Magnetic Gradient Amelioration for nEDM@LANL

Austin Reid
Trinity College, Hartford

nEDM 2021 ~~Les Houches~~ Zoom
2020 02 19

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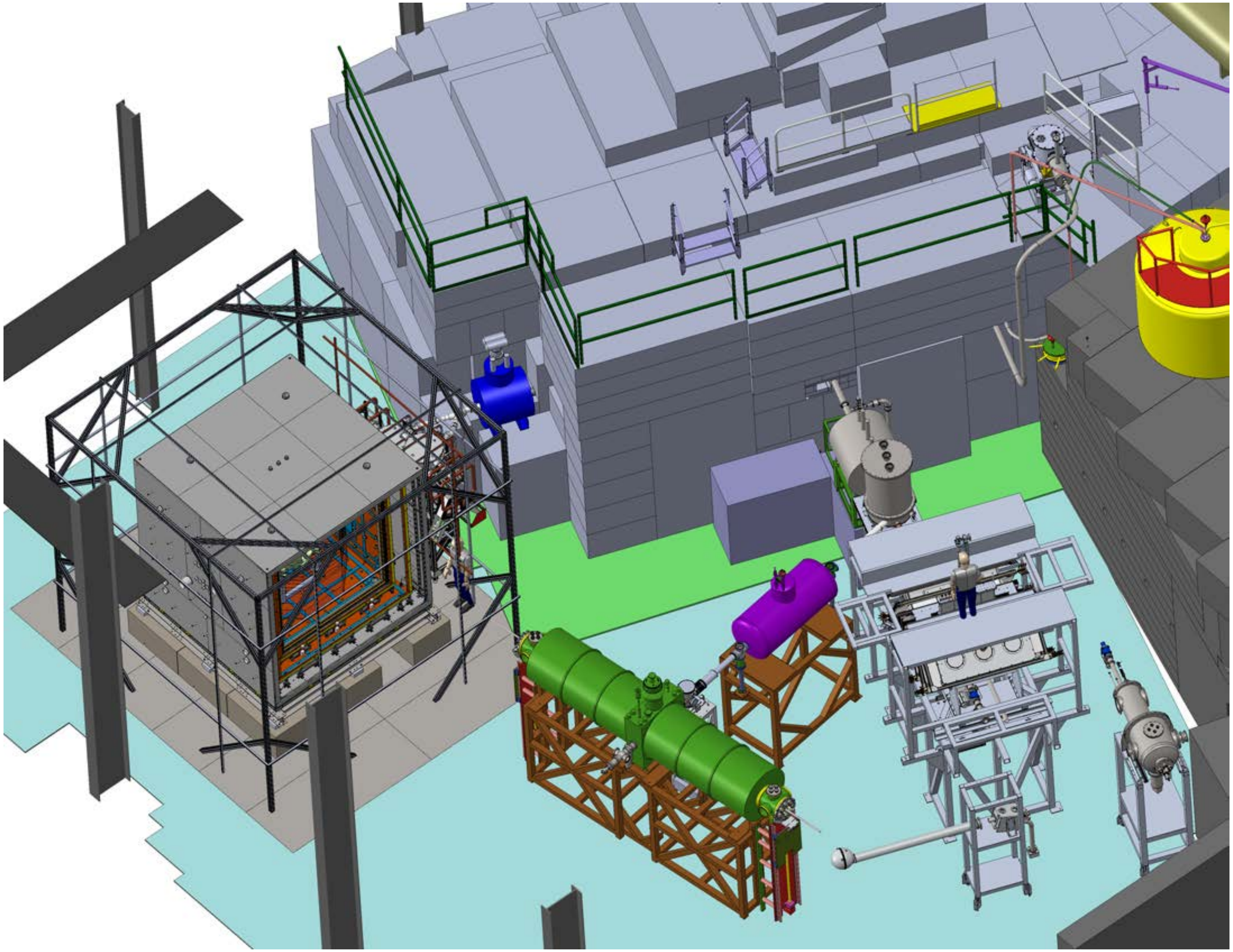

Image by Chris O'Shaughnessy

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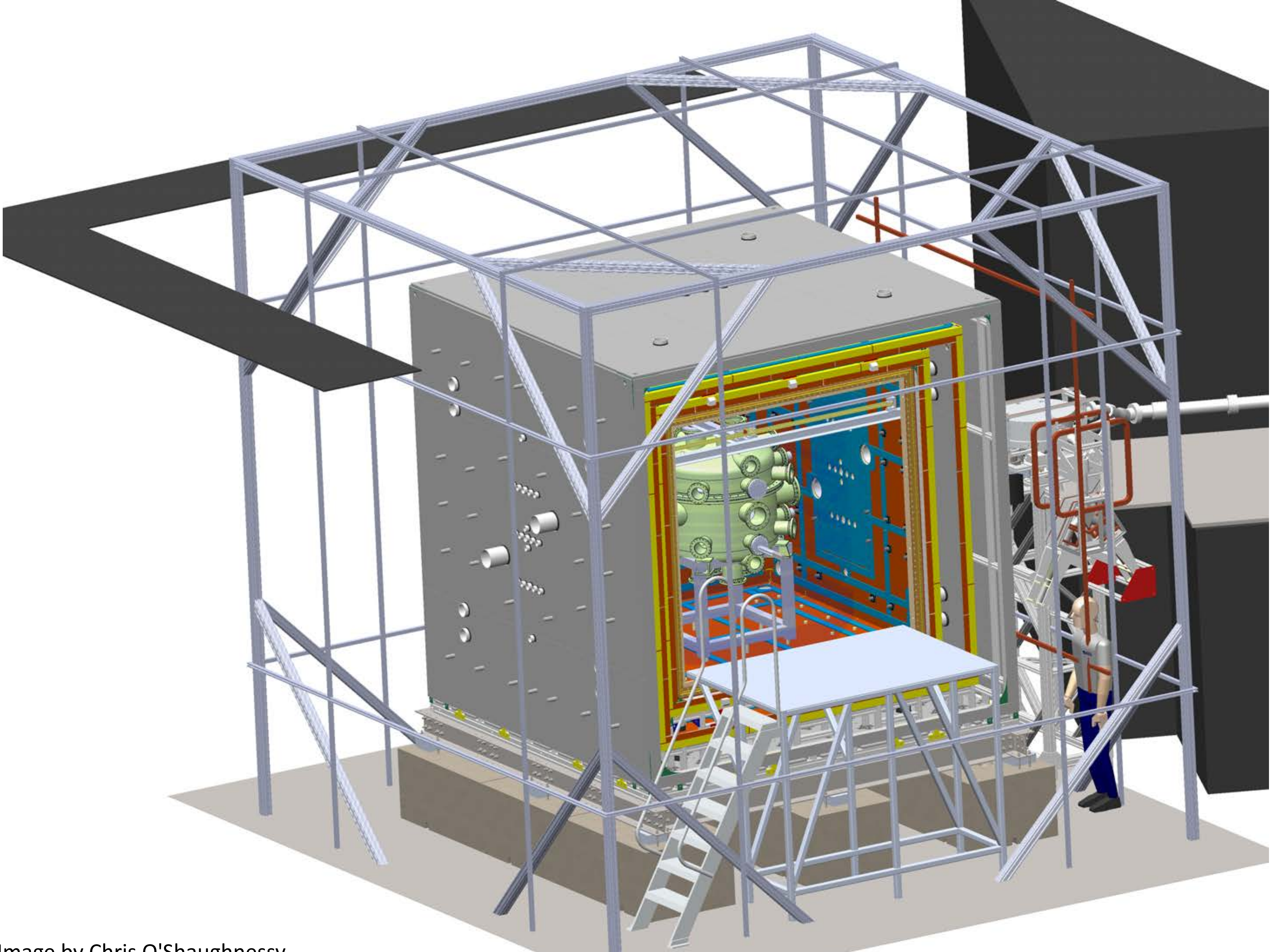

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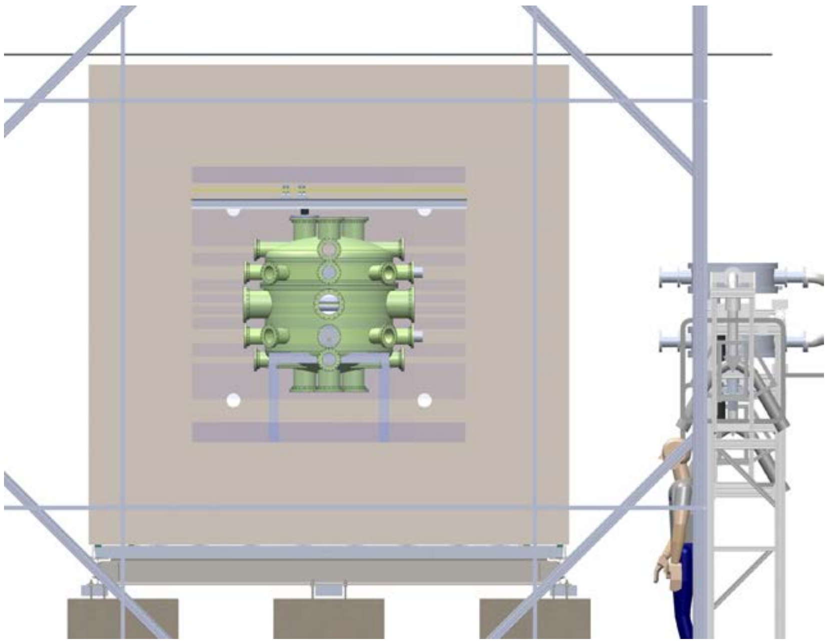
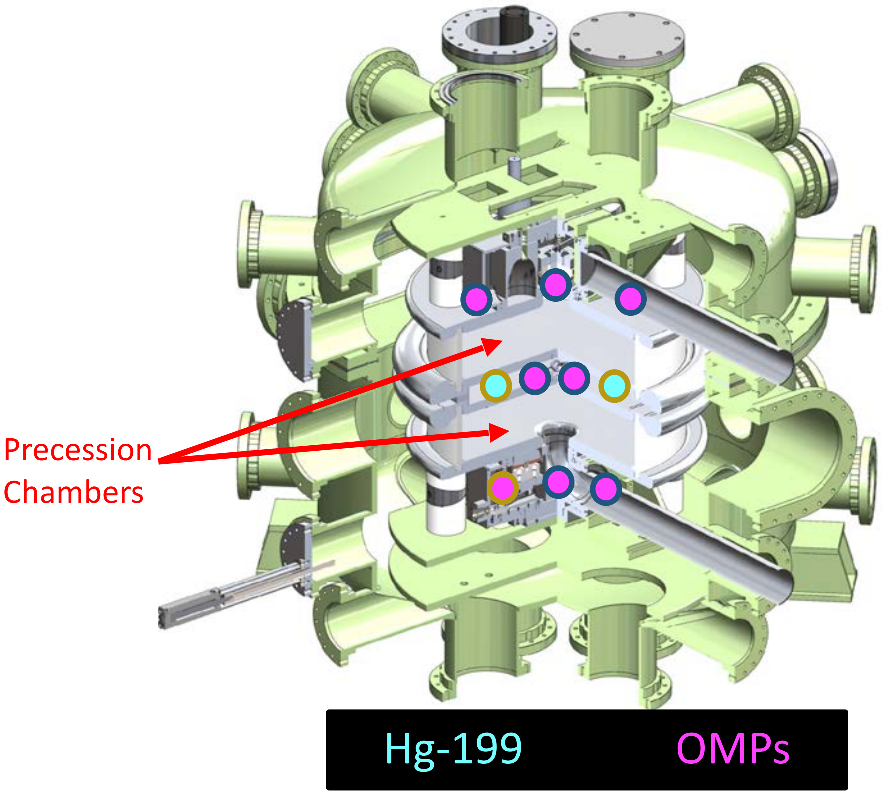
LANL nEDM Layout





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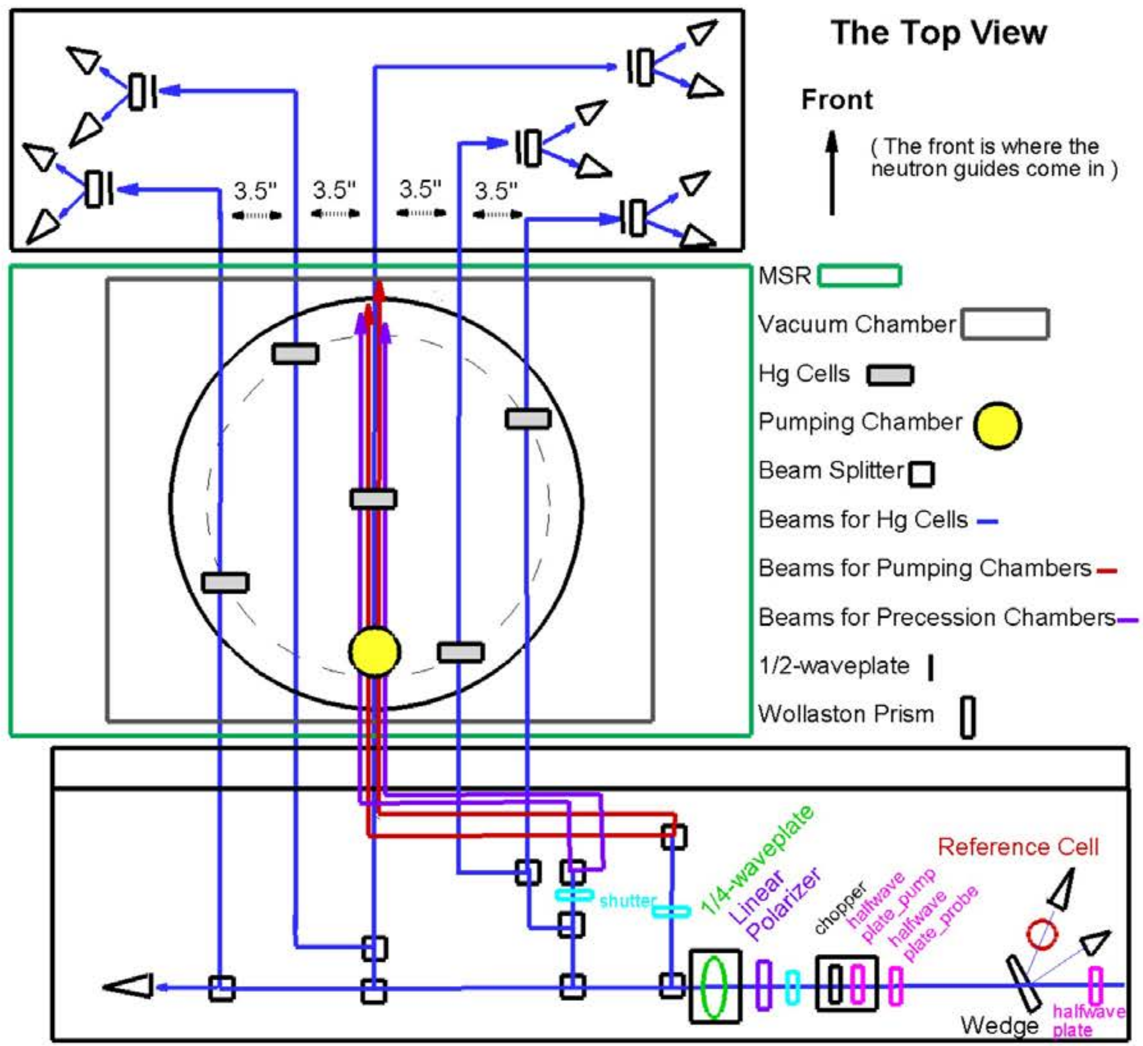
Felicity Hills

HV Hg Probes

Status

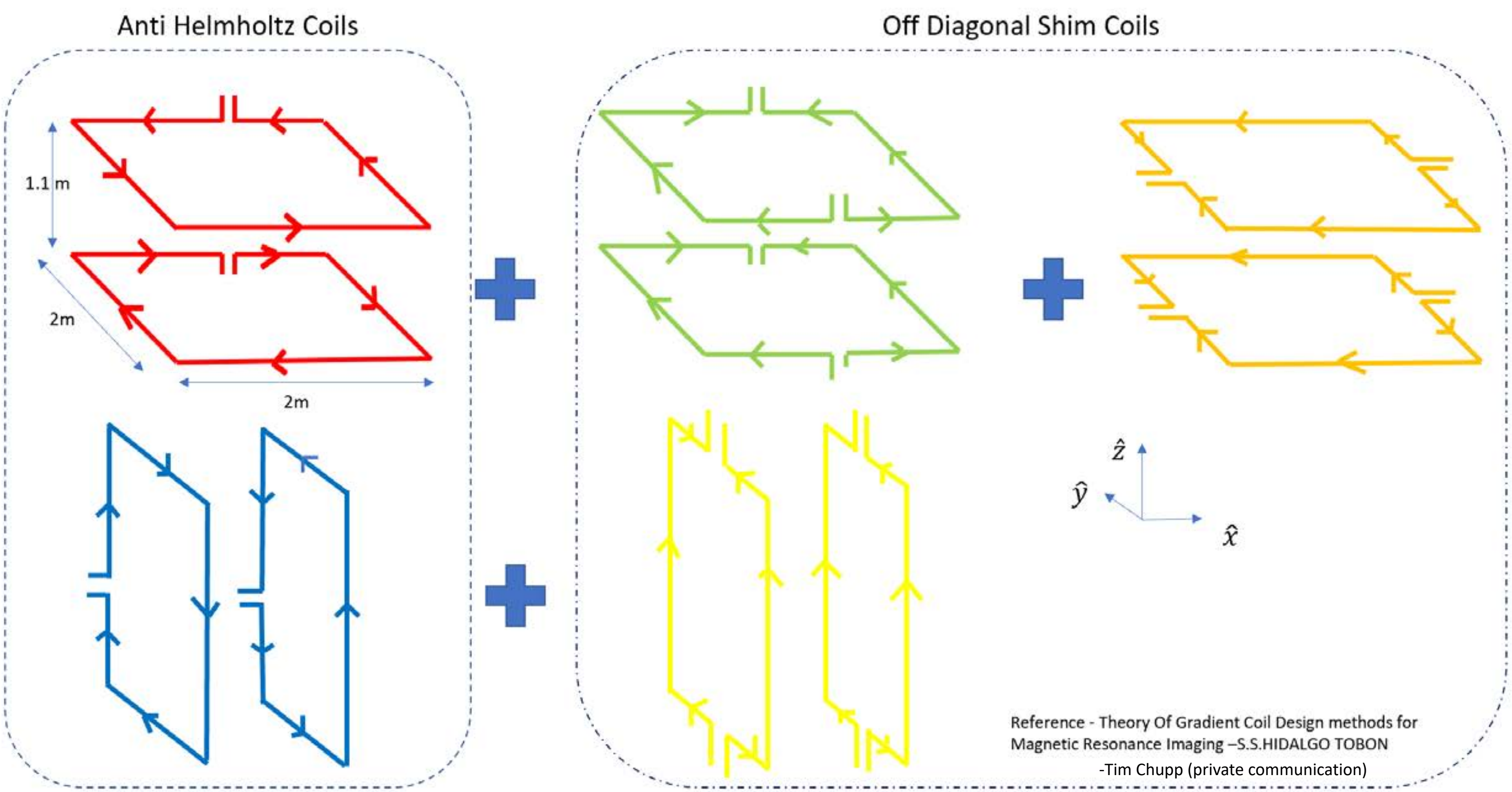
- Optics setup for nEDM@LANL
- The Larmor precession frequency is detected by the Faraday rotation of the laser polarization.
- Lock the laser frequency during the pump and probe phases with a Hg reference cell.
    - Frequency locking circuit design and fabrication
- Hg cell fabrication with various coatings



Jennie Chen

Anti Helmholtz coils and off diagonal shim coils

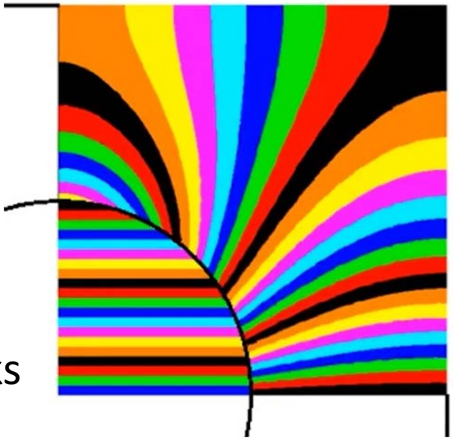
Gradient Coils along x and z axis to create ∂B_z, ∂B_z, ∂B_z, ∂B_x, ∂B_x



Scalar Potential Coil Design

In free space:

$\vec{\nabla} \times \vec{H} = 0 \qquad \vec{\nabla} \cdot \vec{H} = 0 \quad \Rightarrow \quad \vec{H} = -\vec{\nabla} u \qquad \nabla^2 u = 0$



Thanks to Chris Crawford. For more detail, see one of his talks here: https://youtu.be/LTuk-sz-ApE

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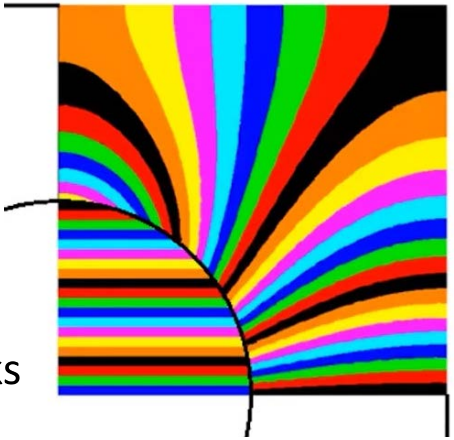

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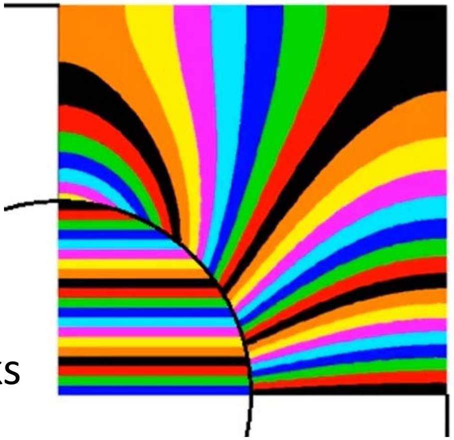
Surface discontinuity:

$\hat{n} \times -\vec{\nabla}(u_{out} - u_{in}) = \vec{K} \qquad -\Delta u = I$



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Tx: Calculate, invert transfer function

- Given a full basis set of Vm: $\Sigma_{m,\ell}$
- Simulate coil response for each Σ
- Decompose coil response across sample region to $\Sigma_{m,\ell}$
- Orthogonalize response matrix, hope it isn't singular
- Generate a linear sum of Σ's that yield any desired $\Sigma_{m,\ell}$

$$\Sigma_{l,m} = C_{l,m}(\phi) r^l P_l^{|m|}(\cos\theta), \tag{4}$$

with

$$C_{l,m}(\phi) = \frac{(l-1)!(-2)^{|m|}}{(l+|m|)!}\cos(m\phi) \quad \text{for} \quad m \geqslant 0,$$

$$C_{l,m}(\phi) = \frac{(l-1)!(-2)^{|m|}}{(l+|m|)!}\sin(|m|\phi) \quad \text{for} \quad m < 0. \tag{5}$$

Finally, the modes are obtained by calculating the gradient of the magnetic potential:

$$\Pi_{x,l,m} = \partial_x \Sigma_{l+1,m}, \;\; \Pi_{y,l,m} = \partial_y \Sigma_{l+1,m}, \;\; \Pi_{z,l,m} = \partial_z \Sigma_{l+1,m}. \tag{6}$$

TABLE II. The basis of harmonic polynomials sorted by degree.

l	m	Π_x	Π_y	Π_z
0	−1	0	1	0
0	0	0	0	1
0	1	1	0	0
1	−2	y	x	0
1	−1	0	z	y
1	0	$-\frac{1}{2}x$	$-\frac{1}{2}y$	z
1	1	z	0	x
1	2	x	$-y$	0
2	−3	$2xy$	x^2-y^2	0
2	−2	$2yz$	$2xz$	$2xy$
2	−1	$-\frac{1}{2}xy$	$-\frac{1}{4}(x^2+3y^2-4z^2)$	$2yz$
2	0	$-xz$	$-yz$	$z^2-\frac{1}{2}(x^2+y^2)$
2	1	$-\frac{1}{4}(3x^2+y^2-4z^2)$	$-\frac{1}{2}xy$	$2xz$
2	2	$2xz$	$-2yz$	x^2-y^2
2	3	x^2-y^2	$-2xy$	0
3	−4	$3x^2y-y^3$	x^3-3xy^2	0
3	−3	$6xyz$	$3(x^2z-y^2z)$	$3x^2y-y^3$
3	−2	$-\frac{1}{2}(3x^2y+y^3-6yz^2)$	$-\frac{1}{2}(x^3+3xy^2-6xz^2)$	$6xyz$
3	−1	$-\frac{3}{2}xyz$	$-\frac{1}{4}(3x^2z+9y^2z-4z^3)$	$3yz^2-\frac{3}{4}(x^2y+y^3)$
3	0	$\frac{3}{8}(x^3+xy^2-4xz^2)$	$\frac{3}{8}(x^2y+y^3-4yz^2)$	$z^3-\frac{3}{2}z(x^2+y^2)$
3	1	$-\frac{1}{4}(9x^2z+3y^2z-4z^3)$	$-\frac{3}{2}xyz$	$3xz^2-\frac{3}{4}(x^3+xy^2)$
3	2	$-x^3+3xz^2$	$-3yz^2+y^3$	$3(x^2z-y^2z)$
3	3	$3(x^2z-y^2z)$	$-6xyz$	x^3-3xy^2
3	4	x^3-3xy^2	$-3x^2y+y^3$	0

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Abel 2019 doi:10.1103/PhysRevA.99.042112

Rx:

1. Solve for idealized Vm
2. Extract windings from #1
3. Add MuMetal, energize windings
4. Solve for Vm across fiducial volume
5. Decompose #4 into $\Sigma_{m,\ell}$
   - Surface or Volume integral?
   - Is there a difference in theory?
   - What about FE considerations?

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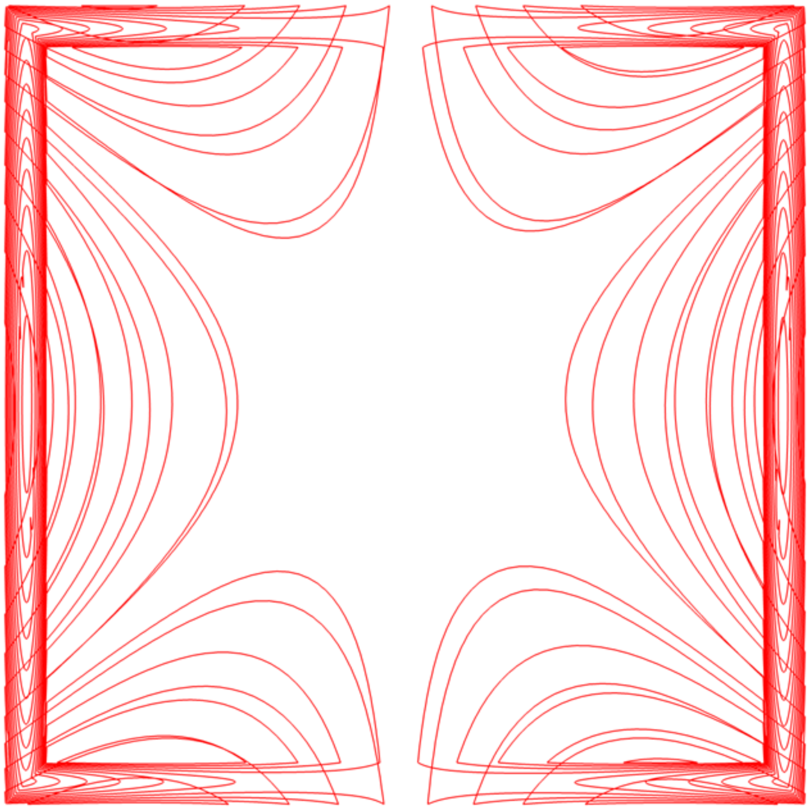

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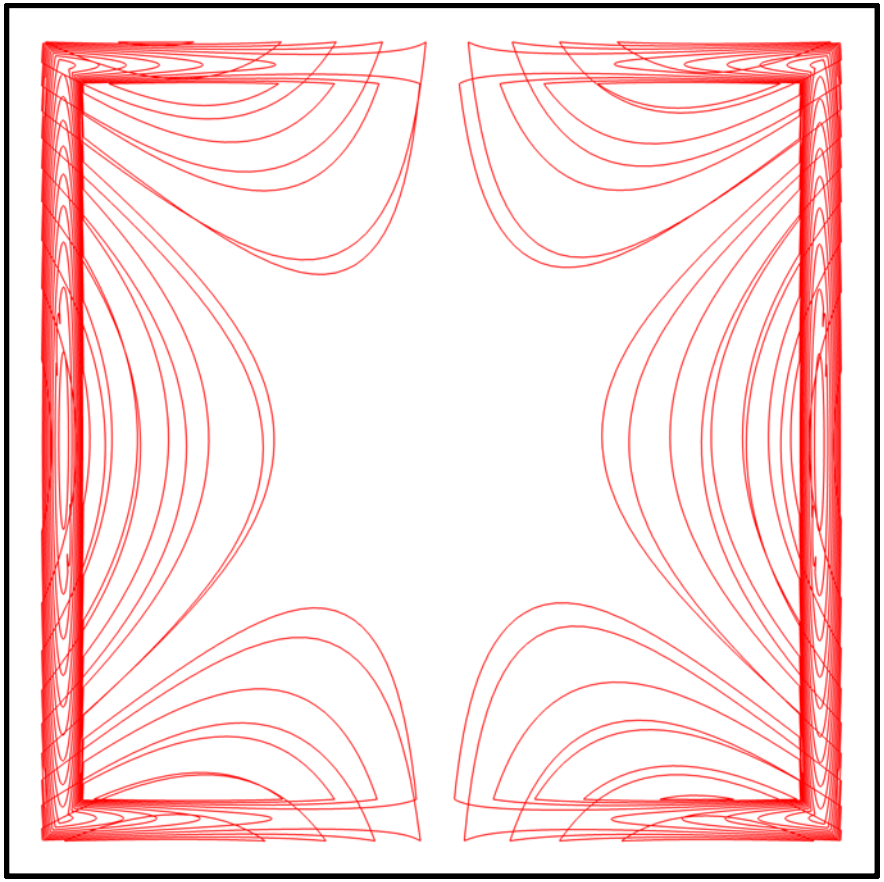

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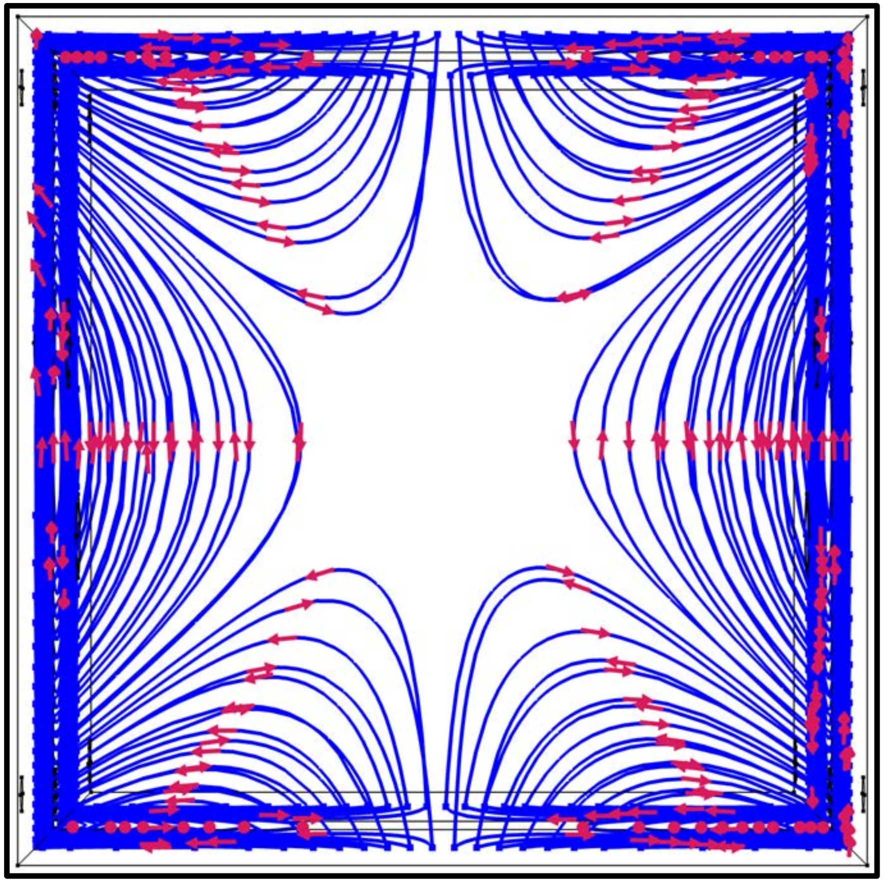

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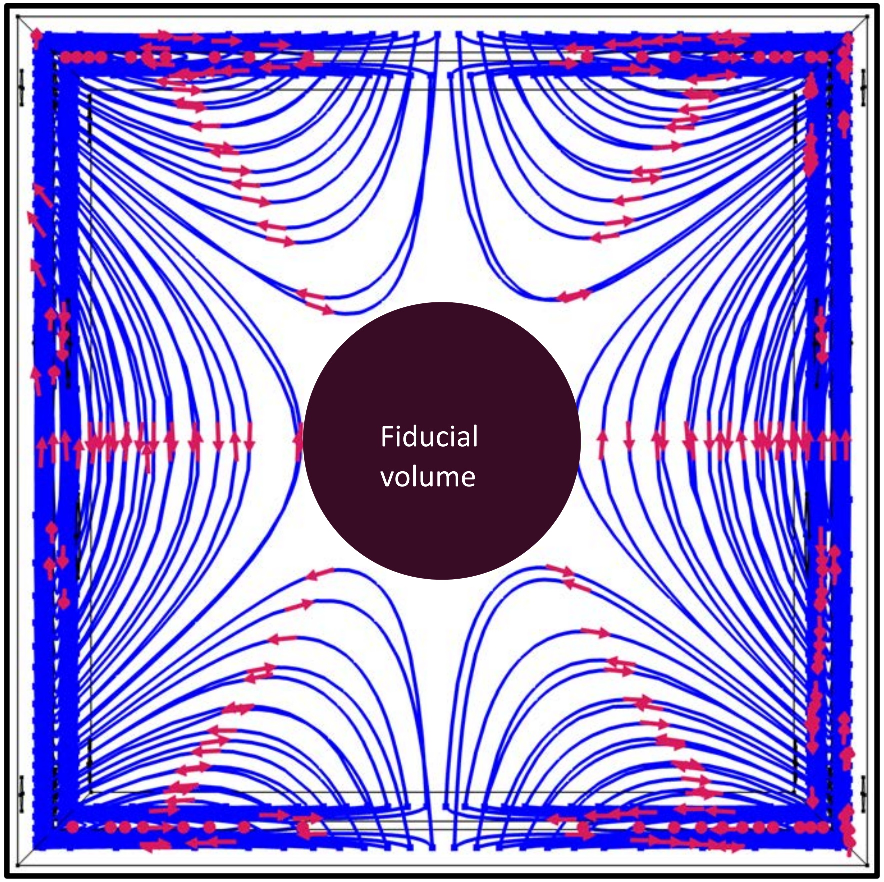

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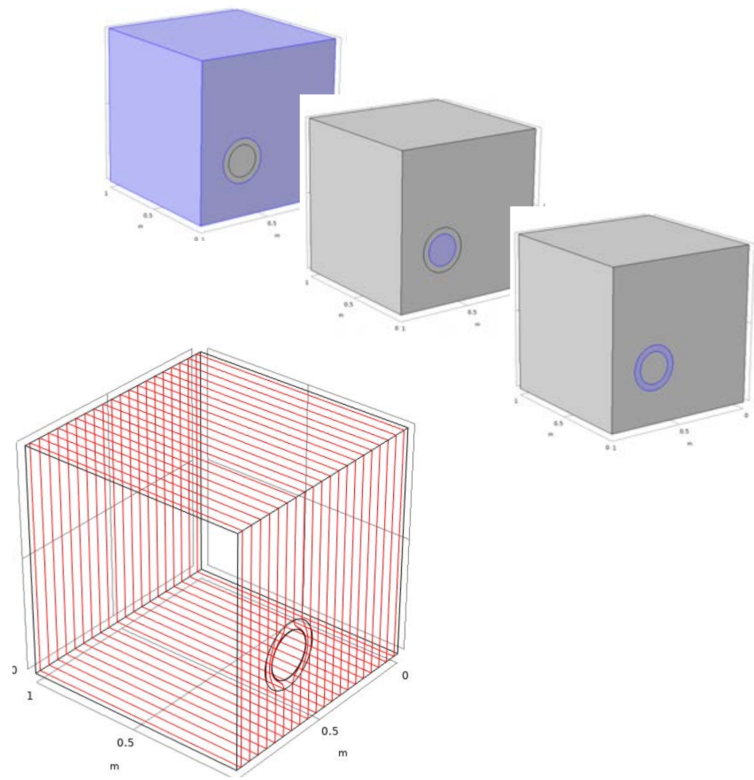
Scalar Potentials and Finite Elements (e.g. COMSOL)

- $\vec{\nabla} V_{m,\,\mathrm{surf}} \times \vec{I}$ is surface normal, so check that all contours have same orientation
- Simplifications:
  - Restrict to planar geometry
  - Don’t try to connect adjacent faces
- Results need an enclosed volume
- https://github.com/MengerSponge/CoilSolver

Step 1: Penetrations

- Set surface to $\Sigma_{m,\ell}$
- Set hole Vm to $\langle \Sigma_{m,\ell} \rangle_{\text{hole}}$
- Allow annulus to float



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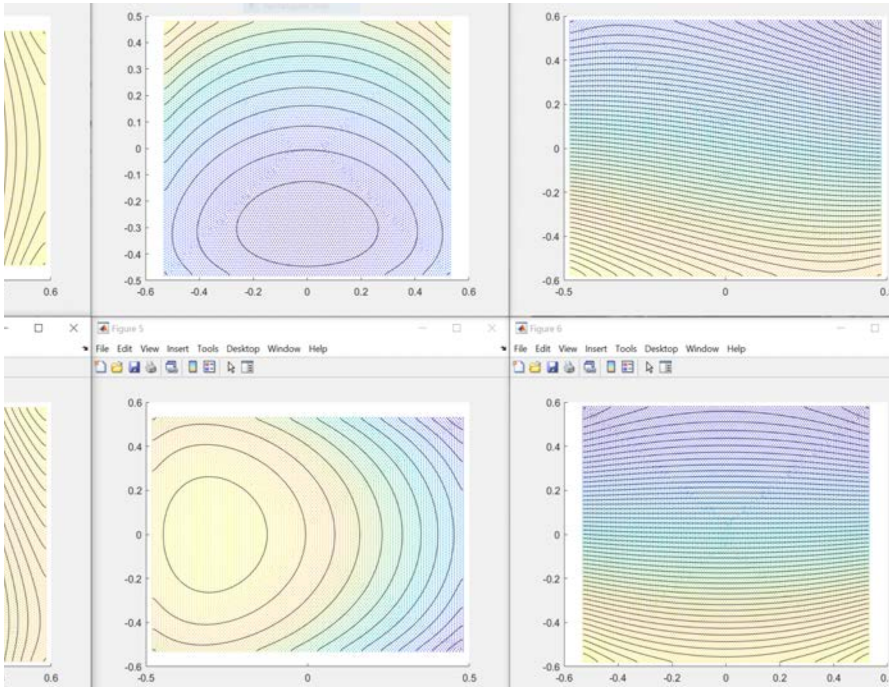
Step 2: Getting Contours

- Pick a set of planar faces
- Transform each one to 2D
- Find contour lines across mesh
- Correct direction of contour lines
  - Line collections in 2D are ready to build
  - Line collections need some processing to model robustly



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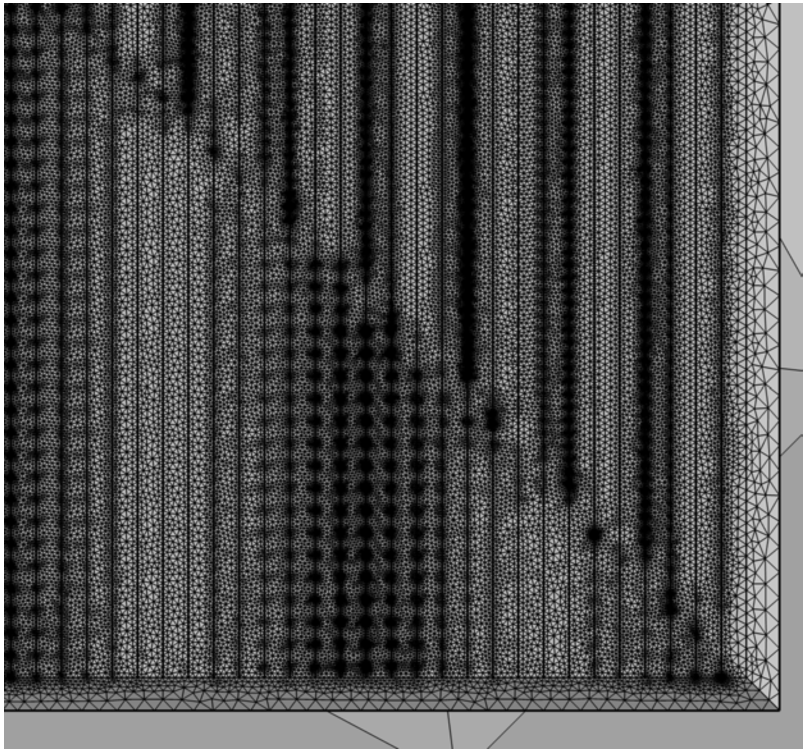
Step 3: Mesh Wires

- Points from plane contour are irregular
- Irregular points lead to poorly defined interpolation curves
- Resample each contour
- Need finer resolution near penetration



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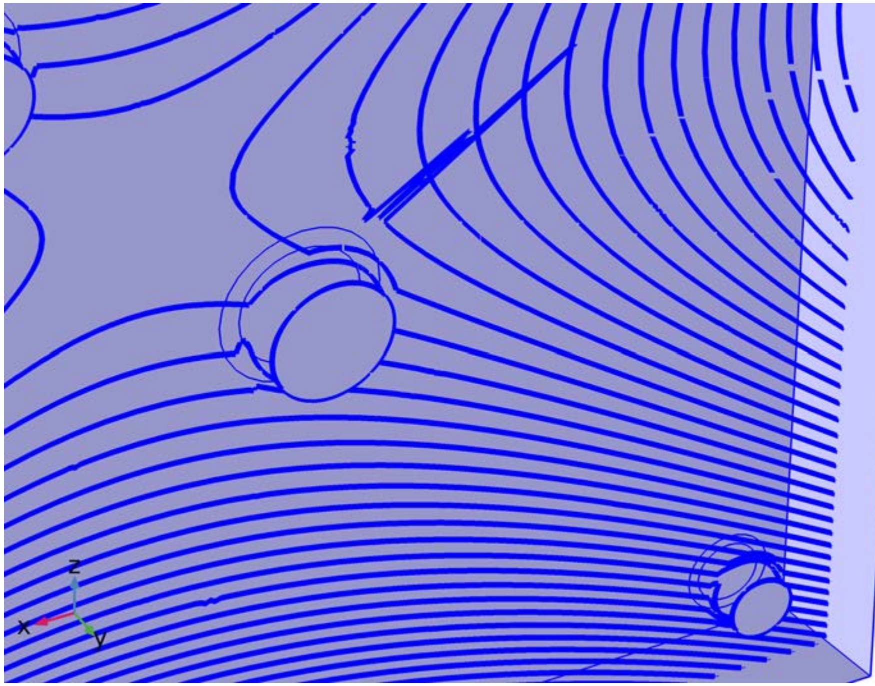

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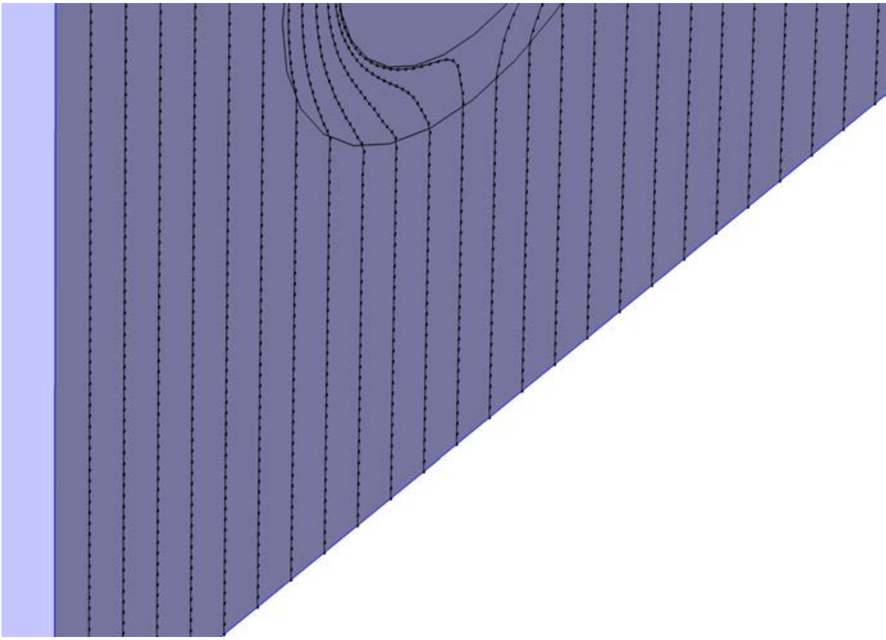

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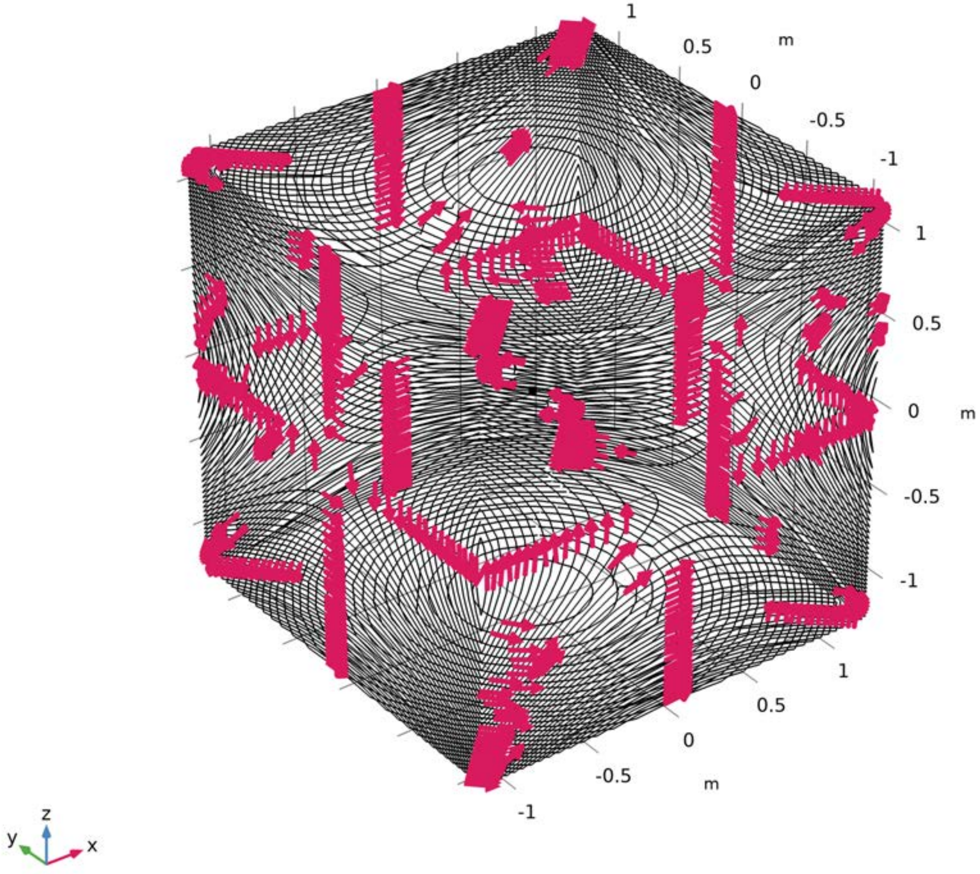
Automated ℓ=2 m=0 coils with 12 penetrations



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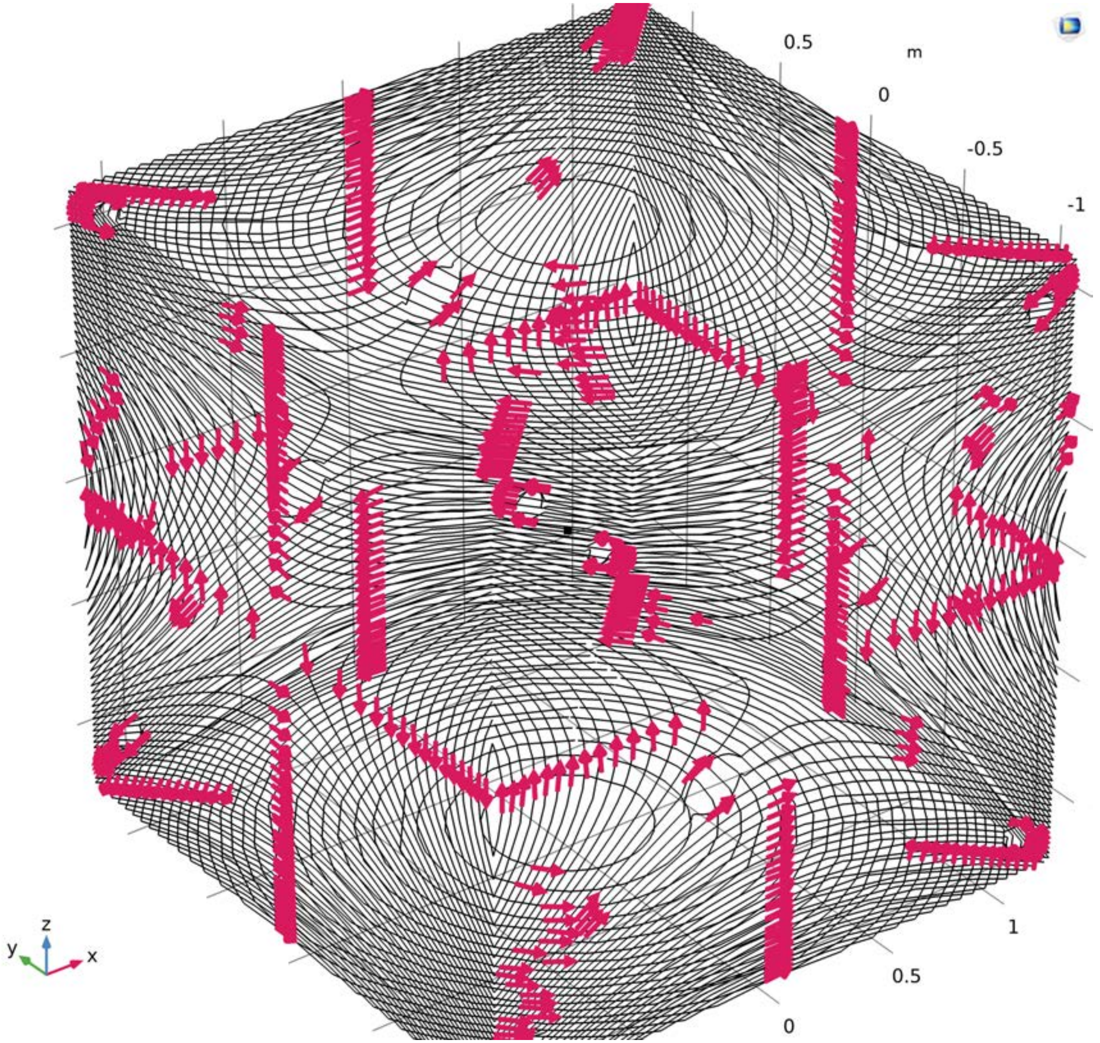

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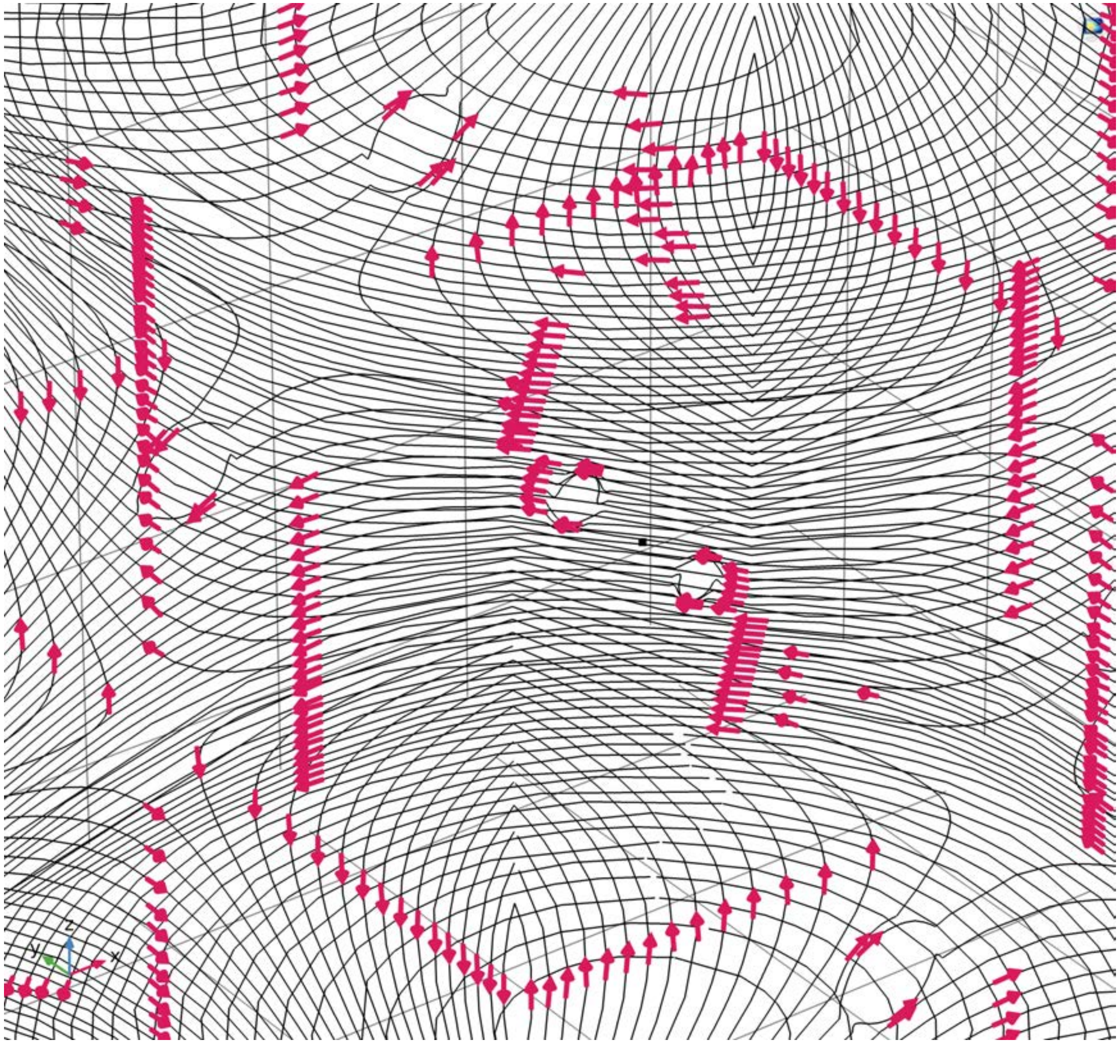

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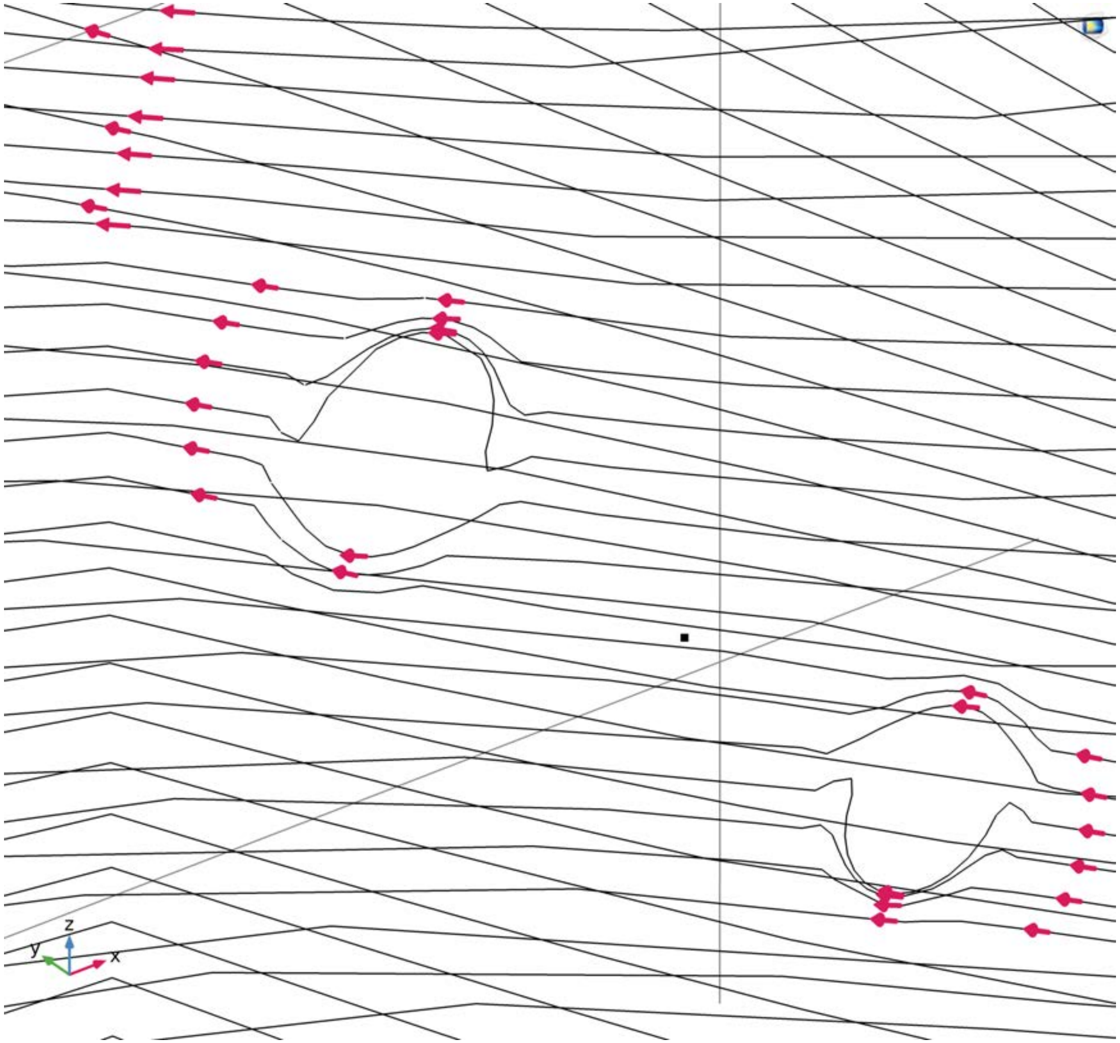

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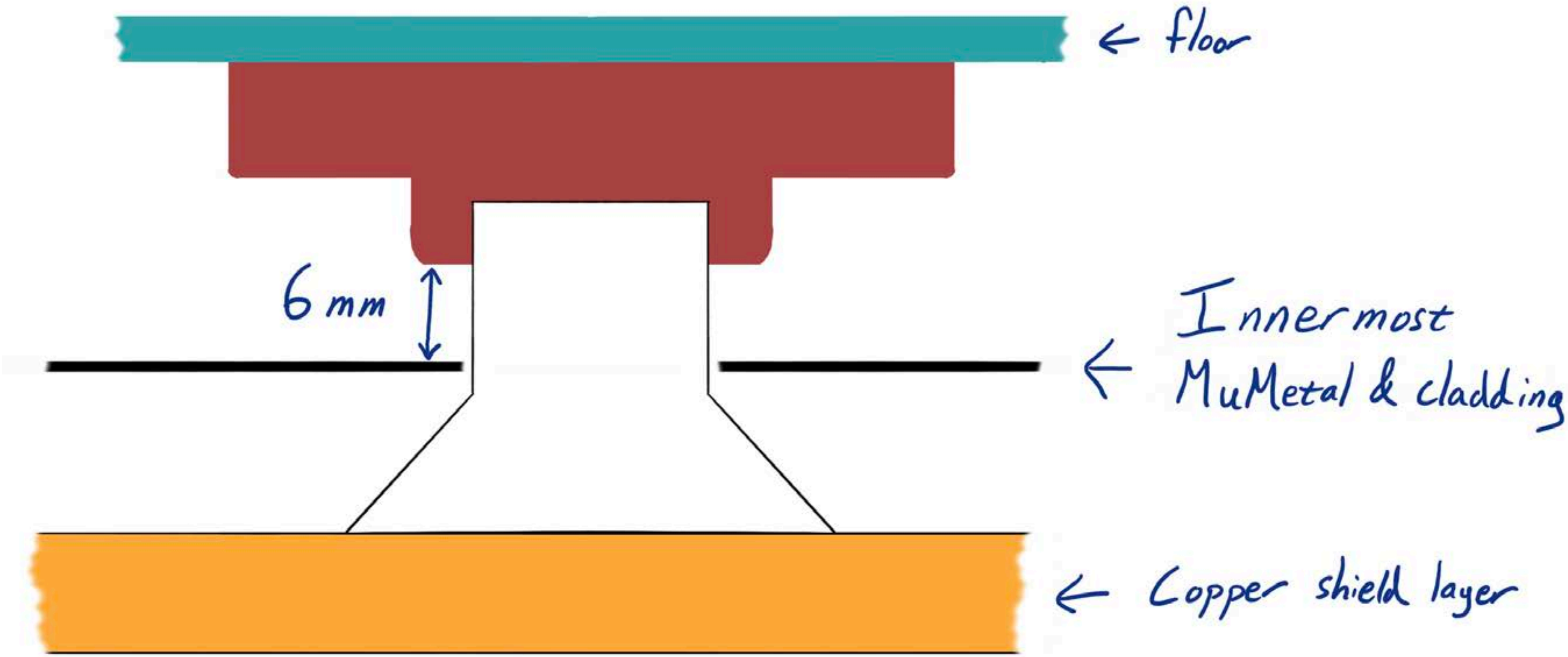
The floor/subfloor problem



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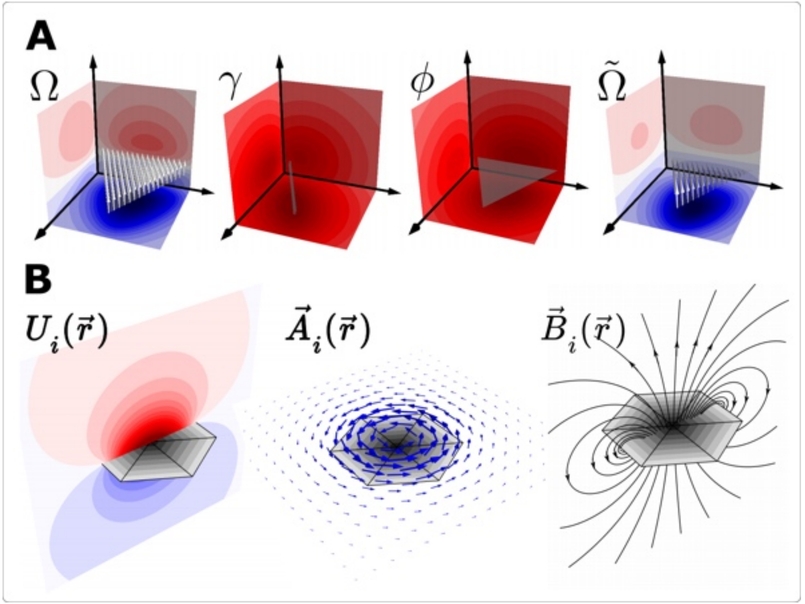
Stream Functions via bfieldTools

- https://bfieldtools.github.io/
- “From the theory of harmonic potentials, we know that U can be determined uniquely in the volume (up to a constant) when either the potential or the normal derivative of the potential is specified on the boundary enclosing the volume. Thus, any external source distribution whose potential reproduces the boundary conditions of a given U, can be used to generate U in the volume.”
  Mäkinen 2020 doi:10.1063/5.0016090

Surface Triangulation



Mäkinen 2020 [doi:10.1063/5.0016090](https://doi.org/10.1063/5.0016090)

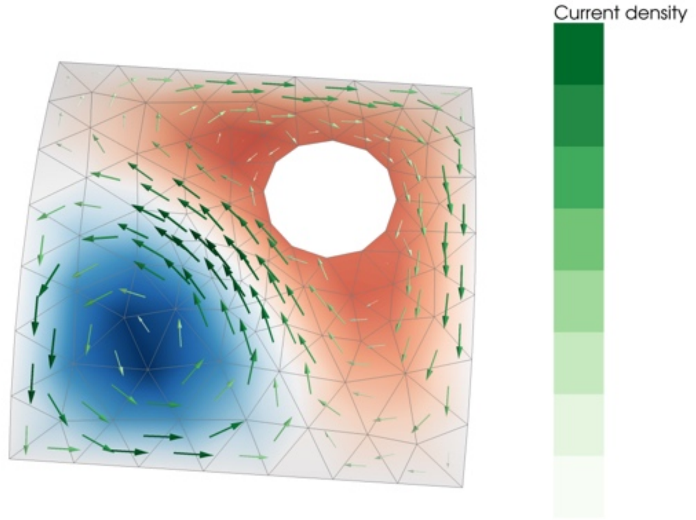


FIG. 1. An example stream function (red–blue colormap) and its rotated gradient, i.e. the surface current density (arrows; green colormap) on a surface mesh with a hole in it. The surface normal is oriented up towards the reader.

Zetter 2020 [doi:10.1063/5.0016087](https://doi.org/10.1063/5.0016087)

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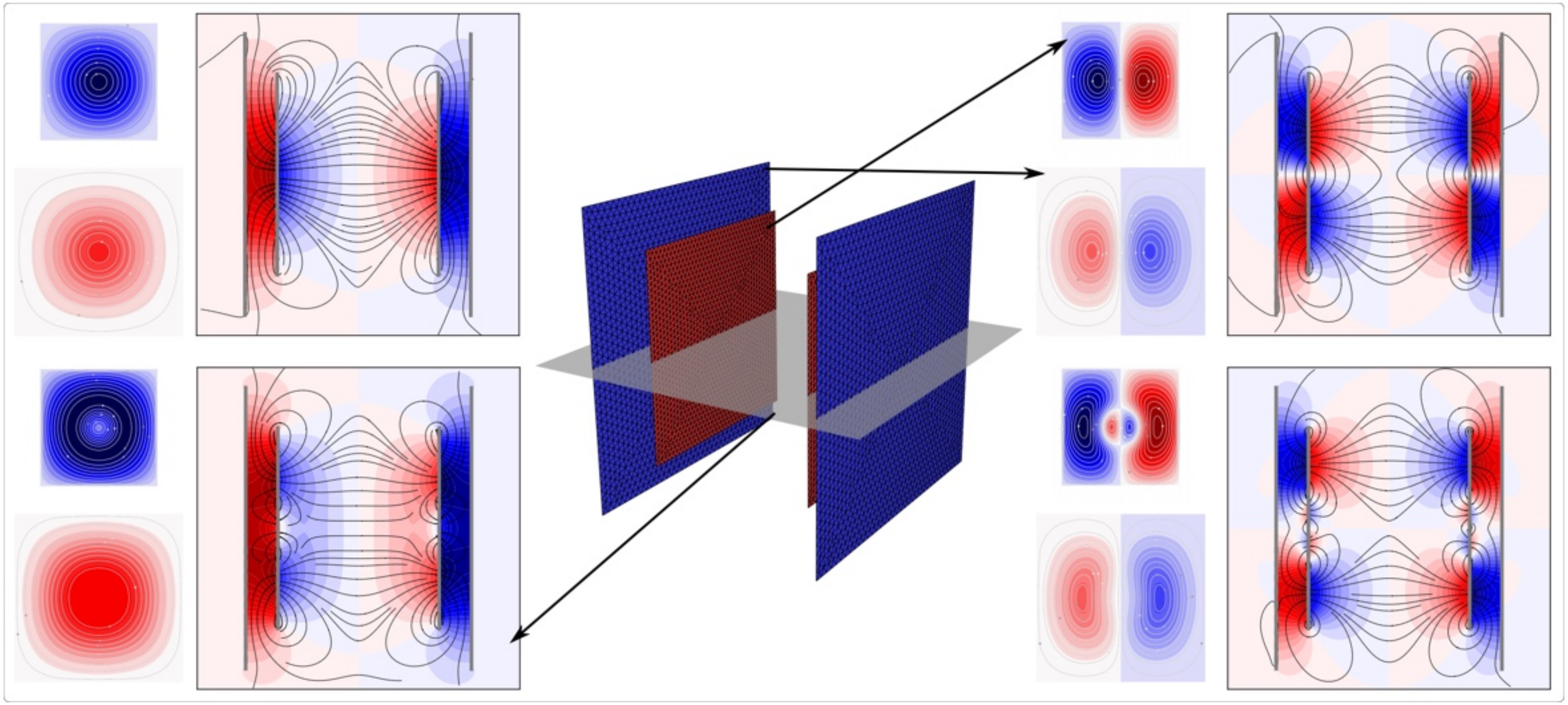
Double Planar Coil Example



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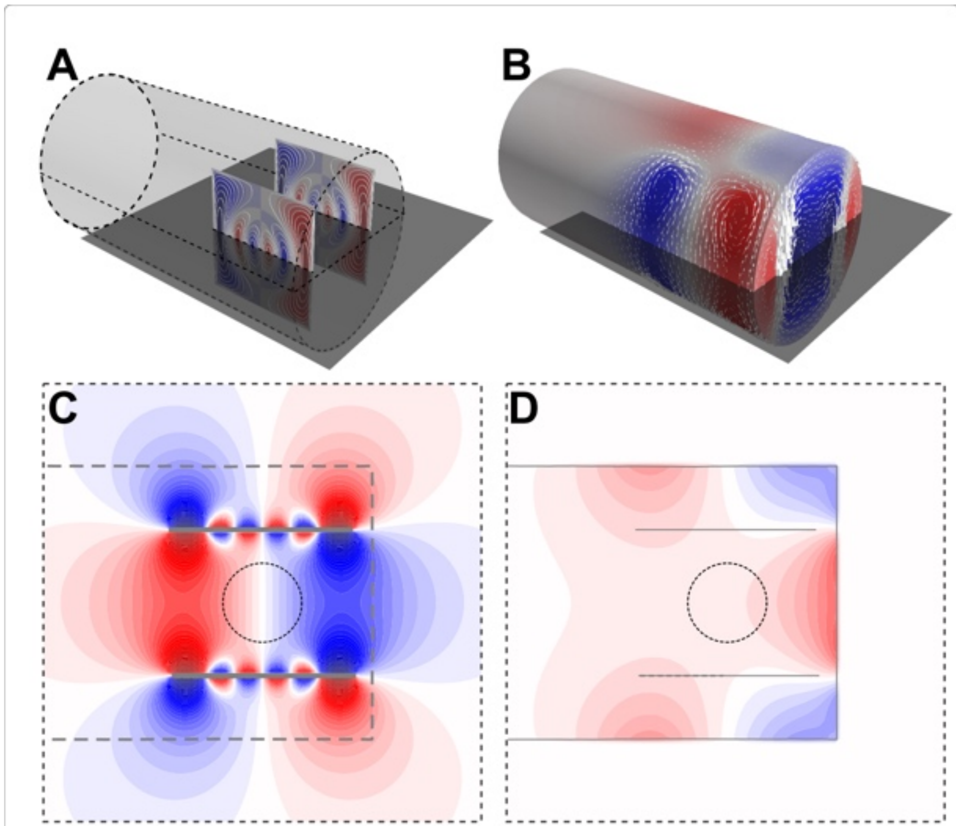
Coil+Shielding Interactions:



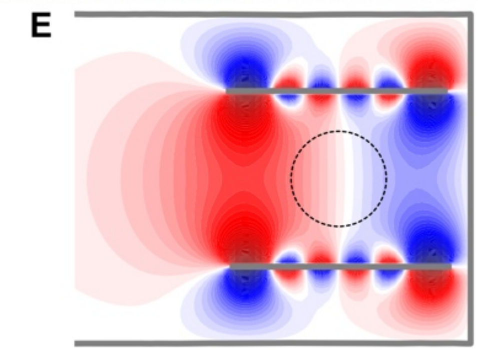
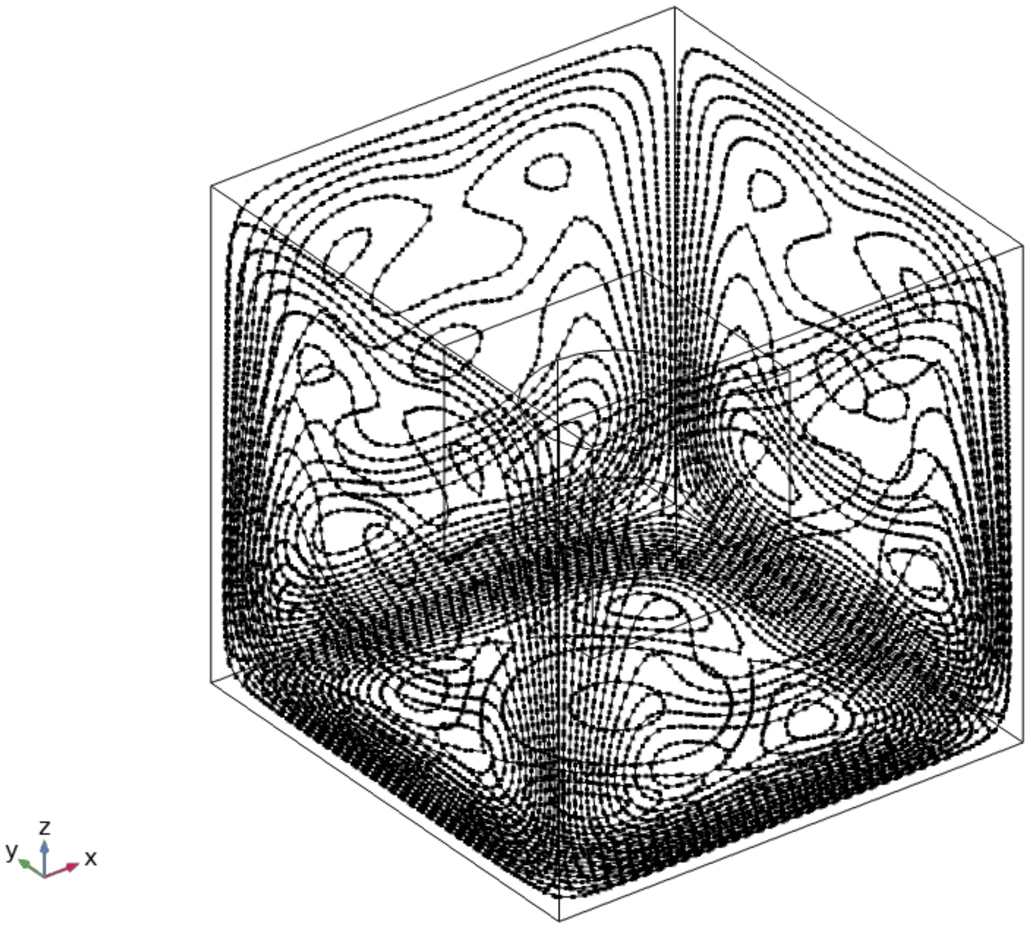


FIG. 8. A current distribution (coil) on a bi-planar surface (**A**) inside a perfect cylindrical μ-metal magnetic shield, an equivalent surface current on the shield surface (**B**), and associated magnetic scalar potentials (**C**,**D**,**E**) plotted on the horizontal plane shown in **A** and **B**. **A**: The stream function of the primary current distribution on the bi-planar surfaces inside the shield. **B**: The equivalent surface-current distribution (stream function and surface-current density) representing the induced field source on the μ-metal shield. **C**: The primary magnetic scalar potential generated by the primary source in **A**. **D**: The magnetic scalar potential generated by the equivalent current in **B** inside the shield surface. **E**: The combined potential that satisfies the constant-potential boundary condition. The dashed circle represents the volume of interest.

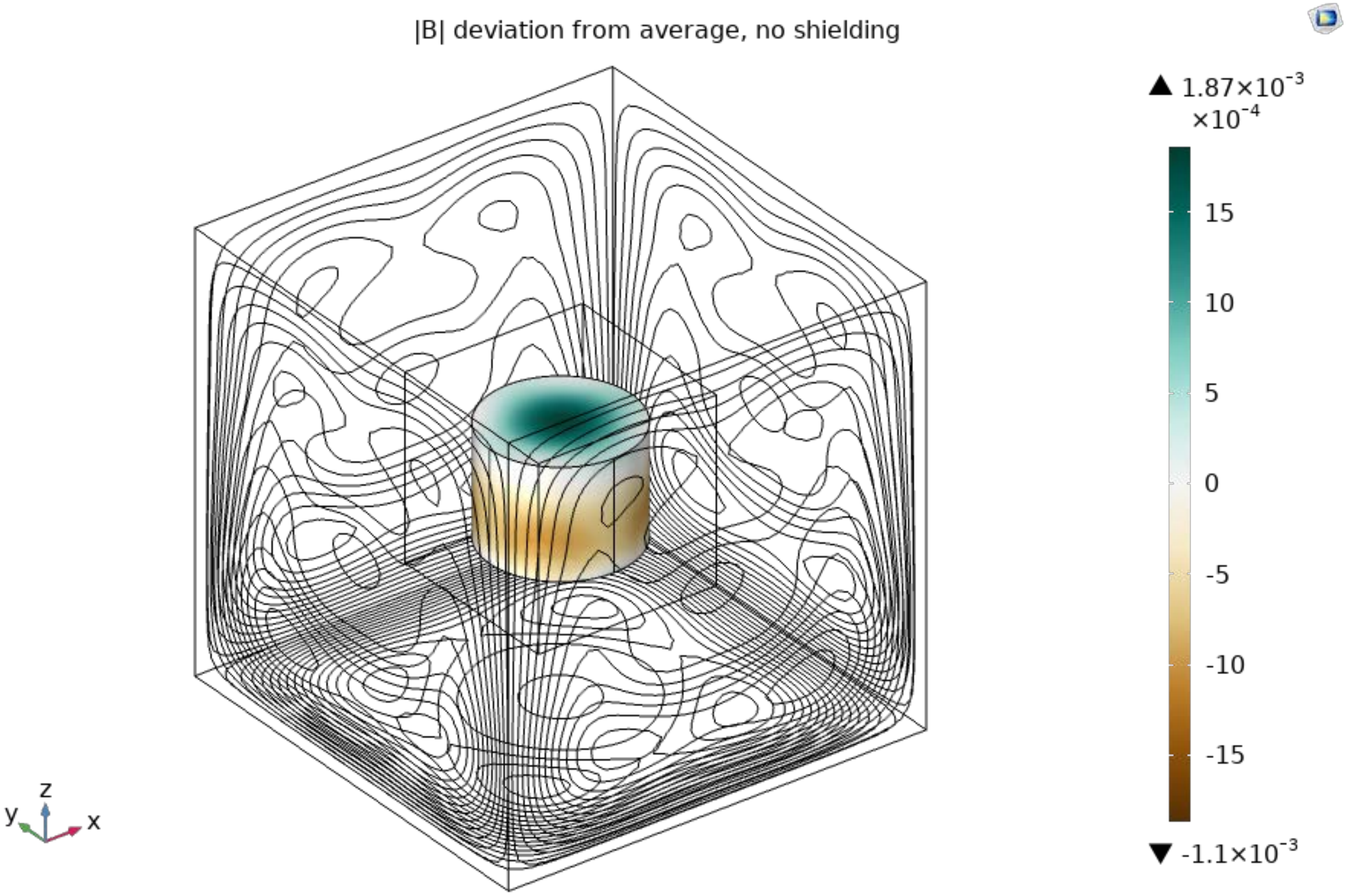
Mäkinen 2020 doi:10.1063/5.0016090

5 disconnected coils



Andrew Mullins

No shielding in model:



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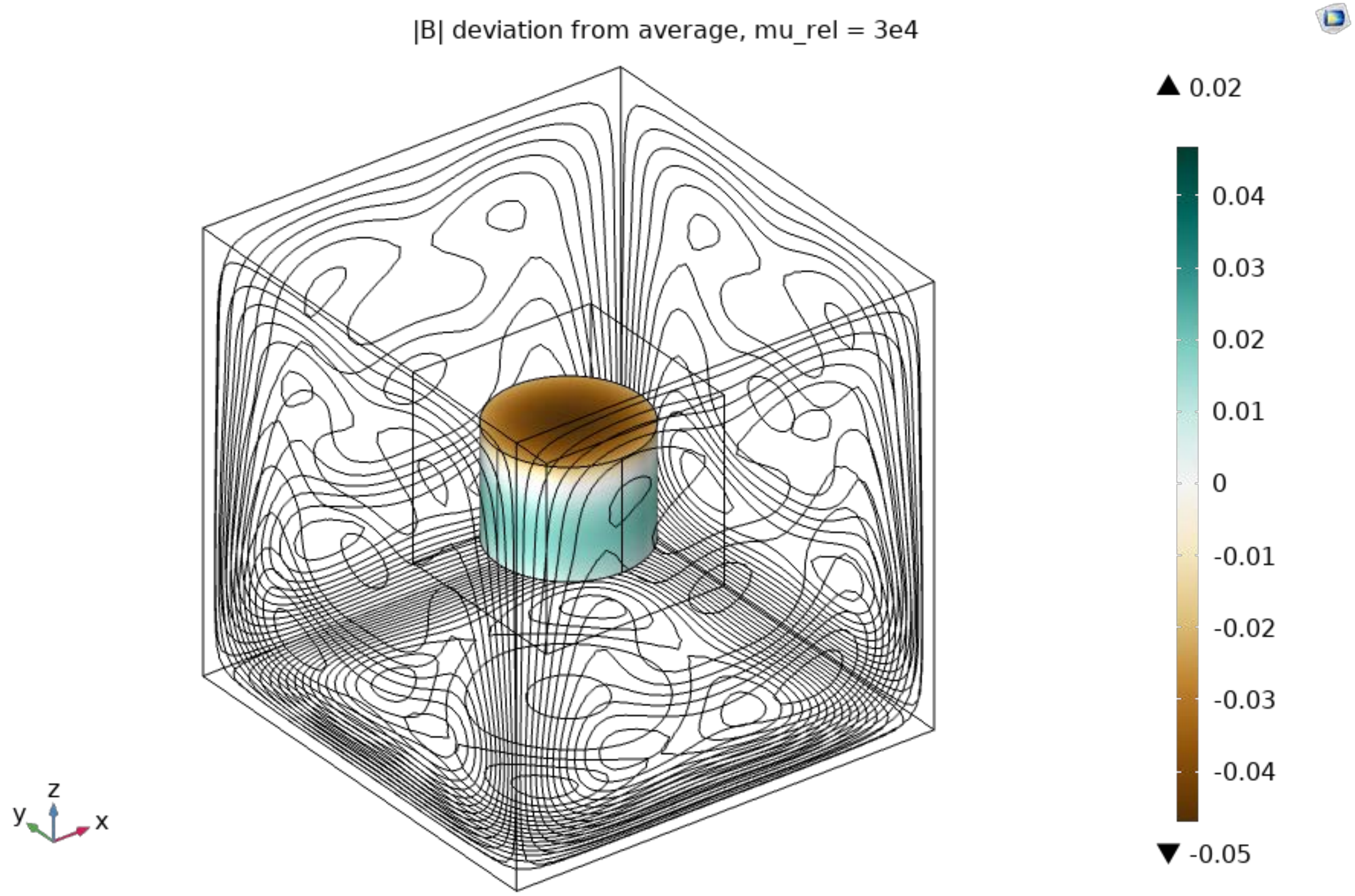
Naïve Design Result:



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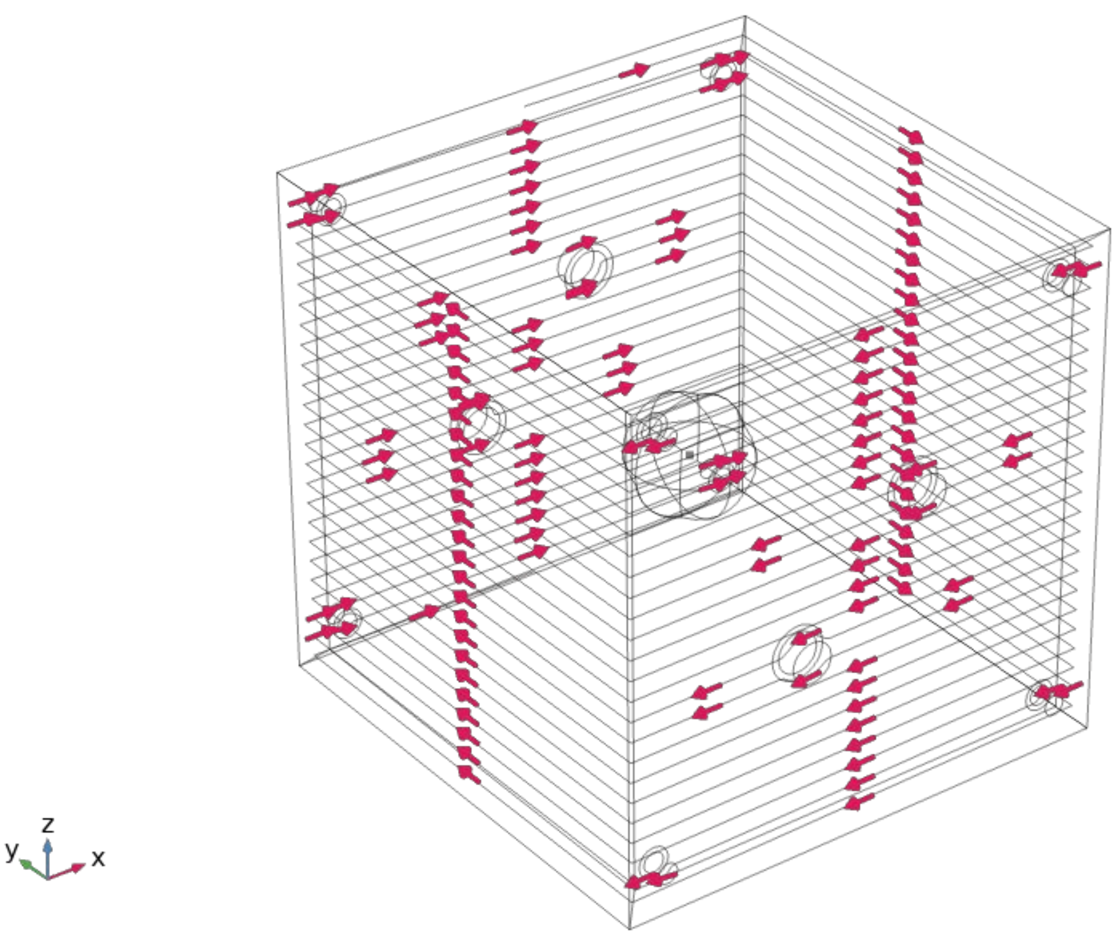
Fabrication/Validation

- CNC Router + MDF to validate
- 3D-print smaller test frames (OpenScad/SolidPython?)

Implementation

- PCB (flex PCB) or CNC PVC panels
- Specifying inductance/current for IU's electrical engineers…

Single-turn coil design



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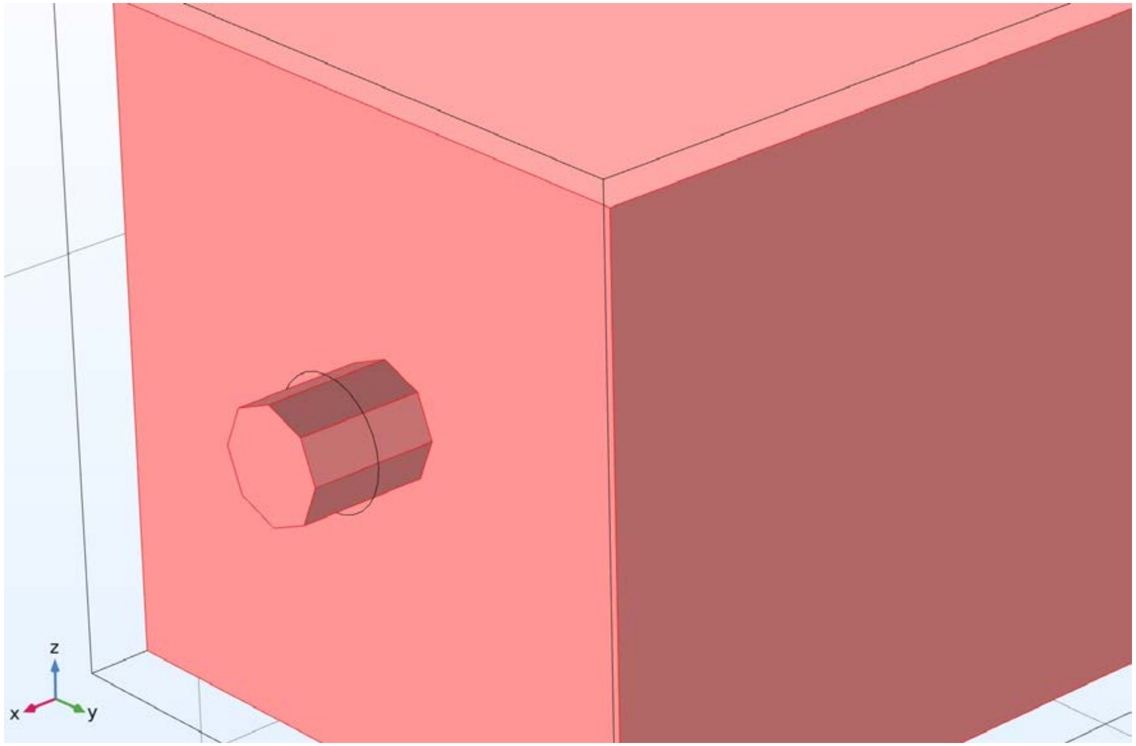
Snorkels?

- Correction loops generate a moment
- Put that loop outside the inner shield wall



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Thank you! Questions?

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nEDM@LANL Collaboration

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University of Michigan: N. Sashdeva, T. Chupp

Yale University: S. Lamoreaux

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Caltech: C. Swank

East Tennessee State University: R. Pattie

Tennessee Technol. University: A. Holley

Trinity College: A. Reid

Mississippi State University: D. Dutta

Chinese Spallation Neutron Source: T. Xin

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