Internal Coil Systems

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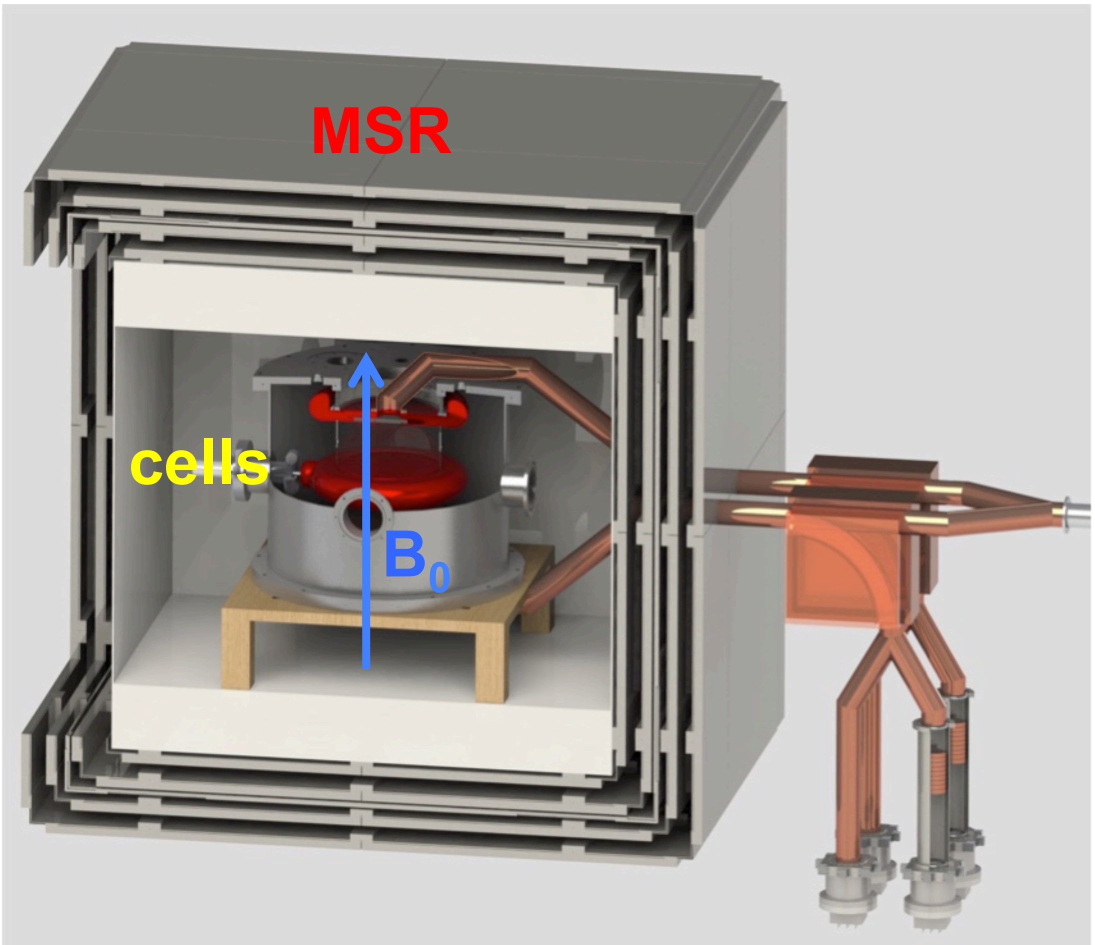
Introduction – internal coil systems



Magnetic field: B_0 ~ 1uT
Uniformity: < nT/m
Stability: < pT

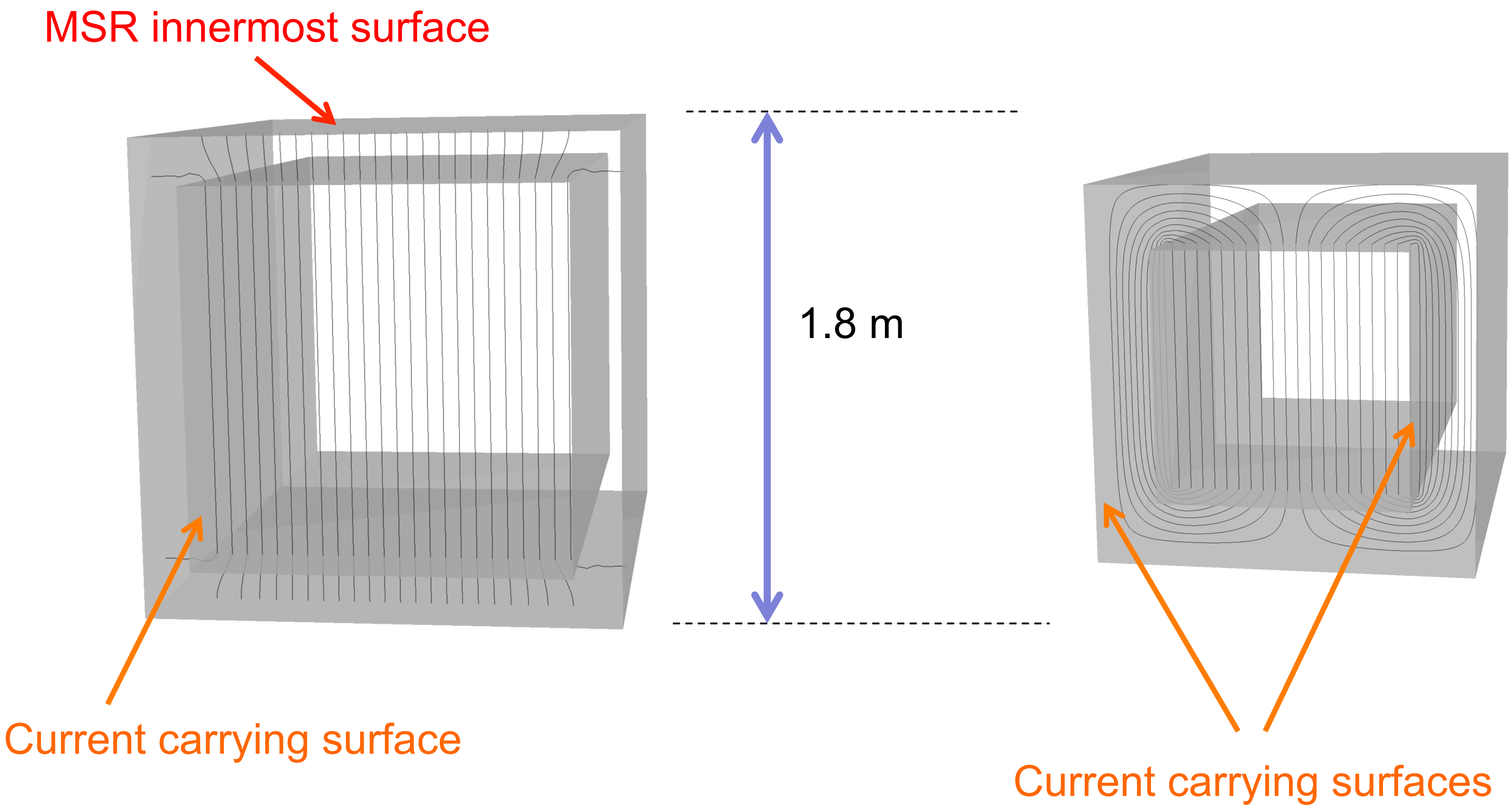
Design type:
Shield-coupled vs. self-shielded

Volume:
1.8 x 1.8 x 1.8 m^3

Access:
UCN guides, HV leads,
magnetometry (e.g. laser beam)

Precision current supply:
e.g. Krohn-Hite 523
10nA – 111mA, 100V, 11W
1ppm stability

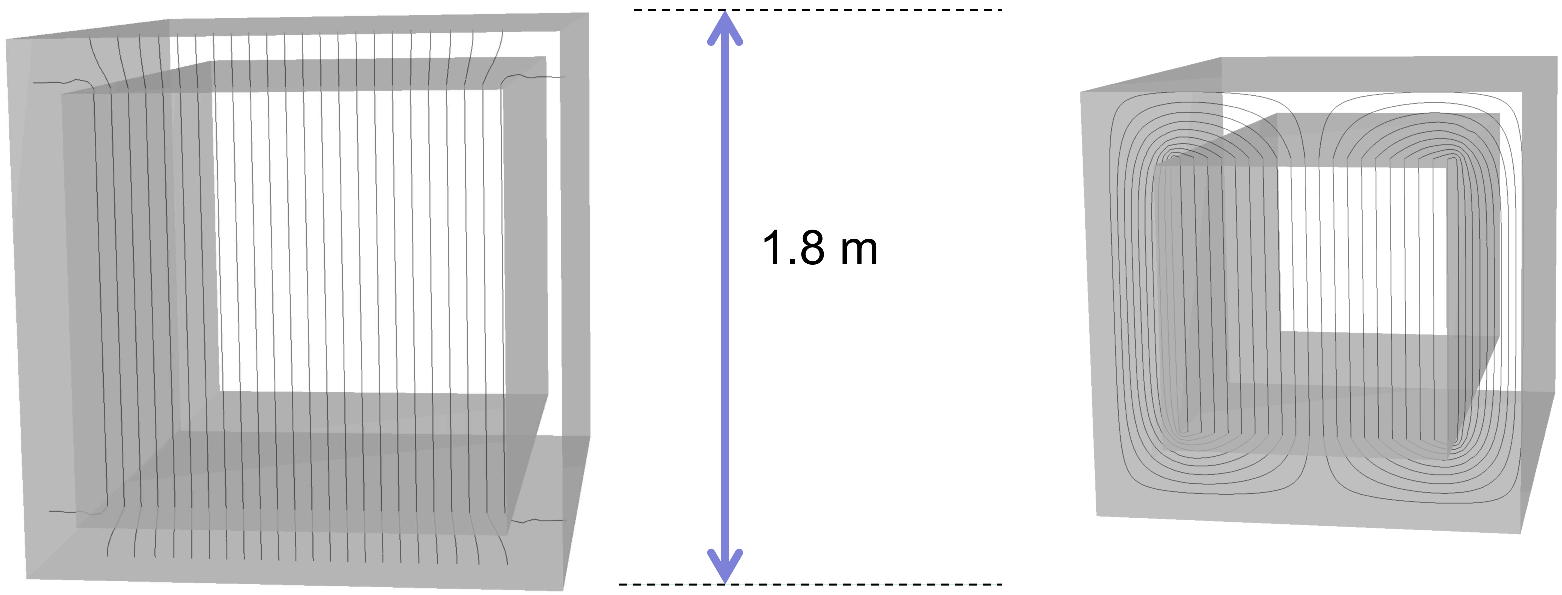
Shield-coupled vs. self-shielded



Flux return through mu-metal

Flux return through free space

Shield-coupled vs. self-shielded



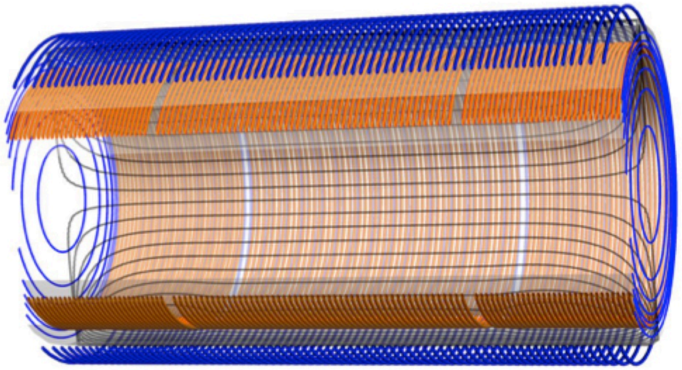
Pros:
- single current surface
- large volume (space, homogeneity)

Cons:
- linked to shield, μ(T,t)
- μ-dependent reaction factor

Pros:
- independent of shield properties

Cons:
- two current surfaces
- smaller working volume

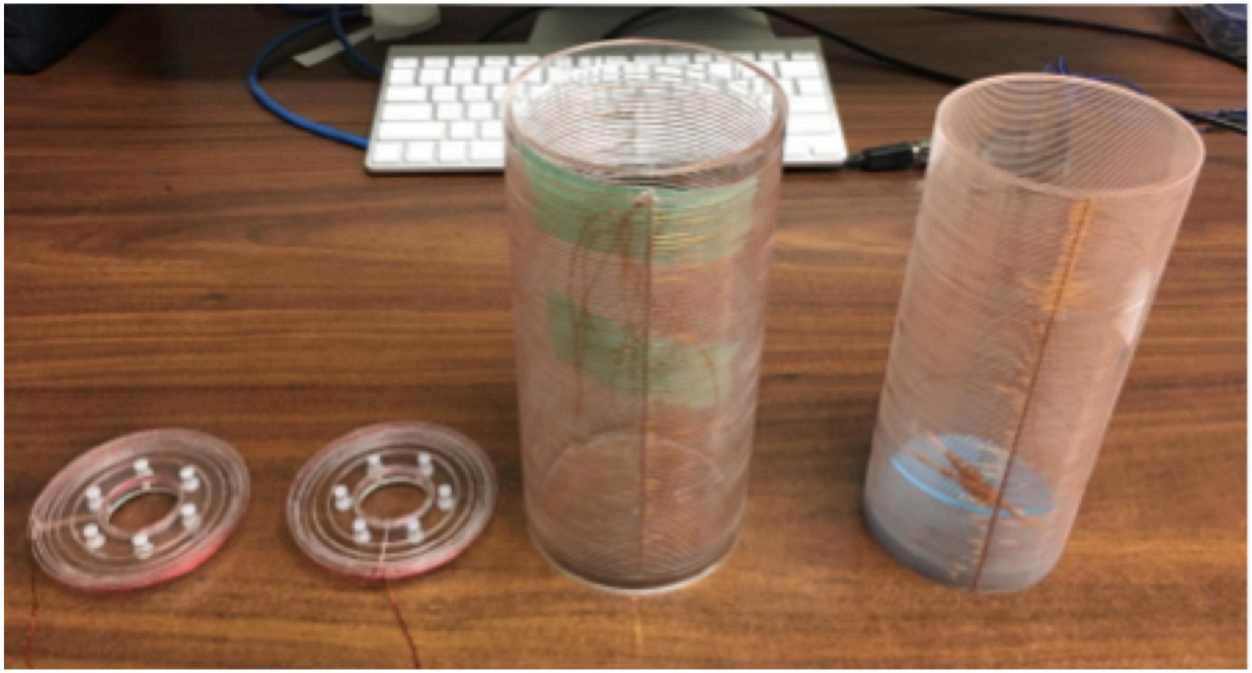
Prototype of self-shielded coil



Design – cut-away with field lines

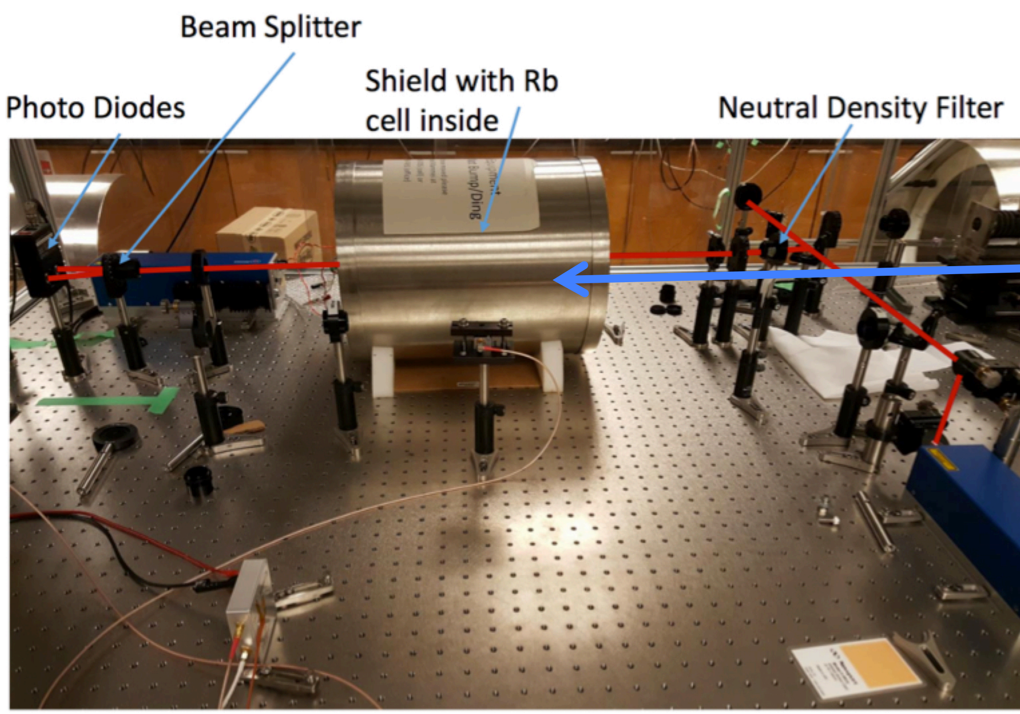
Laser cut formers and grooves.

Wound by hand under microscope.



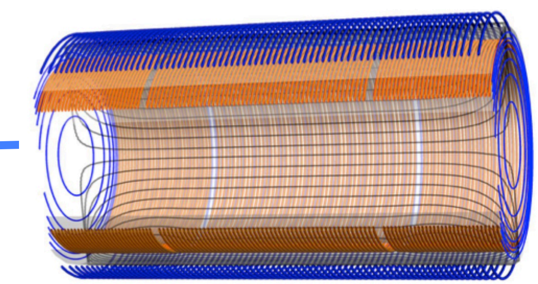
End caps Outer cylinder Inner cylinder

Precision tests of stability via NMOR



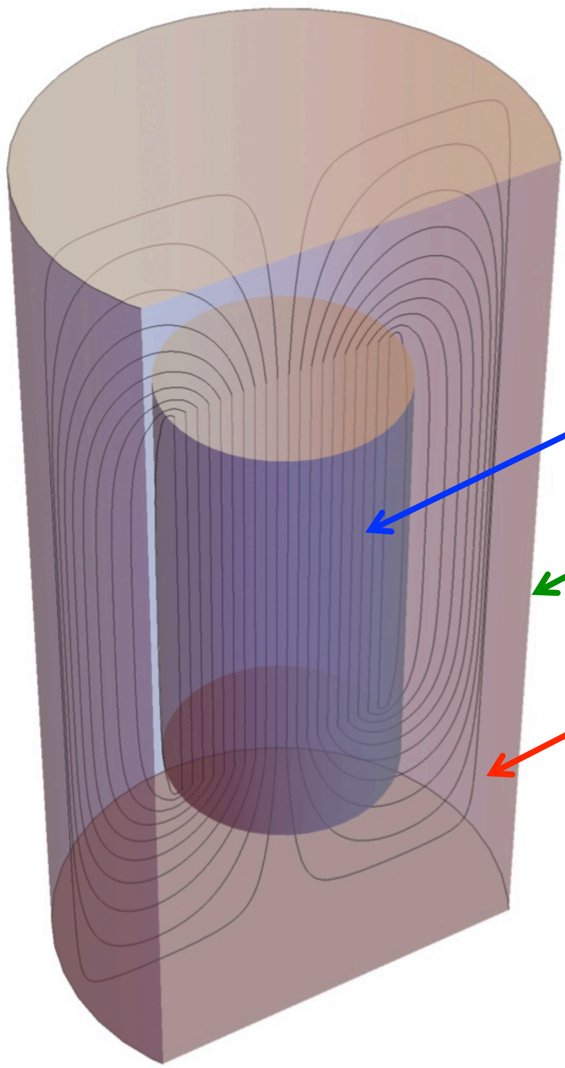
NMOR apparatus at UW

Shield-coupled vs. self-shielded



Temporal dependence
of reaction factor

A general design method – scalar potential



Numerically solve Laplace equation for <u>any</u> geometry and field profile (C. Crawford)

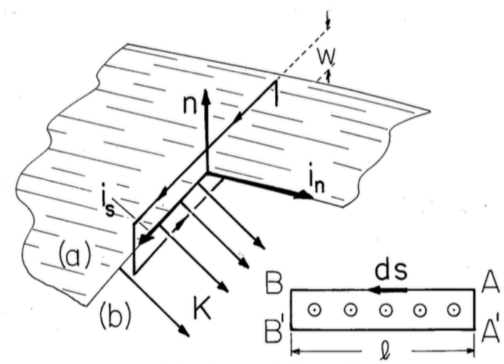
Specify Φ internally

Choose magnetic or superconducting boundary

Solve Φ between surfaces subject to boundary conditions

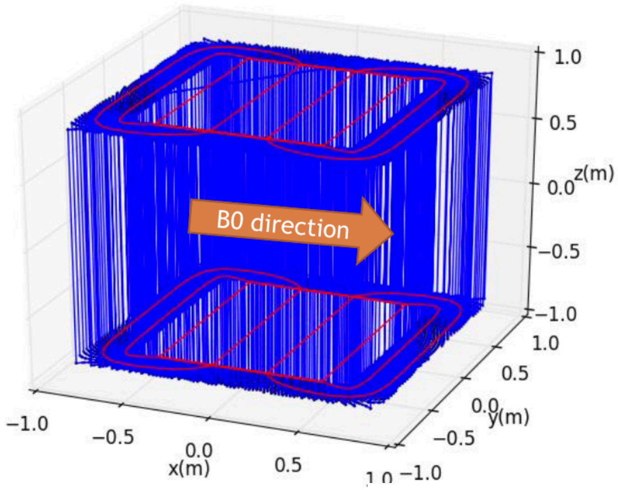
Evenly spaced contours of $\Delta\Phi$ give winding pattern

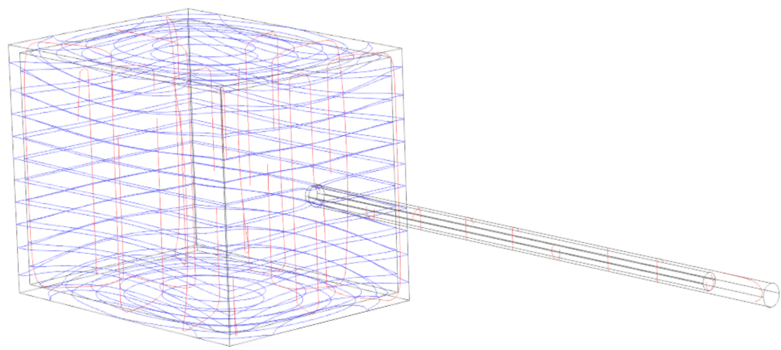
$$\Delta\Phi_B - \Delta\Phi_A = -\int_A^B \vec{K} \cdot \hat{i}_n ds$$

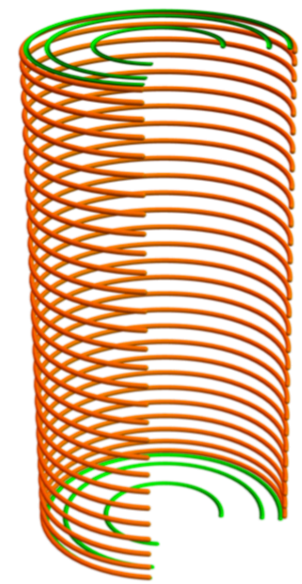


HA Haus & JR Melcher,
EM Fields and Energy, (Prentice-Hall, 1989), §8.5

A general design method – scalar potential







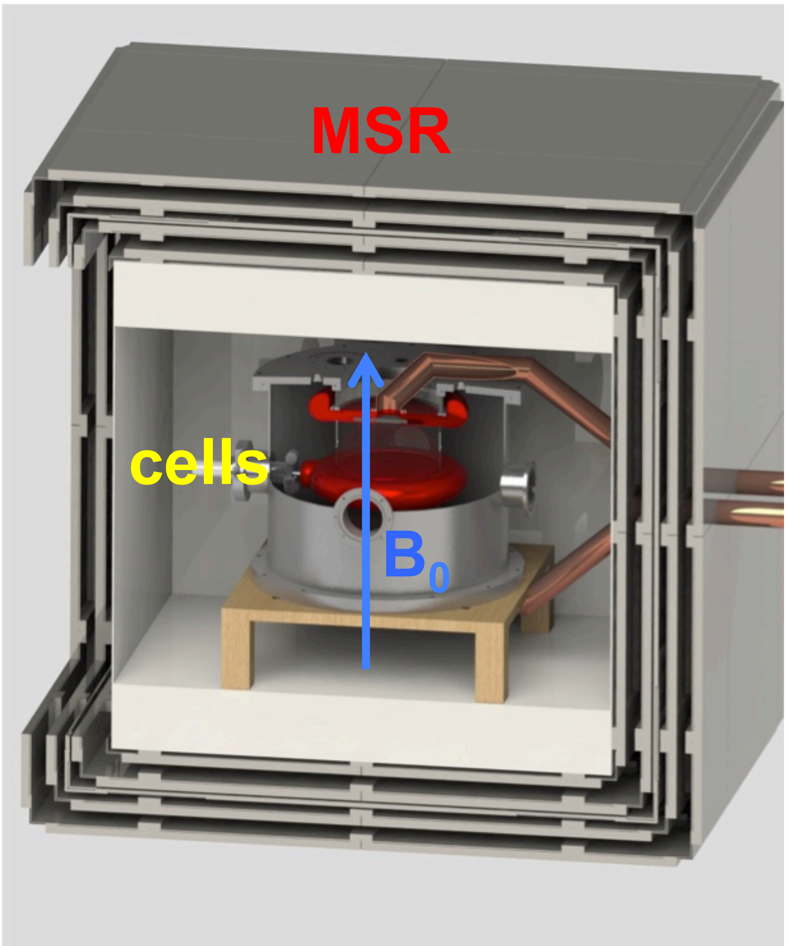
Self-shielded box coil without/with guide field
- UCN nEDM

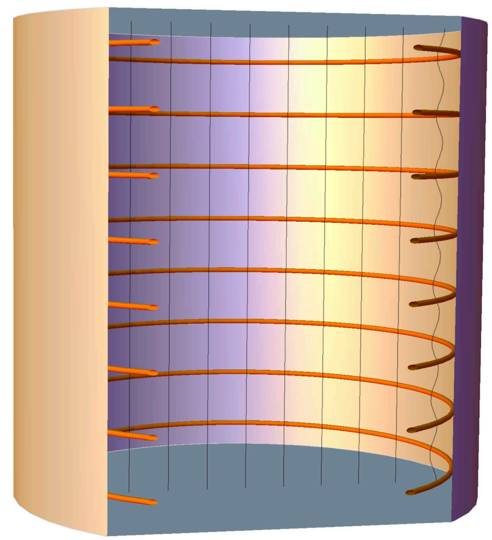
(R Burroughs, M Anderson, J Martin, R Mammei, C Crawford)

Truncated solenoid
- Low field NMR
- Super Kamiokande

(K Smith, C Bidinosti, S King)

Shield-coupled – solvable analog

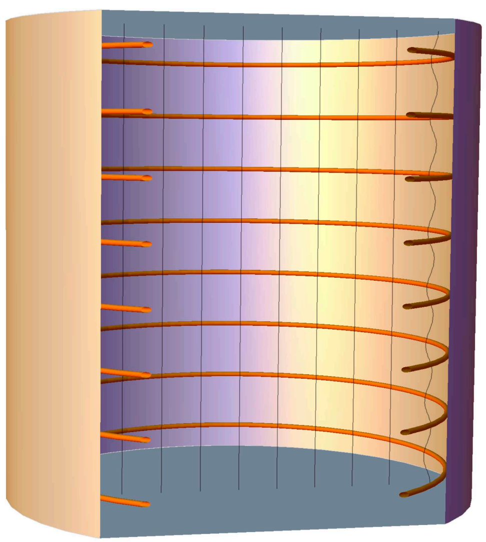




Discrete solenoid in high-μ cylinder

(CB, T Andalib, D Ostapchuk)

Shield-coupled – solvable analog



Discrete solenoid in high-μ cylinder

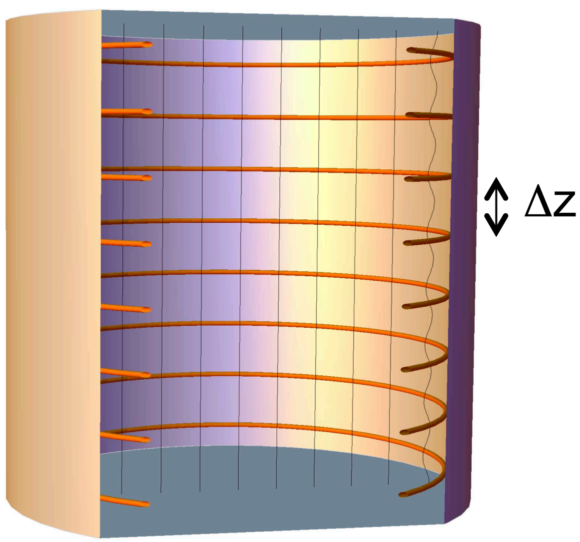
Harmonic decomposition

$$\frac{B_\rho(\varrho,\zeta)}{B_z(0,0)} = \sum_{n=3,5,\ldots}^{\infty} \frac{b_n}{b_1}\,\mathcal{P}_n(\varrho,\zeta)$$

$$\frac{B_z(\varrho,\zeta)}{B_z(0,0)} = 1 + \sum_{n=3,5,\ldots}^{\infty} \frac{b_n}{b_1}\,\mathcal{Q}_n(\varrho,\zeta)$$

n	$\mathcal{P}_n(\rho,z)$	$\mathcal{Q}_n(\rho,z)$
1	0	1
3	$-\rho z$	$-\frac{1}{2}(\rho^2 - 2z^2)$
5	$\frac{1}{2}(3\rho^3 z - 4\rho z^3)$	$\frac{1}{8}(3\rho^4 - 24\rho^2 z^2 + 8z^4)$
7	$-\frac{3}{8}\left(5\rho^5 z - 20\rho^3 z^3 + 8\rho z^5\right)$	$-\frac{1}{16}(5\rho^6 - 90\rho^4 z^2 + 120\rho^2 z^4 - 16z^6)$

Shield-coupled – solvable analog



Discrete solenoid in
high-μ cylinder

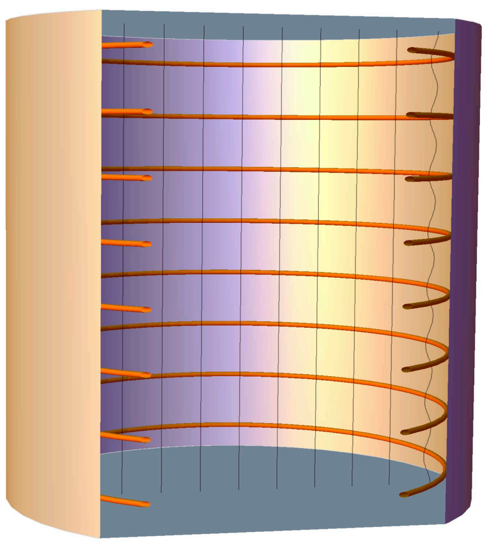
shield diameter = 1.8 m
coil diameter = 1.6 m
length = 1.8 m

Loop spacing versus
number of loops?

Δz = length / N

N	**Δz (cm)**
8	22.5
16	11.25
32	5.63
64	2.81

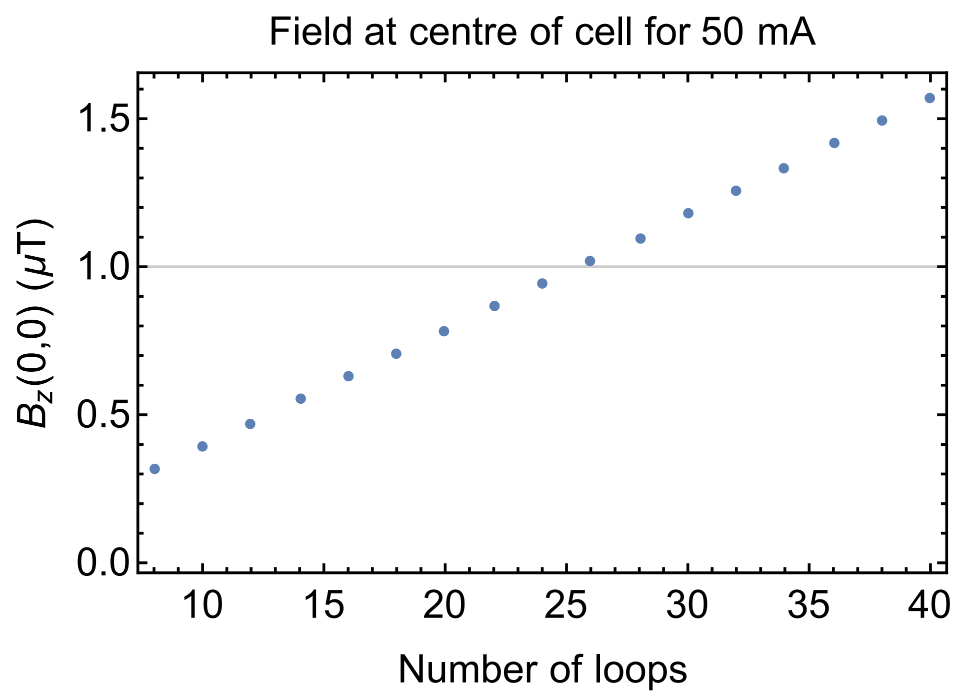
Shield-coupled – solvable analog



Discrete solenoid in
high-μ cylinder

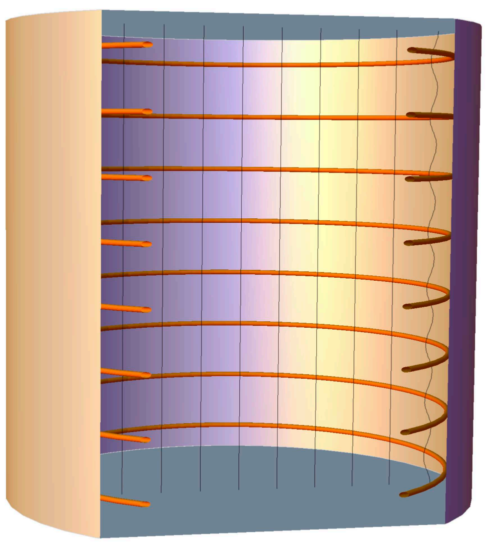
shield diameter = 1.8 m
coil diameter = 1.6 m
length = 1.8 m

How many current loops
to reach magnitude goal?



E.g. 26 turns of AWG #22 wire:
Power ~ 20 mW

Shield-coupled – solvable analog

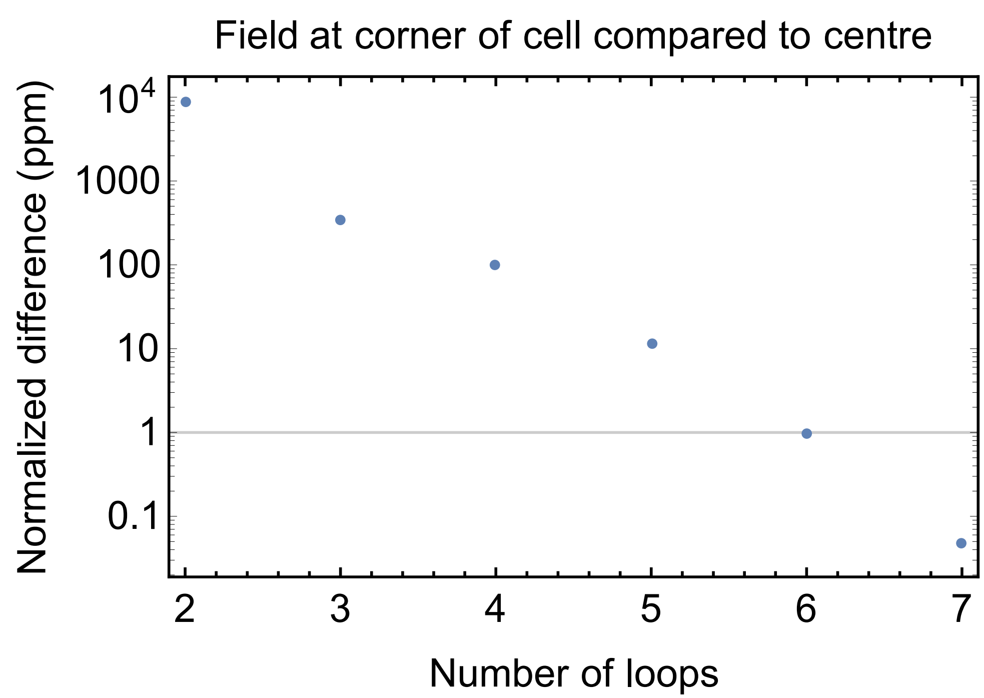


Discrete solenoid in
high-μ cylinder

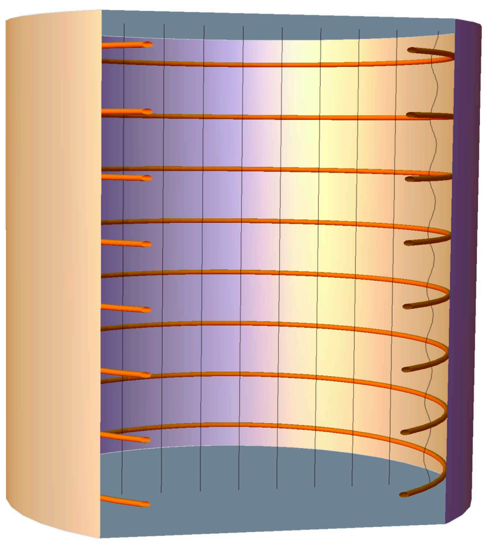
shield diameter = 1.8 m
coil diameter = 1.6 m
length = 1.8 m

How many current loops
to reach uniformity goal?

EDM cell:
radius 18 cm, height 15 cm



Shield-coupled – solvable analog



Discrete solenoid in high-μ cylinder

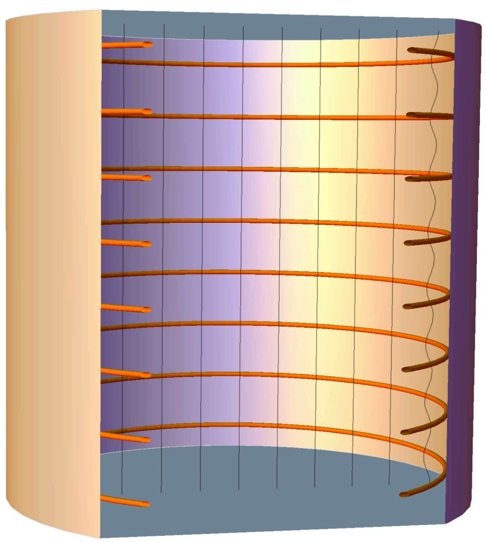
Estimation of construction tolerances by monitoring evolution of 1st order gradient term

Coil/shield misalignment:
- shift entire coil structure (along z- axis)

Loop location accuracy:
- displace single loop (along z- axis)

Machining precision:
- add random axial displacement to all loops

Shield-coupled – solvable analog



Discrete solenoid in high-μ cylinder

Estimation of construction tolerances by monitoring evolution of 1^{st} order gradient term

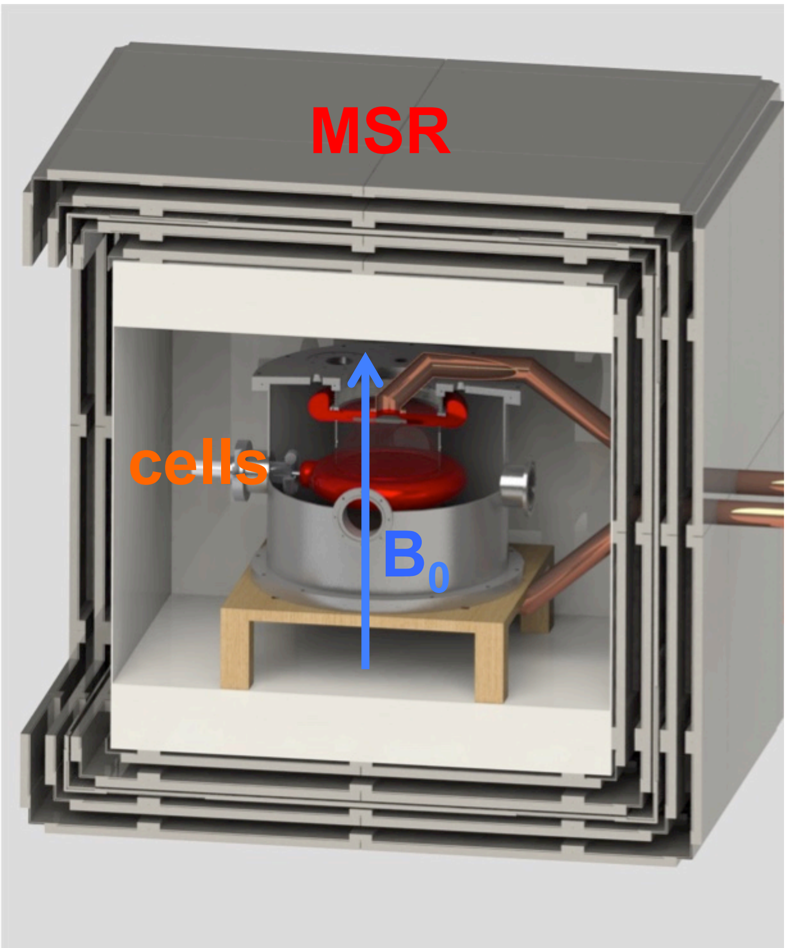
Coil/shield misalignment:
- shift entire coil structure (along z- axis)

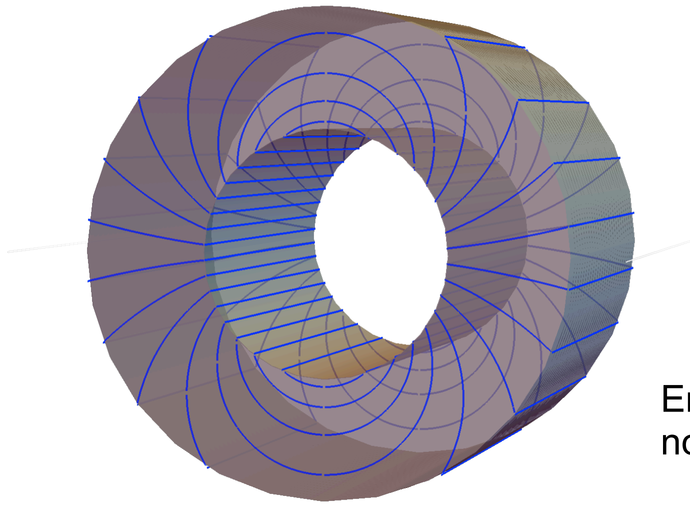
Loop location accuracy:
- displace single loop (along z- axis)

Machining precision:
- add random axial displacement to all loops

Things that need FEA (e.g. Opera): μ(T,t), access holes, deformation/sag of shield, coil tilt, loop distortion, etc.

Self-shielded – solvable analog

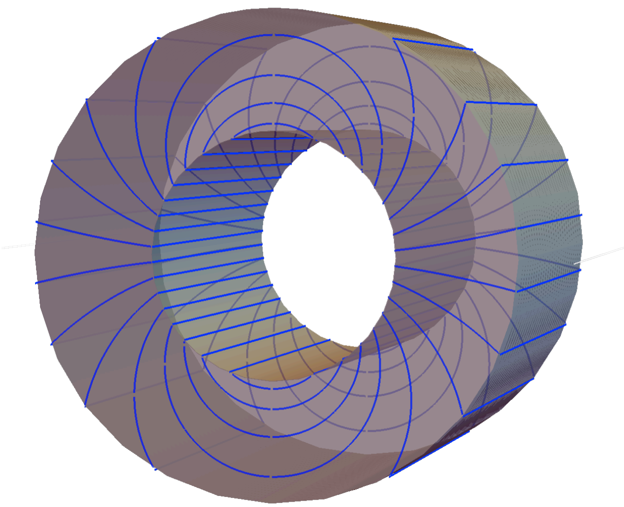




Truncated cylindrical sine-ϕ coil

(CB notes)

Self-shielded – solvable analog

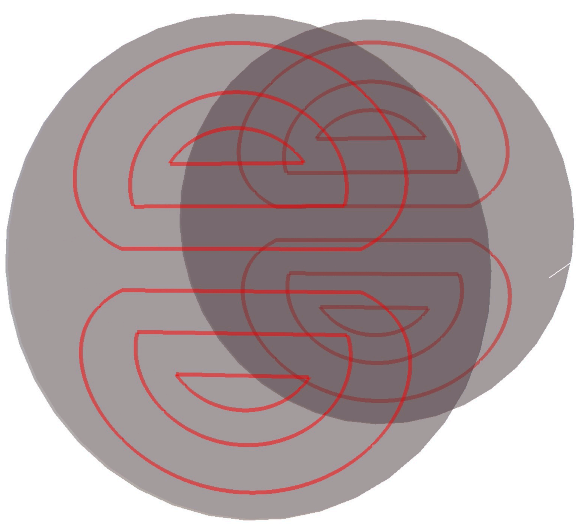


Surface currents on body:
(a = inner radius, b = outer radius)

$$\boldsymbol{K}_a = K \ \sin\phi$$

$$\boldsymbol{K}_b = -\left(\frac{a}{b}\right)^2 \ K \ \sin\phi$$

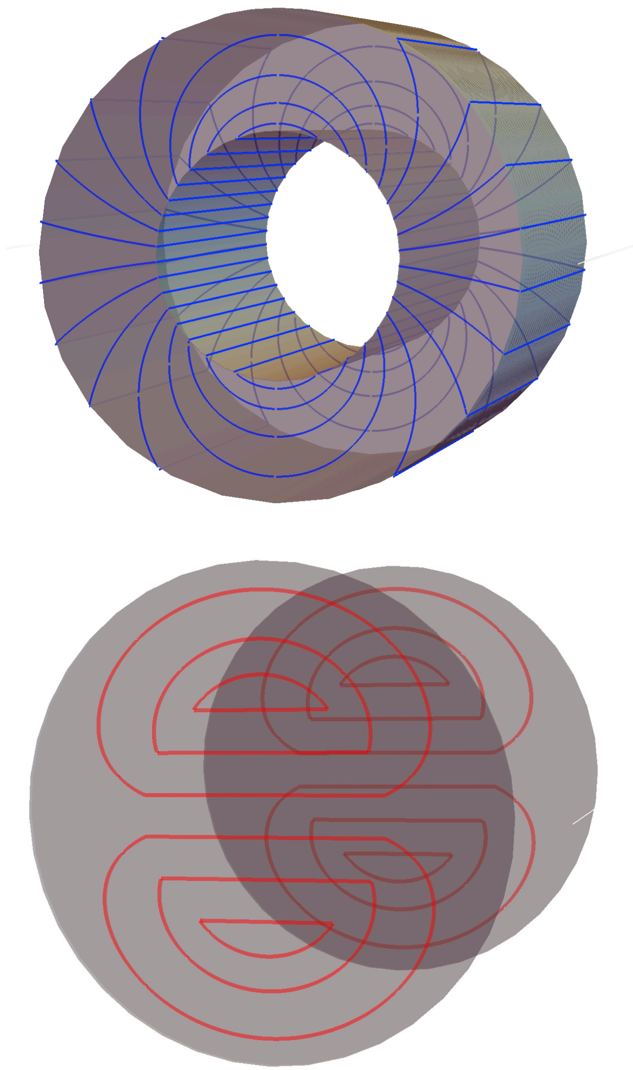
Central field reduced by $(1 - a^2/b^2)$



Surface currents on caps:

$$\boldsymbol{K}_{\pm l} = \frac{\mp K}{2} \begin{cases} (1 - a^2/b^2)\left(\sin\phi\,\hat{\boldsymbol{\rho}} + \cos\phi\,\hat{\boldsymbol{\phi}}\right), & \rho < a \\ -a^2(\rho^{-2} + b^{-2})\sin\phi\,\hat{\boldsymbol{\rho}} & \\ \qquad + a^2(\rho^{-2} - b^{-2})\cos\phi\,\hat{\boldsymbol{\phi}}, & a < \rho < b \\ 0, & \rho > b\,. \end{cases}$$

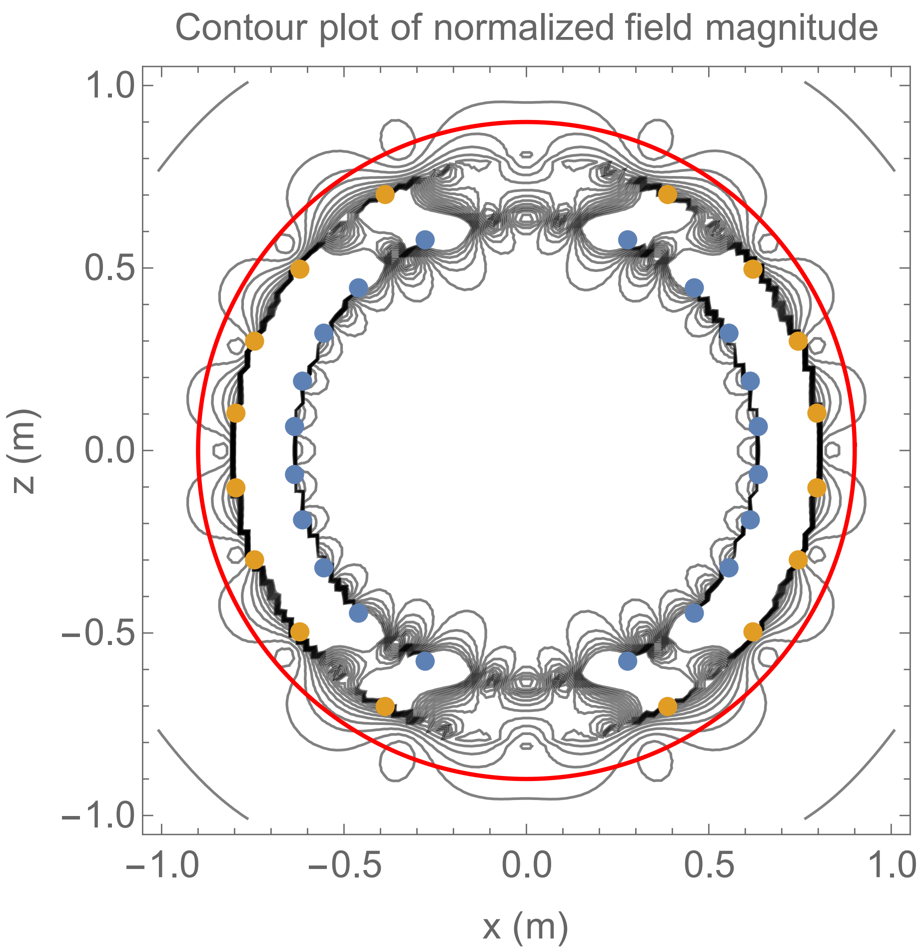
Self-shielded – solvable analog



Wire traces + Biot-Savart:

Access, homogeneity, efficiency, power, leakage field, proximity to MSR, tilt, twist, offsets, construction tolerances, etc.

Self-shielded – solvable analog



Limit on leakage field?

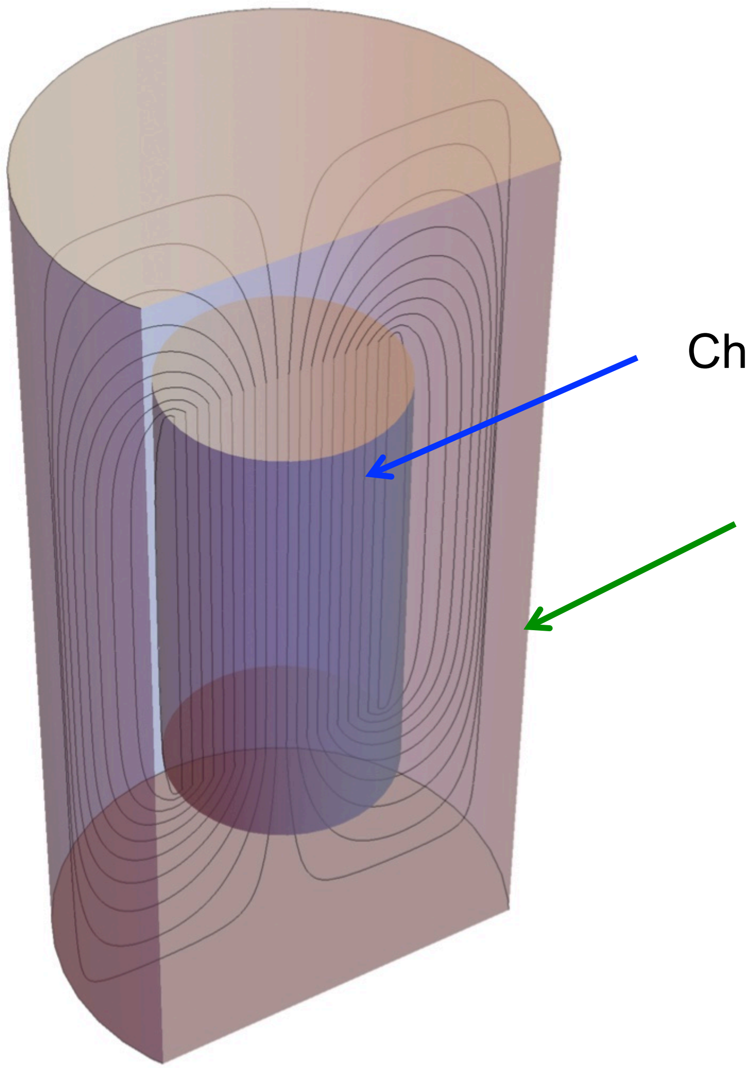
How many wires on outer current surface?

Example:
20 wires on inner surface
16 wires on outer surface

Field at location of MSR reduced to 0.1 – 0.4.

Can include reaction factor of shield with results from AIP Advances **4,** 047135 (2014)

Shim coil design – scalar potential



Choose appropriate spherical harmonic for Φ

Magnetic boundary (shield-coupled) or superconducting boundary (self-shielded)

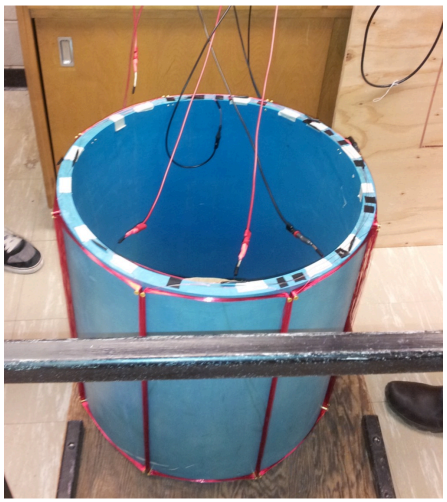
BUT reaction factor ~ $1 + (a/b)^{2n+1}$ where $n \geq 2$. So coupling to shield is greatly reduced.

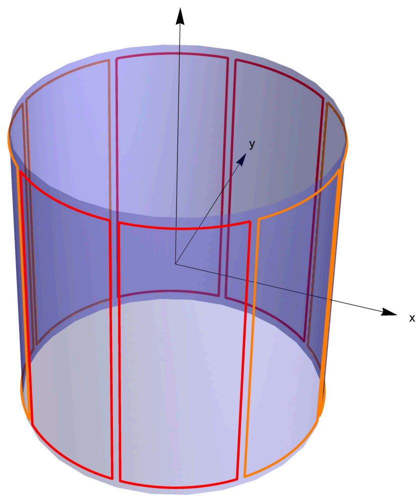
Choose shield-coupled shim coils for ease and more experimental space.

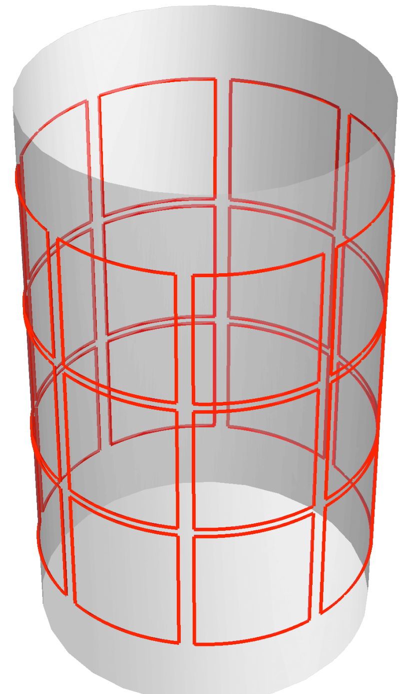
AIP Advances **4,** 047135 (2014)

Shim coil design – array

Independent current control of each element.







8-element array – transverse uniform and gradient fields.

C. Loftson, BSc Thesis, 2013

How many elements?
Array configuration?

Thanks

Profs:
R Mammei, J Martin, C Crawford, S King

Students:
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