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Person-sized shields for biomagnetic measurements

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Sandia National Laboratories

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Outline

- Introduction
  – General shielding principles
- Sandia's person-sized magnetic shield
  – Design process
  – Performance
- Survey of other person-sized shields
- Conclusion

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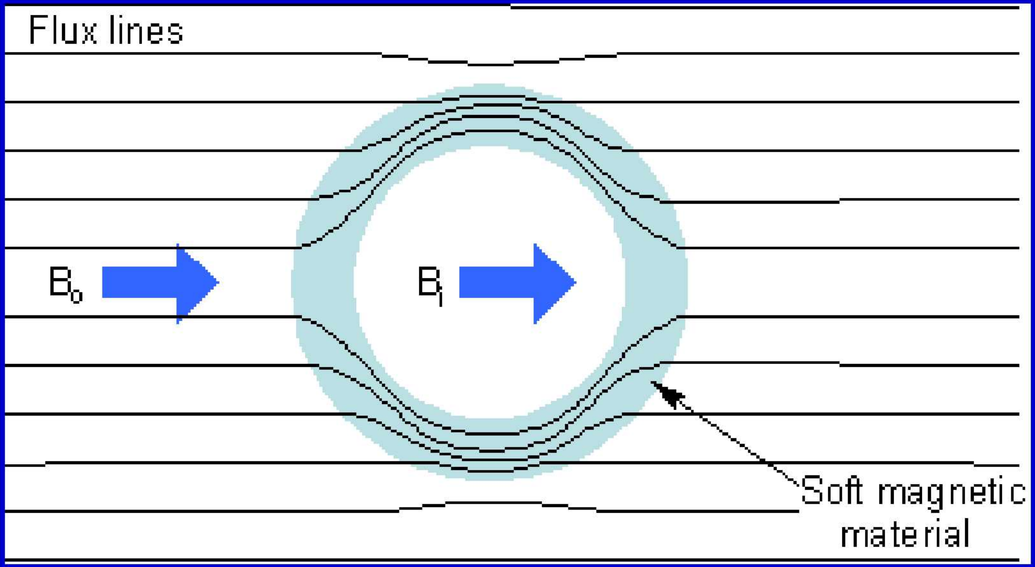
Introduction

- Why consider a person-sized magnetic shield?
  - Cost!!!
  - Potentially better shielding
  - Smaller size
  - OPMs give a flexible system
- OPM MEG system
  - Shield: $62,000 (2014)
  - 20 channel OPM system: $180,000

Princeton OPM MEG System

Magnetic Shielding



Shielding Factor

$$S = \frac{B_O}{B_I}$$

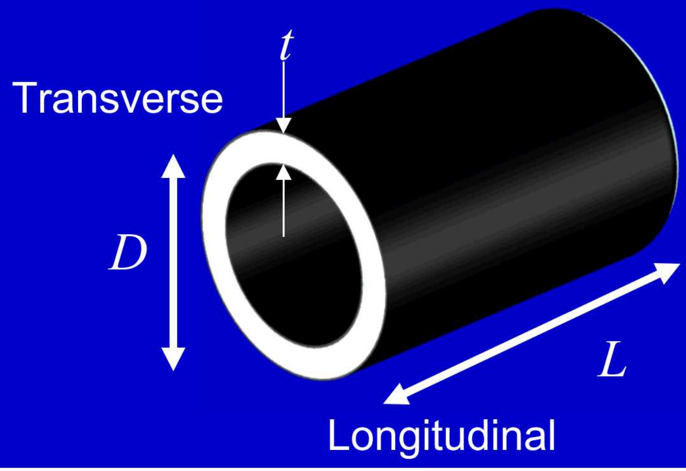
B_O = outer magnetic field
B_I = inner magnetic field

- Best geometry: sphere
- Next best: cylinder
- Good: cube
  - 90° corners do not guide flux as well
- Holes let flux inside

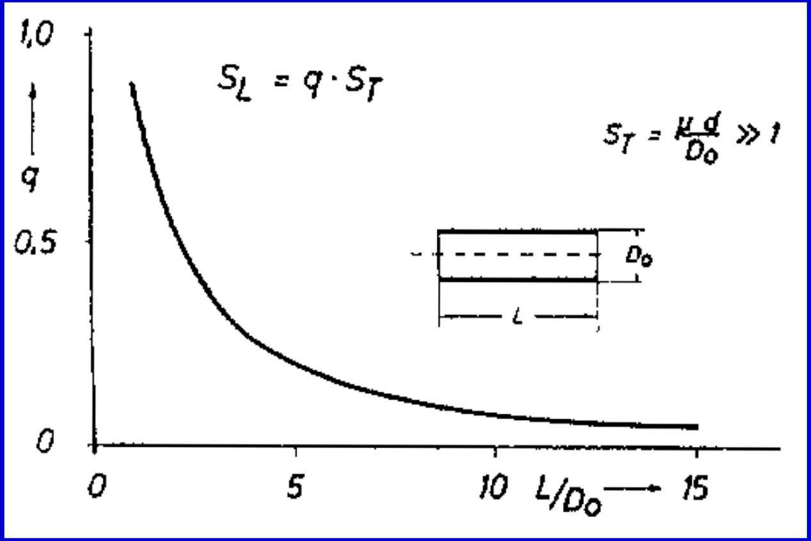
General Shielding Considerations

Cylinder

- Transverse shielding
  - $S_T \approx \frac{\mu\, t}{D}$
  - μ is the relative magnetic permeability, mu-metal: μ = ~40,000



- Longitudinal shielding
  - Various analytical approximations



"Magnetic Shields", Albrecht Mager, IEEE Transactions on Magnetics, March 1970.

- Nested shells

$$S_T \approx S_{T1}S_{T2}\left(1 - \frac{D_{in}^2}{D_{out}^2}\right) + S_{T1} + S_{T2} + 1$$

$$S_L \approx S_{L1}S_{L2}\left(1 - \frac{L_{in}}{L_{out}}\right) + S_{L1} + S_{L2} + 1$$

- Openings require numerical modelling

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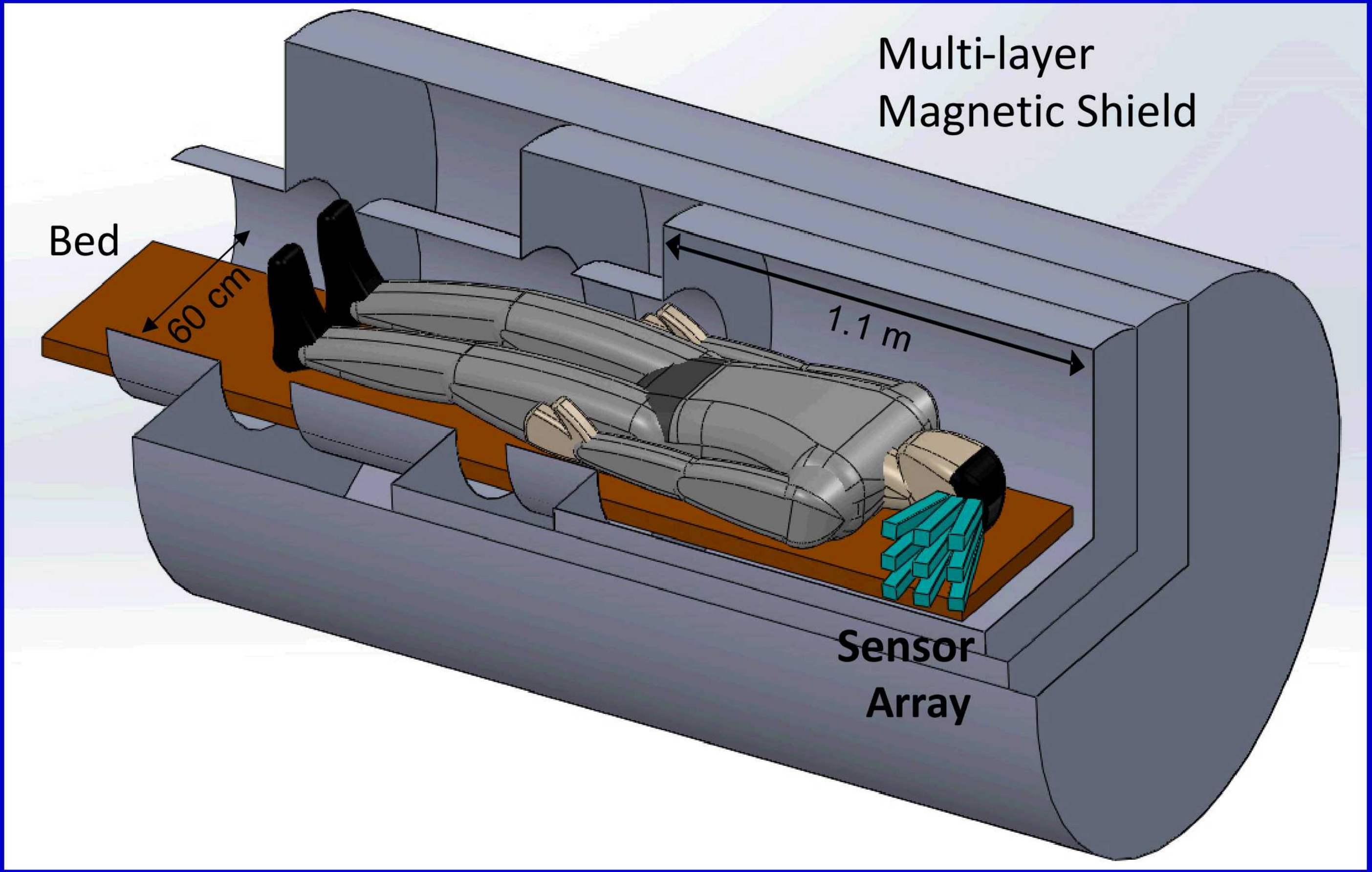
Magnetic Shield Design Goals

- Have a permanent opening for the human subject.
- Maximize shielding factor and minimize gradients.
  - Minimize the effect of the opening
- Removable endcaps and must fit through lab door, 1.5 m



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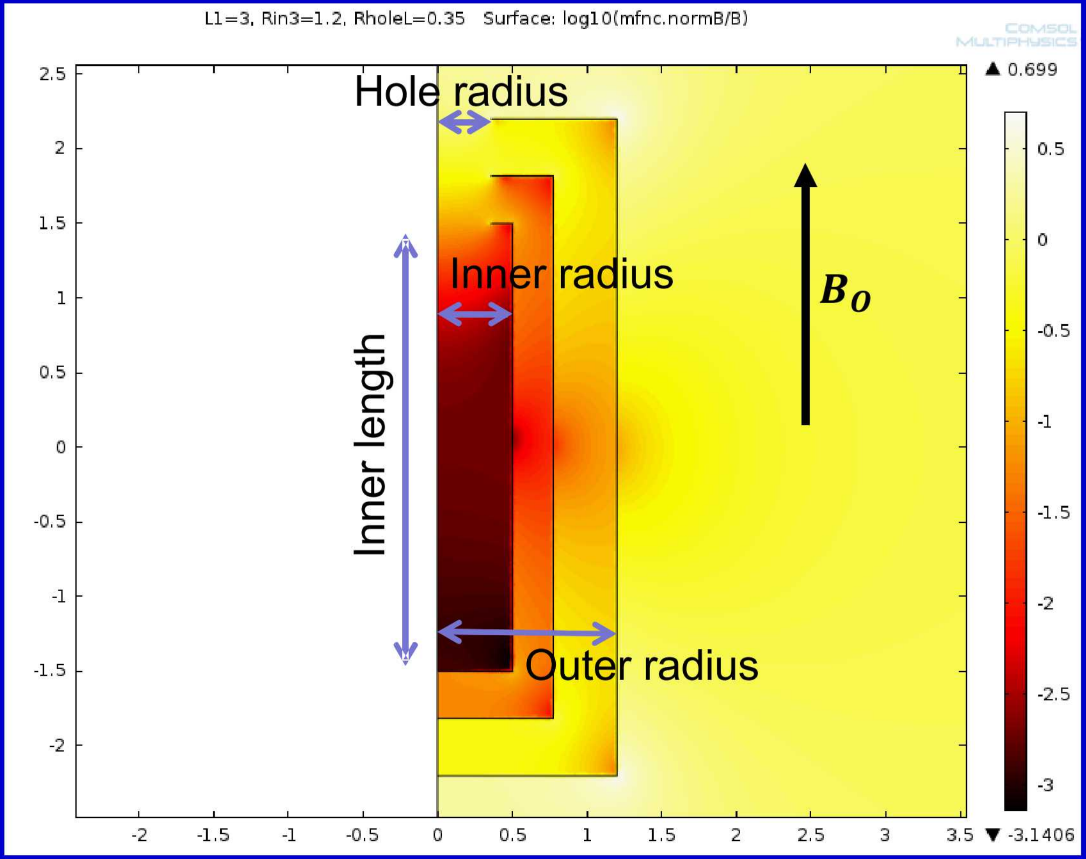
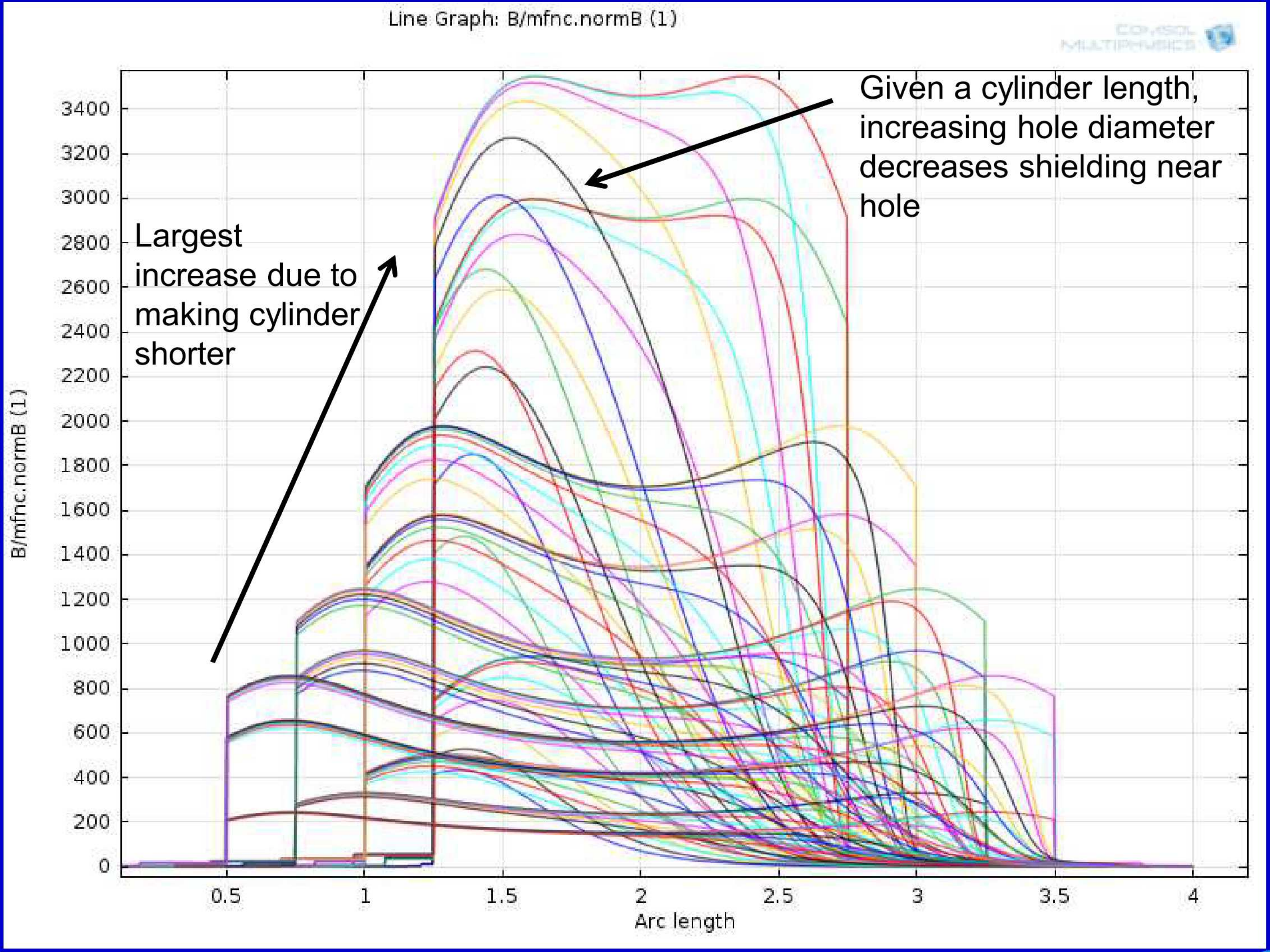
Cylindrical, 3 layer shield

- Finite element modeling: COMSOL
- 2D axially symmetric
- Constants
  - μ_r = 40,000
  - Shield thickness = 0.04”
  - Inner radius = 0.5 m
- Variables
  - Inner length
  - Outer radius
  - Hole radius

Longitudinal Shielding Factor



Shielding factor vs geometry



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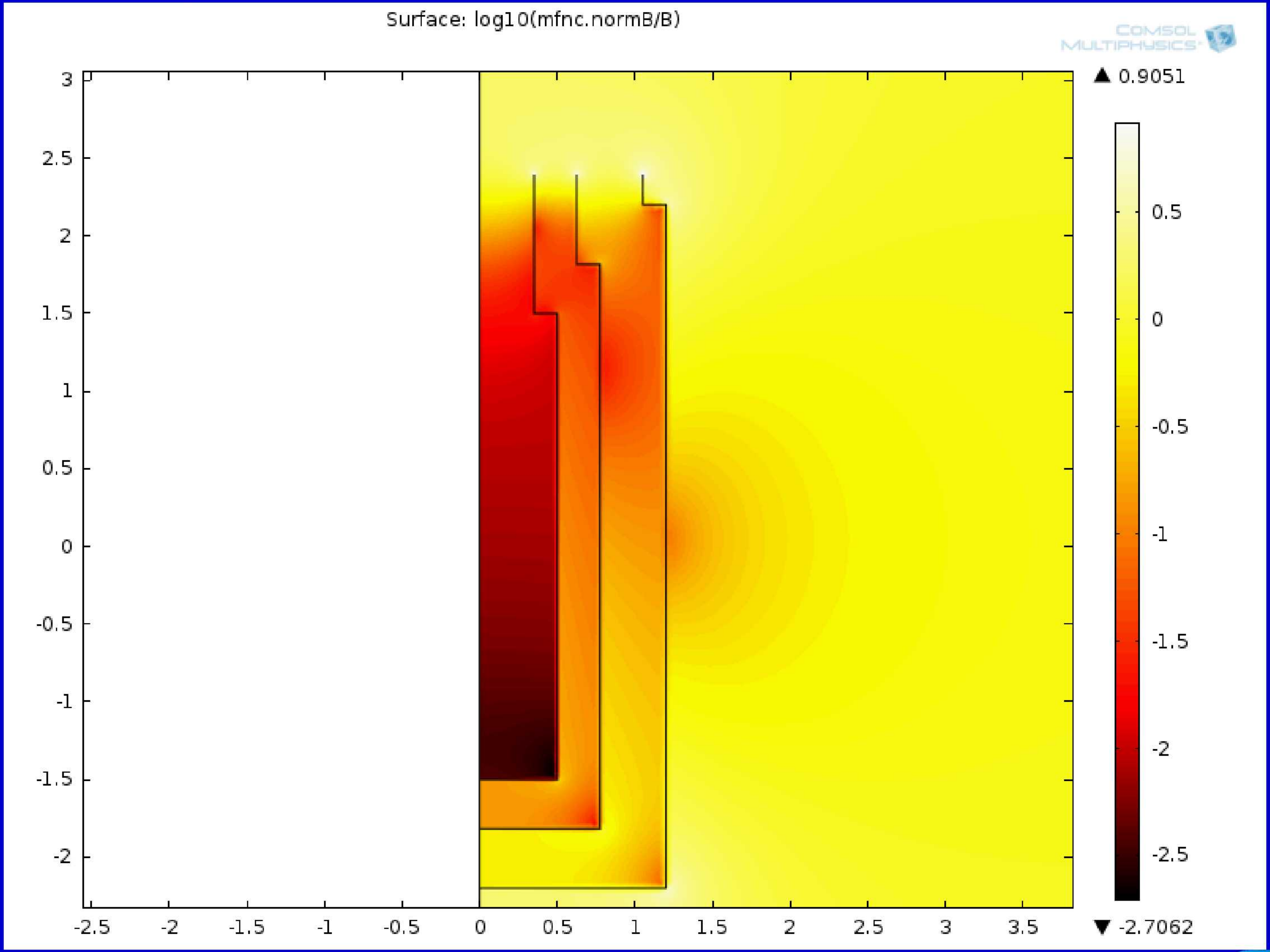
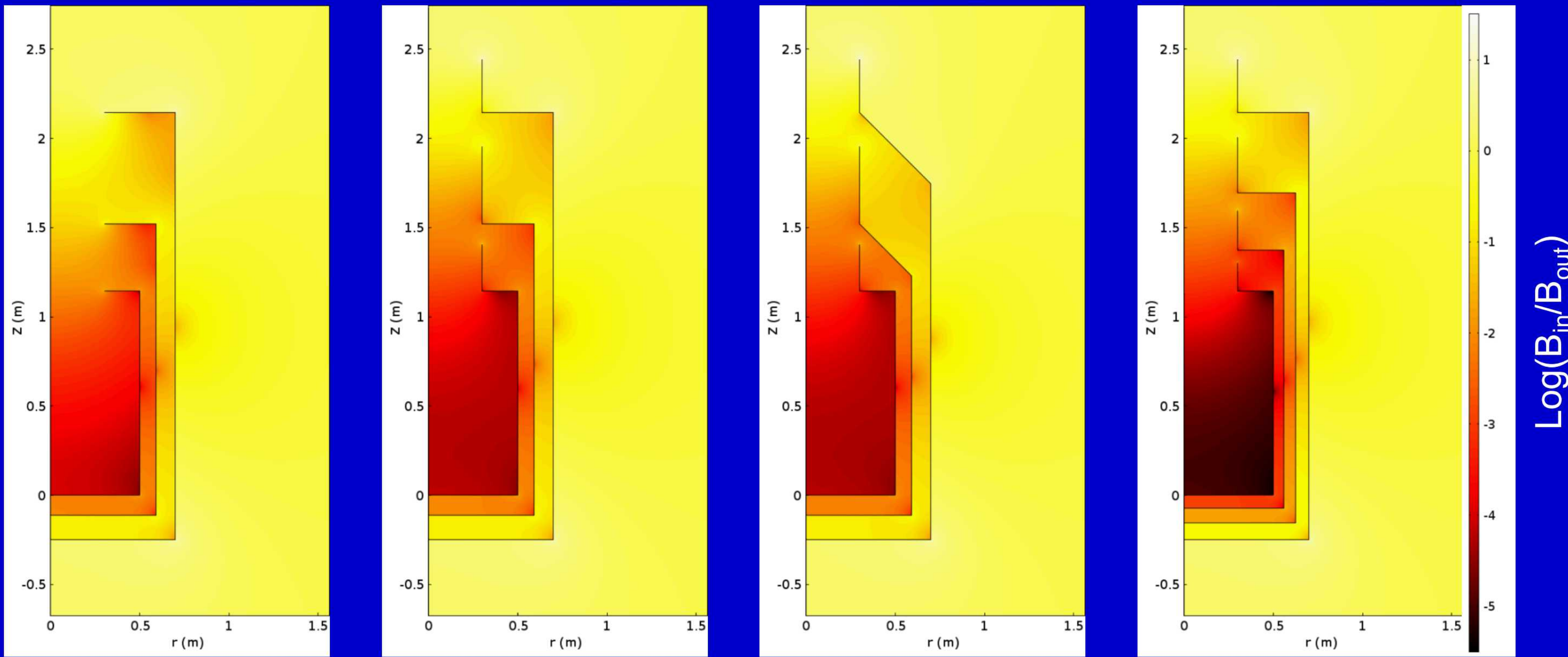
A Bad Idea



Surface: log10(mfnc.normB/B)
COMSOL MULTIPHYSICS
▲ 0.9051
▼ -2.7062
0.5
0
-0.5
-1
-1.5
-2
-2.5
3
2.5
2
1.5
1
0.5
0
-0.5
-1
-1.5
-2
-2.5
-2
-1.5
-1
-0.5
0
0.5
1
1.5
2
2.5
3
3.5

Some Good Ideas

3-Layer Cylinder | 3-Layer Cylinder with tubes | 3-Layer Cylinder with Chamfer | 4-Layer Cylinder with tubes

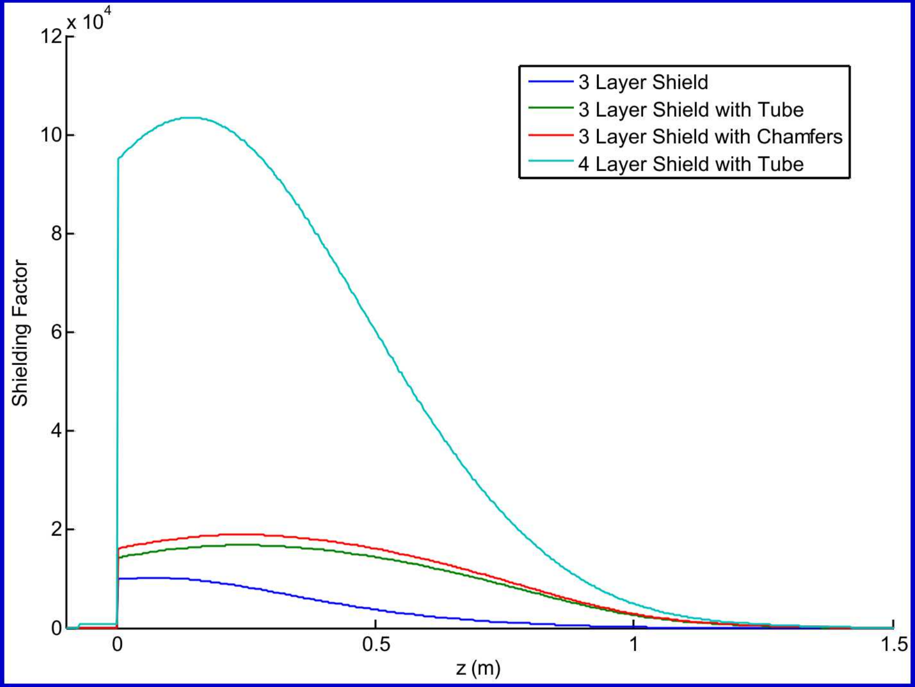


- Focused mainly on longitudinal shielding (transverse shielding much better)
- Asymmetric shield design with tubes leads to larger area of uniform field

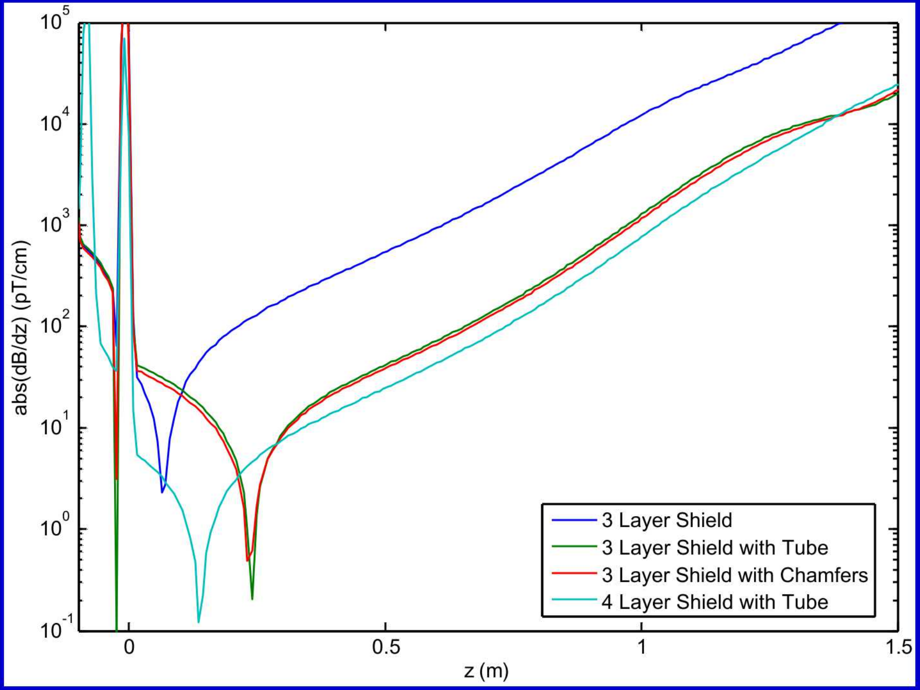
- Permeability = 40,000
- Thickness = 1/16”

Longitudinal Field

Longitudinal Field



Longitudinal Field Gradient



- 4-layer performs better
- Gradient minimum closer to the center of the shield with 3-layer
- 3-layer is about $20k cheaper

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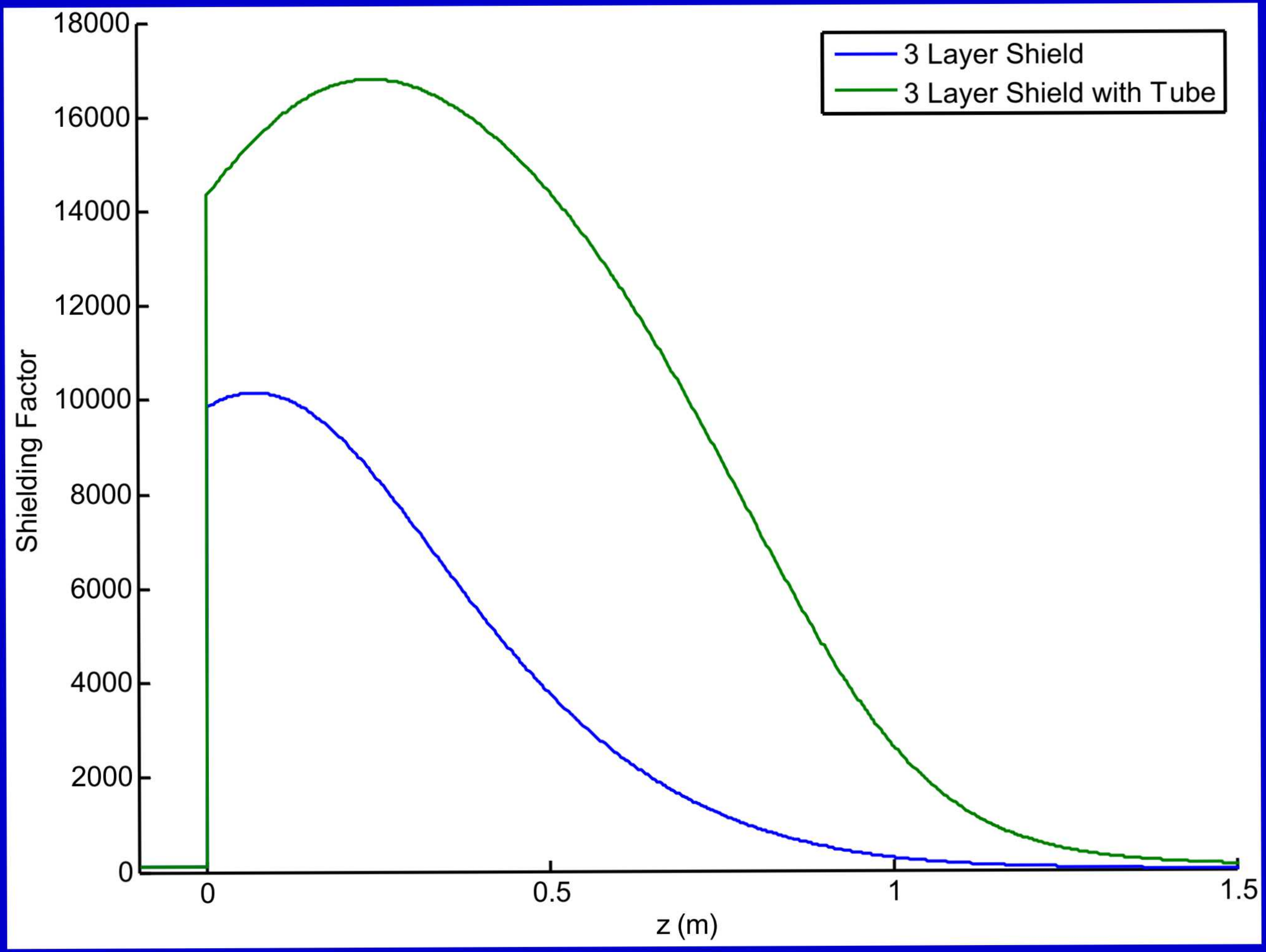
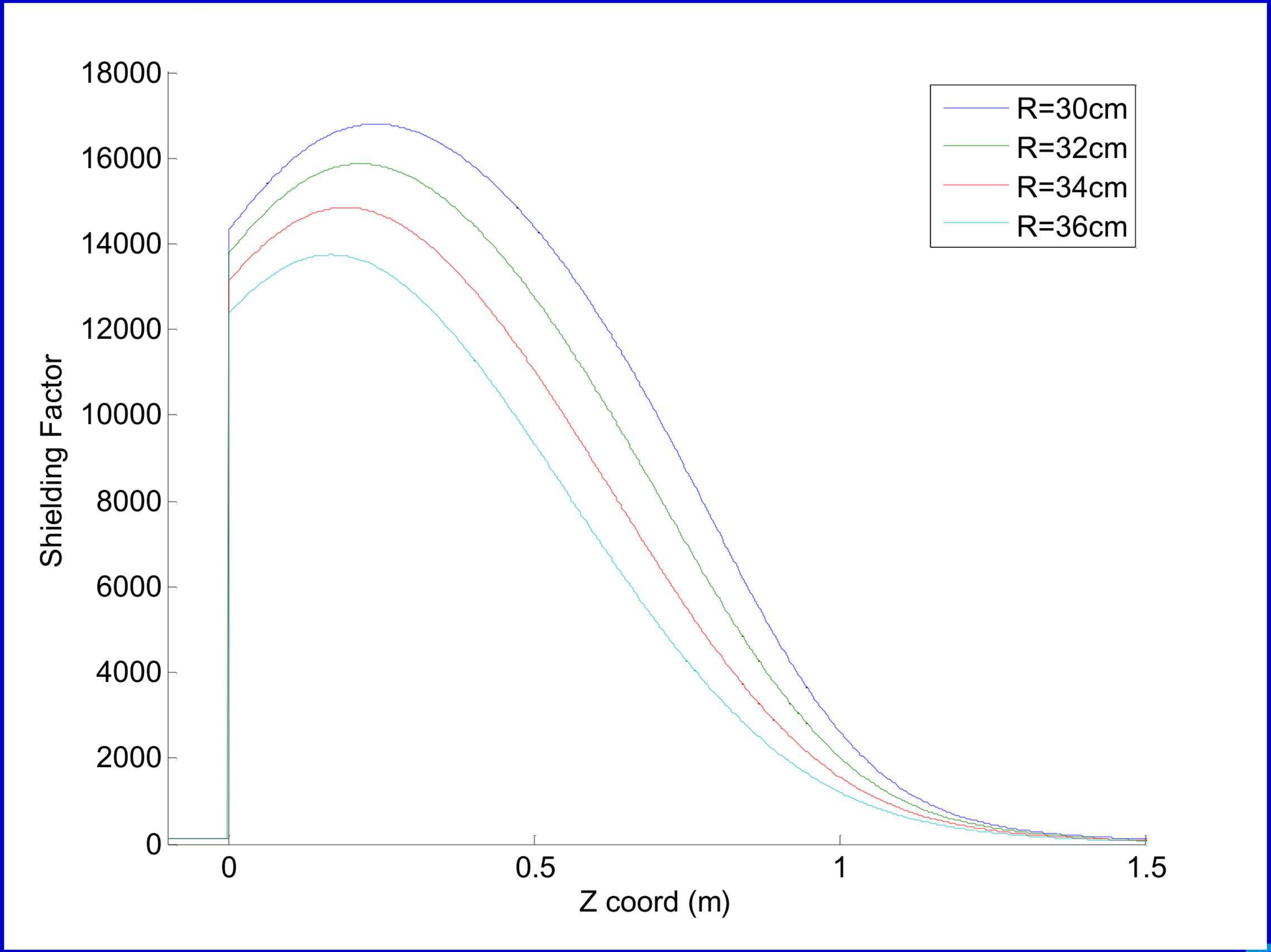
3-Layer Shields



- 3-layer shield with tube shielding factor = 17,000

Shielding factor for various hole radii



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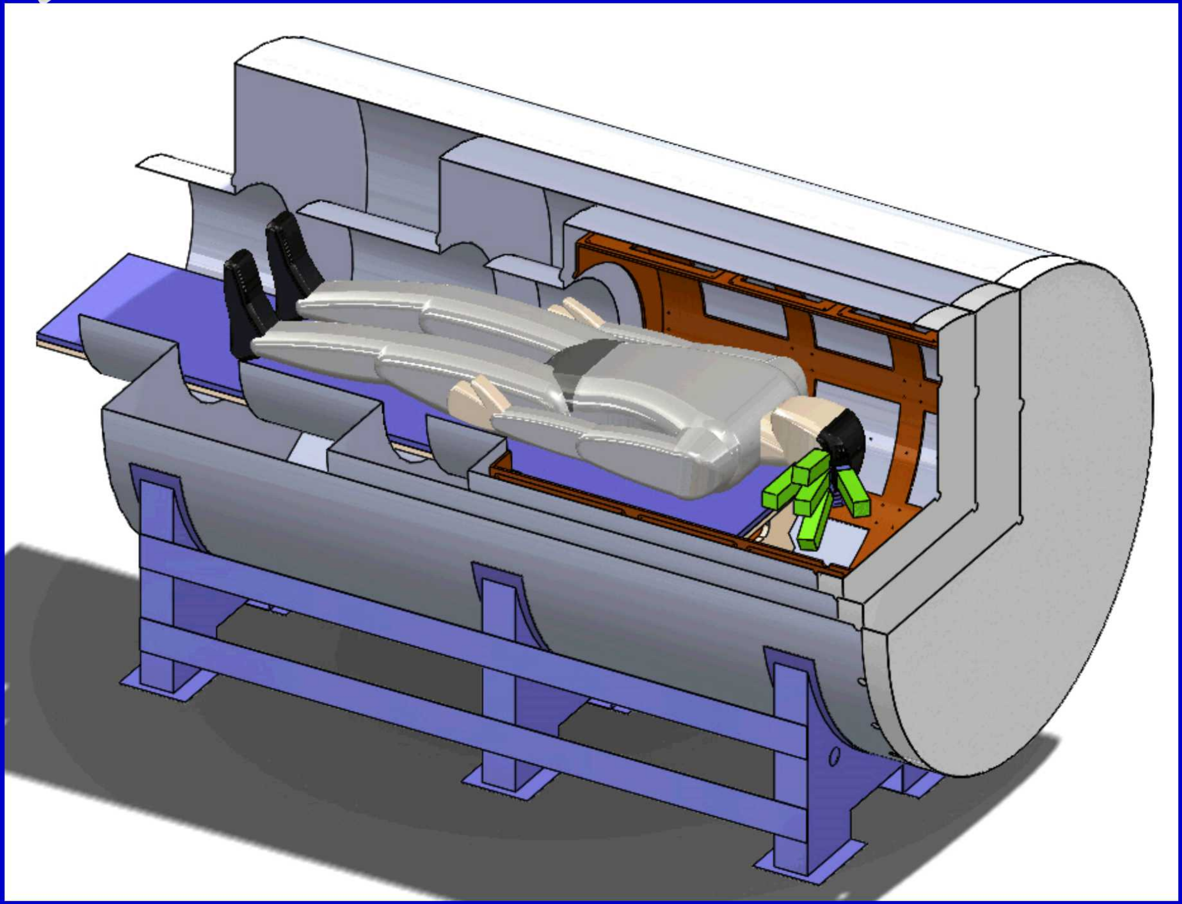
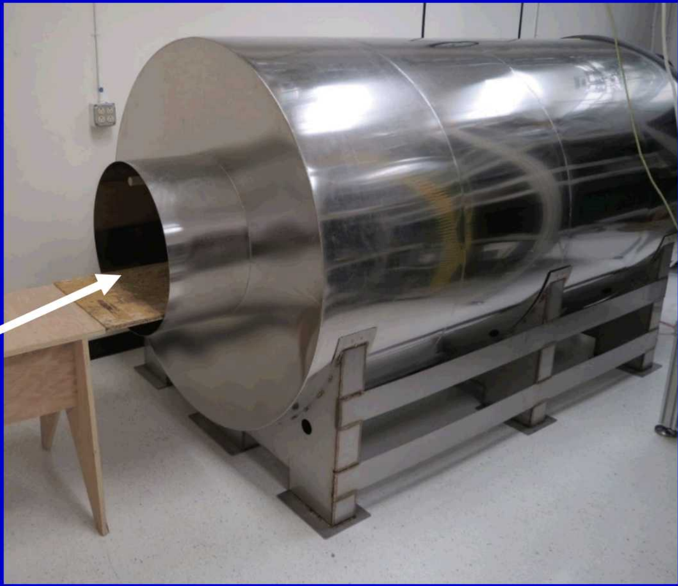
Magnetic Shield



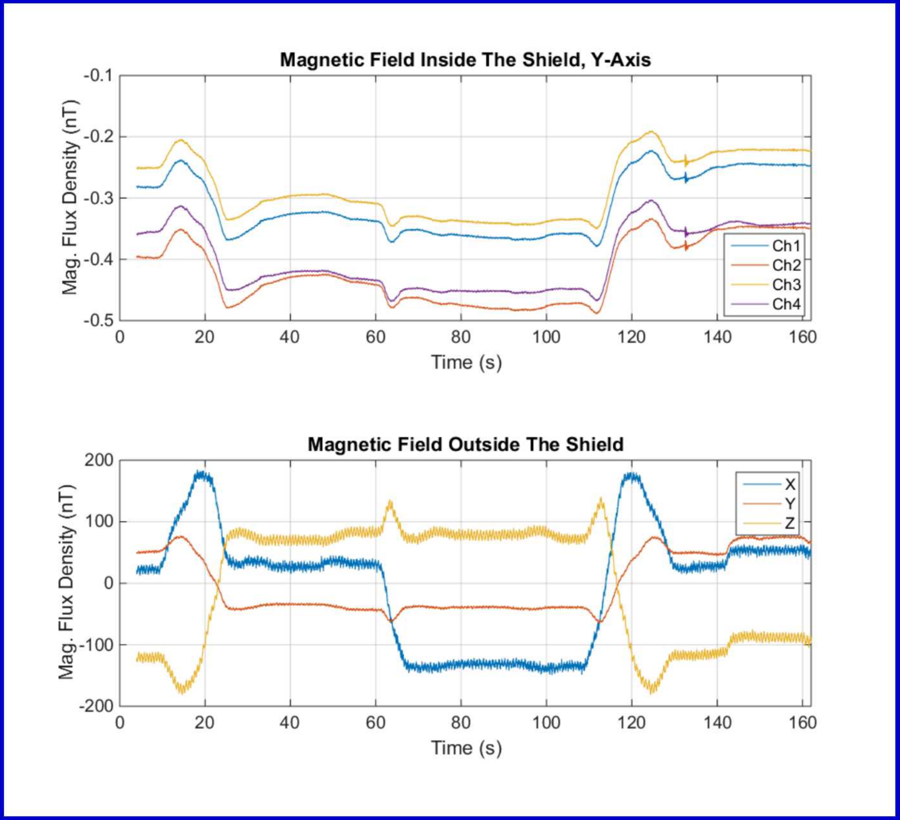
Outer shield: L = 2.7 m, D = 1.4 m
Inner shield: L = 1.1 m, D = 1.0 m
Tube diameter = 0.6 m
Manufacturer: Advance Magnetics
Cost: $62,000

Insert
Person
Here



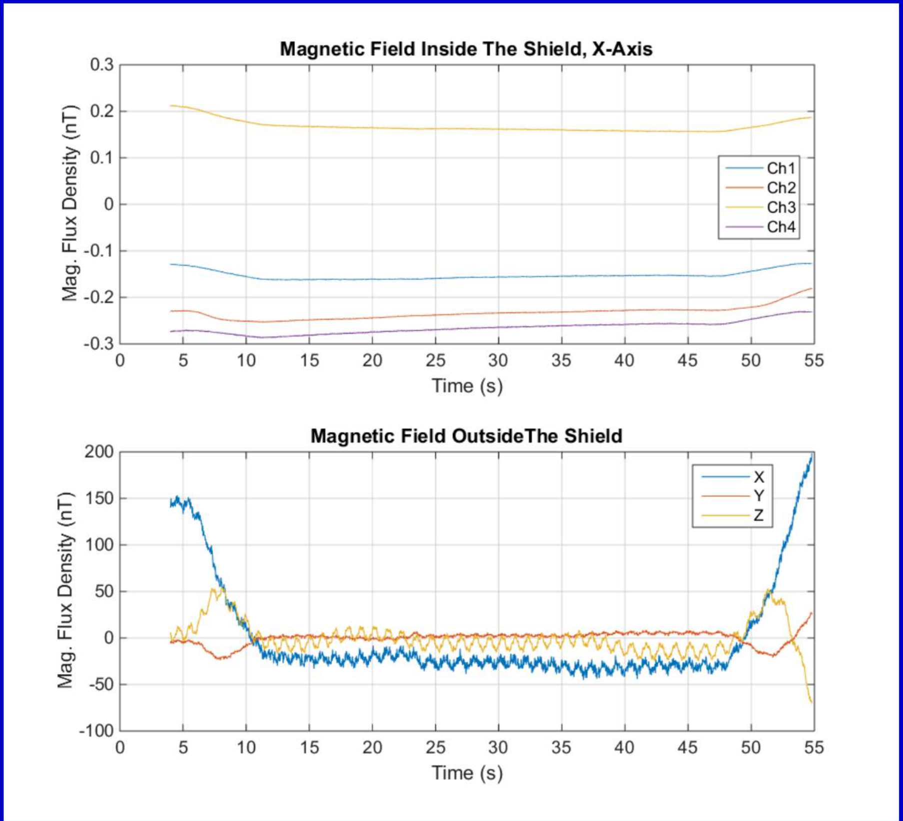
Shielding Factor Measurement

Longitudinal, $S_L = 1300$



- Measure with nearby freight elevator
- Why 10x lower than expected?
  - Poor measurement technique
  - Permeability too low
  - Imperfect geometry

Transverse, $S_T = 10{,}000$



- Remnant field
  - 50 nT
- With degaussing
  - ~1 nT
  - Coil: 5 turns, ~100 A, 60 Hz

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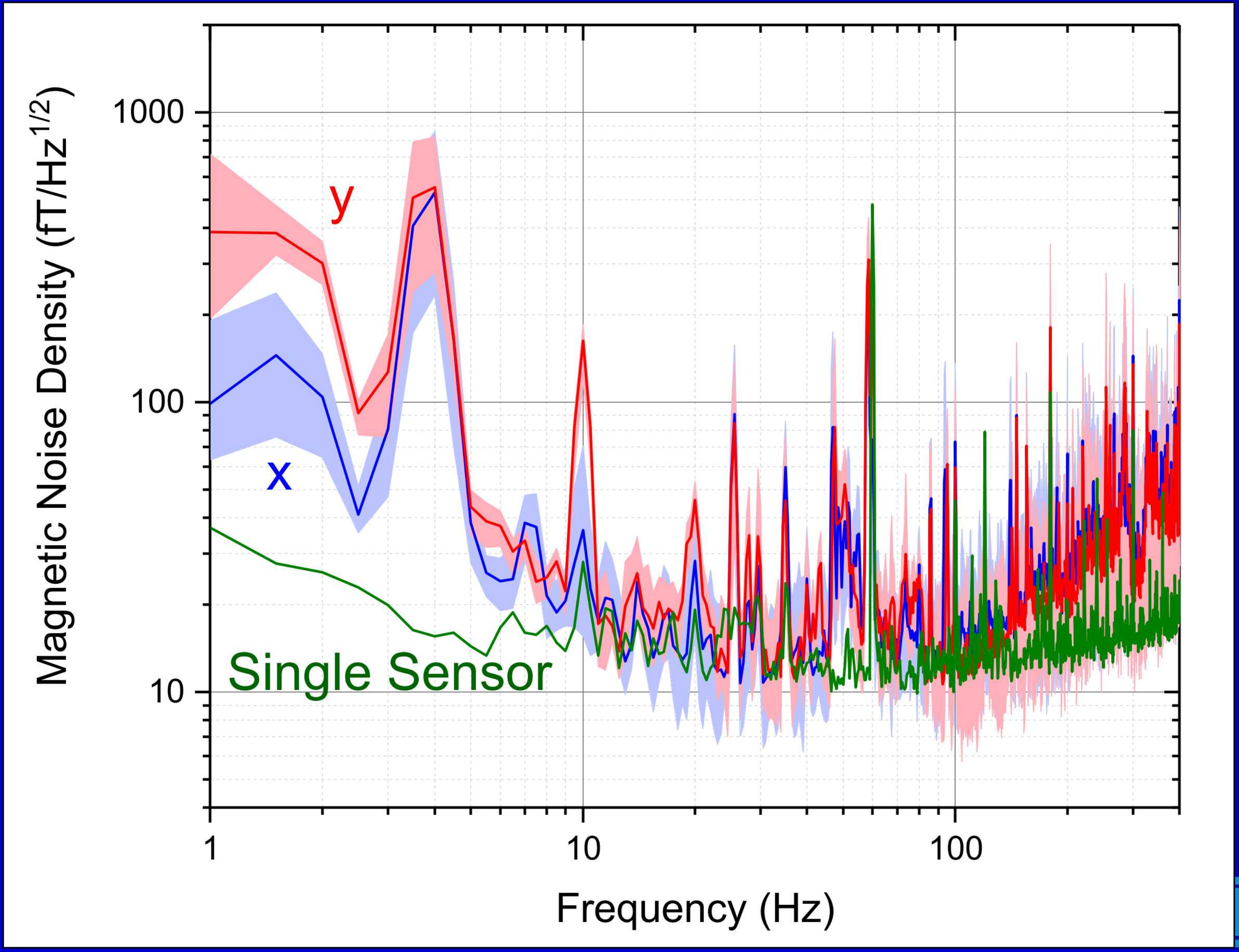
Sensor noise inside the shield



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Other considerations

- Vibration
- Aluminum layer
- Degaussing
- Shaking
- Internal coils for field control
- Moving the subject in and out of the apparatus
- Stimulation
  - Auditory and electrical stimulation: easy
  - Visual: needs work
    - Perhaps adapt MRI visual system

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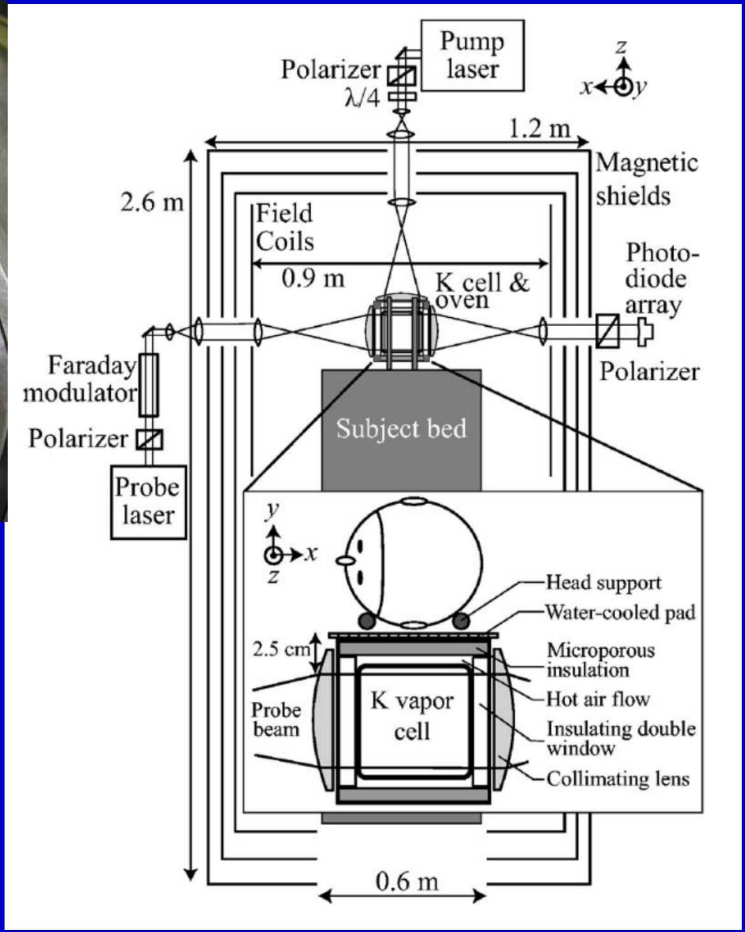
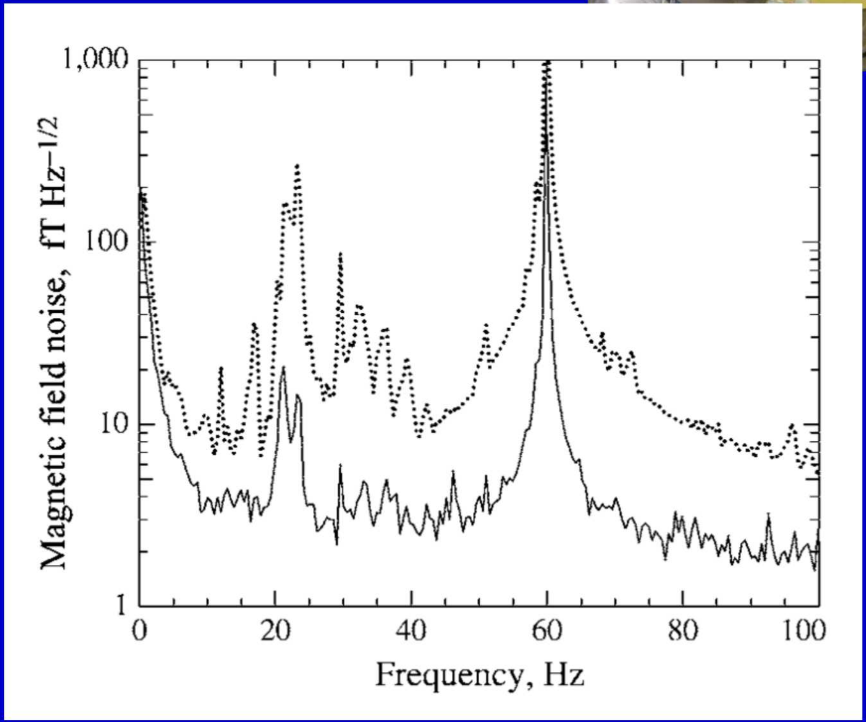
Princeton Magnetic Shield

- Shielding Factor:
  - $S_L = 1000$
  - $S_T = 7000$





H. Xia, A. Ben-Amar Baranga, D. Hoffman, and M. V. Romalis. "Magnetoencephalography with an atomic magnetometer." *Appl. Phys. Lett.* **89**, 211104 (2006).

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Genetesis Magnetic Shield

- Magnetocardiography
- Mu-metal, 3 layers
- Aluminum, 1 layer
- Cost: ~$60,000

- Mumetal Layer 1: L = 2.78 m, D = 0.97 m (ID)
- Layer 3: L = 2.96 m, D = 1.25 m
- Aluminum outer Layer: L = 3.09 m, D = 1.38 m

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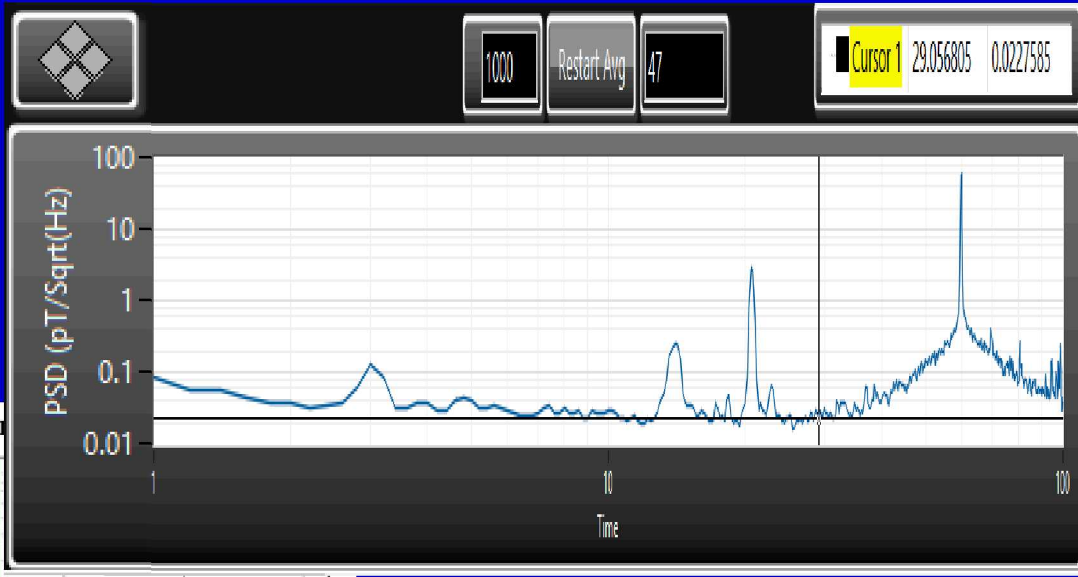
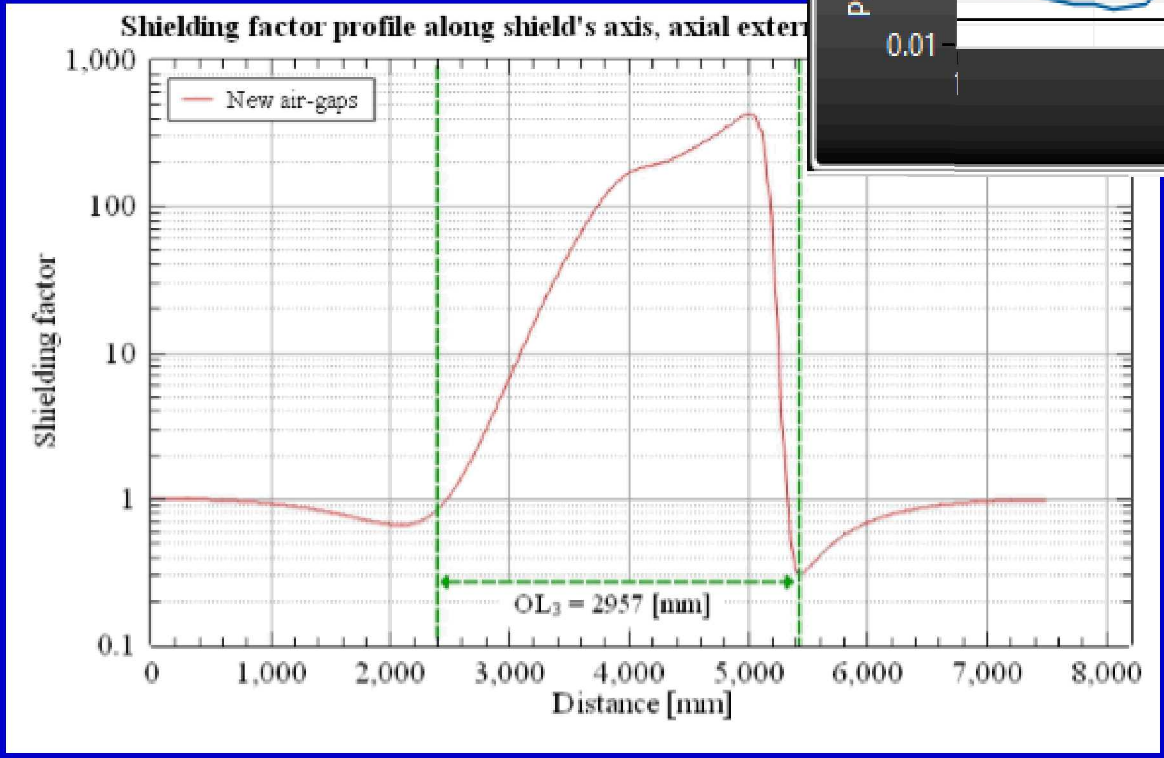
Performance

- Remnant field after degaussing: < 2 nT





- Noise taken in a noisy industrial environment

Conclusion

- Flexibility in the design of the shield
- Practical longitudinal shielding factors at low frequency of ~1000
    - Careful design and more layers should improve this
- Noise floor 10-20 fT/rt-Hz
    - Vibration is a problem
- Subject interaction/stimulus not as convenient
    - Careful design needed
- Inexpensive and relatively small size

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Use of human-sized shields

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