Starburst Galaxy M82

Credit: NASA, ESA, and the Hubble Heritage Team (STScI/AURA) , Apr 24, 2006

MAARSS

Magnet Architectures and Active Radiation Shielding Study with High Temperature Superconductors

Presentation to the SR2S Workshop

April 9, 2014

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William Burger, Ph.D. – INFN, University of Perugia, Italy
Andrew Ilin, Ph.D. – Ad Astra Rocket Company
Shaun Nerolich – Capstone
Scott Washburn, Ph.D. – University of Colorado, Boulder

Active Shielding – A New Approach

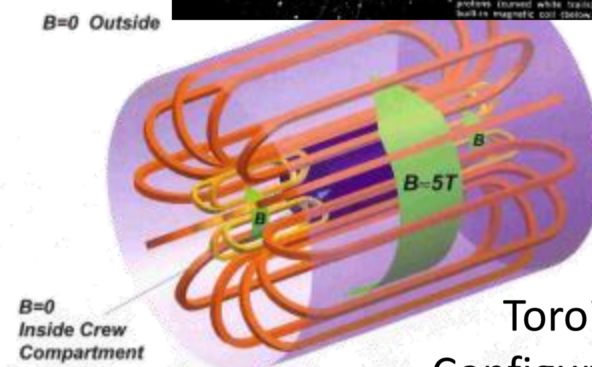
- Recent advances in superconducting magnet technology and manufacturing have opened the door for re-evaluating active shielding solutions as an alternative to mass prohibitive passive shielding

- Main Objectives
  - Analyze new coil configurations with maturing superconductor technology
  - Develop vehicle-level concept solutions and identify engineering challenges and risks
  - Shielding performance analysis

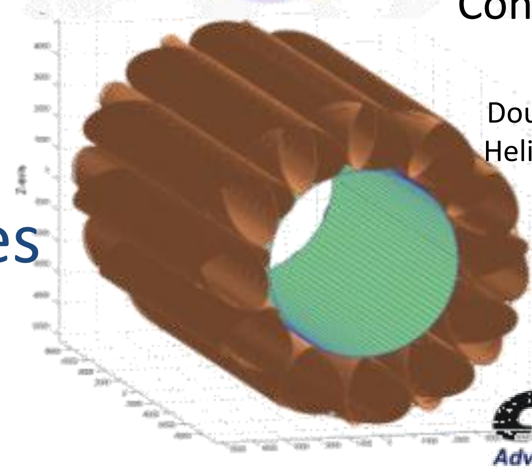
Phase 1 Report http://www.nasa.gov/directorates/spacetech/niac/westover_radiation_protection.html

A Foundation in Active Shielding

- Wernher von Braun, 1969
  - Mighty Magnets, Superconductivity
- J. C. Sussingham, 1999
  - Significant list of references
- L.W. Townsend, 2000
  - Active shielding summarized
- J.Hoffman, 2005
  - NIAC LTS toroid, AMS
- Battiston, 2011
  - ARSSEM, Double Helix Toroid
- Among many other studies



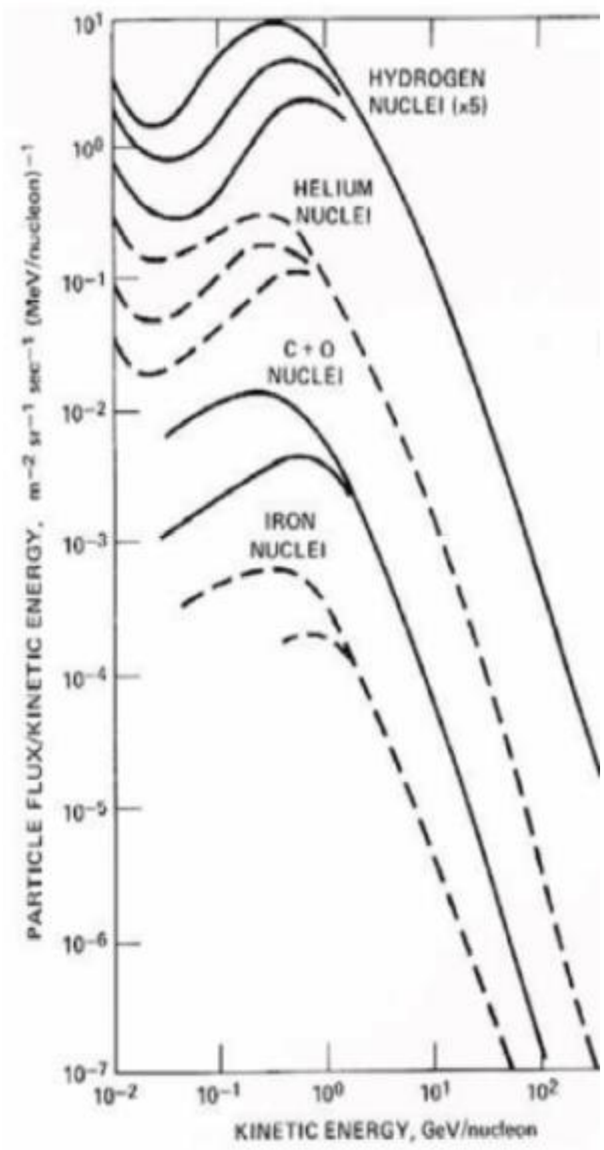
Toroid
Configuration



Double
Helix ™

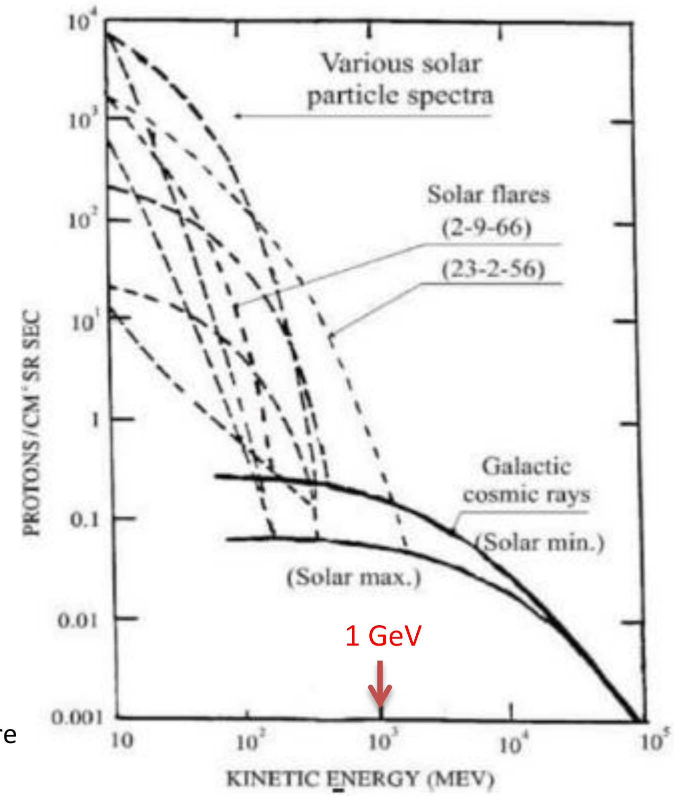
Advanced Magnet Lab

Radiation Environment



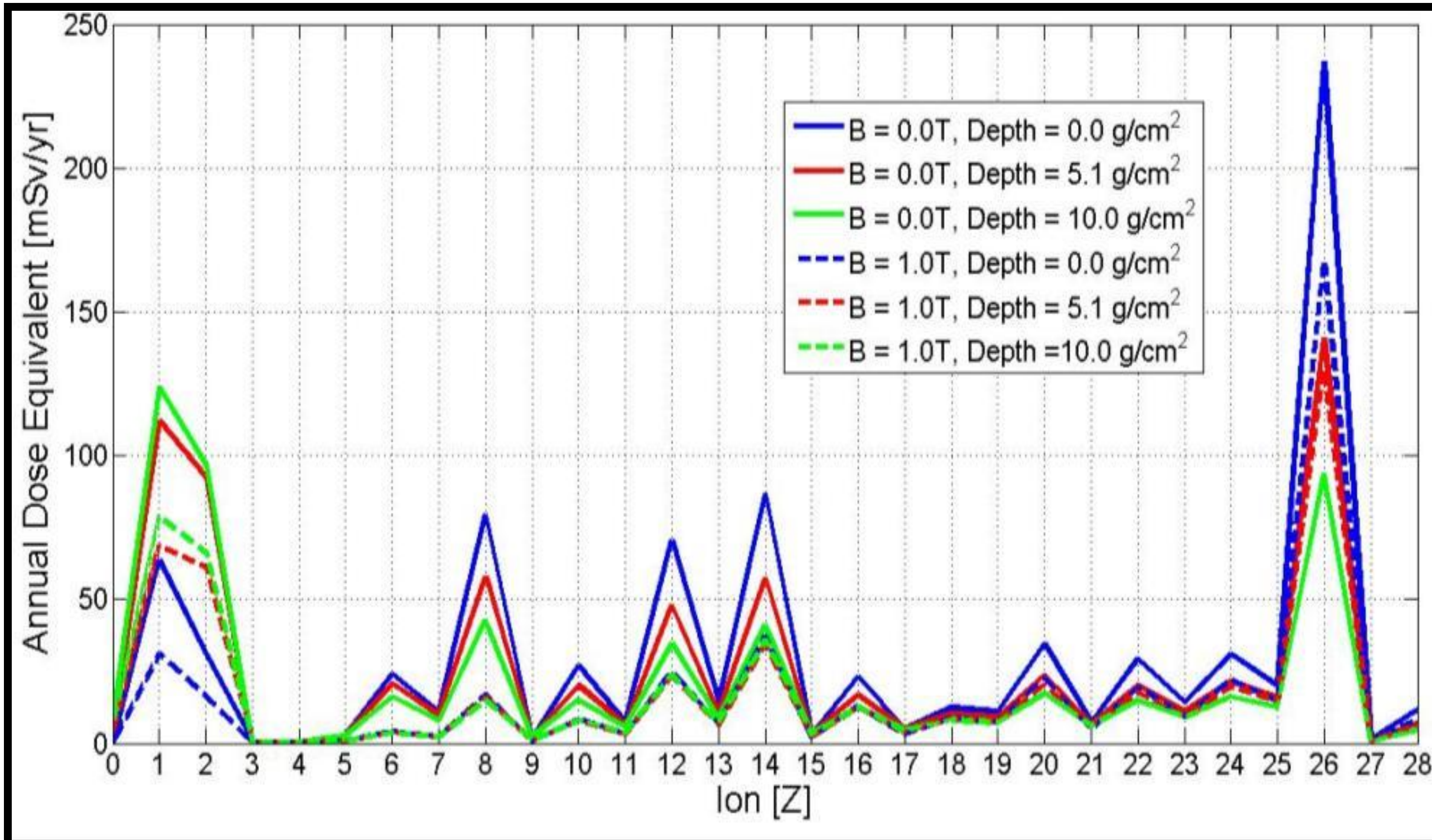
Common GCR species on the left graph.
Note the solar effects on the lower energy particles, hence the multiple curves per species. The GCR/SPE graph below shows the energy differences. *(Physics Today, Oct. 1974)*

Graphic of Earth's Magnetosphere
Credit: THEMIS, nasa.gov



GCR: Galactic Cosmic Radiation
SPE: Solar Proton Event

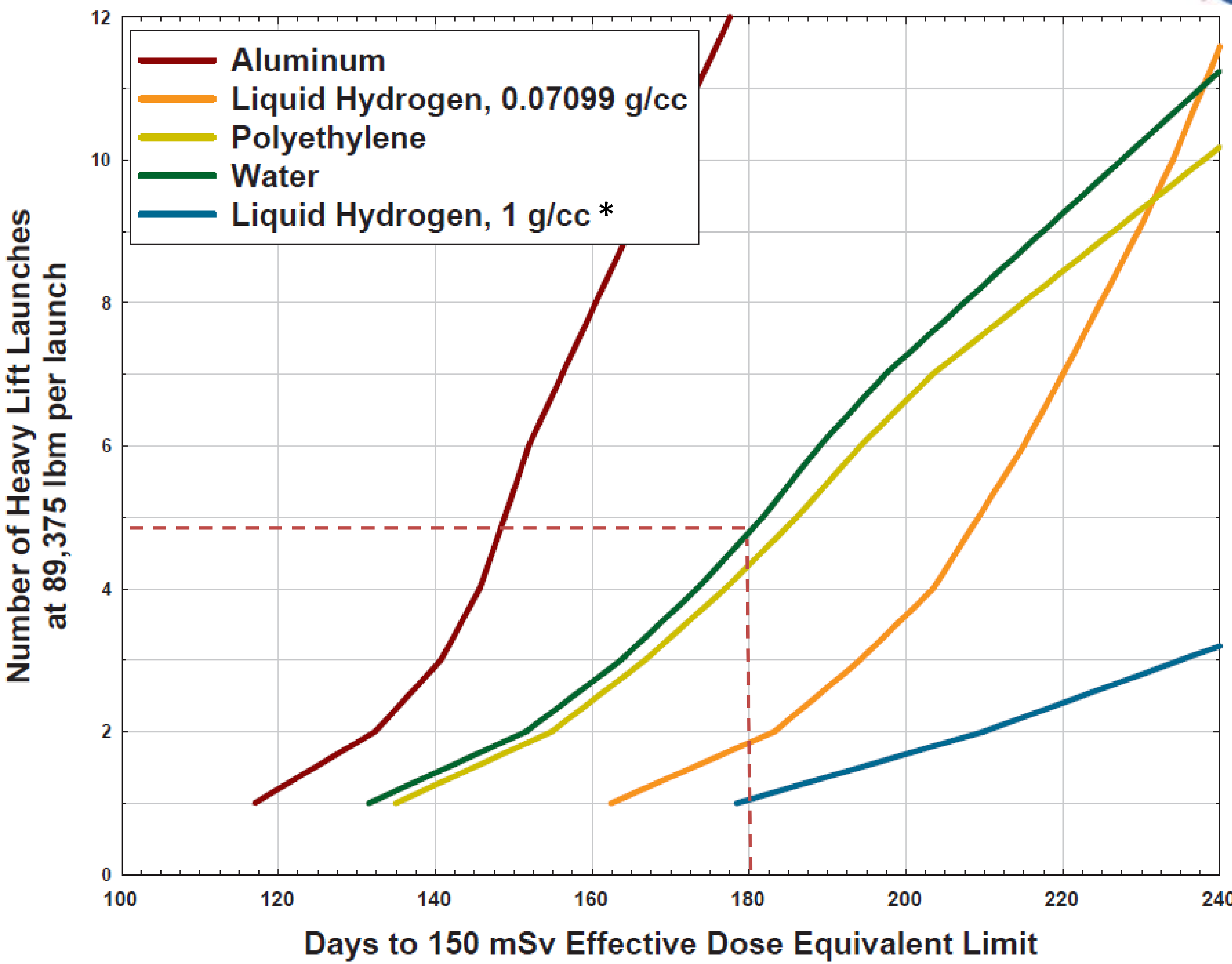
Ion Contribution to Total Annual Dose Equivalent



Ion Contribution to Total Annual Dose Equivalent (r_i = 4m, r_o = 12m)

- Eight tesla-meter field analyzed
- Aluminum shielding assumed

Passive Shields



*Note the Liquid H2, 1 g/cc is fictional

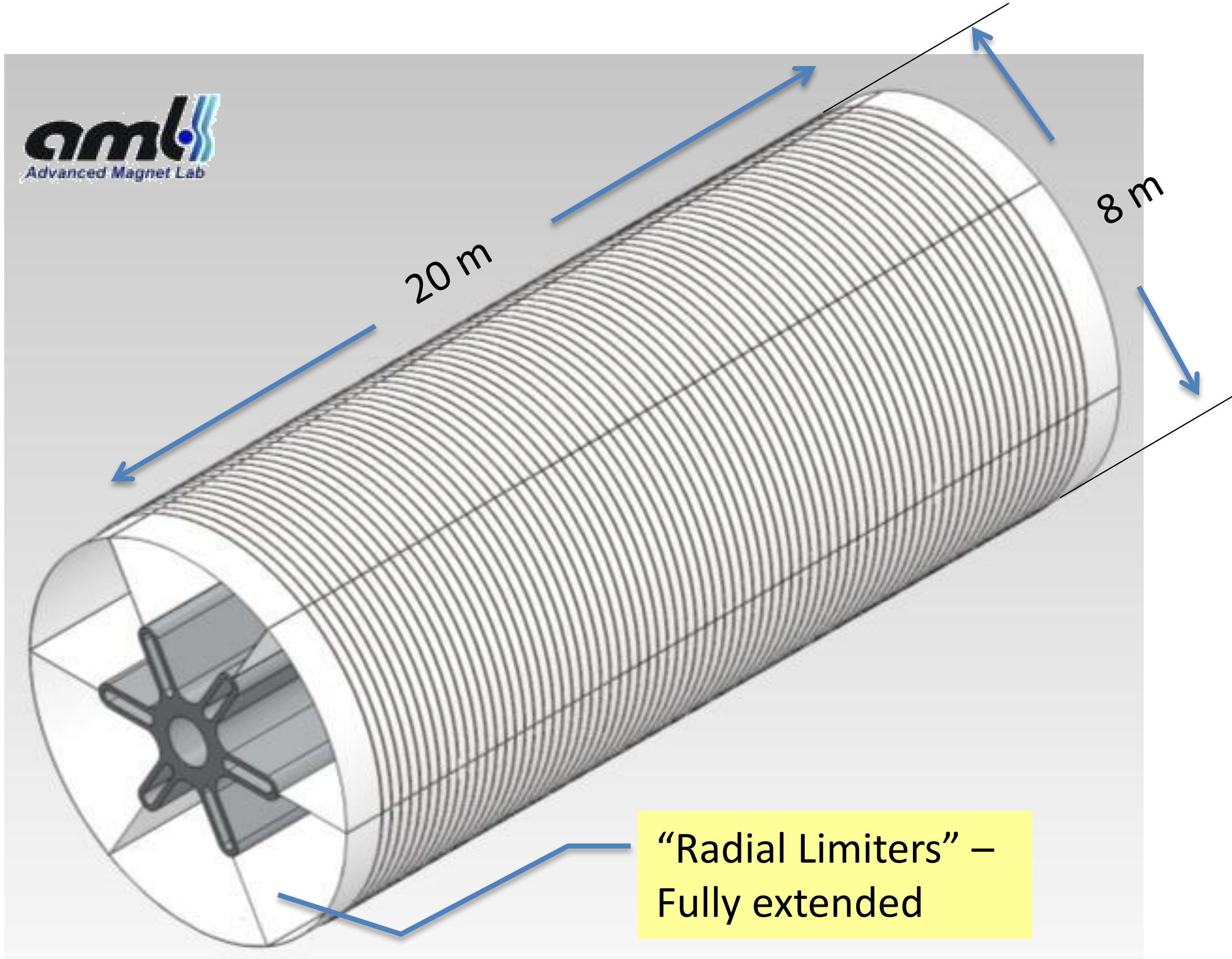
Per LaRC/R. Singleterry

6+1 Configuration

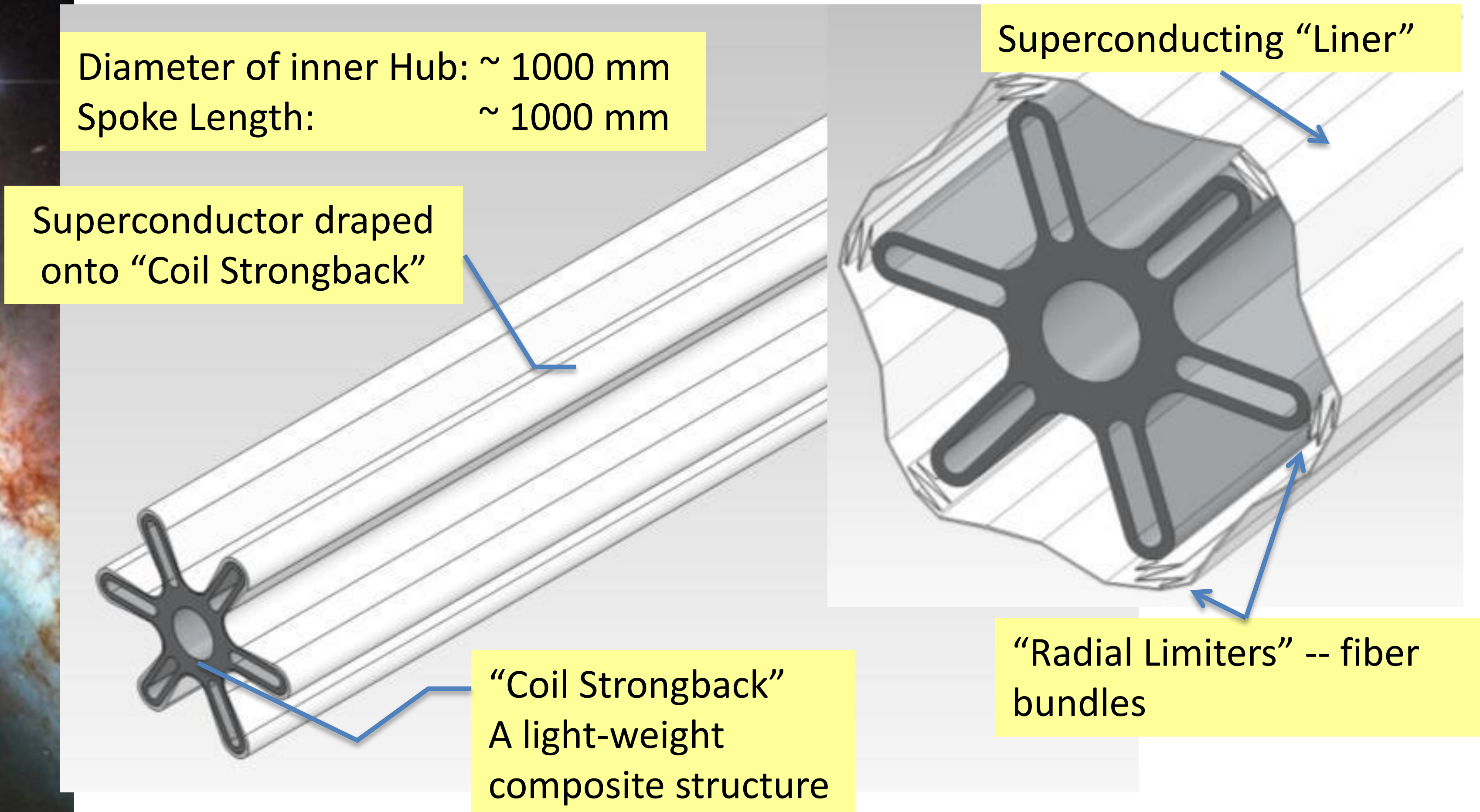
Parameter	Unit	Value
6 Solenoids Surrounding habitat		
Diameter	m	8.0
Length	m	15-20
Nominal Field	T	1.0
Nominal Current	kA	40
Stored Energy	MJ	400
Inductance	H	0.5
Magnetic Pressure	atm	~4

- Persistent mode operation
- Flux Pump charged
- Expandability considered

Large Fully Inflated Coil



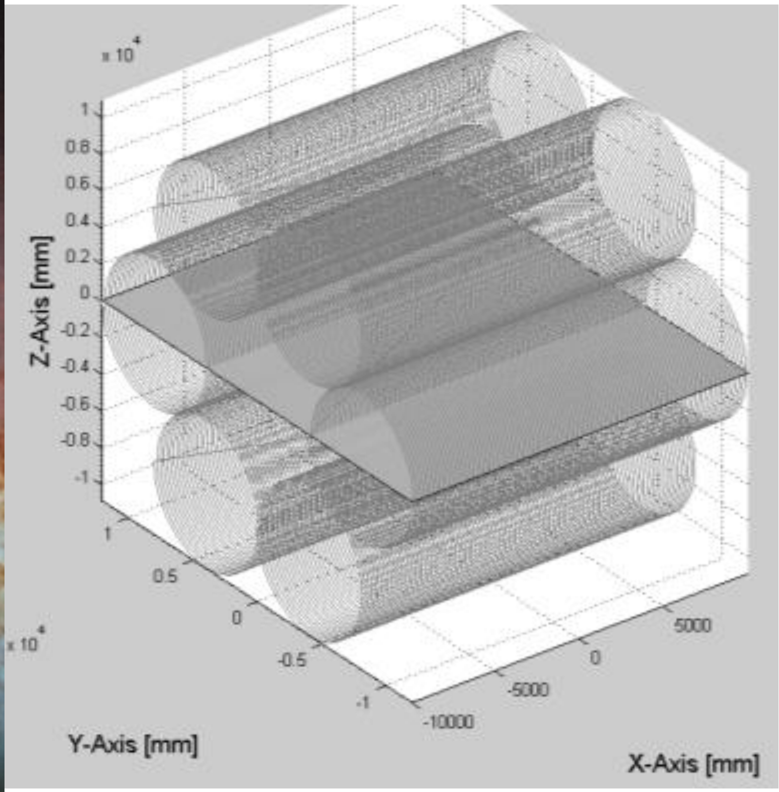
Solenoid Coil Fully Deflated then Partially Expanded



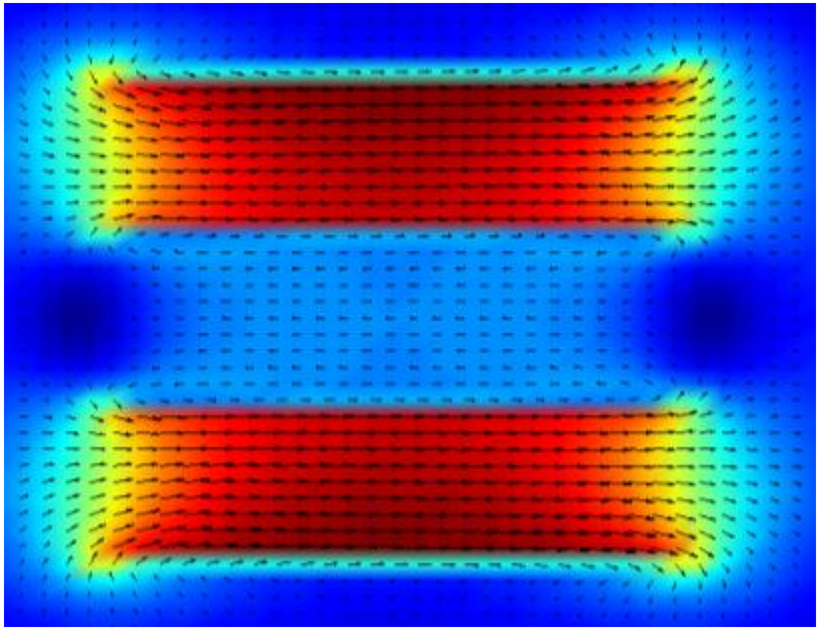
By vacuum pumping, the superconducting “Liner” is sucked to the “Strongback Coil” surface, closely following its contour of the “Spokes”.

AML/R. Meinke

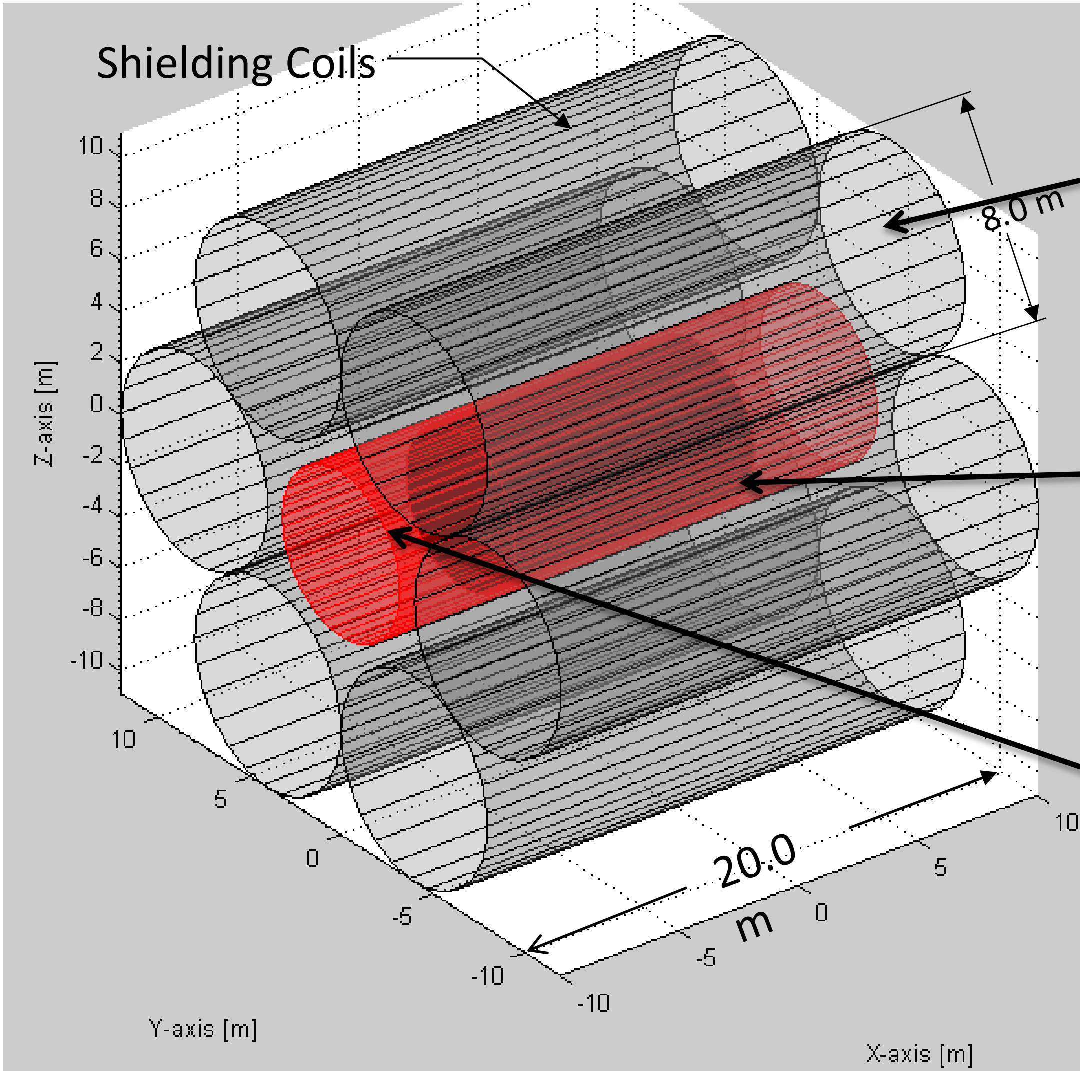
Analyze Field in Indicated X-Y-Plane



Field in X-Y-Plane



Shielding Coils with Habitat and Compensation Coil



6 shielding coils of 8 meter dia.

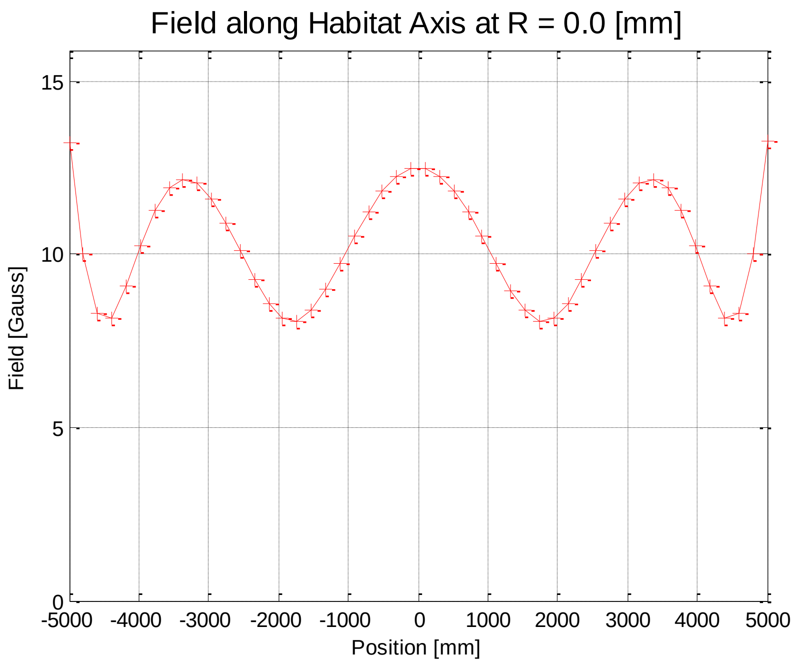
6 meter dia. Habitat

Compensation Coil

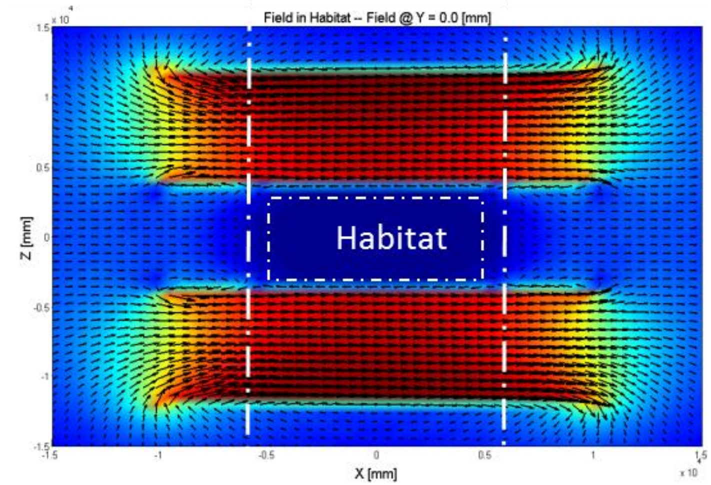
**Reduces magnetic field in habitat area from 2,500 Gauss to less than 20 Gauss

Rest Field with Modulated-Pitch Solenoid

Single Compensation Coil



Split Compensation coils reduce this field further



Pitch length decreases towards coil ends
Similar to MRI Gradient Coils

Diameter, *pitch length* and current of Compensation coil optimized:

Diameter of Compensation Coil	7.20 [m]
Length of Compensation Coil:	15.8 [m]
Current in Compensation Coil:	10220 [A]
Mean Field in Habitat:	**10.3 [Gauss]**

Assembly & Operations Approach

- A deep space cycler is our approach for an active shield architecture
  - An active shield approach would need to be re-useable for multiple missions
    - Architecture cost
  - An active shield design is less complex when maintained in deep space
    - Simplify thermal management systems

- Launch, Assembly and Voyage
  1. Heavy lift delivery of shielding coils to low earth orbit (LEO)
     - Deploy coil array in LEO
  2. Heavy lift delivery of compensation coil and habitat (LEO)
     - Dock with Shielding coil assembly in LEO
  3. Delivery of mission support (food/water/propulsion/power)
     - Mission dependent
  4. Transport spacecraft to high earth orbit (HEO) beyond electron belt
     - Solar electric propulsion tug or chemical propulsion
     - Solar array deployment for coil charging and expansion in HEO
  5. Delivery of crew (Crew Module)
     - Field charging for systems checkout. Discharge/recharge for crew arrival
  6. Round trip to destination and return to HEO with CM/SM lifeboat
     - Crew Undock and return home in MPCV-like vehicle

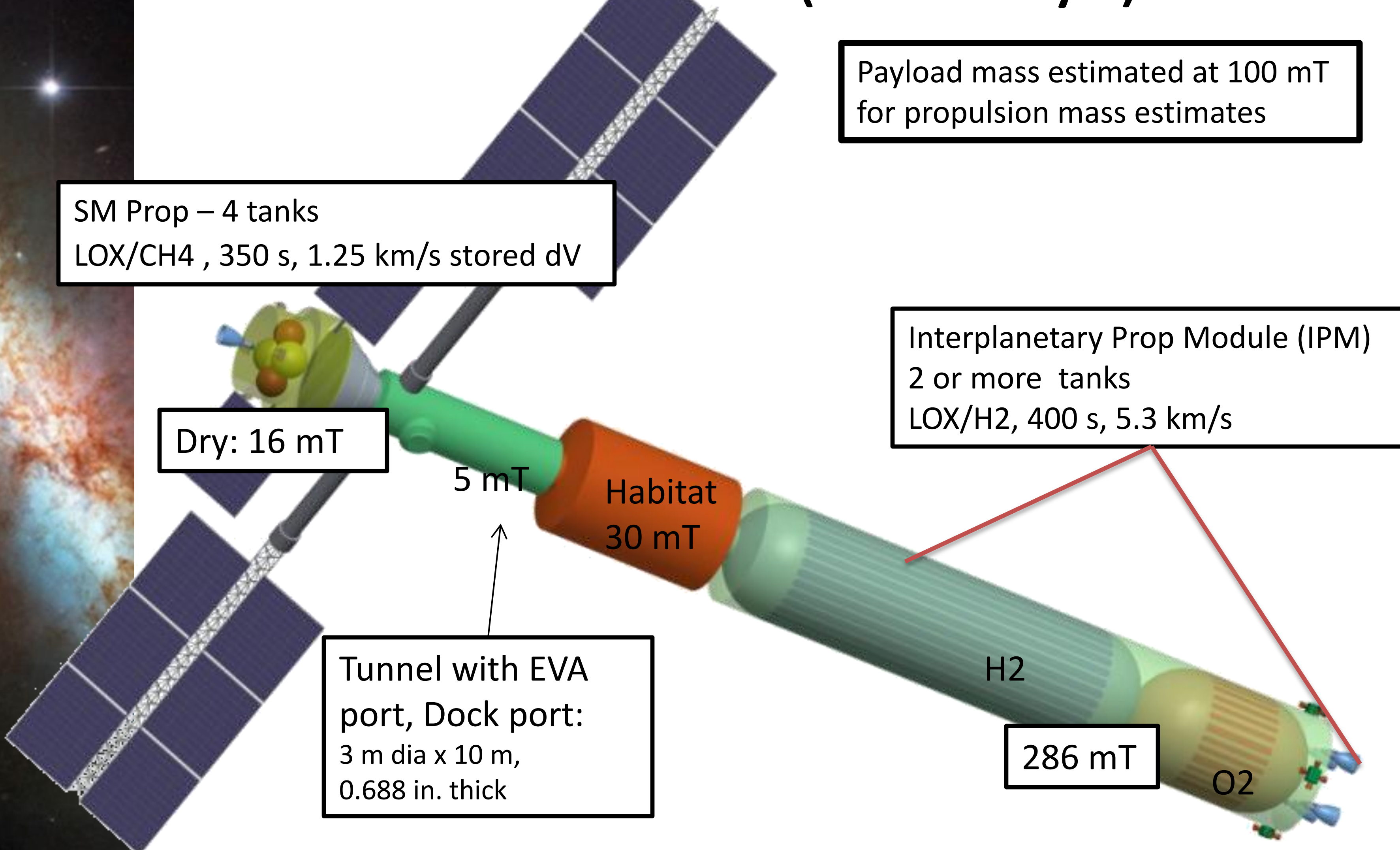
Consider a “cycler” approach for planetary missions to minimize delta V propulsion needs using gravity assist

Active Radiation Shielding
6 + 1 Expansion Coil Architecture
Two-Launch Assembly
Six-Coil Launch
Habitat & Compensator Coil Launch
Orion Spacecraft
Helium Vapor Cooling System
Logistics Module
Habitat Module
Exploration Propulsion Module
Habitat View
NIAC

Propulsion Shielding Potential

- Two in-space propulsion architectures selected to envelope passive shielding potential
  - Chemical (LOX/LH2): selected for significant mass; in space cryo storage remains a challenge, but was used in this study to evaluate the significant hydrogen content for shielding
  - Very High Power Solar Electric Propulsion (SEP): selected for minimal mass (less shielding potential).

NEA – Chemical (365 days)



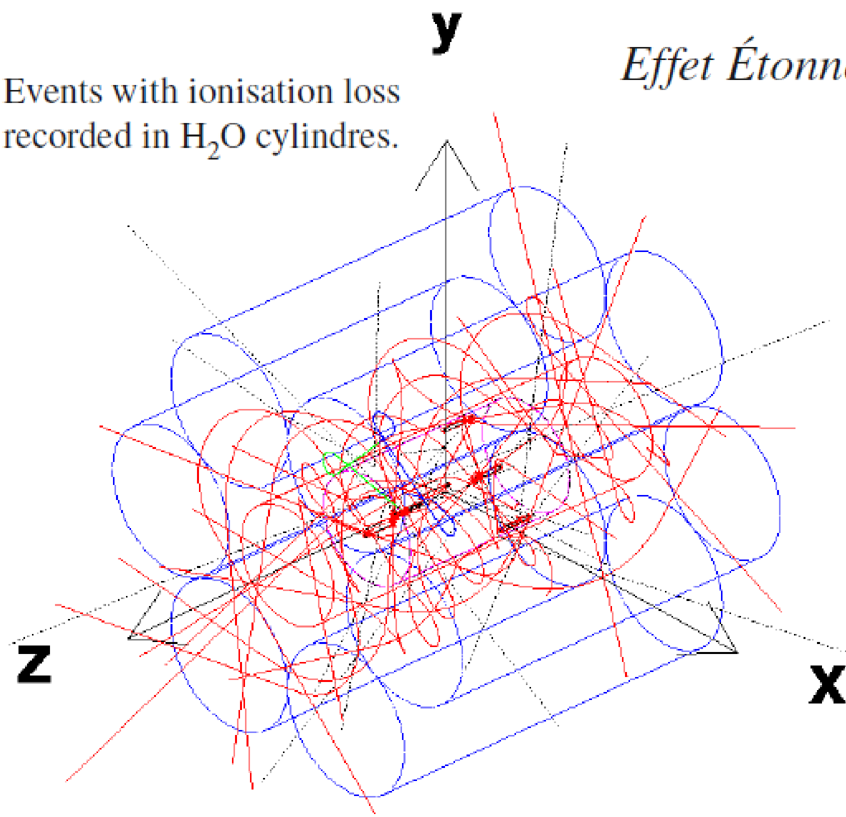
Comp coil, 8 Tm coils (not shown): 53 mT (iteration 1)

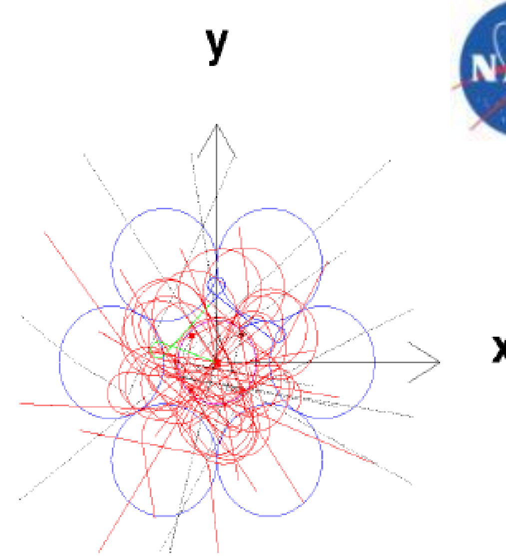
6+1 Expandable Solenoid Shield

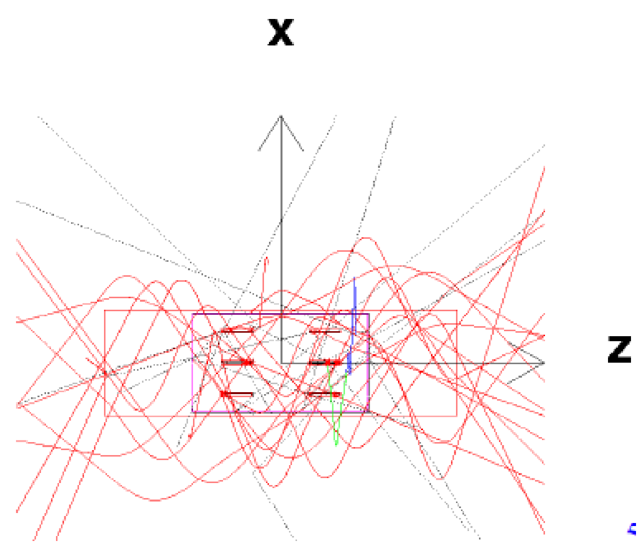
1 GV (0.43 GeV) Protons

Effet Étonnoir

Events with ionisation loss recorded in H_2O cylindres.







3000 protons generated uniformly across the two surfaces in the **xy** plane used to define the acceptance.

The chemical propulsion model did not reduce the equivalent dose due to lack of geometry efficiency and secondary production.

Annual Skin, BFO and Body Equivalent Doses

Barrel Region for Solar Minimum

(cSv/rem)

Z	habitat(2)			6+1 no field			6+1 field		
1	10.0	9.3	9.2	10.4	9.6	9.4	9.5	8.5	8.5
2	4.7	5.8	4.0	4.9	4.2	4.0	4.3	3.8	3.8
3-10	13.4	9.3	4.6	11.6	8.1	4.0	11.7	8.2	4.0
11-20	10.2	5.8	4.3	8.0	4.5	3.4	8.2	4.5	3.4
21-28	4.1	1.6	1.4	2.7	1.2	1.0	3.0	1.1	1.1
Total	42.4	31.8	22.5	37.6	27.6	21.8	36.7	26.1	20.8

fraction of habitat dose: 0.89 0.87 0.97 0.87 0.82 0.92

Habitat (2) refers to the 10 m long, 6 m diameter, 4.0 cm thick aluminum habitat (35 t habitat) including water and food estimates for a 1 year mission. Propulsion not included.

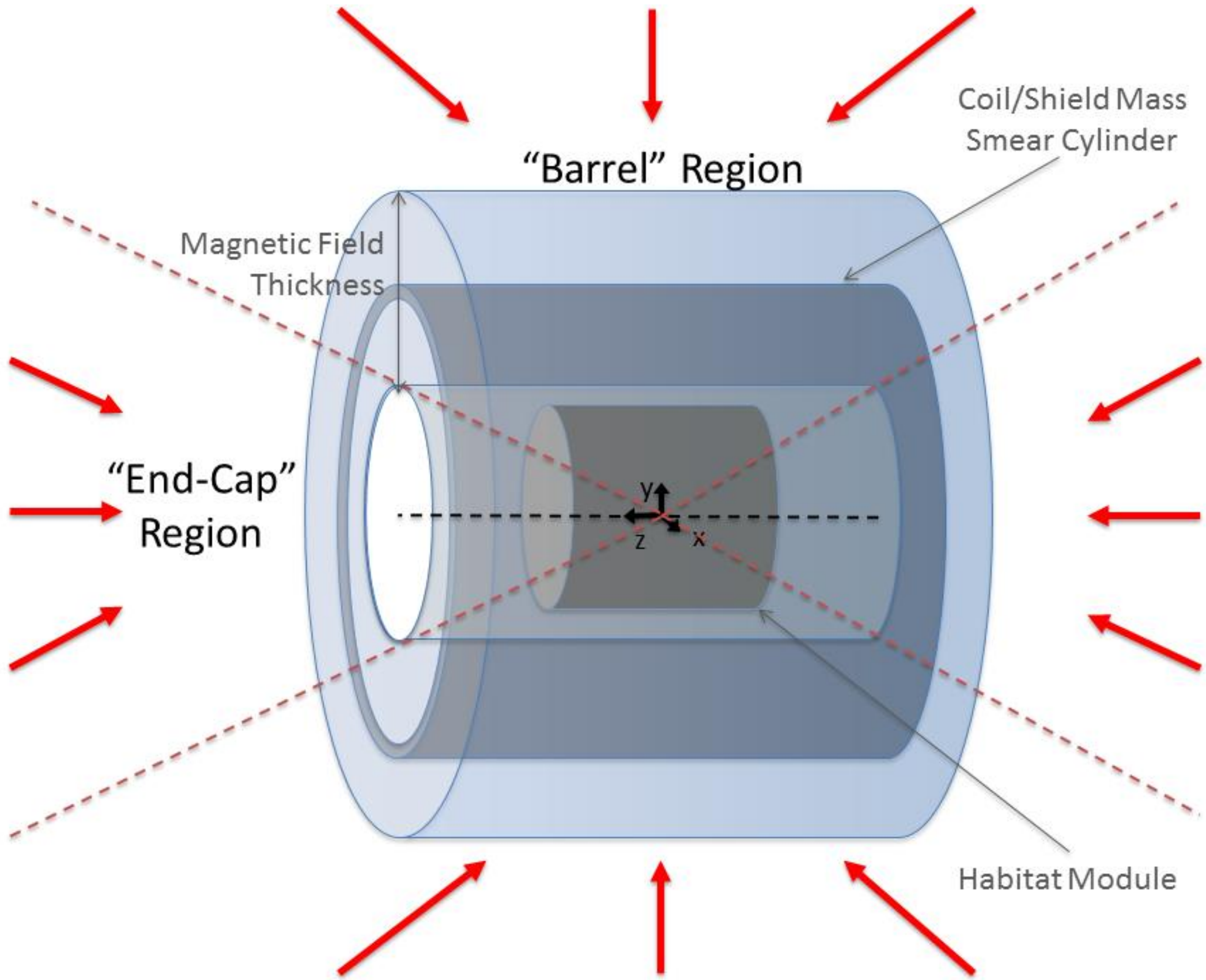
The benefit of the 8 Tm field is washed out when evaluating the total acceptance to the Barrel Region only. A scalable architecture is required as shown with the Analytical Model and HZETRN study

Model & HZETRN

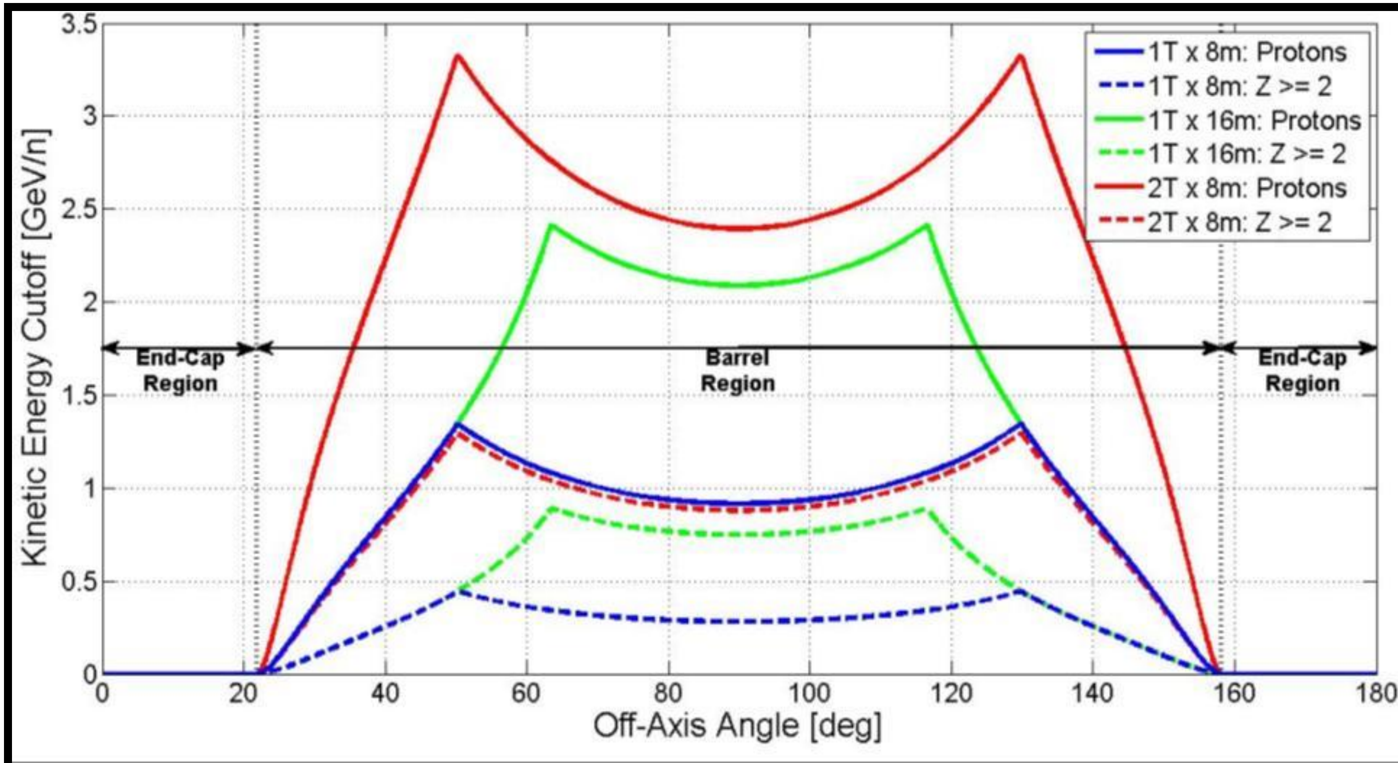
- An analytical-HZETRN model was developed to allow the rapid analysis of a broad range of trade space variables for a solenoid shaped, active magnetic shield design
- This model assumes a single solenoid around the spacecraft for simplicity and provides a shielding performance analysis (mass and dose equivalent) of the 6-around-1 coil design
  - Mass assumes commercial off the shelf materials

HZETRN = High Charge and Energy Transport

Open Ended Cylinder Model

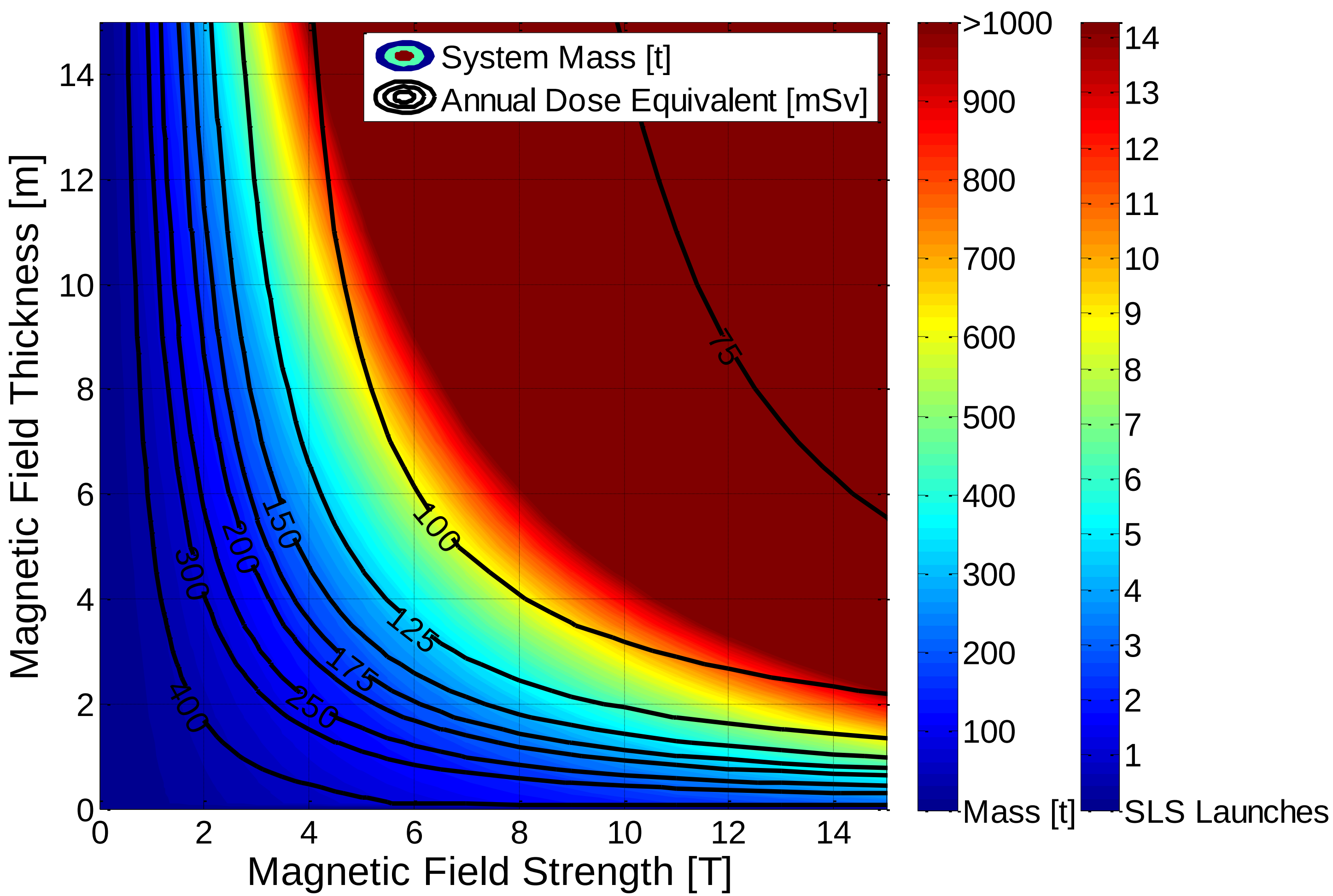


Open Ended Cylinder Cutoff Energy



Open-Ended Cylinder Cutoff Energy
at the Center of a 4m diameter Habitat (r_i = 4m)

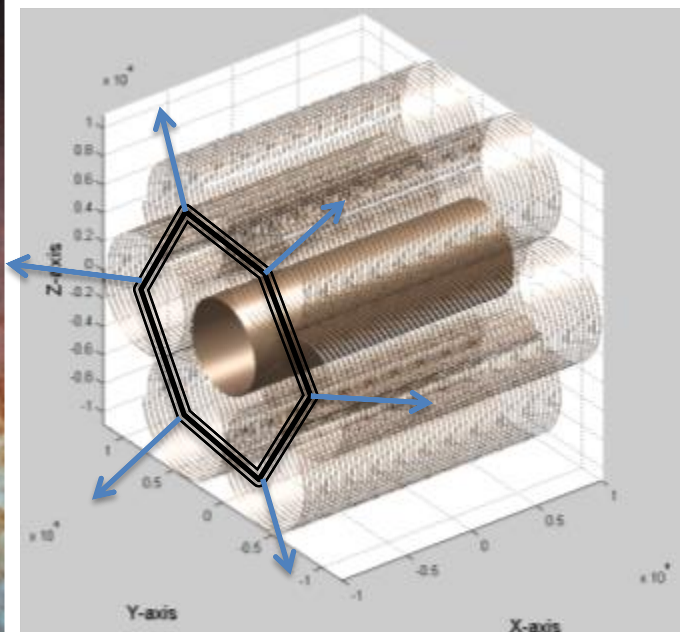
Model & HZETRN



Mass and materials inputs need to be updated based on Phase II structures analysis

Loads and Structural Response

Forces Acting on Shielding Coil



Coils behave like 6 permanent magnets with strong repulsive forces

Inter-coil support structure needed

Forces act on conductors that are bonded to flexible fabric liner

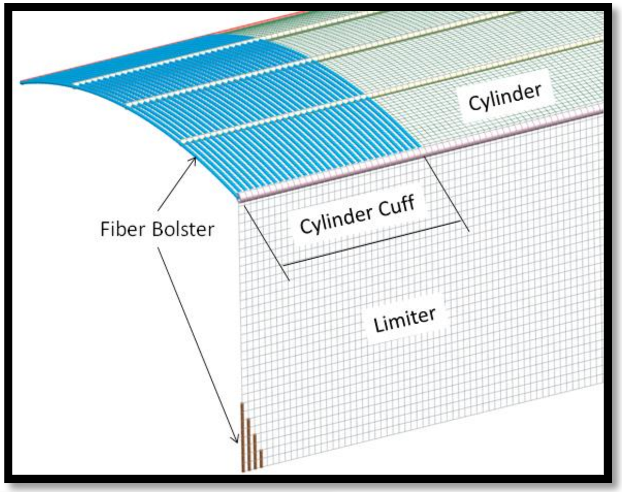
Forces not uniform over length of solenoids

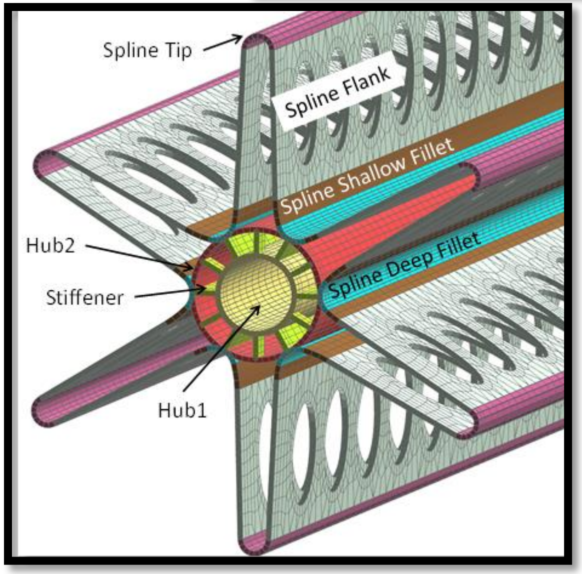
Possible bending on strong back

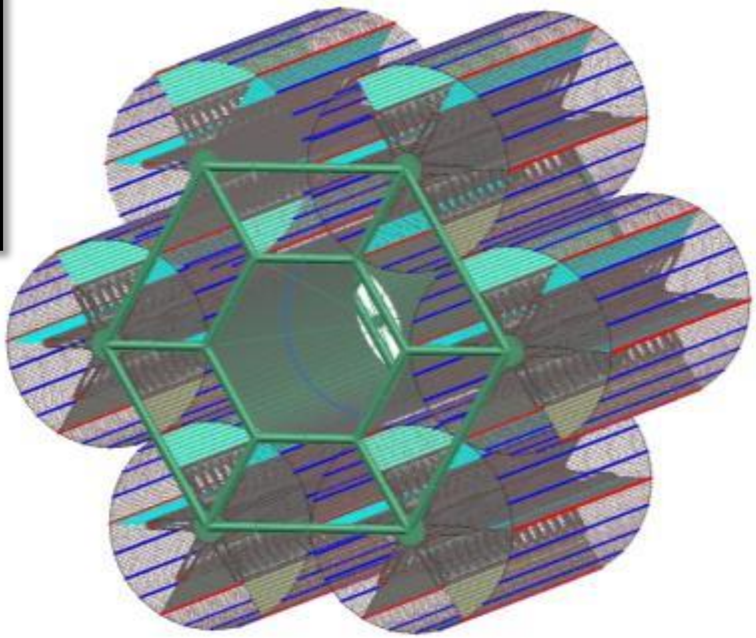
Distortion of 'ideal' cylinder geometry of each individual coil

Baseline Structural Design:

- Primary differentiation between single and multi coil simulations are: mesh density, loads definition and coil connectivity structure (Yoke)

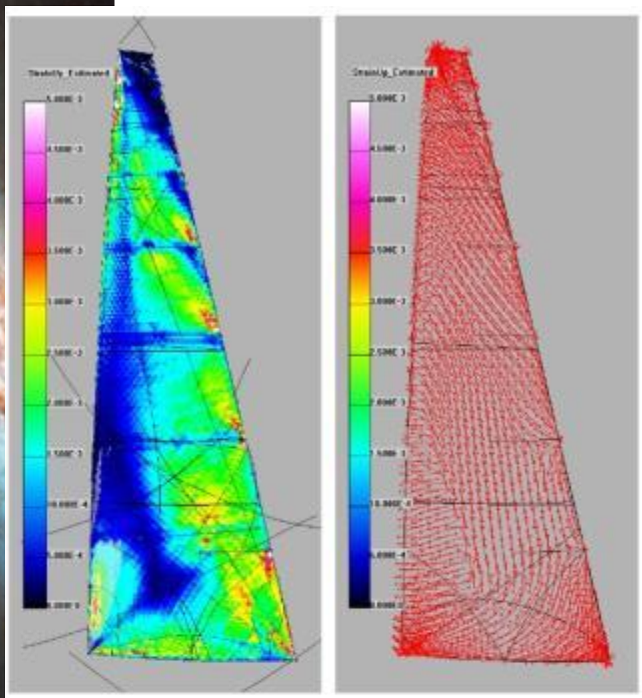






Bolstering: Flexible Laminate Reinforcement

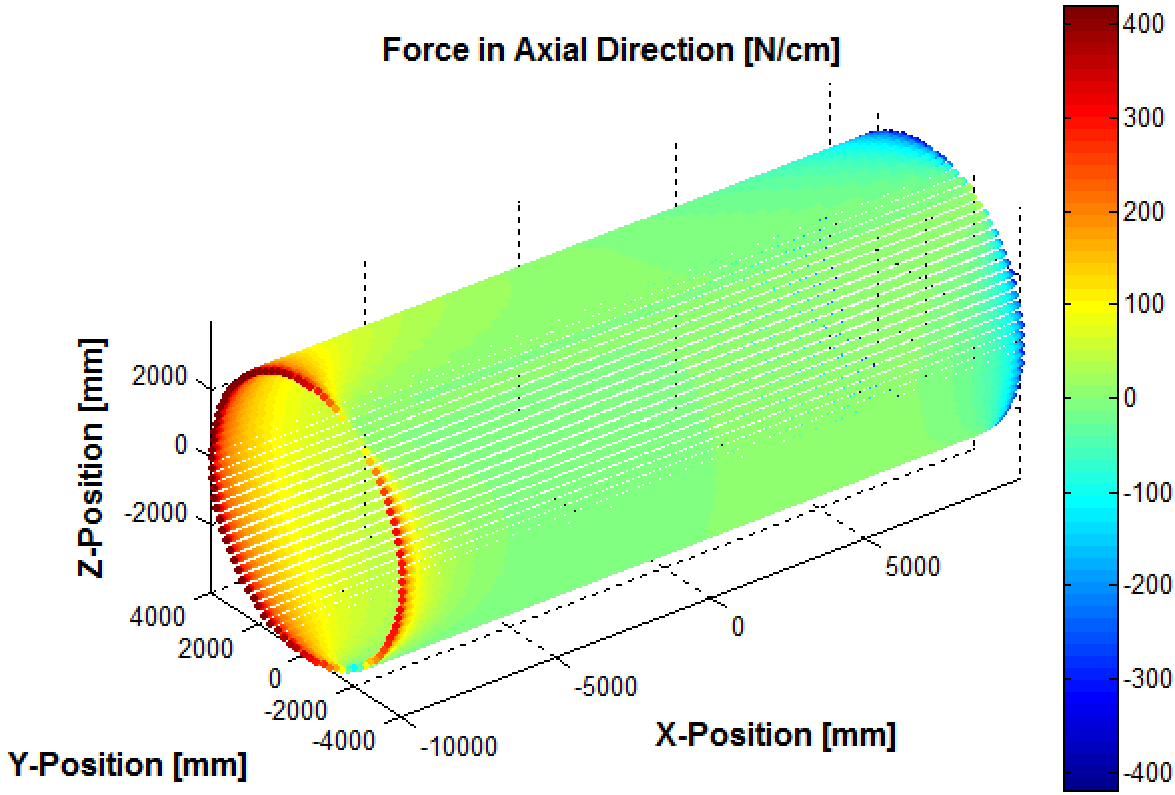
- Bolstering based on strain mapping (sail boat sails analogy)



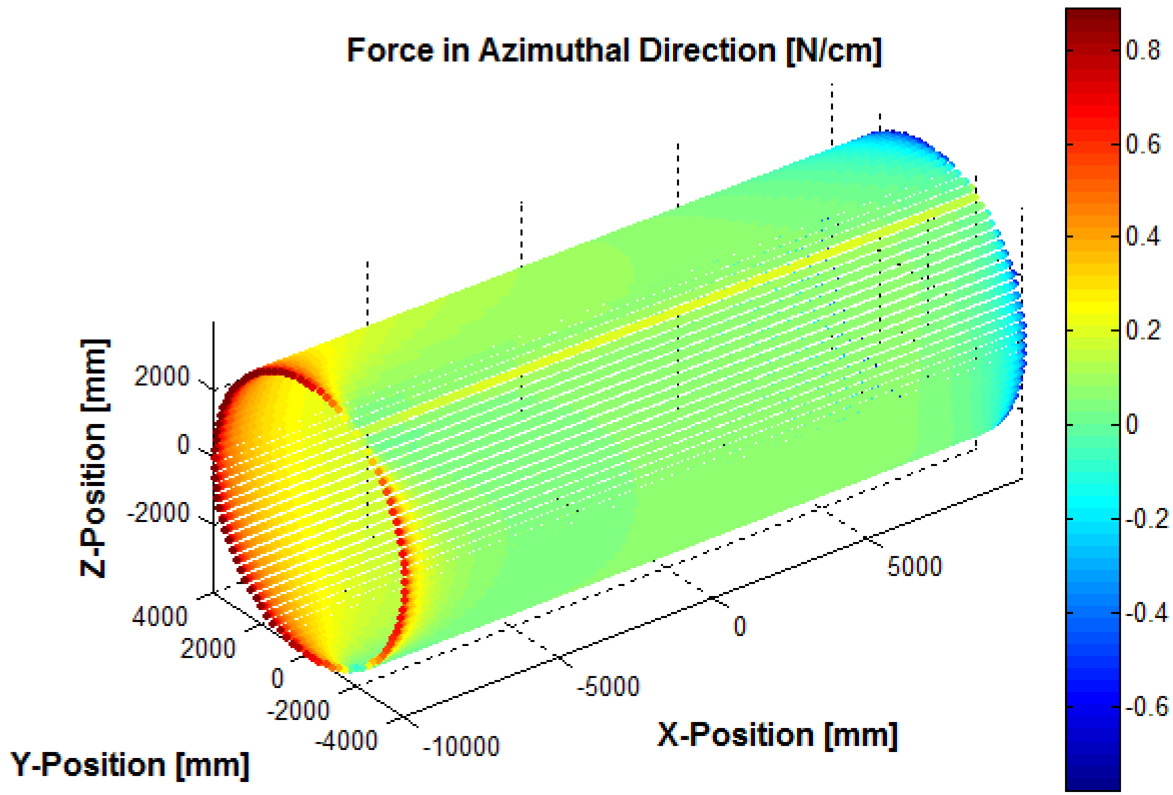
Membrane Loads and Deformations
(Strain mapping)

Bolster Design and Fabrication
(targeted fiber tow reinforcement)

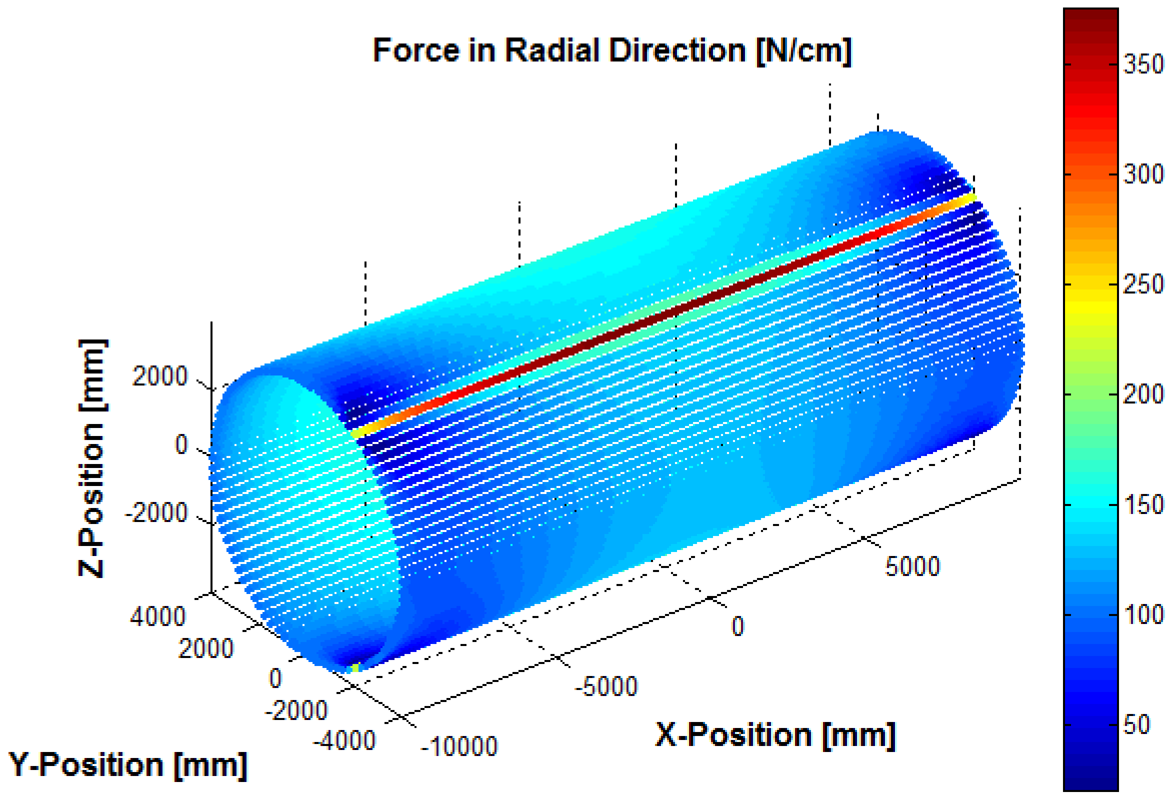
Axial Forces on Undistorted Array Solenoid



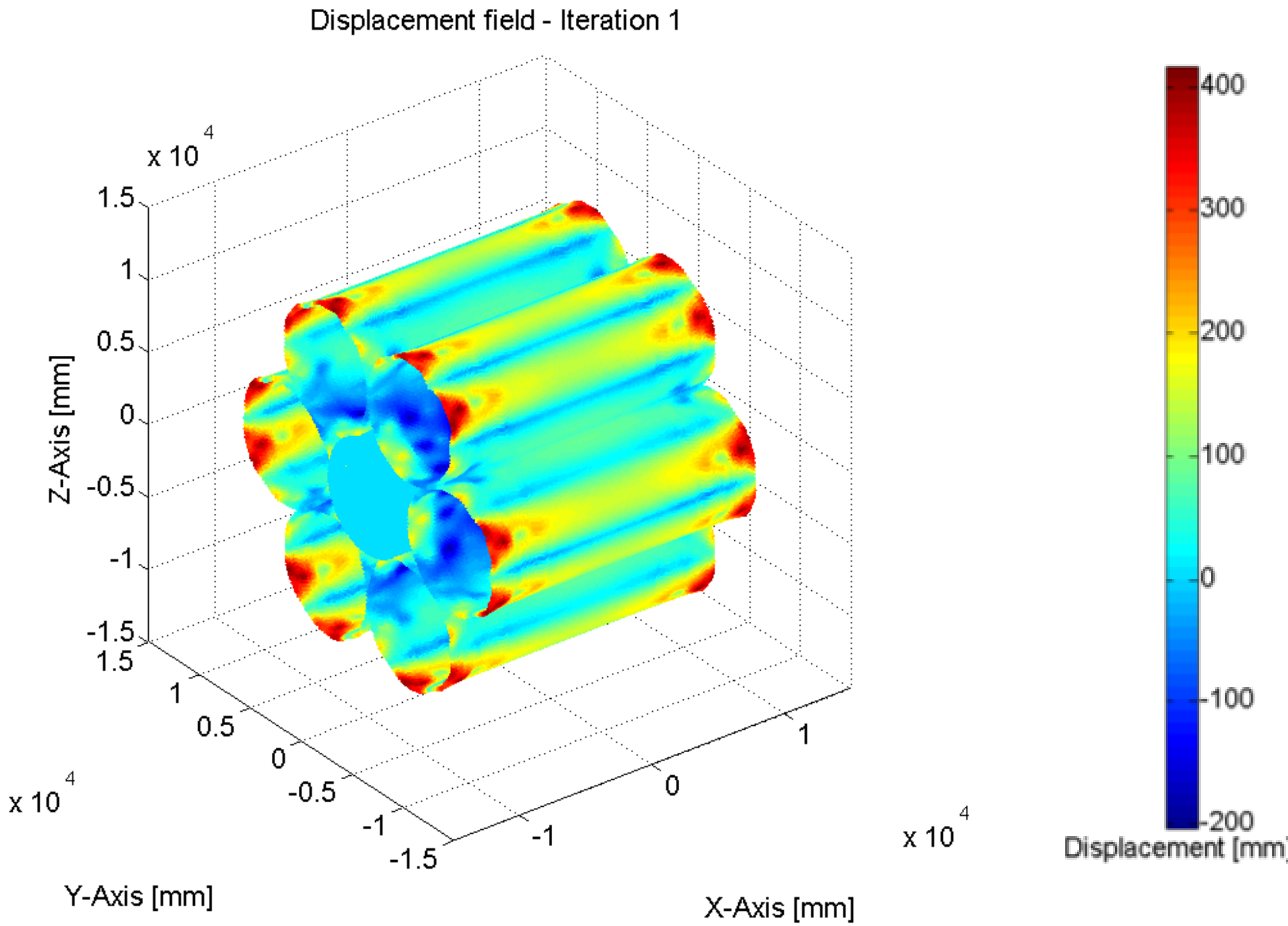
Azimuthal Forces on Undistorted Array Solenoid



Radial Forces on Undistorted Array Solenoid



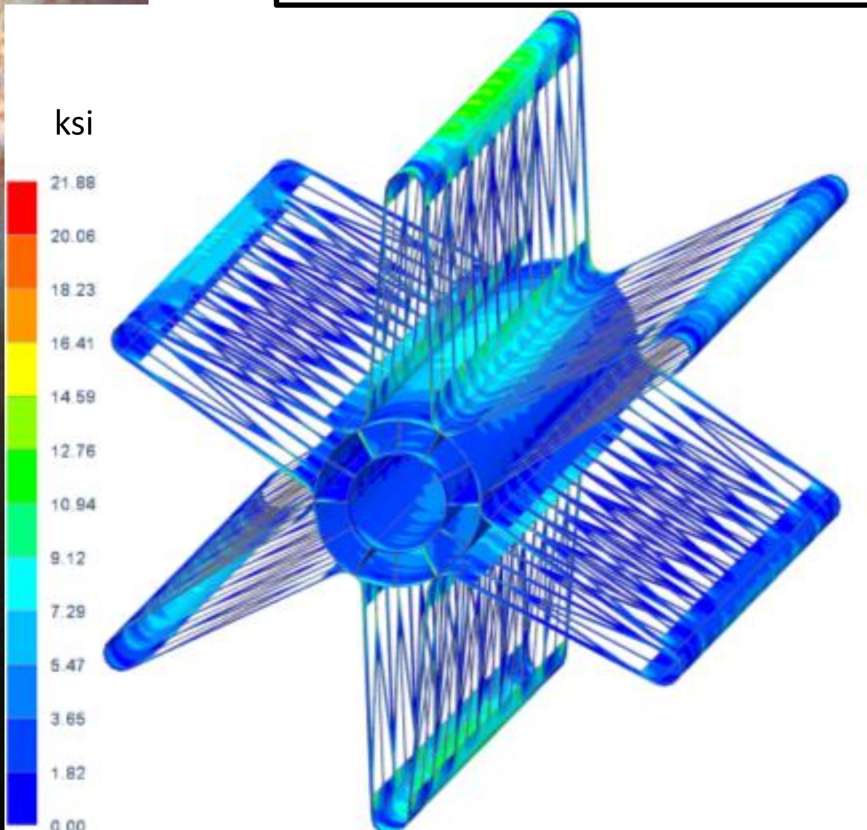
Induced Deformation in Shielding Array



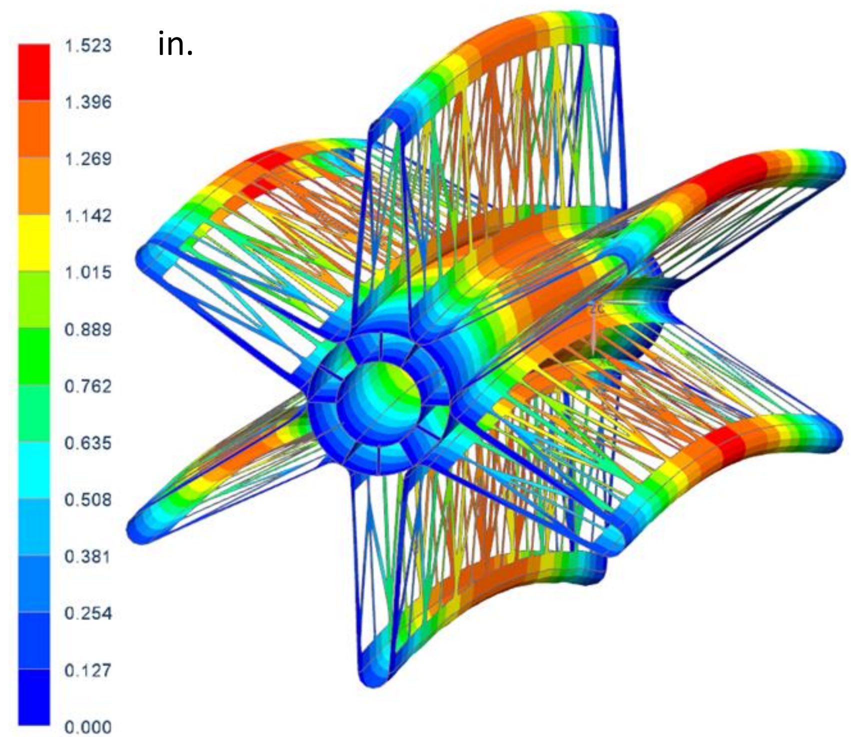
Structural Modeling: Coil Alone – Rigid Laminate

- Models 1 & 2 (model 2 shown):
  - von Mises Stress Comparison: Maximum Model 2 stress is 39.9% less than Model 1. Highest stress in fillet, far from imposed loads @ spline tip. Compliant structure spreads load.

Model 2 vs. Model 1: lighter, not as stiff and maximum operational σ may be lower. How does added displacement affect the field?



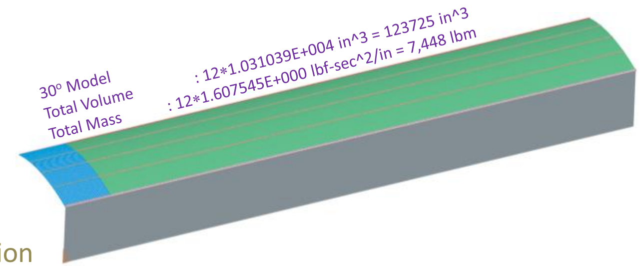
Displacement scale: 4x



Advanced Magnet Lab

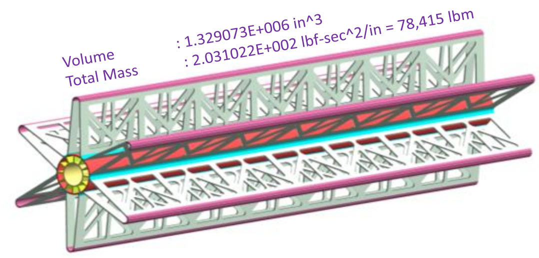
Summary: Weight Performance As Analyzed

- Performance relative to current technology readiness level (TRL) 6-7
  - Rigid and flexible composite structures perform well with regards to strength requirements
  - Estimated mass



- **Cylinder – 7,448 lbm**

  Fiber *Material:* ToraycA T1000G
  Construction: 2 plies @ ±45° orientation
  Cylinder: ¼" diameter tows
  Limiter: 0.354" diameter tows
  Local Bolster: ½" diameter tows
  Matrix: HexPly 954-6 cyanate epoxy resin.
  Film: DuPont Kapton E.



- **Strongback – 78,415 lbm**

  Fiber *Material:* Strongback: ToraycA M55J
  Spar and Batten: ToraycA T100G
  Construction: 0 °/90 ° orientation
  Strongback: fiber, 32 plies @ Spars: fiber, 2"x1/2" tube, plies TBD
  Battens: 1" diameter rod , plies TBD
  Matrix: HexPly 954-6 cyanate epoxy resin.

- **Yoke – 2,608 lbm**

- **Total – 88,471 lbm**

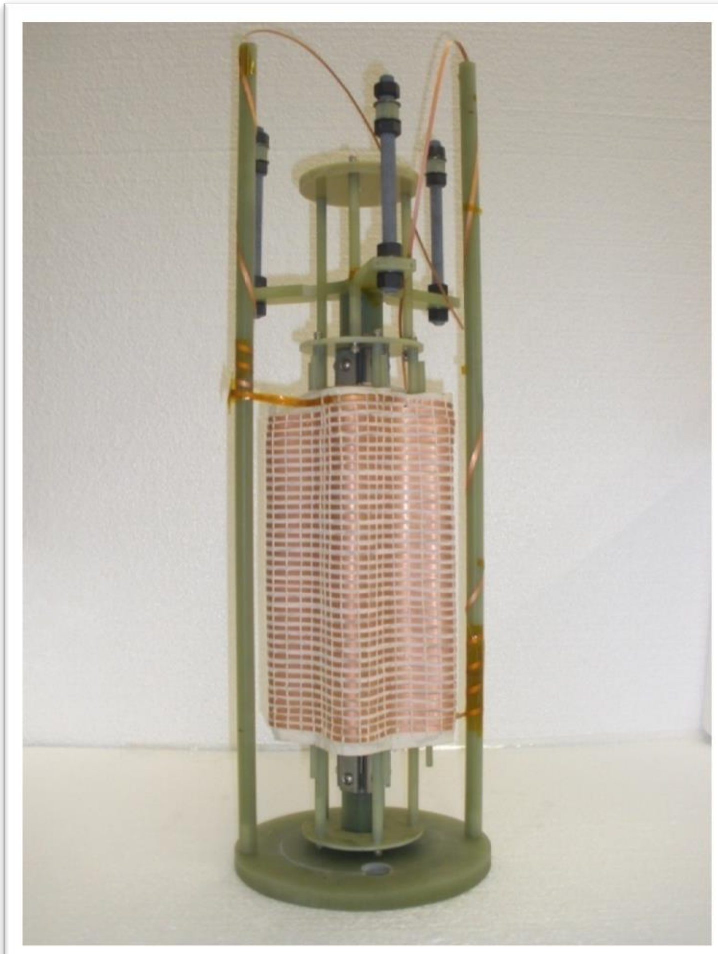
Mass Summary

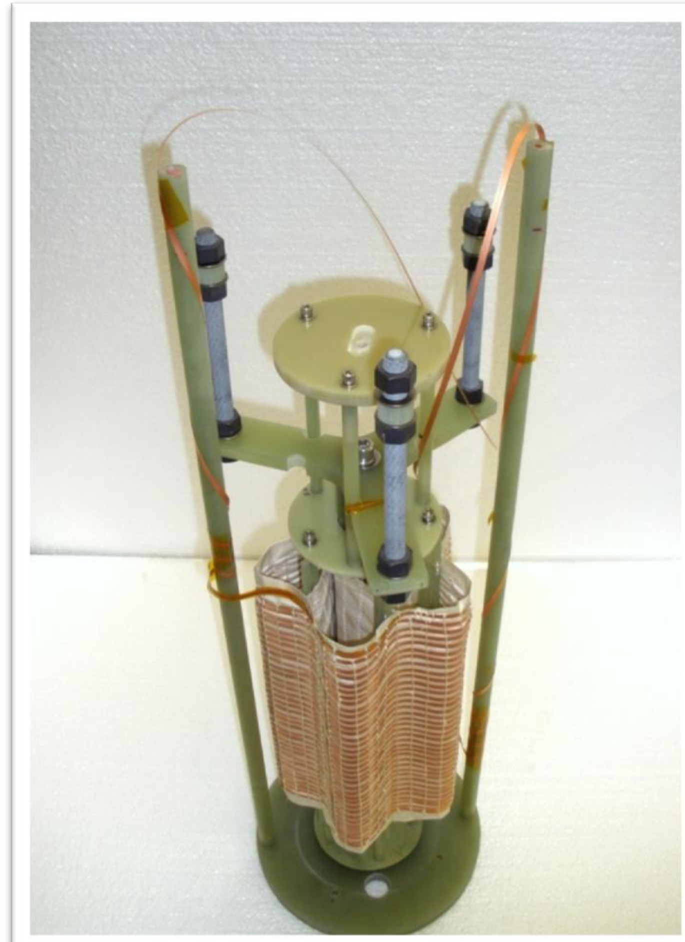
- Strong-back mass needs work
  - Current design utilizes today's available materials and is a foundation to future iterations on design and incorporation of advanced materials
- Minimize launch mass and assembly complexity
  - Goal: single launch of 6 coils to LEO
  - Analysis suggests SLS Block 2 delivery of 3 coils to LEO is possible with current off the shelf composites

SLS = Space Launch System (assumes 130 metric-ton lift capacity)

Testing

Expandable Coil – Collapsed (AML)



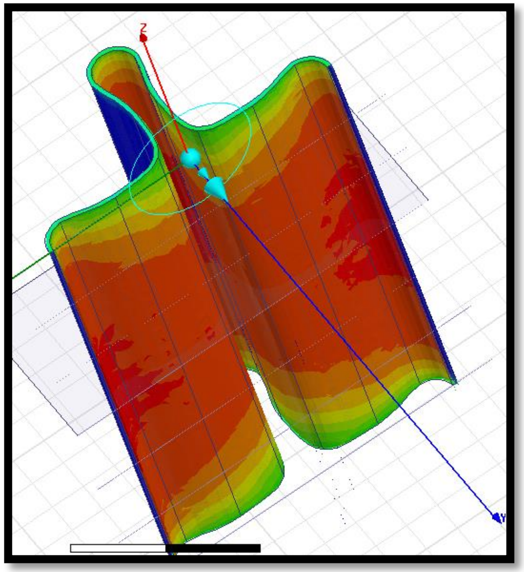


Coil Fully Collapsed

Inserting into Helium Cryostat

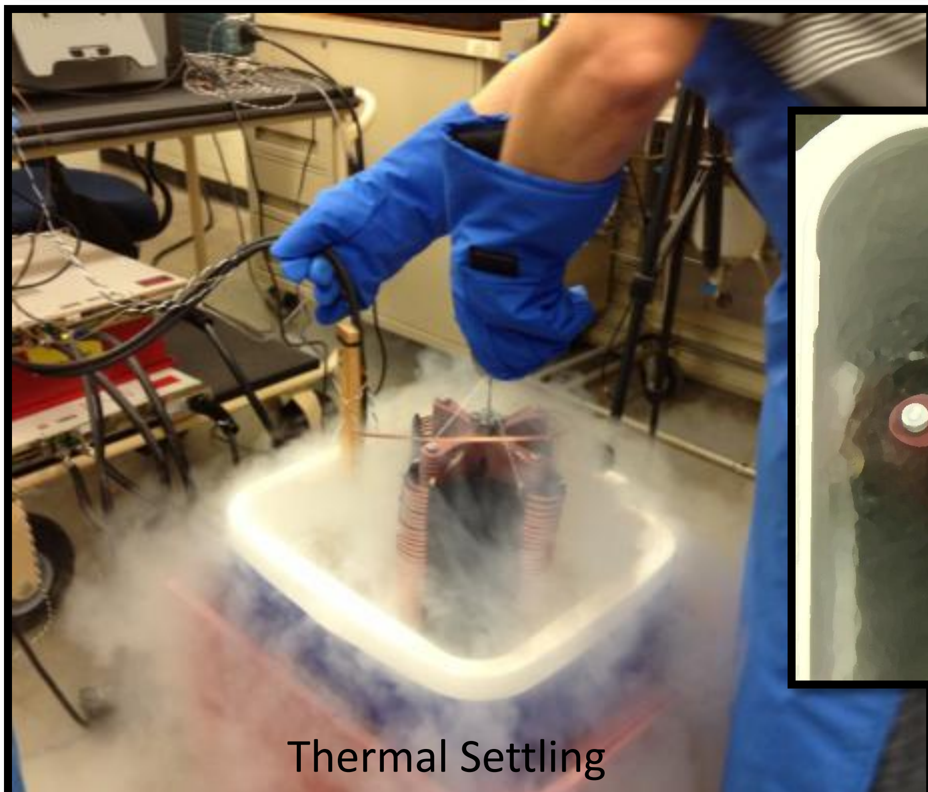
YBCO Test (JSC)

Coil Expansion Test (JSC)

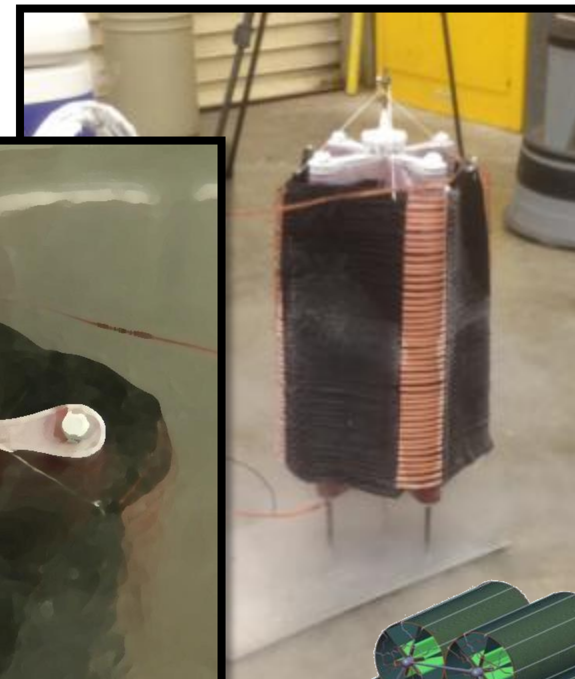


Arrival to Test Site

LN2 Bath Refill



Thermal Settling



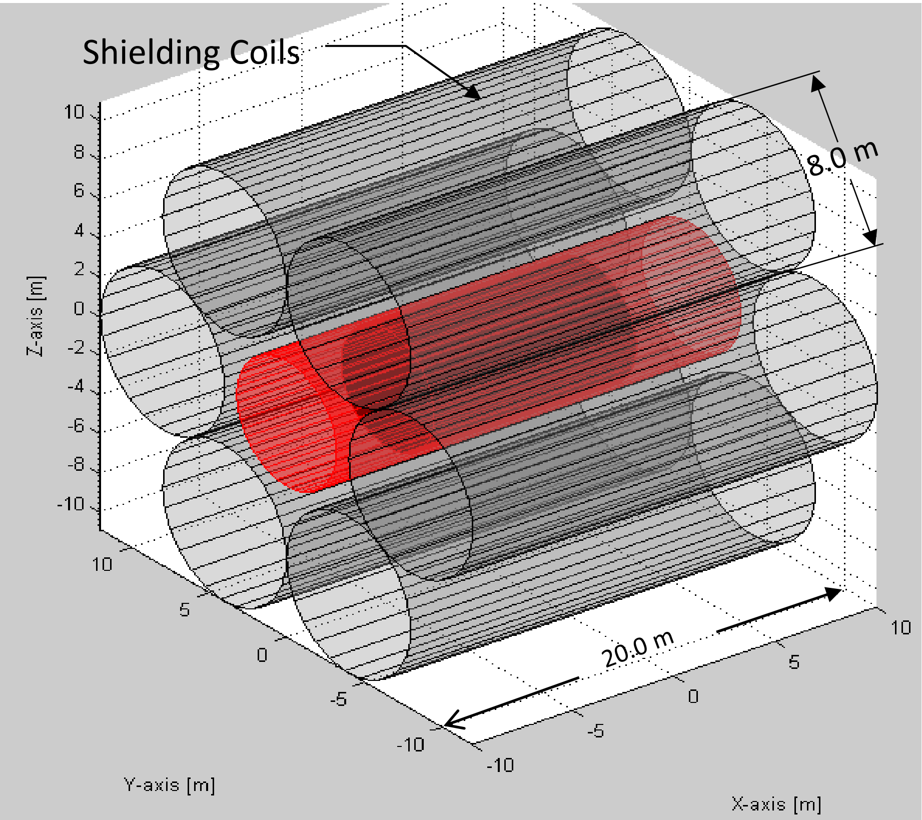
Quench Highlights

Stored Energy

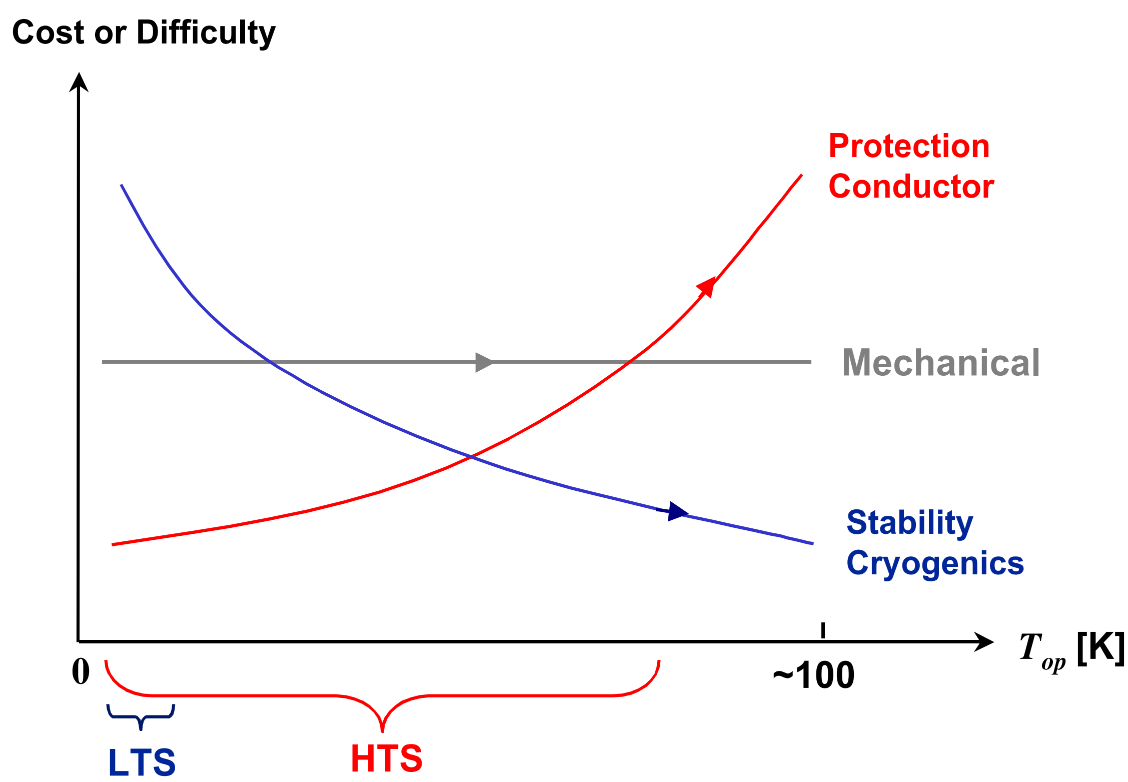
6+1 coil array system to protect the crew from solar and galactic radiation.

Volume per Coil:	~ 1000 m^3
Nominal Current:	~ 40 kA
Stored Energy:	~ 400 MJ
Inductance:	~ 0.4 H

Stored Energy sufficient to melt ***570 kg Cu*** starting at 50 K



HTS Quench Protection Issues



Y. Iwasa (05/08/03)

Acknowledgements:

A lot of the presented information on quench has been borrowed from publications of the following people:

- P. Ferracin
- Y. Iwasa
- C.E. Oberly
- S. Prestmon
- J. Schwartz

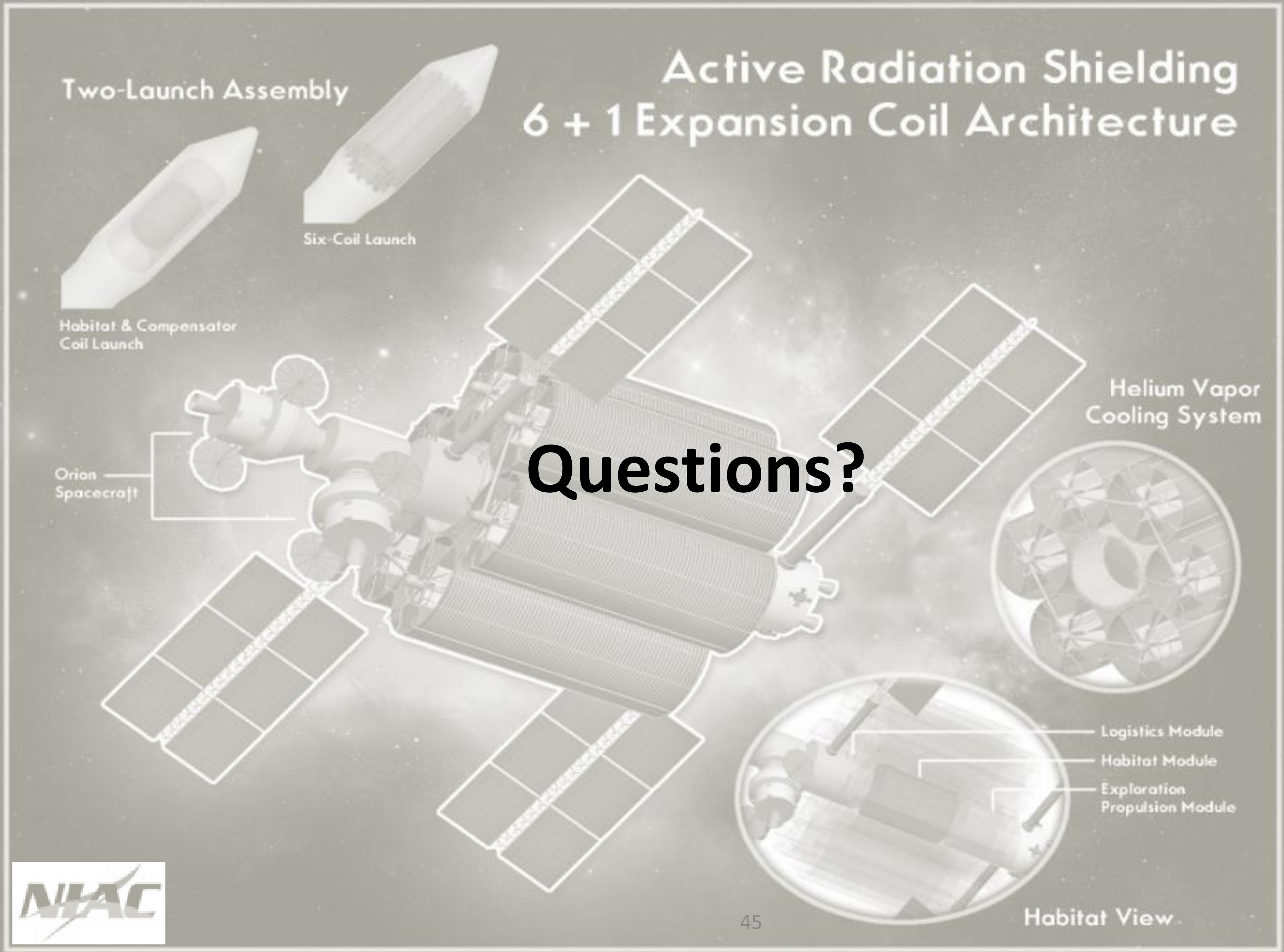
Phase 2 Goals (Remaining)

- The remaining tasks, as planned, include:
  - Failure Scenarios / Quench Protection
  - Shielding Optimization
  - Continued Dose Reduction Performance Analysis (Fringe Field, Habitat mass, GEANT4)
  - Finalize Technology Roadmap, Cost Analysis
  - Coil Expansion Test
  - Final Reporting

Considerations

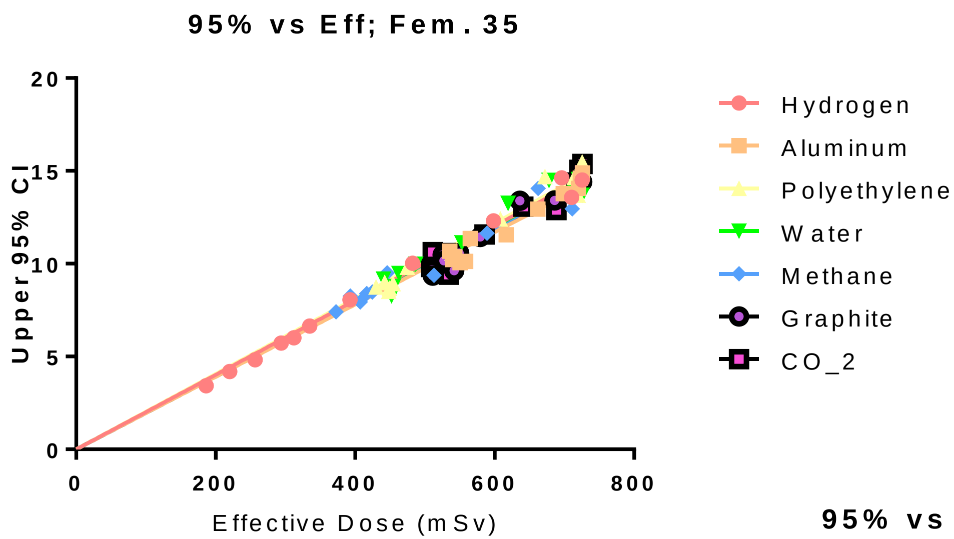
- How to better manage end cap dose?
  - Fringe field MC analysis
  - Multiple LH2 propellant tanks instead of 1 tank?
  - Expandable habitat benefit?
  - Can solar arrays play a part in thermal management?
  - Can shielding coils be used as energy storage?

Questions?

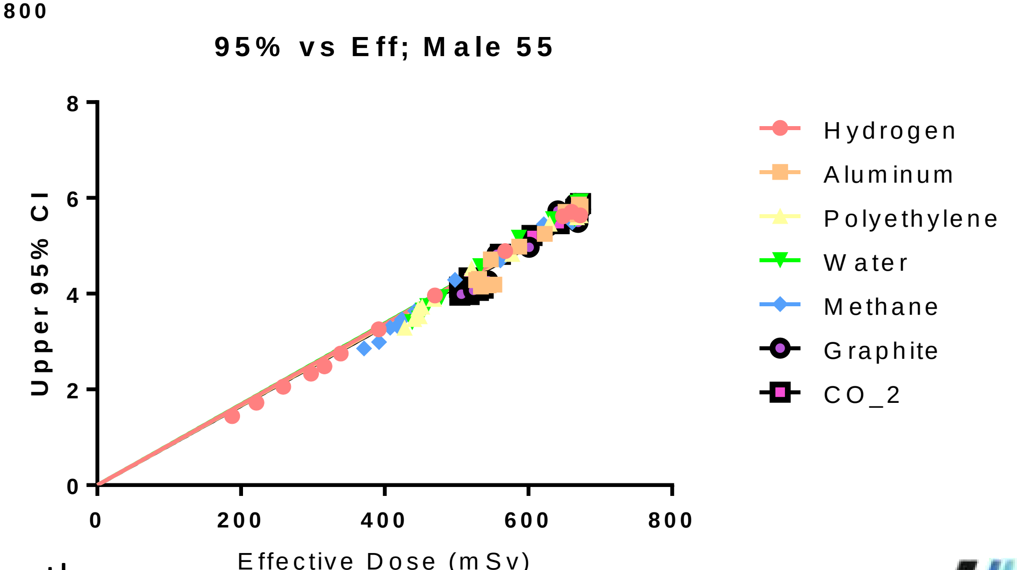

Active Radiation Shielding
6 + 1 Expansion Coil Architecture
Two-Launch Assembly
Six-Coil Launch
Habitat & Compensator
Coil Launch
Orion
Spacecraft
Helium Vapor
Cooling System
Logistics Module
Habitat Module
Exploration
Propulsion Module
Habitat View

Backup

Effective Dose is Approximately Linear with REID*



Composite data includes multiple analyses with varying material thickness (~5 to 40 g/cm^2)



* REID: Risk of Exposure Induced Death

Analysis conducted by LaRC intern/Roslyn V. Jones

Environments

- Publications on static magnetic field environments and its bio-effects were reviewed. Short-term exposure information is available suggesting long term exposure may be okay. Further research likely needed.
- Magnetic field safety requirements exist for controlled work environments. The following effects have been noted with little noted adverse effects
  - Magnetohydrodynamic (MHD) effects on ionized fluids (e.g. blood) creating an aortic voltage change
  - MHD interaction elevates blood pressure (BP)
    - 5 Tesla equates to 5% BP elevation
  - Prosthetic devises and pacemakers are an issue (access limit of 5 gauss).
    - Earth field ~0.5 gauss

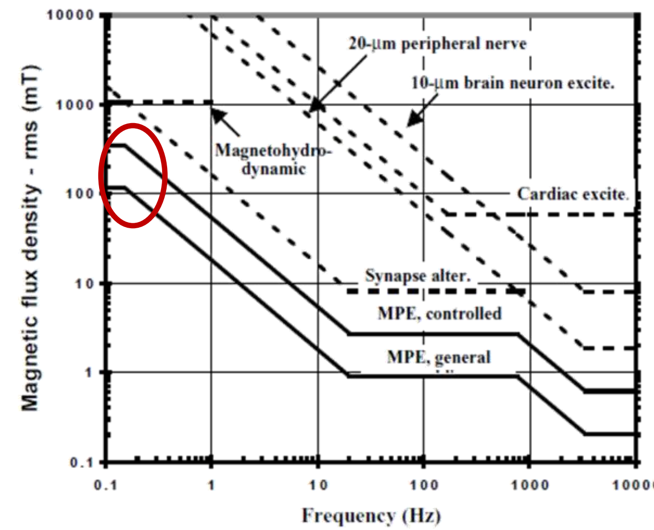


Figure 1— Median thresholds for adverse stimulation from magnetic field exposure (broken lines) and recommended maximum permissible exposure limits (solid lines); whole-body exposure to spatially constant field

Ref.:

1. IEEE C95.6 Safety Standard (2002, revisit 2007)
2. G. Miller, Exposure Guidelines for Magnetic Fields (1987)

Advanced Magnet Lab

Thermal System

- Requires flexible low pressure helium gas circulation loop development for an expandable coil system
- A solar shield was considered in lieu of the helium vapor cooling system however, such a solar shield would not get the coils down to the desired temperature of 40 – 60K
- Power required
  - Cryocoolers will need 600 W at COP 32 W/W and 1.25 contingency for a total of 24kW
    - includes 380 W for compensation coil
    - Cools to 40 K, coolant loop picks up 10W with a 2 K temperature rise in the circuit for a pressure drop of ~200 Pa.

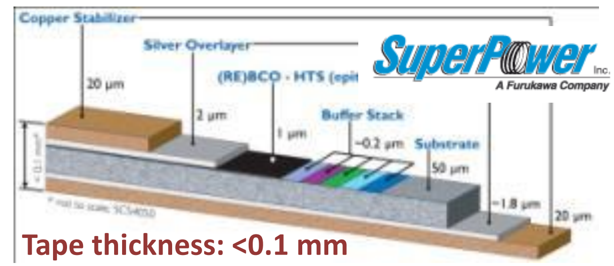
*COP – Coefficient of Performance

State of the Art High Temperature Superconductor (HTS)

- Low Temperature Superconducting
  - Typical Operation: <5K - Boiling point of liquid Helium
    - Most prevalent use is with MRI medical machines
- High Temperature Superconducting
  - Typical Operation: ≤ 77K - Boiling point of liquid Nitrogen
    - HTS, such as YBCO, is not sensitive to conductor movement such as the supersensitive LTS
    - HTS can operate in deep space environment
    - A tape conductor is needed for solenoid coils such as the magnet systems presented here.

YBCO

Yttrium Barium Copper Oxide



Tape thickness: <0.1 mm

Tape thickness: 0.21- 0.23 mm