SR2S

Space Radiation
Superconducting Shield

A Novel Configuration for Superconducting Space Radiation Shield

The Pumpkin Configuration

Valerio Calvelli

Mar 11th, 2016

Overview

SR2S Project

- **The Problem of the Radiation Shielding in the Deep Space**
- **Passive Shields: Principles, Advantages and Drawbacks**

- **Principles for the Design of Superconducting Active Shields**
  - Boundaries Conditions
  - Requirements

- **Toroidal Magnets as Active Shields**
  - Working Principles and Design
  - Results

- **The Pumpkin Configuration**
  - Working Principles and Design
  - Results

Look at the future

SR2S Project

"…Explore the feasibility of a superconducting magnetic shield as well as the challenges related to it, developing some key abilitating technologies to be used to…"

INFN Istituto Nazionale di Fisica Nucleare

Columbus Superconductors

OHB CGS

ThalesAlenia Space
A Thales / Finmeccanica Company

cea
DE LA RECHERCHE À L'INDUSTRIE

CERN

Carr Communications

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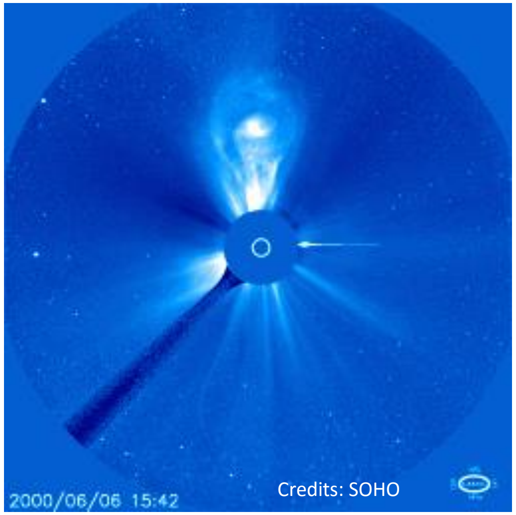
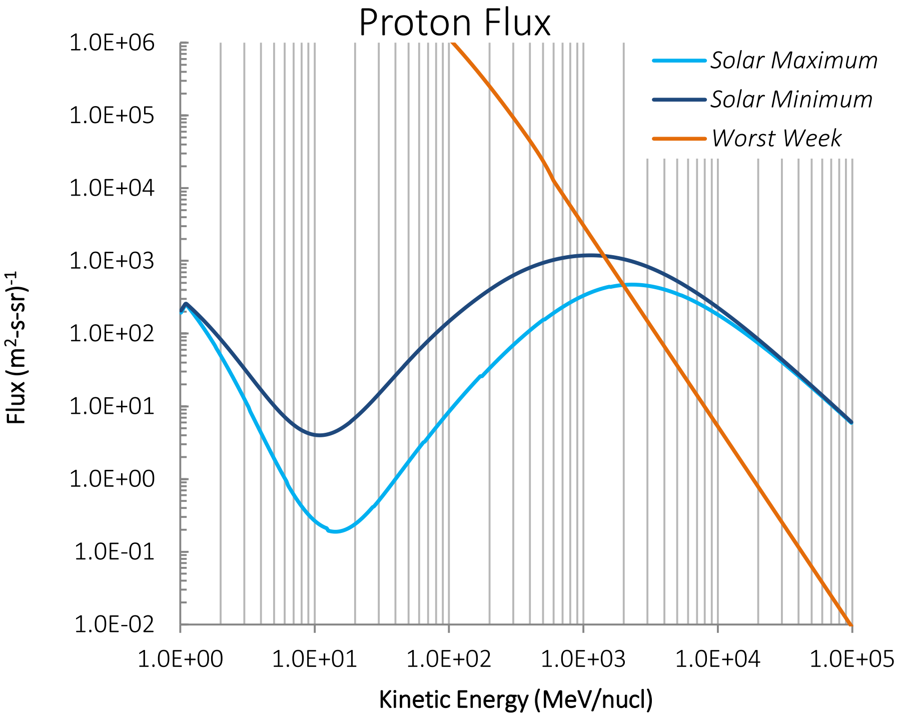
Space Radiation – Composition

Primary Cosmic Rays

- **SPE (Solar Particle Events)**
  Protons and **elia** from Sun
  High Flux – Low Energy



- **GCR (Galactic Cosmic Rays)**
  Protons, elia and **ions**
  Low Flux – High Energy

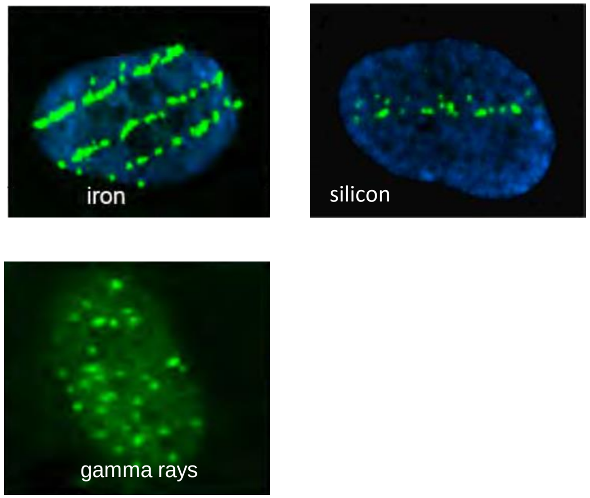


Solar Activity Effect

- Anti-correlation with CGR Flux
- Correlation with SPE Flux

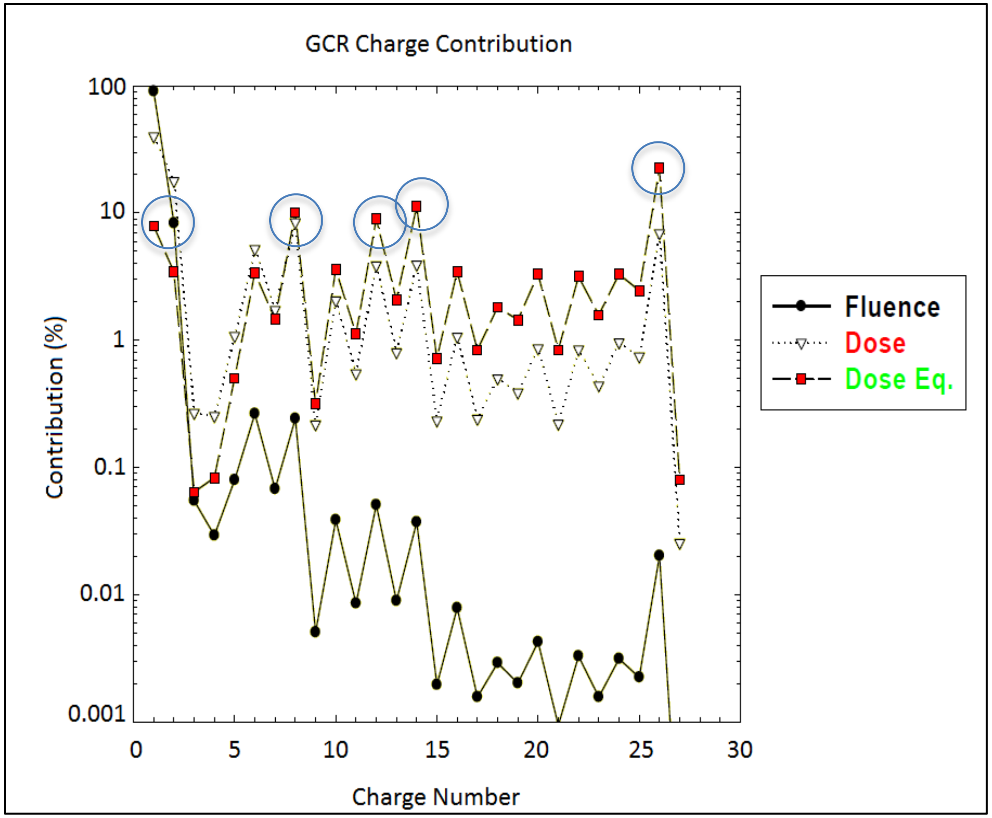
Space Radiation – Biological Effects

« …Different Particles,
Same Physics,
Different Effects…»



Ionization tracks in cell nuclei (optic microscope)

Cucinotta, Durante, *Lancet Oncol. 2006*



CGR Contribution for unshielded astronauts

p, C, O, Si, Fe **contribute most to the equivalent dose**

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Dose per Mission Scenario and 95% CL Mortality Level

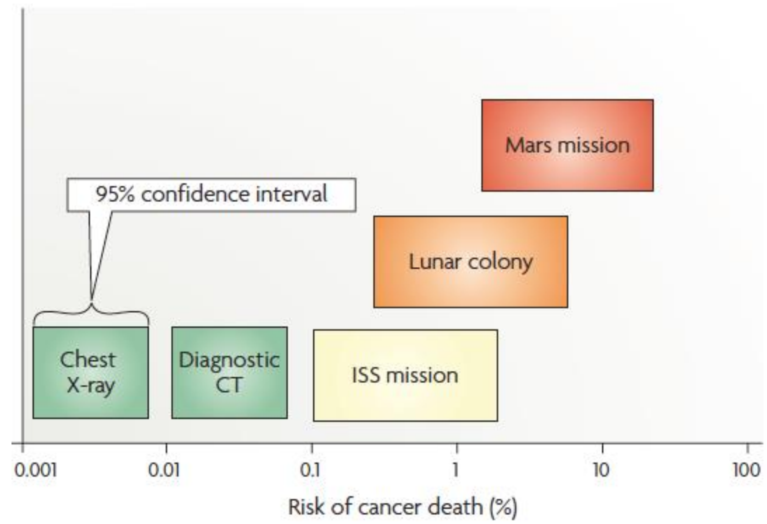
Mission Scenario	Equivalent Dose (mSV/y)
Free Space	1200
Spacecraft ($20g/cm^2$ Al shield)	700/800
Mars (surface)	100/200
Moon (surface)	223
ISS	150

Maximum dose for professional workers 20 mSv/year – 1 Sv career

On the ISS, maximum 3 missions for 18 months total (and only for men)

A mission to Mars have up to 40% risk of cancer death and acute effects (95% CL)

High uncertainties for dose estimation and effects (up to 500%)



Cucinotta, Durante, *Nat. 2008*

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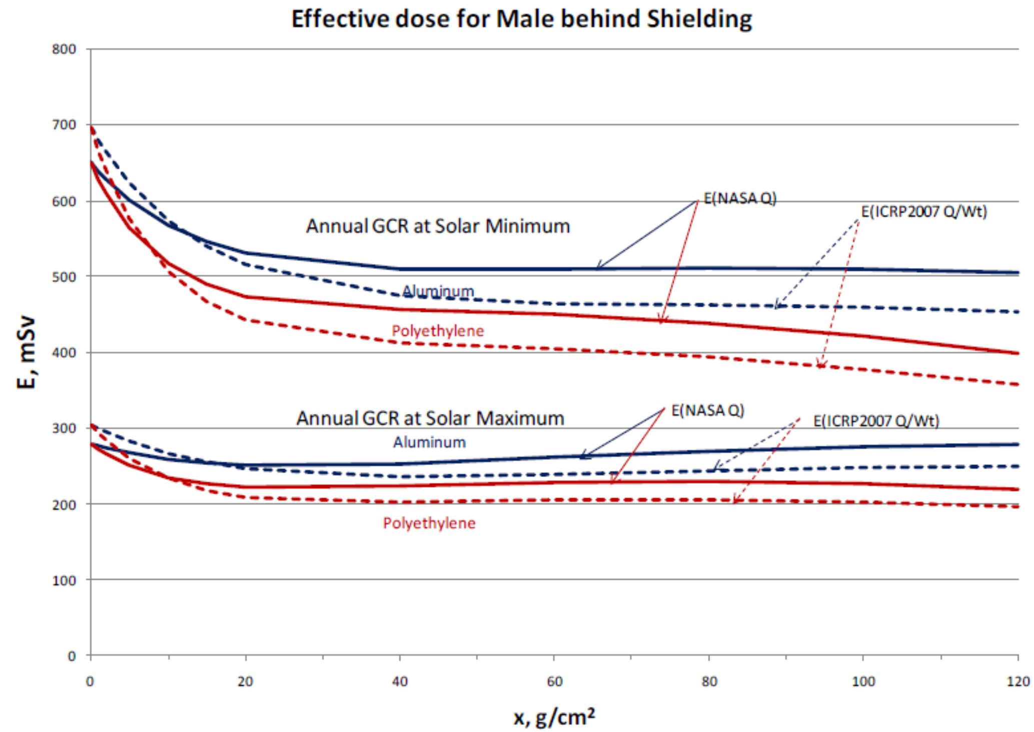
Passive Shields

Passive Shields

- **Easiest thing to use**
- **Stopping Power** $\propto Z^2$
  very effective for heavy ions, not for protons
- **Large thickness for shielding light ions**
  ($480\ g/cm^2$ of Al for $1\ GeV$ protons)
- **Secondary particles production** (n, p) ∝ penetration length



$50 g/cm^2$~140 days for mission
Thousands of tons for a Mars spacecraft

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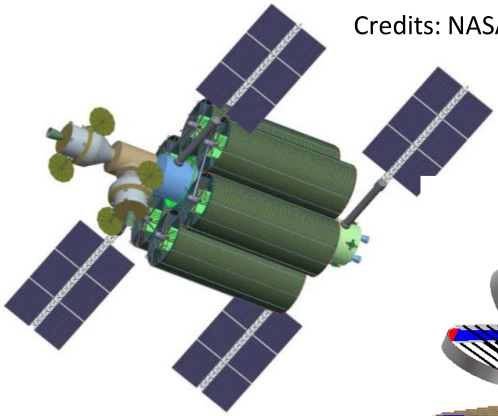
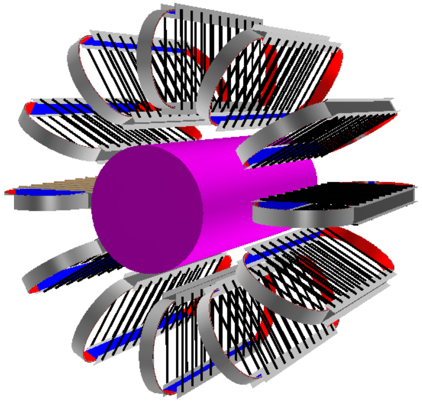
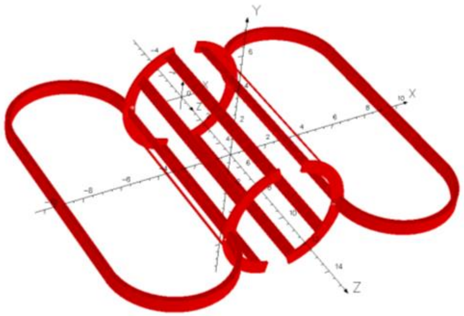
Design of Superconducting Active Shield

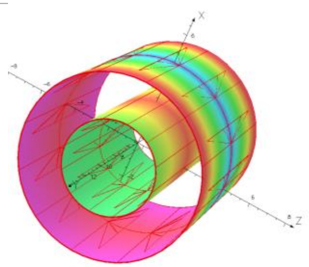
Researches on Active Shields last about 50 years

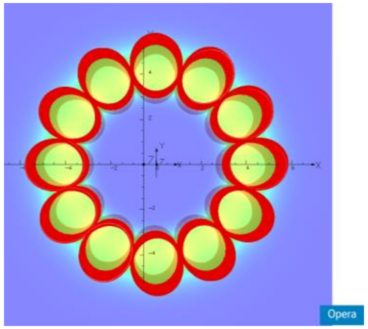
- Many configurations proposed (double helix, giant single coil, solenoids, toroids…)


Credits: NASA









With SR2S

- Better understanding of the particles environment
- Definition of the basis requirements
- Materials effects considered
- Possible Conceptual Design

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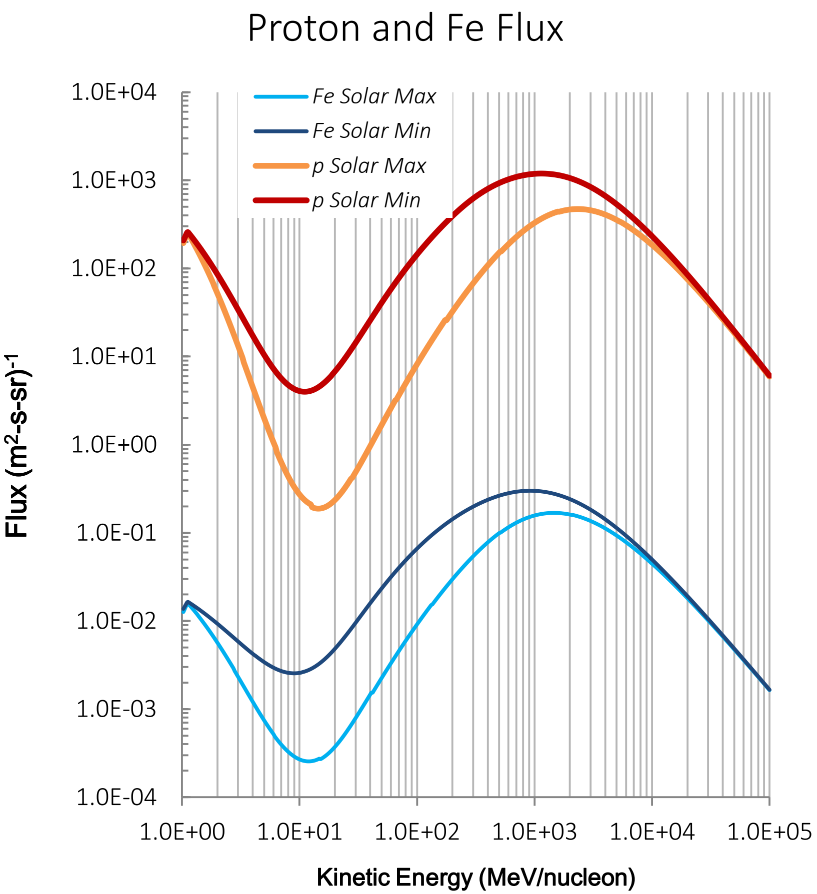
The Particles Environment

Particles Environment

- Charged particles from $Z = 1$ to $Z = 26$ (Fe)
- No primary neutrons
- Kinetic Energy from MeV to PeV and more
- Maximum Flux
  Protons $\longrightarrow \sim 1\ GeV$
  Ions $\longrightarrow \sim 1\ GeV/nucleon$

«Homogeneous» Distribution in Space

What does it mean?



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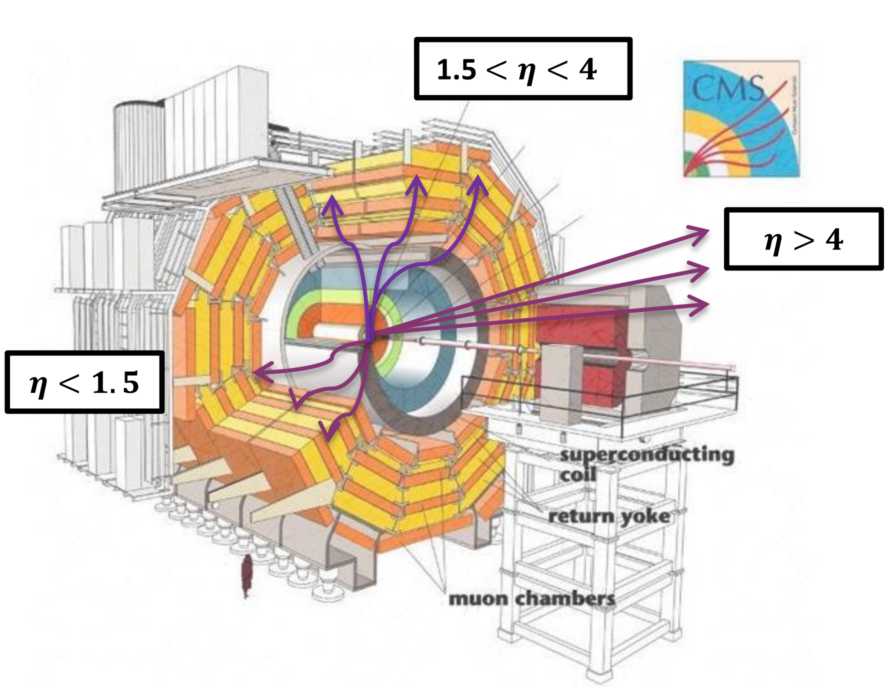
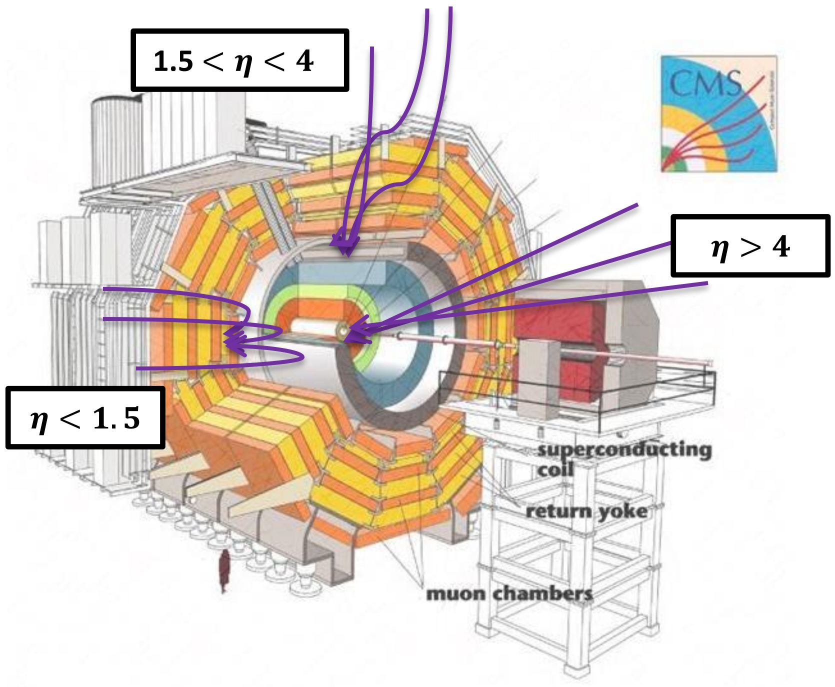
The Problem with the «Homogeneous» Flux

SINGLE POINT IN ⟹OUT



OUT ⟹IN SINGLE POINT



CMS Bending Power $\propto 1/\eta \;\; (\eta > 1.5)$

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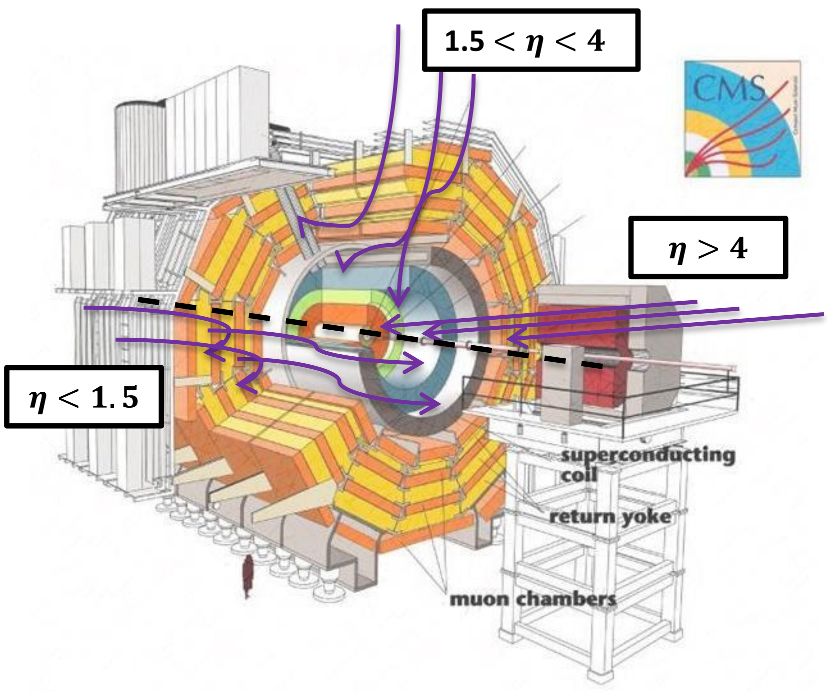
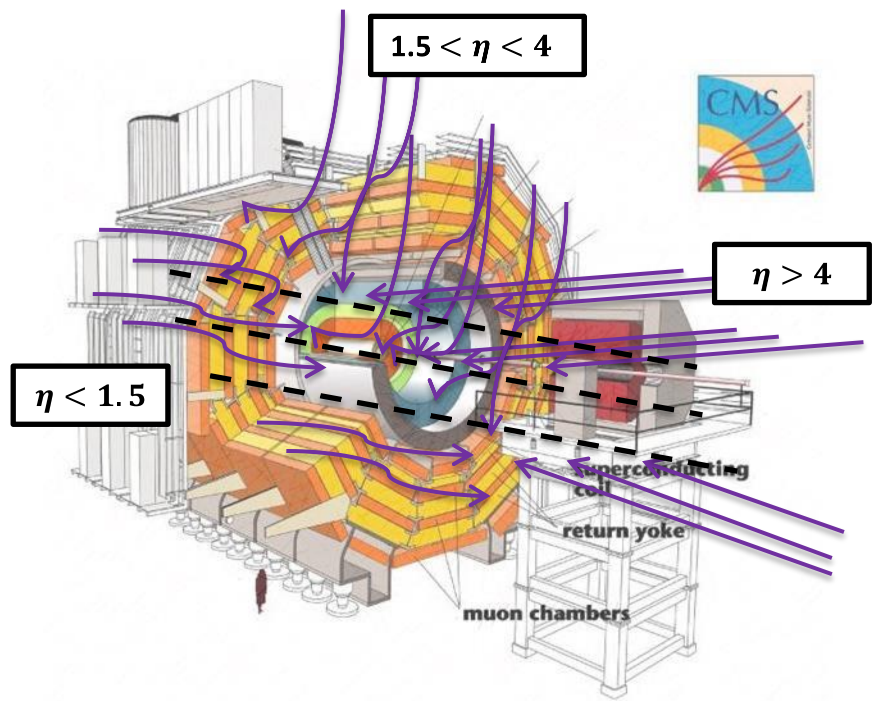
The Problem with the Homogeneous Flux

OUT ⟹IN CENTRAL AXIS



OUT ⟹IN HOMOGENEOUS FLUX



Classic Solutions can deal with this? → **Particles from every directions pointing to every axis**

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Spacecraft Requirements

MUST TO BE Requirements for Active Shieldings

Physics Requirements

- Low Magnetic Field inside the Habitat (less than 40 Gauss)
- Maximum Protection
- Uniform Protection

Technical Requirements

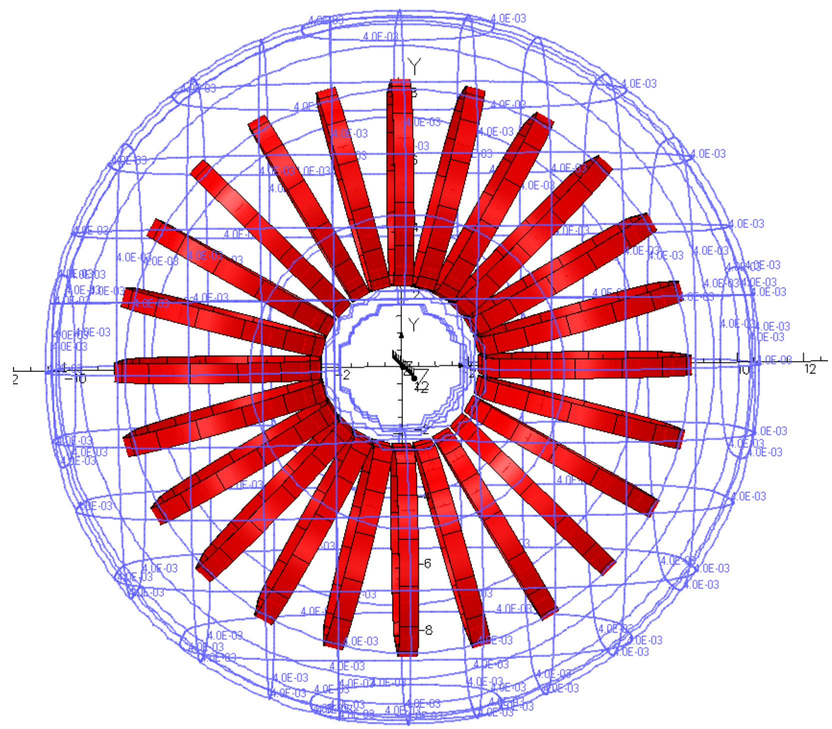
- Launchability ⟶ (limits on dimensions and mass)
- Reliability
- Redundancy
- No LHE (AMS-02 experience)

The Best, Classic Solution: Toroids

Physics

Technical

Requirements	
Low B field inside the habitat	**OK** Lowest fringe field
Maximum Protection	**OK** B field always perpendicul to particles trajectories
Uniform Protection	**OK** Cylindrical Symmetry
Launchability	**Depends** on mass and dimensions
Redundancy	**OK** Two or more separated circuits
No LHE	**OK** HTC Superconductors
Reliability	**Critical** Quench problems High Loads towards the habitat



B = 40G isolines
B over conductor = 4T

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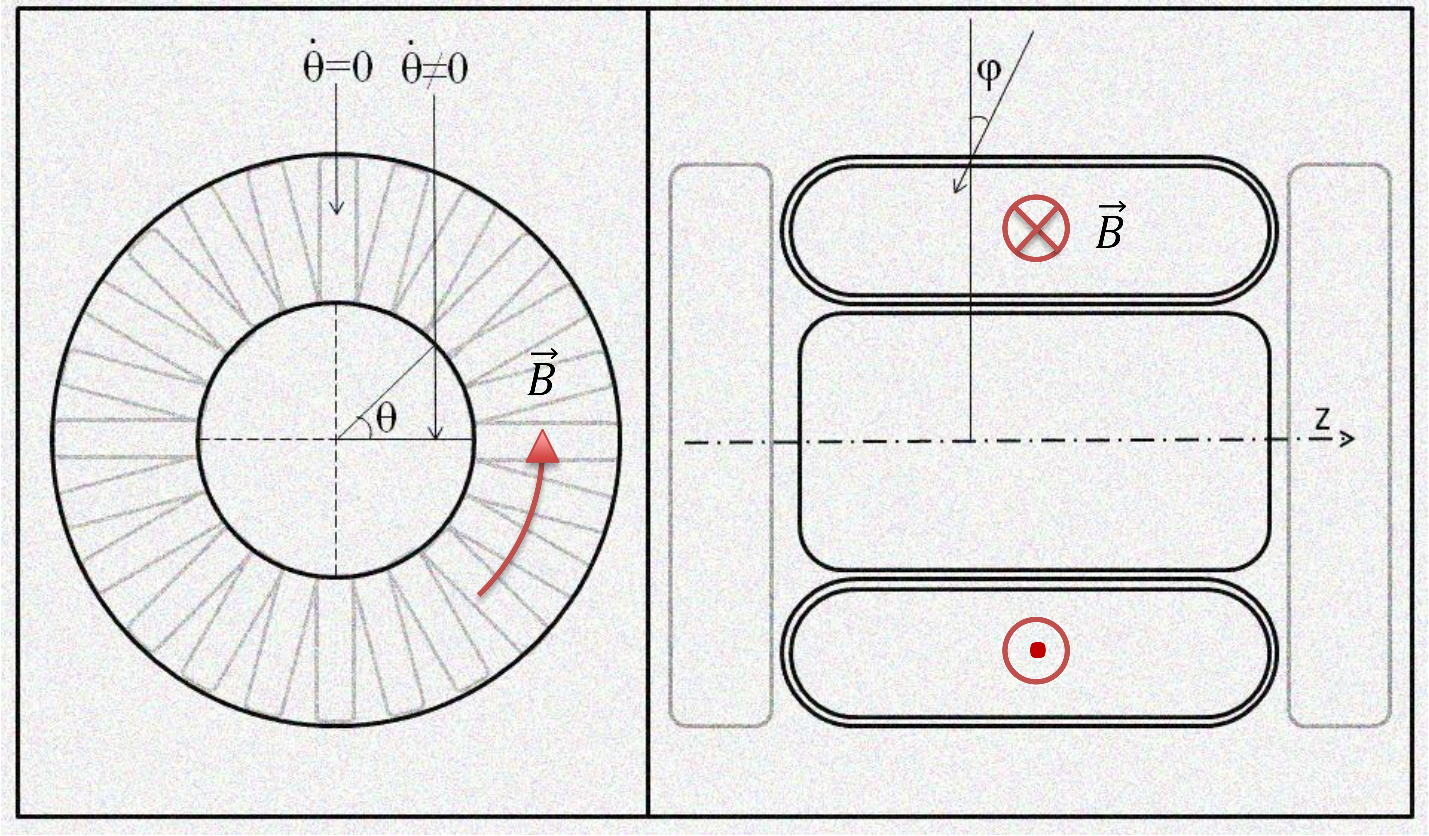
Maximum and Uniform Protection

«Whatever trajectory you consider, $\vec{B}$ is always perpendicular to it»



The Shielding Power

Bending Power

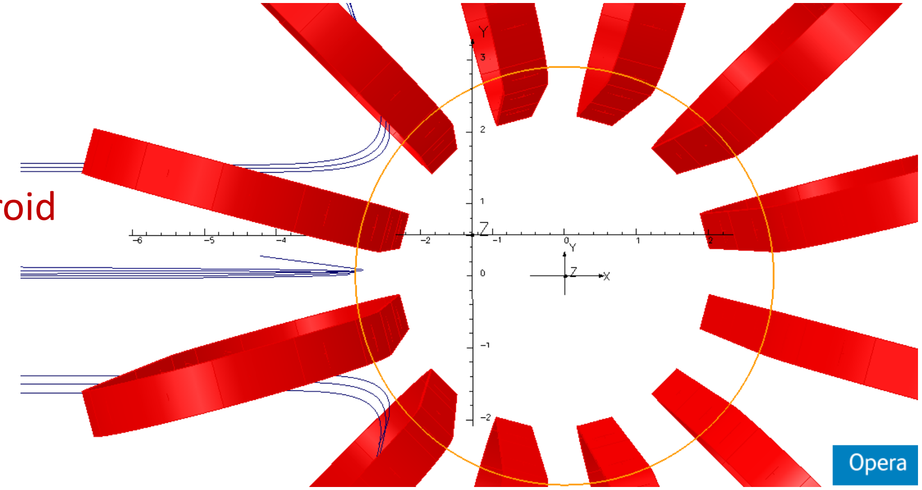
$$\xi = \int_0^L B_\perp dl = BL\ (B = cost)$$

Maximum Bending Power for an ideal toroid

$$\xi = \int_{r_i}^{r_e} B dr = \frac{\mu_0 n i}{2\pi} \ln \frac{r_e}{r_i}$$

if $r_i = r_m$ (maximum penetration radius),

ξ is related to the physical properties of the incident particle



Orange r_m analytic solution
blue proton tracks

Bending Power ⟶ Shielding Power

$$\xi = \frac{\mu_0 n i}{2\pi} \ln \frac{r_e}{r_m} = \Xi = \frac{m_0}{q} c\sqrt{\gamma^2 - 1}\,(1 - \sin\varphi)$$

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The Shielding Power

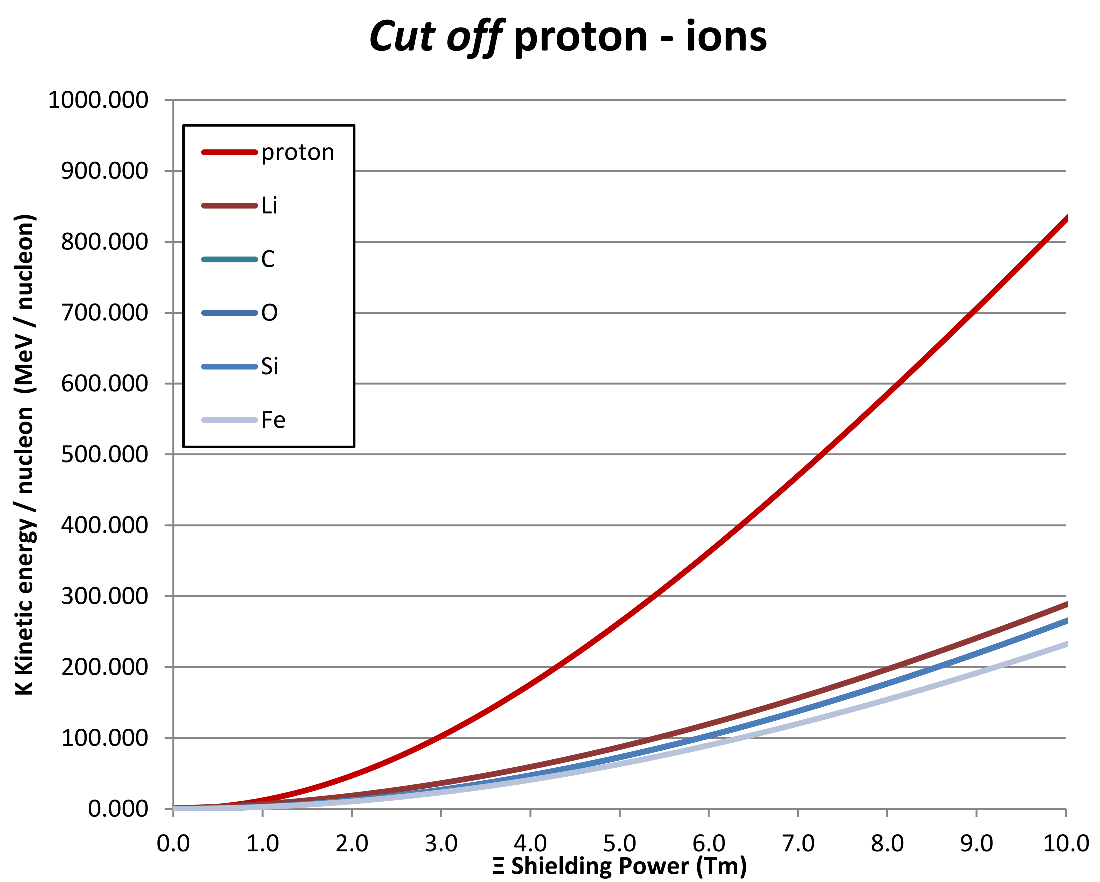
Active Shields

- High efficiency for protons
- Low efficiency for ions

But... They are made of materials

⇩

Act as Passive Shields



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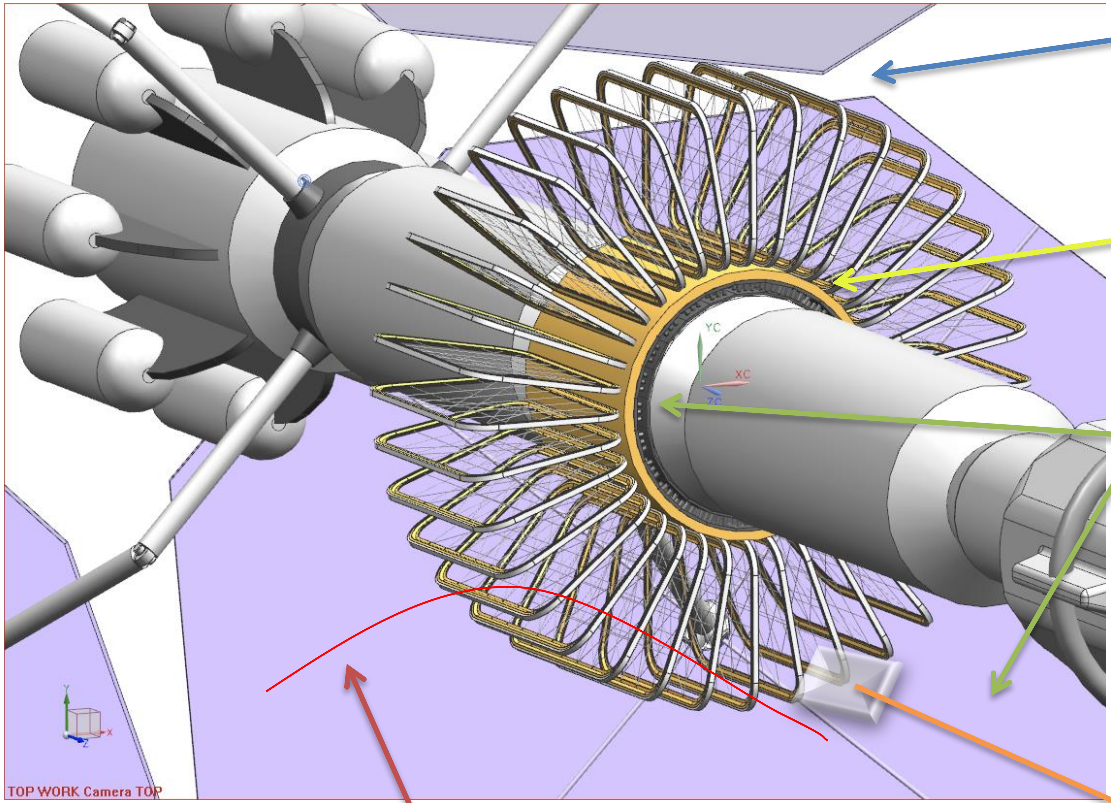
SR2S Toroids Design



Preliminary design of the magnet
- Dimensions / weight / materials
- No magnetic field inside the habitat
- Reliability of the Active Shield

Mechanics
- containing compressing forces/displacements
- protect the habitat

Cryogenics and thermal interfaces
- Decoupling the magnet from the habitat / heat sources (sun, planets)
- Cool down the magnet

Superconductive cable
- Testing and Validating Ti clad MgB2 cable
- How to protect the magnet from quenches

Dose reduction:
- Optimize secondary particles production with materials
- Reduce primary and secondary particle flux & dose with the magnetic field

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The Cable and the Magnet Design

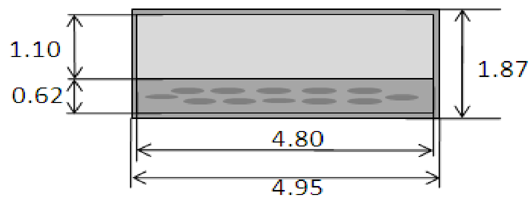
The lighest superconductor

$\rho = 3000\ kg/m^3$

Ideal

Ti clad MgB_2 with Al Strips

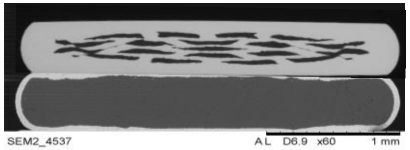
Ti/MgB_2 ratio 2.7/1

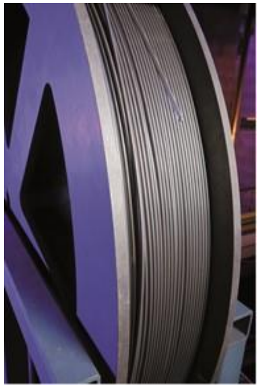


Real

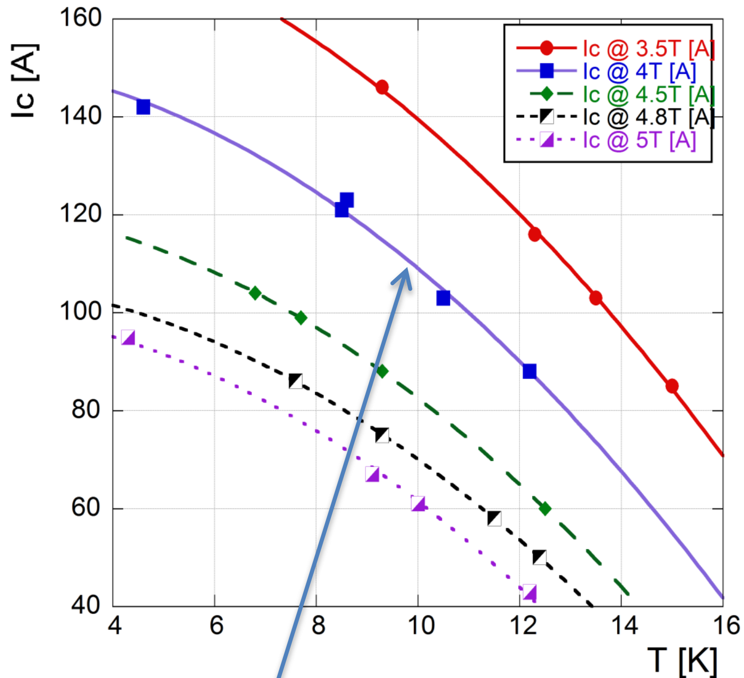
(for now but known how to solve it)

Ti clad MgB2 with Cu Strips





380 m prototype



Choose for the magnet design

Assuming the nowadays I_C as 80% I_e

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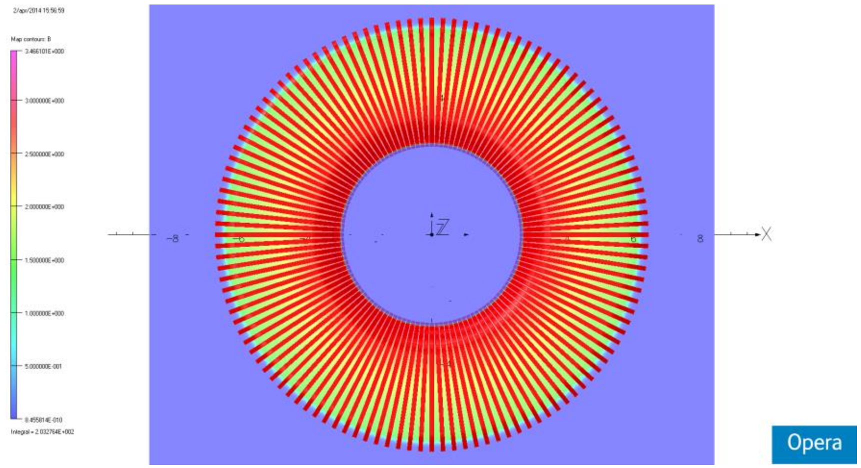
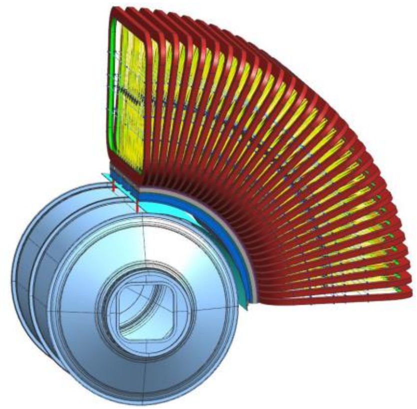
Main Characteristics

MAGNET MAIN PARAMETERS	
Current Density	70 A/mm^2
# of turns	55
# of layers	10
# of racetracks	120
Bending Power	7.51 Tm
Bmax over conductor	3.7 T
Stored Energy	953 MJ
Inductance	3890 H
SC Mass	36.7 tons
E/M ratio	**26 KJ/Kg**
Inward force per racetrack	**4.2 MN**
Mechanical Structure	91.0 tons

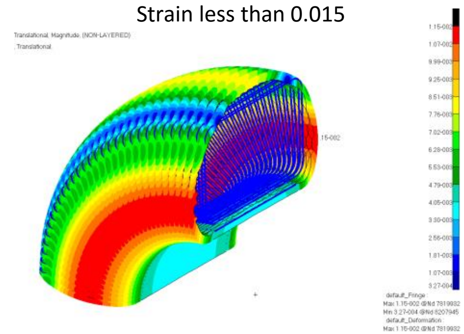


Magnetic field map

5.5 m long toroid



Coil former deformation
Strain less than 0.015



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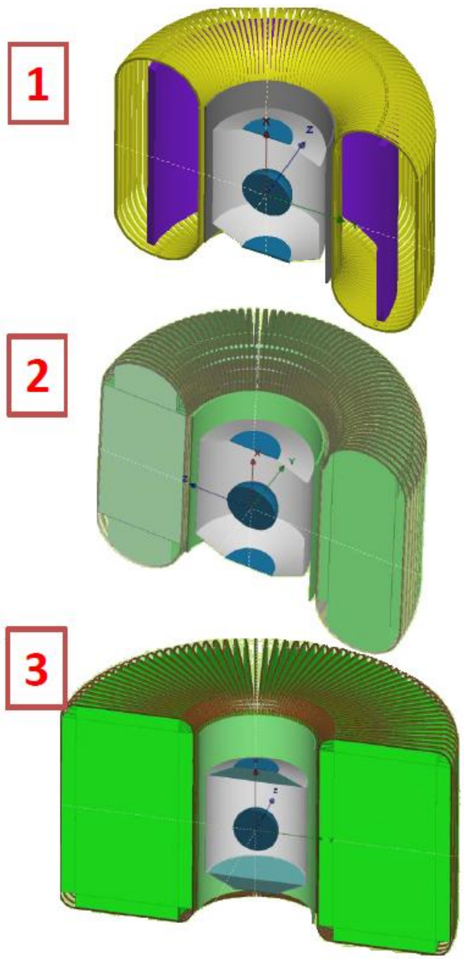
SR2S Toroids Design



Configuration A
- 10 m
- Main material: Titanium
- **Mass = 300 tons**
- BL = 7.9 Tm

Configuration B1
- 10 m
- Main material: Kevlar
- **Mass = 100 tons**
- BL = 7.9 Tm

Configuration B2
- 10 m
- Main material: Kevlar
- **Mass = 100 tons**
- BL = 11.9 Tm

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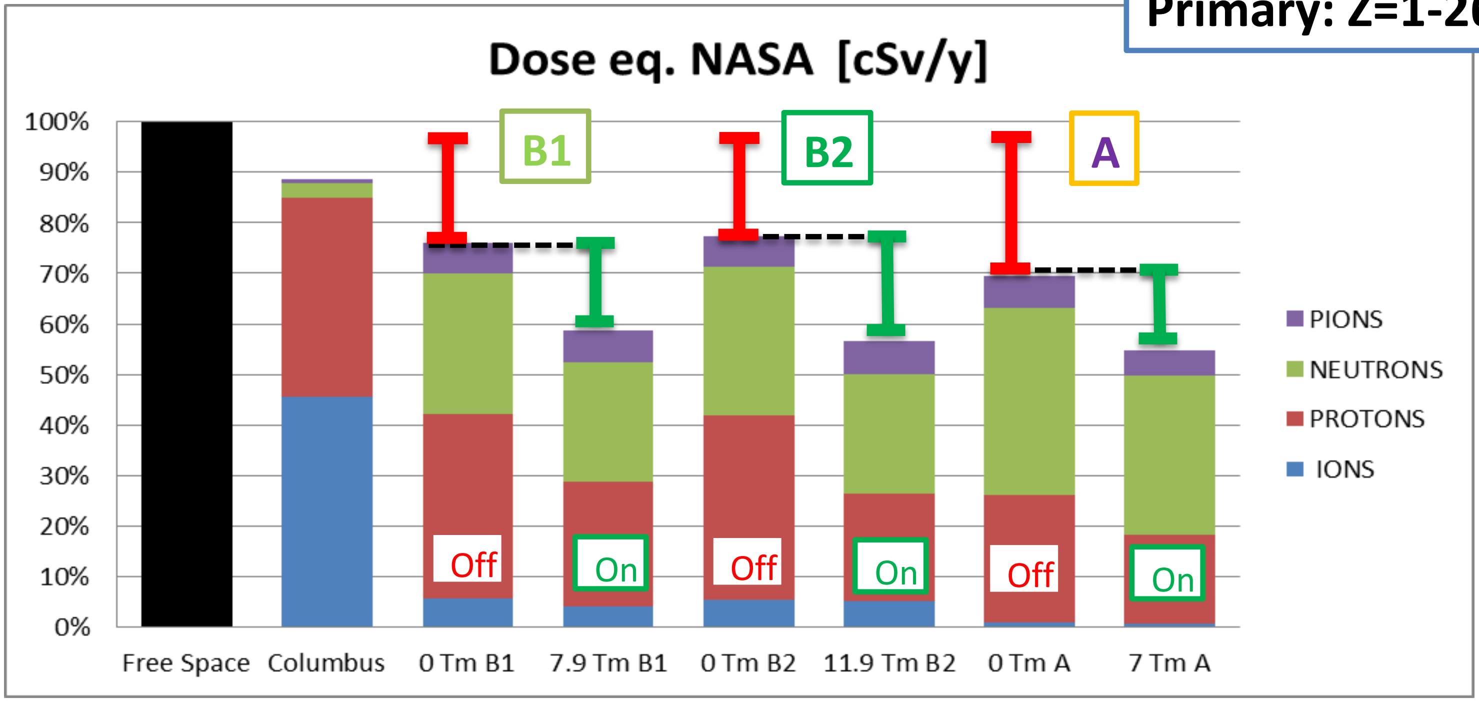
Dose Reduction Results

Primary: Z=1-26



What to say

- HZE stopped (as forecast) by uniformity of materials
- Secondary particle productions: neutrons are privileged over protons (new result) $\Longrightarrow$ **Toroids efficiency estremely reduced**

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Towards the Pumpkin Configuration

Evidences from the toroidal configuration:

Uniform Protection

- Confined magnetic field
- Materials distributed (almost) homogeneously
  around the Habitat

Maximum Protection

- Most effective field to deflect charged particles
- Heavy loads towards the axis of the spacecraft

Conflict between the two requirements

⇩

Massive secondary particles production

The Active Shield cannot be used as Passive Shield

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Towards the Pumpkin Configuration

Solution

Abandon the Uniform Protection

- **Unconfined field** -> play with geometry and reduce the necessary angle of deflection
- **Asymmetric distribution of materials** -> reduce the cross-section for the secondary particles production

Keep the Maximum Protection

- **Keep the magnetic field as most toroidal** as possible -> maximize its efficiency
- **Minimize the loads** towards the axis of the spacecraft -> reduce the mechanical structure

Physics Oximorons

Is it possible to create an unconfined «toroidal» field?

And minimize the loads with asymmetric distribution of materials?

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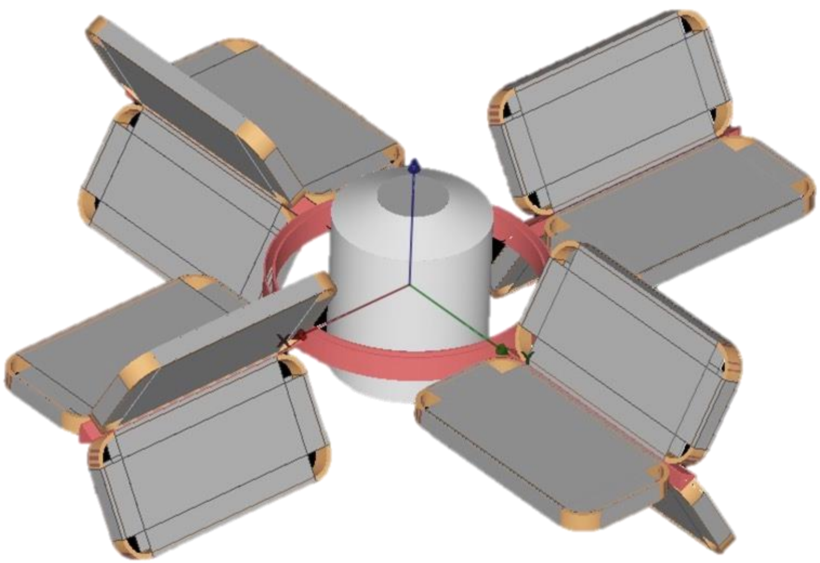
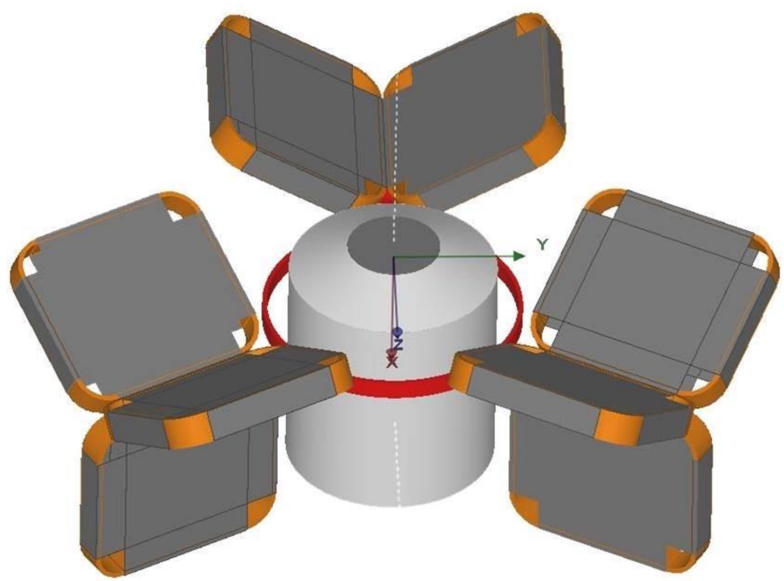
The Pumpkin Configuration

MT4



MT3



- **The Pumpkin Configuration**

The Pumpkin Configuration

Maximum Protection

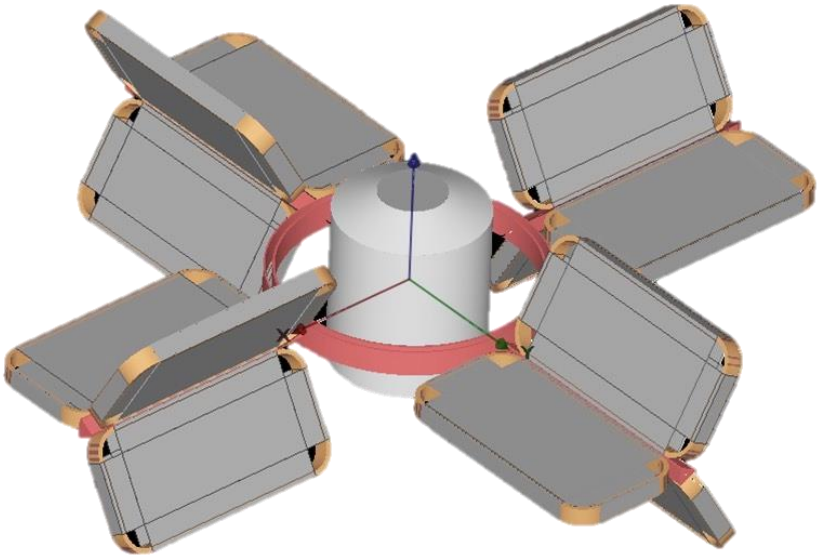
Toroidal magnets perpendicular to the axis of the module

Unconfined simil-Toroidal Field

Maximize the fringe field (3 racetracks maximum)

Restore (a little) the Uniform Protection

Chain the fringe field on toroids



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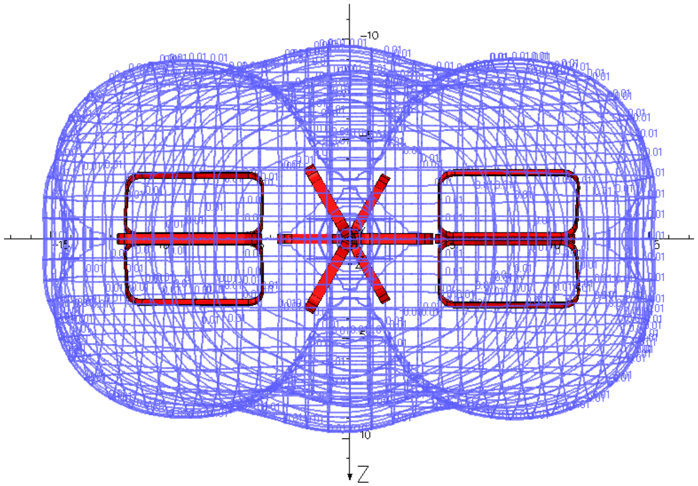
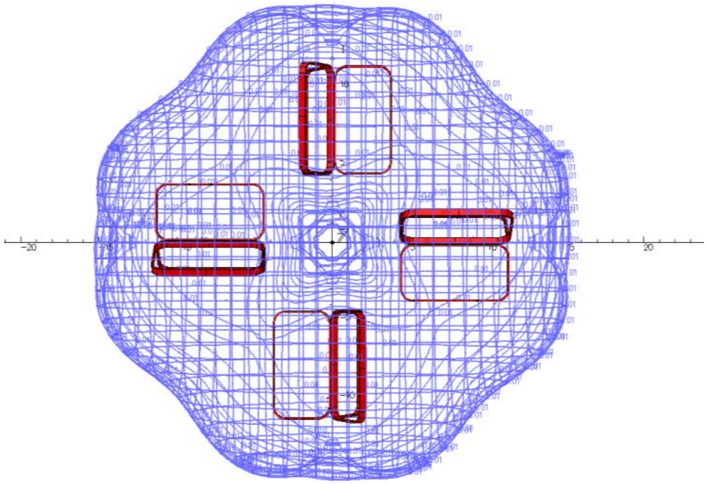
Magnetic Field





- Unconfined field outside the spacecraft

  AND

- No field inside the habitat and on the axis of the spacecraft

- Number of pumpkin lobes depending from the number of toroids

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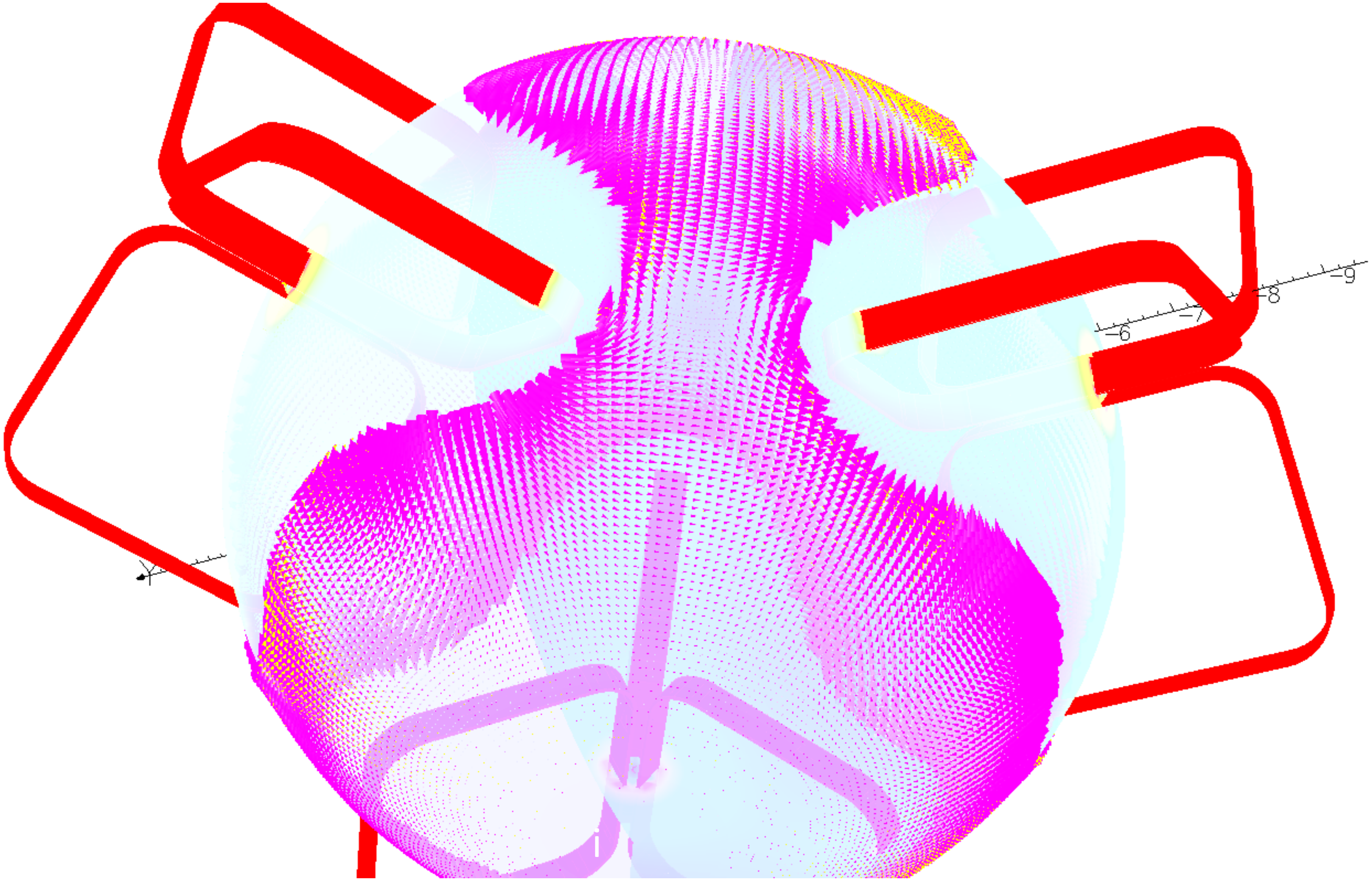
Chain of the Fringe Field



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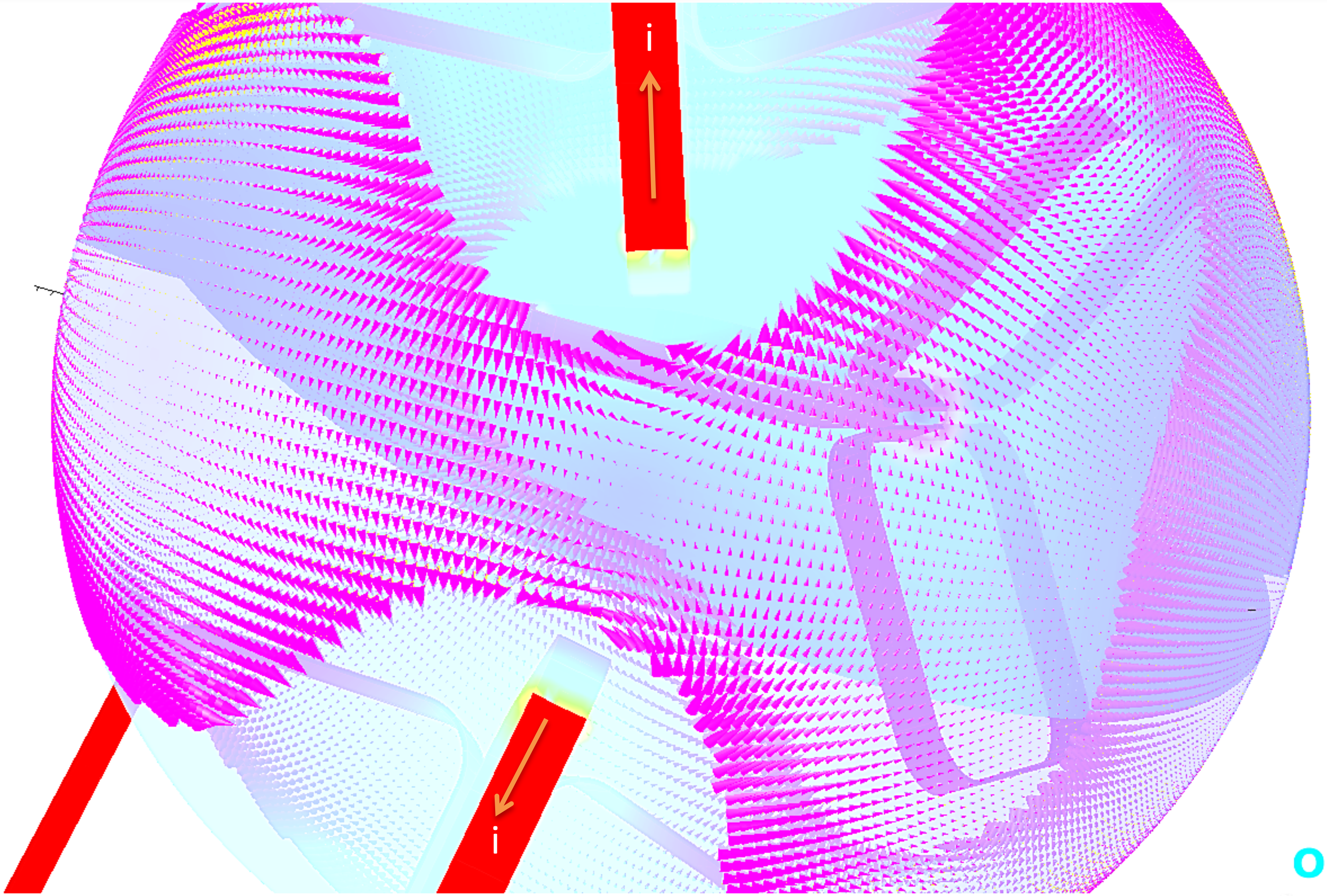
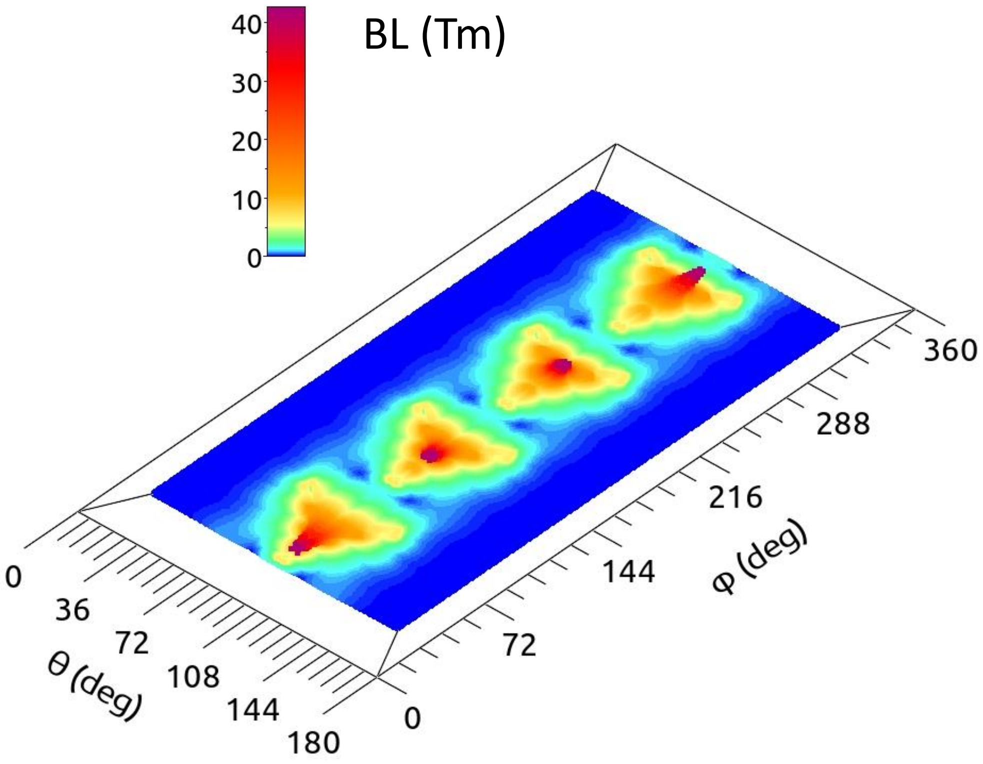
Chain of the Fringe Field



Magnetic Field Effects

- **Non-homogeneous bending power.**
- **Very high bending power (till 40 Tm) under certain angles -> possibility to have very well shielded areas in the habitat.**
- **Important geometrical effects for particles deflection (higher bending arm)->reduce the overall mass and increase the efficiency.**



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Magnetic Field Effects

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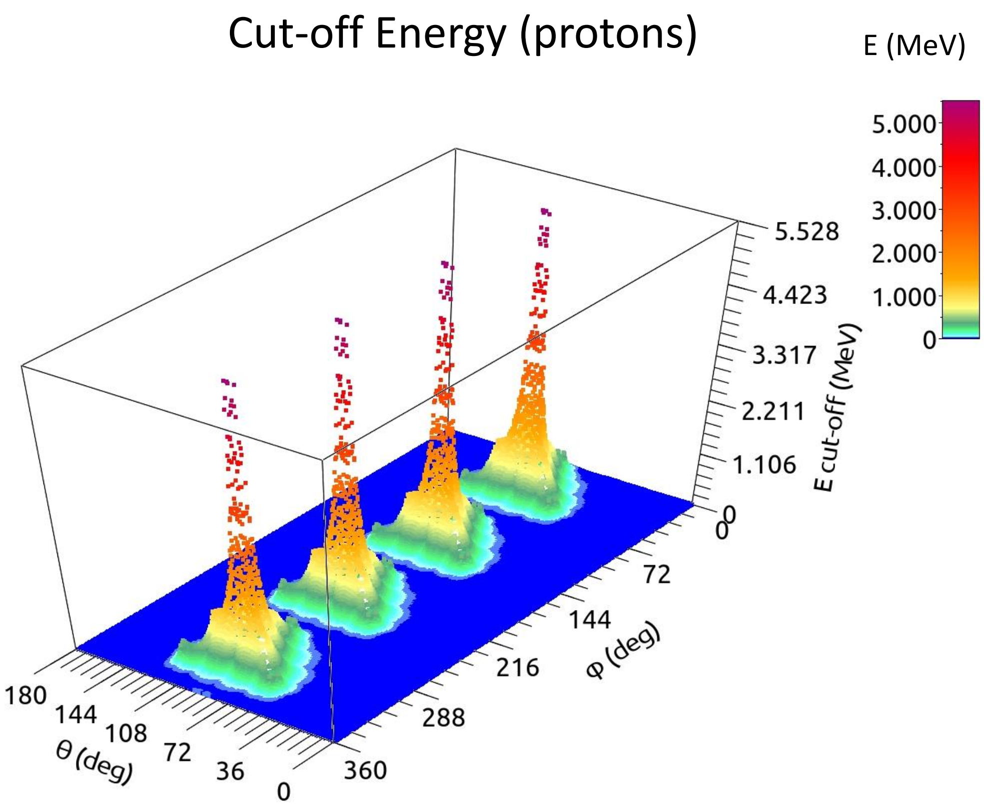
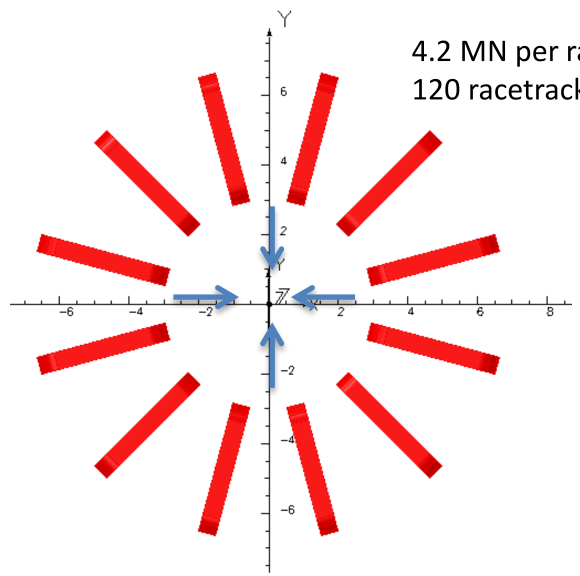
- **Very high bending power (till 40 Tm) under certain angles -> possibility to have very well shielded areas in the habitat.**
- **Important geometrical effects for particles deflection (higher bending arm)->reduce the overall mass and increase the efficiency.**

A lot of possibilities for future optimizations



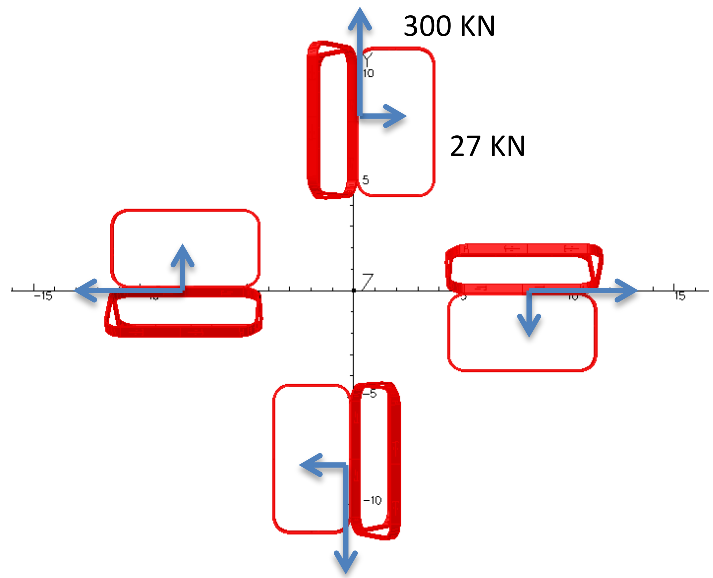
Design Parameters

Axial Toroidal Configuration



$$\frac{superconductor}{mechanical\ structure} mass < 1$$

Pumpkin Configuration



$$\frac{superconductor}{mechanical\ structure} mass > 1$$

Optimization of the mechanical structure and potential mass reduction

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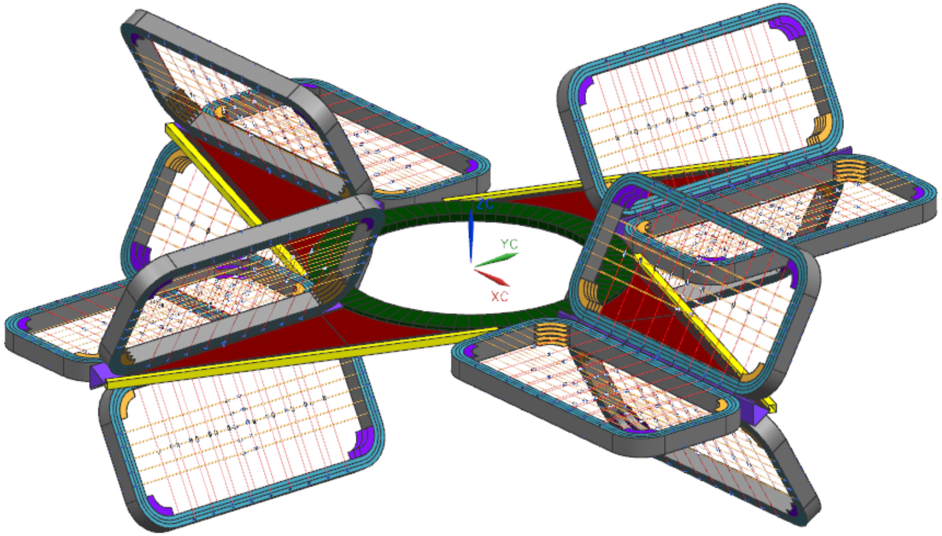
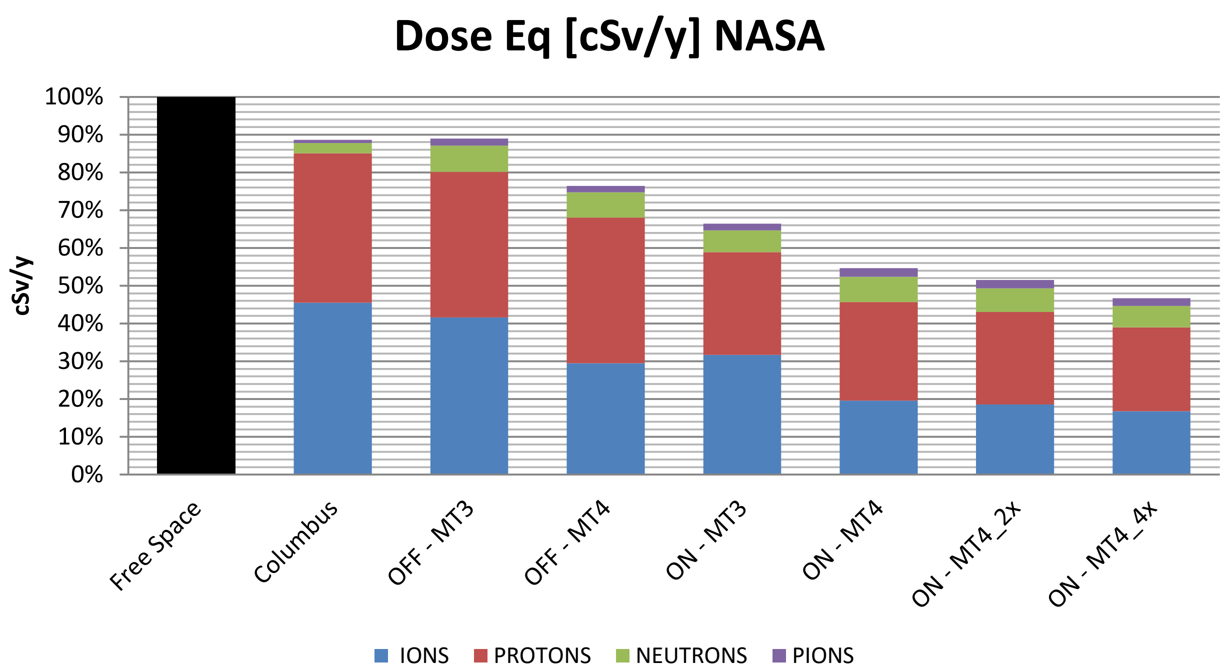
Design Parameters

MT4 Masses	
Superconductor	31 tons
Coil formers	17.6 tons
Tie rods	1.6 tons
Supporting bars	1.6 tons
Connecting mechanical structure	2.1 tons
TOTAL	**53.8 tons**



Dose Reduction Results



What to say

- **Non uniform protection** ⟹ **inhibition of neutron production**
  BUT
  Angle solid problem (MT4x2, MT4x4)

- With 1/6 of the mass, same results on toroidal configuration A

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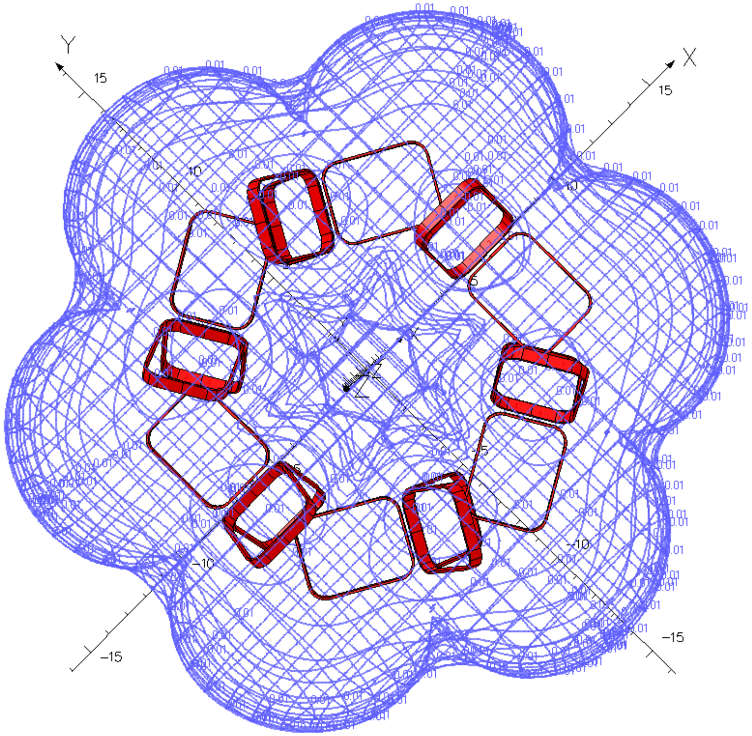
Look at the Future

The Pumpkin Configuration is NOT the definitive answer to the active shield

But it is on the right way.

Still many mechanisms to understand

- Maximization of the fringe field chain
- **Geometric effects**
  - how the distance from the habitat change
    the shielding power?
  - What about the different dose in certain areas of the habitat?
- **What is the upper limit?**



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THE PUMPKIN CONFIGURATION
Questions Time