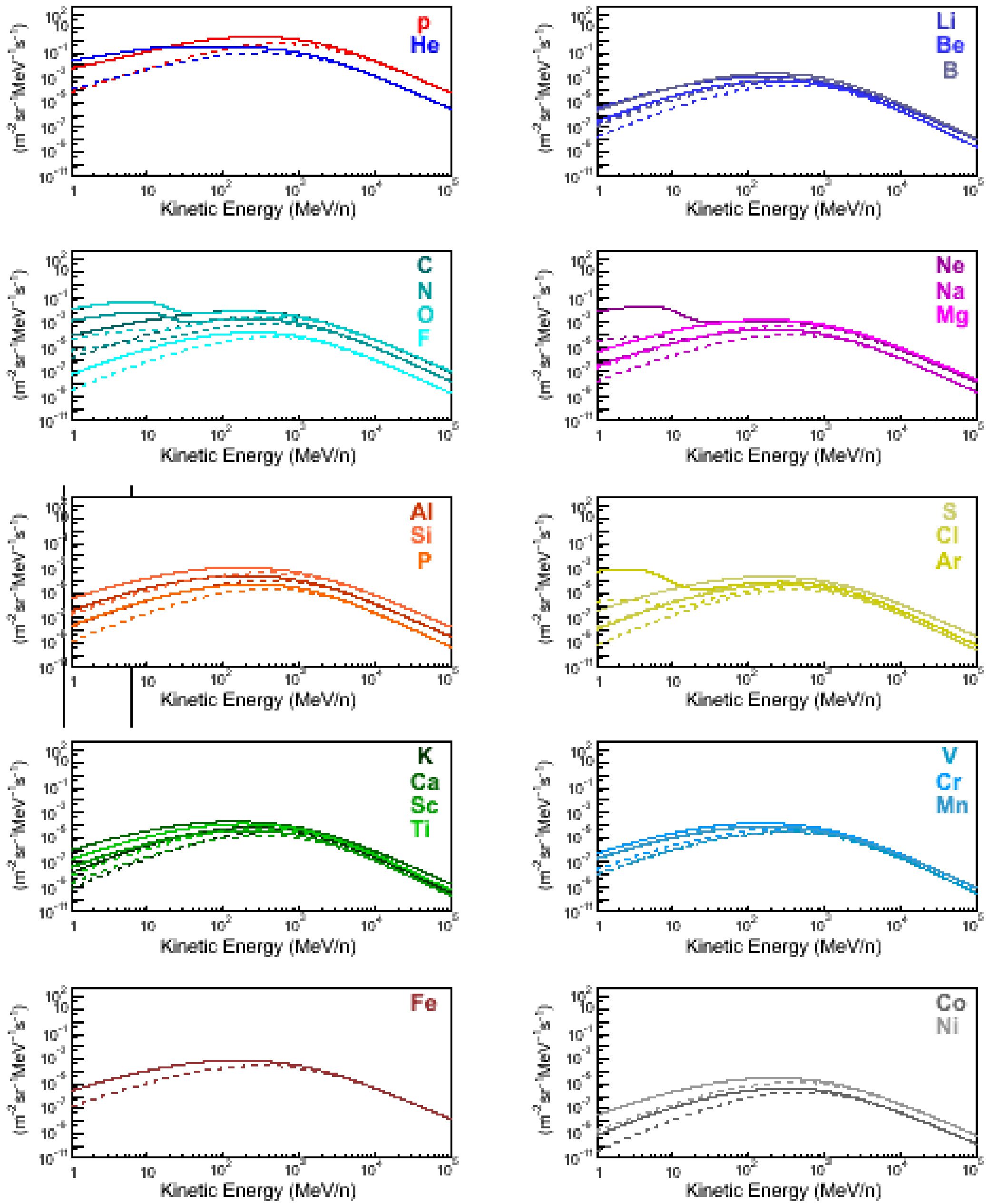
GCR protons and nuclei

cumulative dose,

increased ionization of high charge nuclei (HZE)



Galactic Cosmic Ray Fluxes – CREME 2009

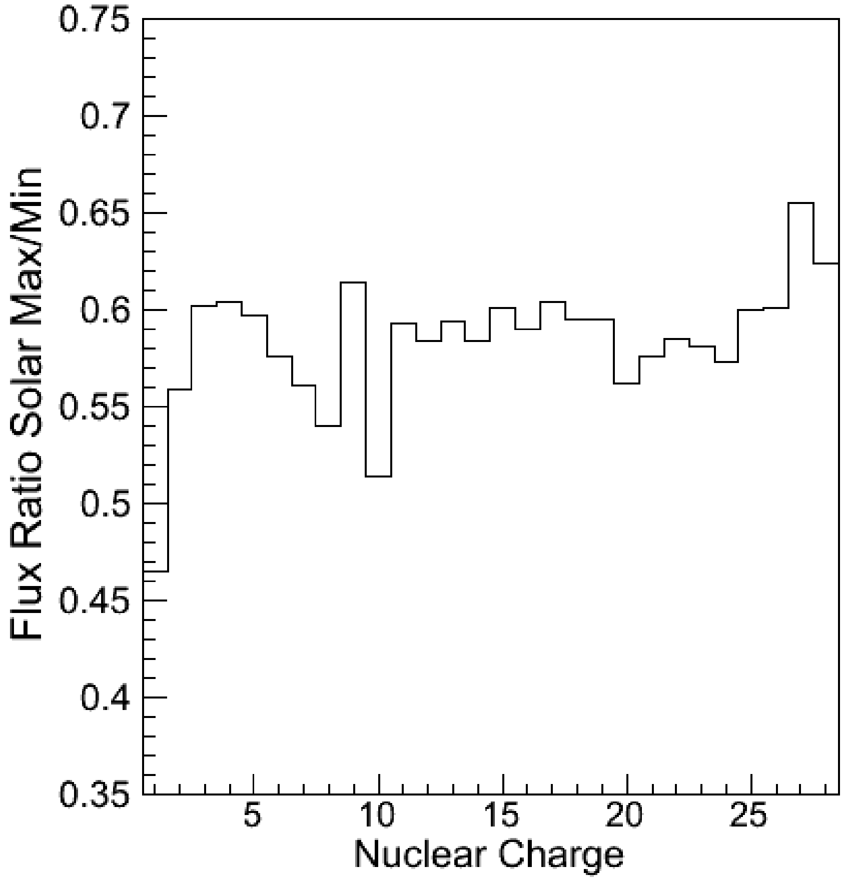


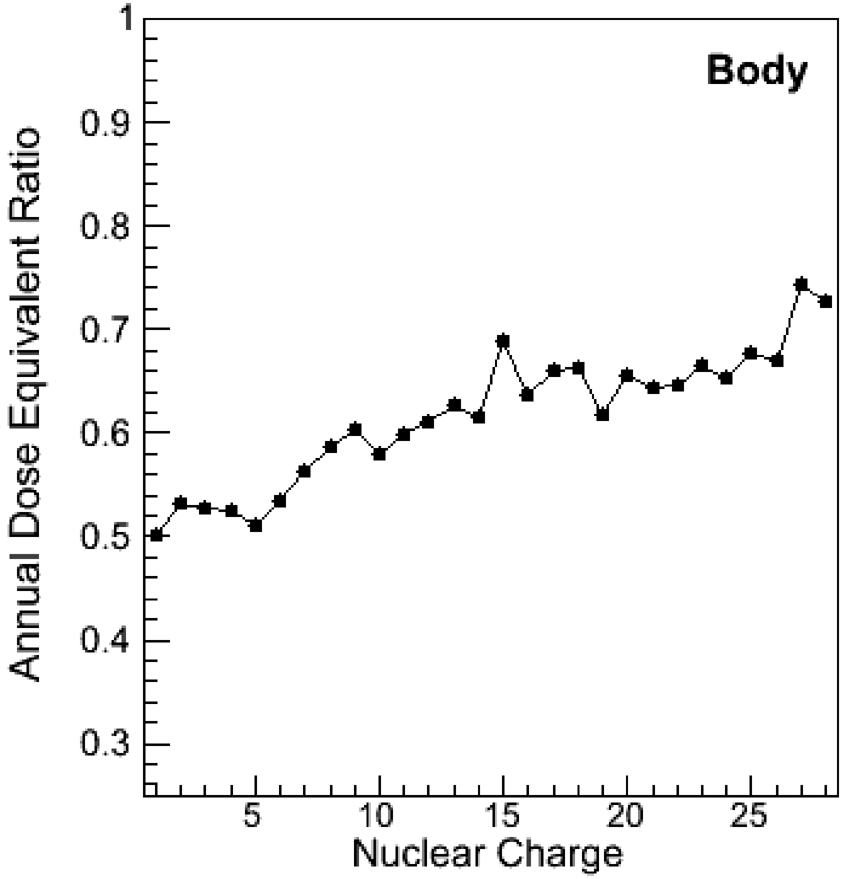
Solar Min 1977

Solar Max 1990

CREME - Cosmic Ray Effects on Micro Electronics

Solar Maximum/Minimum GCR
Integrated Flux and Free Space Dose Ratios





Passive vs Active Magnetic Shields

The ionization losses,

$$dE/dx \sim (z^2 / \beta^2)\,(Z / A)$$

z, β particle charge,velocity

Z, A material atomic number, mass

are responsible for the harmful radiation dose in human tissues and sensitive electronics. The same ionization is responsible for the stopping power characterizing the materials of passive shields. In addition to ionization losses the protons and nuclei are subject to strong interactions, which produce lower energy secondary charged particles and neutrons. A passive shield should be sufficiently thick to contain the generated secondary particles.

The corresponding containment parameter of a magnetic shield is the bending power BL.

Magnetic Shielding Based on Particle Deflection

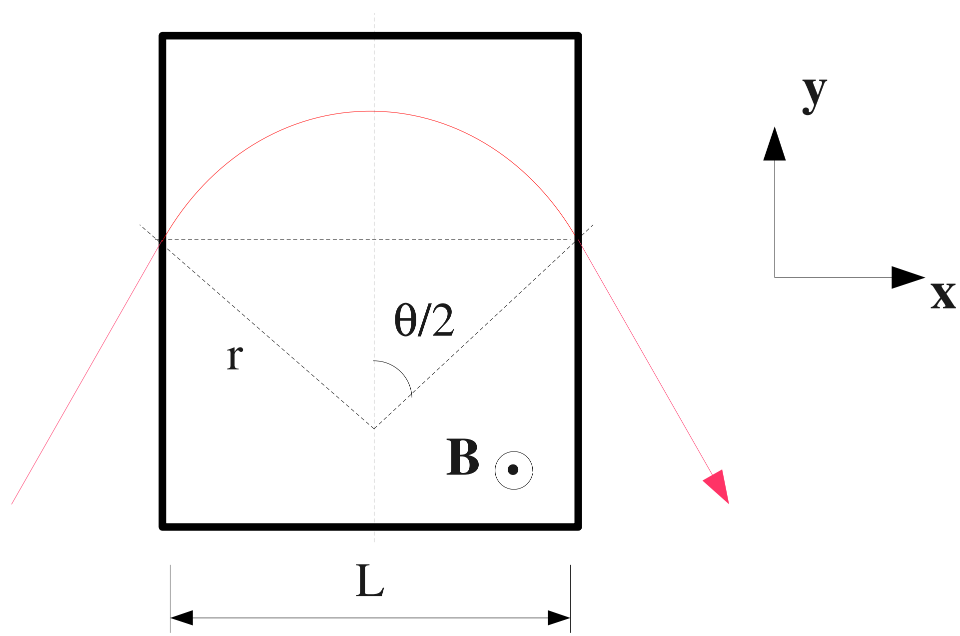
Lorentz Force $\mathbf{F} = q\mathbf{v} \times \mathbf{B}$

With $\mathbf{B} = B\mathbf{z}$, the particle of charge q moves in a circle of radius r in the **xy** plane. The centripetal acceleration is given by

$$a = \frac{v^2}{r} = \frac{F}{m} = \frac{qvB}{m}$$

$$r = \frac{mv}{qB} = \frac{R}{B}$$

$$2\sin\frac{\theta}{2} = \frac{L}{r} = \frac{BL}{R}$$

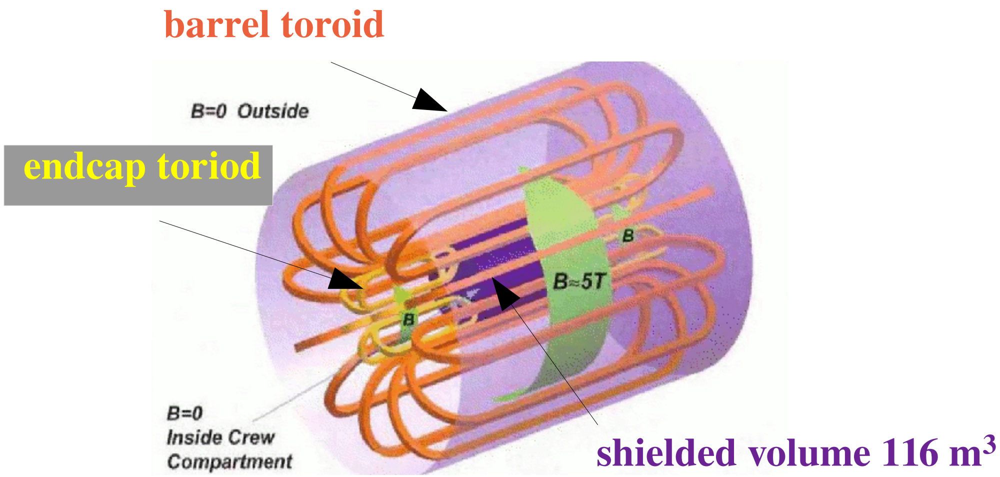


Rigidity $R = \dfrac{mv}{q}$

Bending Power BL

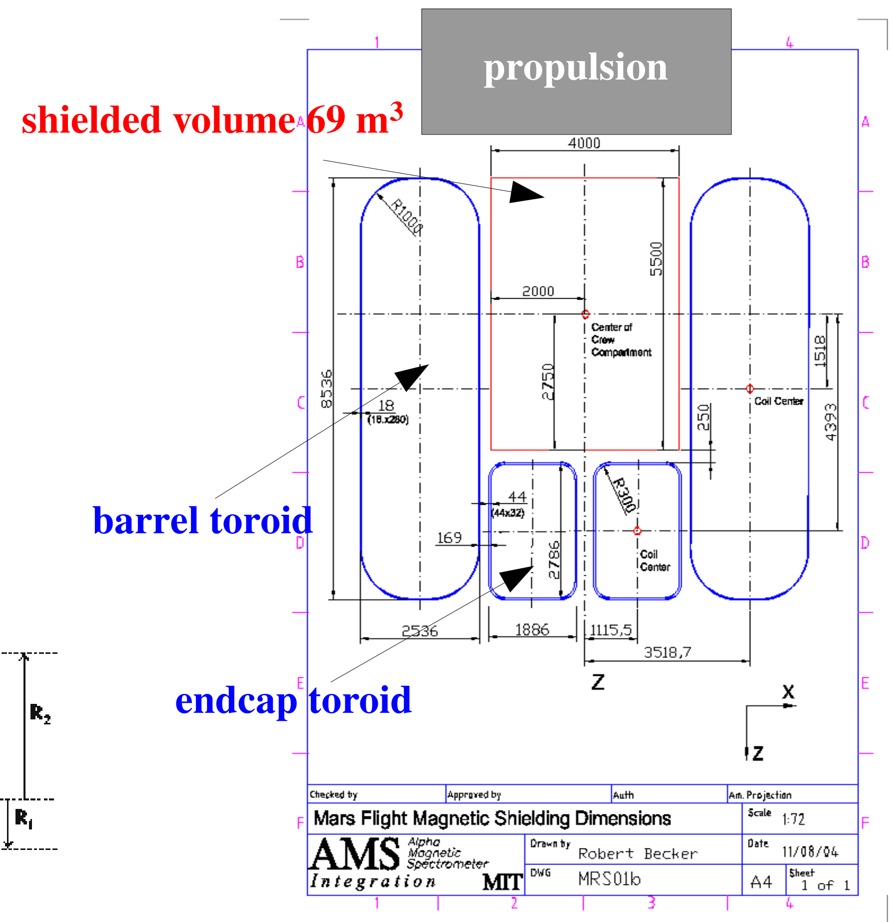
Previous Studies - Confined Field Configurations

(1) *J. Hoffman et al., NASA / NIAC Phase 1 Final Report (2005)*



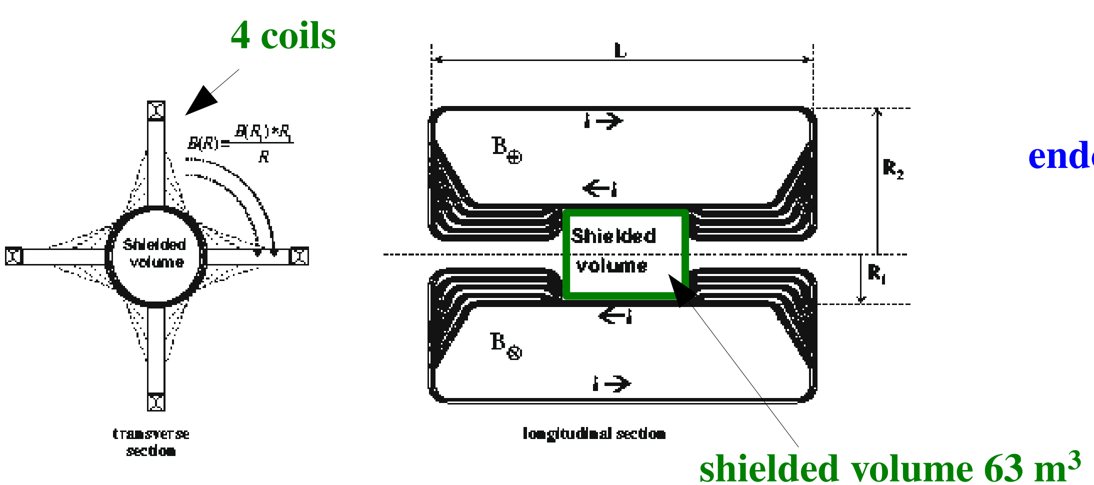
Endcap/Barrel Toroids

(2) *V. Choutko et al., NASA Radiation Shielding Workshop (2004)*



Endcap/Barrel Toroids

(3) *P. Spillantini, Advances in Space Research 43 (2010) 900*



Barrel Toroid

Confined Field Shield Configurations

Configuration	1	2	3
Magnet Mass (t)	400-1600 (1)	31 (2)	10-20 (3)
BL (Tm)	15.6	17	6
Flux Reduction Factor	10	4-7	2
Dose (cSv/y)	9 (Body)	18-33 (BFO)	(1.7) (4)
Diameter/Length (5) (m)	10 / 10	9.6 / 8.5	8 / 10
Shielded Volume (m^3)	116	69	63

(1) total mass including coils, mechanical structure, cyrocooler, liquid He
(2) refers to “magnet system weight”
(3) cold mass (superconducting cable and stabilizing material) x 1.5
(4) reduction of the GCR absorbed dose (Gy)
(5) dimensions of cylindrical envelope containing the magnet configuration

ESA / NIAC Magnetic Shield Studies

- Engineering studies of shield configurations based on High Temperature Superconductors (HTS):
  Double-Helix Solenoids with YBCO tape (AML)
  Toroid configuration based on MgB_2 cables (INFN-Genoa / ASG)

- The physics simulations for the equivalent dose levels:
  Free space **Geom00**
  Reference LTS toroid configuration **Geom02**
  HTS double-helix solenoid configuration **Geom14**
  HTS racetrack toroid configuration **Geom15**
  Spacecraft without shield **Geom01**
  Polyethylene absorber **Geom20**
  HTS expandable solenoid configuration **Geom21**

  ESA

  NIAC

- The configurations are evaluated in terms of the estimated mass and dose.

ESA Study Contract No. 4200023087/10 /Nl /AF

Active Radiation Shield for SpaceExploration Missions (ARSSEM)

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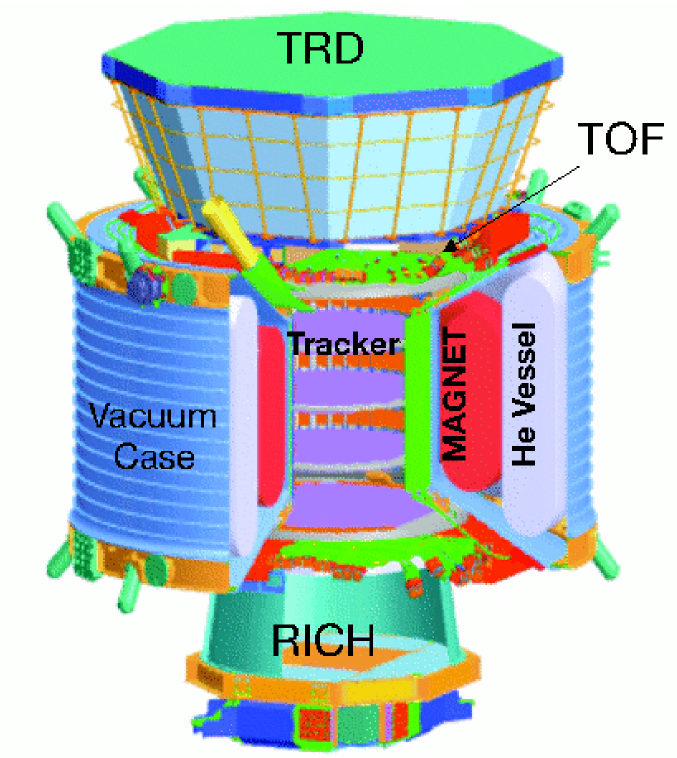
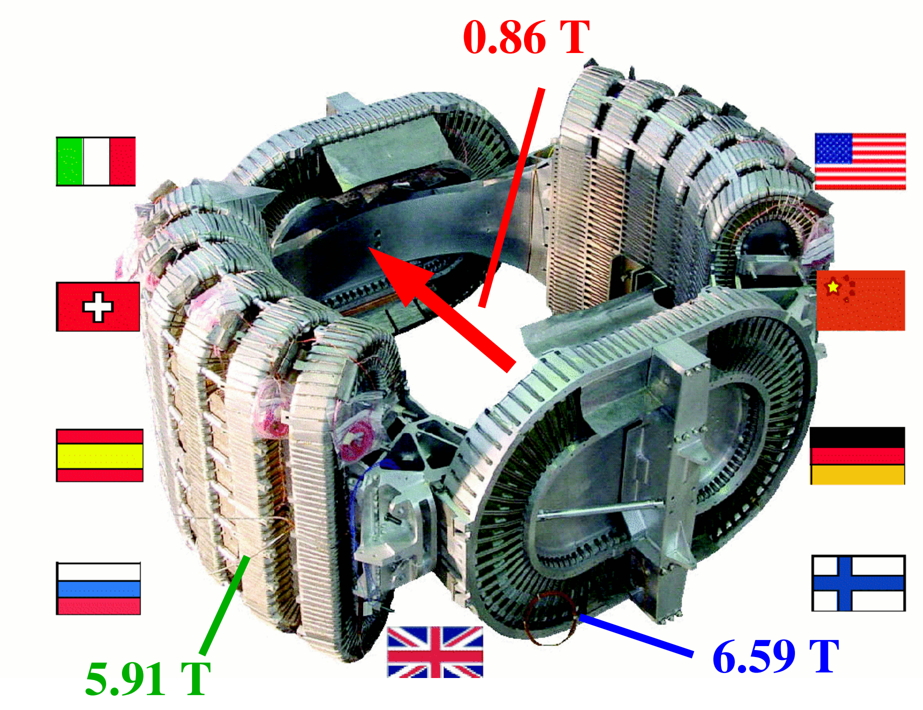
ESA Study Manager
S. Hovland, ESTEC, Noordwijk, The Netherlands

Alpha Magnetic Spectrometer (AMS)

AMS-02



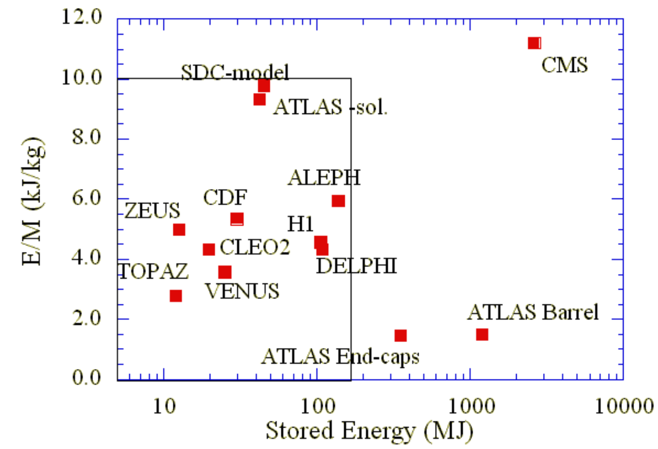
Superconducting Magnet



Al stabilized SC NbTi wire @ 1.8K
Stored Energy: 5.15 MJ
Total Mass: 3T
  42% coils and support structure,
  24% vacuum vessel, 11% He vessel, 12% He


AMS02 installed on ISS
20..05.2011
with a NdFeB permanent magnet

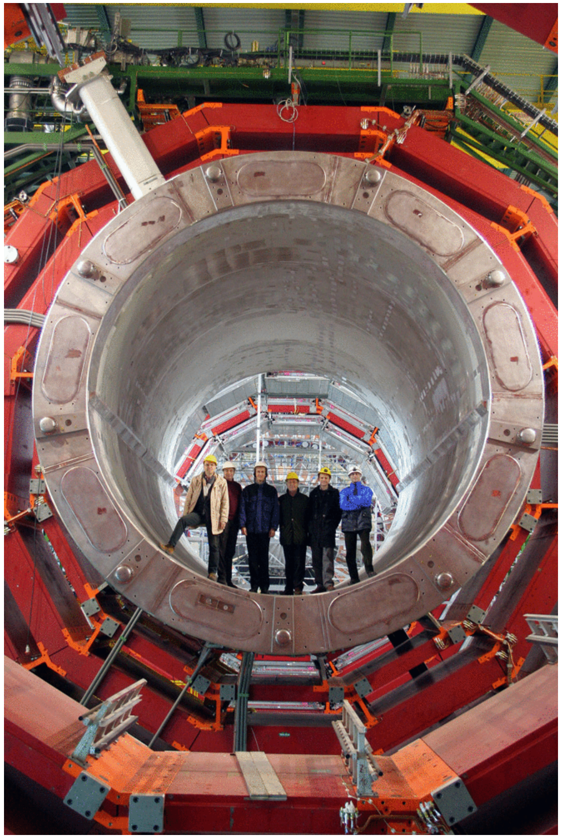
Low Temperature Superconducting NbTi Magnets



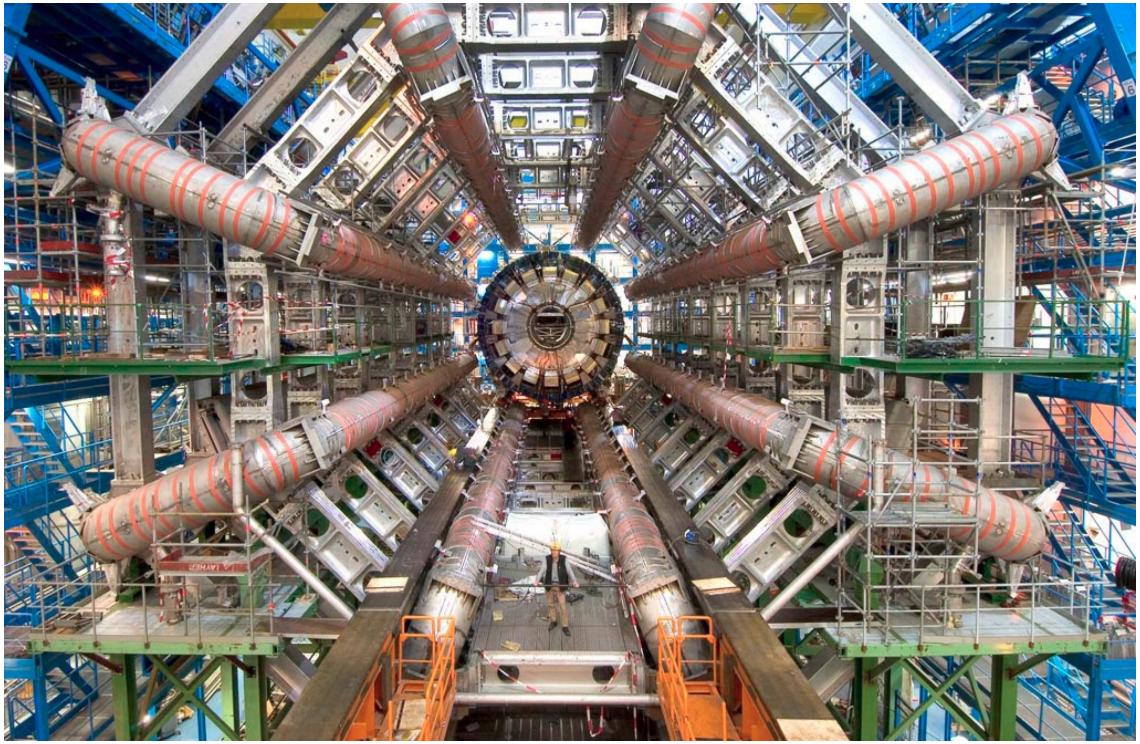
ATLAS Barrel Toroid:
830 t, 25.5 m long, radial extent 9.4-20.1 m,
max. flux density 3.9 T, BL 2-6 Tm

CMS – Compact Muon Solenoid:
220 t, 5x2.5 m long, int. dia. 6 m,
max. flux density 4.0 T, (max. BL 24 Tm)

CMS

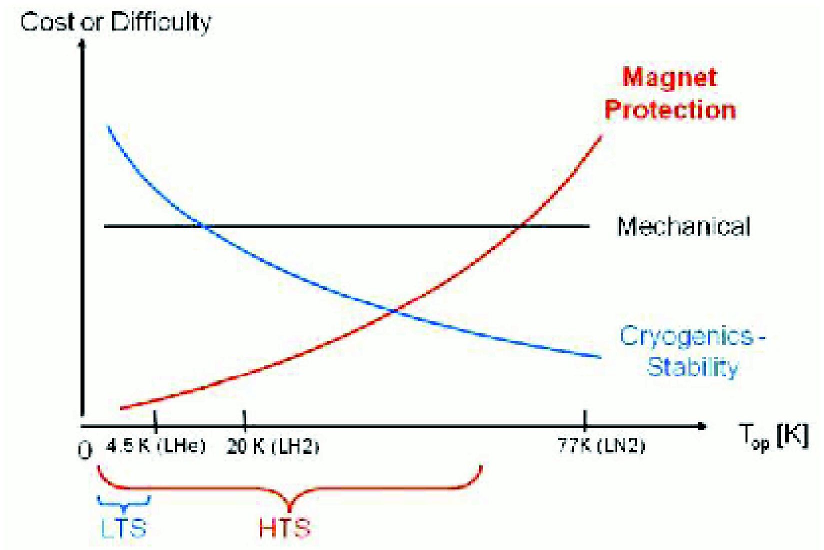


ATLAS



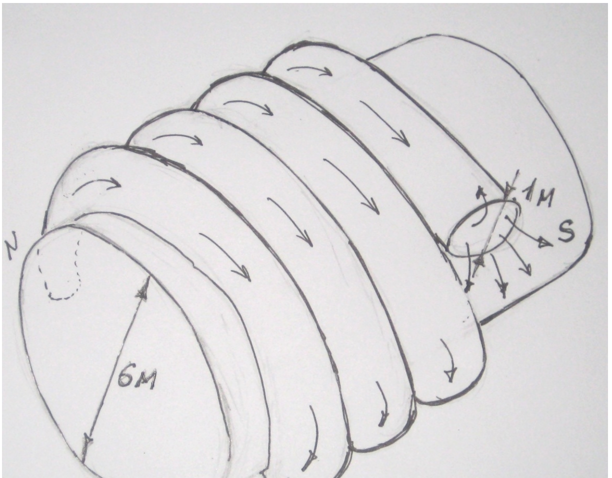
High Temperature Superconductors (HTS)

HTS represent a realistic alternative due to the the lower operating temperature, and provide interesting possibilities for the space application.



Y. Iwasa, MIT

Flexible spiral coil design :
low external field, modularity,
low internal forces



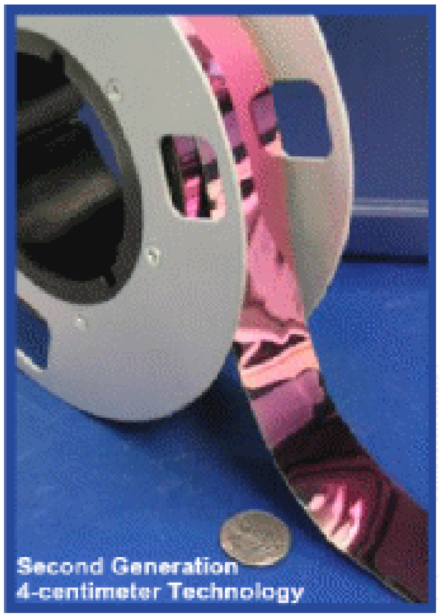
V.I. Datskov

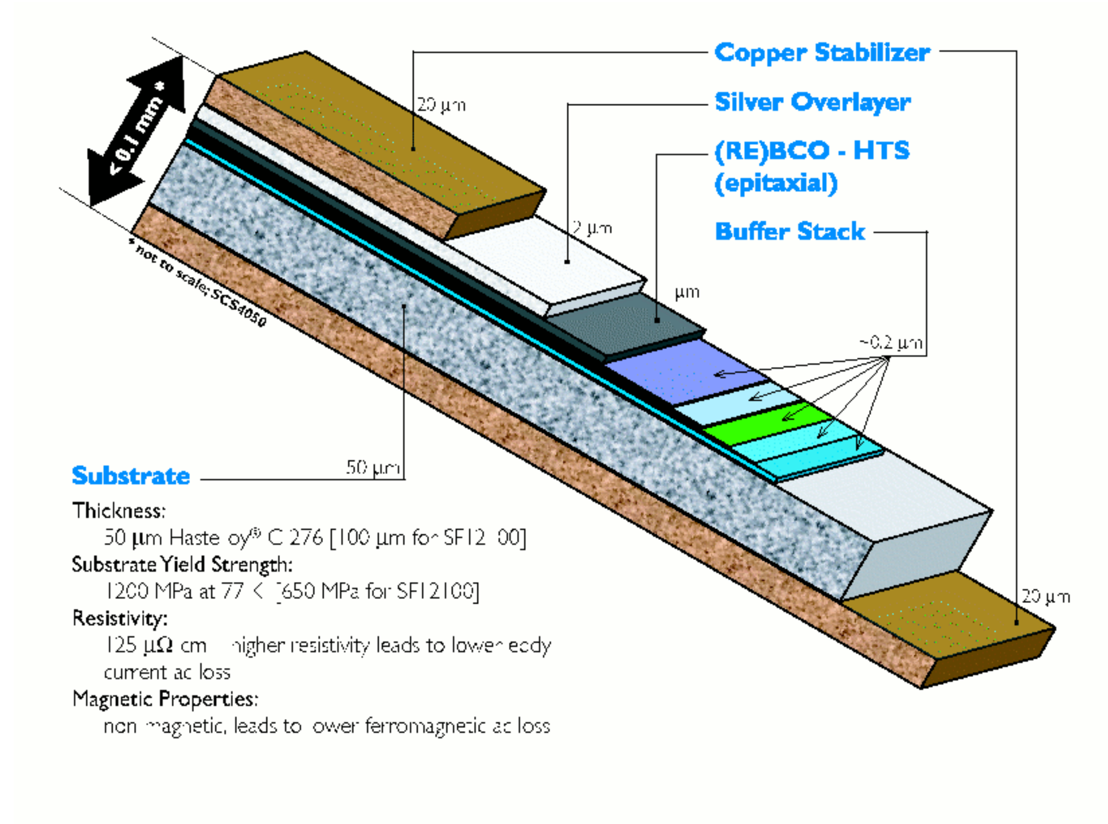
The two HTS chosen for the active magnetic shield studies:

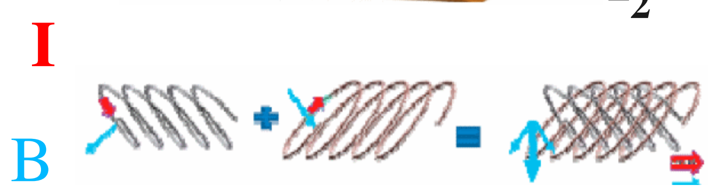
(1) YCBO tapes capable to carry 1.25 kA/mm^2 at T_{OP} = 77 K (sf 0 T)

(2) MgB_2-Cu-Ti-Al cable with J_E = 155 A/mm^2 at T_{OP} < 10 K

YBCO Tape Conductor – Double-Helix Solenoid Coil



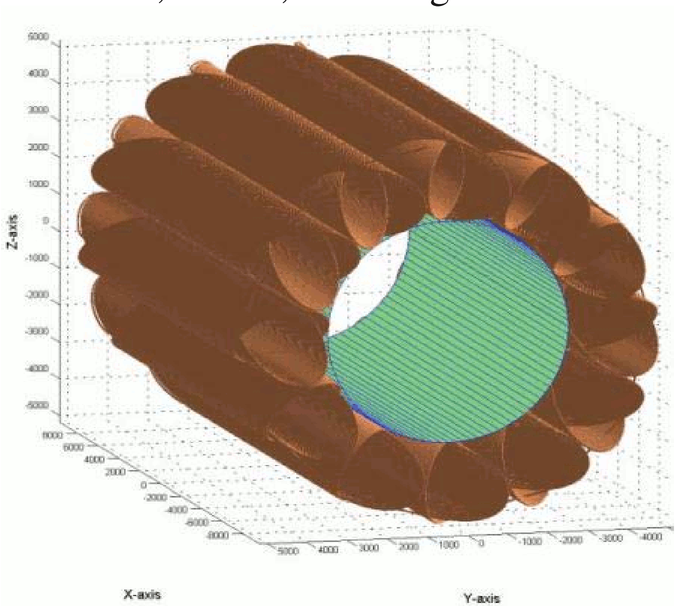




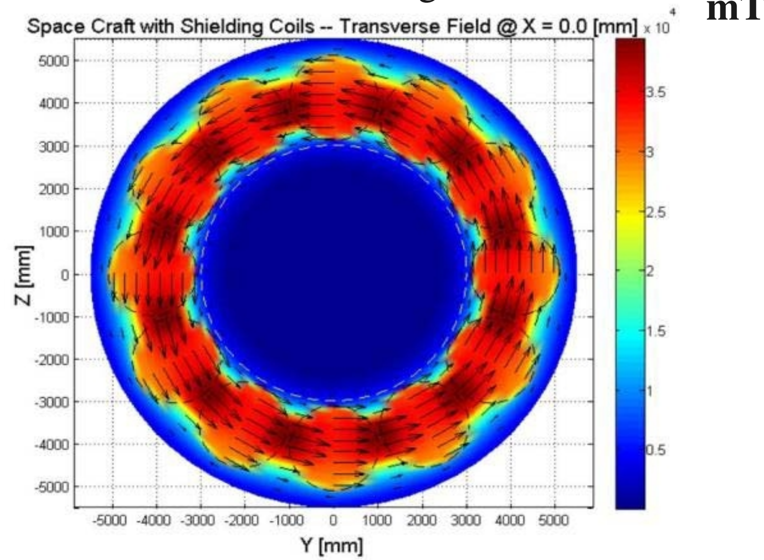
Double-Helix Solenoid Shield Configuration

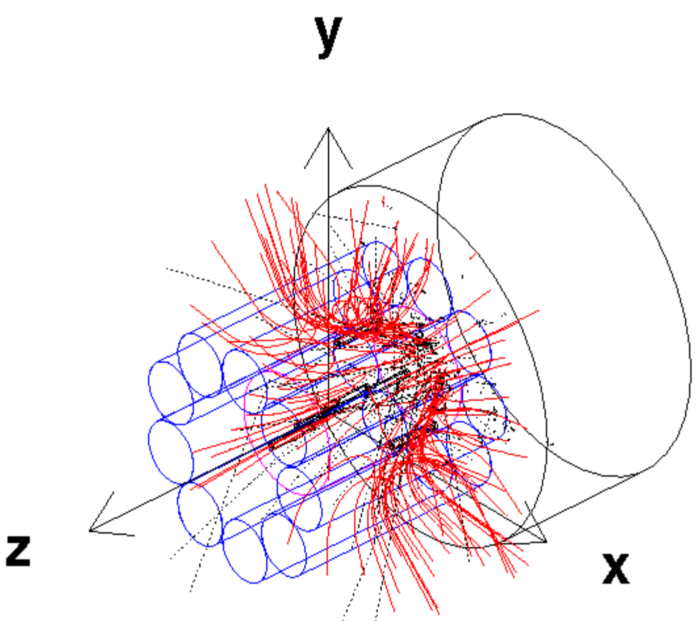
Advanced Magnet Lab (AML)

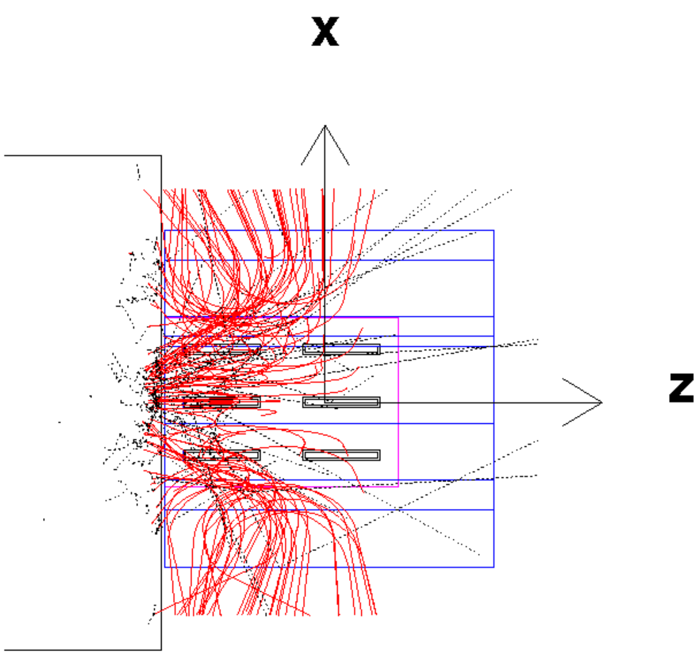
12, 2m ∅ , 18m long coils



Flux Channeling

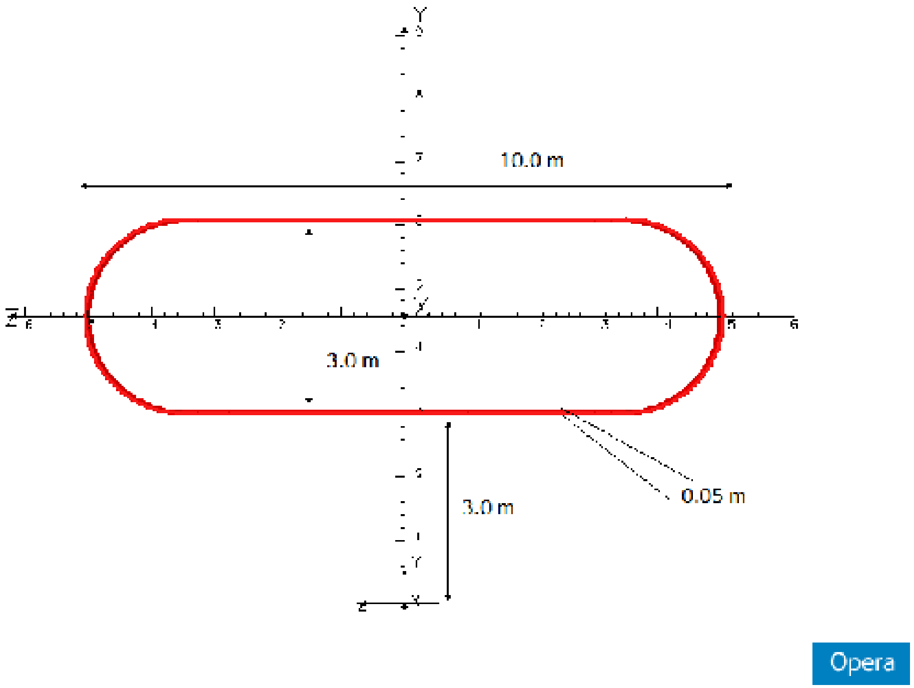


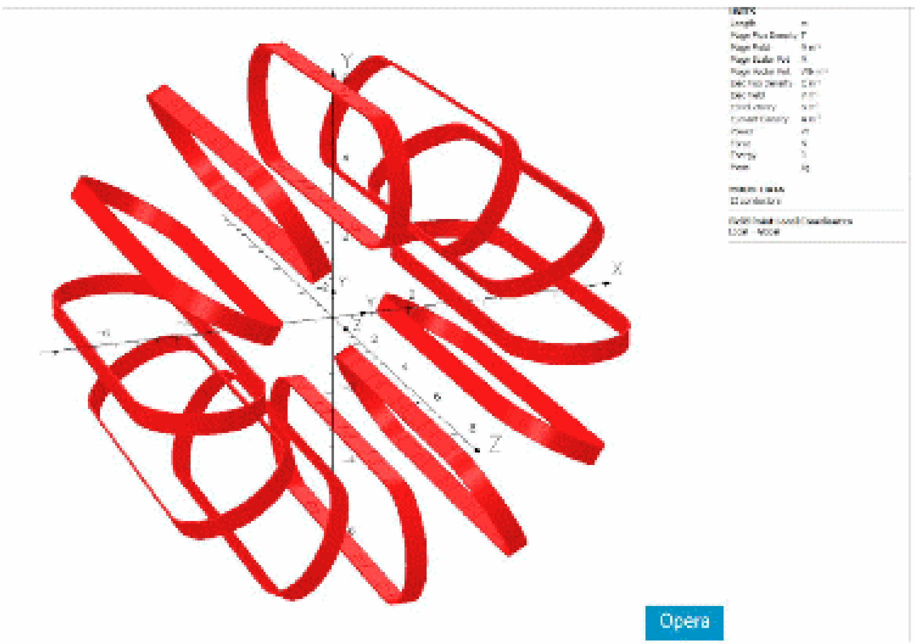




MgB_2 Racetrack Toroid Shield Configuration

INFN-Genoa / Ansaldato Supercoduttori Genoa (ASG)



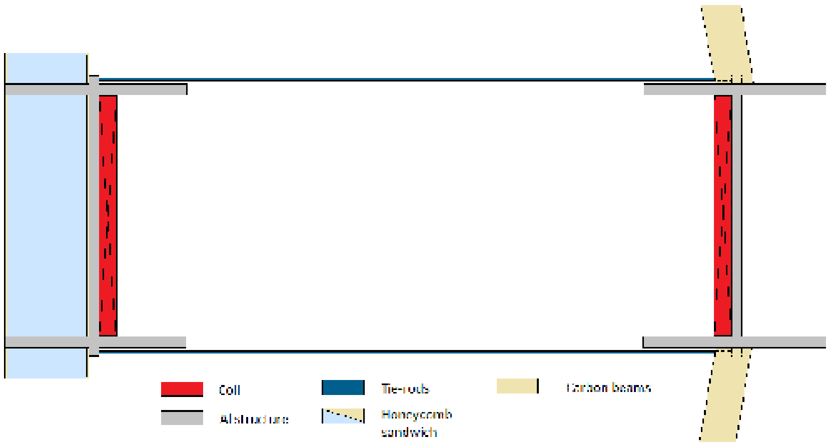


Toroid (12 racetrack coils)	
Inner radius	3000 mm
Outer radius	6100 mm
Axial length	10000 mm
Racetrack coil	
Width b	50 mm
Length a	500 mm
Section	0.025 m^2
Inner diameter	3000 mm
Arc radius	1525 mm
Volume	0.5896 m^3

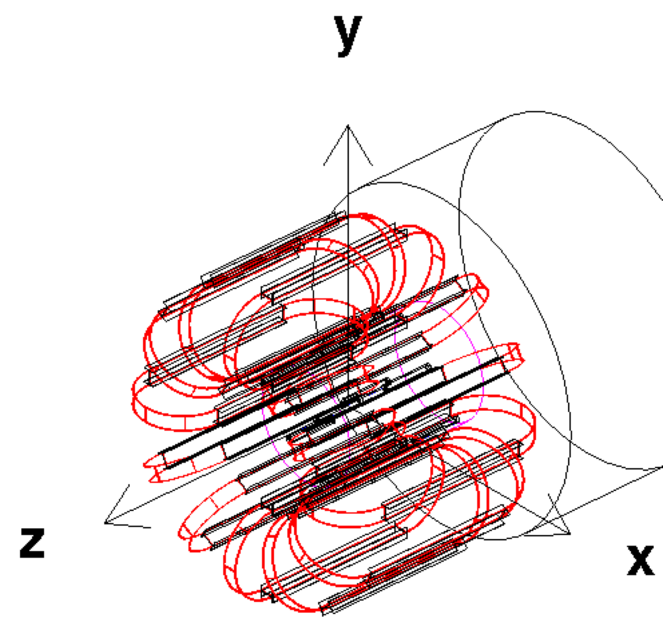
$$\vec{B} = \frac{6.9}{r}\hat{u}_\varphi \ \mathrm{T}$$

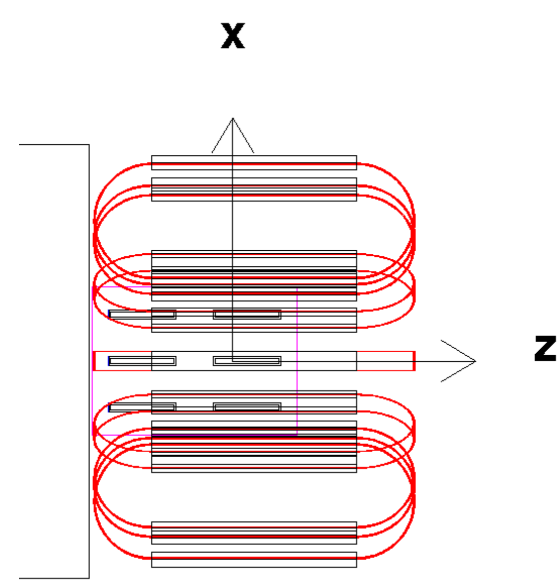
Toroid	
Overall current density	117 A/mm^2
Overall current per coil	$2{,}92 \cdot 10^6$ A
Average integral of field	4.989 Tm
Maximum integral of field	4,902 Tm
Minimum integral of field	4,987 Tm

Racetrack Toroid Support Structure



TOROIDAL MAGNET		
dimension and number of racetracks		
Number of racetracks	12	
Axial height	10.0	m
Inner radius	3.0	m
Outer radius	6.1	m
Volume	7.075	m^3
Volume free for the cockpit	246	m^3
Supply		
Current per cable	1168	A
Maximum voltage	3000	V
Energy and inductance		
Total energy	9.85E+08	J
Inductance L	1444	H
Mass		
Coils	2.62E+04	kg
Tie-rods	3.93E+03	Kg
Mechanical structure	6.98E+03	Kg
Bearing structure	4.44E+03	Kg
Torque retaining beams	4.66E+03	Kg
Total mass	**4,64E+04**	**kg**





ESA Study Shield Dimensions
Engineering Studies vs Physics Simulation

The DH solenoid shield design consists of 12, 2 m ∅, 18 m long coils which surround a 6 m ∅, 10 m long cylindrical habitat.

The racetrack toroid shield design consists of 12, 10 m long racetrack Coils. The inner (outer) radius of the toroid with respect the center of the habitat is 3.0 (6.1) m.

The shield dimensions of the engineering studies were rescaled to the spacecraft geometry in the simulation, which was used for the earlier LTS Barrel-Endcap Toroid configuration study. The dose estimates quoted for the latter were recalculated in the present study. The spacecraft consists of a 4 m ∅, 5.5 m long cylindrical habitat closed on one end by a large aluminium cylindre representing the propulsion system.

Physics Simulation Software

The performance of the different shielding configurations considered in the ESA and NASA studies have been evaluated using a physics simulation based on **GEANT3**, which performs particle propagation in magnet fields and materials with a detailed treatment of electro-magnetic interactions.

Hadron interactions of protons, helium nuclei, the secondary mesons and baryons, deuterons, tritons are simulated with **GEANT-FLUKA**.

The Relativistic Quantum Molecular Dynamics (**RQMD**) is used for the higher charge nuclei.

Dose Equivalent

In the **GEANT3** simulation, the **ionization energy losses** during track propagation are converted to an **dose equivalent** *(Sv)* by multiplying the **absorbed dose** *(Gy)* by the **Quality Factor** defined by the **unrestricted linear energy transfer in water** *(keV/μm)* :

$$\varepsilon_i = Q(L) \cdot \frac{dE_i}{m}$$

with $L = \frac{dE_i}{dx}$ $\qquad Q(L) = \begin{cases} 1 & \text{for} \quad L \leqslant 10 \\ 0.32 \cdot L - 2.2 & \text{for} \quad 10 < L < 100 \\ 300/\sqrt{L} & \text{for} \quad L \geq 100 \end{cases}$

The **total dose equivalent** $d_z(E_j)$ *(Sv)* for an exposure time *t*, due to the GCR of charge *z* and kinetic energy E_j, is the sum of the recorded **dose equivalents** produced by the N_j particles generated with the flux $f_z(E_j)$ *($cm^{-2}sr^{-1}s^{-1}$ MeV^{-1})* over the acceptance *A* *(cm^2sr)* :

$$d_z(E_j) = A \cdot t \cdot \sum_i \varepsilon_i \cdot \frac{f_z(E_j)}{N_j} \cdot \Delta E_j$$

The Galactic Cosmic-Ray (GCR) Dose Equivalent

The GCR **dose equivalent** *D (Sv)* is obtained by extending the event generation over suitable ranges in energy and charge. The contribution from charge *Z* is given by

$$d_z = A \cdot t \cdot \sum_j \left[\sum_i \varepsilon_i \right]_j \cdot \sum_j \frac{f_z(E_j) \cdot \Delta E_j}{N_j}$$

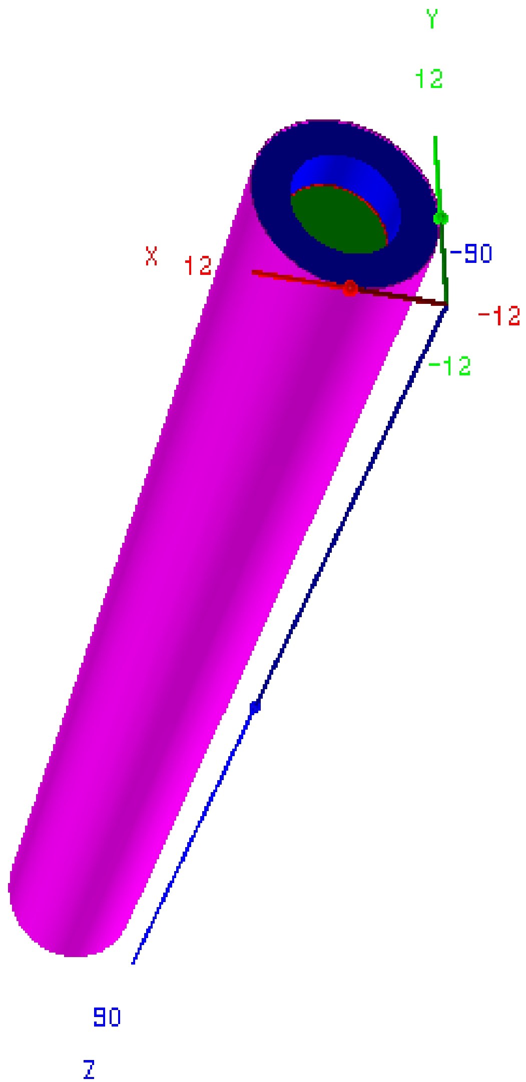
and the equivalent dose for *Z* up to 28 (Ni) ,

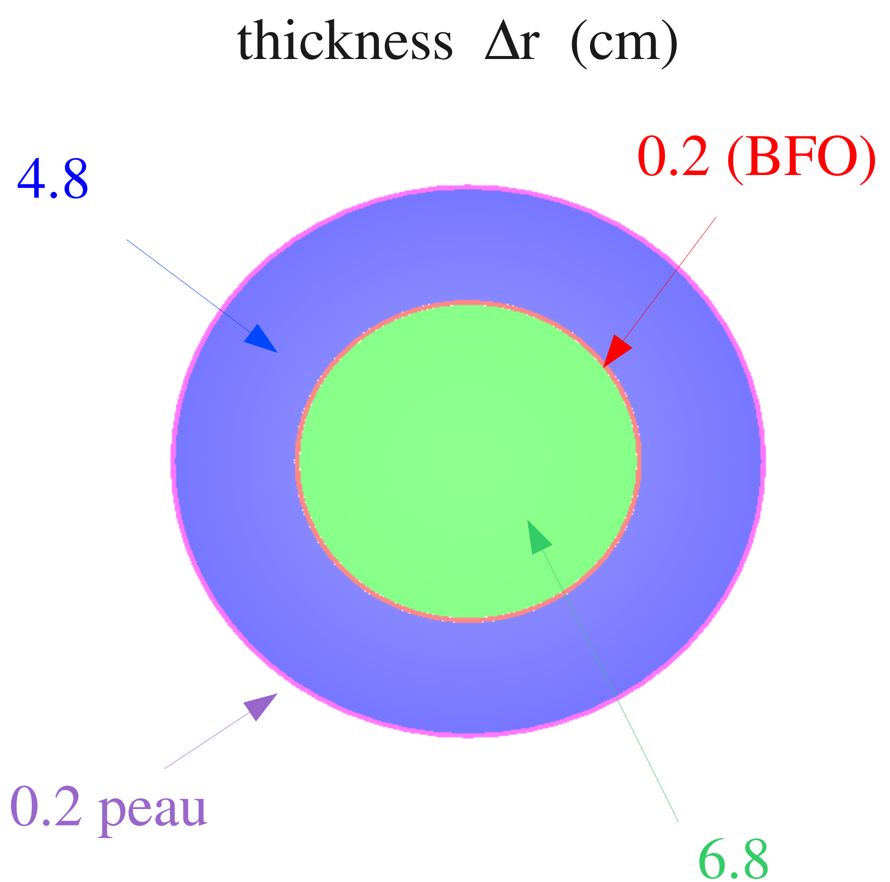
$$D = \sum_{z=1}^{z=28} d_z$$

The GCR kinetic energy spectra $f_z(E)$, 1 to 10^5 *MeV/n*, are taken from CREME* 2009 database. They include the contribution of anomalous cosmic rays which contribute at low energies. The dose equivalent is evaluated at solar minimum.

* *Cosmic Ray Effeccts on Micro Electronics*

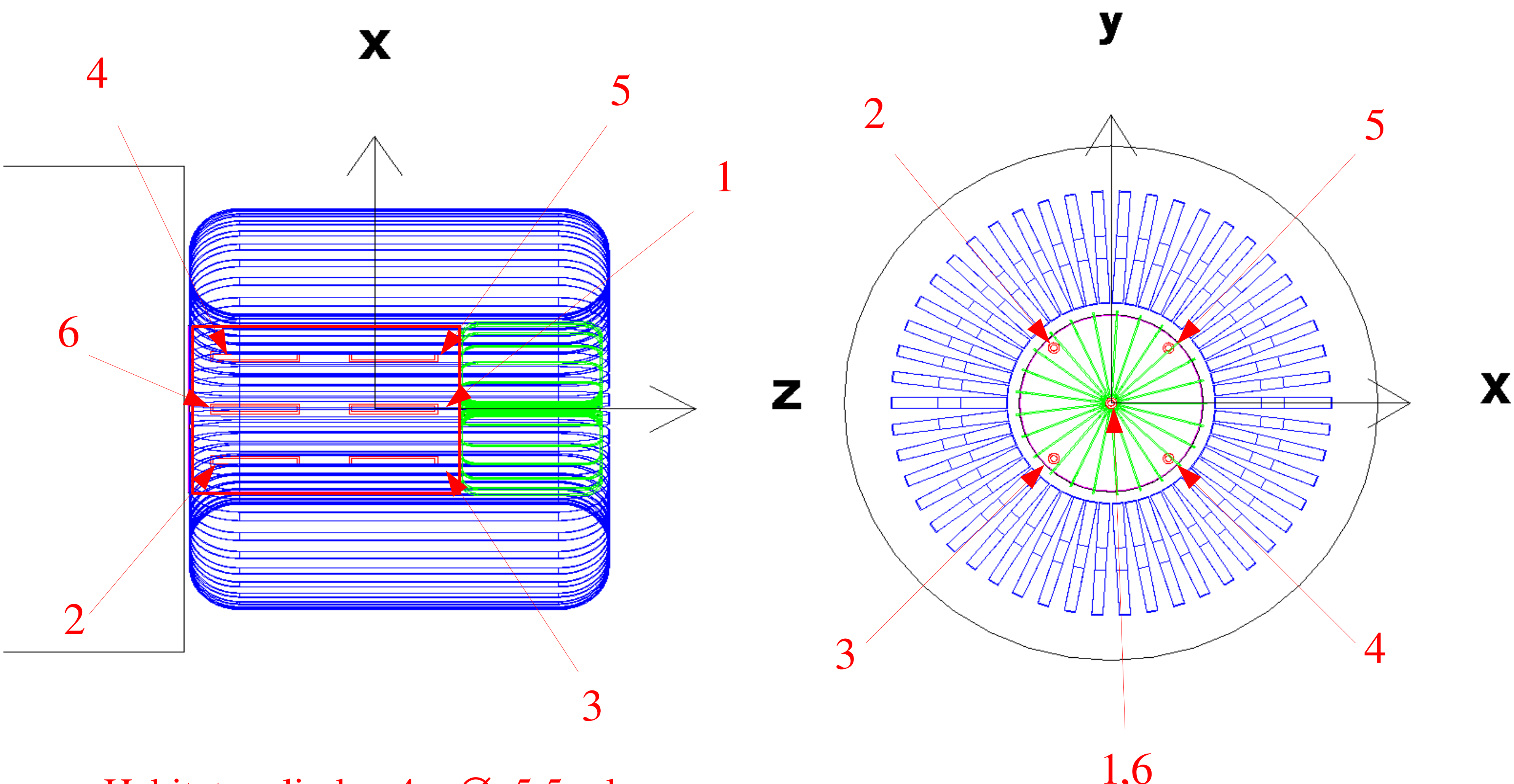
« L'Homme-Cylindre »





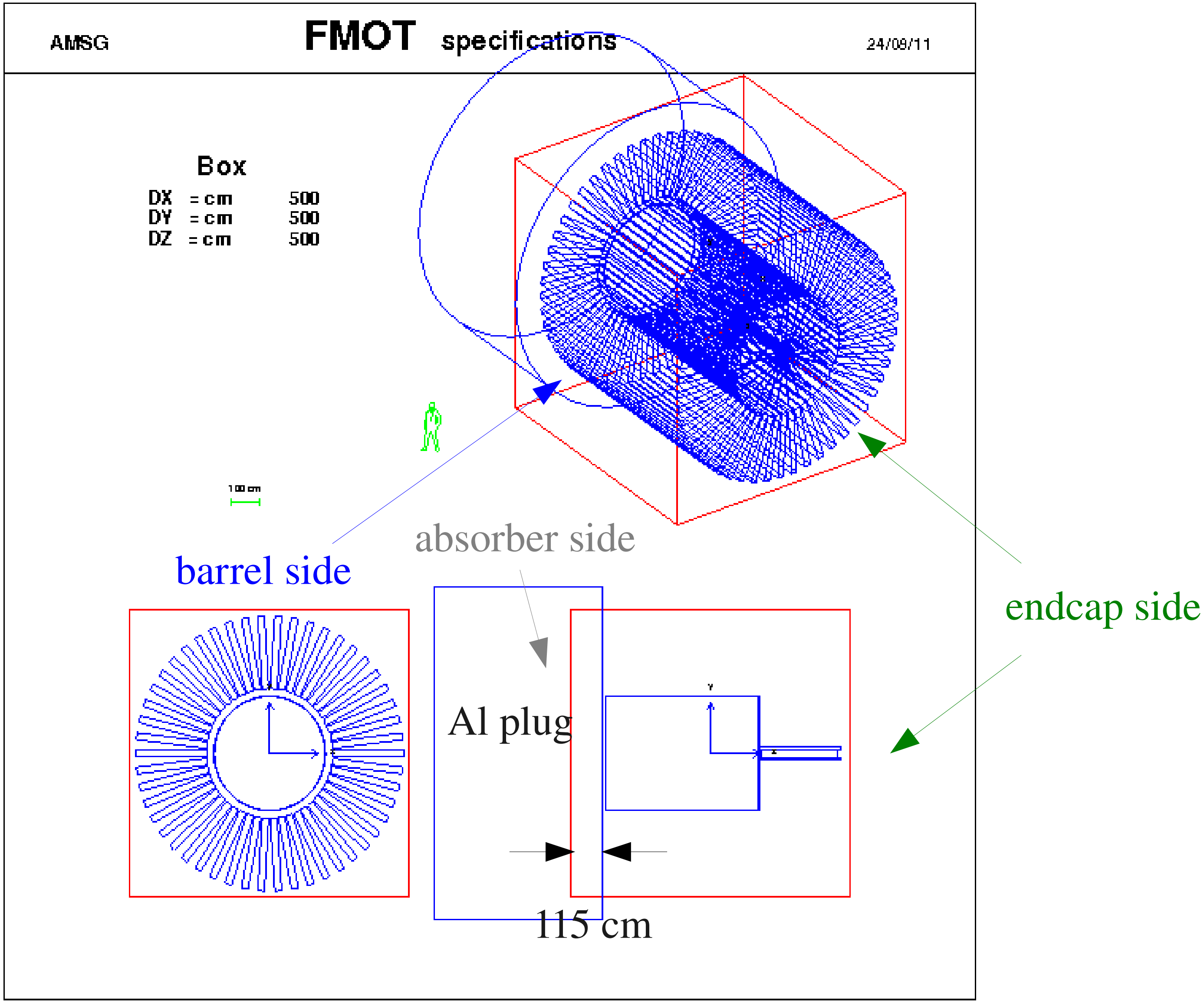
H_2O cylinder: ∅ 24 cm, length 180 cm, mass 81.4 kg

Sampling Sites for the Dose Determination



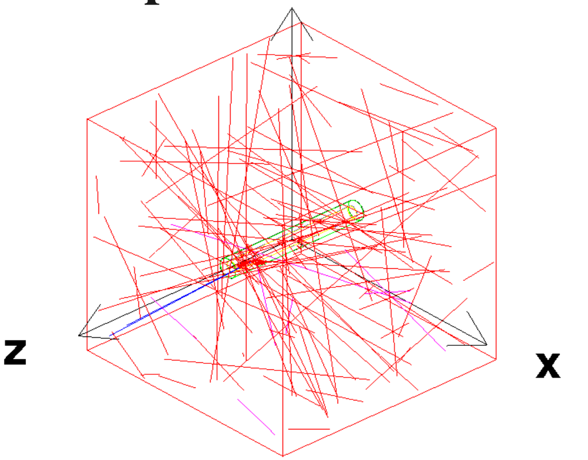
Habitat: cylinder, 4m ∅, 5.5m long

The Generation Surface

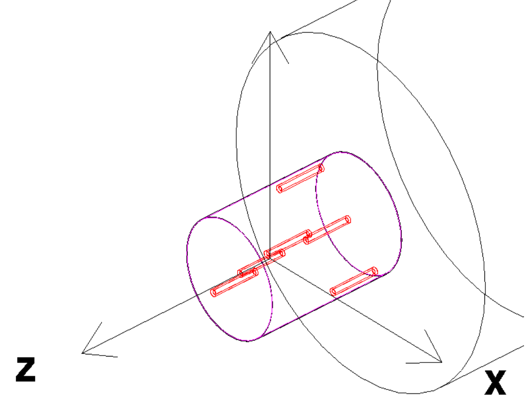


ESA Study Configurations

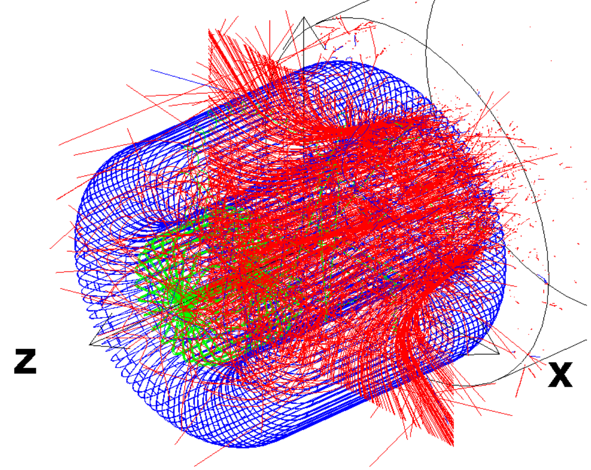
Free Space



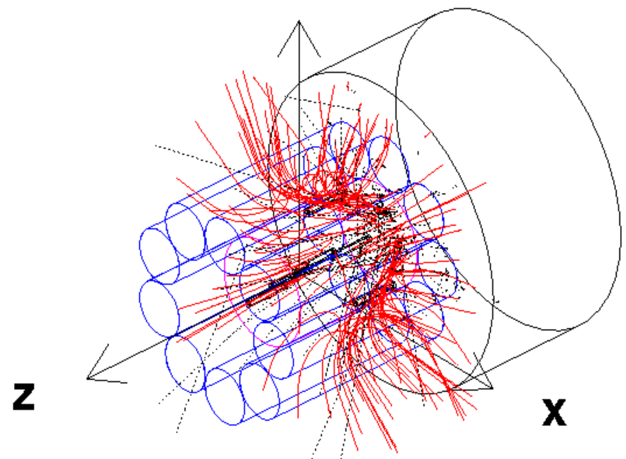
Spacecraft



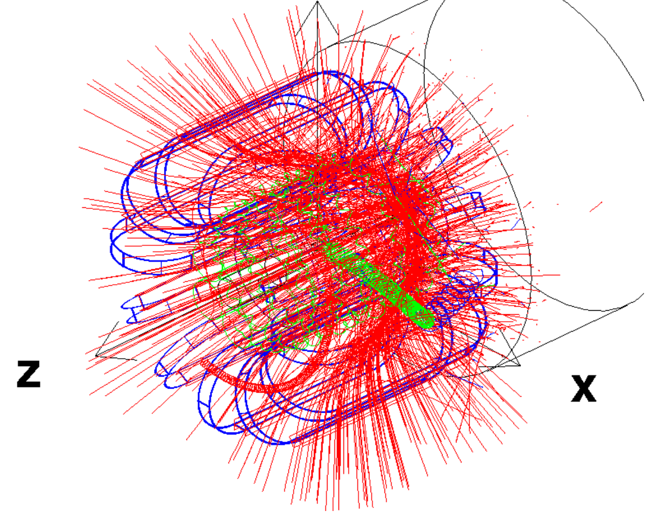
LTS Toroid



HTS DH Solenoid



HTS RT Toroid



p He $e^{\pm}$ $\pi^{\pm}$ $\mu^{\pm}$ γ

Summary of the Results of the ESA Study

Configuration	BL (Tm)	Mass (sim) (t)	Mass (eng) (t)	BFO Dose Eq. (cSv/y)
LTS Reference Toroid	19	12.5	-	19.2
HTS DH Solenoid	4	11.2	46.3-48.2	29.3
HTS Racetrack Toroid	4.9	28.0	46.4	26.7
Spacecraft	-	4.54	-	35.6

The masses in the simulation and of the engineering study are indicated, the former are extrapolated to the larger volume habitats used for the engineering studies. The BFO doses refer to the contribution of the barrel regions of the generation cube.

50 cSv/y is the BFO dose equivalent limit for Low Earth Orbit (LEO)
Payload mass limit for the 143 t Space Launch System is 45 t

NASA Innovative Advance Concepts (NIAC) Phase I Study

Magnet Architectures and Active Radiation Shielding Study (MAARS)

Principal Investigator: S.C. Westover, NASA Johnson Space Center, USA

Co-Investigators:
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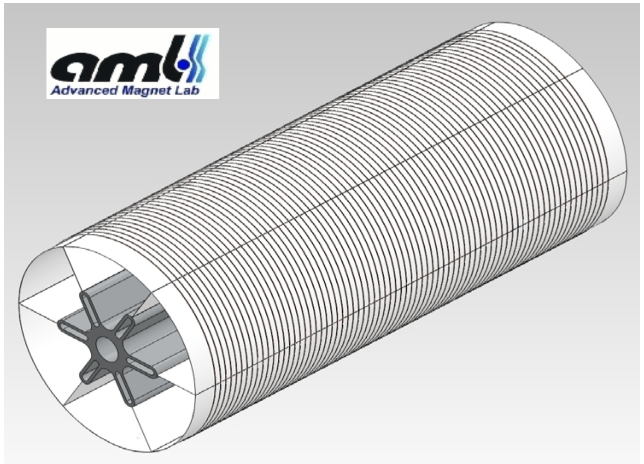
NIAC Study HTS

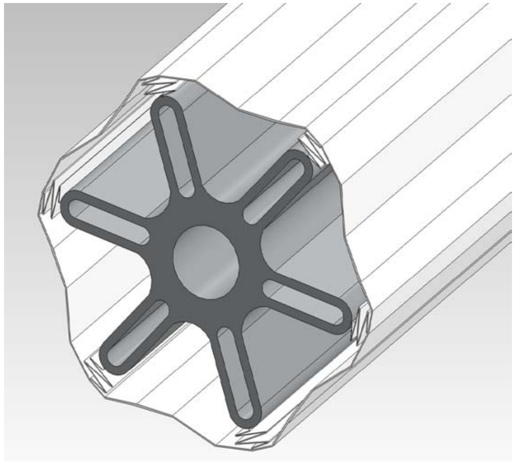
The NIAC active shield design is based on the YBCO tape used by AML in the ESA study. The basic field configuration was modified. The transversal field of the DH coils was abandoned in favour of a simple solenoidal field aligned along the axis of the cylindrical coil.

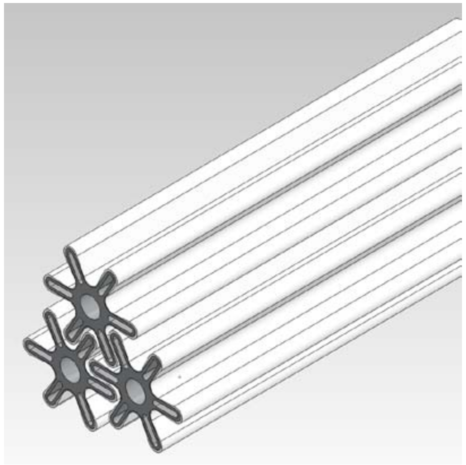
The change in the field orientation reduces the compressive forces acting on the habitat. The modification reduces the number of tape layers (8 to 1) and increases the flexibility of the coils. The required BL may be attained by increasing L (expandable coils) and lowering B, thus reducing the mass of the structural support.

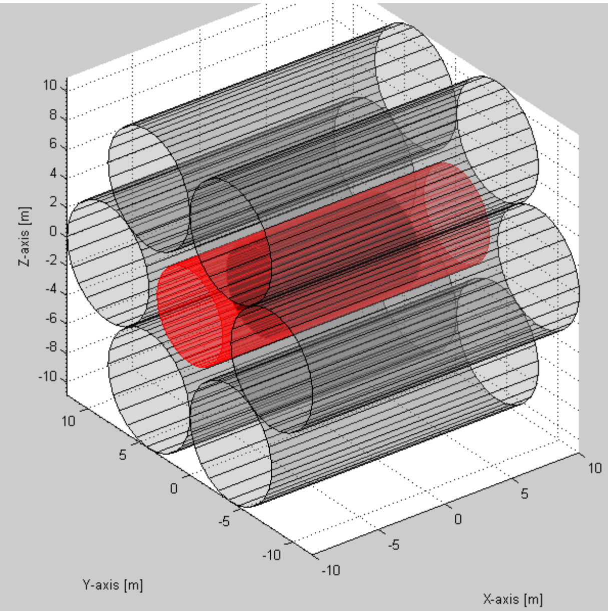
A compensation coil is required to maintain a field-free habitat. The cylindrical coil, which surrounds the habitat, provides thermal insulation between the habitat and shield solenoids.

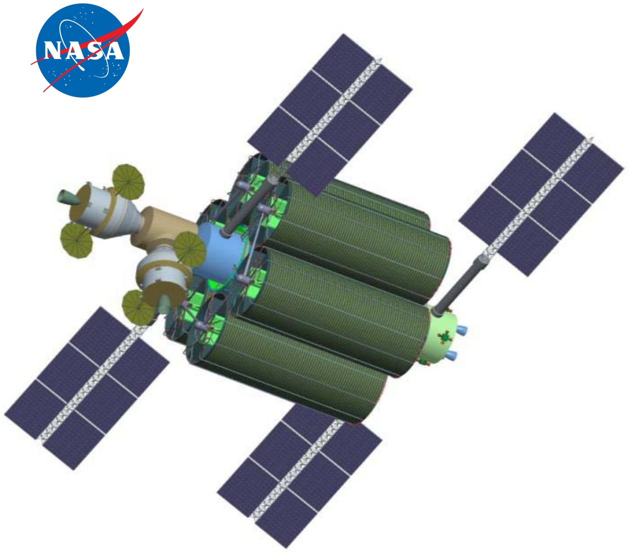
6+1 Expandable Solenoid Coil Shield



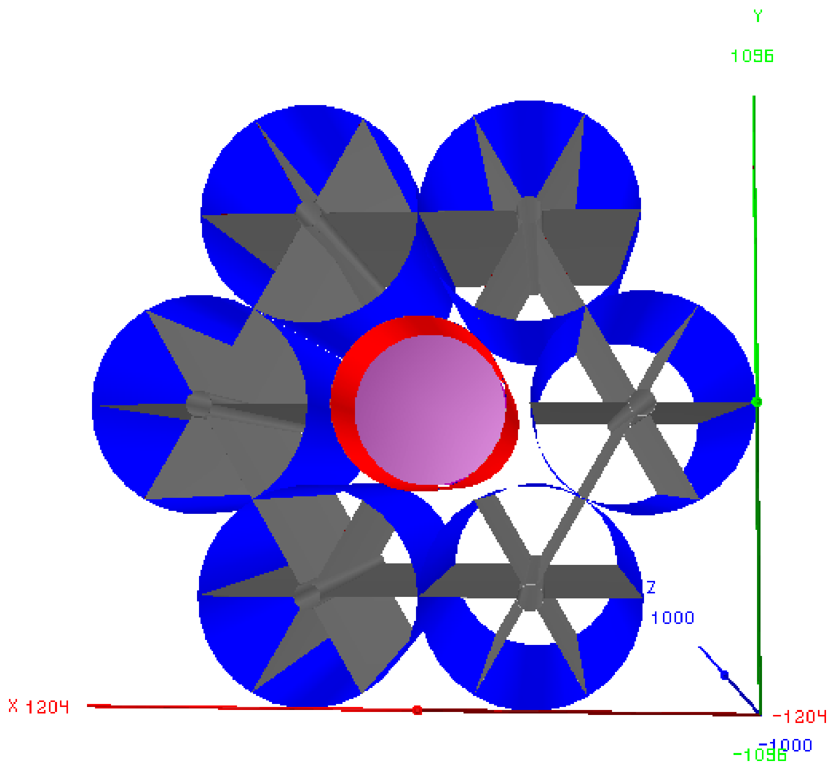


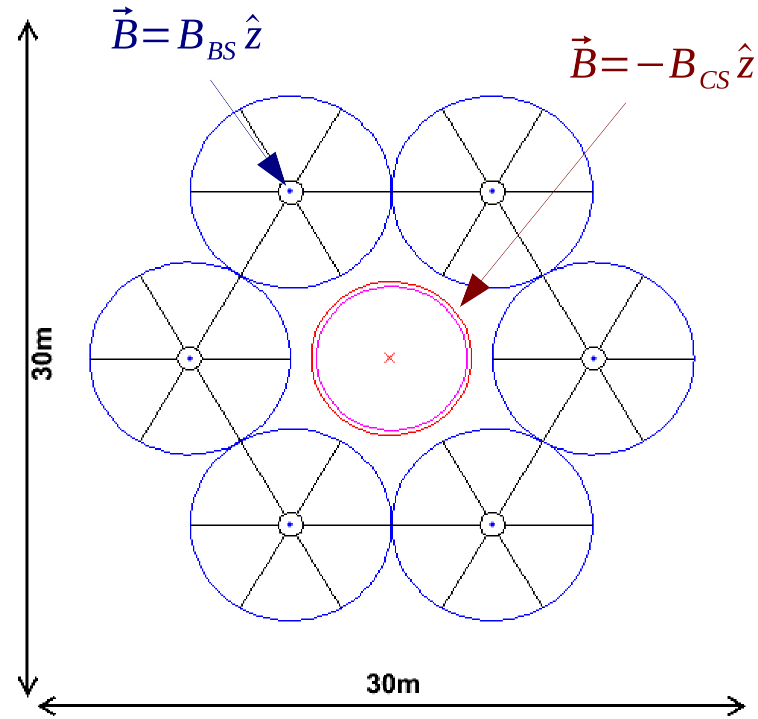






6+1 Expandable Solenoid Coil Shield in the Physics Simulation





Habitat

- ∅ 6m, length 10m cylindre
- Surrounded by 1.8 cm thick Al

Compensation Coil

- ∅ 6.4m, length 20m
- mass 2532 kg
- No external fringe field, no field in habitat

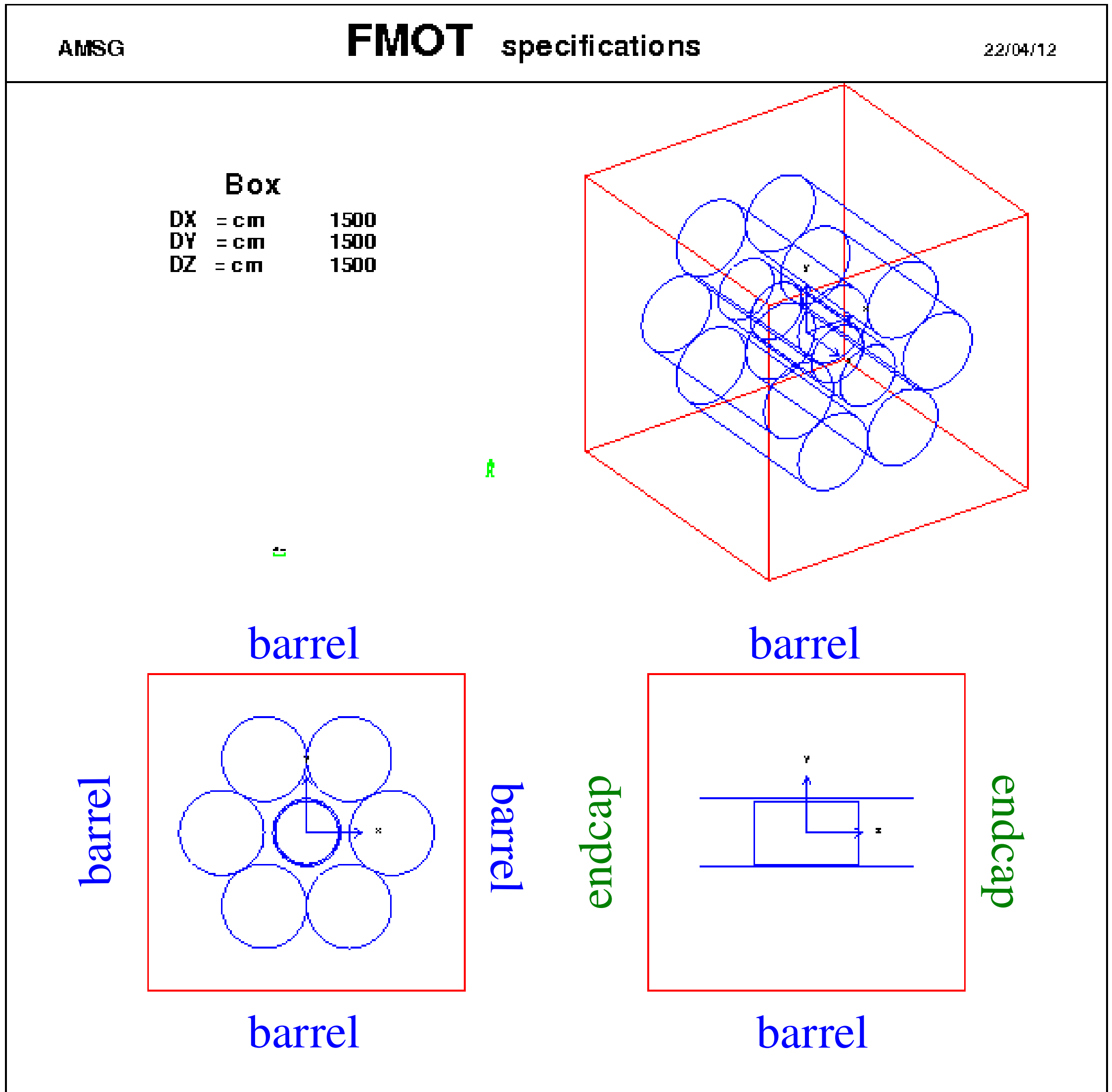
Barrel Coil

- ∅ 8m, length 20m, B_{BS} = 1T
- mass 500 kg

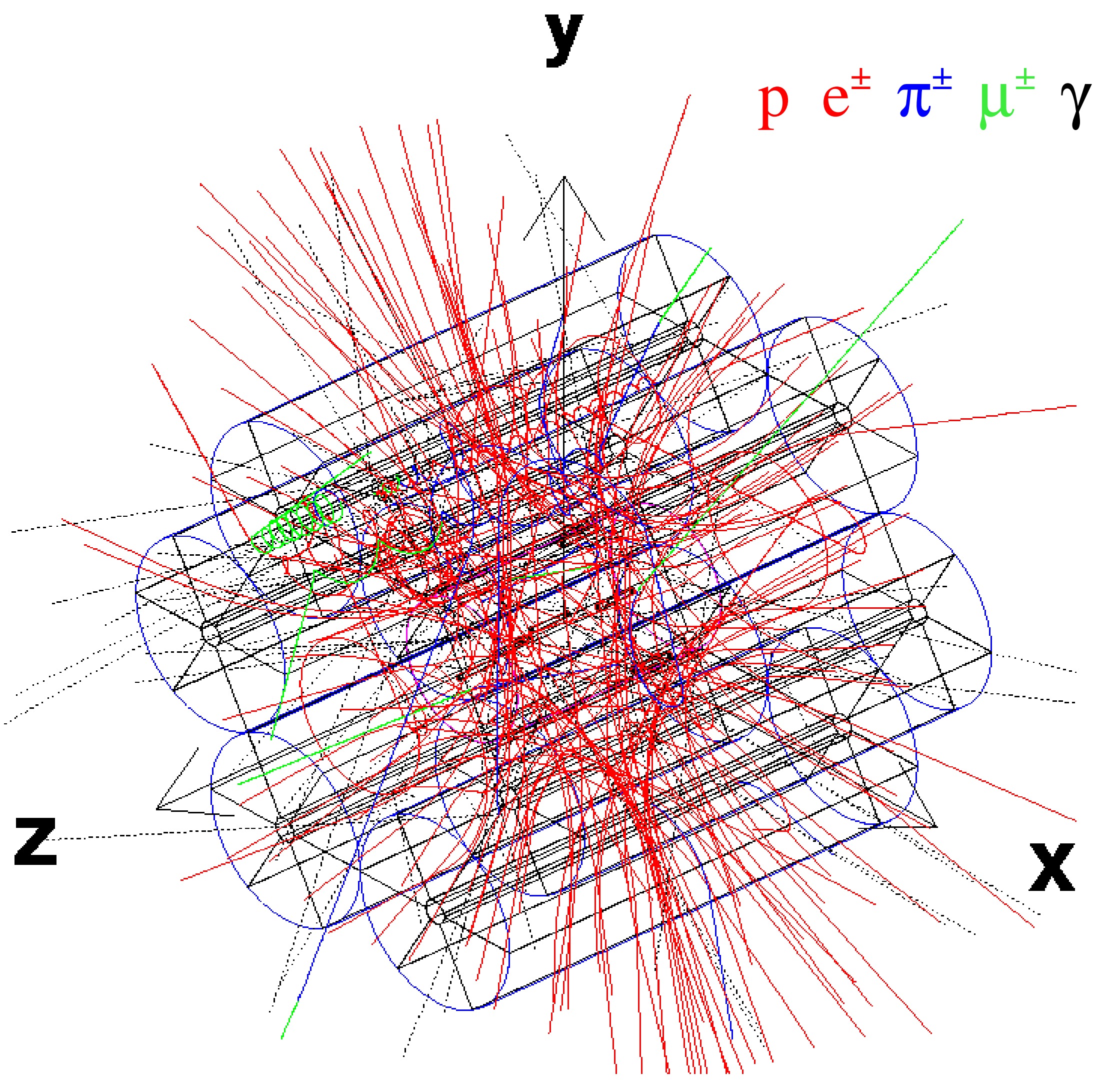
Support Structures

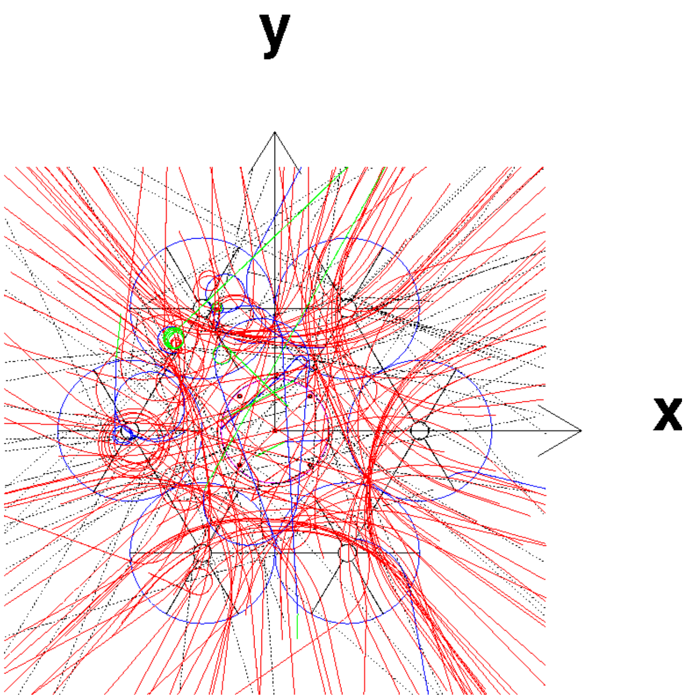
- ∅ 1m, 20m long, 1 cm thick cylindre (2763 kg)
- 6, 25mm thick cloisons (2325 kg)

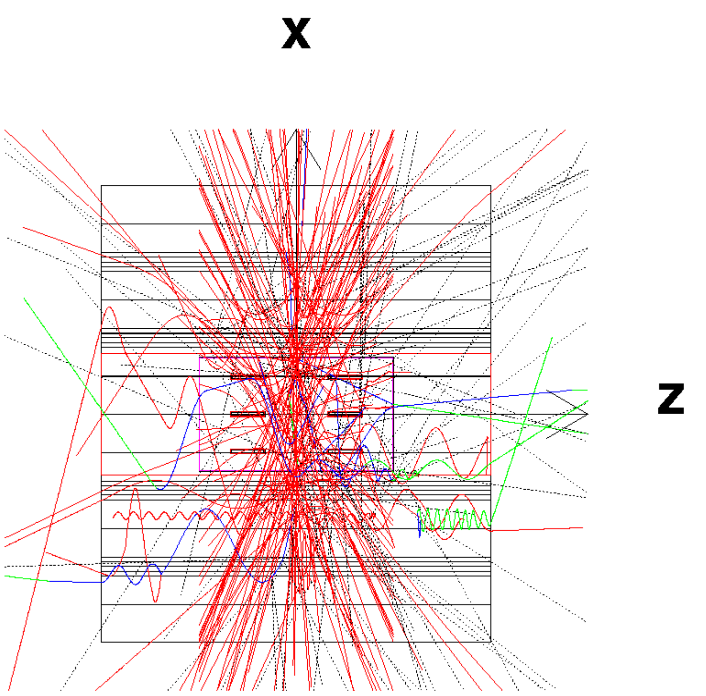
Generation Surface



3 GV (2.2 GeV) Protons

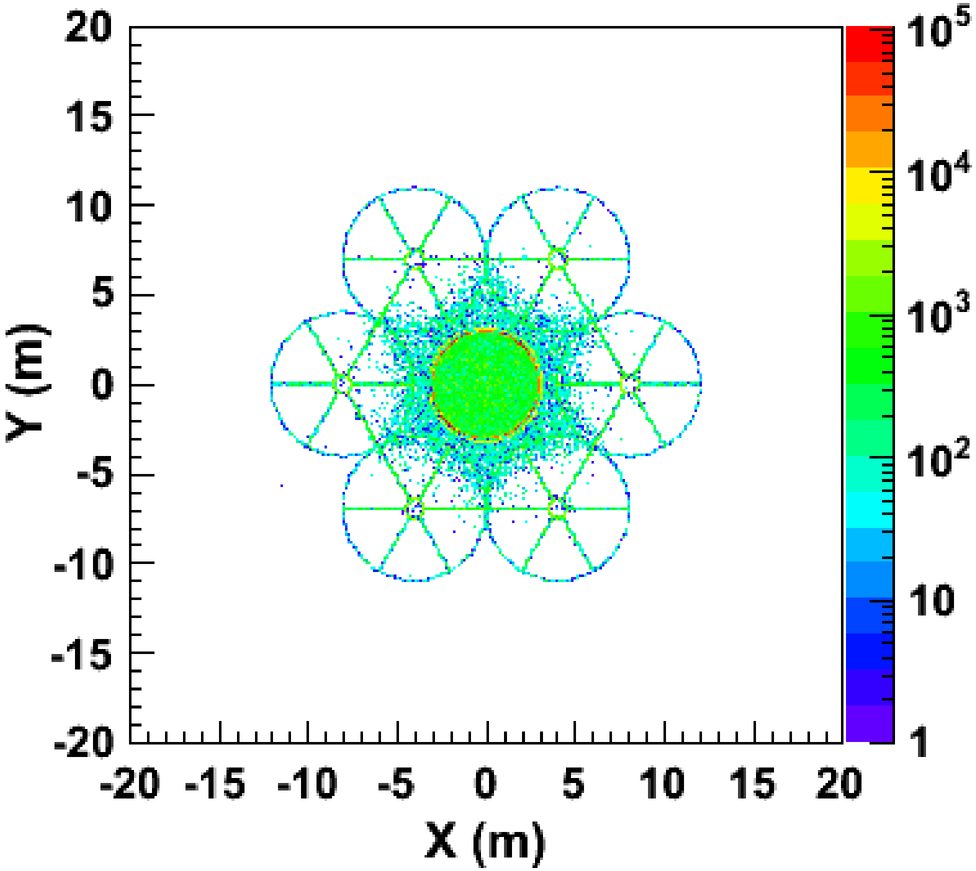






100 protons generated around the habitat in the direction of the orgin (0,0,0)

Production vertex of secondary particles which contribute to the observed dose in the simulation. The distribution includes the decay vertex of unstable secondaries produced in the showers initiated by the GCR protons and He nuclei.



Summary of the Results of the ESA and NIAC Studies

Configuration	BL (Tm)	Mass (sim) (t)	Mass (eng) (t)	BFO Dose Eq. (cSv/y)
LTS Reference Toroid	19	12.5	-	19.2
HTS DH Solenoid	4	11.2	46.3-48.2	29.3
HTS Racetrack Toroid	4.9	28.0	46.4	26.7
Spacecraft (ESA)	-	4.54	-	35.6
6+1 Expandable Solenoid	6.3*	36.1	49.5	30.9
Spacecraft (NIAC)	-	11.8	-	36.7

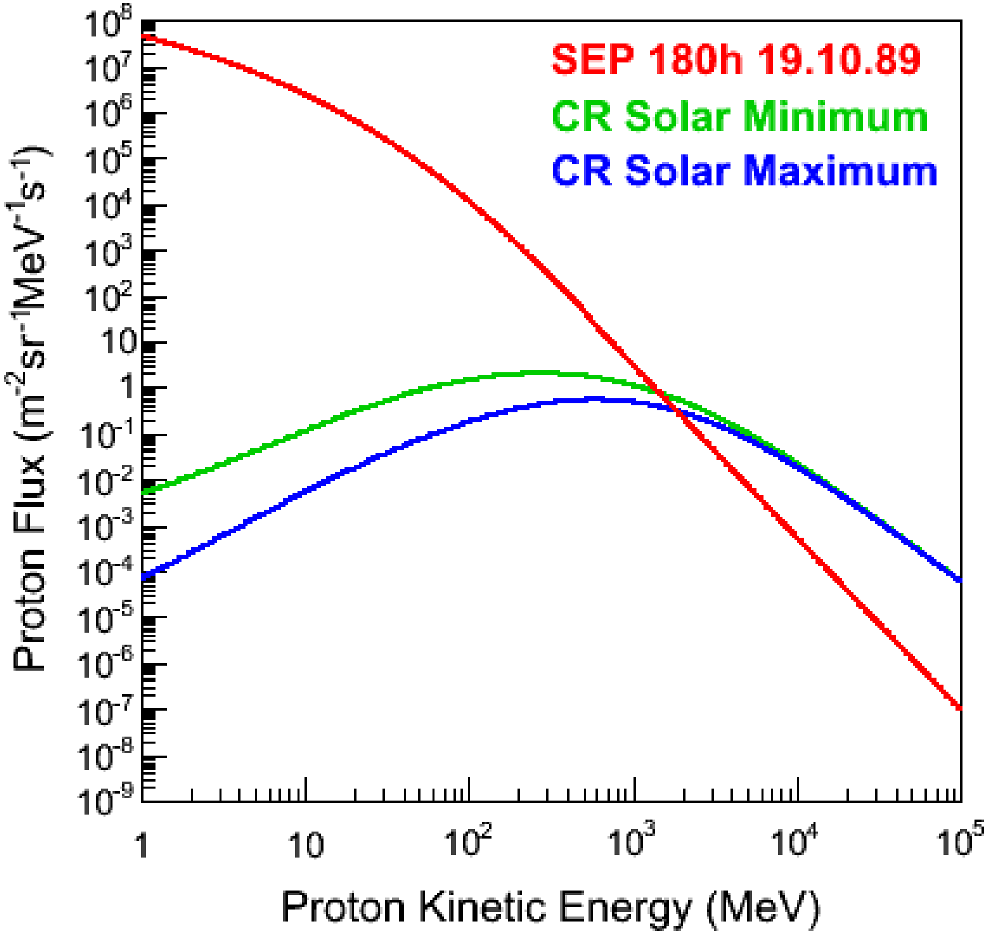
*computed using the average length across the 8m diameter cylindres

The BFO doses refer to the contribution of the barrel regions of the generation cubes.

50 cSv/y is the BFO dose equivalent limit for Low Earth Orbit (LEO)
Payload mass limit for the 143 t Space Launch System is 45 t

Solar Energetic Particles (SEP) – Protons

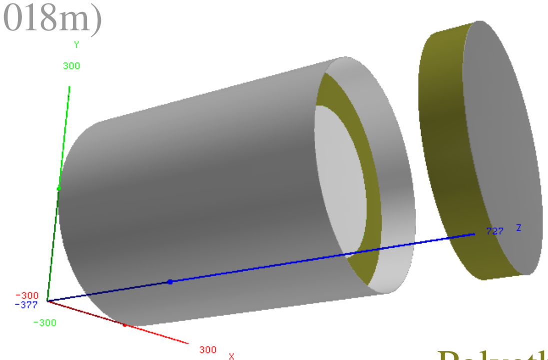
Energy Spectra from CREME*



*Cosmic Ray Effects on Micro Electronics

180h SEP Event Dose and Shield Mass (Barrel Region)

Passive Shield Configuration
in the Physics Simulation

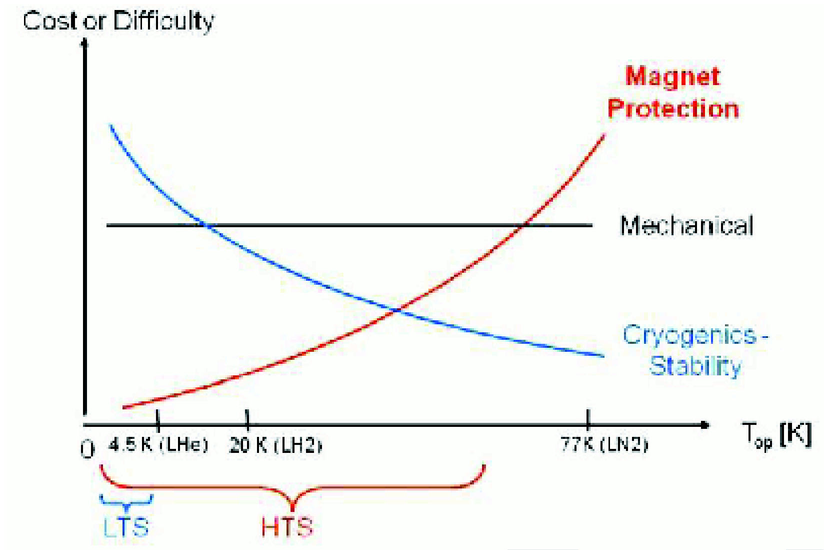


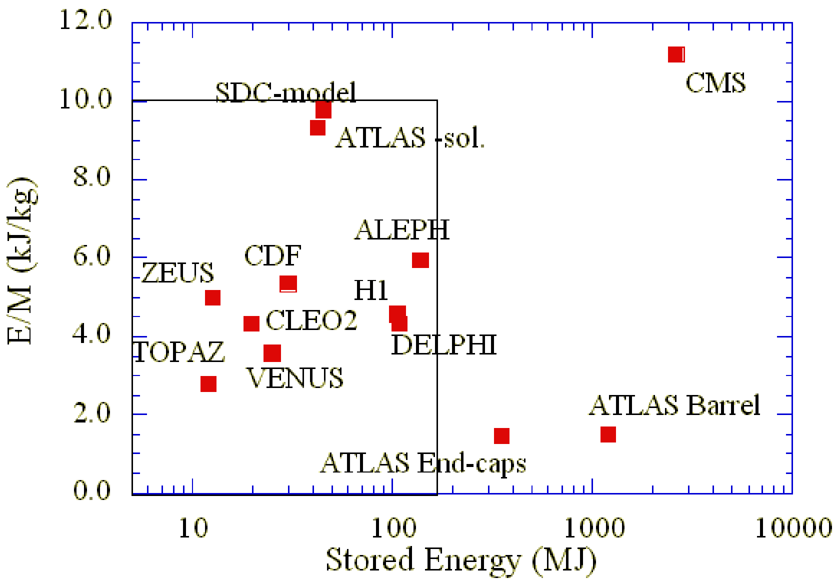
Configuration	Thickness (cm)	BL (Tm)	BFO Dose (cSv)	Shield Mass (t)	Protons ($x10^6$)
Polyethylene	100	-	0.6 ± 0.2	195*	50
Polyethylene	75	-	2.5 ± 0.6	141*	300
Polyethylene	50	-	4.9 ± 1.3	90.4*	250
Polyethylene	25	-	15.2 ± 3.4	43.4*	200
6+1 Solenoid	-	6.3	3.2 ± 0.6	49.5	200

*The masses reported for the polyethylene absorber correspond to a 6 m diameter, 10 m long cylindrical habitat.

Quench Protection

The term quench refers to the rapid transition from the superconducting to normal conduction state, accompanied by a release of the energy stored in the magnetic field.





Configuration	Op. Current	Coil Current	Coil Stored E	coils	Mass	Total Stored E
DH Solenoid	9 kA @ 25 K	20 MA-turns	65 MJ	12	47.2 t	(780 MJ)
RT Toroid	1,2 kA < 20 K	2.6 MA-turns	(83 MJ)	12	46.4 t	1.0 GJ
6+1 Solenoid	43 kA @ 27 K	17 MA-turns	400 MJ	6	49.5 t	2.4 GJ

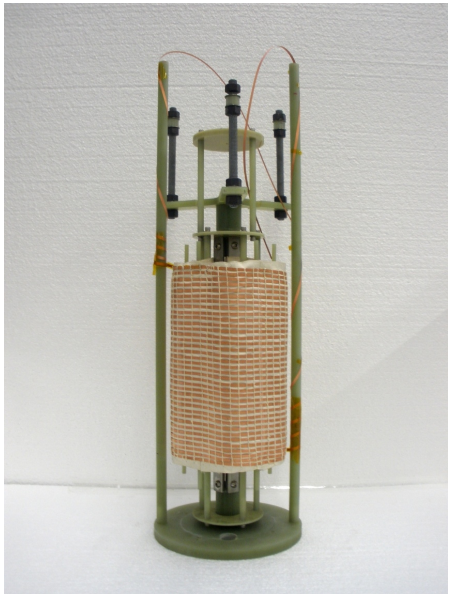
ESA and NIAC Phase I
Summary Statement

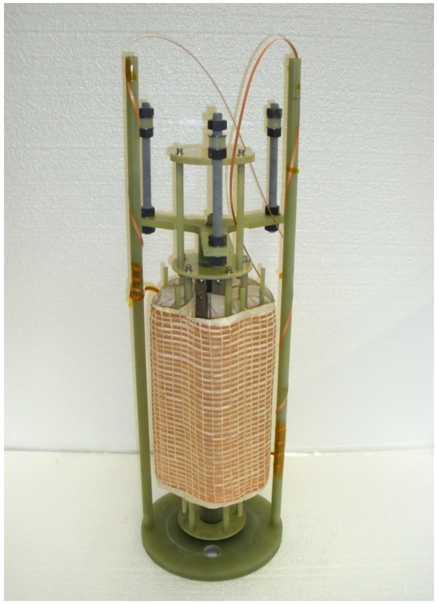
The HTS shields provide reductions of the spacecraft dose level of 18% (DH solenoid), 25% (racetrack toroid) and 16 %(6+1 expandable solenoid), with an estimated shield mass compatible with one heavy launch (45 t). The corresponding reduction for a LTS shield with significantly higher BL and mass is 46%. The scenario for quench protection for the HTS remains to be defined.

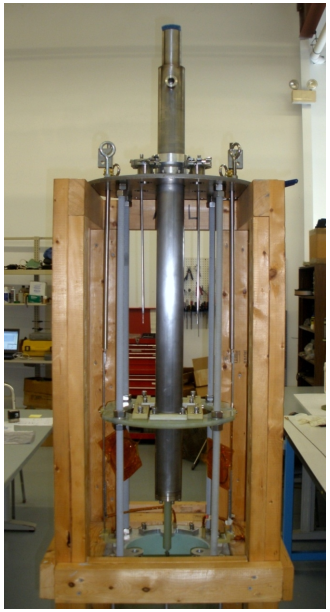
NIAC Phase II

- definition of the mission scenario
- development of the 6-+1 shield concept
  expandability
  fringe field containment
  quench protection
  mass optimization
- identification of key technologies and possible options
- material procurement and fabrication
- evaluation of the shield performance

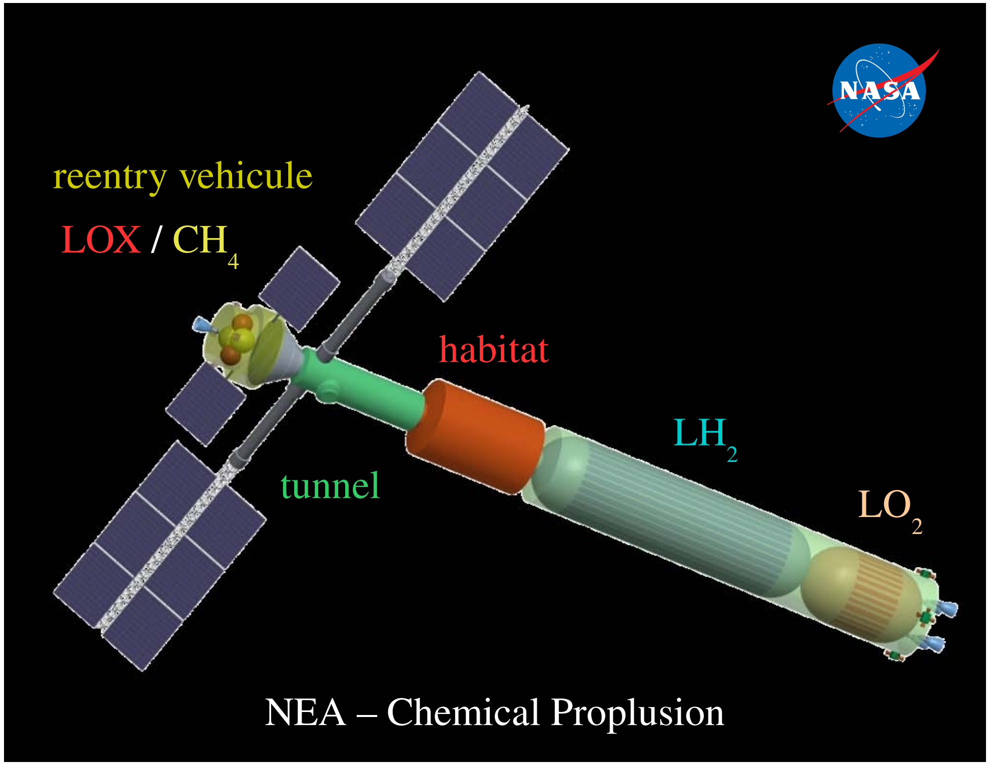
Expandable Coil Prototype and Test



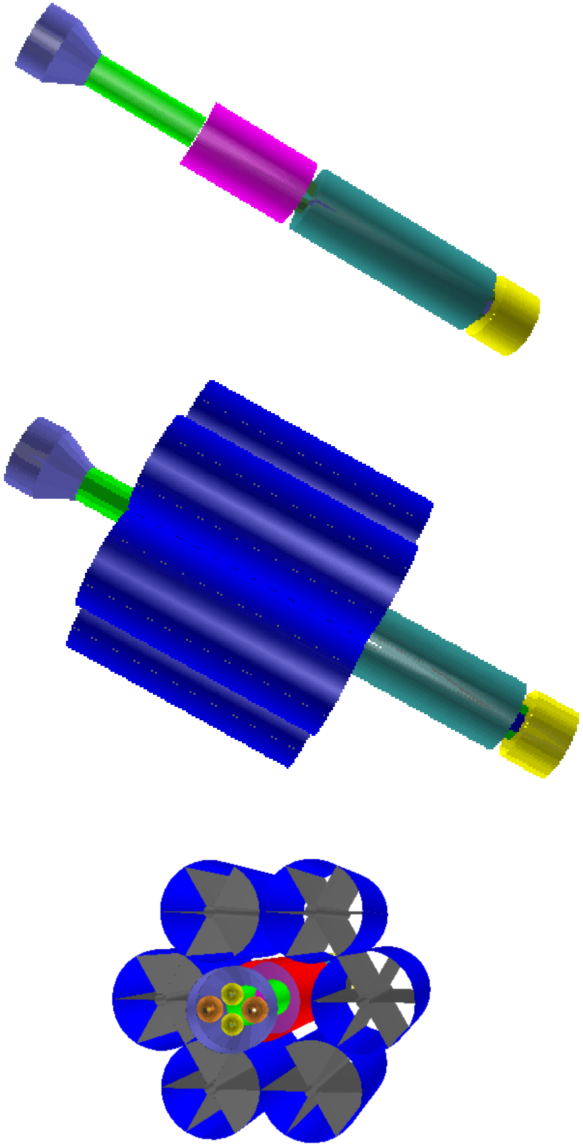




Spacecraft Description in the Physics Simulation

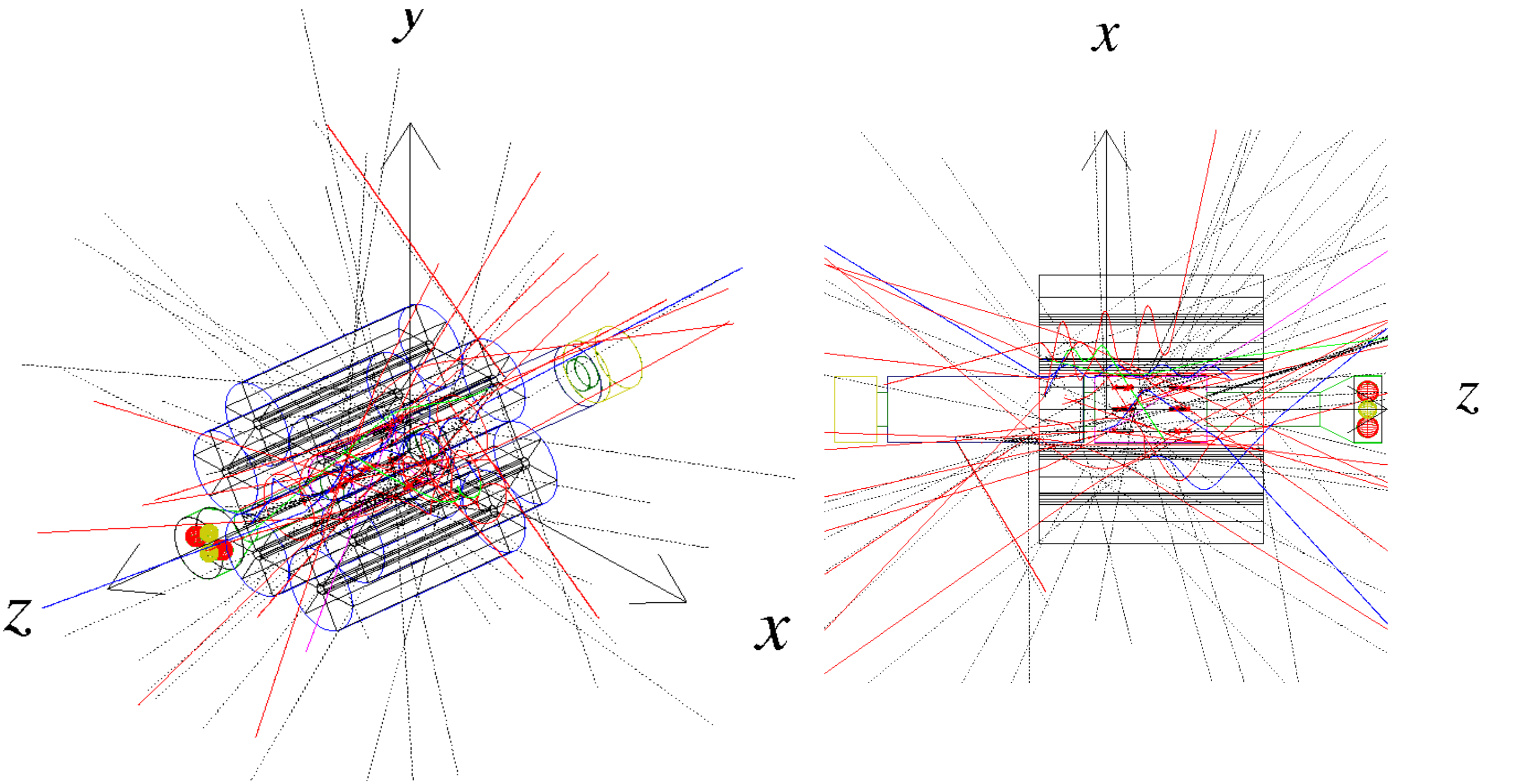


Simulation



5000 GCR Protons and He nuclei Generated in the Endcap Regions

Events with Ionization Losses in the Cylindres



p He $e^{\pm}$ $\pi^{\pm}$ $\mu^{\pm}$ γ

European Seventh Framework Program

Space Radiation Superconductive Shield (SR2S)

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W.J. Burger, Università di Perugia, INFN, Italy
F. Ambroglini, INFN-Perugia, Italy
R. Musenich, INFN-Genova, Italy
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P. Spillantini, INFN-Firenze, Italy
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G. Laurenti, INFN-Bologna, Italy
M. Guerzoni, INFN-Bologna, Italy
P. Rapagnani, INFN-Roma1. Italy
B. Spataro, INFN-Frascati, Italy
P. Fazilleau, CEA, France
B. Baudoy, CEA, France
L. Quettier, CEA, France
A. Ballarino, CERN. Switzerland
C. Gargiulo, CERN, Switzerland
L. Rossi, CERN, Switzerland
V.I. Datskov, CERN, Switzerland
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E. Monchieri, CGS, Italy
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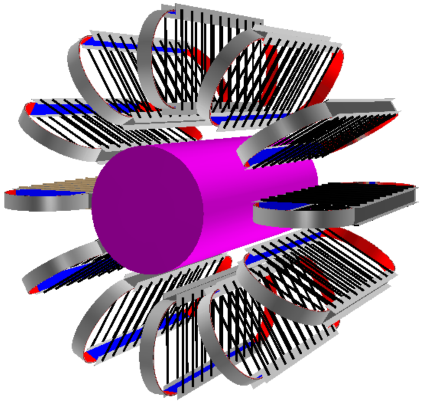
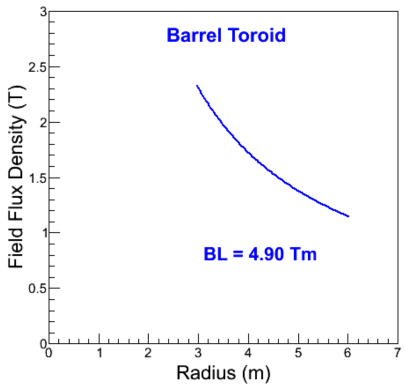
R. Destefanis, Thales Alenia Space, Italy
C. Lobascio, Thales Alenia Space, Italy
E. Gaia, Thales Alenia Space, Italy

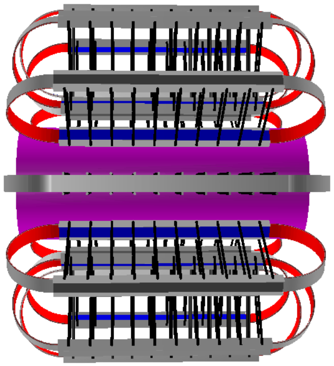
SR2S Study HTS

The starting point of the SR2S is the HTS racetrack toroid shield design of INFN-Genoa/AGS, based on HTS MgB_2 cables.

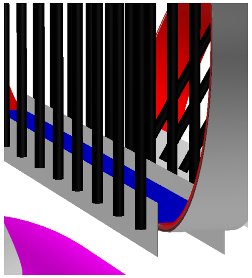
long and curved coil segments,
aluminium plates,
carbon fibre tie rods,
∅ 4 m, 10 m long habitat

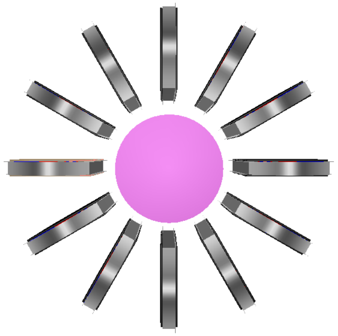






detailed view of racetrack

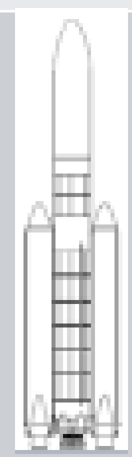
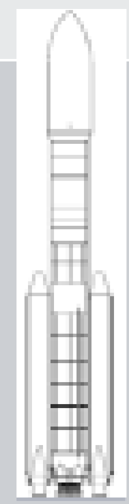




The approach is complementary to the NIAC program since it is *a priori* more conservative, relying on the experience acquired with ATLAS/CMS and promoting a simpler shield deployment.

Constraints Imposed by Launcher on Mass and Volume

Required habitable volume per crew member is 20-25 m^3

Characteristics	Ariane 5ECA/ES	Ariane 5ME	NASA SLS Block 1	NASA SLS Block 1A	NASA SLS Block 2	Russian Heavy Launcher
Max Diameter	4.57m	4.57m	7.5m	7.5m	9.1m	5.4m
Length (*)	10m	10m	19.36m	19.36m	17.2m	9m
Mass to LEO	19-21 tons	20.7 tons	61.7 tons	105 tons	130 tons	60 tons
Mass to GTO	>8 tons	9-11.2 tons	-	-	-	
Launcher picture						

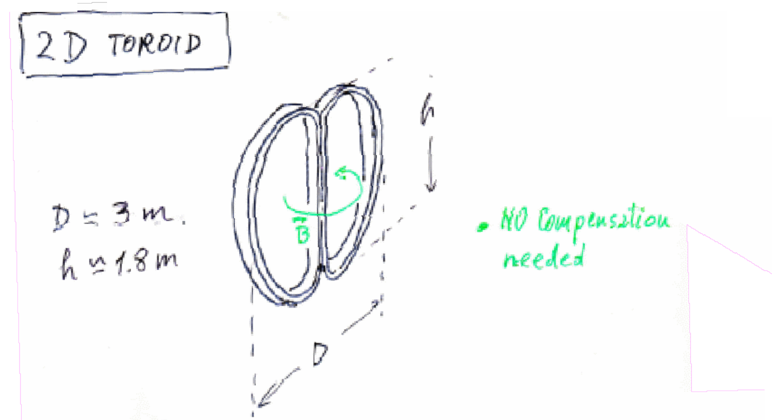
(*) length available in cylindrical volume excluding the ogive

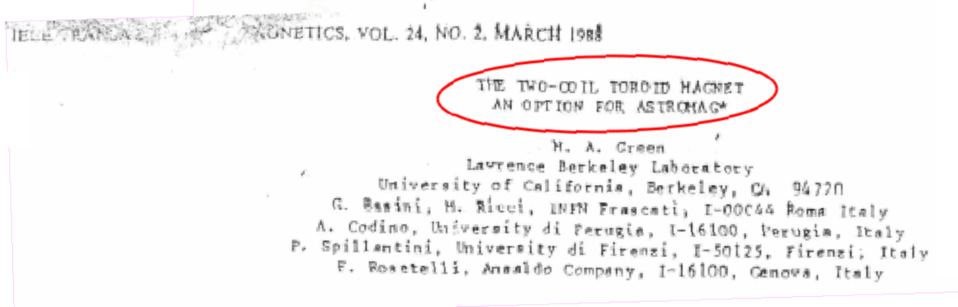
CGS S.p.A. / Parameters for the SR2S shielding study / 16-01-2013

Optimization of the Racetrack Toroid Shield Design
Number of Coils

The minimal two coil toroid is an unconfined field configuration.

ESA Studies
S. Spillantini / G, Volpini Dec 5 2012

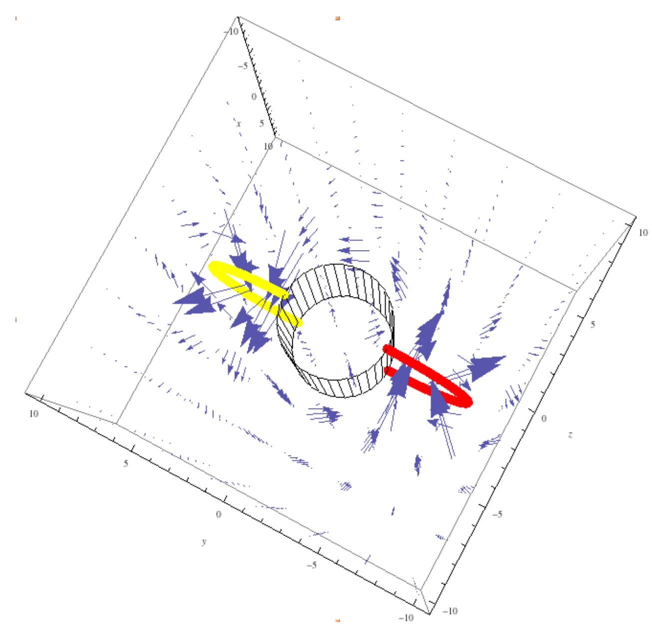



IEEE TRANSA... ...AGNETICS, VOL. 24, NO. 2, MARCH 1988

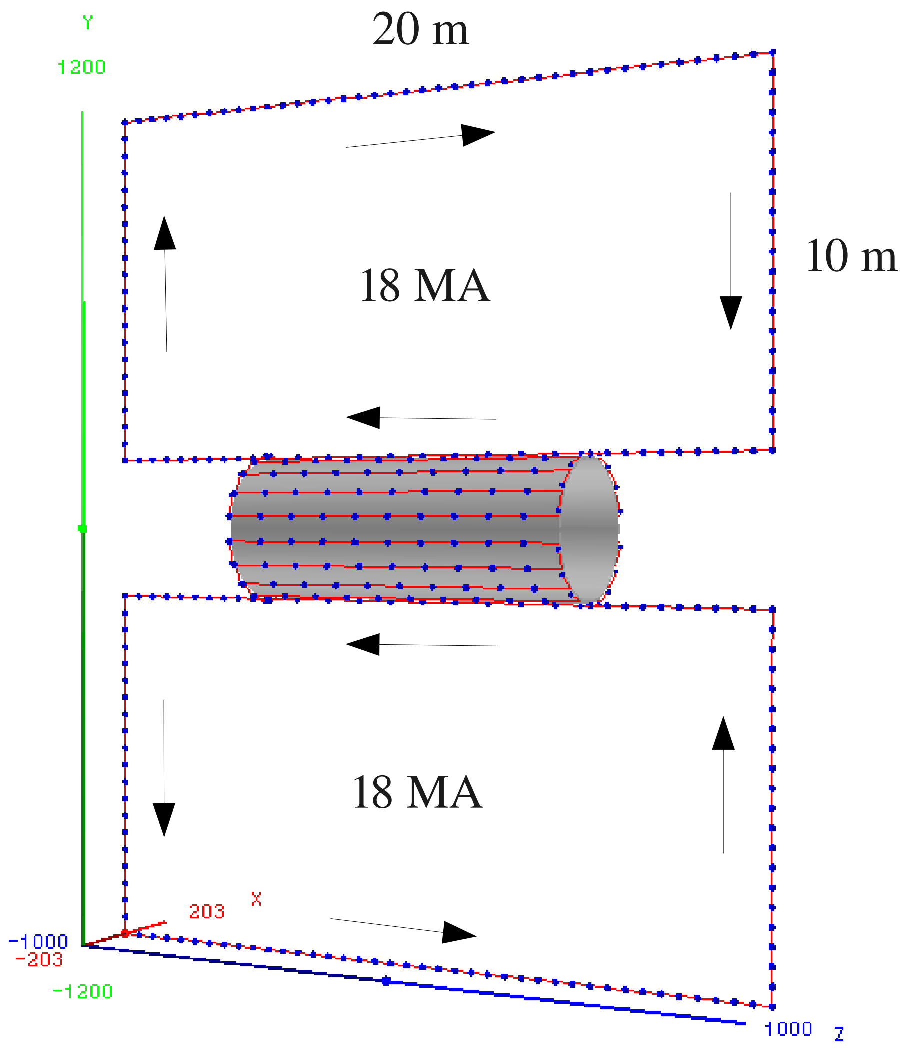
THE TWO-COIL TOROID MAGNET
AN OPTION FOR ASTROMAG*

H. A. Green
Lawrence Berkeley Laboratory
University of California, Berkeley, CA 94720
G. Basini, M. Ricci, INFN Frascati, I-00044 Roma Italy
A. Codino, University di Perugia, I-16100, Perugia, Italy
P. Spillantini, University di Firenzi, I-50125, Firenzi, Italy
F. Rosetelli, Ansaldo Company, I-16100, Genova, Italy

Two coil toroid field
R. Battiston Jan 4th 2013

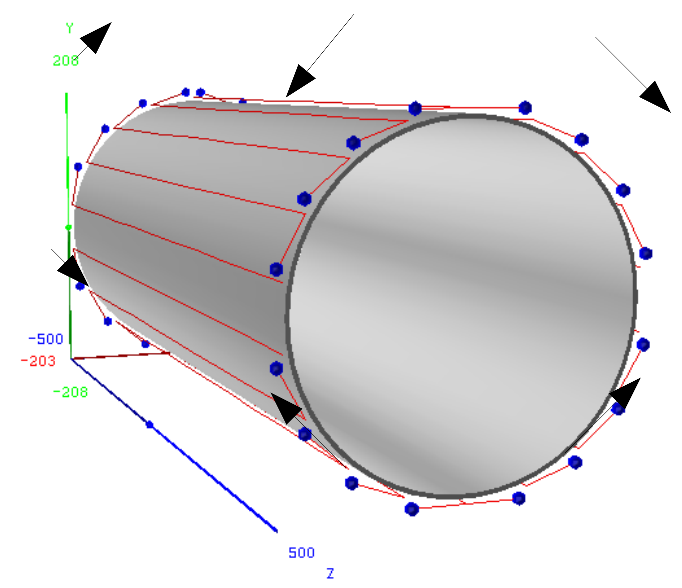


Current Elements used to Compute the Field Flux Density



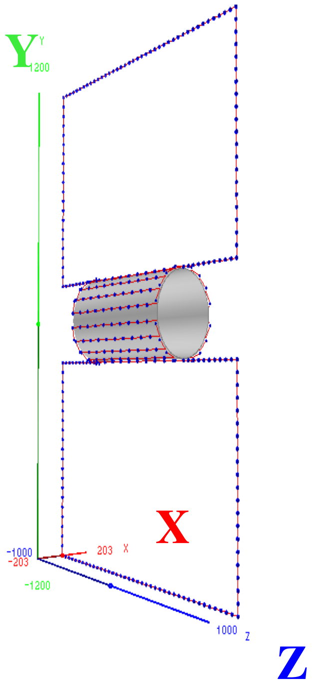
Biot-Savart Law

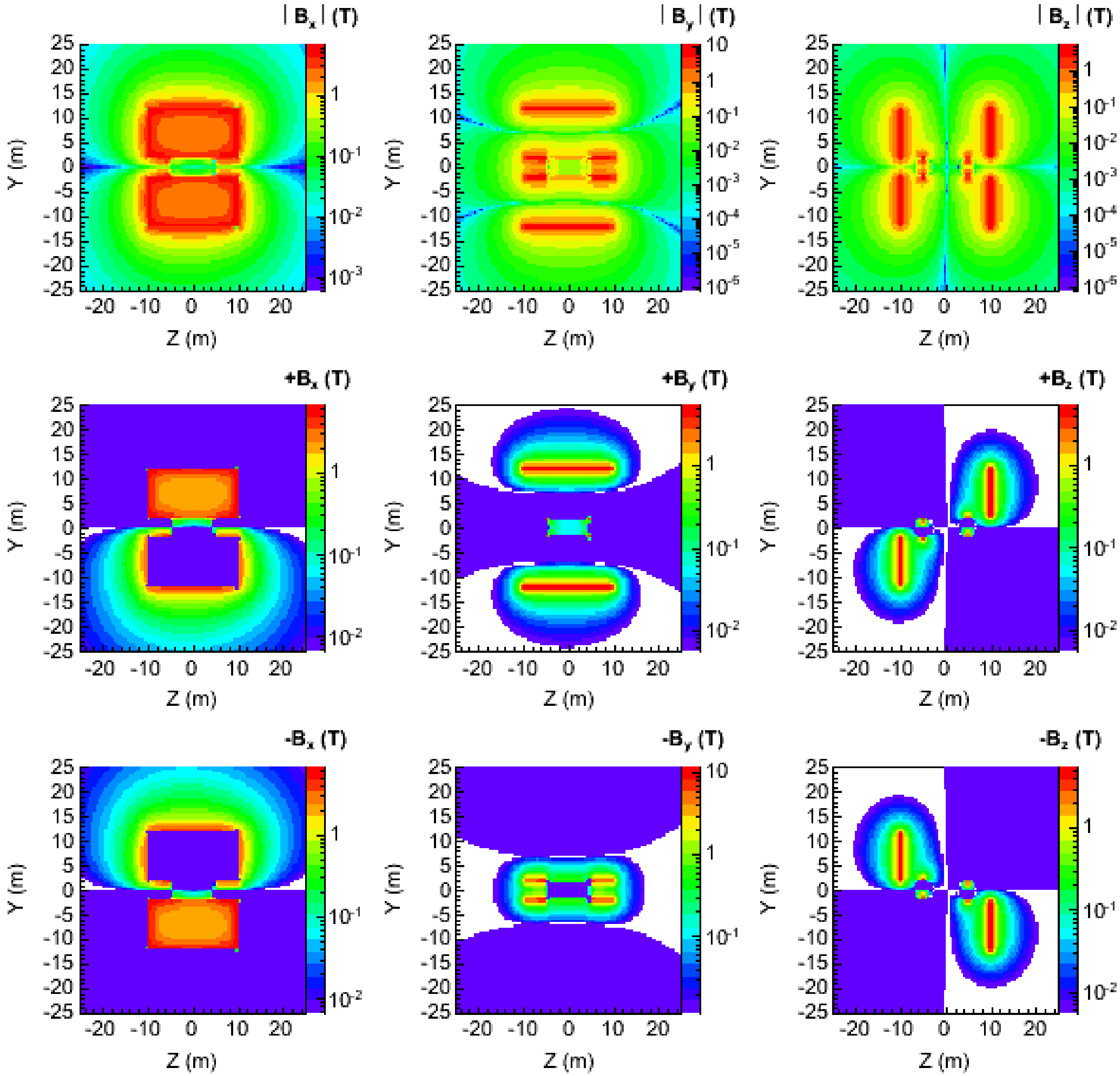
$$\boldsymbol{B} = \frac{\mu_o}{4\pi} \boldsymbol{I} \oint \frac{\boldsymbol{dl} \times \hat{\mathbf{r}}}{r^2}$$



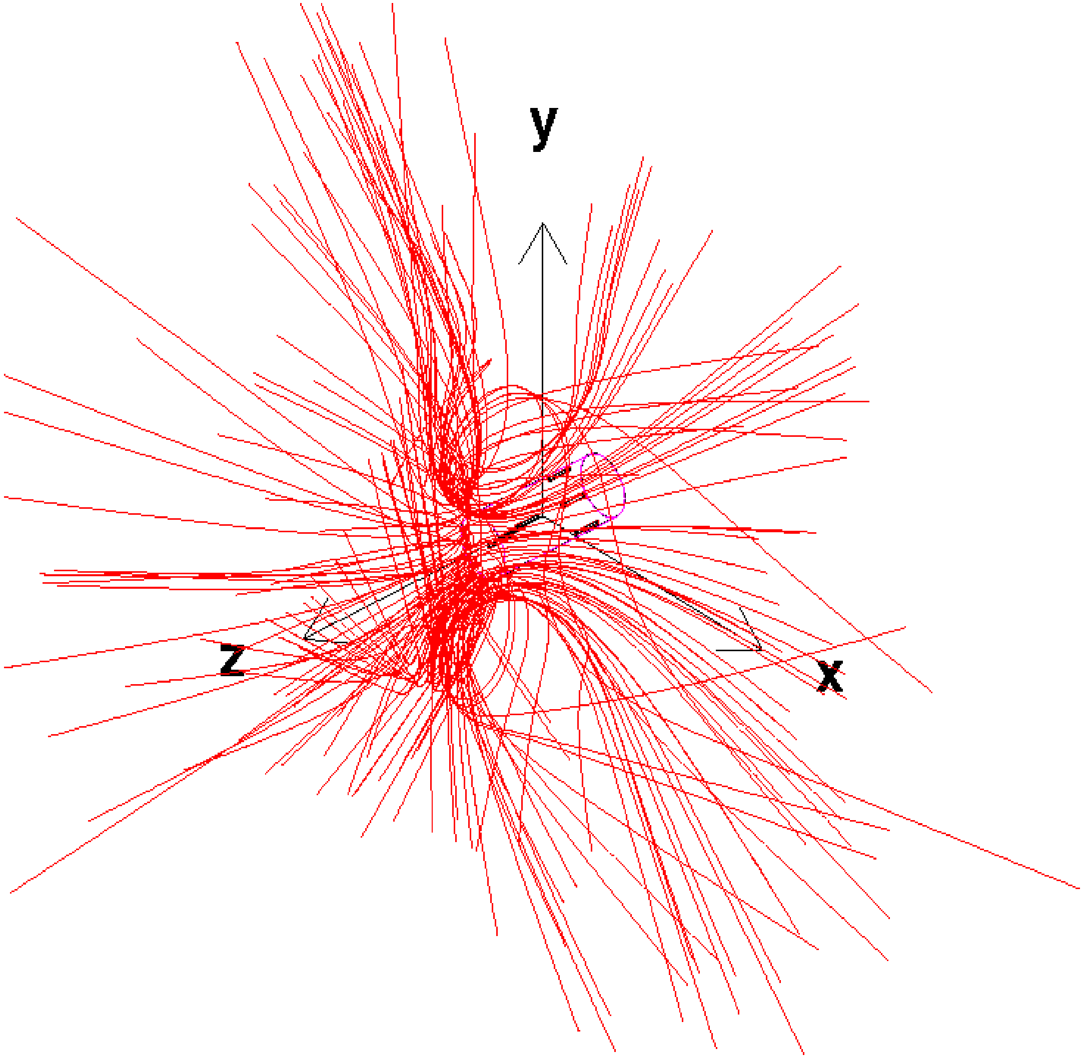
habitat: ∅ 4 m, 10 m long

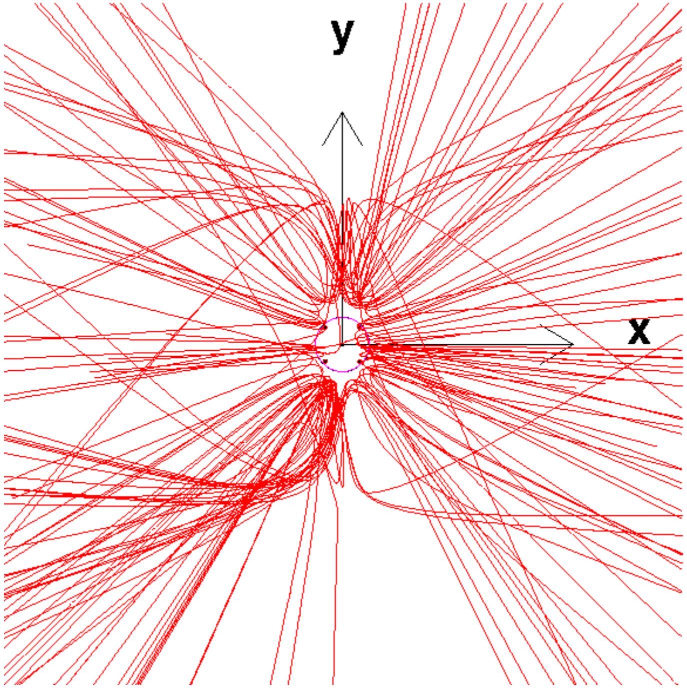
Field Flux Densities in YZ Plane at X = 0

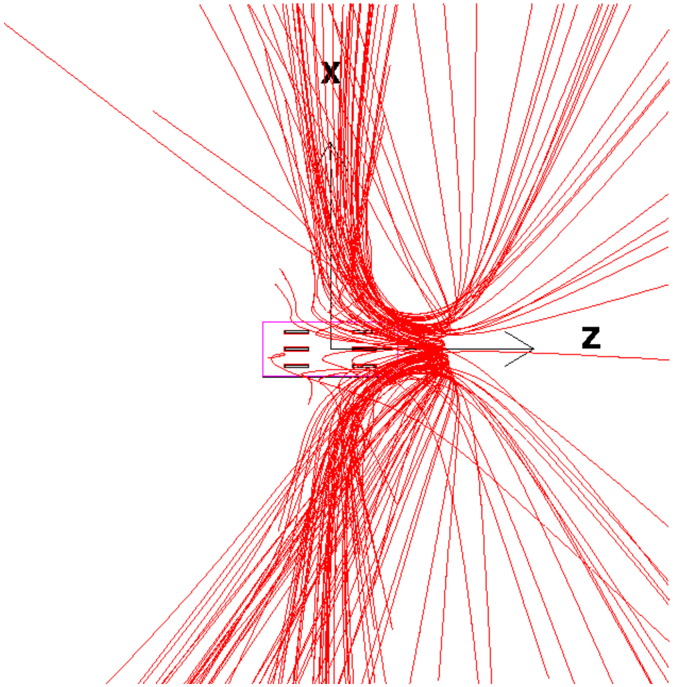




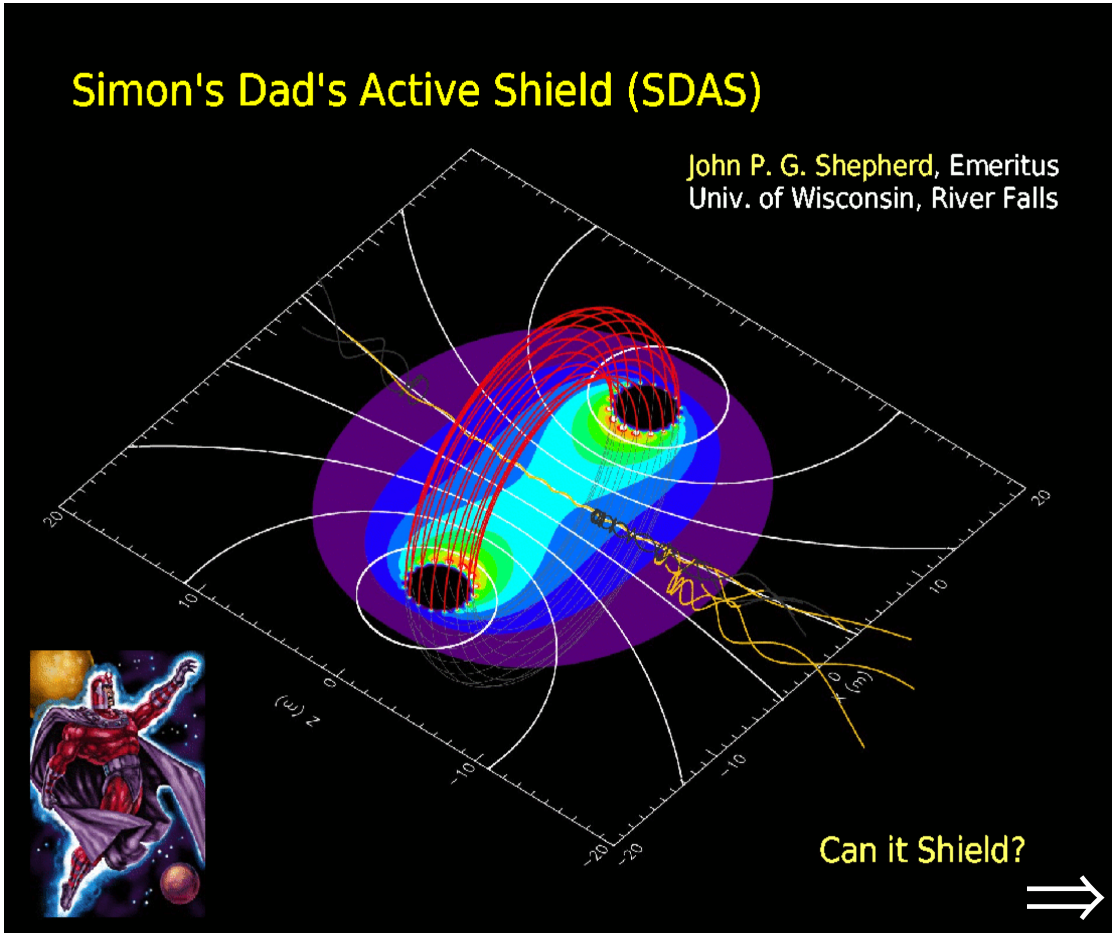
3 GV (2.21 GeV) Protons





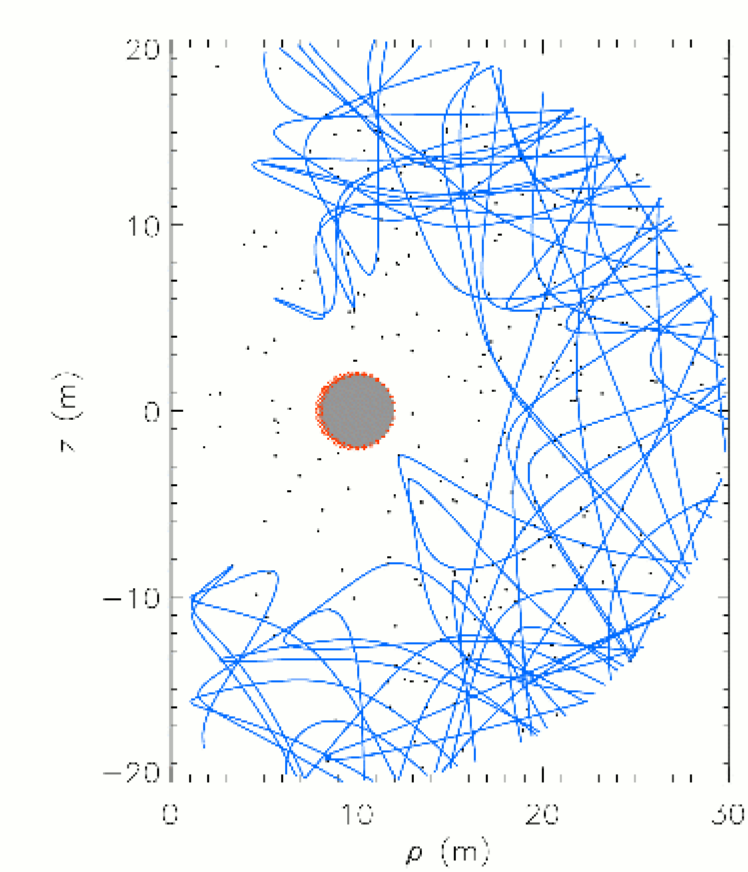


An Unconfined Field Configuration
Toroidal Magnetic Spacecraft Shield (ToMaSS)



"Simulations of Magnetic Shields for Spacecraft"
S.G. Shepard et al.

100 MeV protons

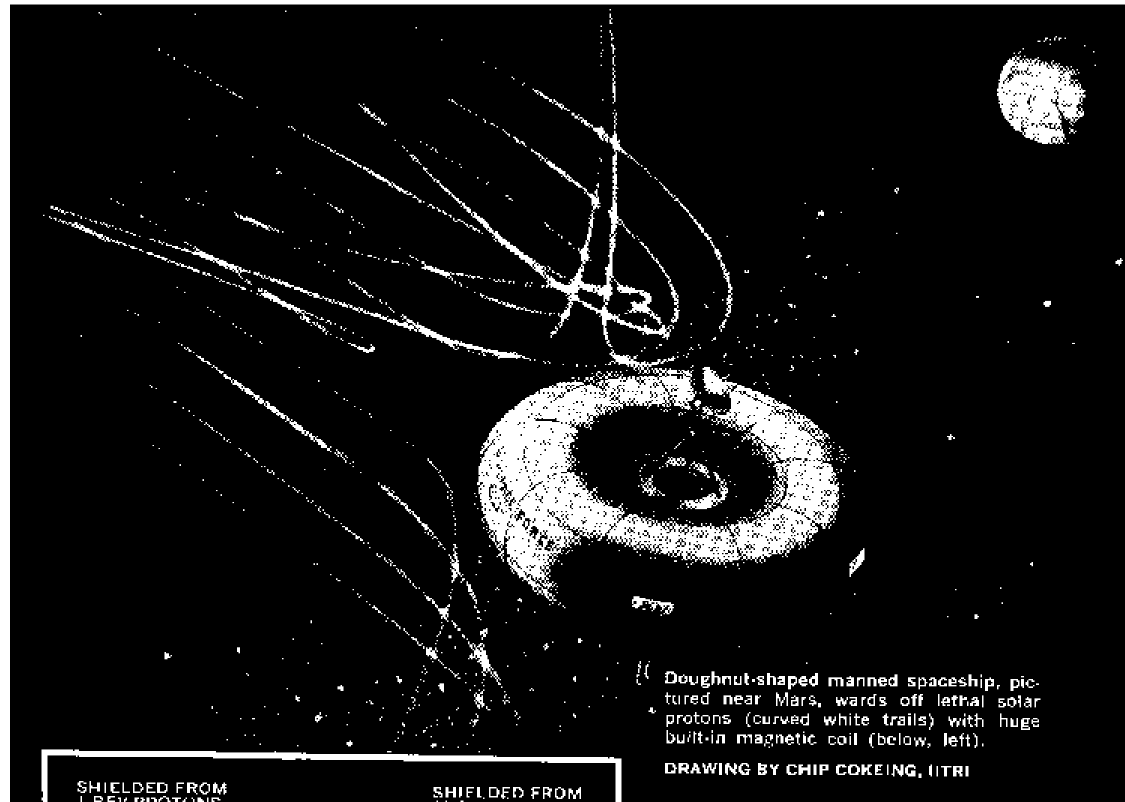


Will Mighty Magnets Protect Voyagers to Planets?

Applying the strange phenomenon of "superconductivity" in space flight promises shields against deadly radiation, gyros without friction, and other innovations in travel beyond the earth

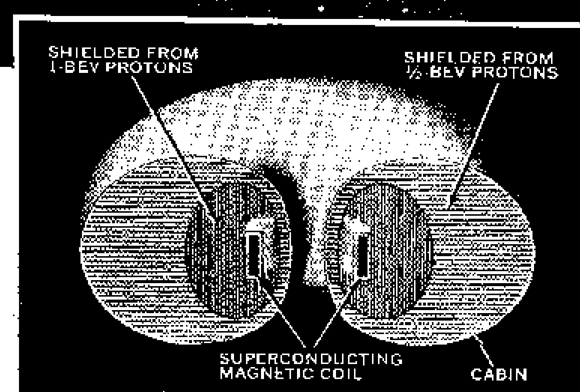
Superconductivity
Heike Kamerlingh Onnes (1911)
SC magnet NbTi (1962)
HTS, T_c > 90 K (1986)

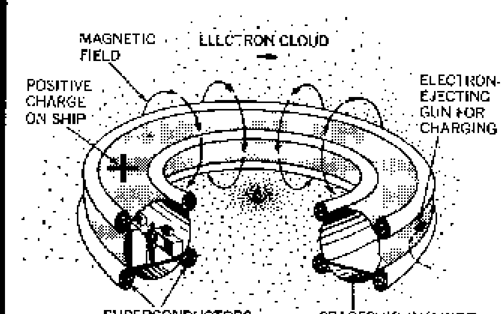
By
DR. WERNHER VON BRAUN
Director of NASA's George C. Marshall Space Flight Center, Huntsville, Ala.



Doughnut-shaped manned spaceship, pictured near Mars, wards off lethal solar protons (curved white trails) with huge built-in magnetic coil (below, left).

DRAWING BY CHIP COKEING, IITRI





Popular Science, Jan. 1969

SRS2 Racetrack Toroid Design

The two coil configuration results in a reduction of 38% of the spacecraft BFO dose equivalent, approaching the performance level of the LTS shield (46%).

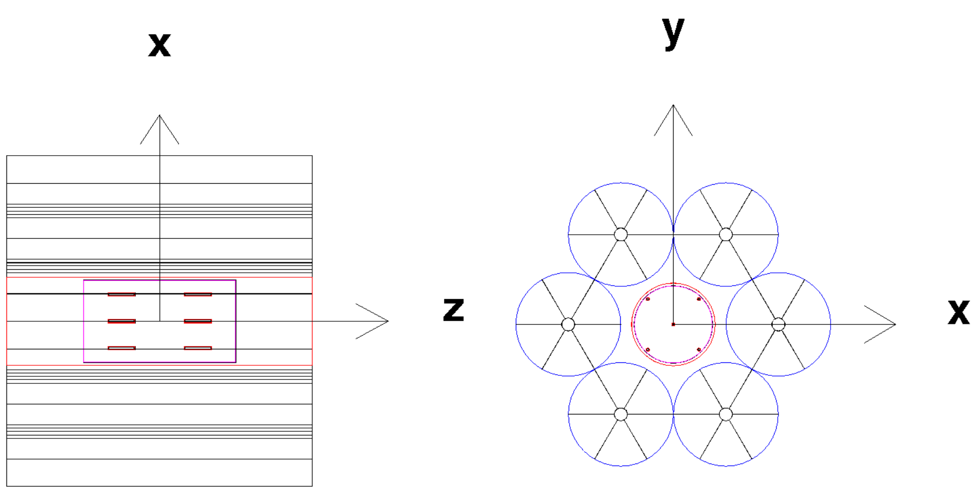
The optimization of the number of coils in terms of the shield mass/performance continues. A high coil multiplicity, or continuous coil configuration is also understudy.

In Parallel
Develop Geant4 Version of the Physics Simulation

F. Ambroglini (INFN-Perugia)

6+1 Expandable Solenoid Configuration

Geant3



Geant4