Space Radiation Superconductive Shield: a new approach

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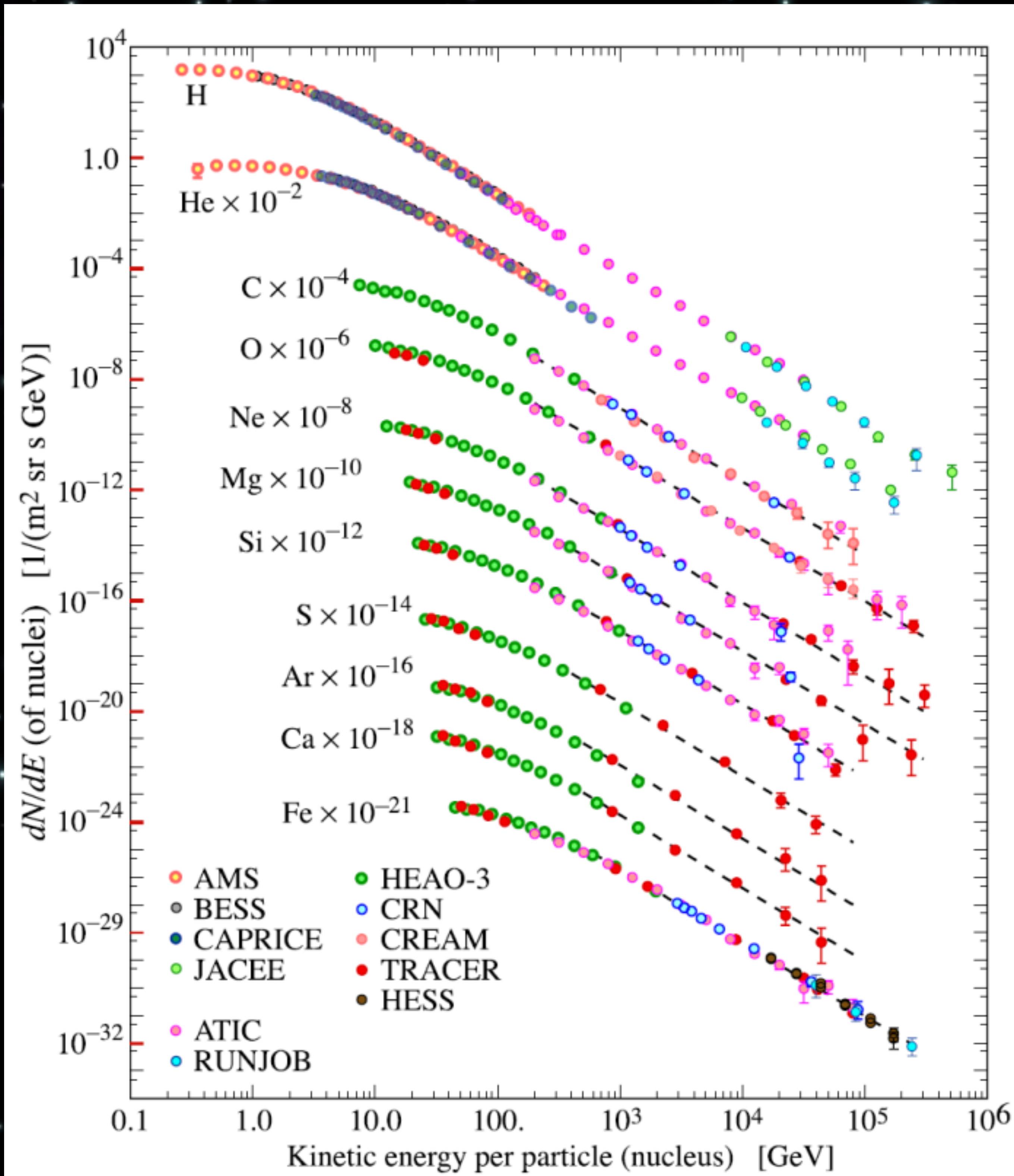
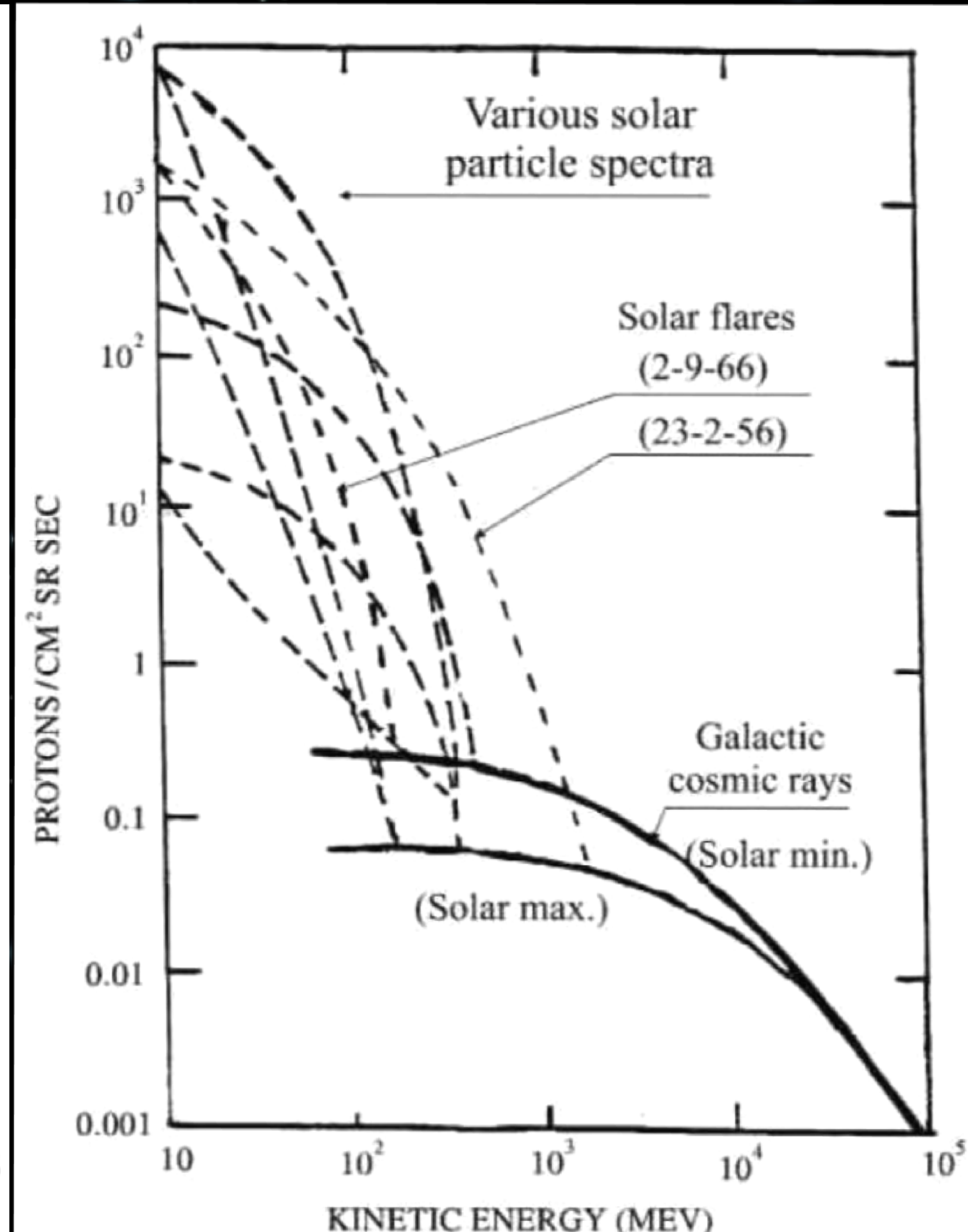
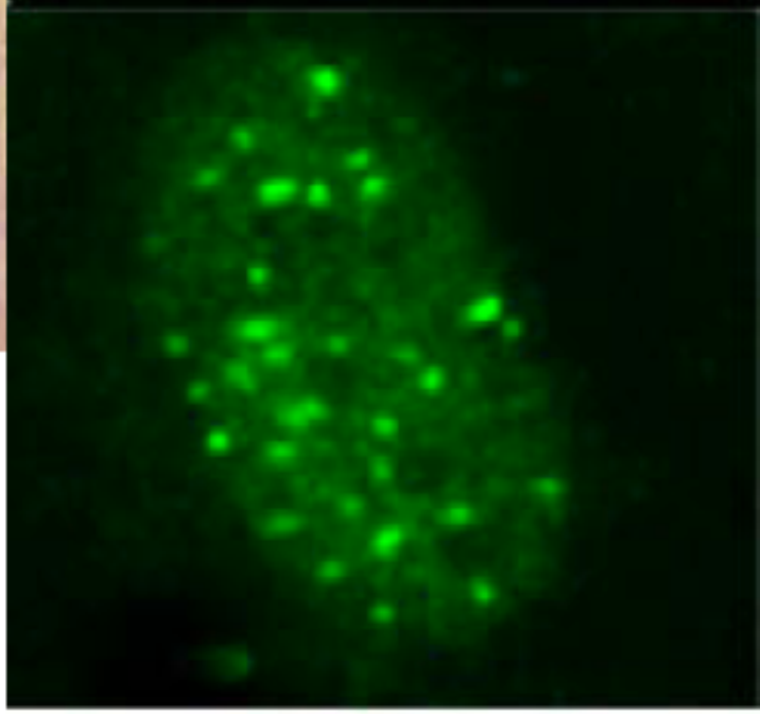
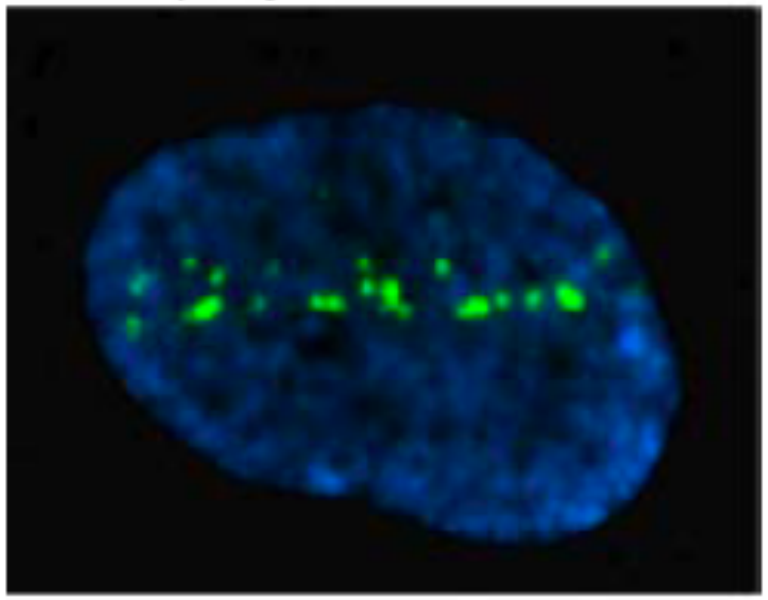

H
He × 10−2
C × 10−4
O × 10−6
Ne × 10−8
Mg × 10−10
Si × 10−12
S × 10−14
Ar × 10−16
Ca × 10−18
Fe × 10−21
AMS
BESS
CAPRICE
JACEE
ATIC
RUNJOB
HEAO-3
CRN
CREAM
TRACER
HESS
dN/dE (of nuclei) [1/(m2 sr s GeV)]
Kinetic energy per particle (nucleus) [GeV]


Various solar particle spectra
Solar flares (2-9-66)
(23-2-56)
Galactic cosmic rays
(Solar min.)
(Solar max.)
PROTONS/CM2 SR SEC
KINETIC ENERGY (MEV)

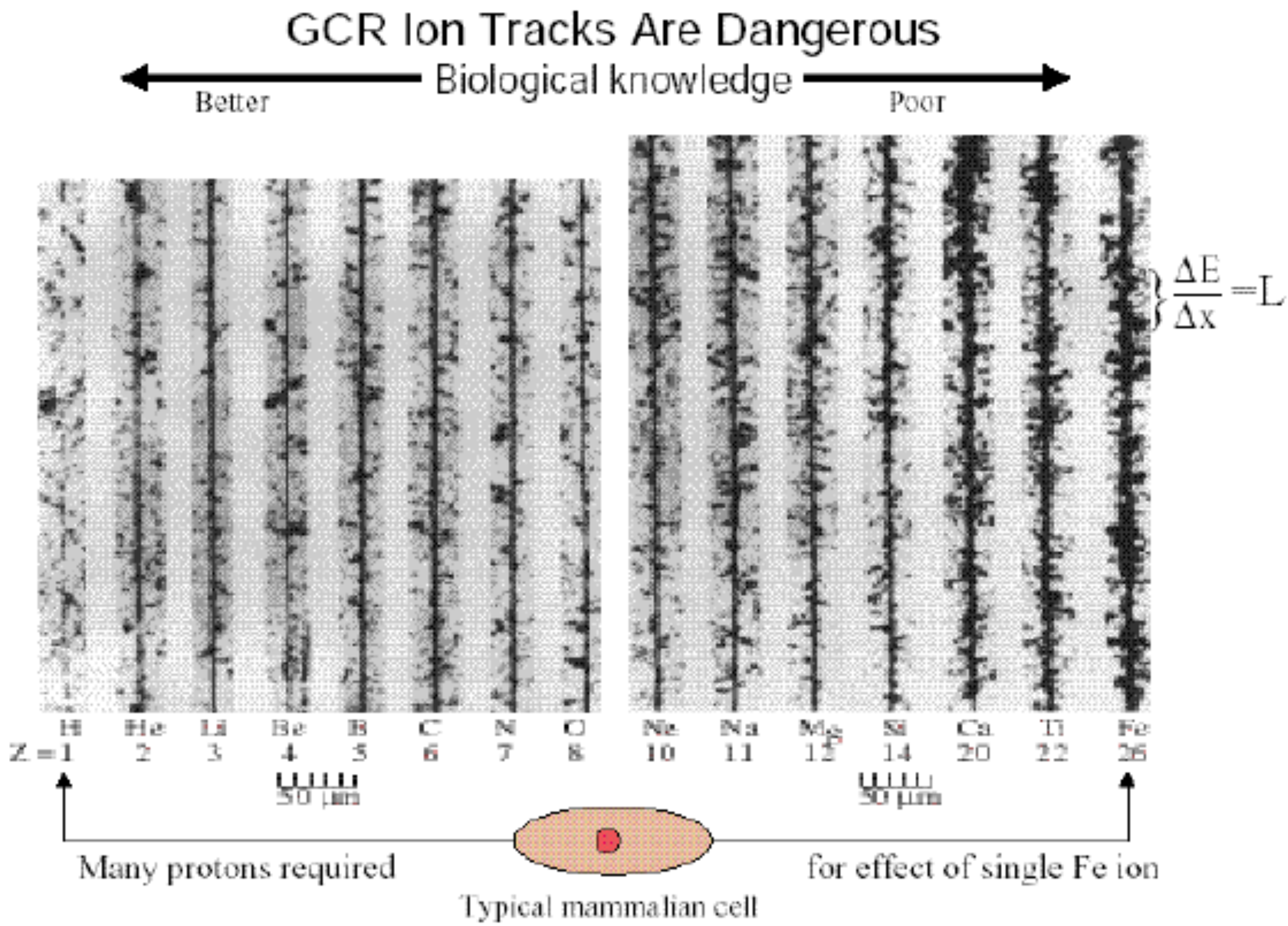
Tracks in cells



γ-rays

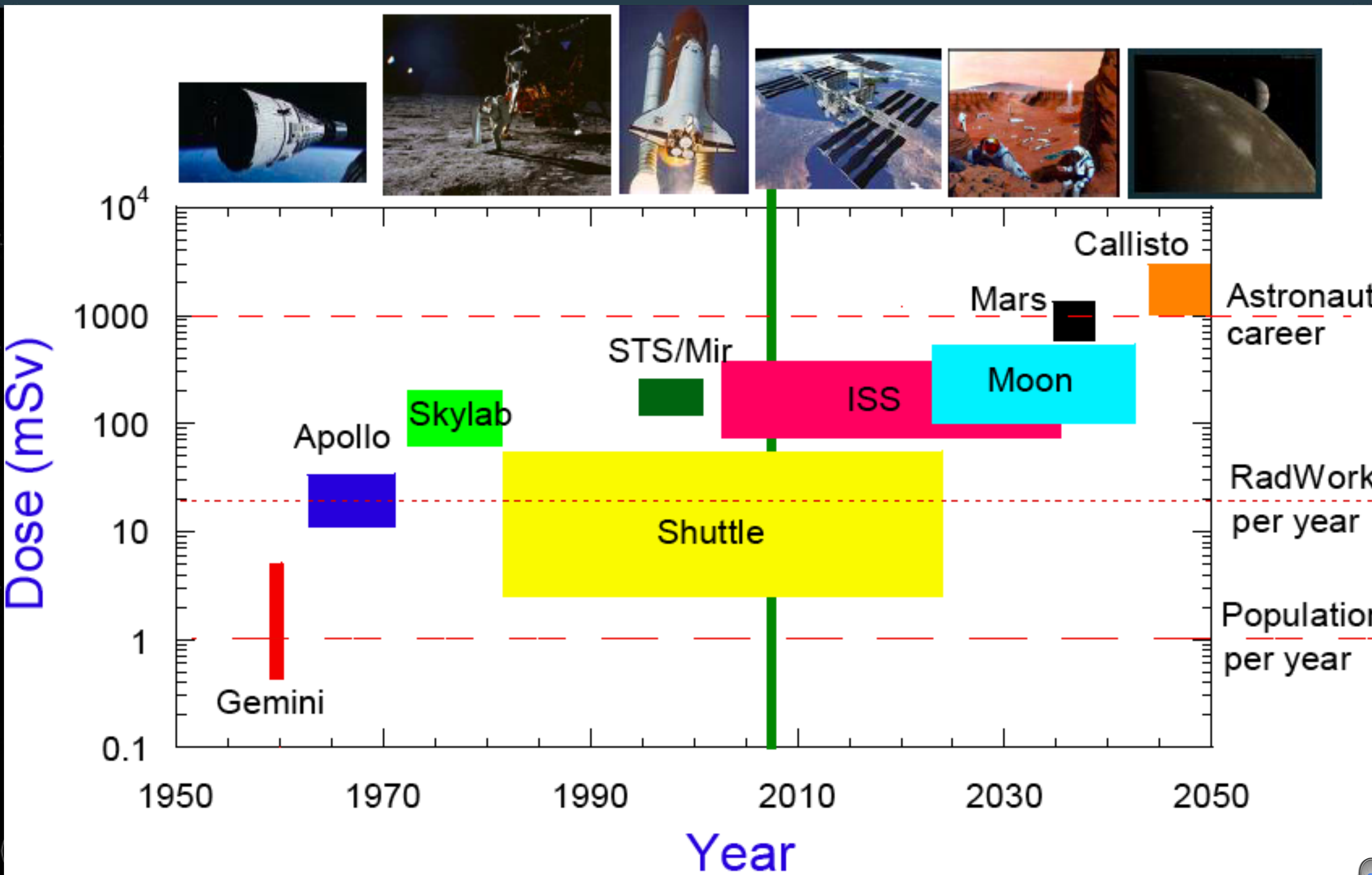


silicon



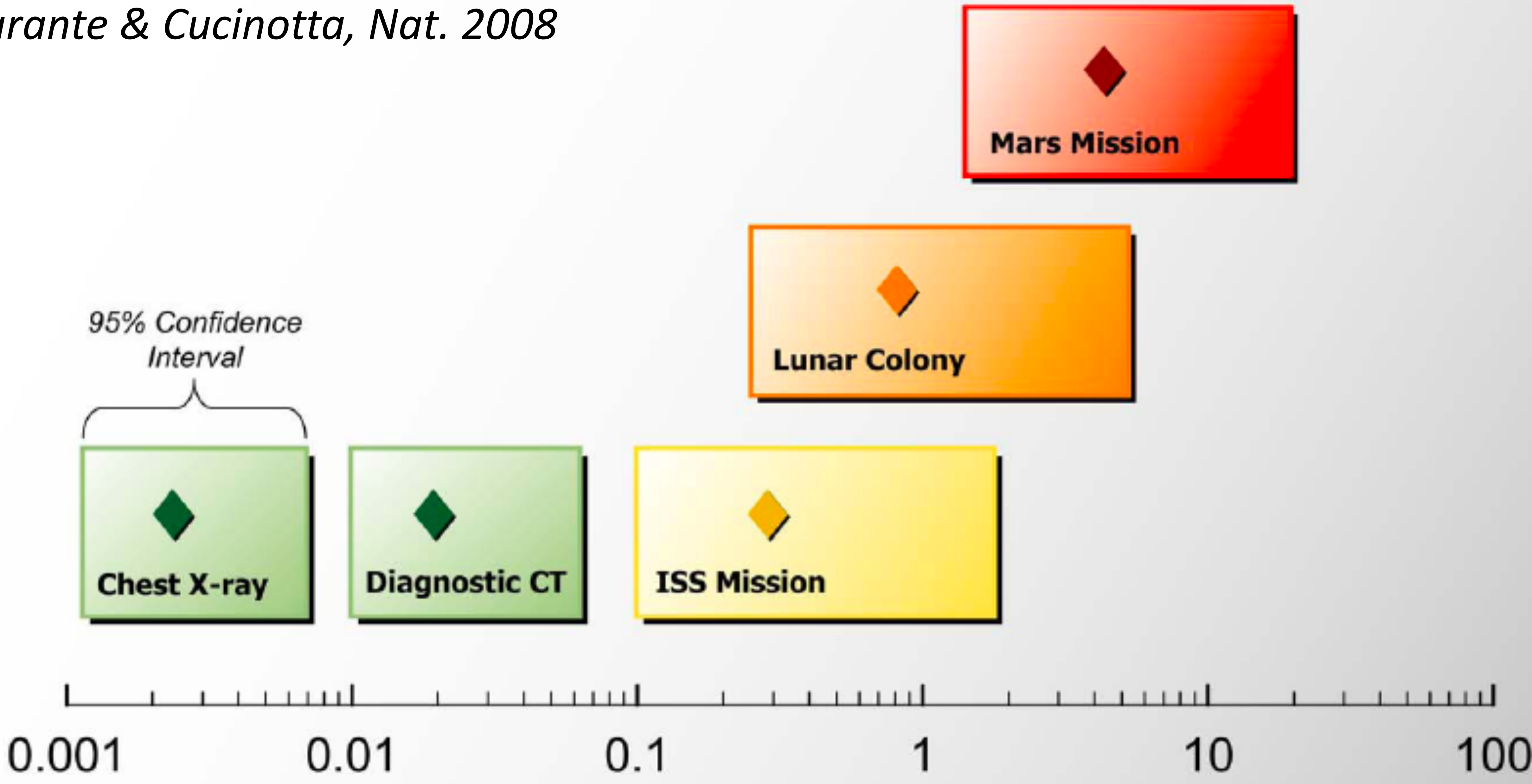
Cucinotta and Durante, *Lancet Oncol.* 2006

Radiation doses in different missions



% of death due to cancer - 95% CL

Durante & Cucinotta, Nat. 2008



SR2S Space Radiation Superconducting Shield

SEVENTH FRAMEWORK PROGRAMME

Doses for exploration missions.....

- FREE SPACE: equivalent doses in excess of ***1.2 Sv /yr*** **(~*120 rem/yr*)**
- SPACECRAFT (thin) SHIELDING: about **700-800 mSv/yr (70-80 rem/yr)**
- *ON THE MARS SURFACE:* between **100 and 200 mSv/yr (10 and 20 rem/yr)**, depending on the location
- ON THE MOON SURFACE : **223 mSv/yr** (**22,3 rem/yr)** with oscillations of ± **10 rem/yr** as a function of solar activity
  - *for comparison: ISS about* ***18 rem/yr --> 6 month expeditions***
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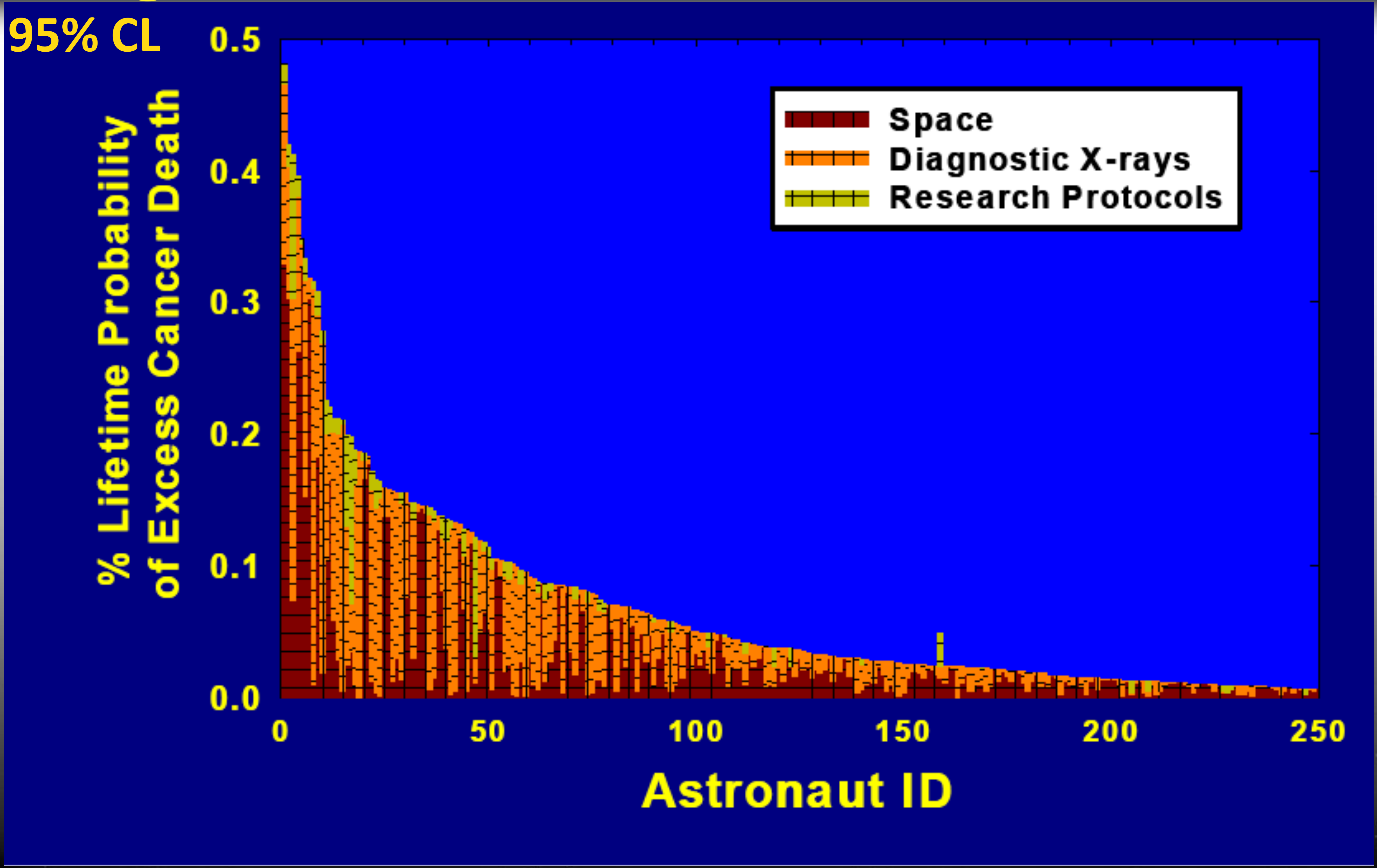
Projection of risk of radiation on biological tissues



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3% REID limit =>increase of P(cancer death)

Table 11: Solar Minimum Safe Days in deep space, which are defined as the maximum number of days with 95% CL [confidence level] to be below the NASA 3%REID limit. Calculations are for average solar minimum with 20 g/cm2 aluminium shielding. Values in parenthesis are the case of the deep solar minimum of 2009.

a_E, y	NASA 2005	NASA 2012 U.S. Avg. Population	NASA 2012 Never-smokers
Males			
35	158	209	271
45	207	232	308
55	302	274	351
Females			
35	129	106	187
45	173	139	227
55	259	161	277

Table 12: Solar Maximum Safe Days in deep space, which are defined as the maximum number of days with 95% CL to be below the NASA 3%REID limit. Calculations are for average solar maximum assuming large August 1972 SPE with 20 g/cm2 aluminium shielding. Values in parenthesis are the case without SPE that also represents the case of an ideal storm shelter that reduce SPE doses to a negligible amount

a_E, y	NASA 2012 U.S. Avg. Population	NASA 2012 Never-smokers
Males		
35	306	395
45	344	456
55	367	500
Females		
35	144	279
45	187	319
55	227	383

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Mars Mission 1000 days in space =>increase of P(cancer death)

Table 19: 1st approximation DRF

Environment	Number of safe days in space	DRF
Solar minimum with SPE	227	4.41
Solar minimum when SPE is negligible	212	4.72
Solar maximum with SPE	319	3.13
Solar maximum when SPE is negligible	394	**2.54**

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SR2S mission scenarios

Table 20: Possible mission scenarios for SR2S

Mission	Total Mission Duration	Outbound	Stay	Return	Total Days in Deep-Space
Lagrange's Points [LEM2]	200	-	-	-	200
NEA	410	~170	30	~210	~380
MARS TITO mission	501	228	-	273	501
MARS Short Stay	545	224	30	291	515
MARS Long Stay (minimum energy)	919	224	458	237	461
MARS Long Stay (fast transit)	879	150	619	110	260

Table 21: DRF for possible SR2S mission scenarios

Mission	Total Mission Duration	Total Days in Deep-Space	Solar maximum DRF	Solar minimum DRF
Lagrange's Points [LEM2]	200	200	-	-
NEA	410	~380	~1,19	~1,67
MARS TITO mission	501	501	1,57	2,21

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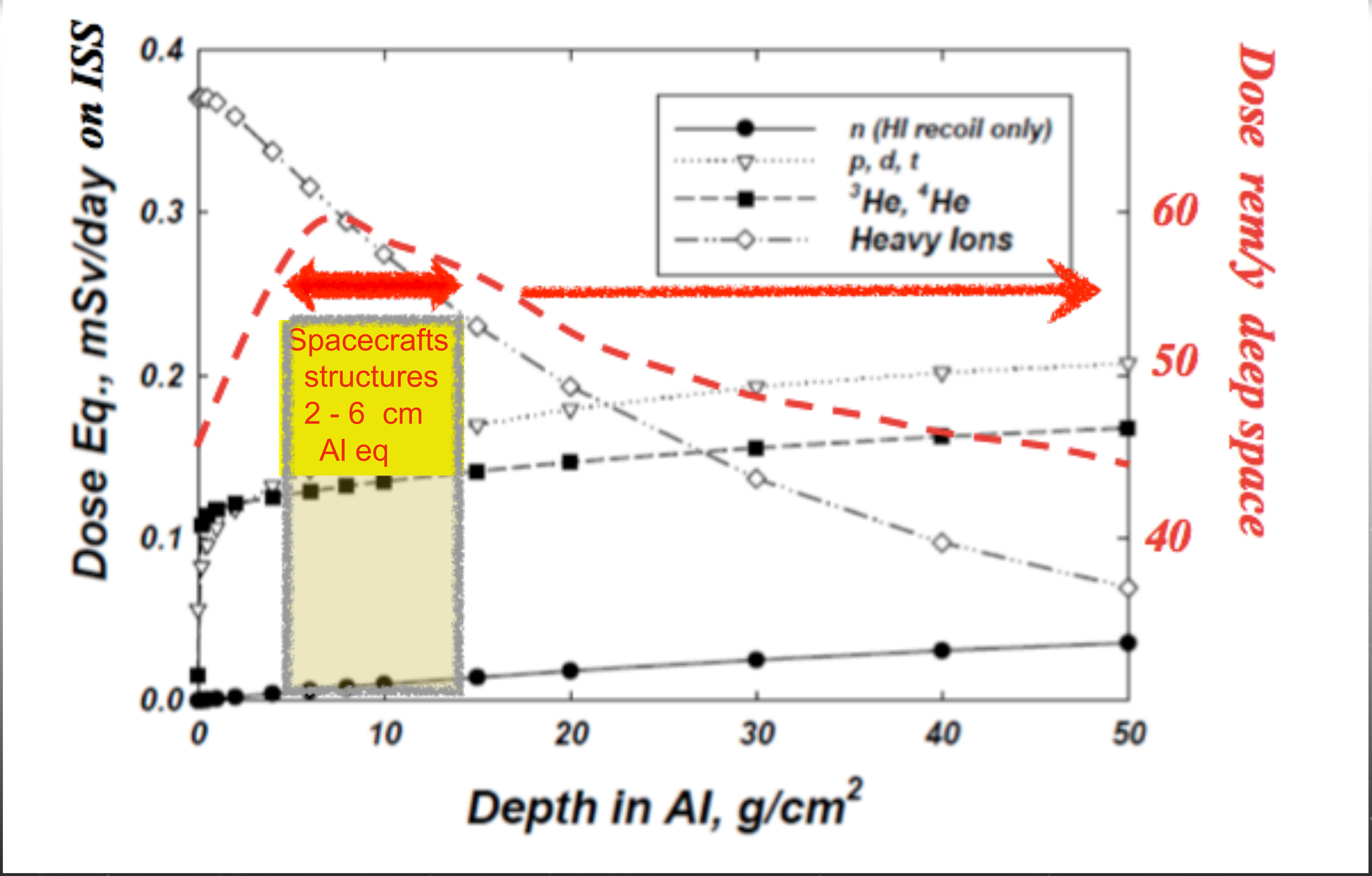
Shield in space if it is "thin" ... .then it "adds" dose



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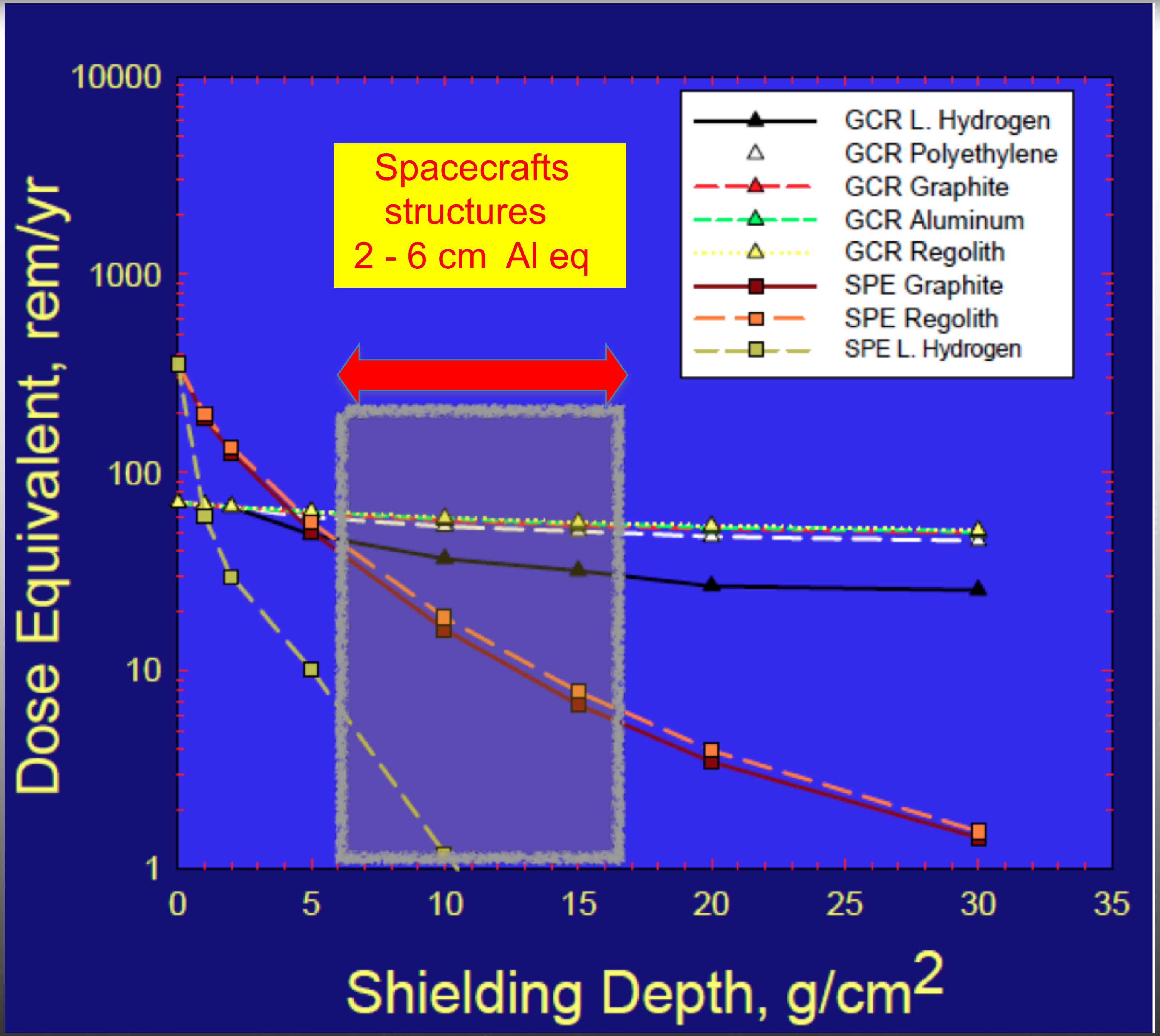
Advanced materials can help SPE not GCR



SR2S Space Radiation Superconducting Shield

SEVENTH FRAMEWORK PROGRAMME

So we turn to active radiation shields

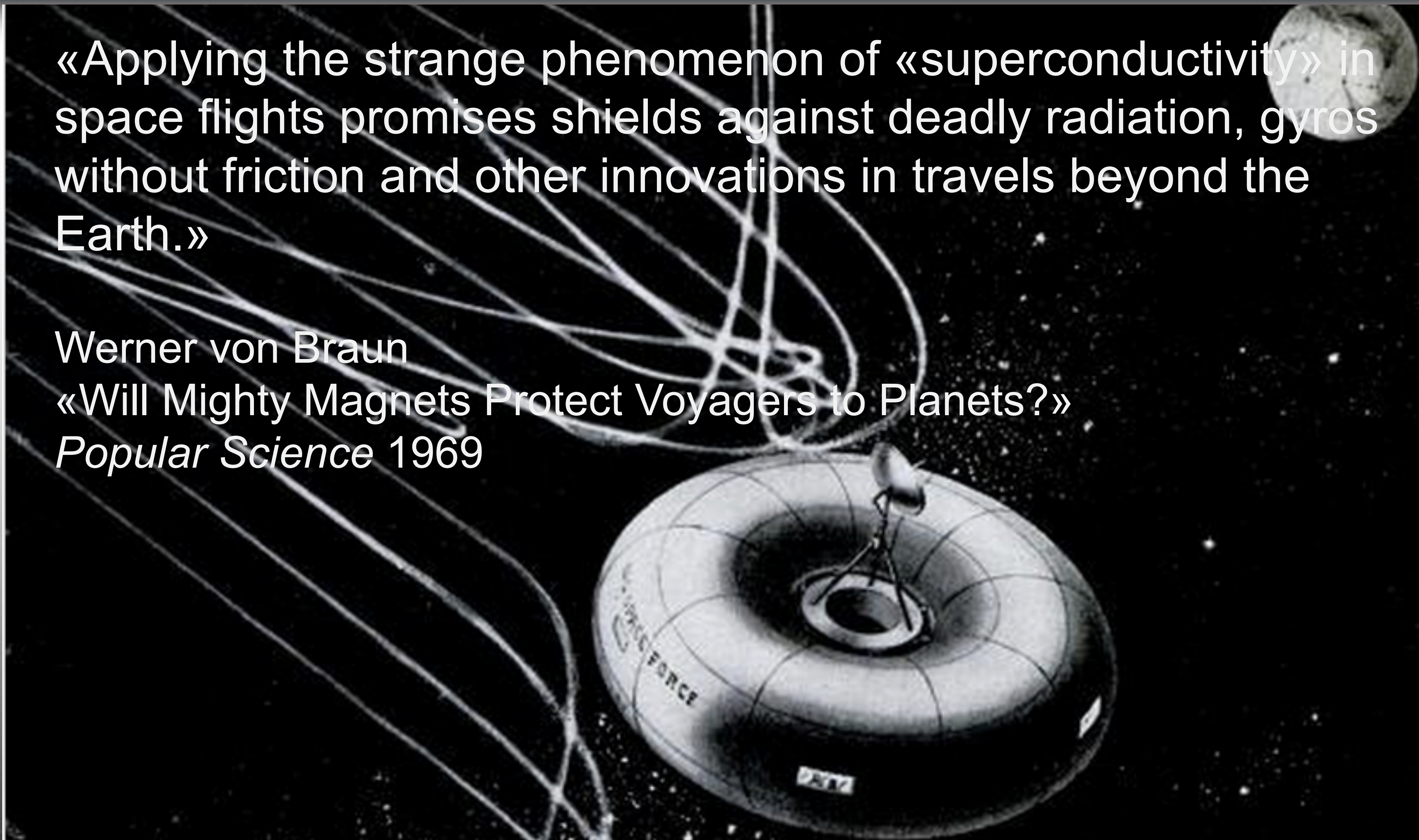
Magnetic shield configurations

- The angular deflection in the magnetic field may be compared to the kinetic energy lost by ionization, where BL replace the electromagnetic and nuclear radiation length to characterizing the shielding performance of the material
- Unconfined Field (e.g. Earth's field), very large volume (L), lower field strength (B)
- **Confined field: small volume (L), higher field (B) and larger mass**

Active magnetic shielding

«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.»

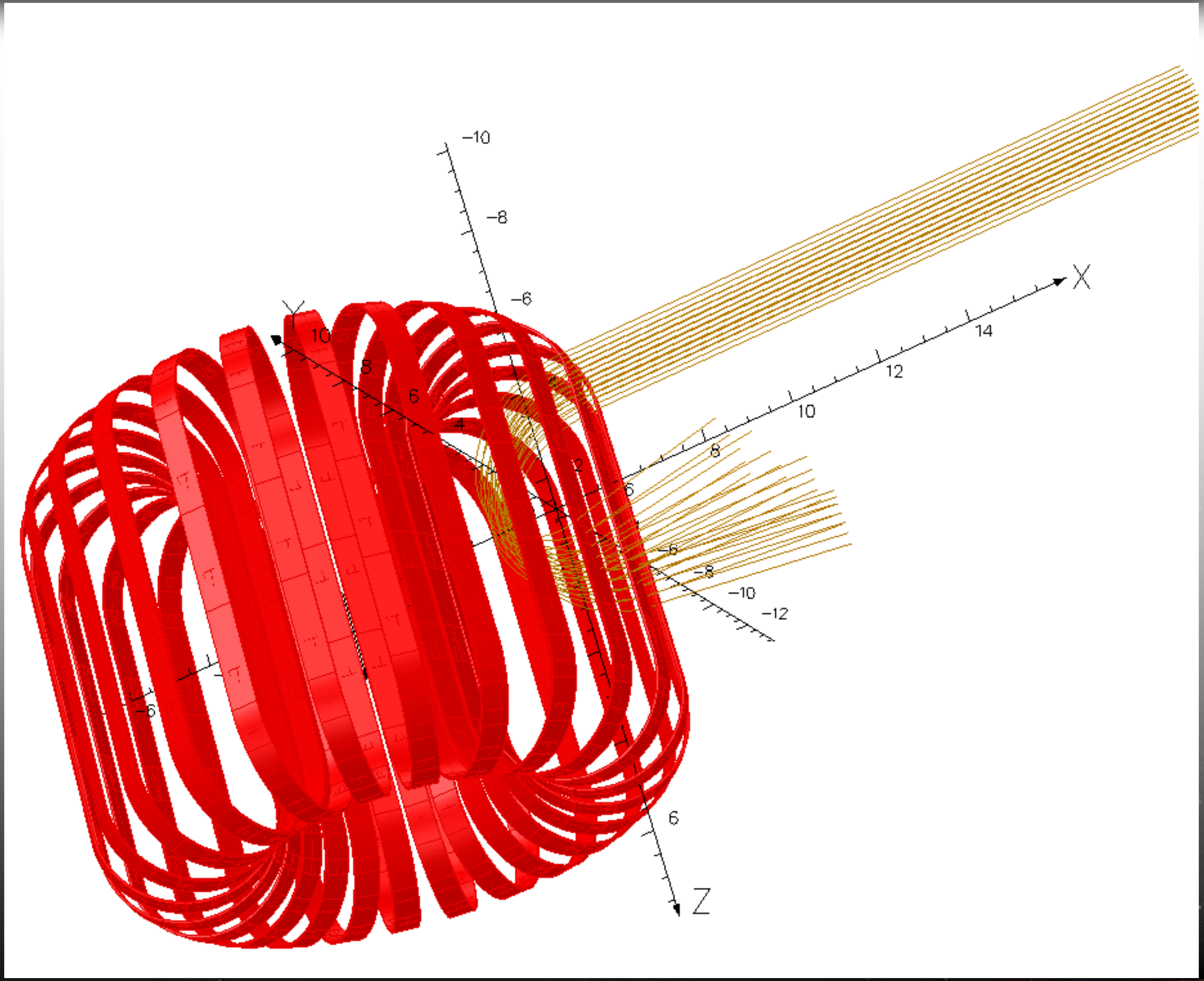
Werner von Braun
«Will Mighty Magnets Protect Voyagers to Planets?»
Popular Science 1969



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

1) TOROIDAL-ORTHOGONAL FIELD

eg. racetracks toroid



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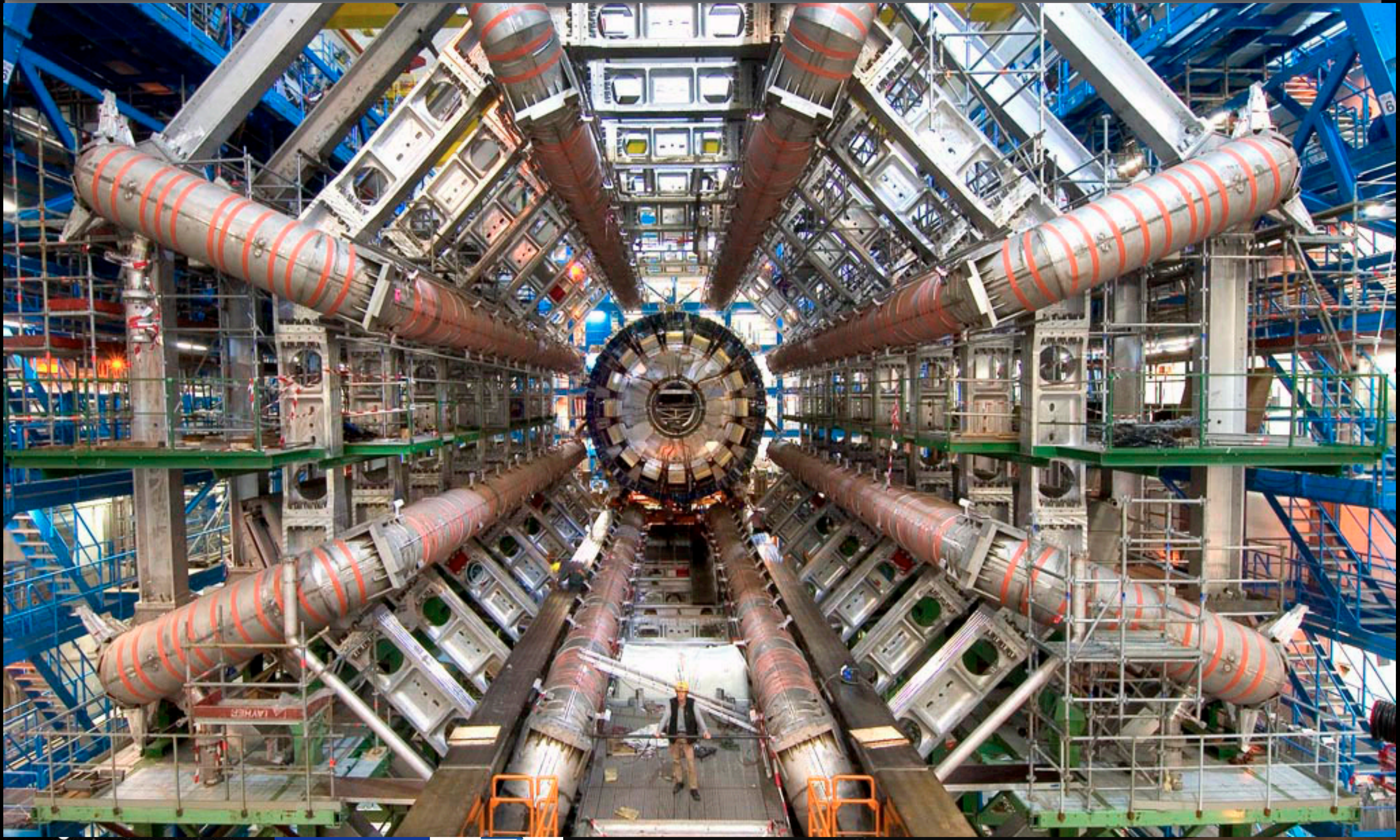
The ATLAS superconducting toroid



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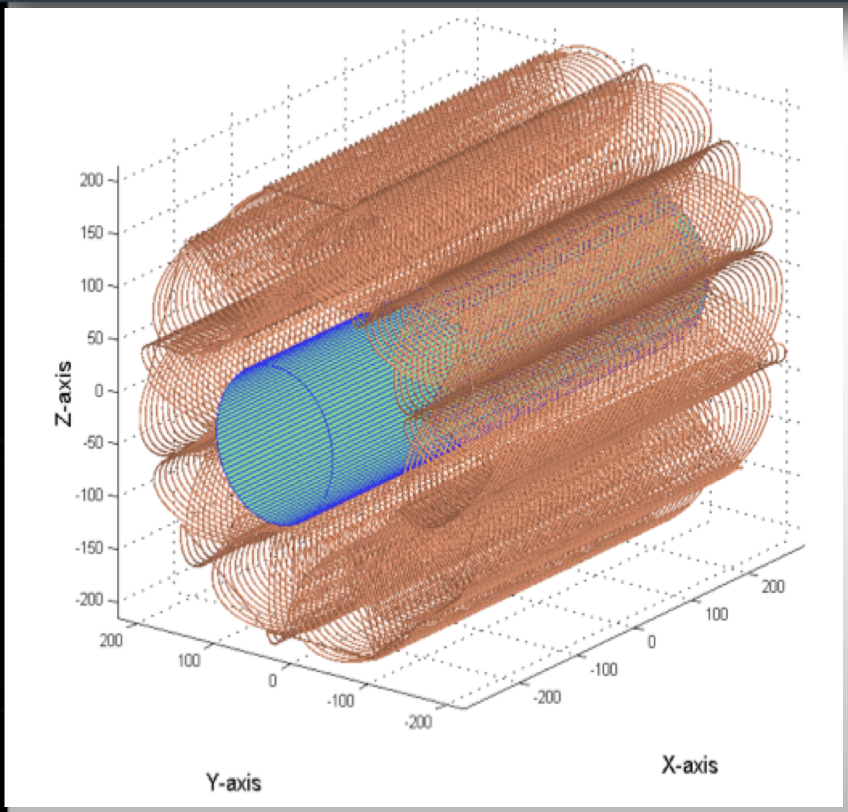
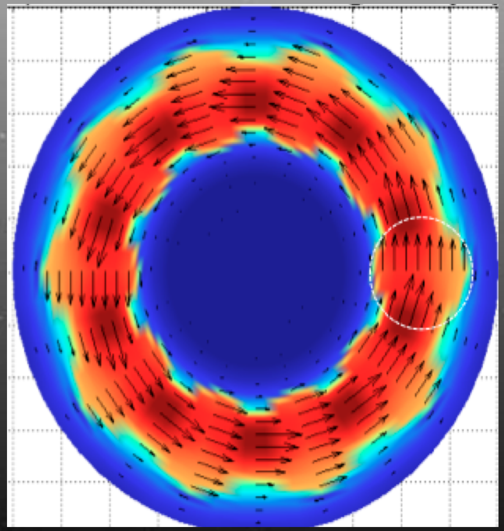
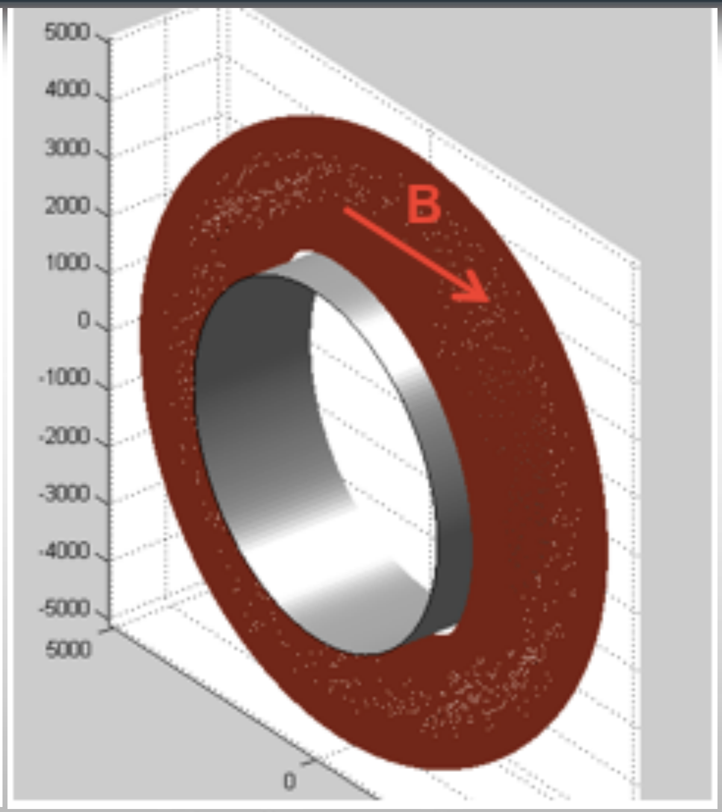
...but also



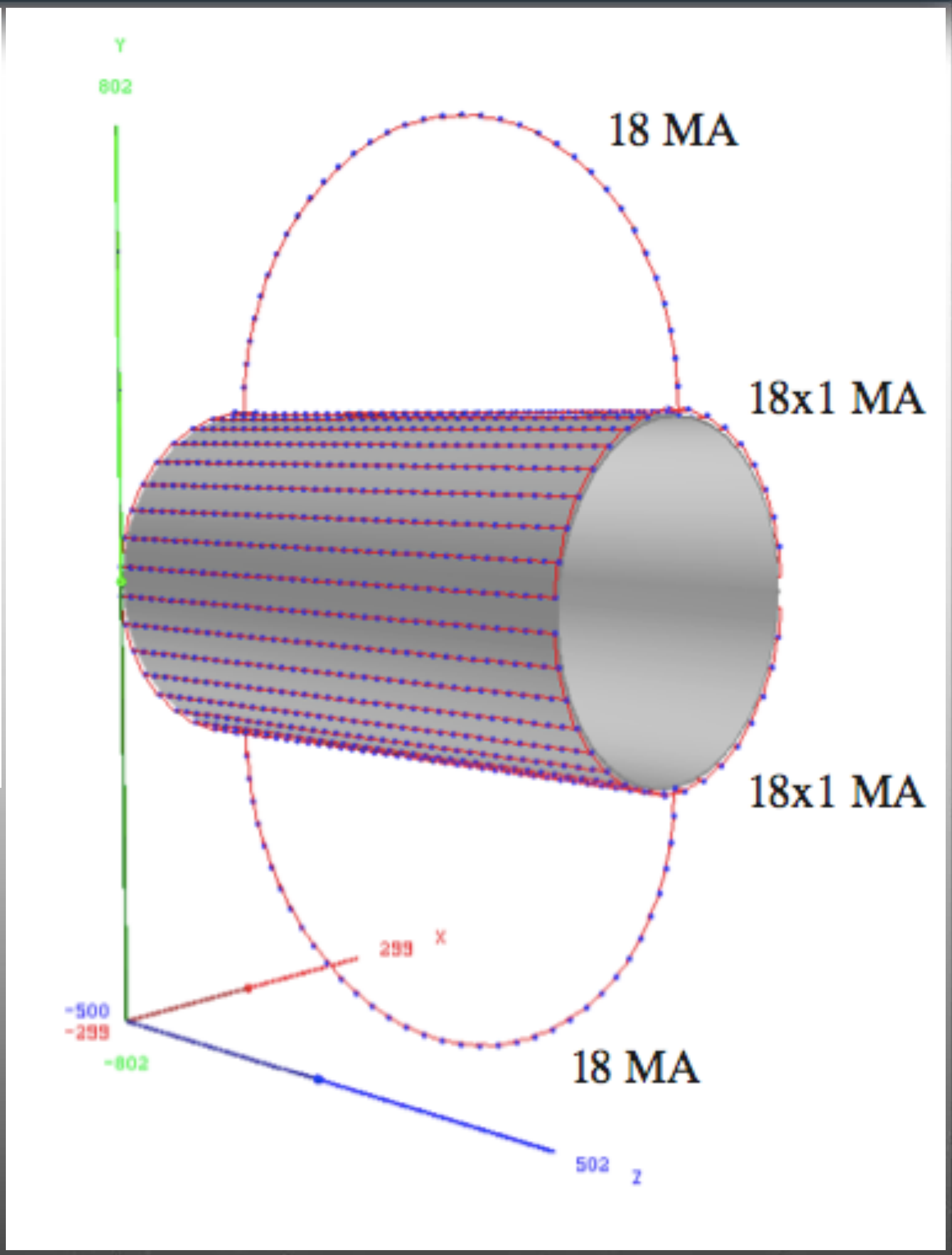
double helix





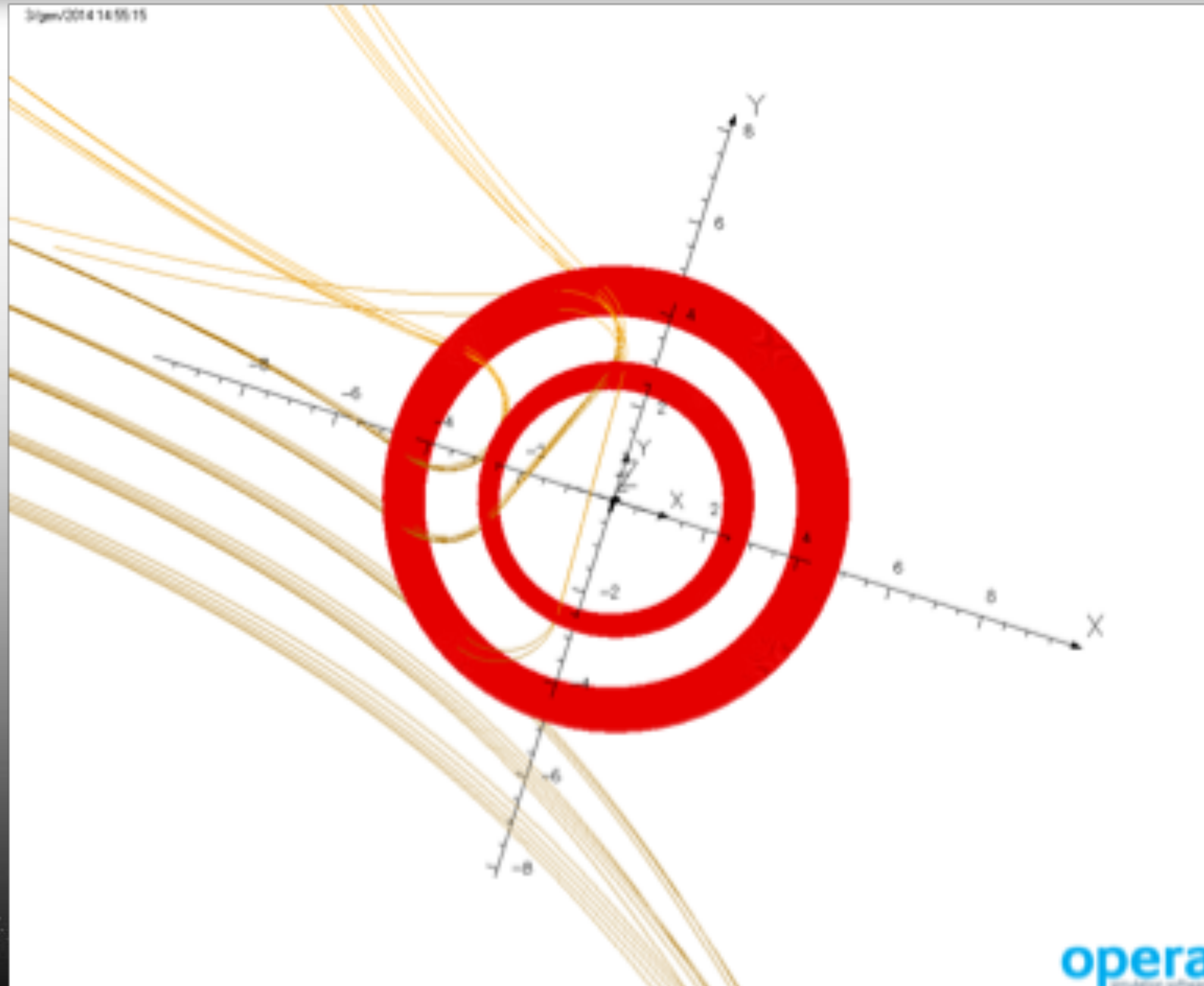
donut

double handle

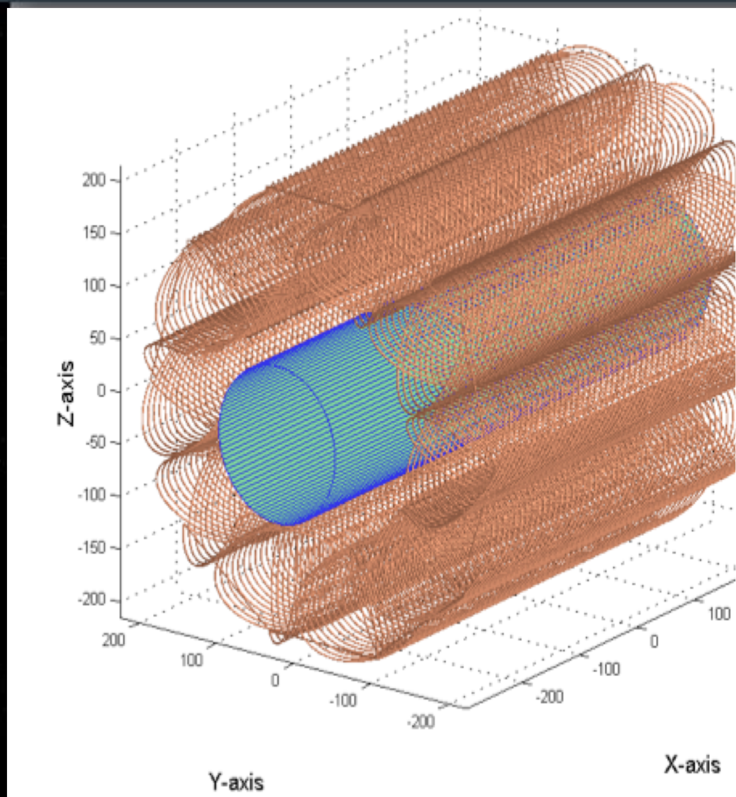


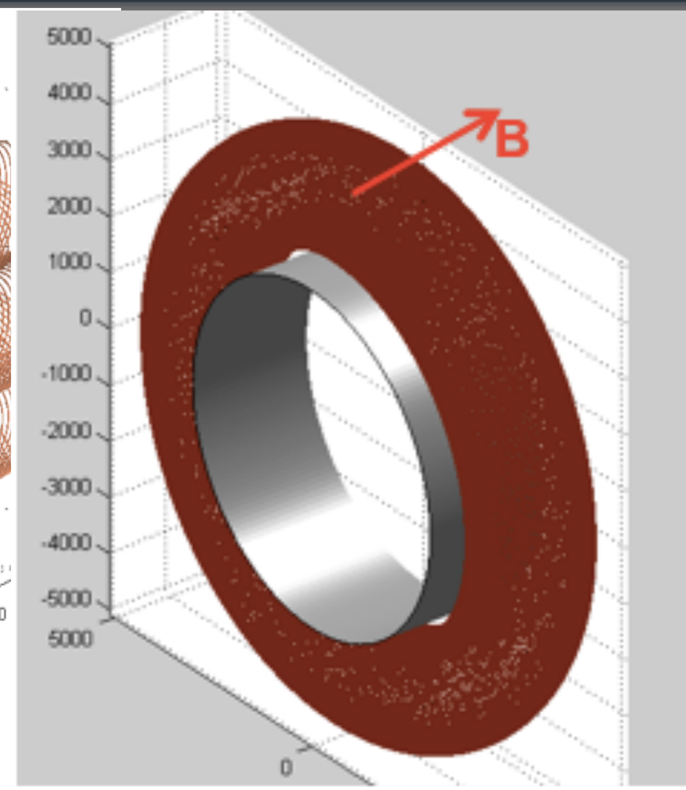
2) SOLENOIDAL-PARALLEL FIELD

eg. coaxial solenoids



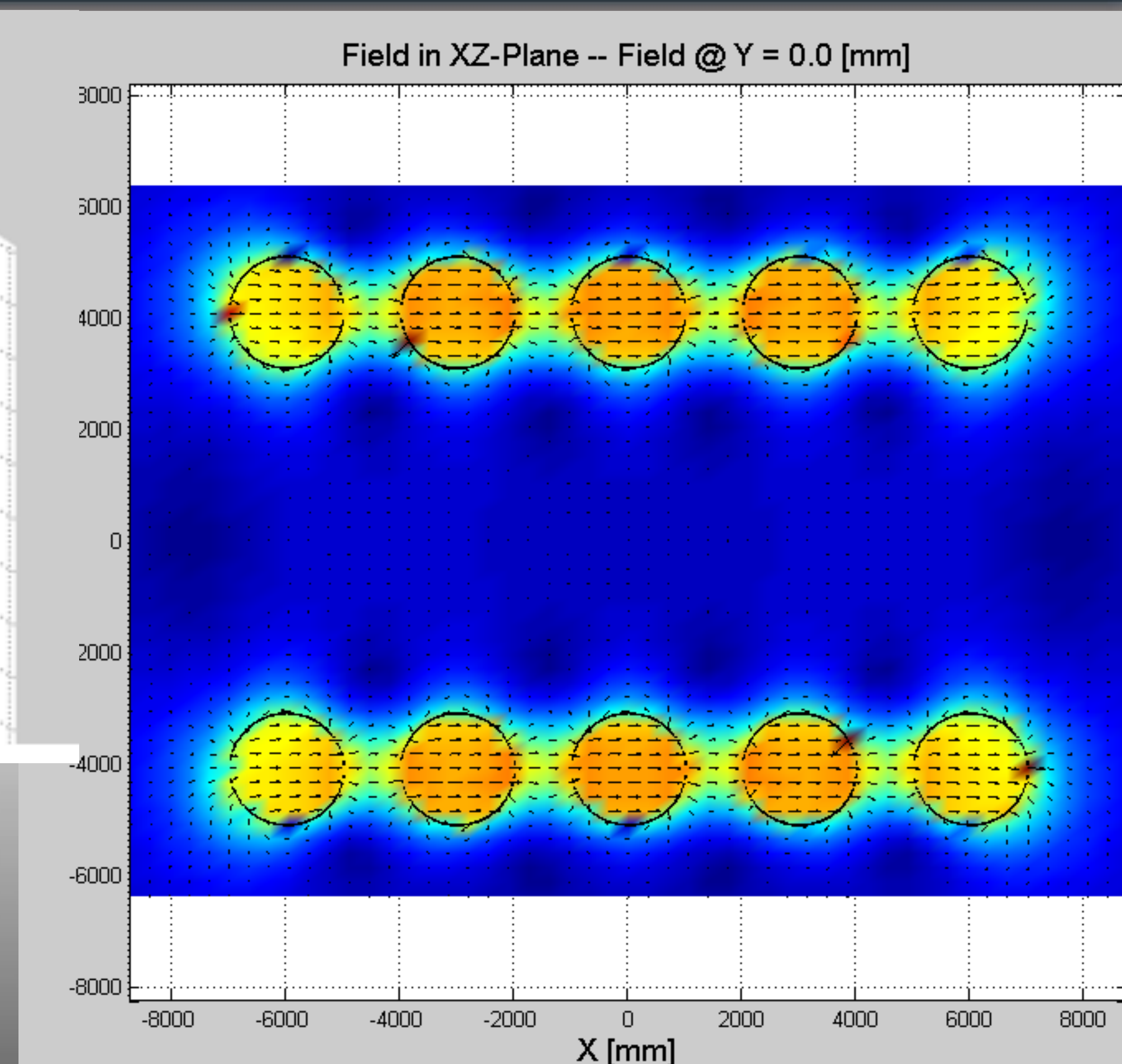
...but also



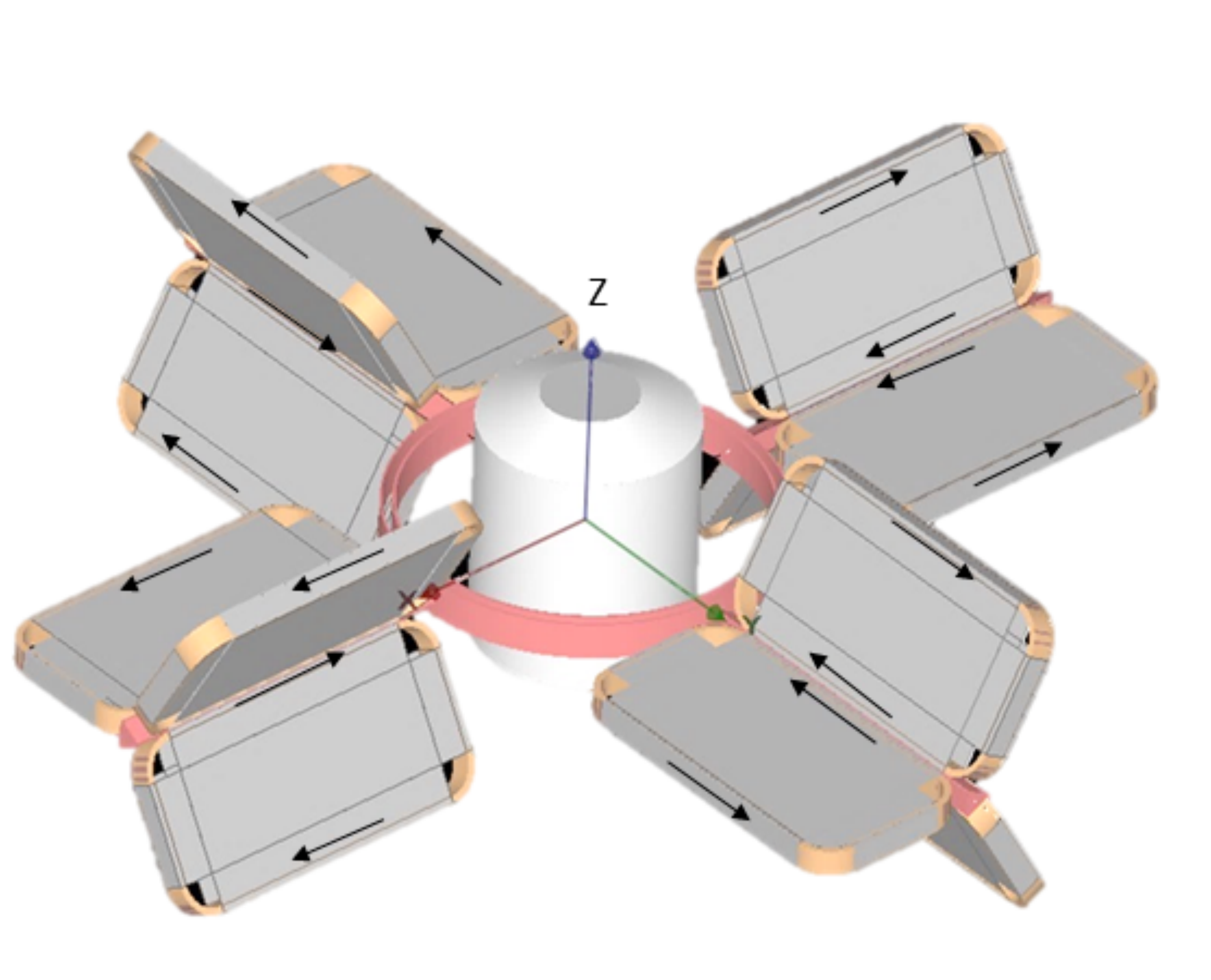


multisolenoid

axial
multidonut

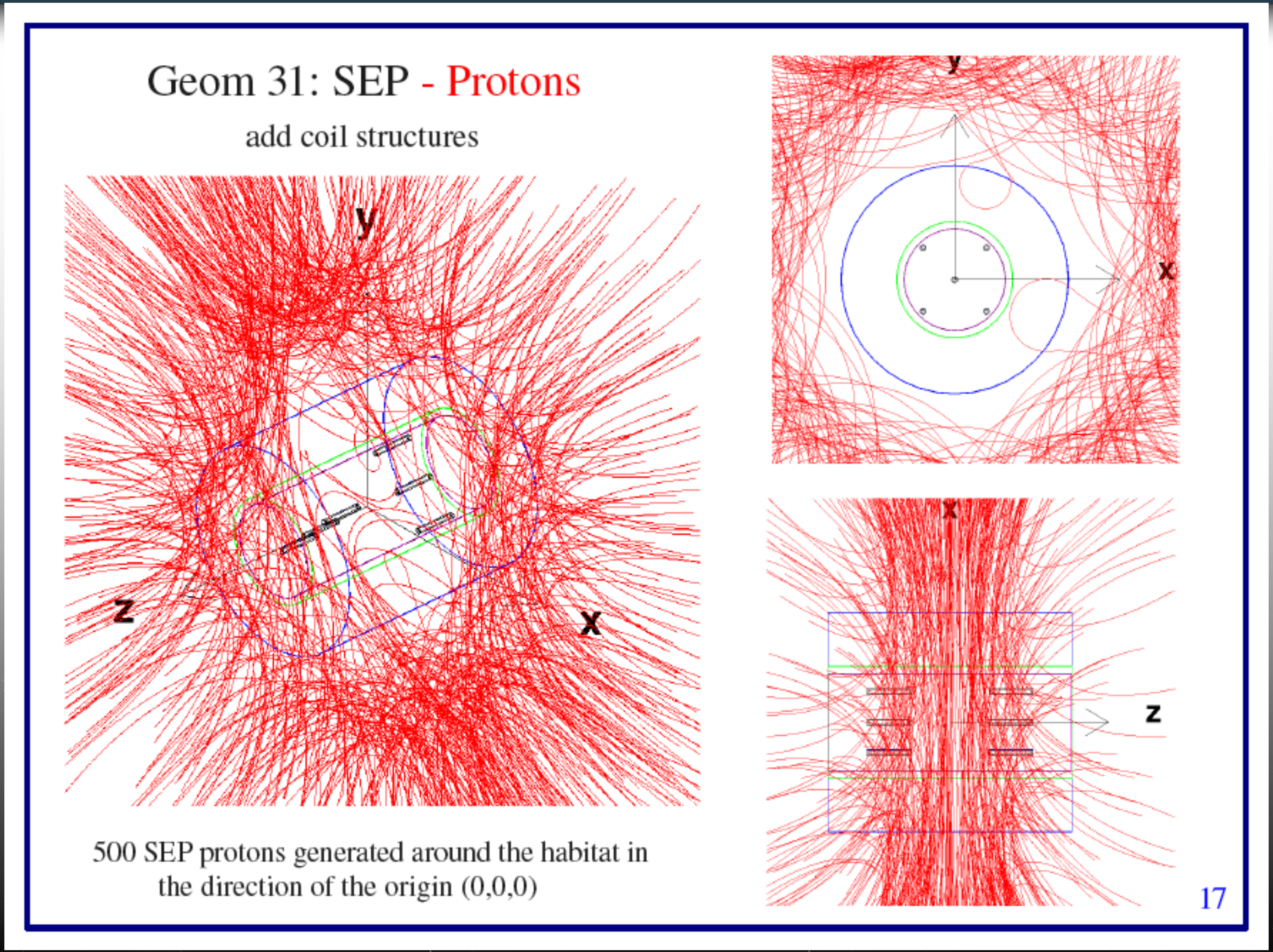


Semi open field «pumpkin» configuration



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

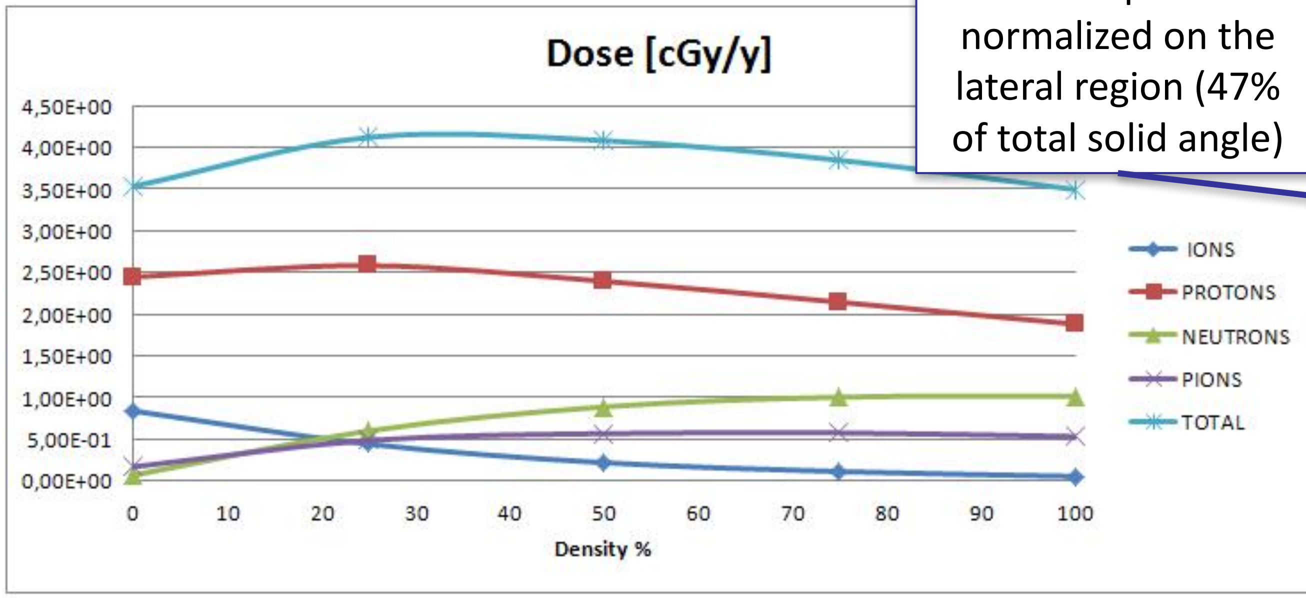
Magnetic shielding of a SPE event



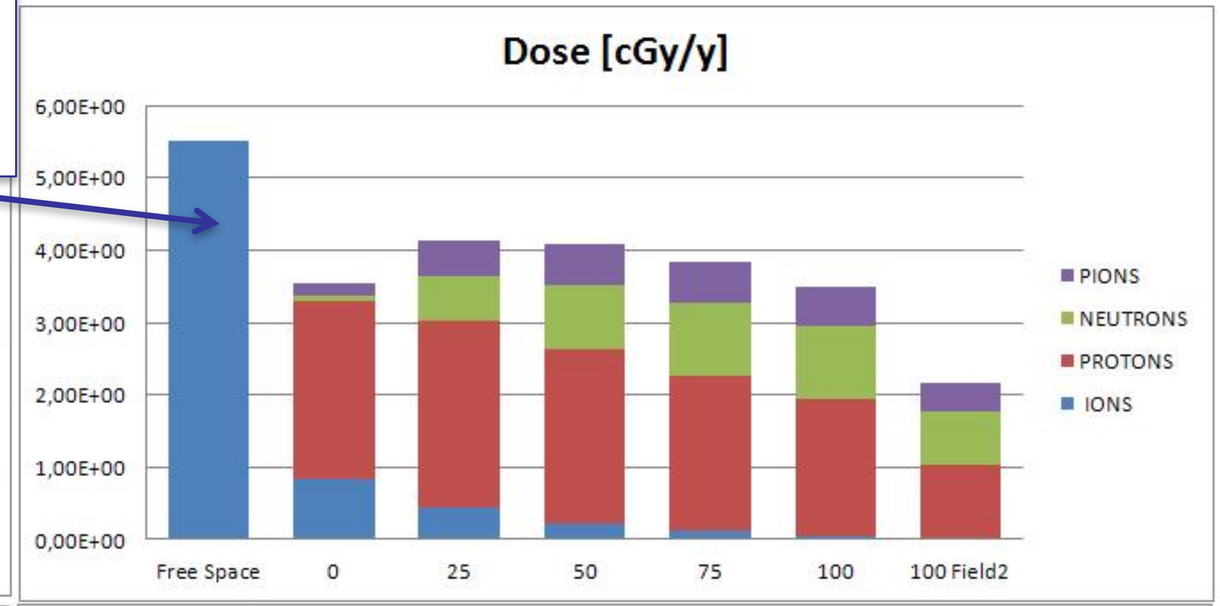
SR2S
Space Radiation
Superconducting Shield

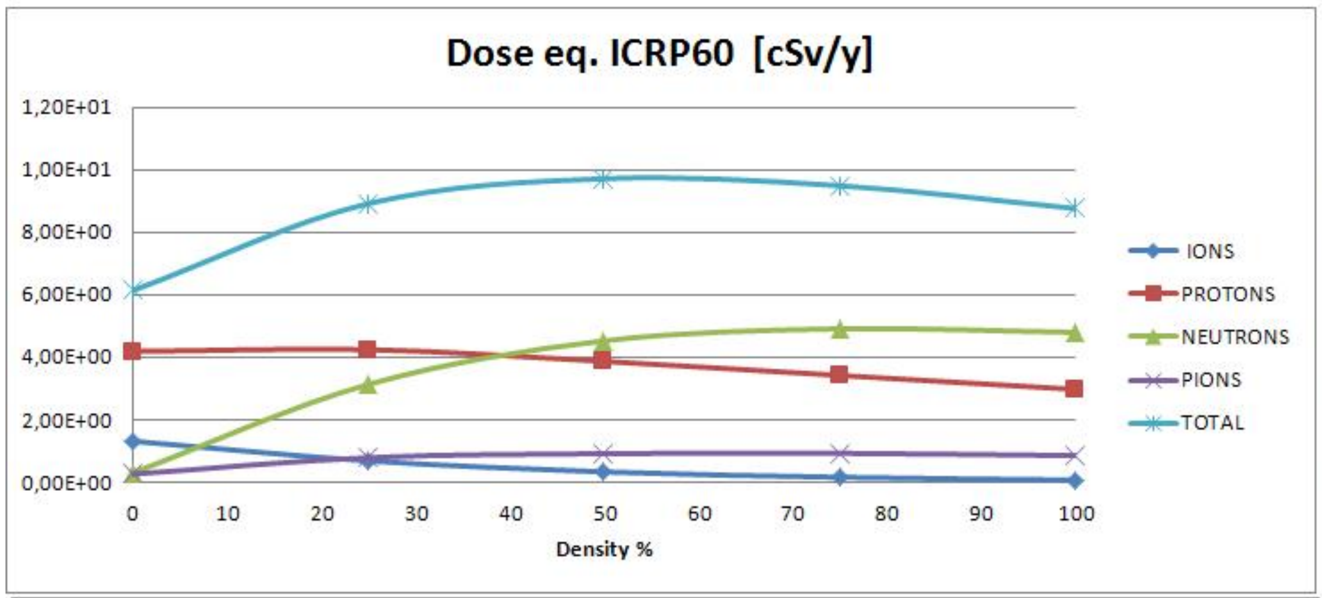
FIELD ON

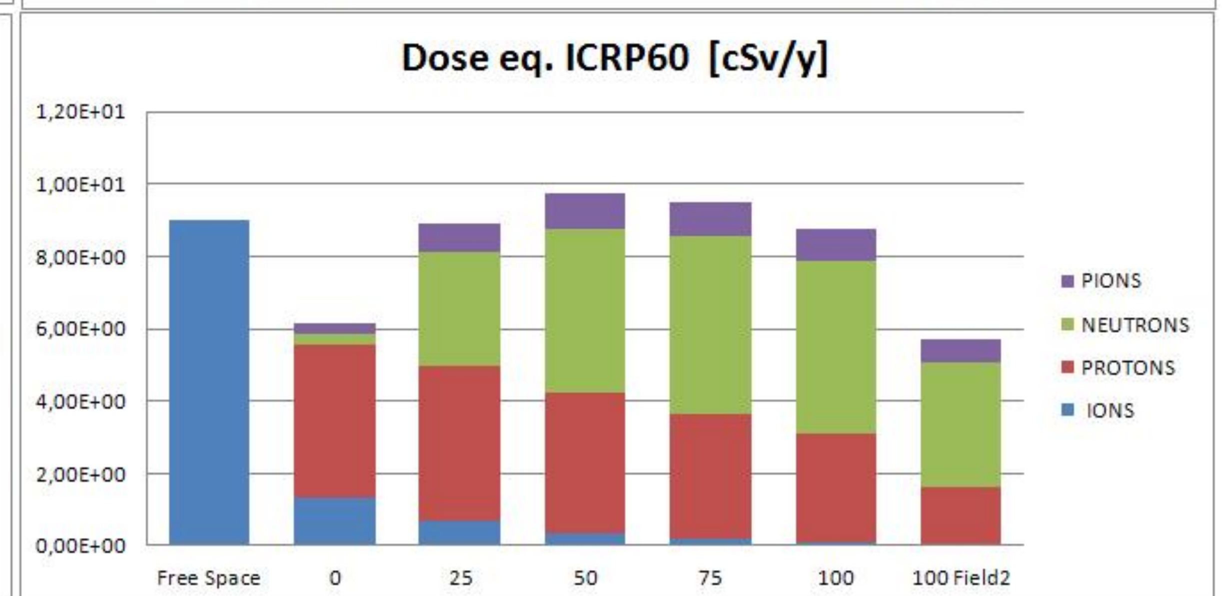
Giraudo, Volo, Lobascio

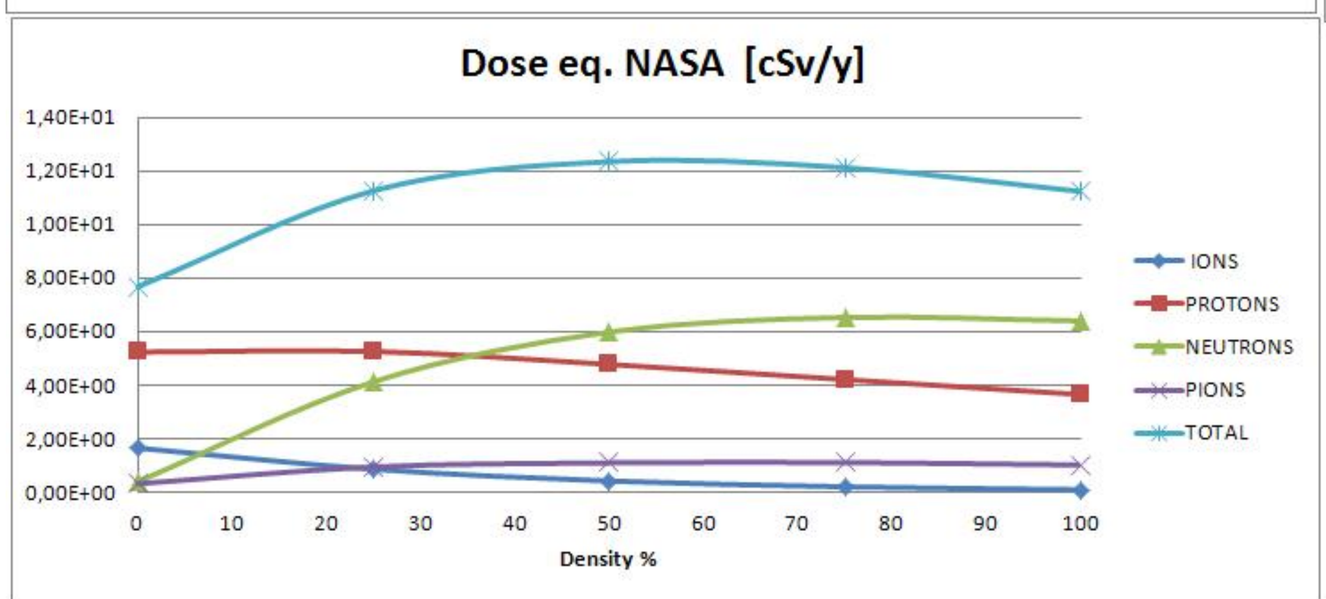


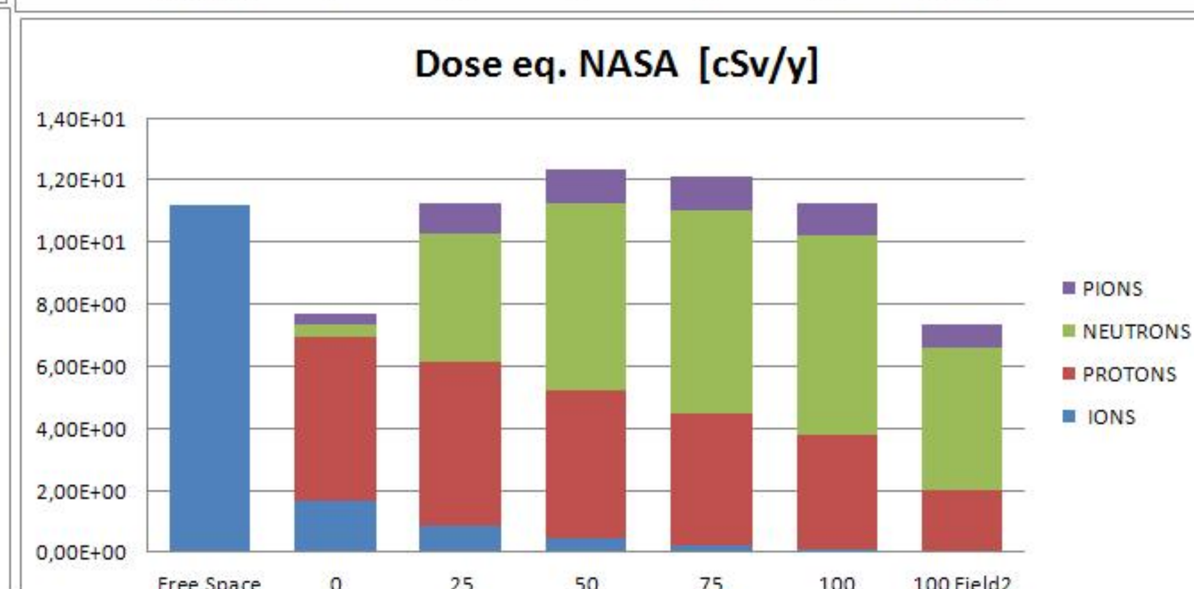
Freespace normalized on the lateral region (47% of total solid angle)





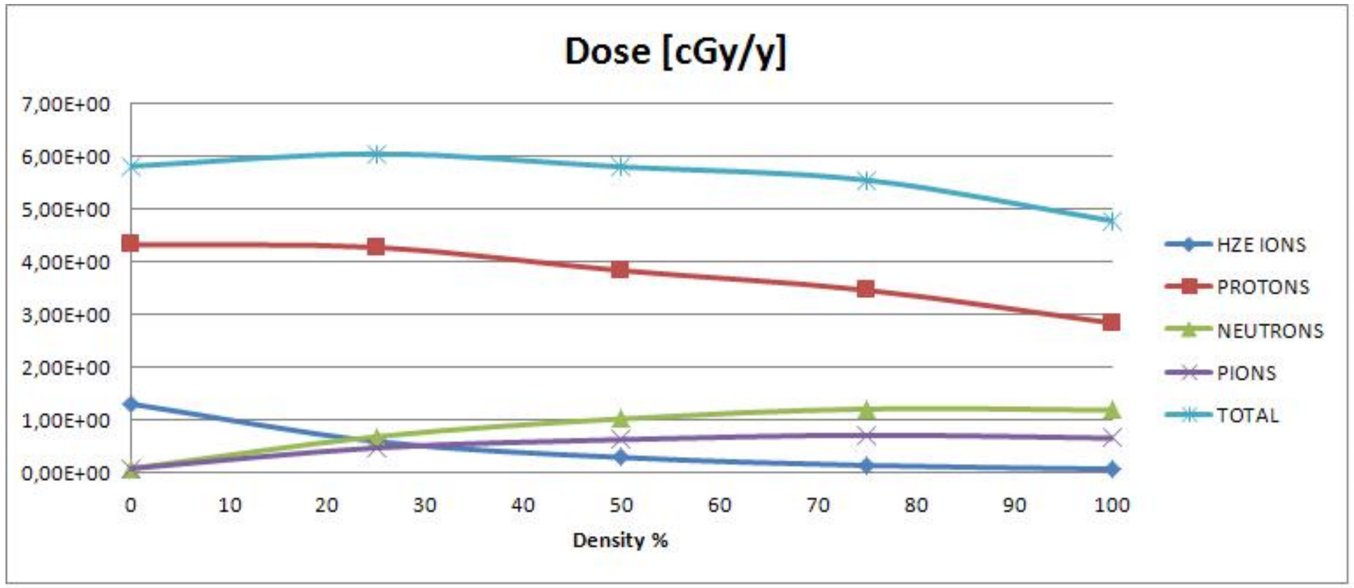


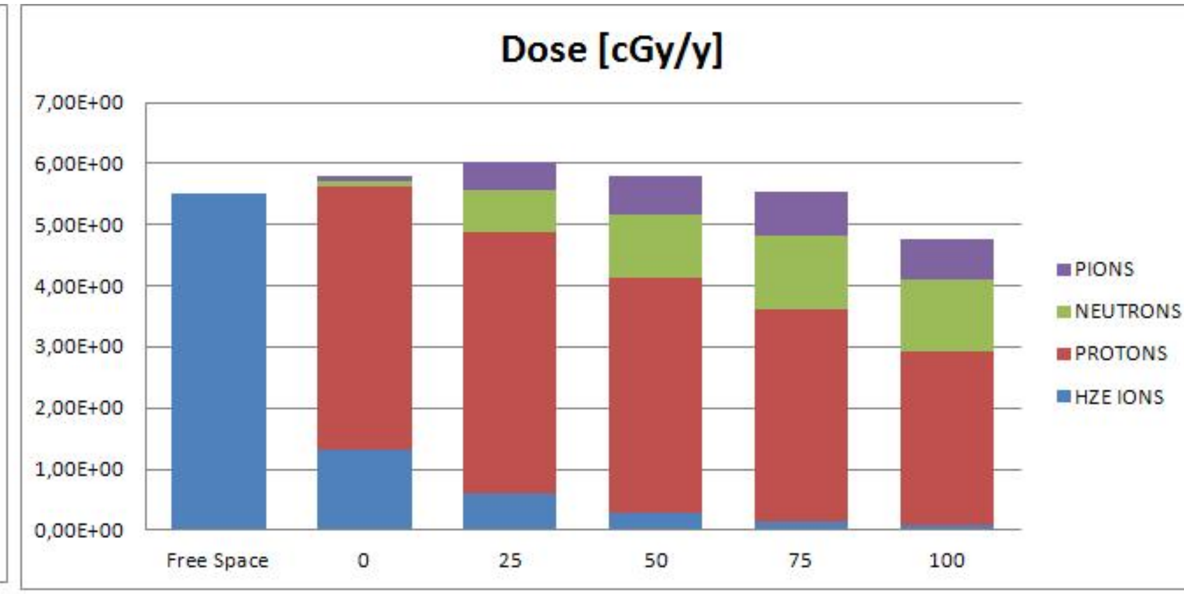


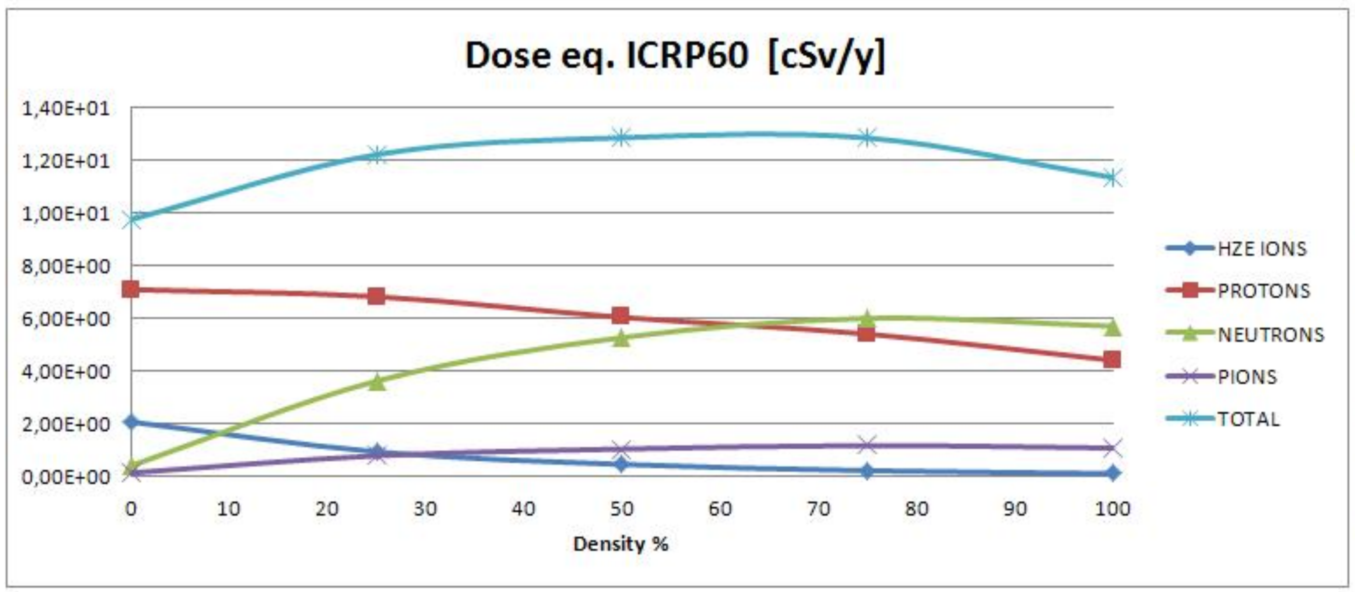


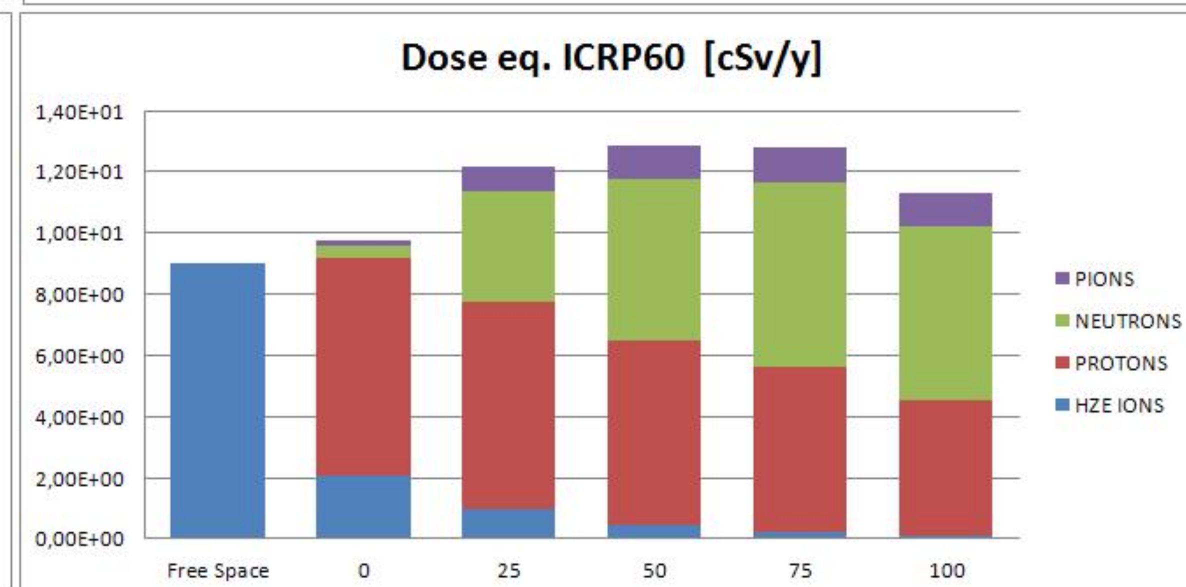
FIELD OFF

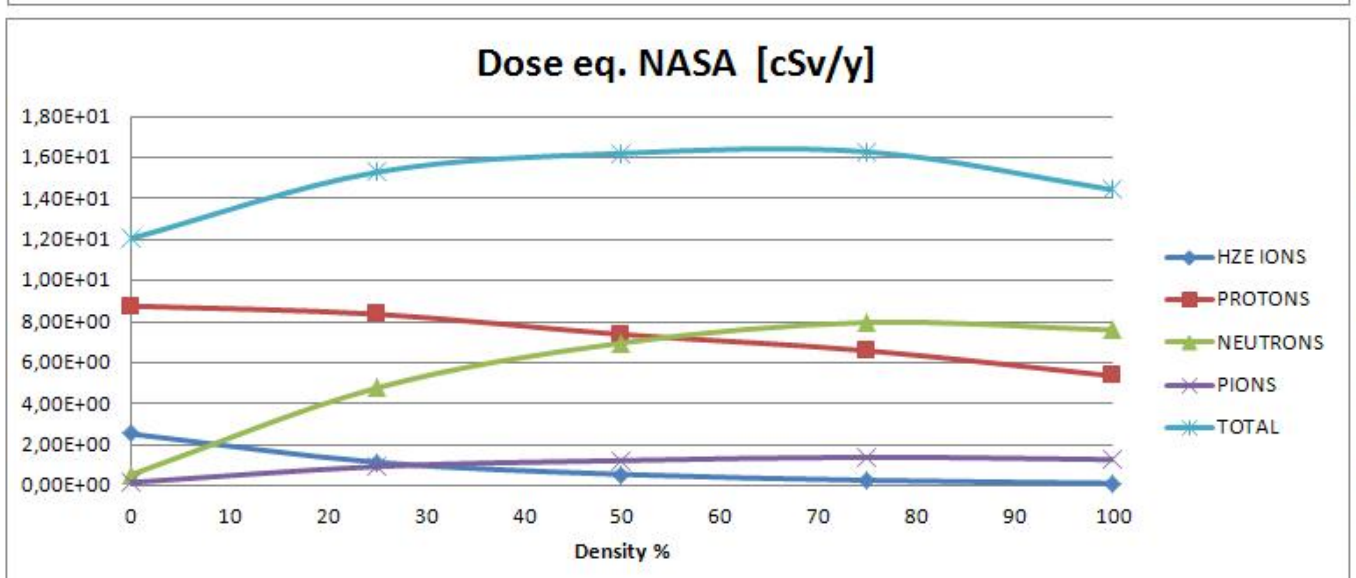
Giraudo, Volo, Lobascio

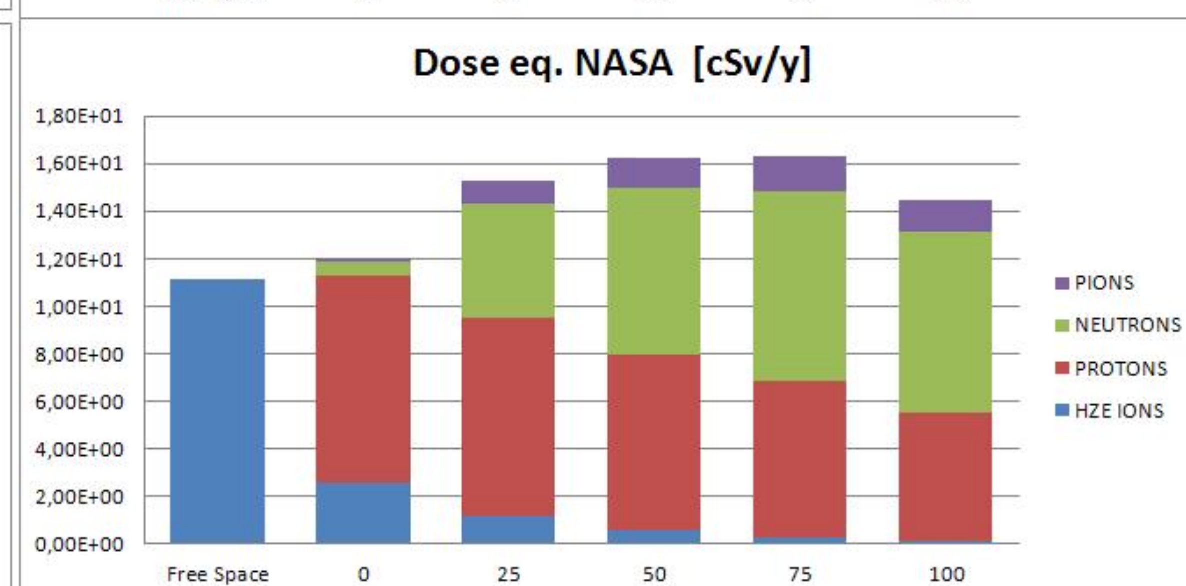






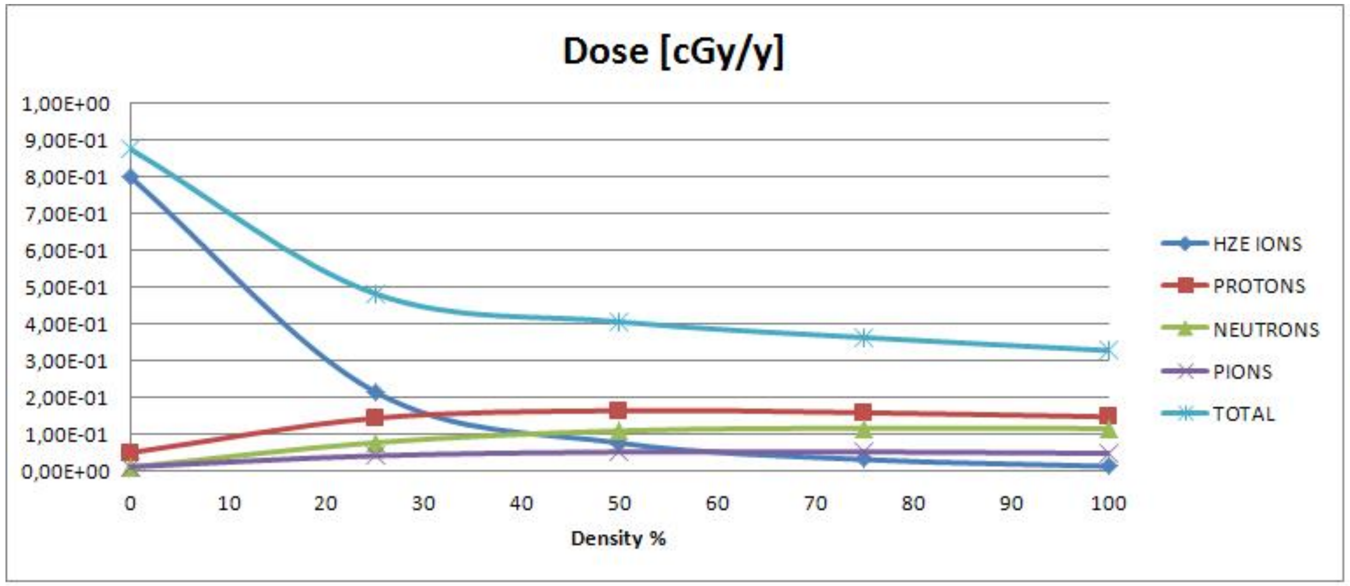


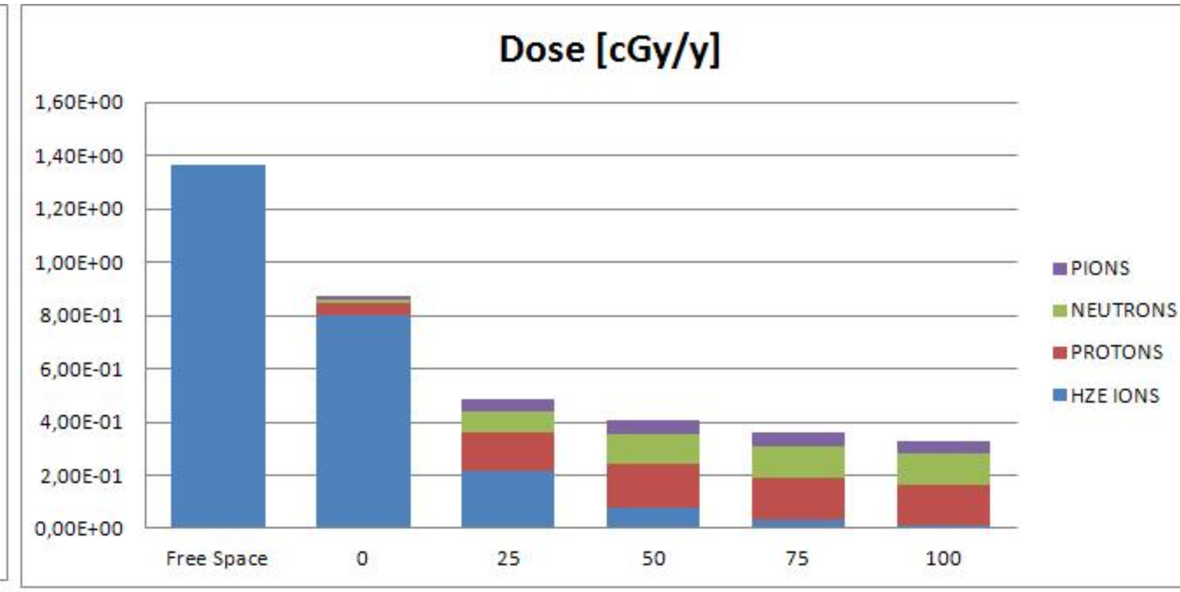


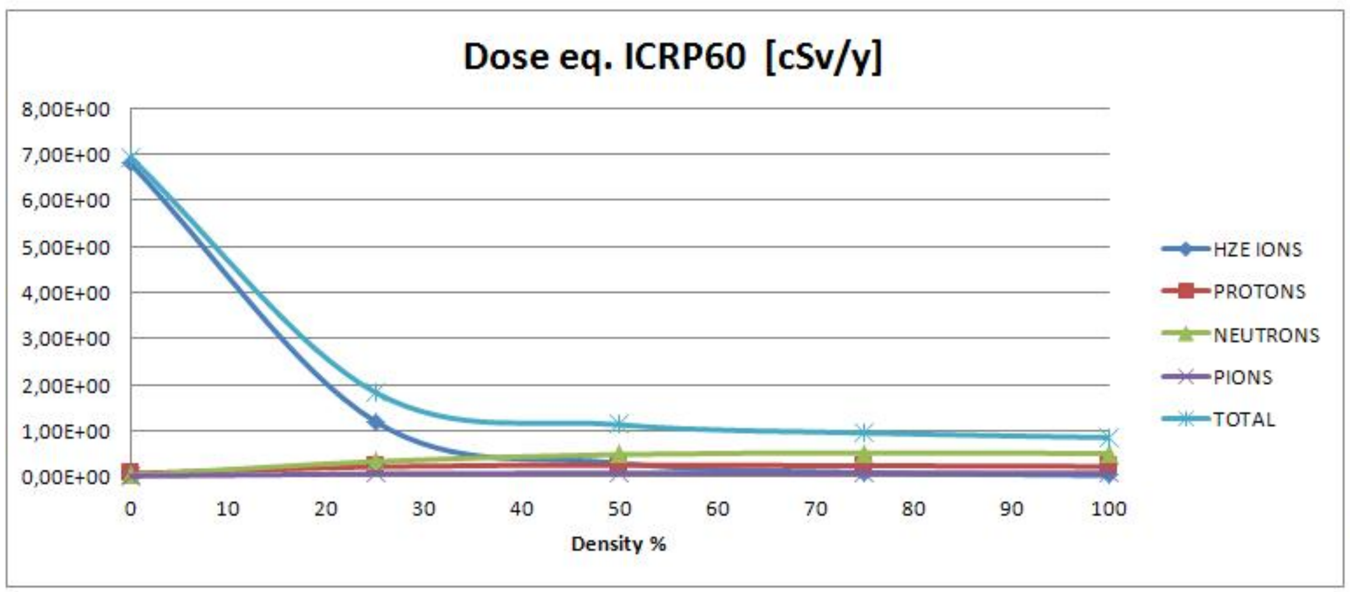


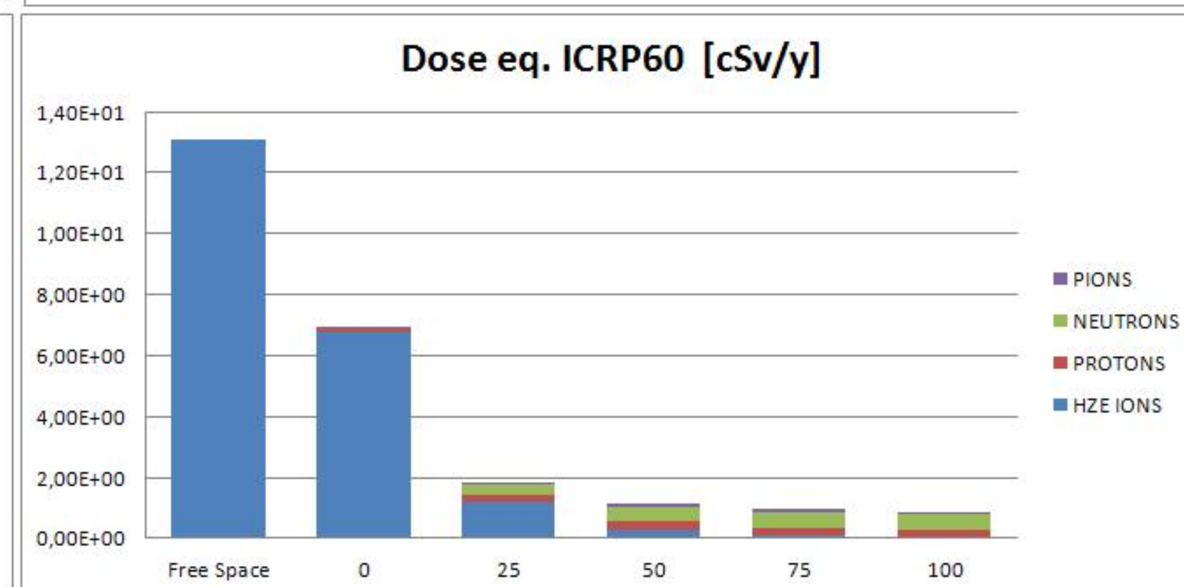
FIELD ON

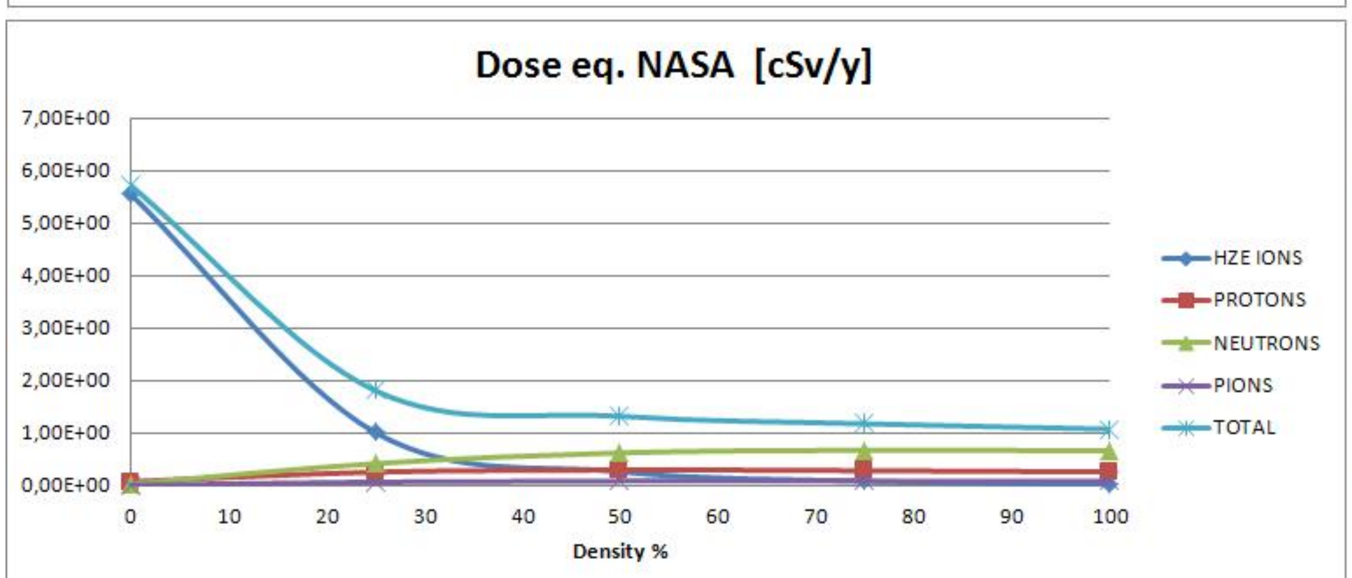
Giraudo, Volo, Lobascio

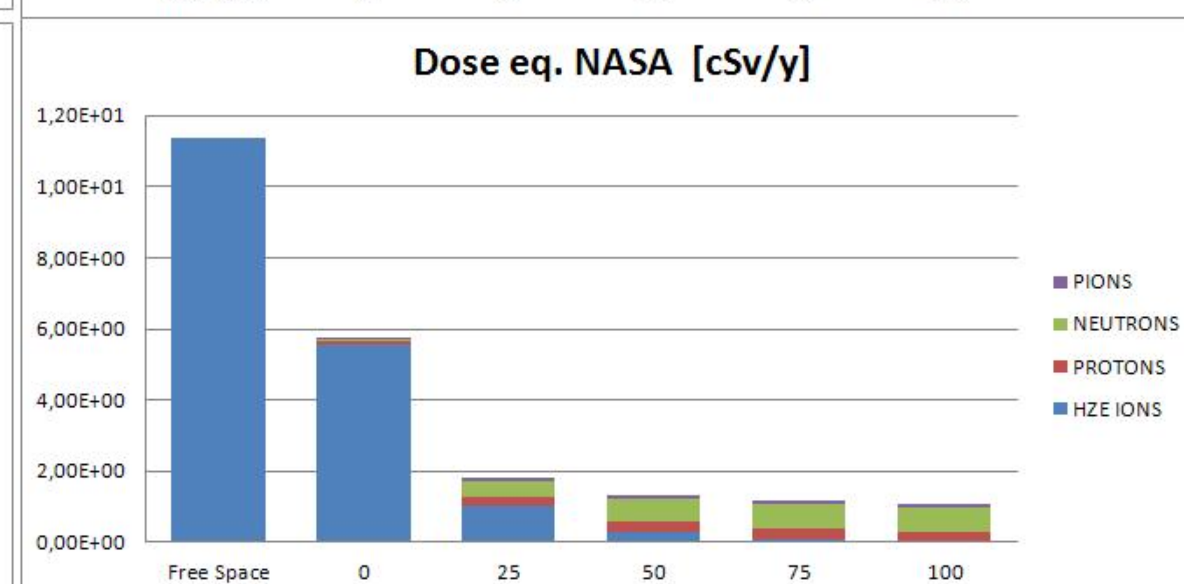






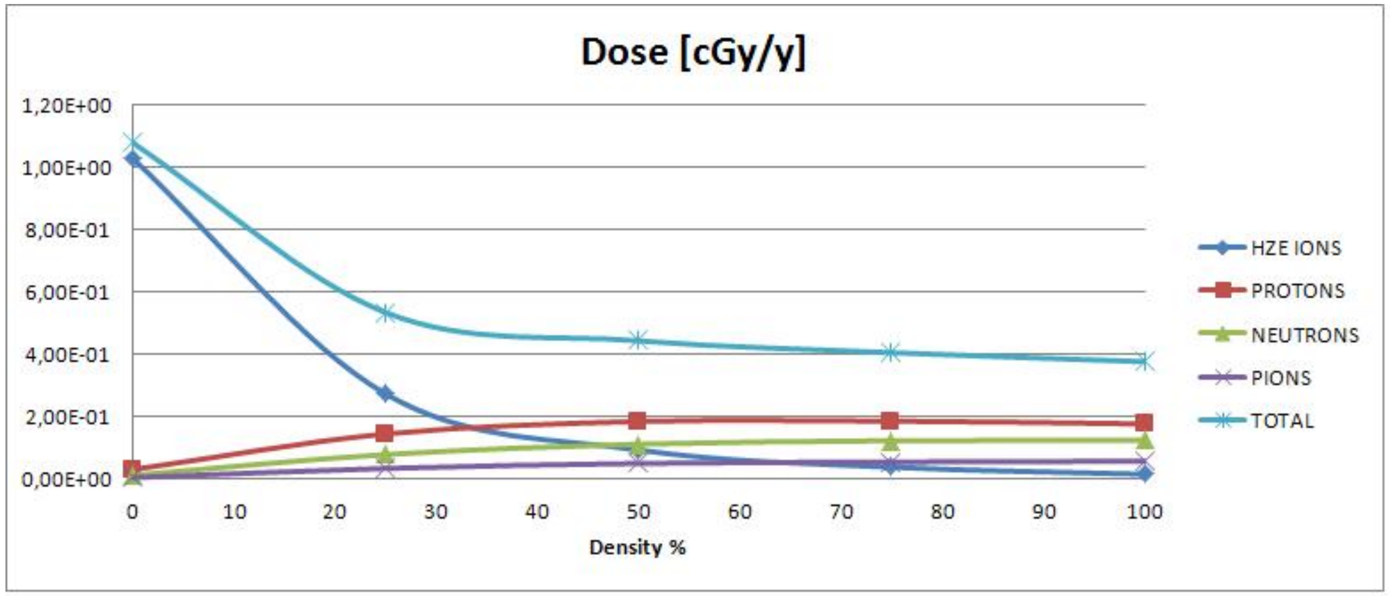


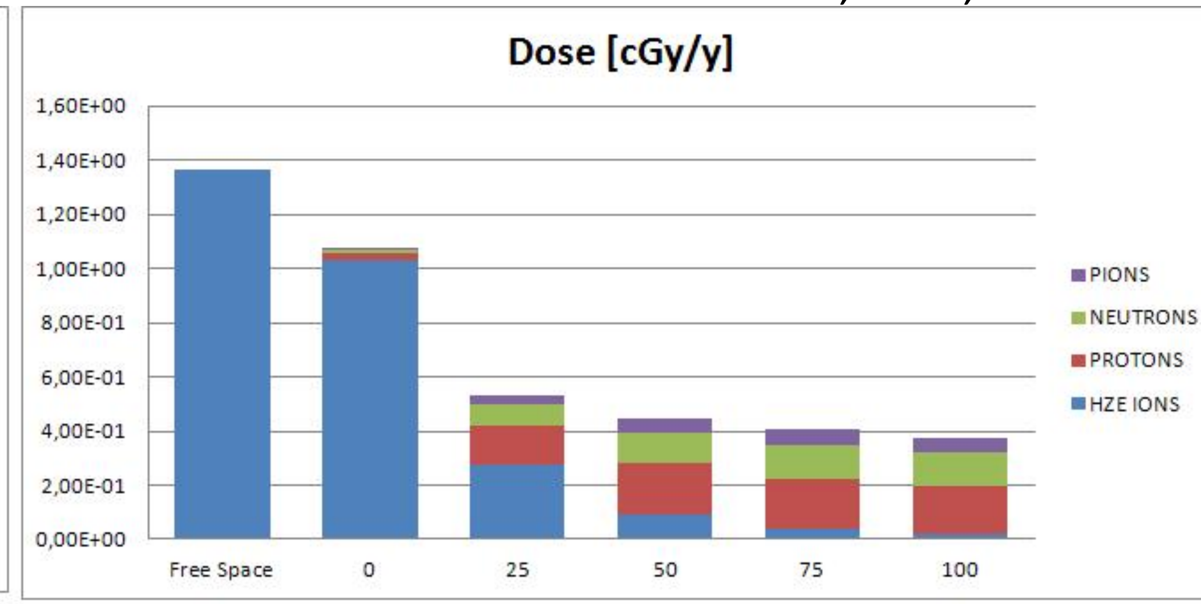


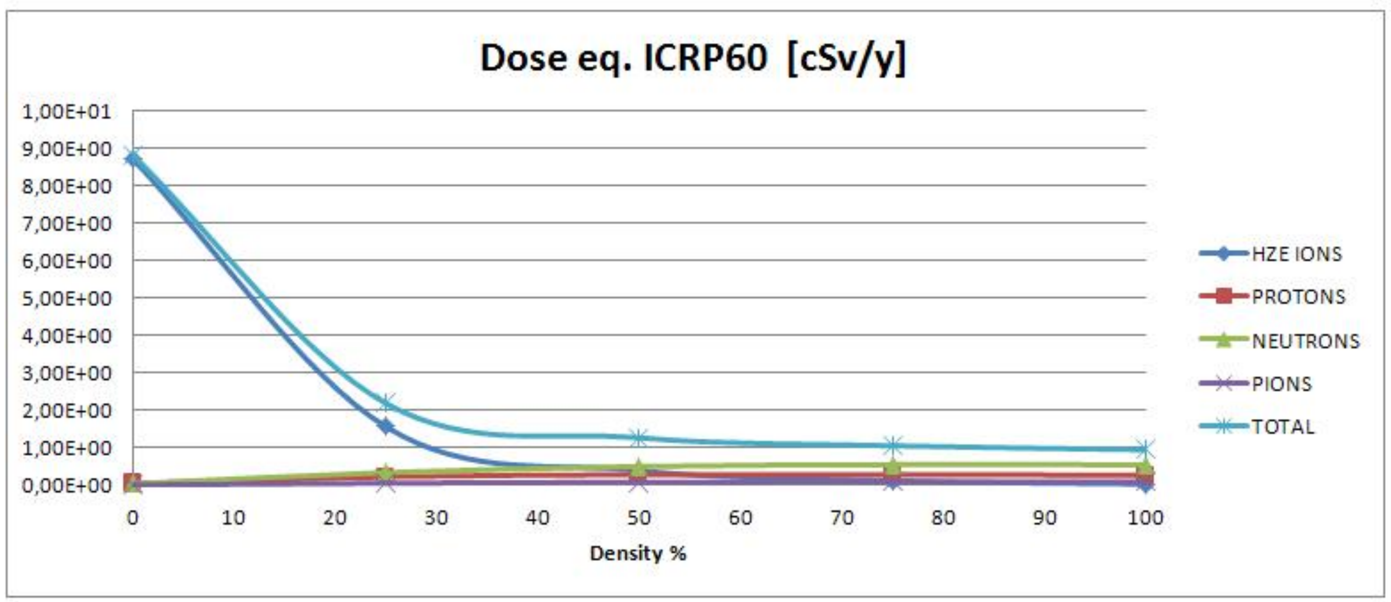


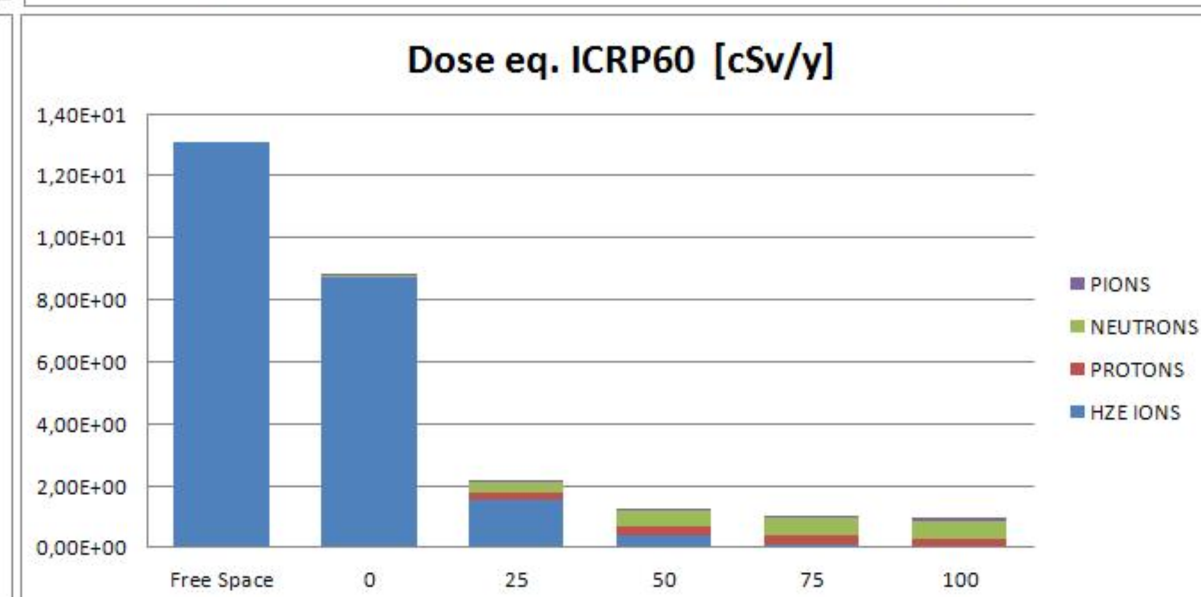
FIELD OFF

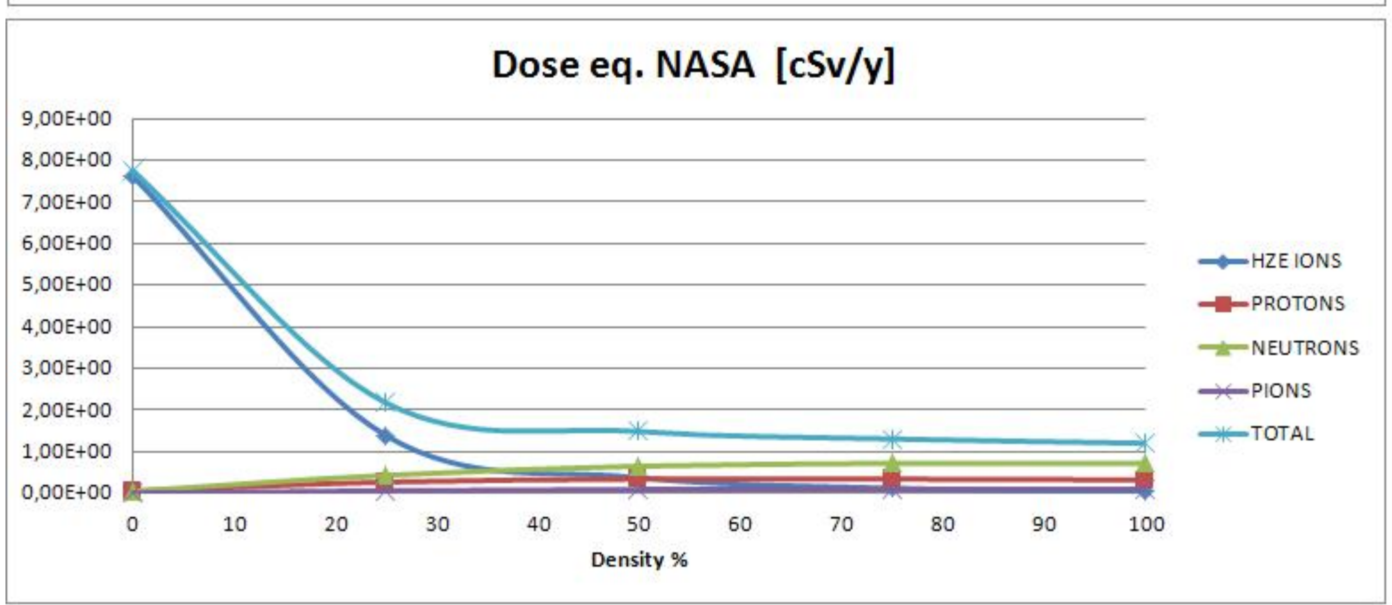
Giraudo, Volo, Lobascio

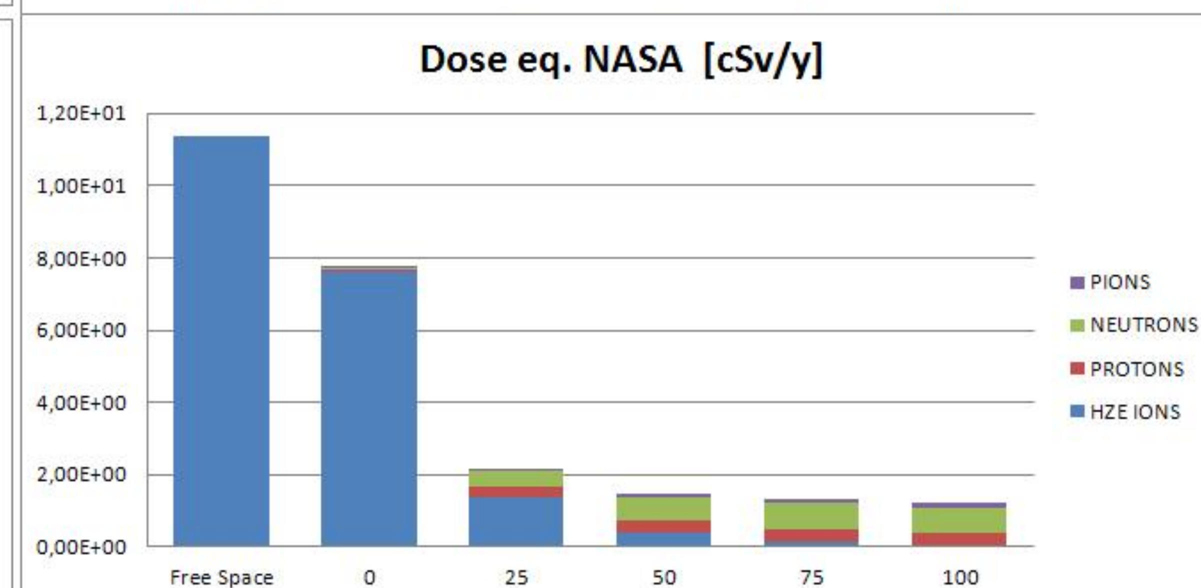


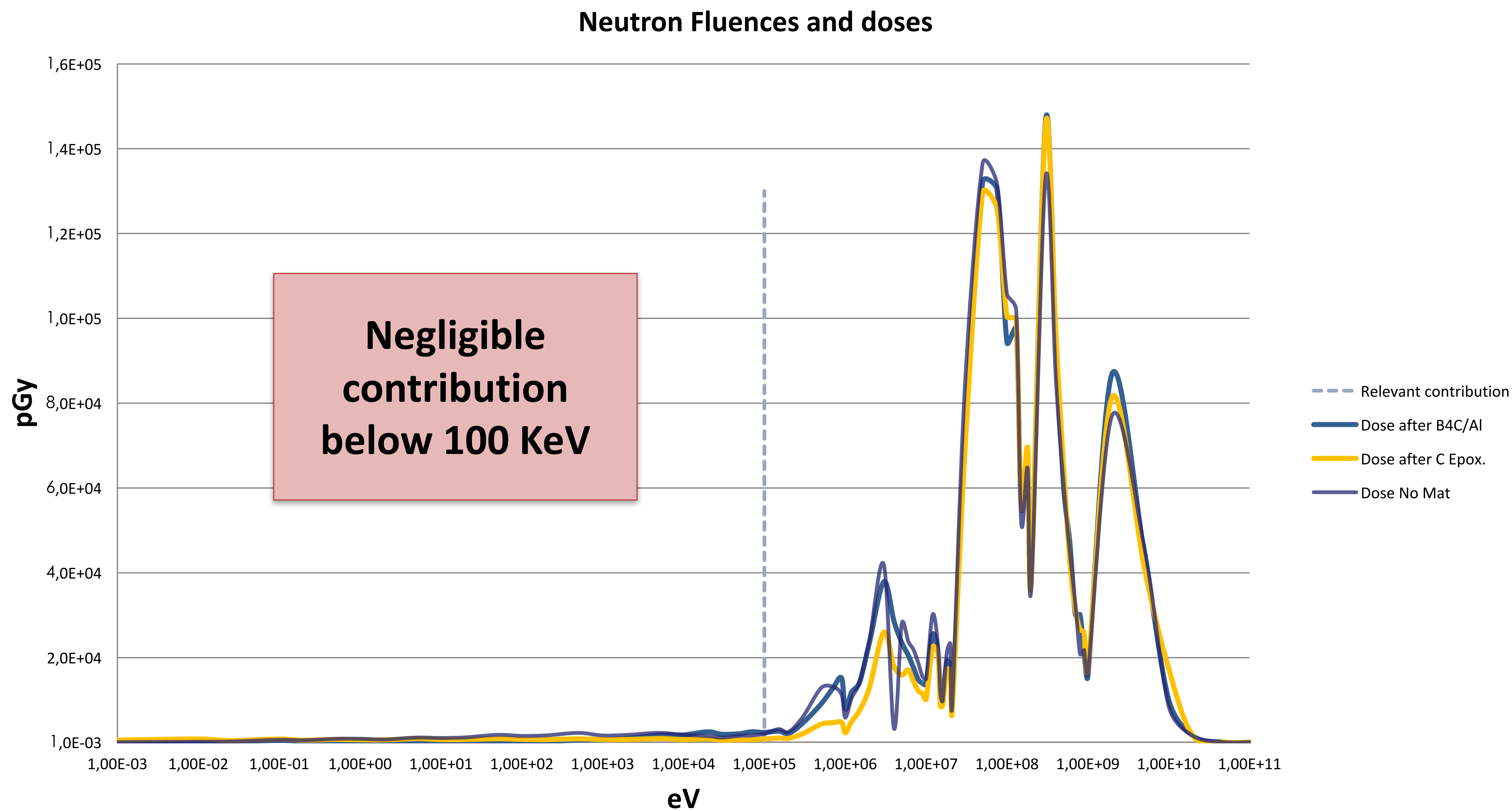






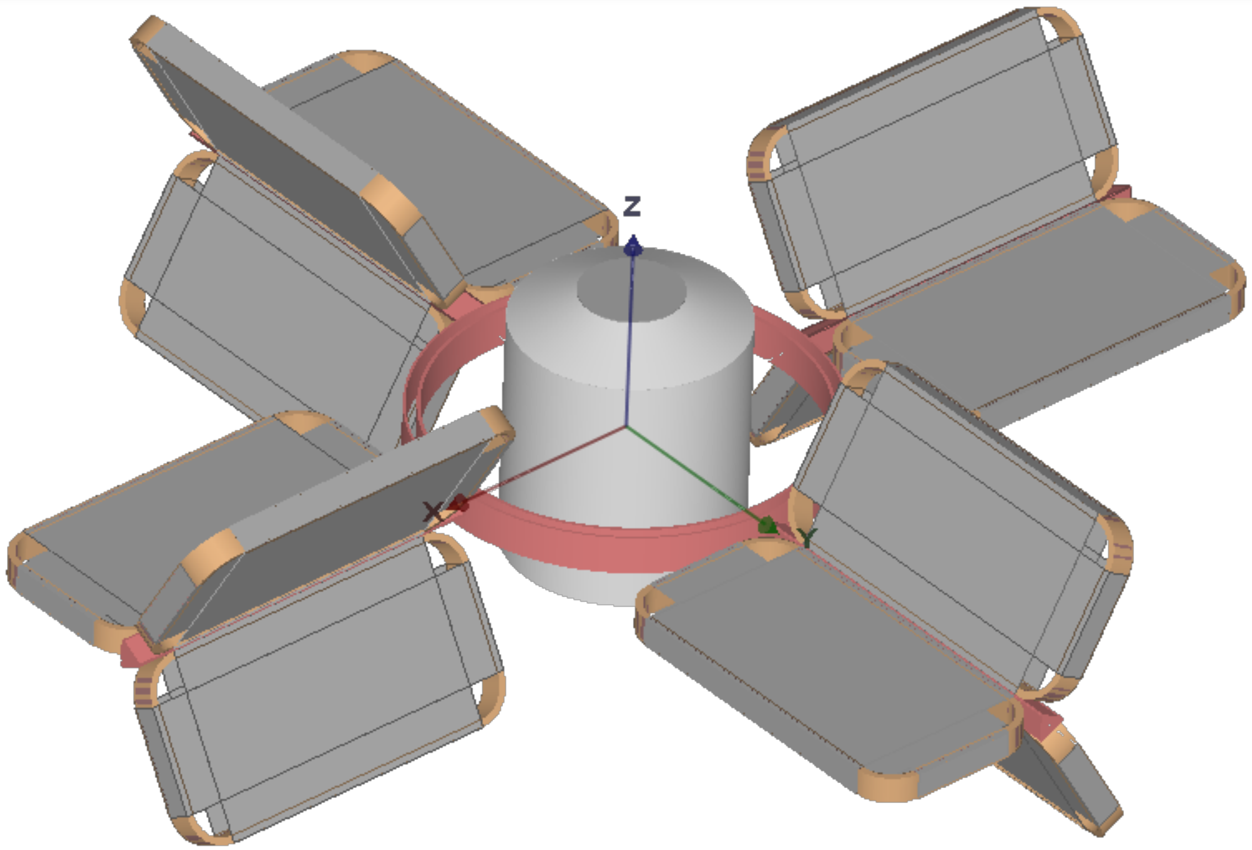


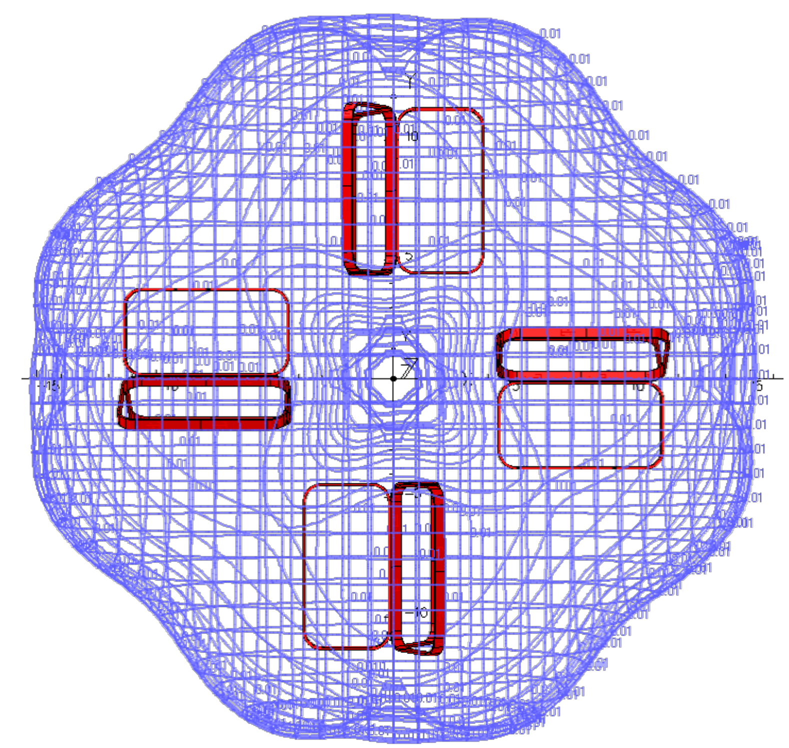




Lin-Log scale

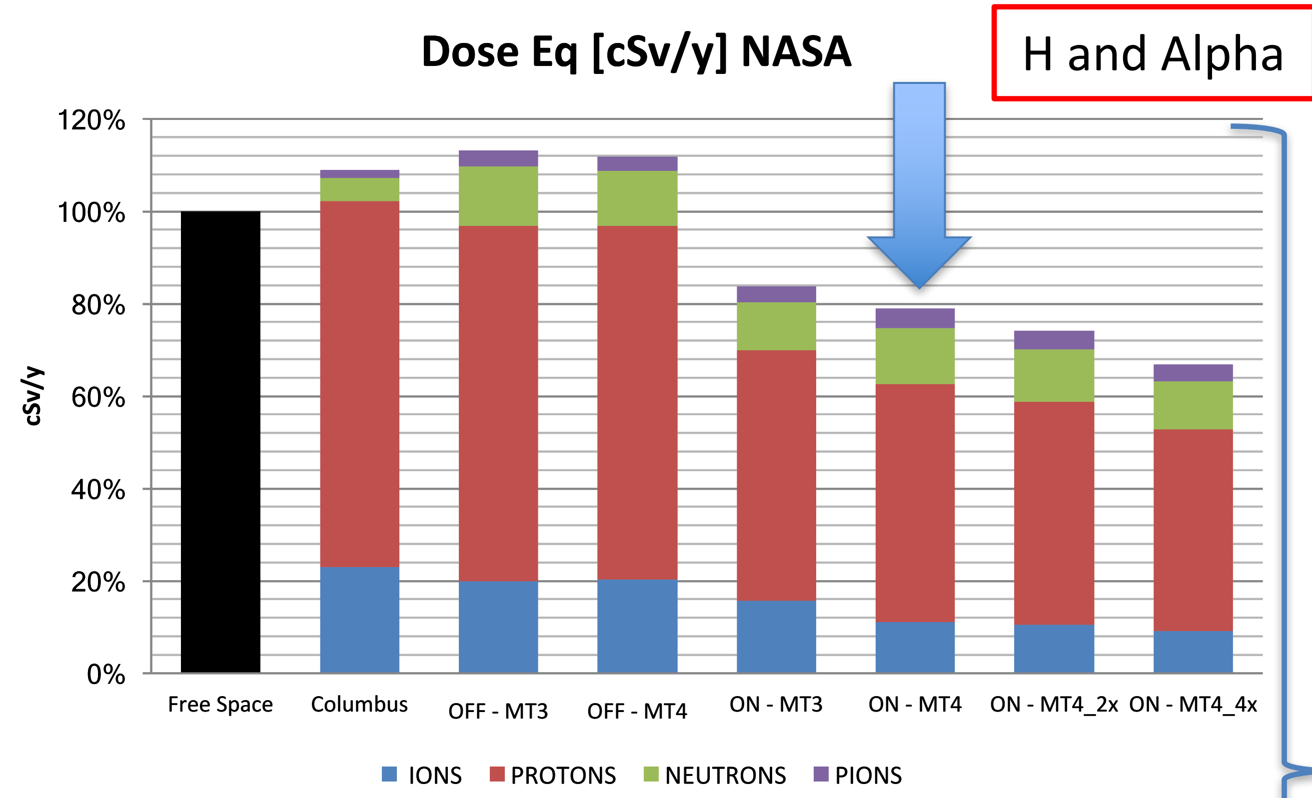
Multi Toroids MT4-”Pumpkins”

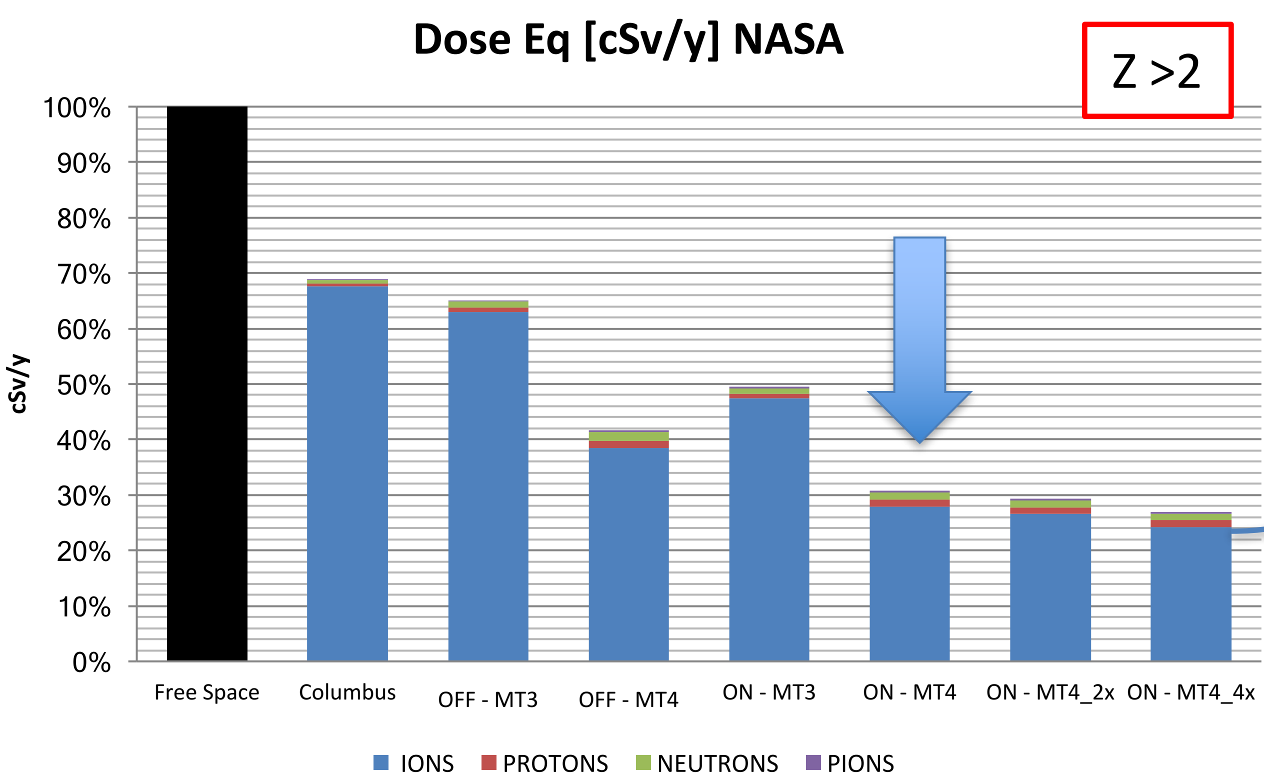


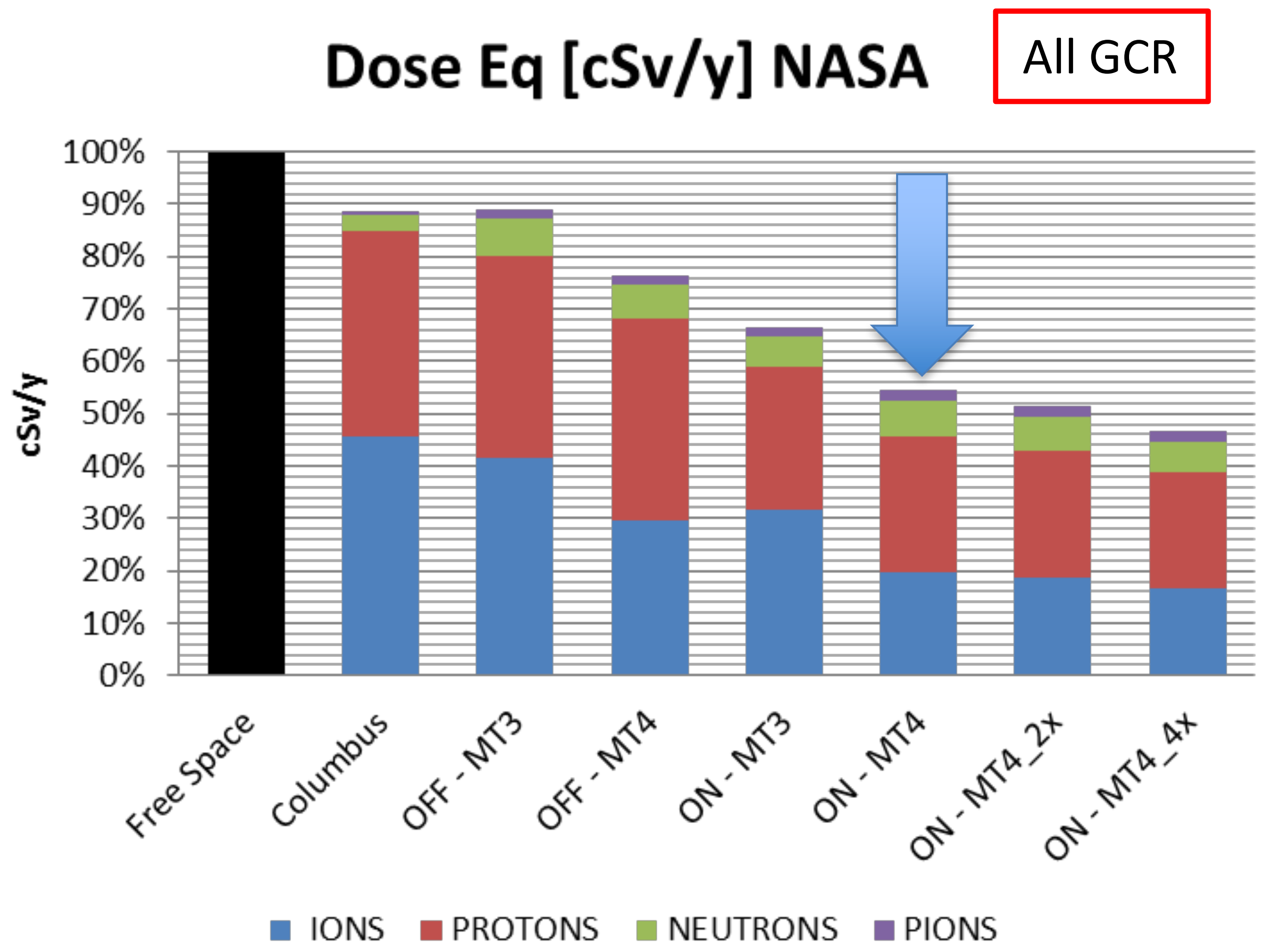


MAGNET MAIN PARAMETERS	
Current Density	75 A/mm^2
Current per cable	660.5 A
# of turns (per racetrack)	41
# of layers (per racetrack)	97
# of Racetracks	12
Bmax over conductor	6.57 T

Magnetic Field/mass vs Dose

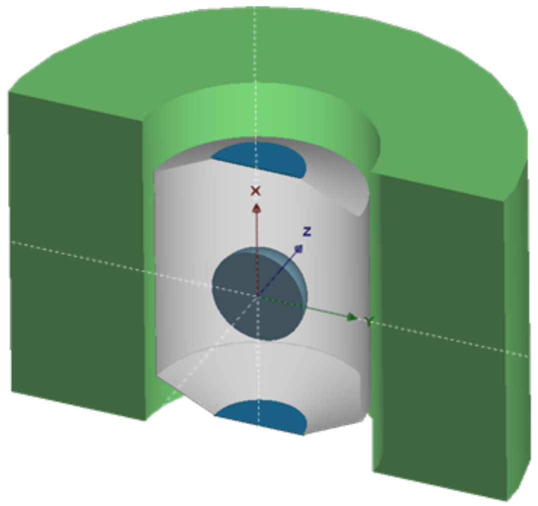


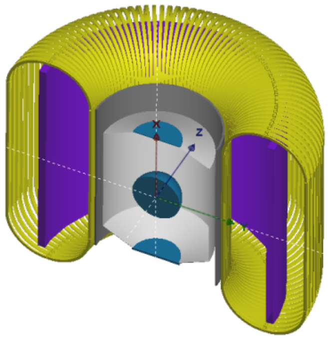




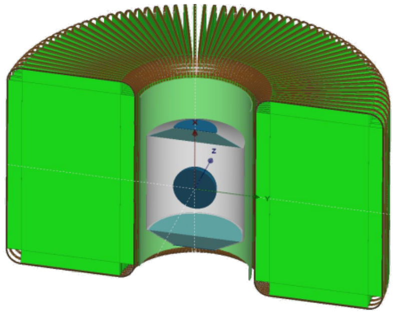
Optimizaztion of Passive shielding vs. Active Shielding

Conf.	Total	Mat.	Field	Mass [t]	Passive HDPE
A	45%	30%	15%	300	61 %
B1	42%	24%	18%	100	38%
B2	44%	22%	22%	147	44%
MT3	33%	11%	22%	39	34%
MT4	46%	24%	22%	76	36%
MT4 x2	49%	24%	25%	76	36%
MT4 x4	53%	24%	29%	76	36%

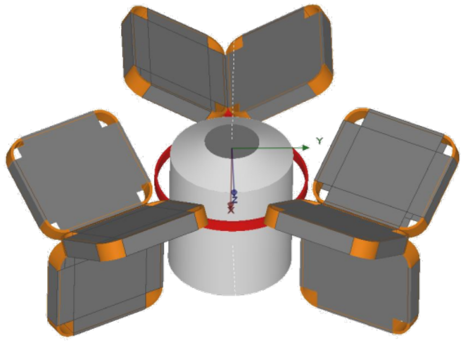




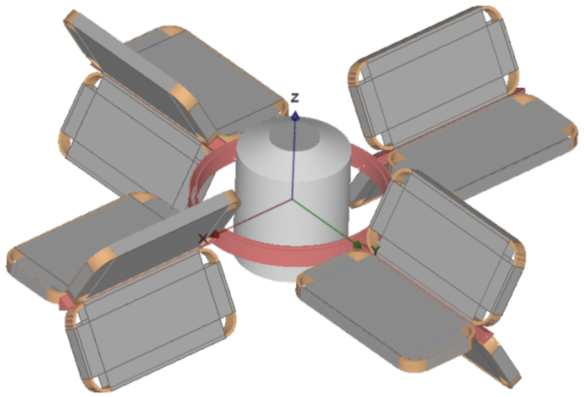
A



B1/B2



MT3



MT4

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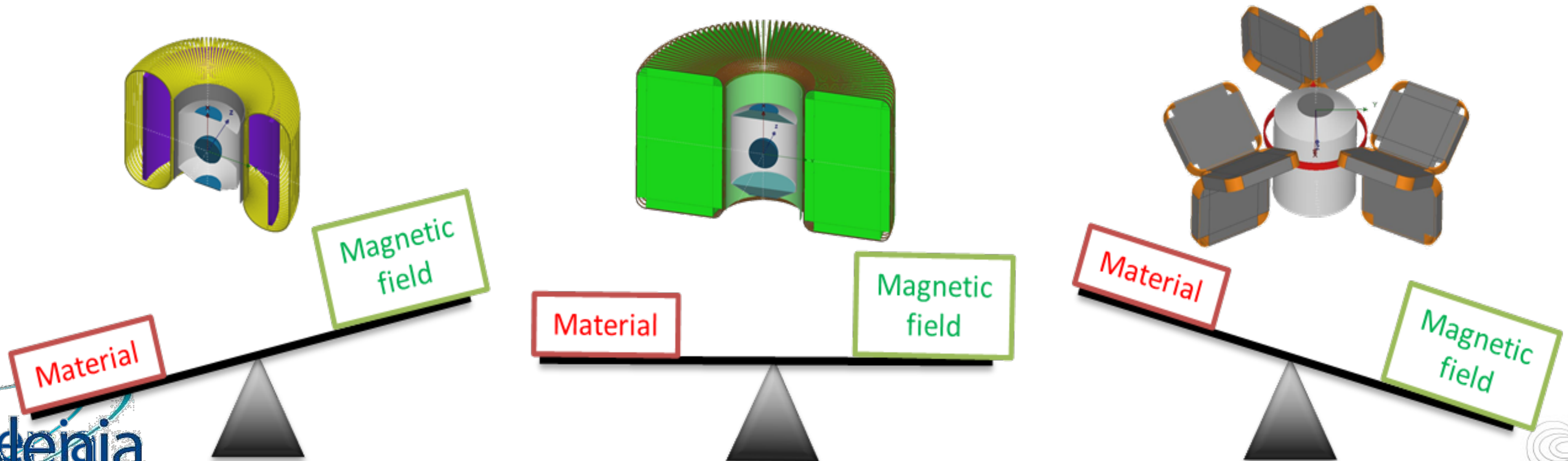
Comparisons against passive shielding

- Active shielding slightly lighter than passive one with same dose reduction
- MT3-MT4 first attempts of pumpkin configuration design,
- Necessity of a series of optimization to achieve better performances of active shielding
- Long term active shielding goal: to obtain same dose reduction with 1/3 of the passive mass



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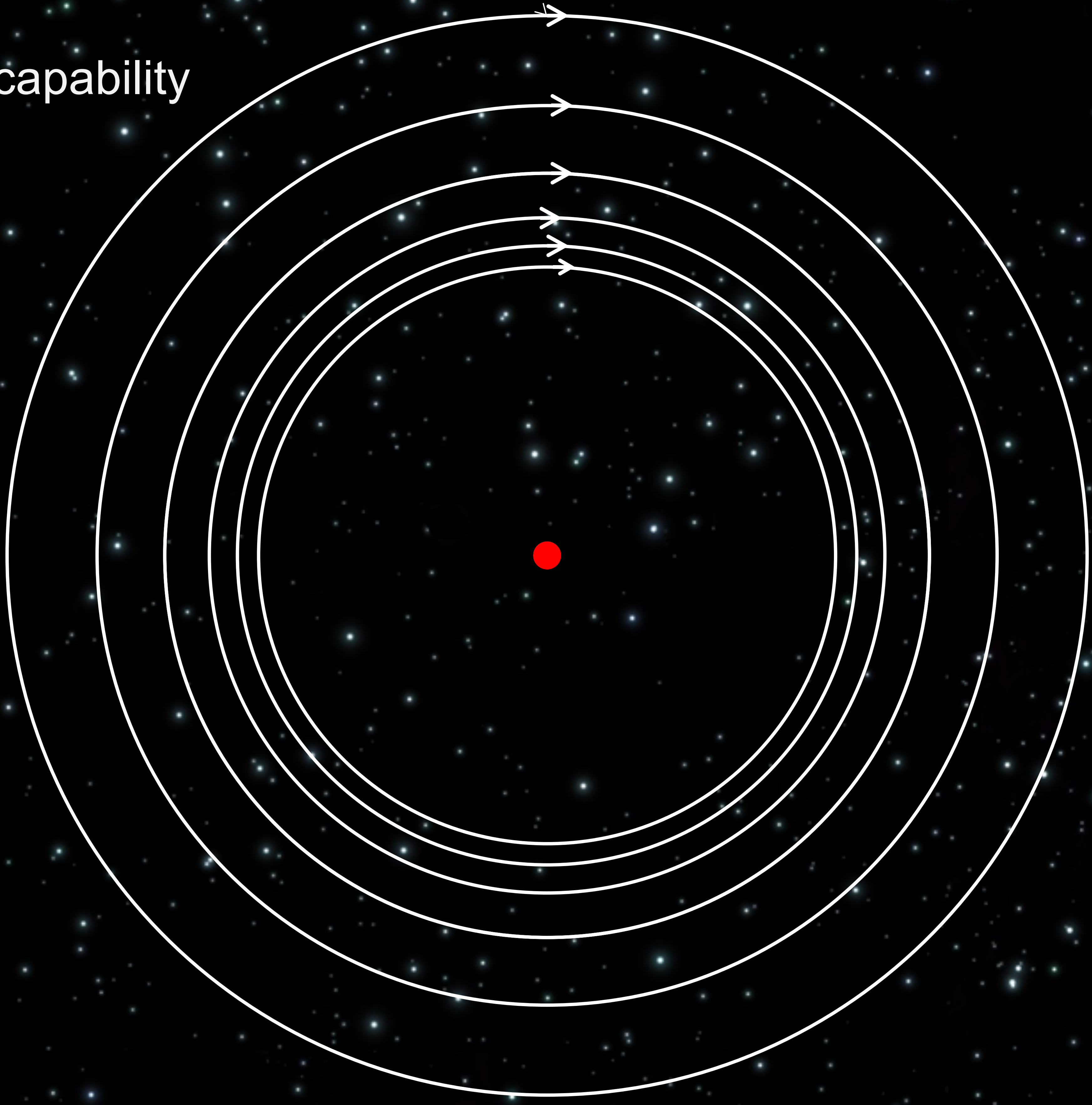
Evaluation of shielding capability of a toroidal field

Isotropic GCR flux

No matter

Infinitely long toroid

Punctual astronauts



Cut-off energy:

$$K(\Xi,\varphi) = \frac{m_0 c^2}{\eta}\left(\sqrt{1+\left(\frac{q}{m_0 c}\frac{\Xi}{(\alpha(r)-\sin\varphi)}\right)^2}-1\right)$$

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

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

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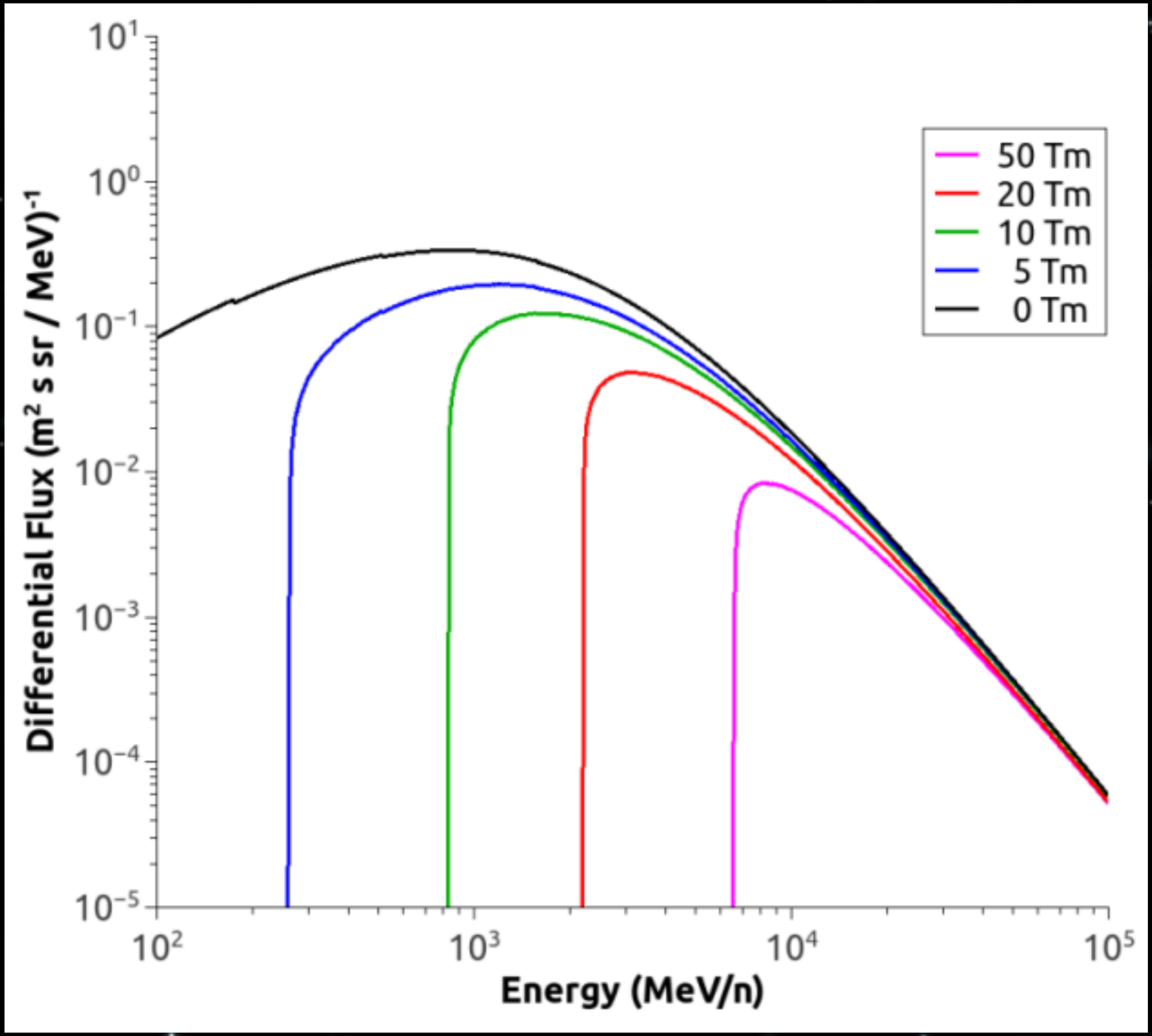
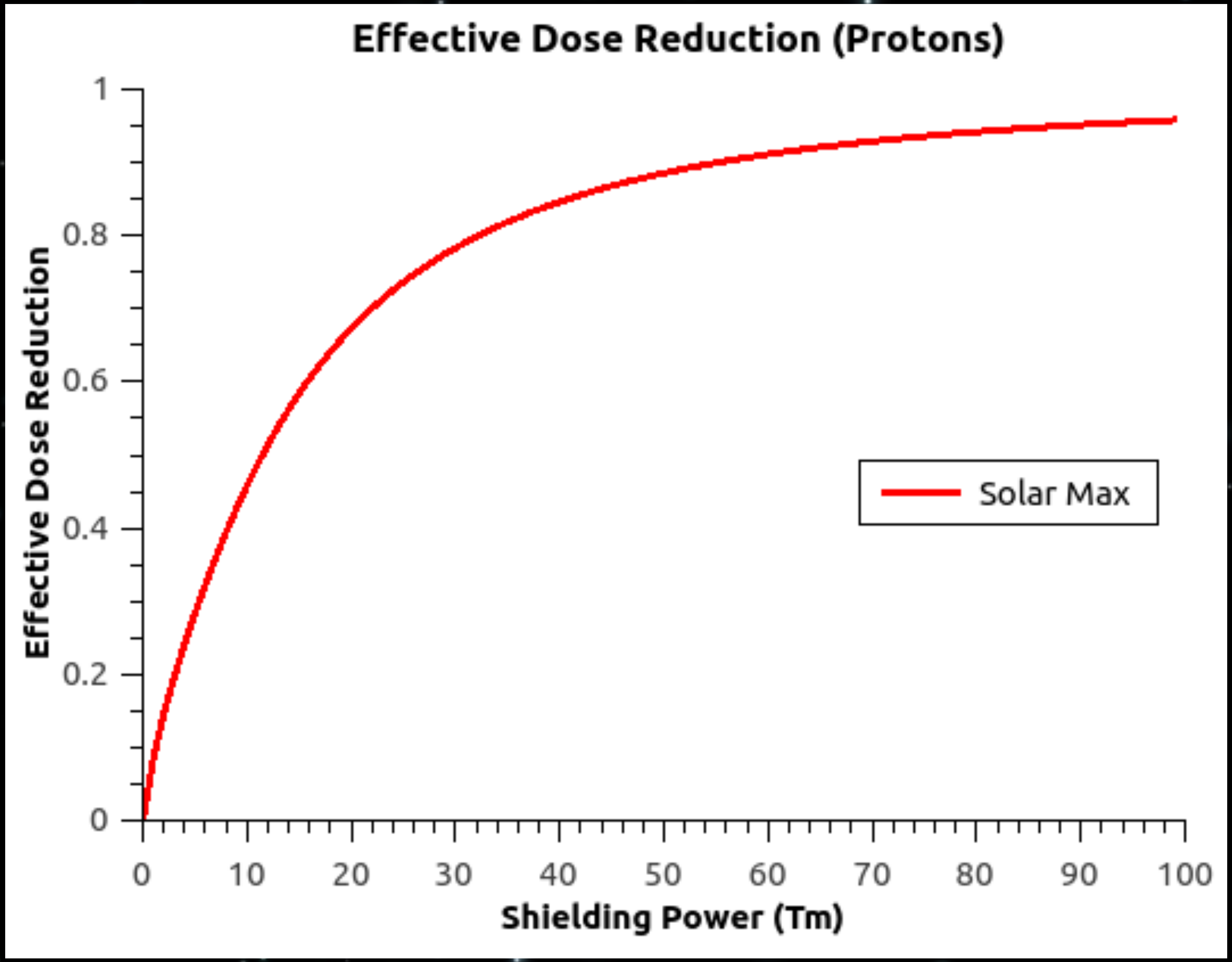


$$D_Z(\Xi) = \frac{1}{\pi} \int_{-\frac{\pi}{2}}^{\frac{\pi}{2}} d\varphi \int_{0}^{\epsilon_f} w_Z\,(\epsilon) Q_Z(\epsilon) \frac{\partial \Phi_Z(\epsilon)}{\partial \epsilon} \Theta\big(K_Z(\Xi, \varphi)\big) d\epsilon$$

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

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

R. Musenich, V. Calvelli - INFN



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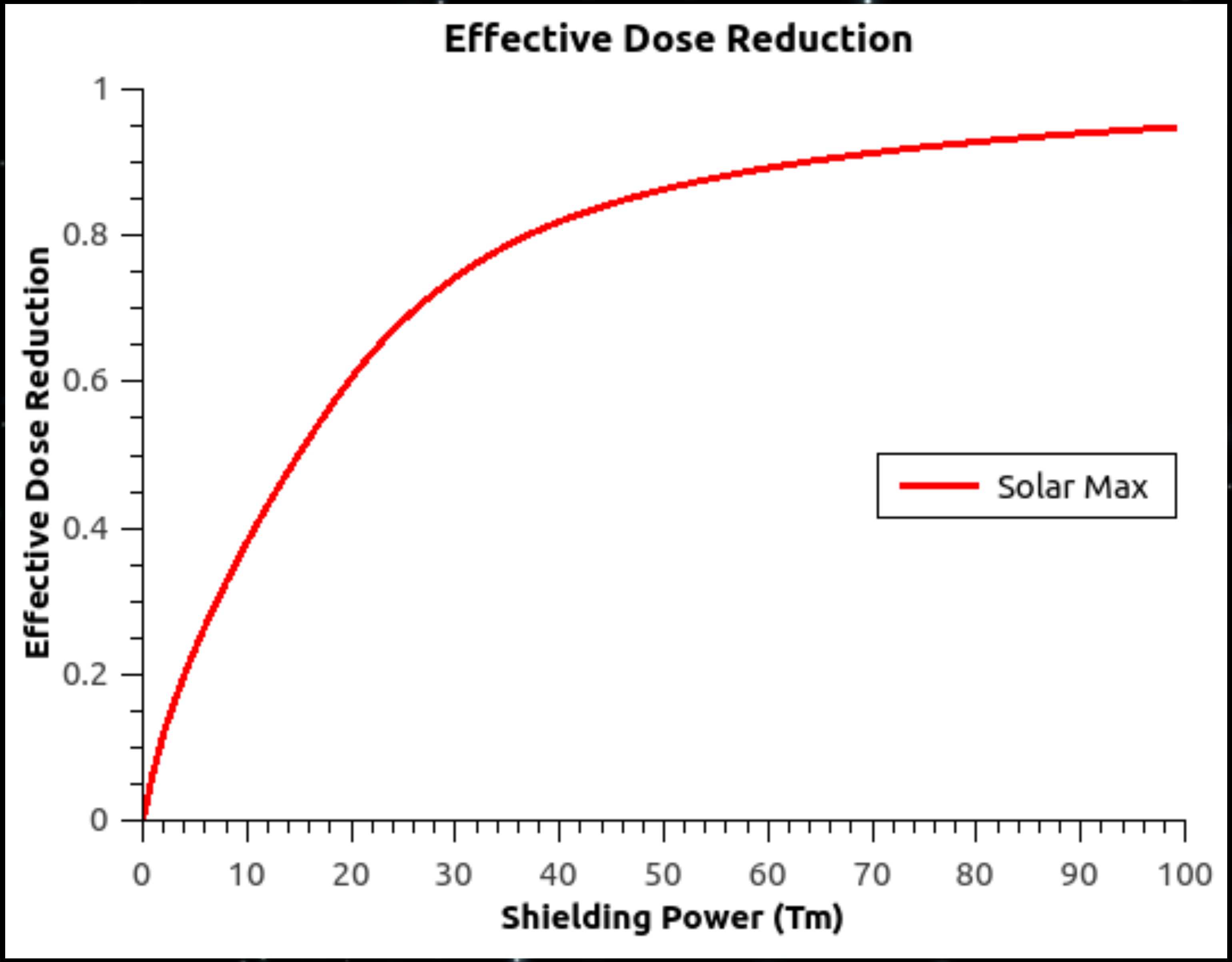


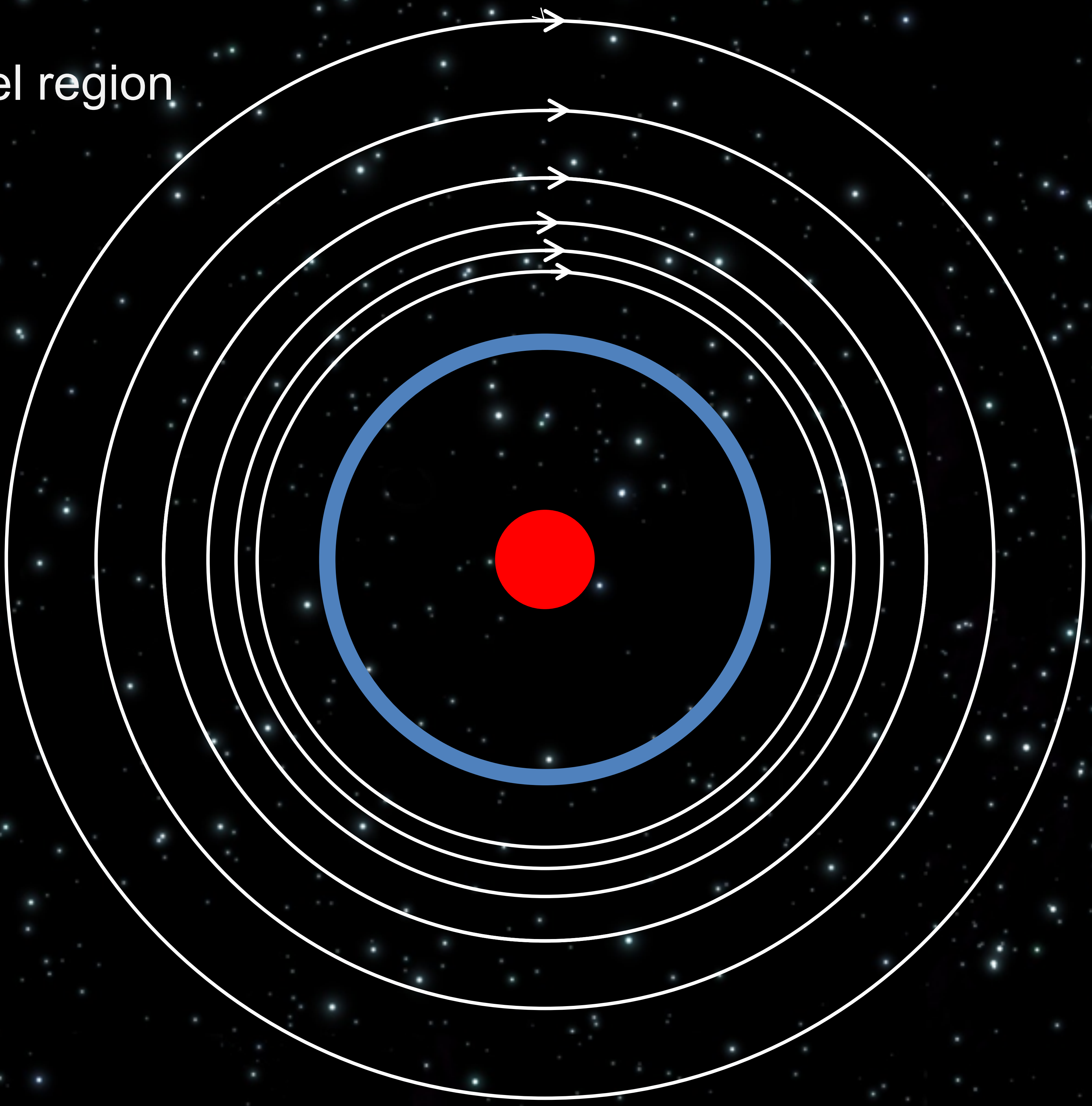
Monte Carlo simulations (ideal model)

GCR flux limited to the barrel region

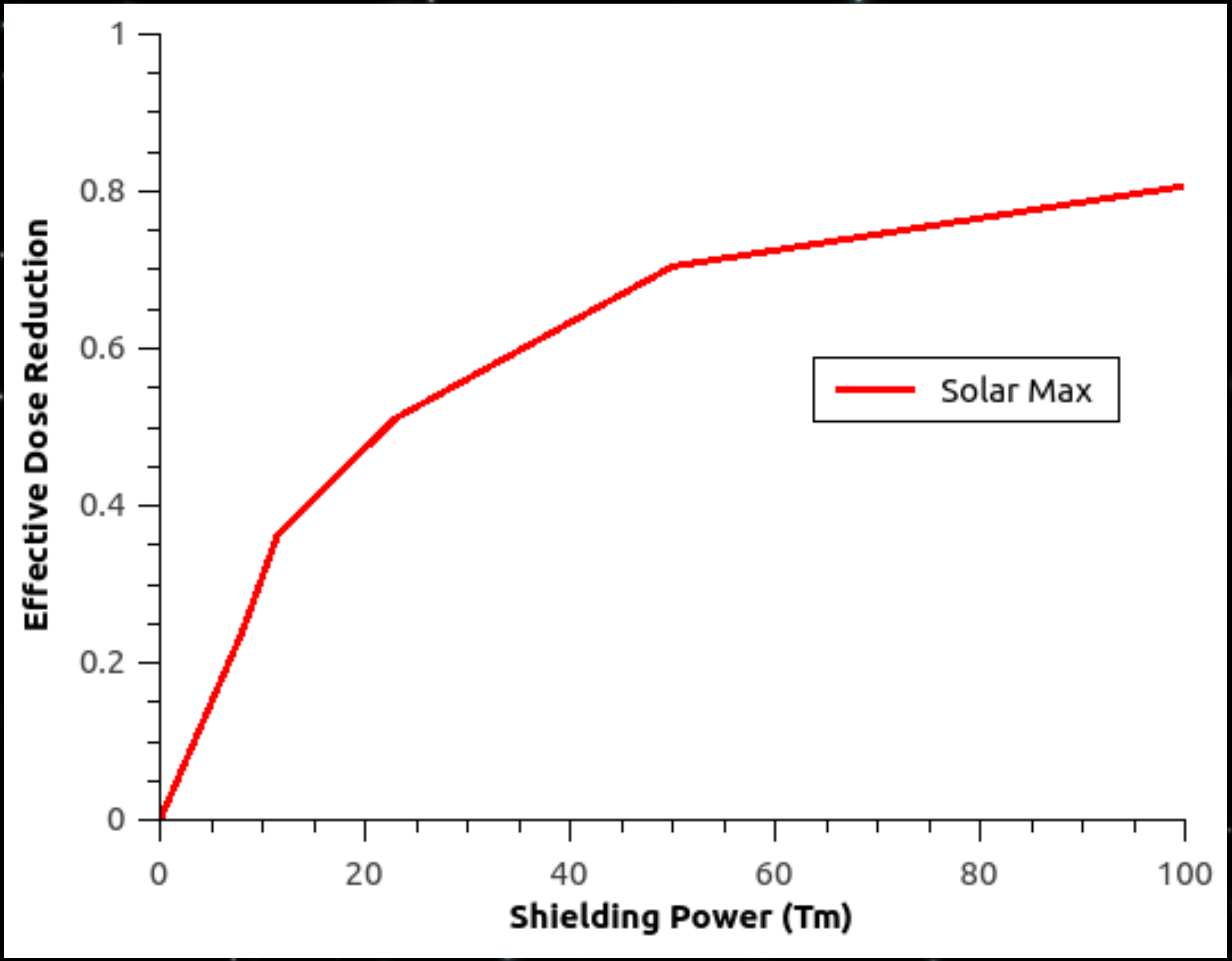
Immaterial magnet

Al spacecraft wall

Spheric astronauts



R. Musenich, V. Calvelli - INFN



- 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.

Previous Monte Carlo Studies

Configuration	1 Hoffman et al.	2 Choutko et al.	3 Spillantini et al.
Magnet Mass (t)	400-1600(1)	31 (2)	90 (3)
BL (Tm)	15,6	17	20,3
Flux reduction factor	10	4-7	10
Dose (rem/y)	9	13-24	-
Diameter/Length (m)	10/10	4/5,5	6/10
Shielded Volume (m^3)	269	69	282
3D Magnetic Transport	No	Yes	No
Full MC CR Simulation	No	Yes	No
Structural mass in MC	No	No	No

(1) total mass including coil, mechanical structure, cryocooler, liquid helium

(2) quoted as "magnet system weight"

(3) cold mass x 1,5

Table 5.1 Summary of previous studies on toroidal magnetic shield systems

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SEVENTH FRAMEWORK PROGRAMME

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

The SR2S Consortium

Istituto Nazionale di Fisica Nucleare

CERN

Commissariat a l'Energie Atomique

Thales Alenia Space Italia

Compagnia Generale dello Spazio

Columbus Superconductors

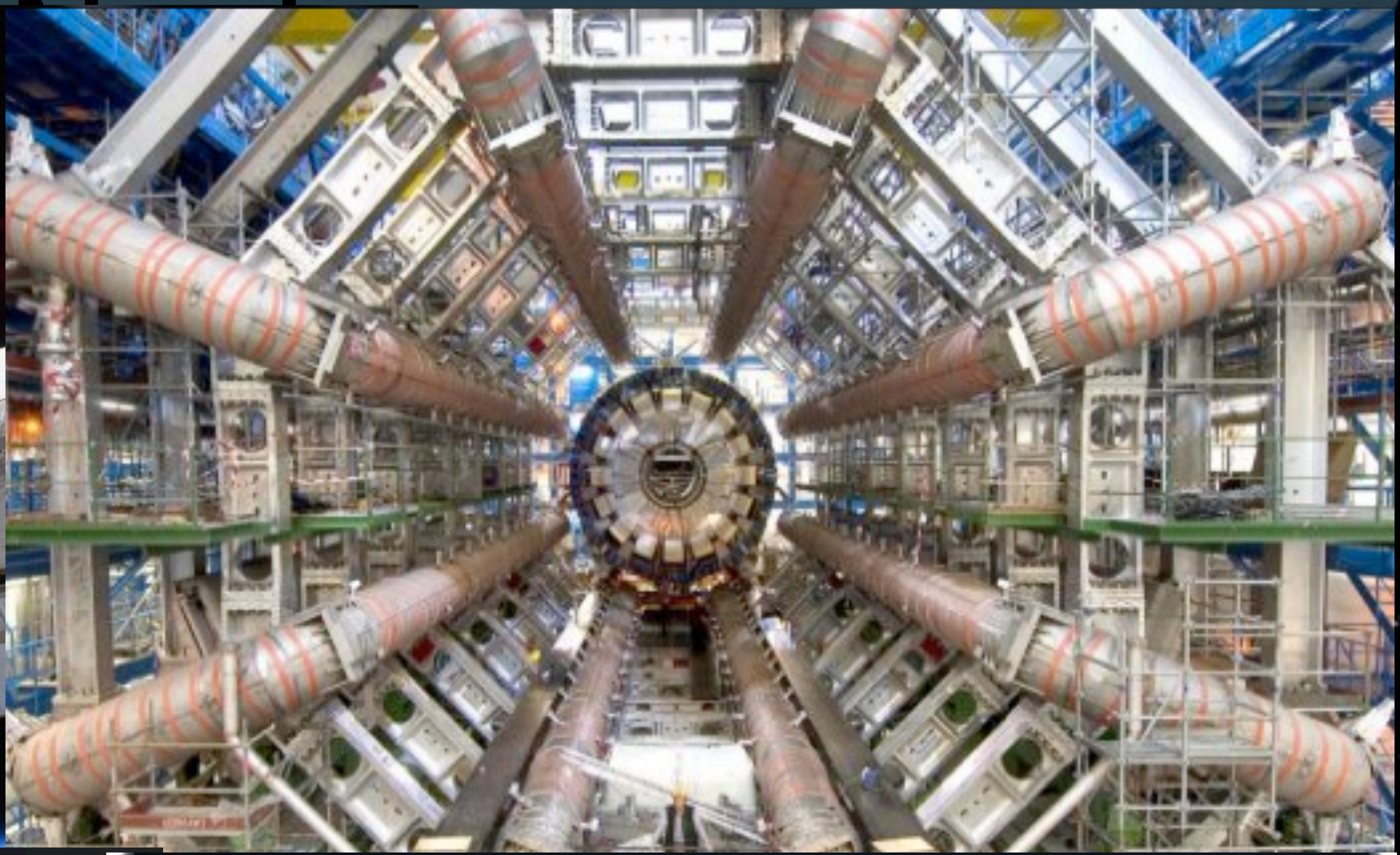
Carr Communication

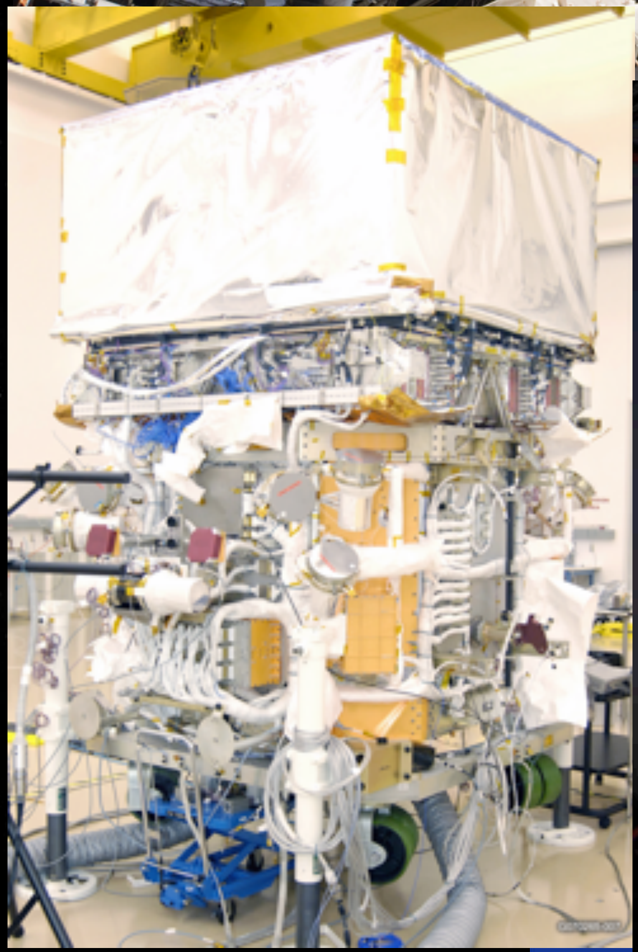
SR2S

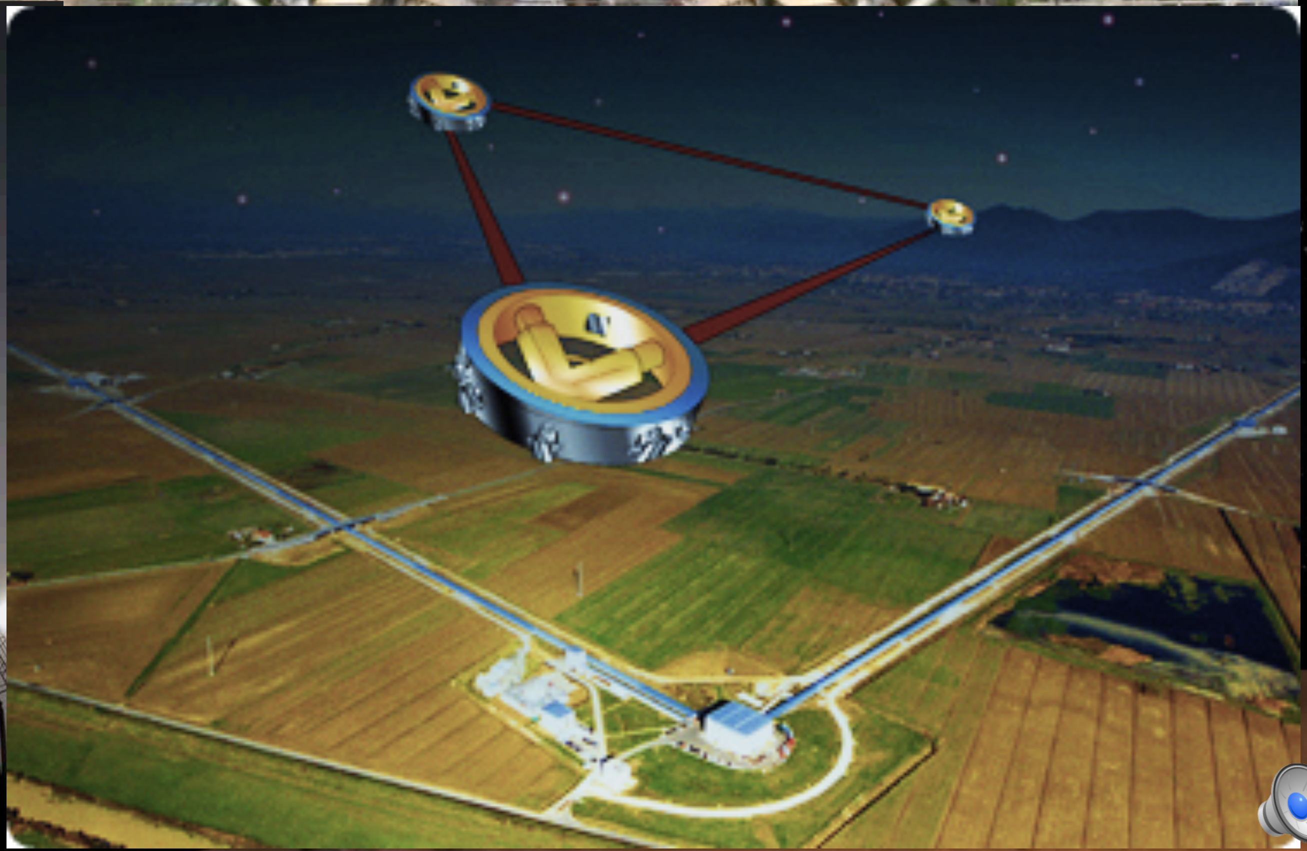
Space Radiation

Superconducting Shield

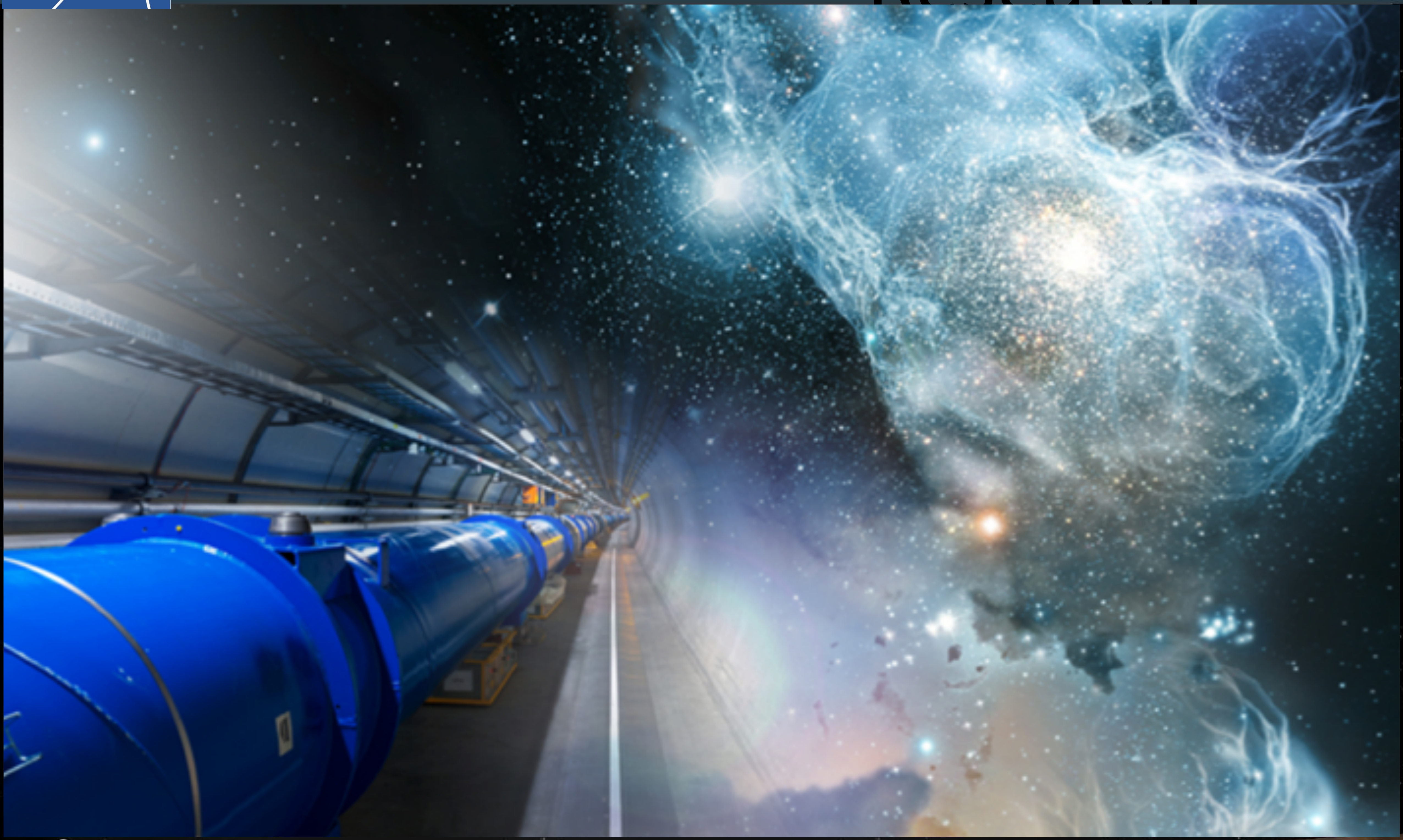
Istituto Nazionale di







European Laboratory for N Research



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SEVENTH FRAMEWORK PROGRAMME

Centre Energie Atomique

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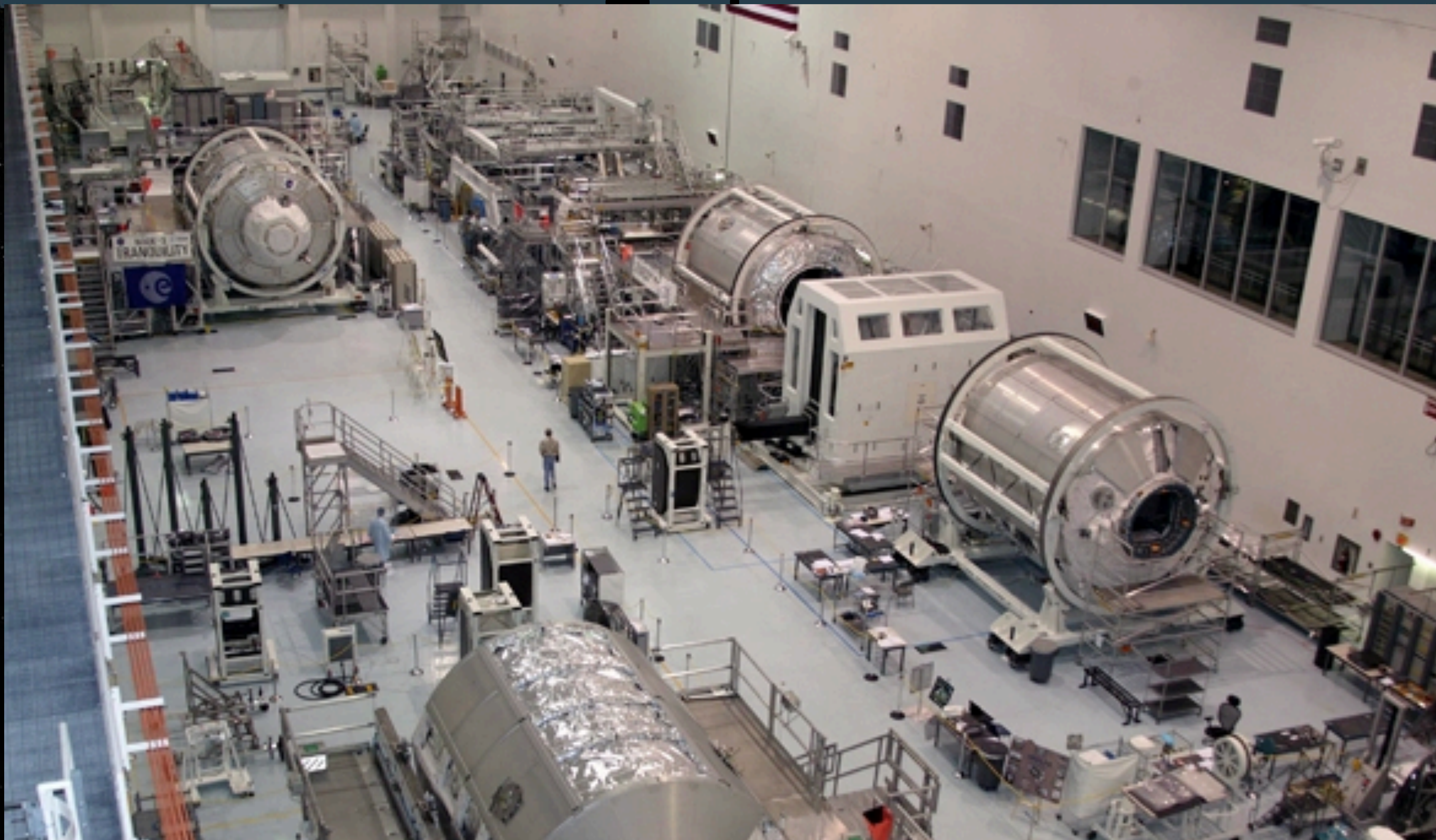

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SEVENTH FRAMEWORK PROGRAMME

Compania

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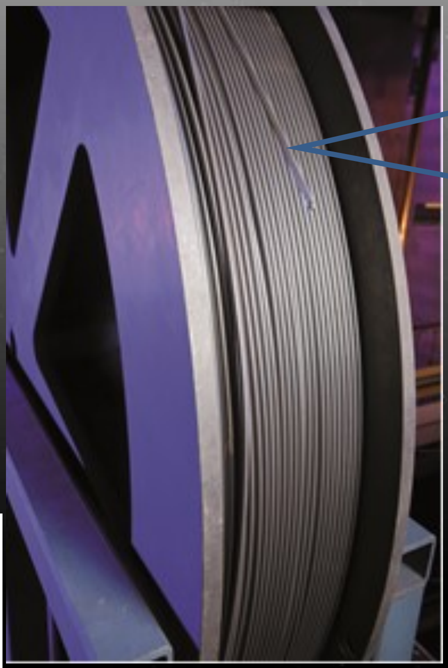
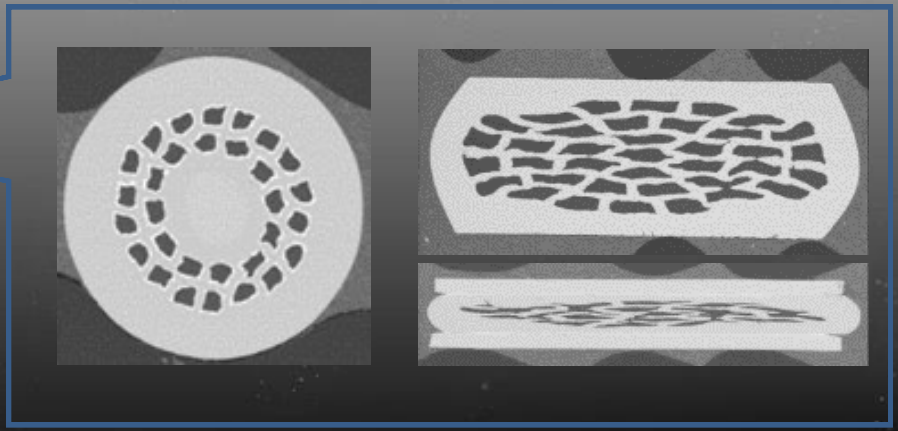
Superconducting Shield

SEVENTH FRAMEWORK PROGRAMME

The Company

- **Columbus** is a world leader in the production of the new superconductor **MgB_2**, that is distinguished for its workability in **long lengths** and **high performances**
- The actual plant is fully operational for **MgB_2 wire production** and has recently completed its scaling up (plant area now is **4’400 m^2)**
- **MgB_2 chemical synthesis** is now also fully implemented
- Wire unit length today possible up to **20 Km** in combination with a nominal plant full capacity exceeding **5’000 Km/ year**
- Columbus **MgB_2 production is** already **implemented in commercial products** and has a **long record** of fully tested and qualified wires





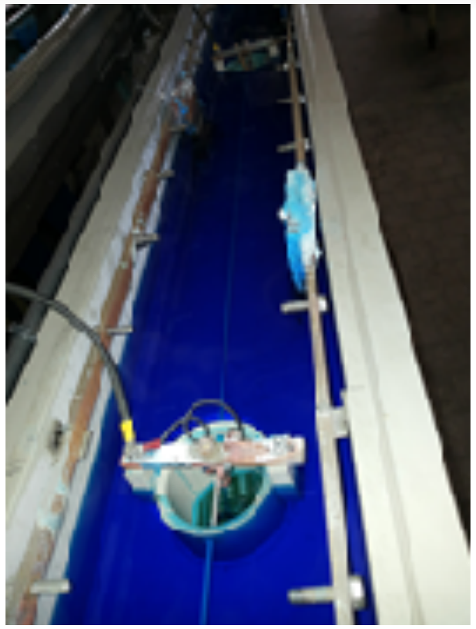
RESULTS OF SR2S

1. New magnetic configurations (pumpkins)
2. Full MC simulation (3D, Materials, Mag Field)
3. Interplay among neutron and charged radiation understood
4. New SC cable 40% lighter for space applications
5. New PHP large scale development
6. List of low TRL technologies

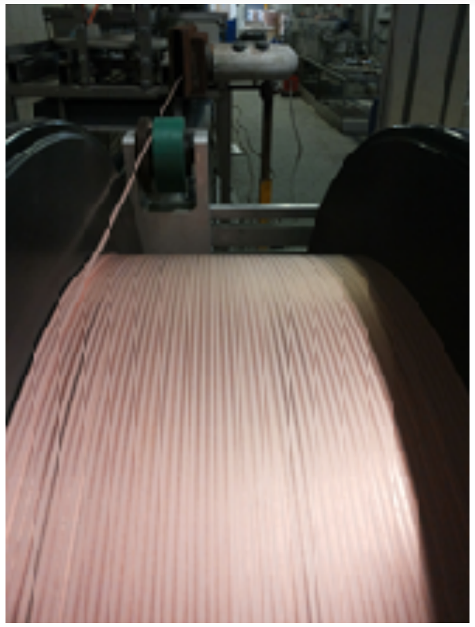
SR2S
Space Radiation Superconducting Shield

MgB2: new cable on Ti frame 40% lighter for space

360 m Ti-MgB_2

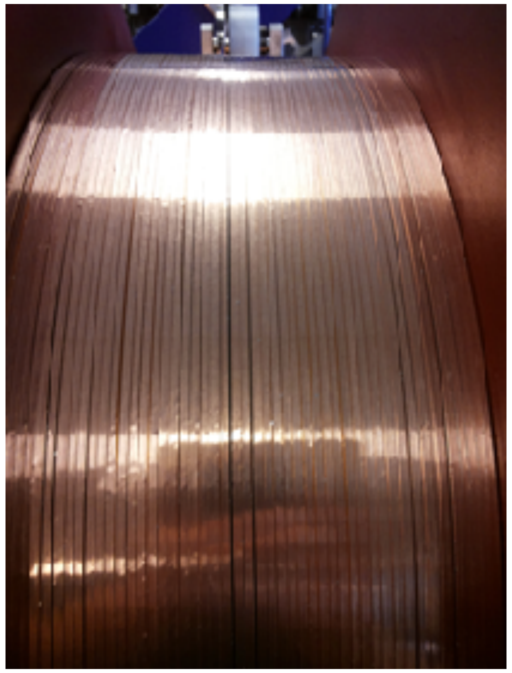


Ti-MgB_2 tape during copper plating



copper plated Ti-MgB_2 tape

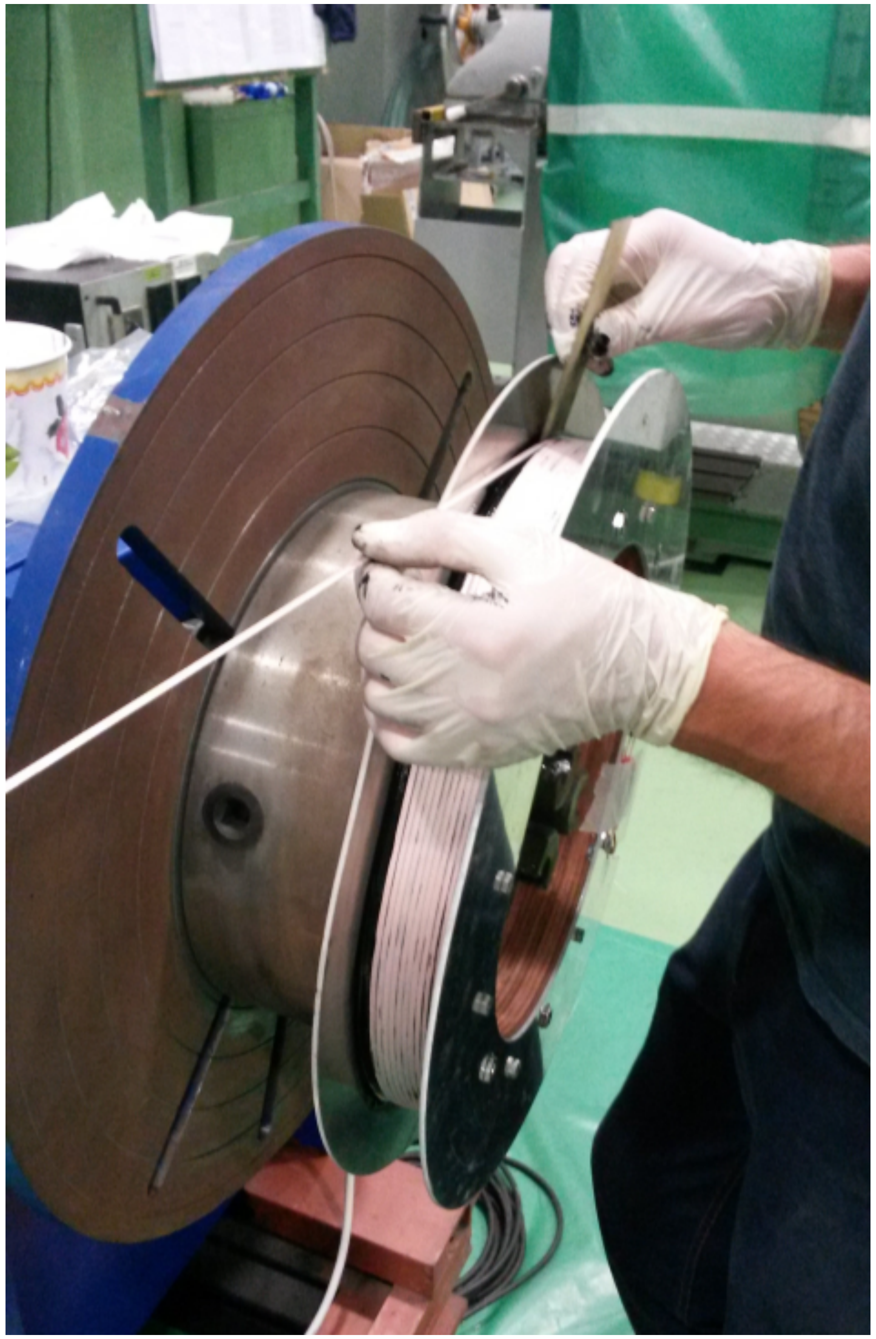
Ti-MgB_2 tape varnished before tin plating



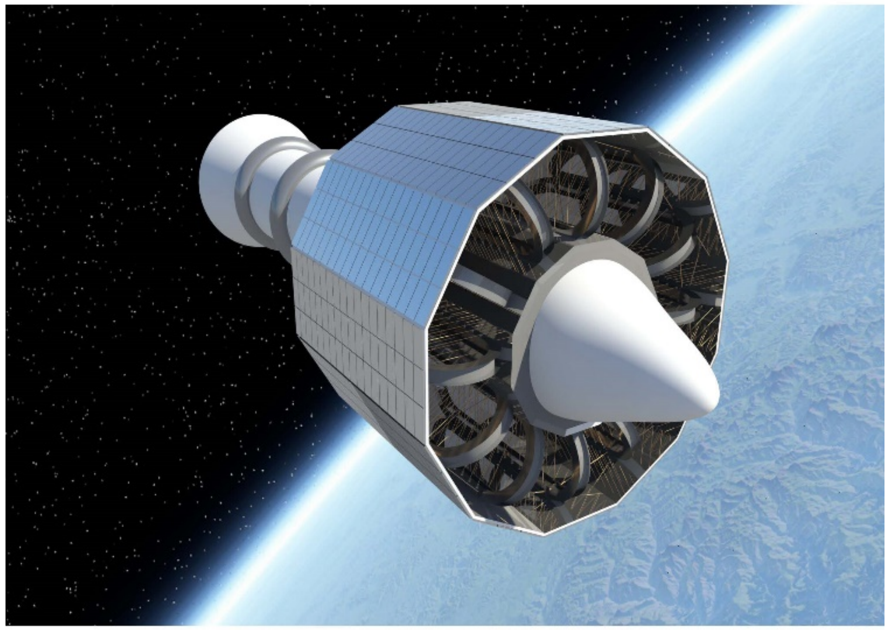
Cu-Ti-MgB_2 tape

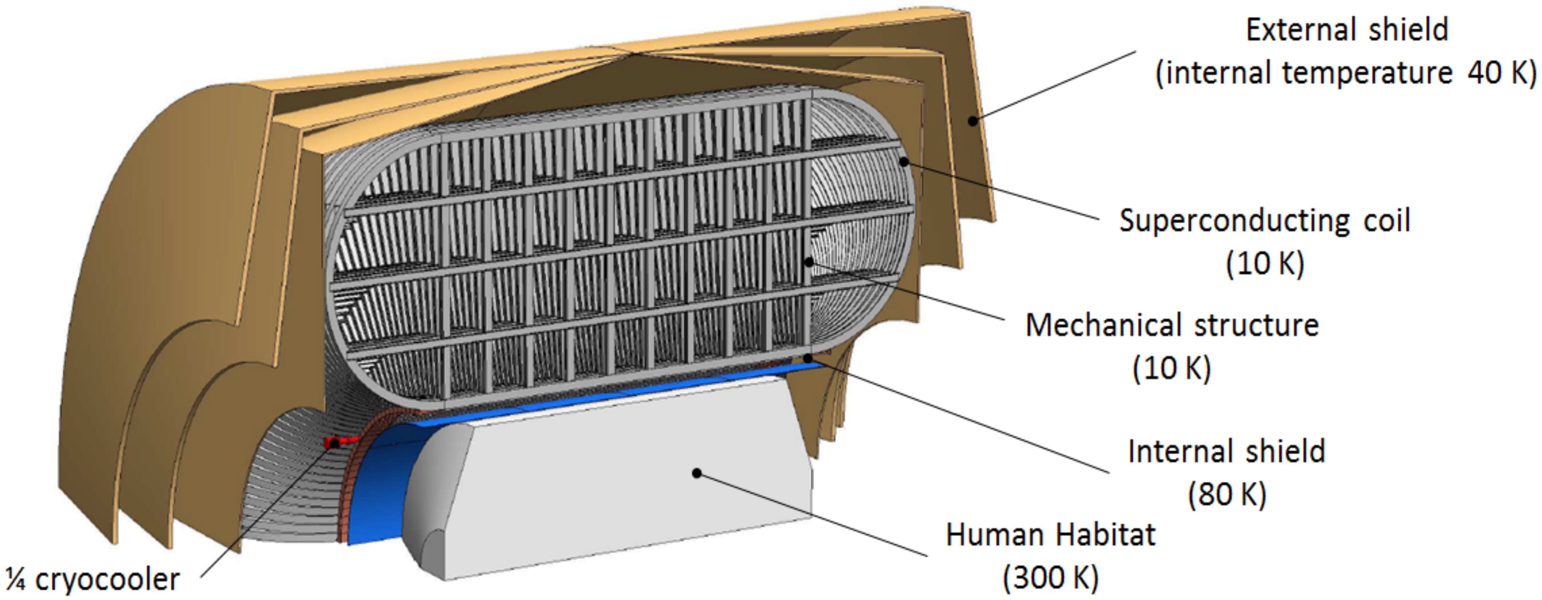
SR2S Space Radiation Superconducting Shield

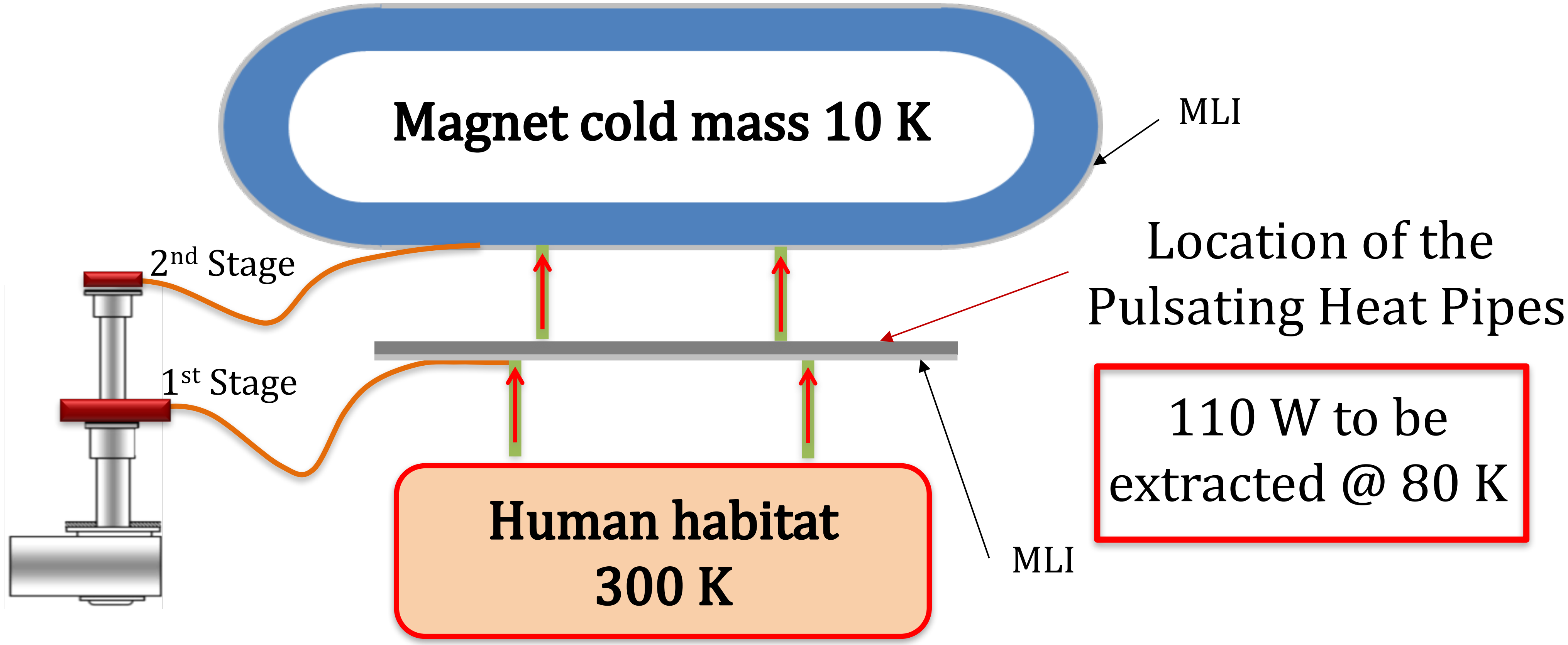
Winding of the prototype coil (racetrack)
Ti-MgB_2 tape + Cu strip



SPACE RADIATION SUPERCONDUCTING SHIELD

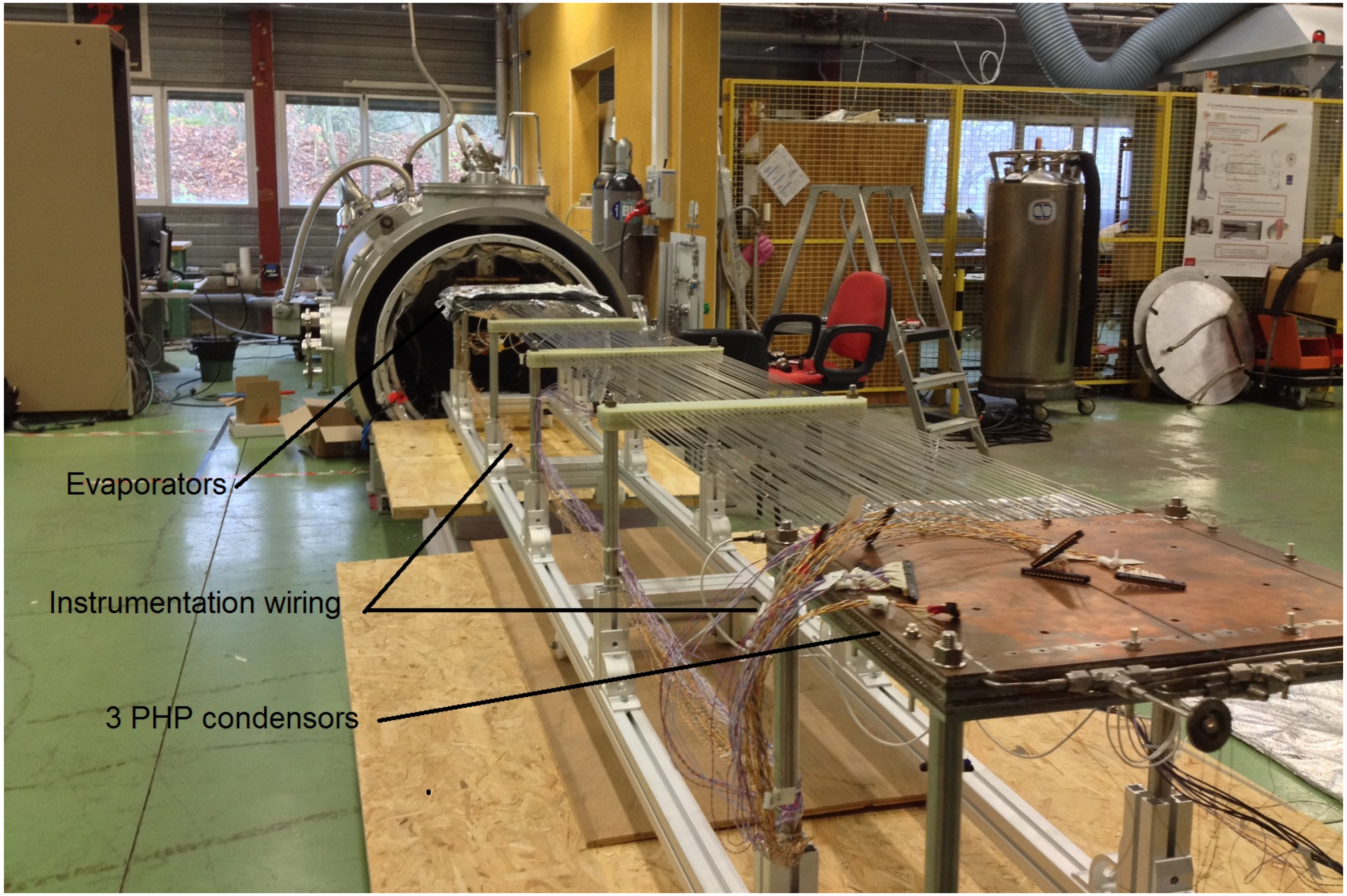






Experimental Study of Large-scale cryogenic Pulsating Heat Pipes

- SR2S PHP design and construction
  - Three PHPs : 12, 24 and 36 tubes

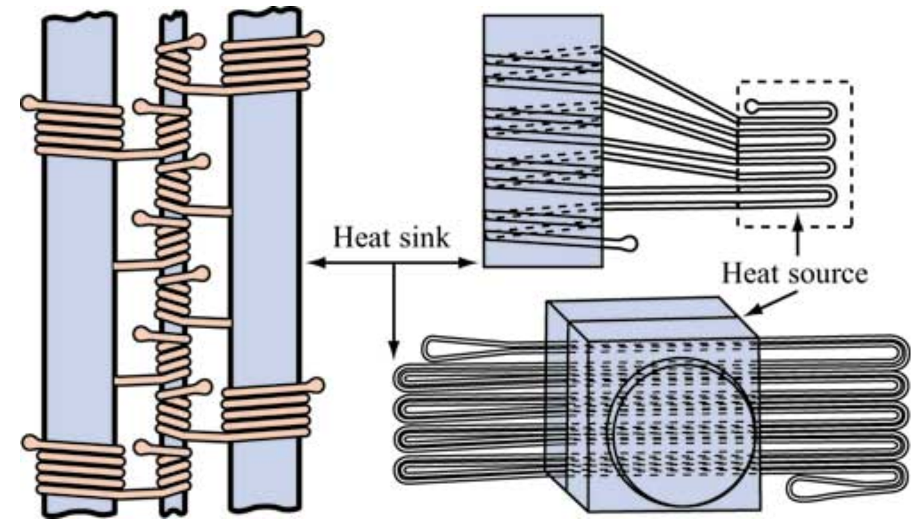


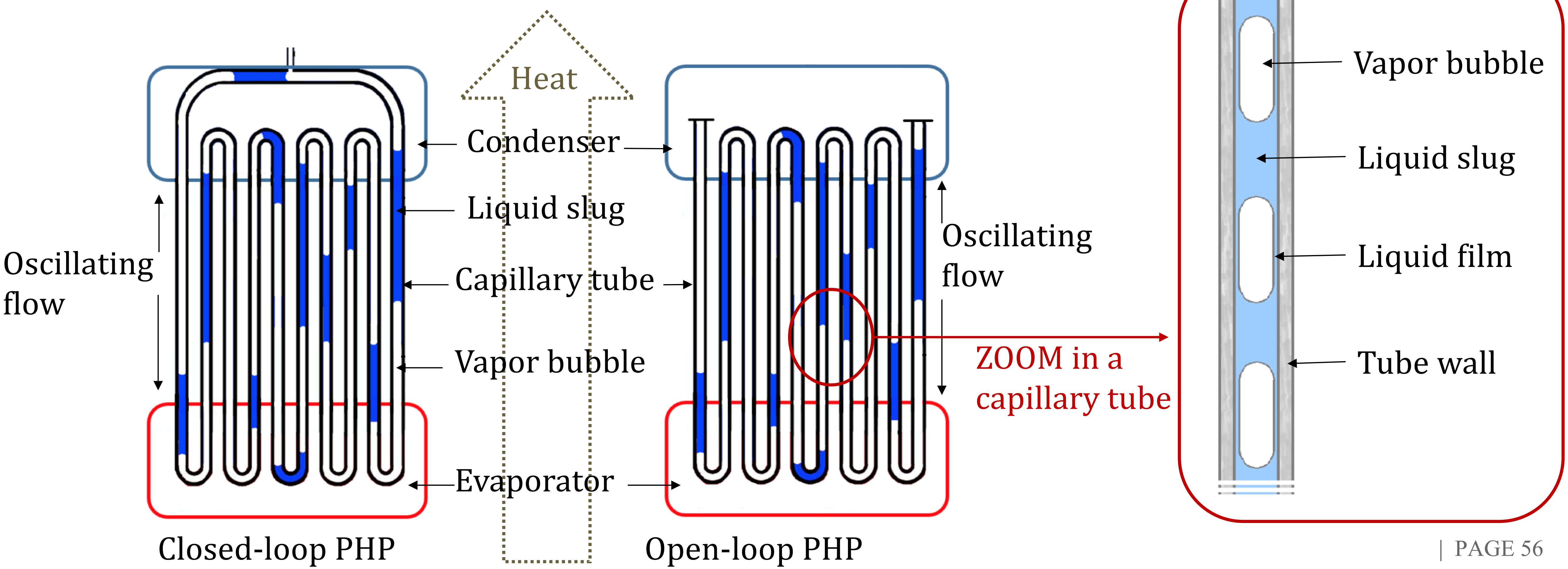
M.Barba, R.Bruce,B. Baudouy

SR2S
Space Radiation Superconducting Shield

PULSATING HEAT PIPES

- Pulsating or Oscillating Heat Pipe (PHP or OHP)
- Passive heat transfer device (without pumping system)
- Tube with capillary dimensions and serpentine shape
- At least one heating part and one cooling part
- Temperature and pressure conditions close to phase-change
- Different possible positions of the heating part: bottom-heating mode, top-heating mode and horizontal position

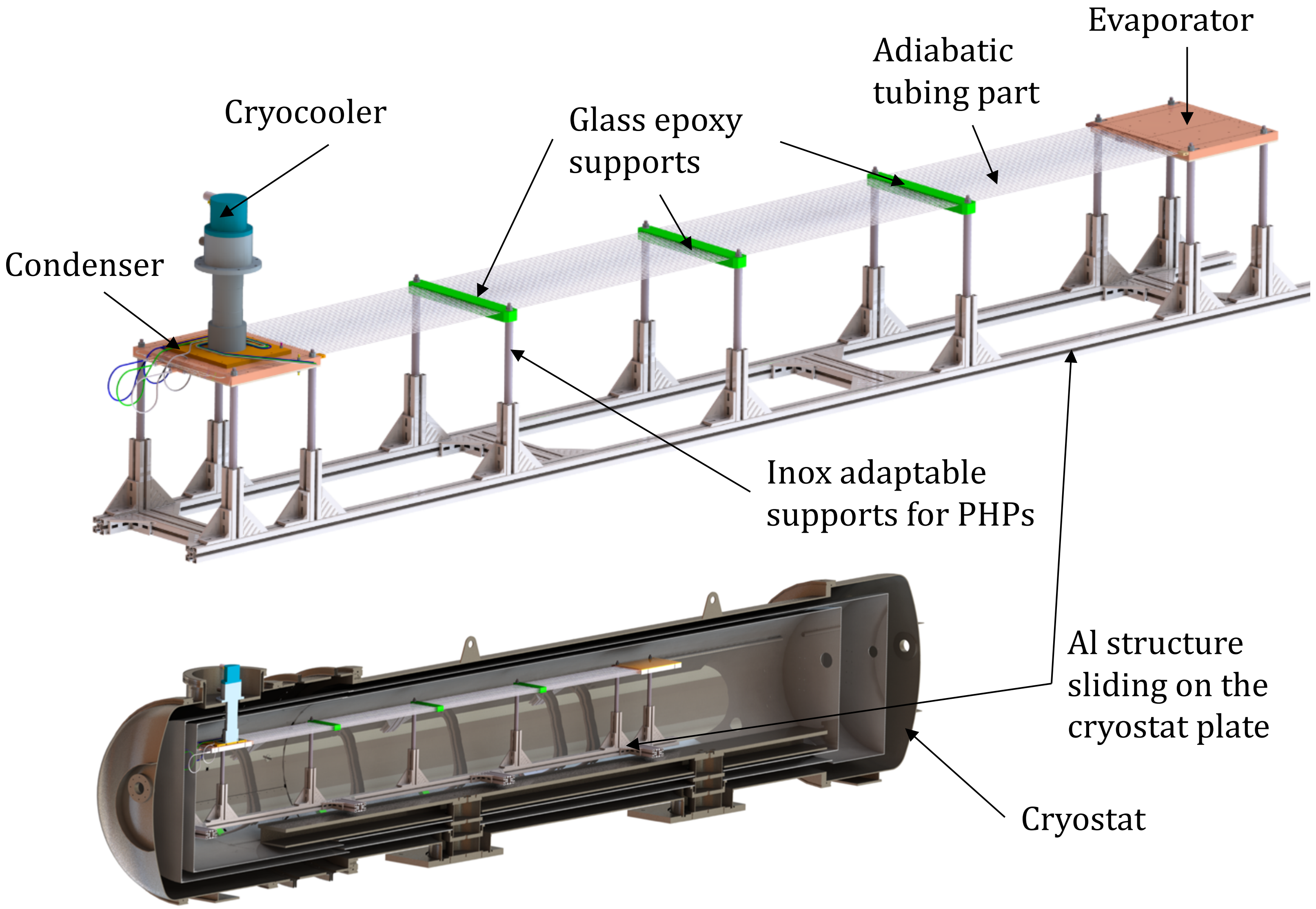




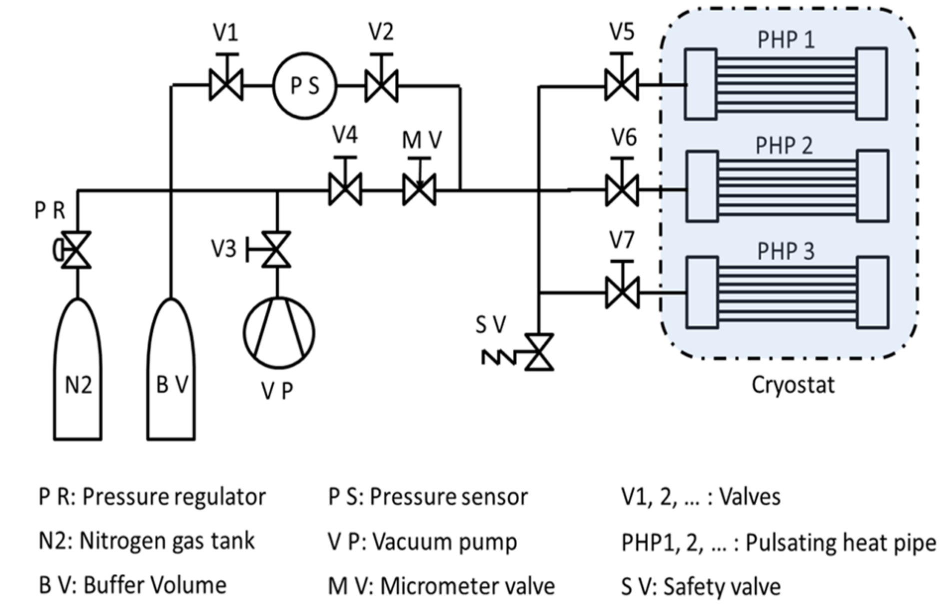
EXPERIMENTAL FACILITY

Characteristics

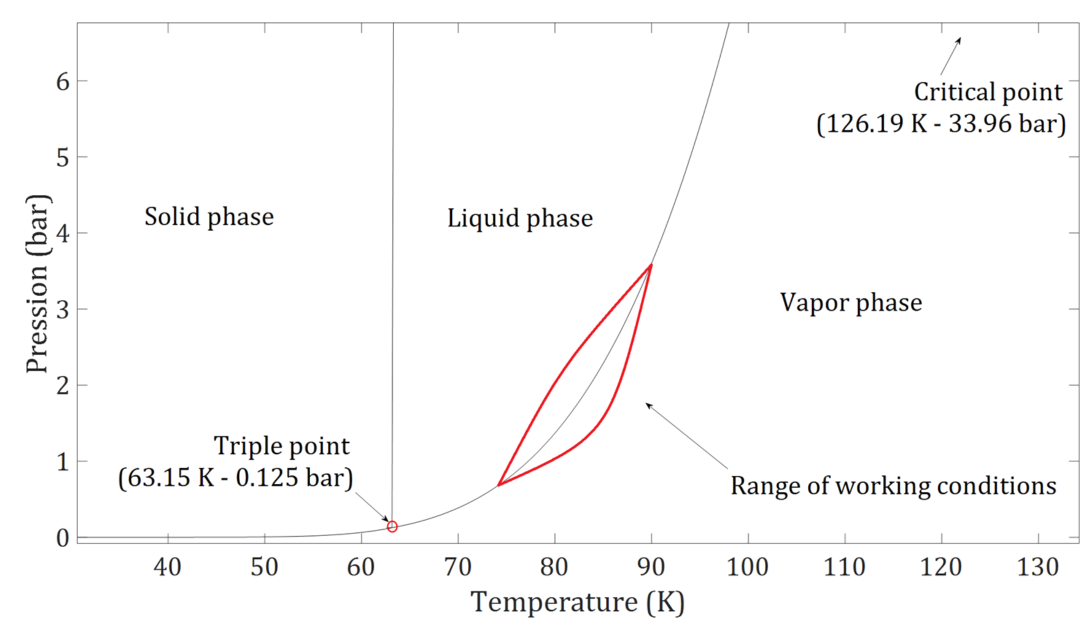
PHP	Position	Parallel tubes	Inner Ø	Outer Ø
3	Horizontal	12, 24 and 36	1.5 mm	2 mm
Material	**Working fluid**	**Total length**	**Liquid filling ratios**	**Heat load**
Stainless Steel	N_2	3.7 m and 1 m	20-90 %	5-10 W



Specific inlet gas system

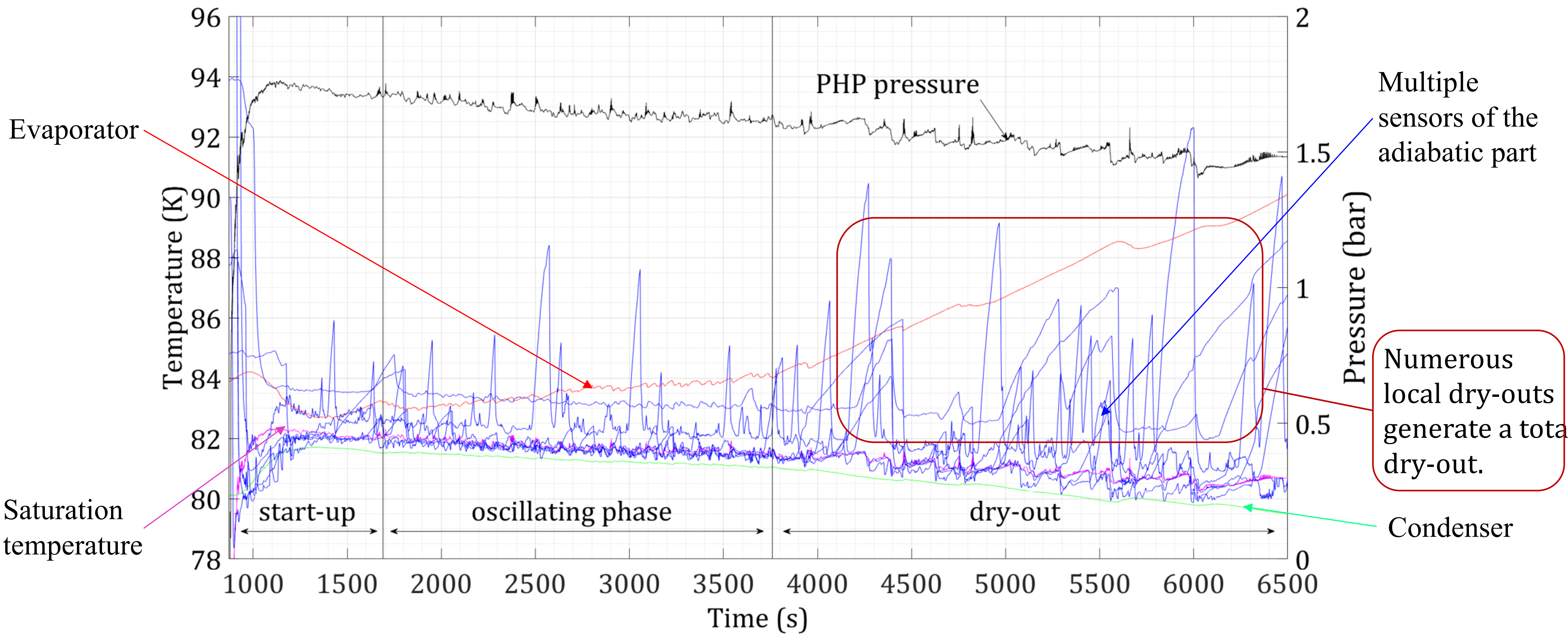


Nitrogen phase diagram



3-M LONG CONFIGURATION: RESULTS

Best results achieved with the Pulsating Heat Pipe of 36 parallel channels
(Heat load of 10 W and liquid filling ratio of 33%)

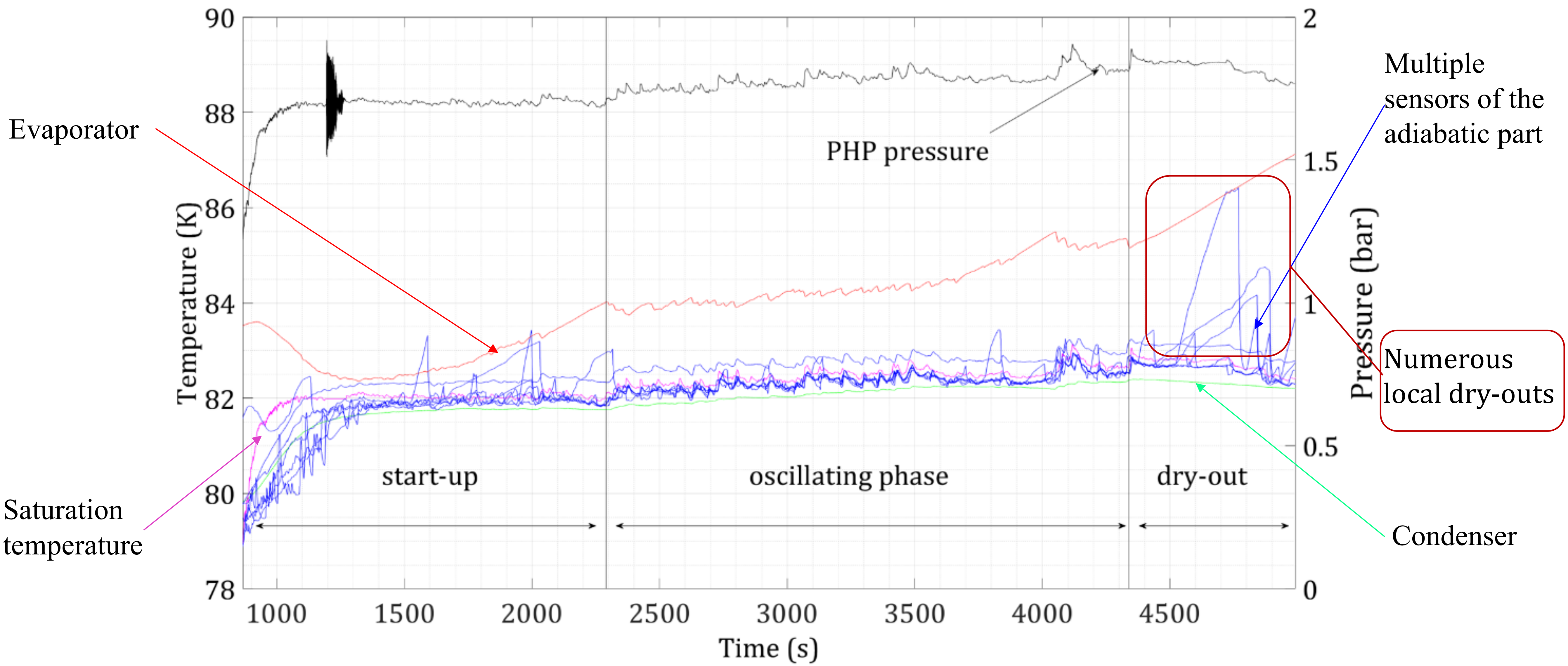


- Buffer volume connected to the PHP.
- Equivalent thermal conductivity during the oscillating phase (35 minutes): 350-160 kW/m.K

Unpredictable dry-out!

3-M LONG CONFIGURATION: RESULTS

Best results achieved with the Pulsating Heat Pipe of 36 parallel channels
(Heat load of 10 W and liquid filling ratio of 33%)

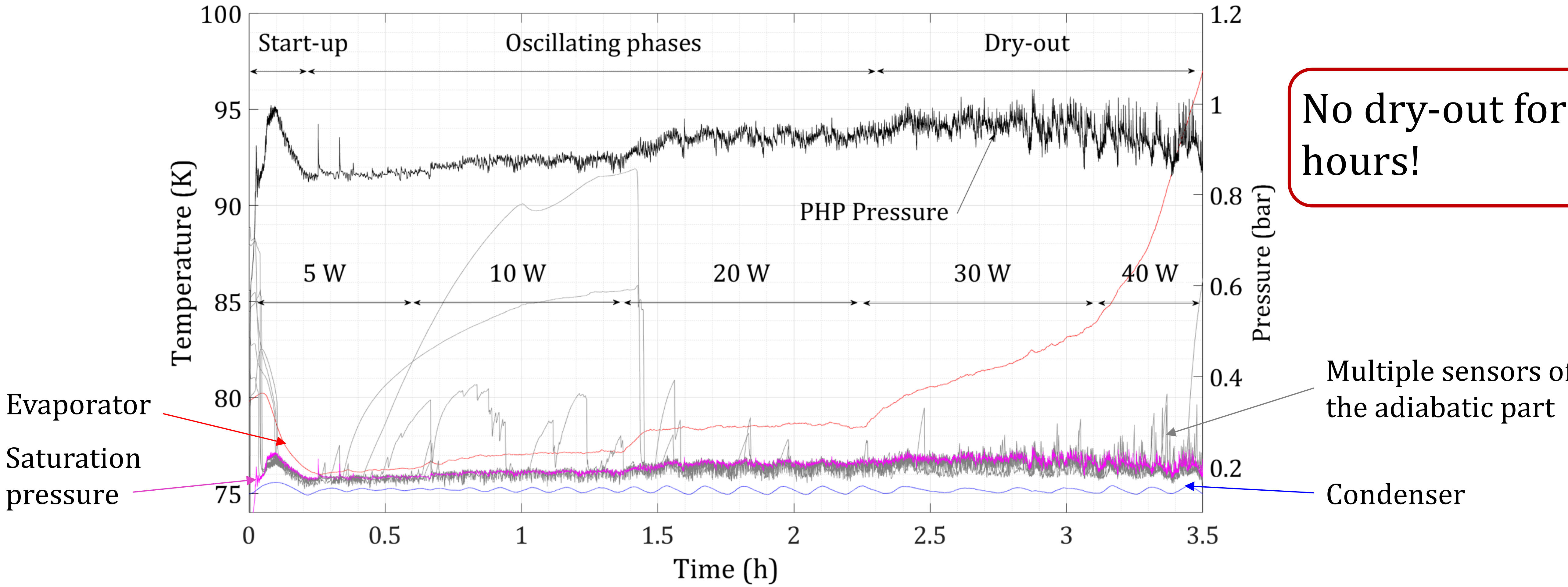


- Buffer volume not used.
- Equivalent thermal conductivity during the oscillating phase (35 minutes): 290-190 kW/m.K

Unpredictable dry-out!

NEW CONFIGURATION: RESULTS

Best results achieved with the Pulsating Heat Pipe of 36 parallel channels (Variable heat loads and liquid filling ratio of 30-40%)

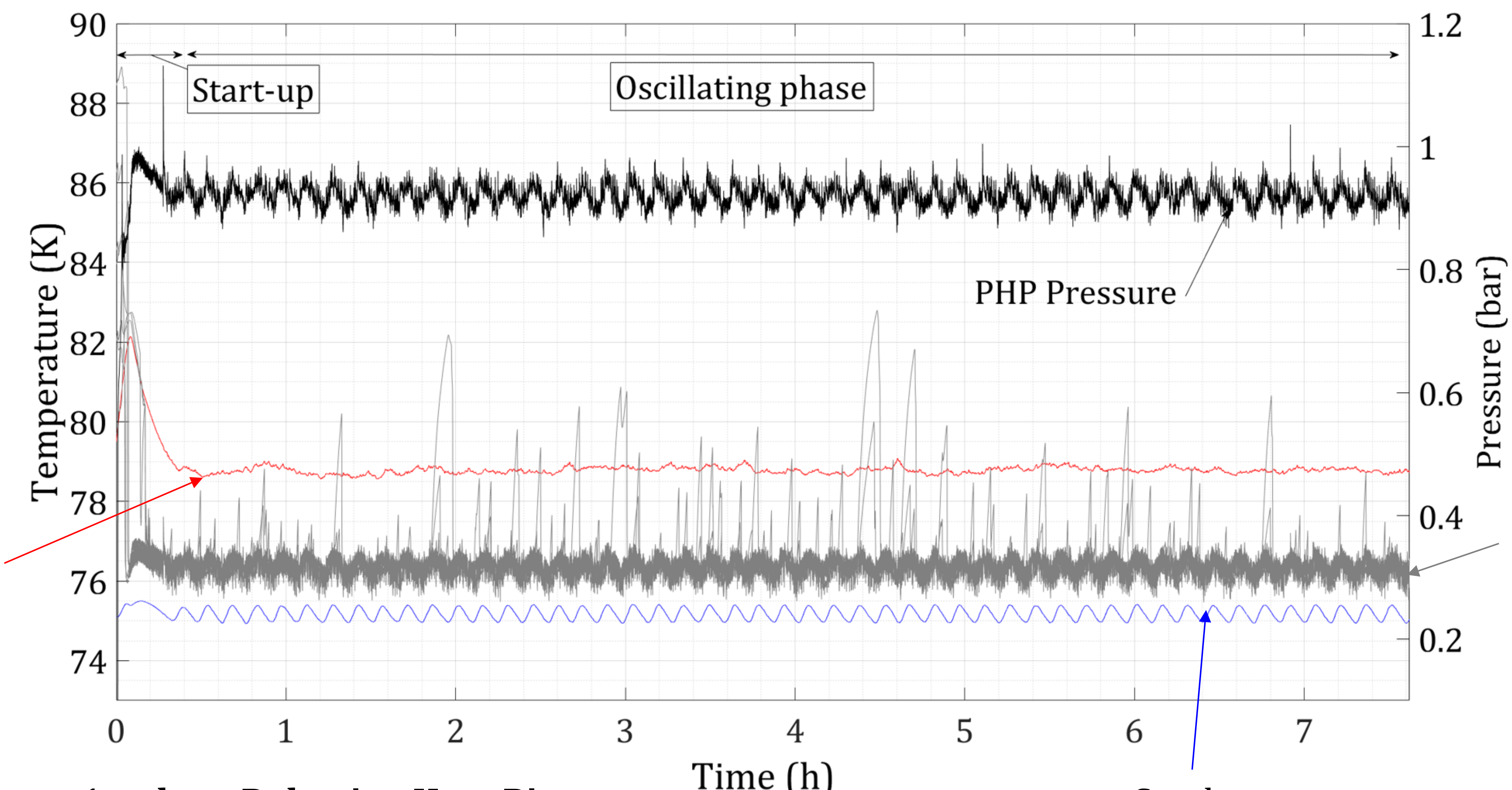


No dry-out for hours!

- **1-m long Pulsating Heat Pipe**
- Buffer volume connected to the PHP.
- Numerous very stable oscillating phases.
- Maximum equivalent thermal conductivity 95 kW/m.K (at 20W).
- The equivalent thermal conductivity is lower because the length of the experimental facility has been reduced.

NEW CONFIGURATION: RESULTS

Stability tests: Pulsating Heat Pipe of 36 parallel channels
(Fixed heat load of 20 W and liquid filling ratio of 35%)



Evaporator

Multiple sensors of the adiabatic part

Condenser
(The temperature of the condenser is fixed with a control system which generates oscillations).

- **1-m long Pulsating Heat Pipe**
- Buffer volume connected to the PHP.
- Very stable oscillating phase during more than 7 hours.
- **Equivalent thermal conductivity: 89 kW/m.K almost 160 times higher than copper!**

Critical technologies and TRL

We have identified *10 Critical Technologies* which would need significant *R&D* to meet the requirements of an active shield for Space Exploration.

Critical Technology #1 *ITSC* and *HTSC* wires of better suitable quality (*MgB_2, YBCCO*

Critical Technology #2 Lightweight coils, configuration, design and assembly

Critical Technology #3 Cryogenically stable, light mechanics

Critical Technology #4 Gas/liquid based recirculating large cooling systems

Critical Technology #5 Cryo-coolers operating a low temperature

Critical Technology #6 Magnetic field flux charging devices

Critical Technology #7 Quench protection for ITS/*HTS* coils

Critical Technology #8 Space deployment and assembly of magnetic elements

Critical Technology #9 Super cryo-insulation, radiation shielding, heat removal

Critical Technology #10 Superconducting Cable splicing in space

SR2S Space Radiation Superconducting Shield

Conclusions (1)

- The SR2S project studies one of the most challenging magnet systems ever considered
- Various of the technologies for such a space superconducting system do not exist yet
- SR2S is an extraordinary technology development field and technology driver

SR2S Space Radiation Superconducting Shield

Conclusions (2)

- Active Radiation Shielding for exploration is a necessity
- Passive shielding for GCR is not adequate and for SPE can only protect limited volumes
- Active magnetic shielding becomes effective at high $\int BdL$ values and only if the material thickness traversed by the GCR is "small"
- Interplay between active and passive shielding is complex and detailed simulations are needed to understand it

SR2S
Space Radiation Superconducting Shield

Conclusions (3)

- Optimization of magnetic and structural forces is mandatory
- The SR2S has developed the basic tools for active shield analysis, started a systematic investigation and achieved important technological developments
- R&D path towards future developments for *light, high field, modular* toroidal shield design has been identified
- Collaboration and synergy with NASA, ESA and EU
- Perspectives for applications in physics, astrophysics medical sciences, in space and on ground

SR2S
Space Radiation Superconducting Shield


Thank you !