R&D on field stability and uniformity for the TRIUMF nEDM experiment

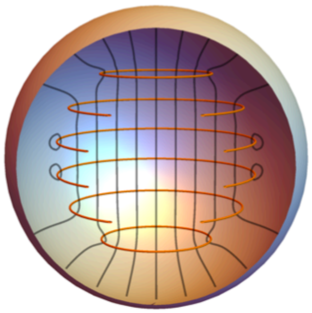
C. Bidinosti & R. Mammei

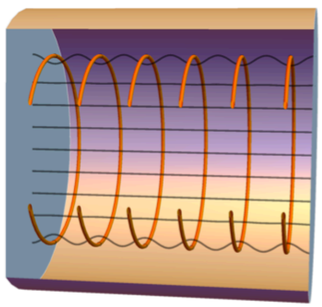
THE UNIVERSITY OF WINNIPEG

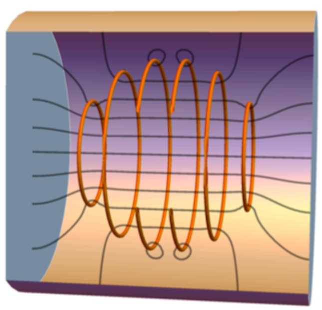
Outline

- Self-shielded B_0 coils – two approaches
- Compensation coils
- NMOR – degaussing, field stability

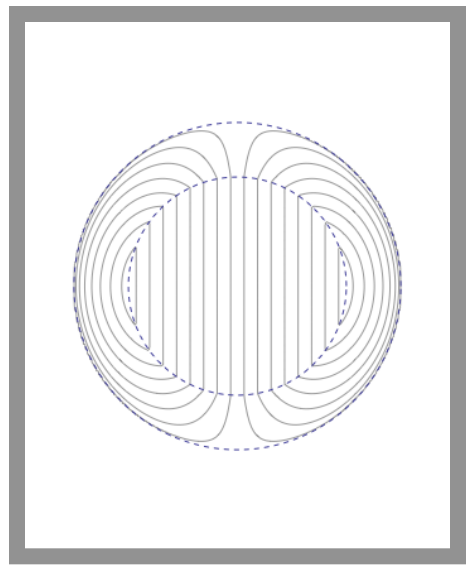
Shield-coupled vs. self-shielded coils





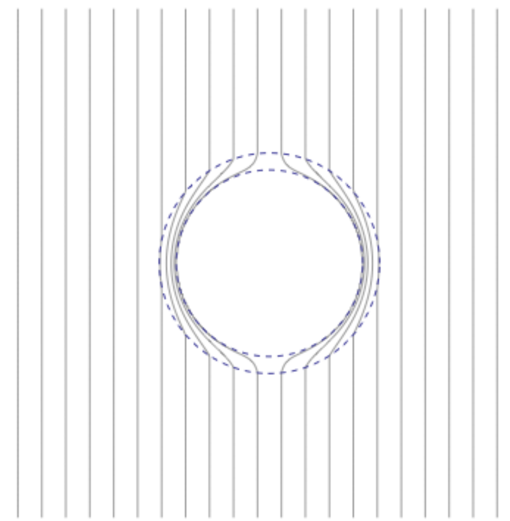


e.g. B_0 flux return through shield, reaction factor, $\mu(T)$



Generate contained fields

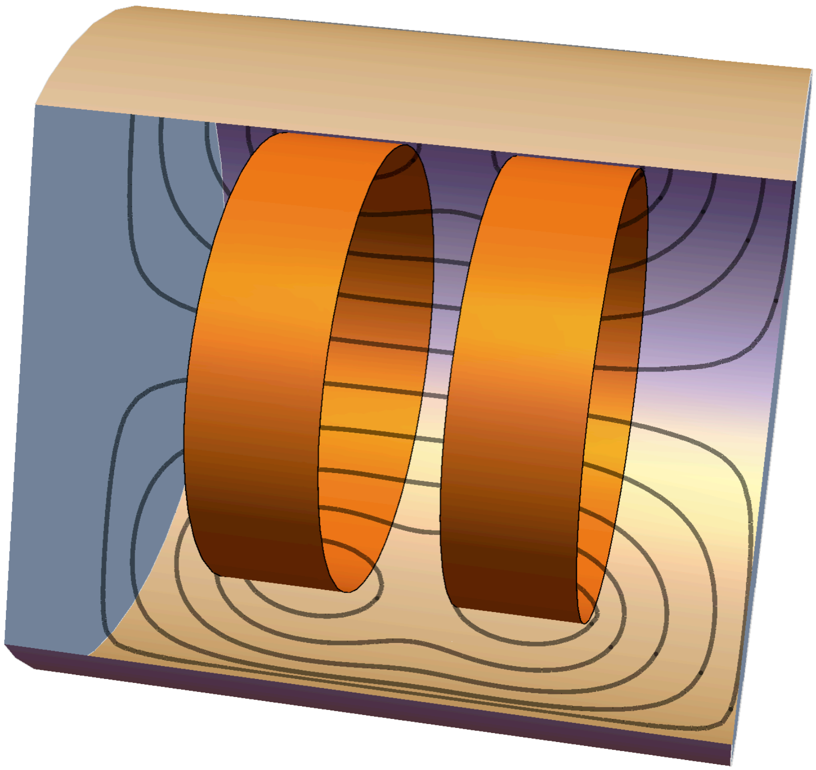
e.g. B_0 that does not interact with passive shields



Create 'cloaked' volumes

e.g. zero-field regions in B_0 for magnetometers

Design principle – self-shielded solenoidal coils



Extension of solenoid inside a superconducting cylinder ($\sigma=\infty$)

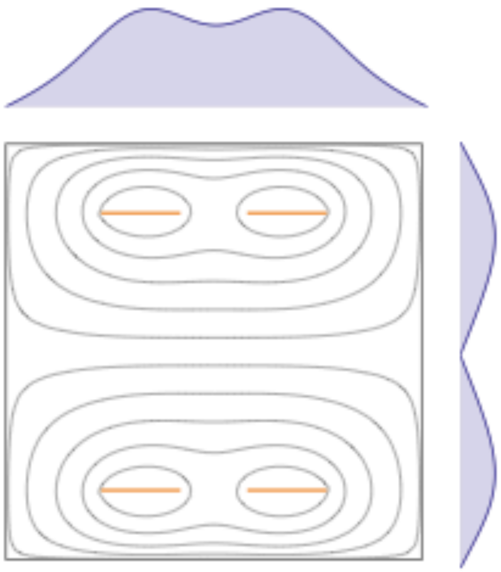
- TJ Sumner, J Phys D: Appl Phys **20**, 692 (1987)
- KW Rigby, Rev Sci Instum **59**, 156 (1988)

Boundary condition

$$B_\perp = 0$$

Design principle – self-shielded solenoidal coils

$K_{cyl}(z) = - B_z(b,z)/\mu_o$



$K_{cap}(\rho) = - B_\rho(\rho,L)/\mu_o$

Given surface current on inner cylinder, know surface current on outer cylinder

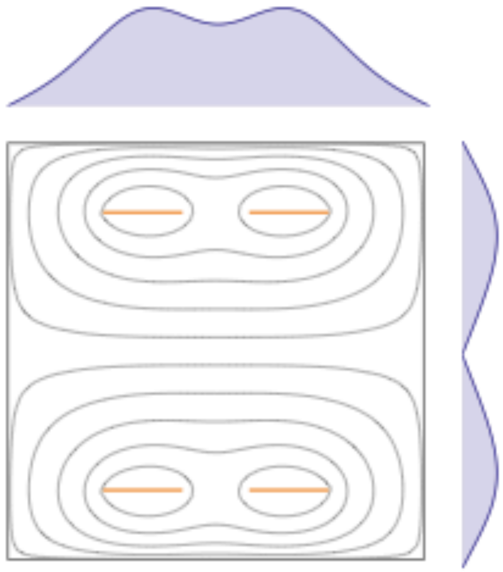
Surface current K

$\Delta B = \mu_o K$

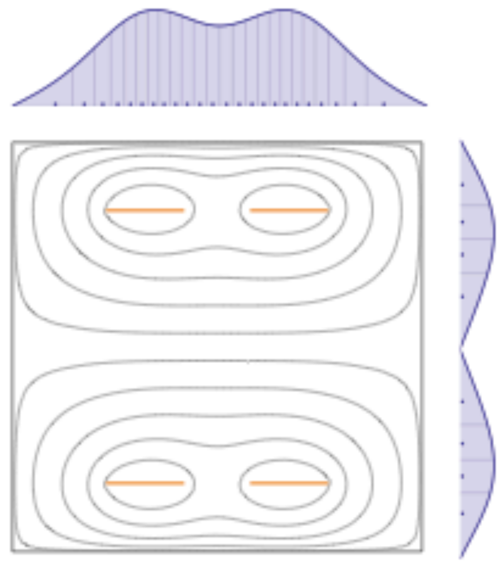
Design principle – self-shielded solenoidal coils

$$K_\phi = \partial\psi/\partial z$$

$$\psi \equiv \Delta\Phi$$



Given surface current on inner cylinder, know surface current on outer cylinder



Segment into regions of equal integrated surface current

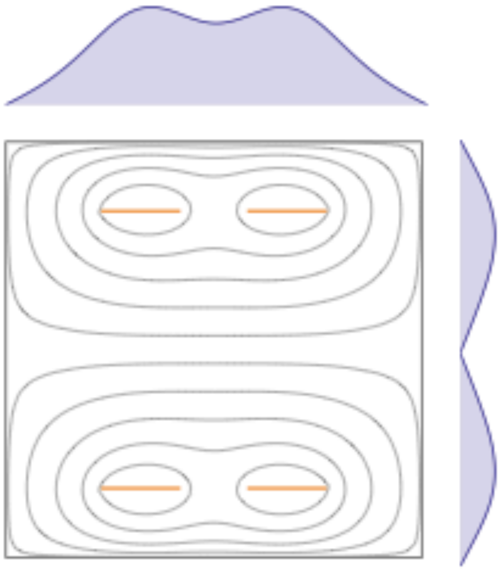
Stream function ψ

Scalar potential ϕ

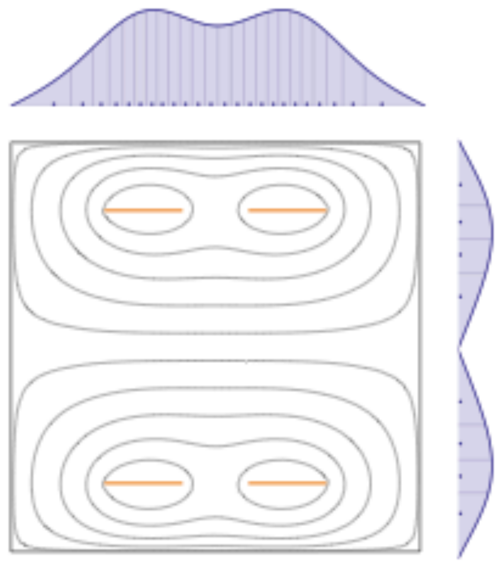
Evenly spaced contours of ψ bound equal current

- JA Stratton, *Electromagnetic Theory* (McGraw-Hill, 1941), §4.2
- HA Haus & JR Melcher, *EM Fields and Energy*, (Prentice-Hall, 1989), §8.5
- CP Bidinosti et al., J Magn Reson **177**, 31 (2005)

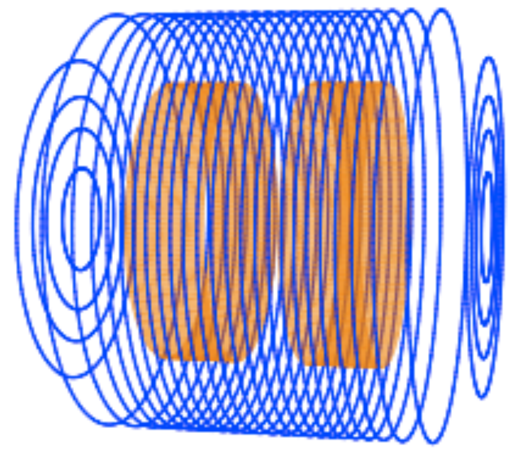
Design principle – self-shielded solenoidal coils



Given surface current on inner cylinder, know surface current on outer cylinder

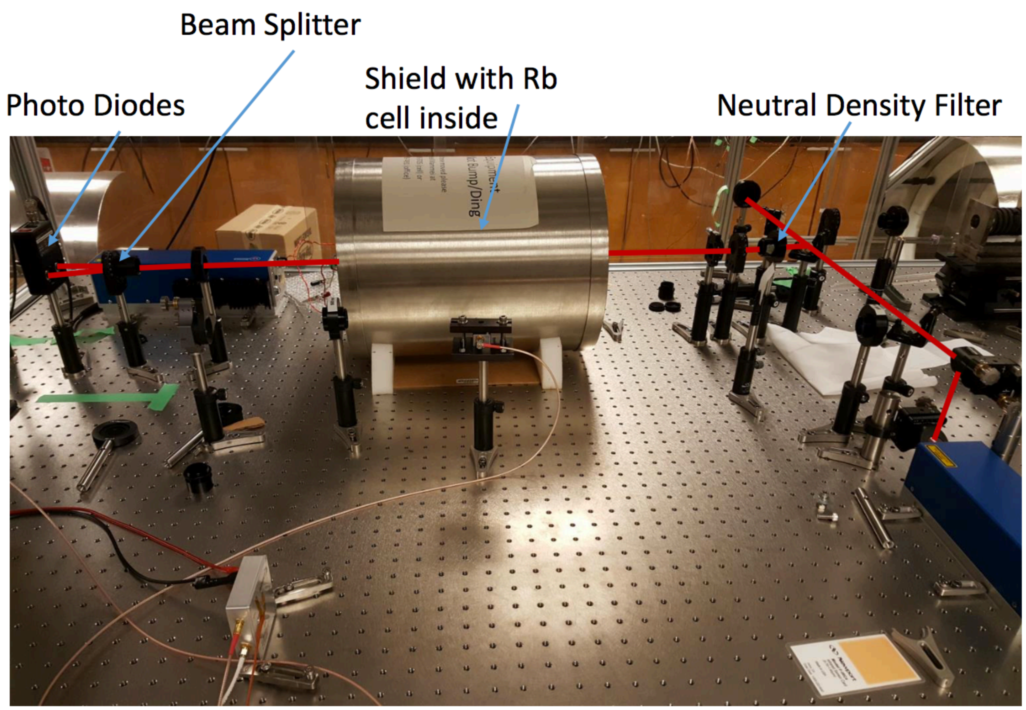


Segment into regions of equal integrated surface current

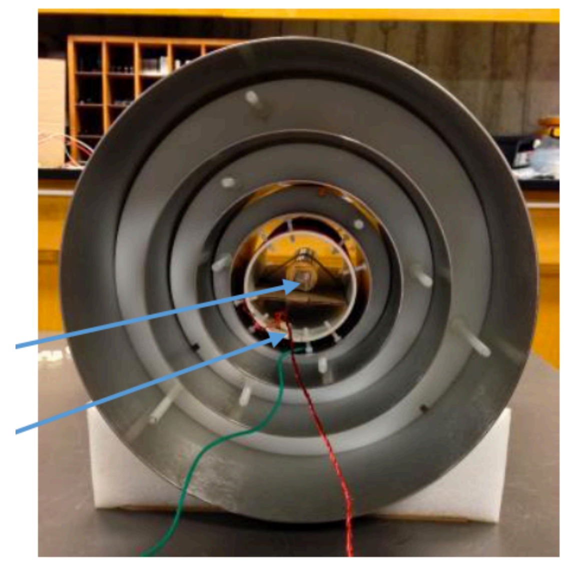


Replace inner and outer surface currents with discrete wires

Design prototype coil for small μ-metal shield set



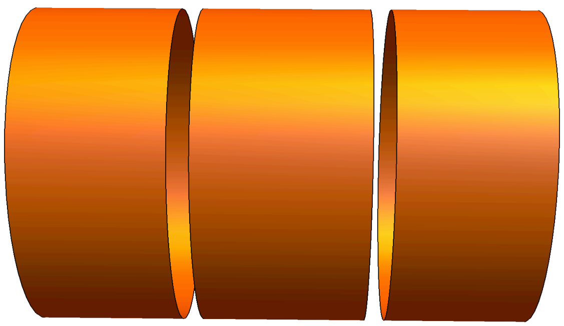
NMOR apparatus at UW



4-layer shield

- J Martin et al, NIMA **778**, 61 (2015)

Choose basic design – split solenoid



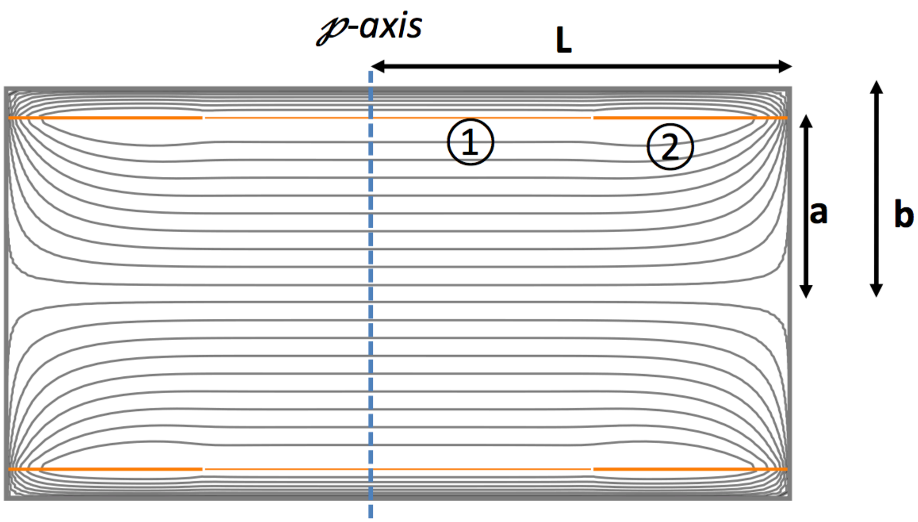
Split inner solenoid with different lengths and surface current densities.

Optimize lengths and current ratios of segments to minimize ΔBz

Example: Split solenoid B_0 coil for ^{129}Xe EDM experiment at Tokyo Institute of Technology

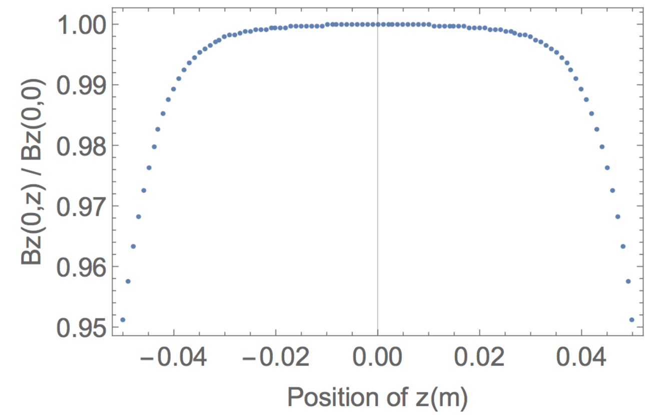
- CP Bidinosti, Y Sakamoto and K Asahi, IEEE Magnetics Letters **5**, 0800304 (2014)
- Y Sakamoto et al, Hyperfine Interact **230**, 141 (2015)

Optimization of inner surface currents

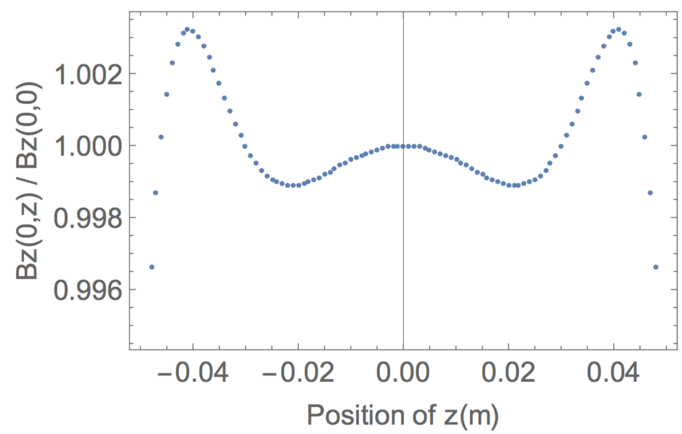


Split inner solenoid with different lengths and surface current densities.

Optimize lengths and current ratios of segments (1) and (2) to minimize ΔBz

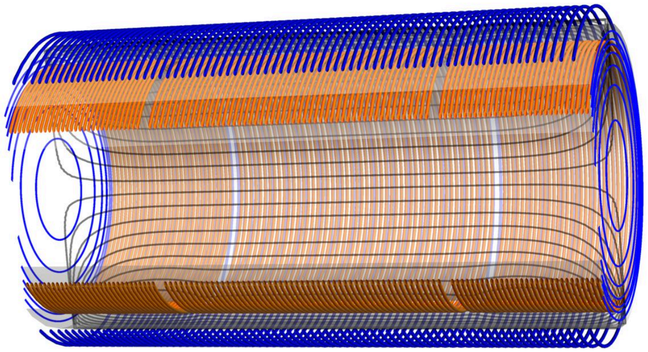


Eliminate z^2, z^4, z^6



Accept lower orders to extend 'useable' range

Construction of coil



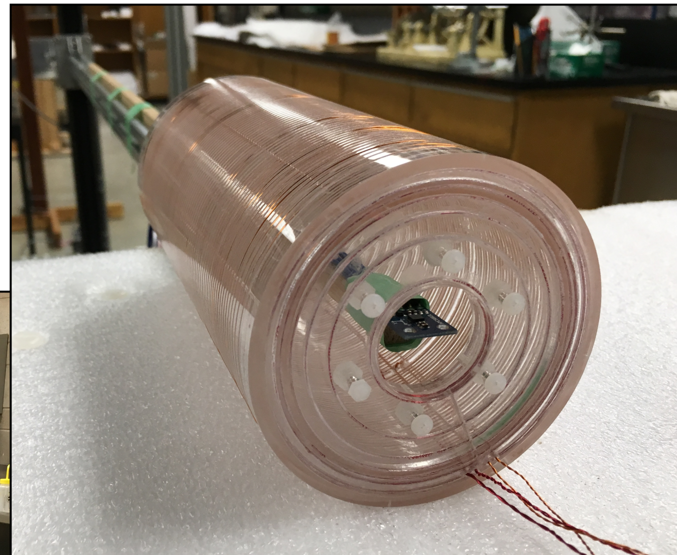
Design – cut-away with field lines

Laser cut formers and grooves.

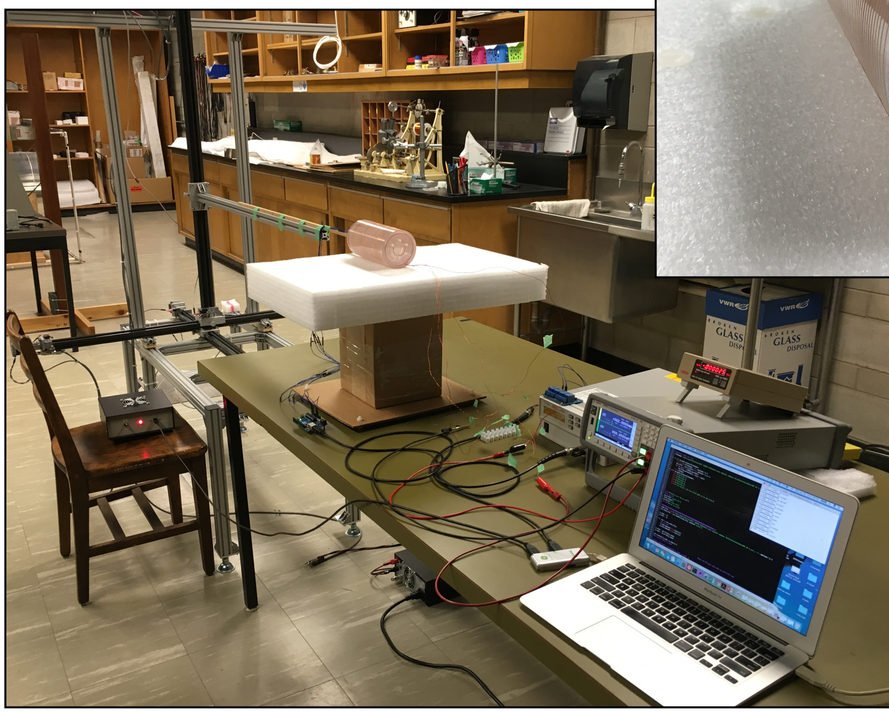
Wound by hand under microscope.

End caps Outer cylinder Inner cylinder

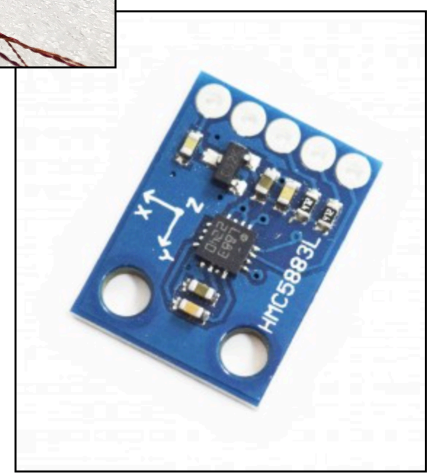
Field mapping



Use relays to activate and de-activate shield current at each position of mapper

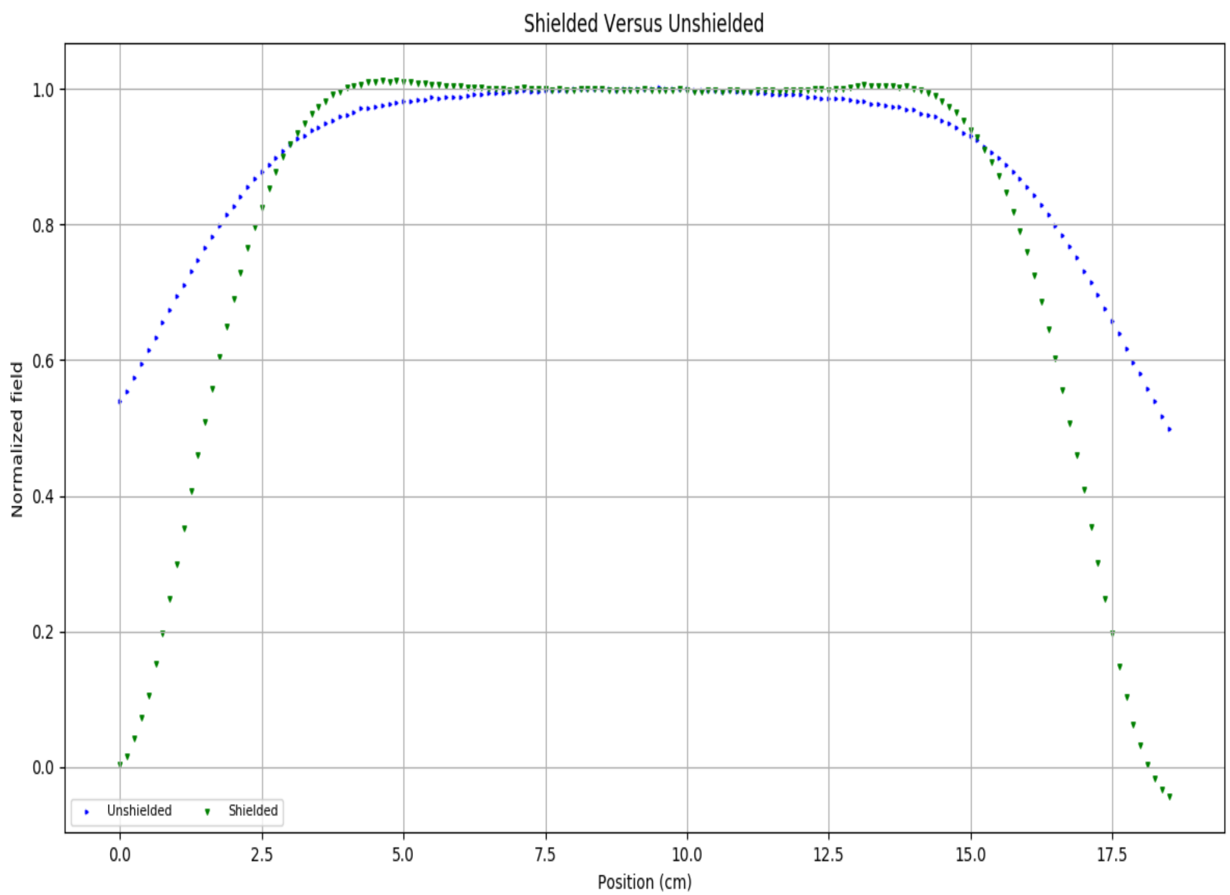


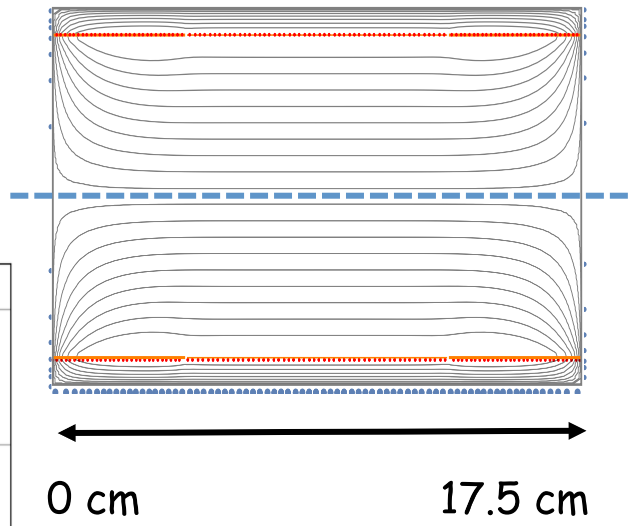
Field mapper, current supply, and relays under computer control



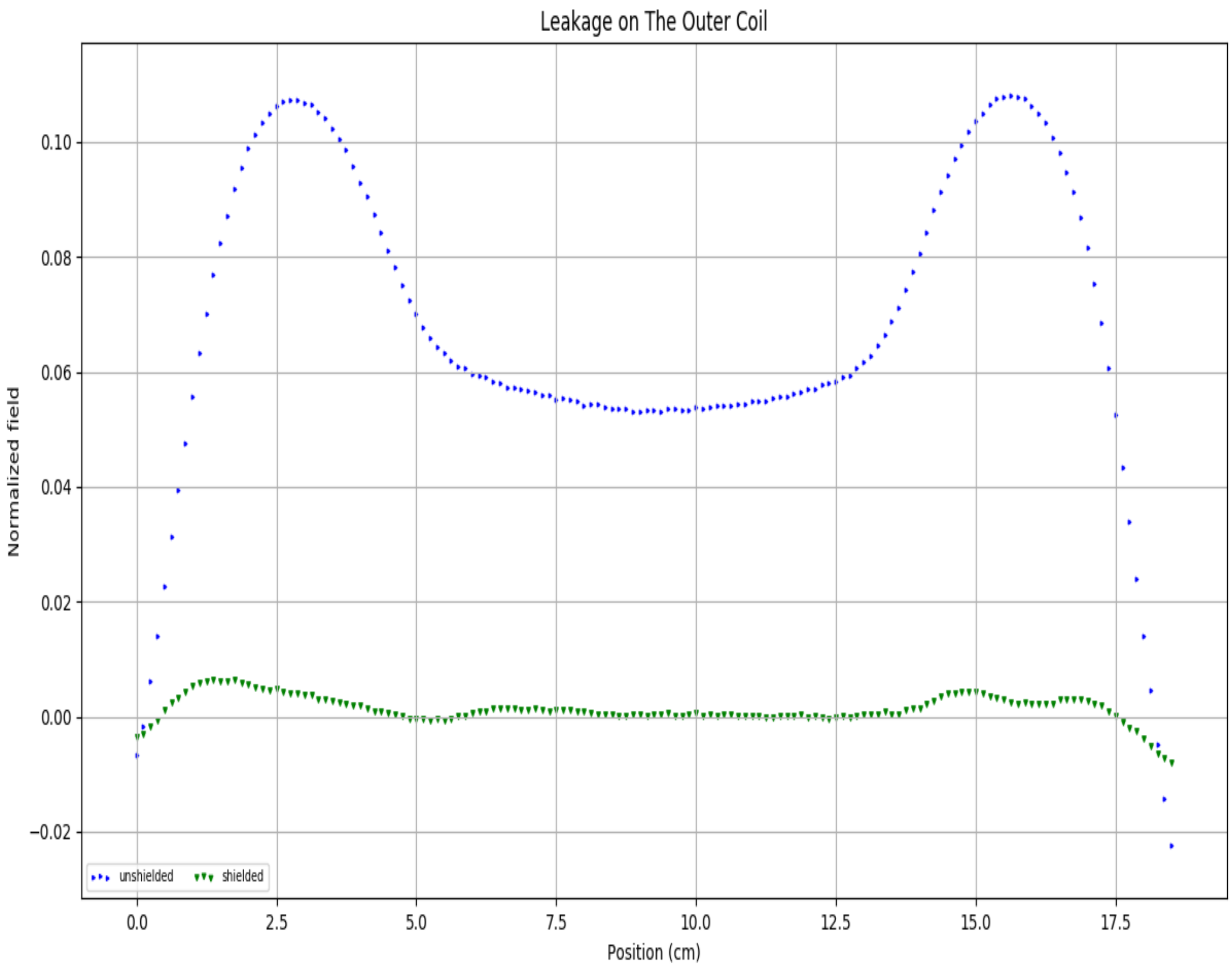
Honeywell HMC5883L 3-axis AMR 'compass'

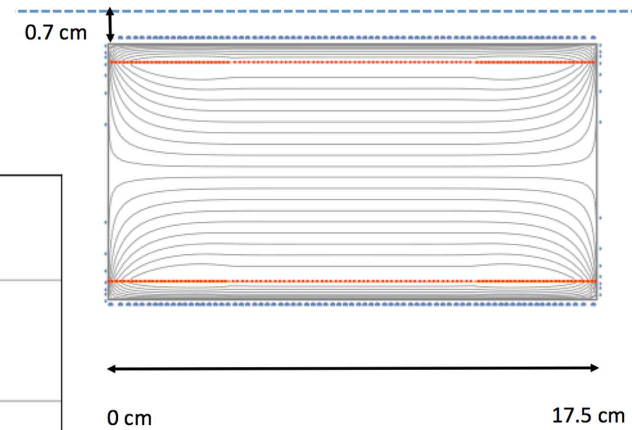
Field map along central axis



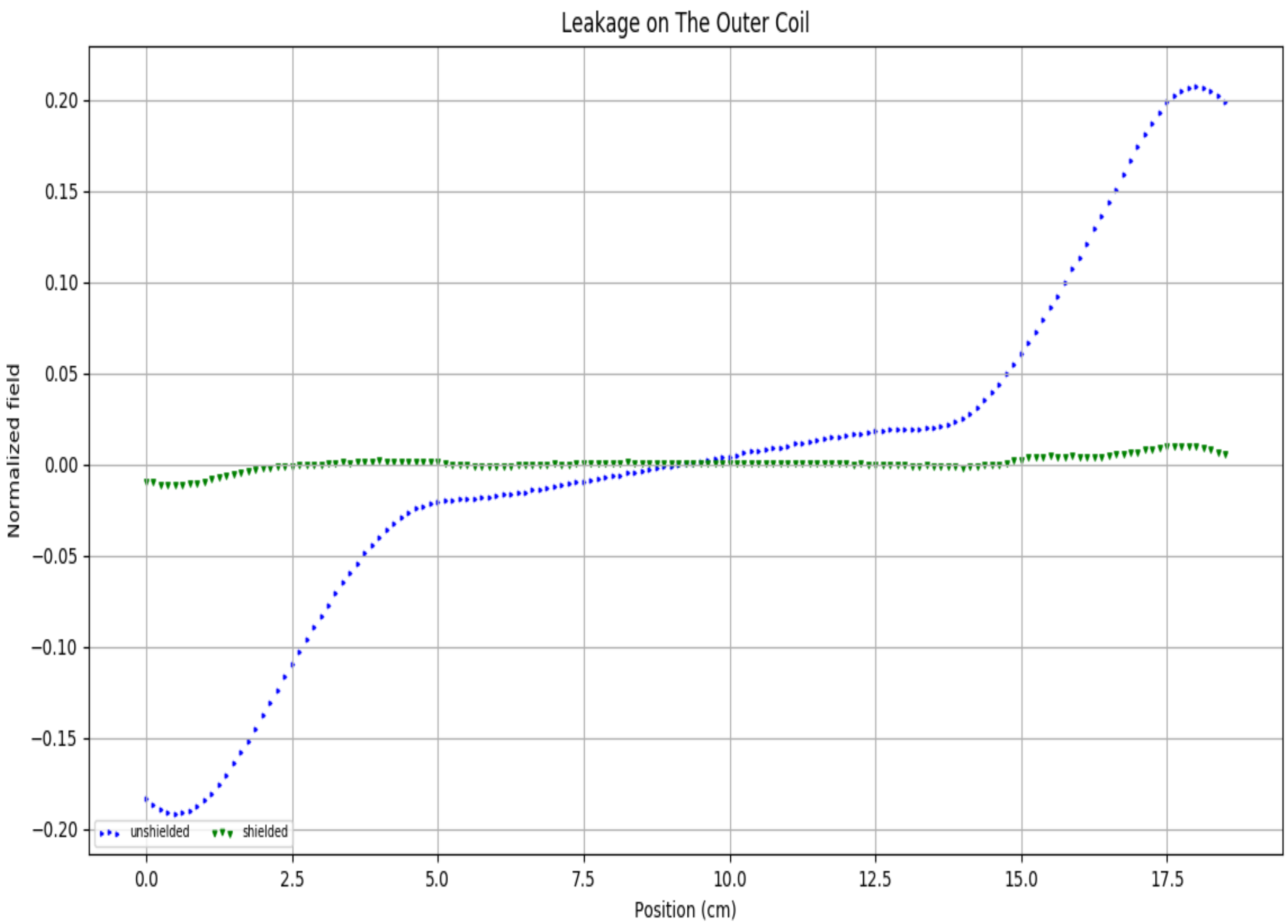


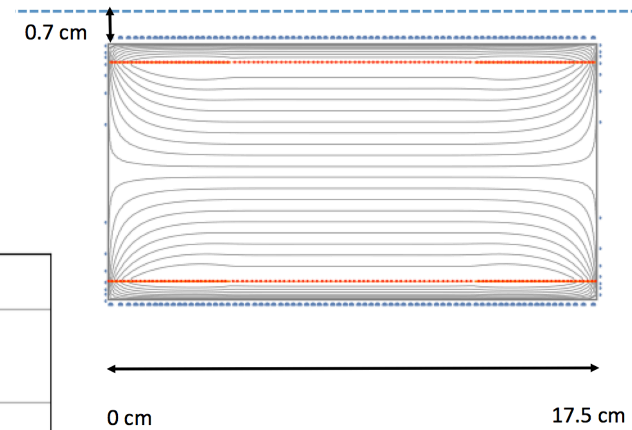
Field map outside coil – Bz leakage field



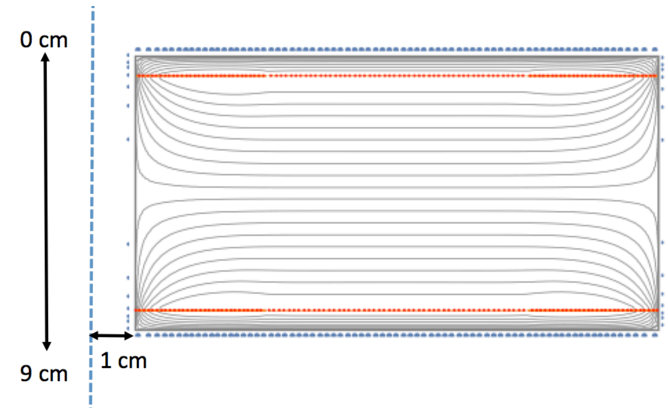


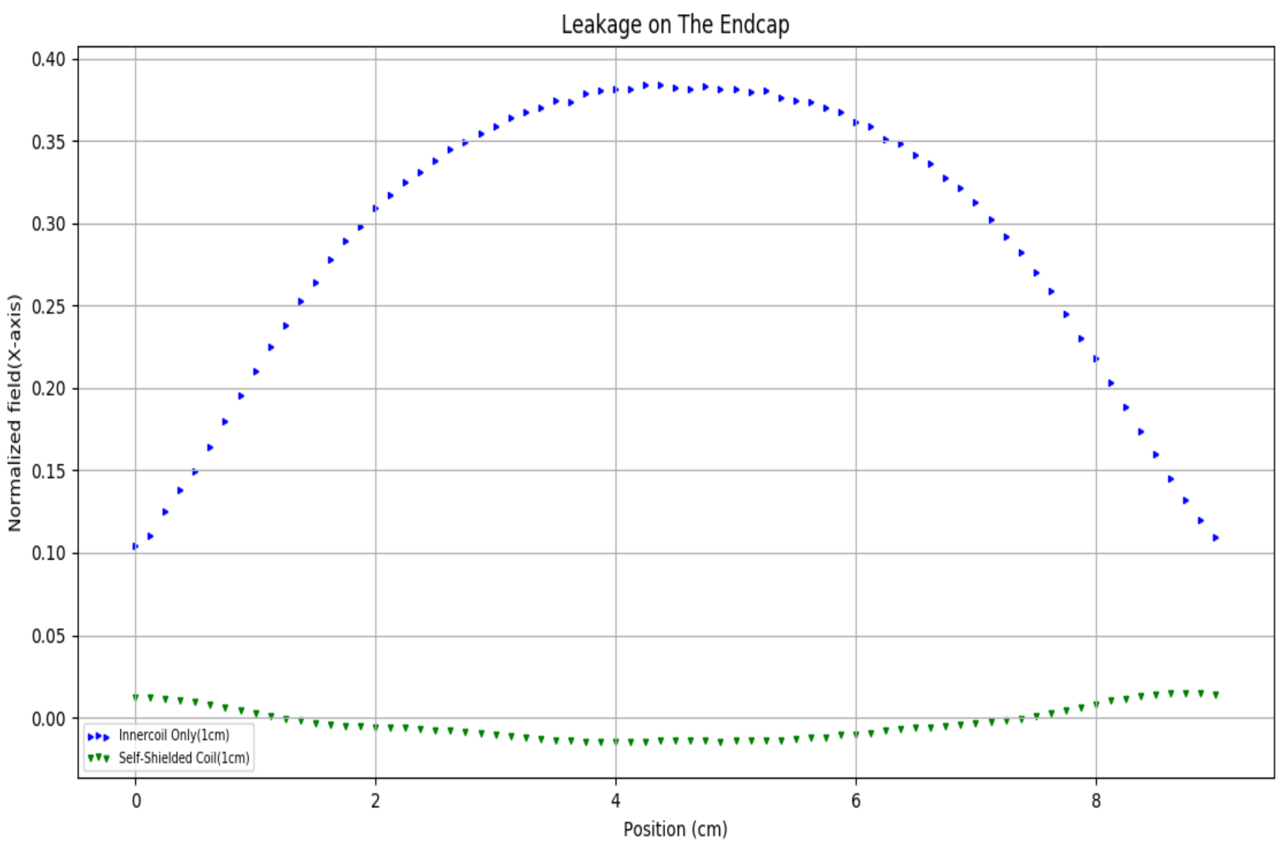
Field map outside coil – Bρ leakage field



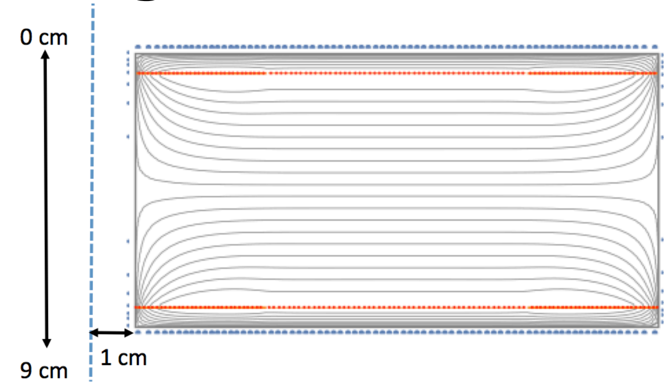


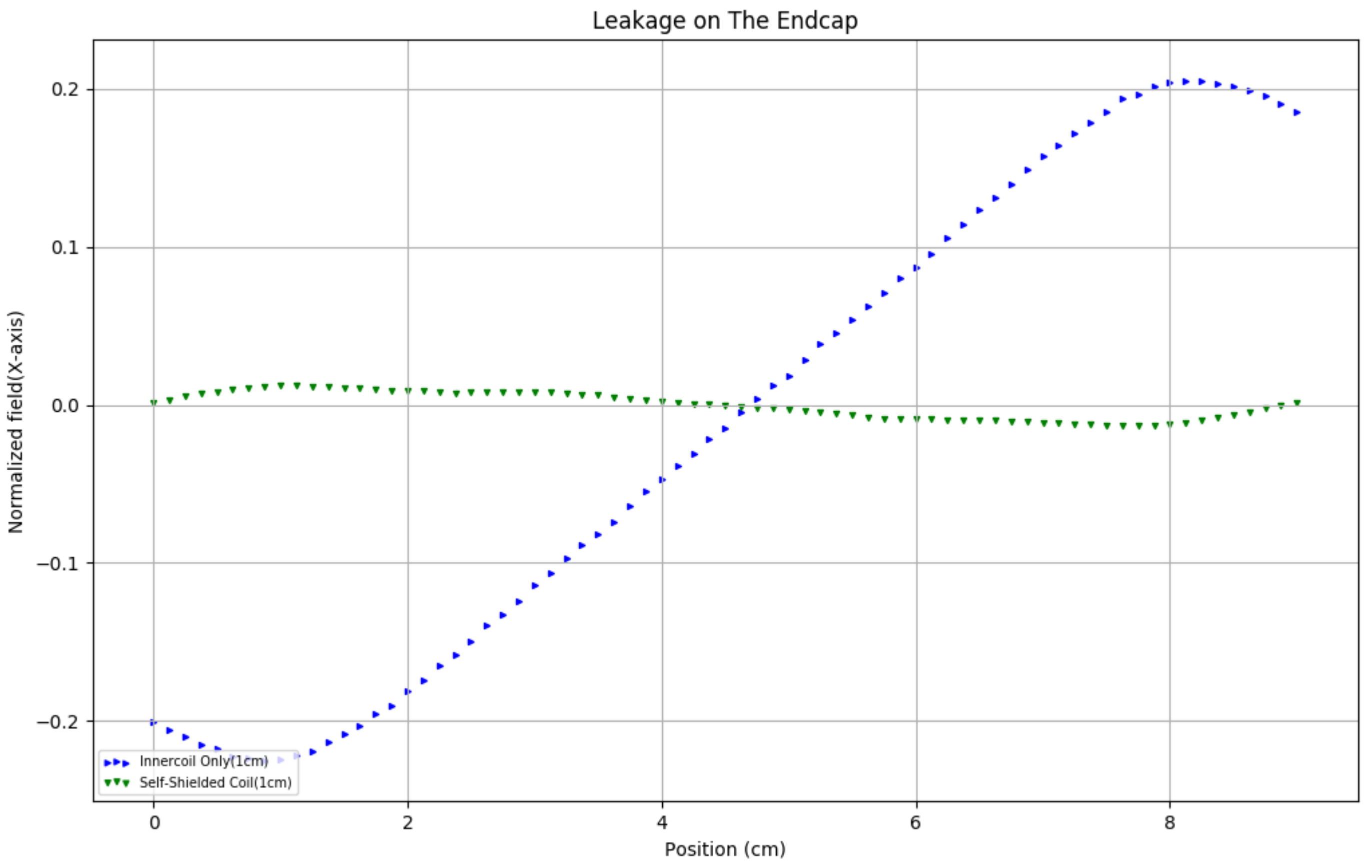
Field map outside cap – Bz leakage field



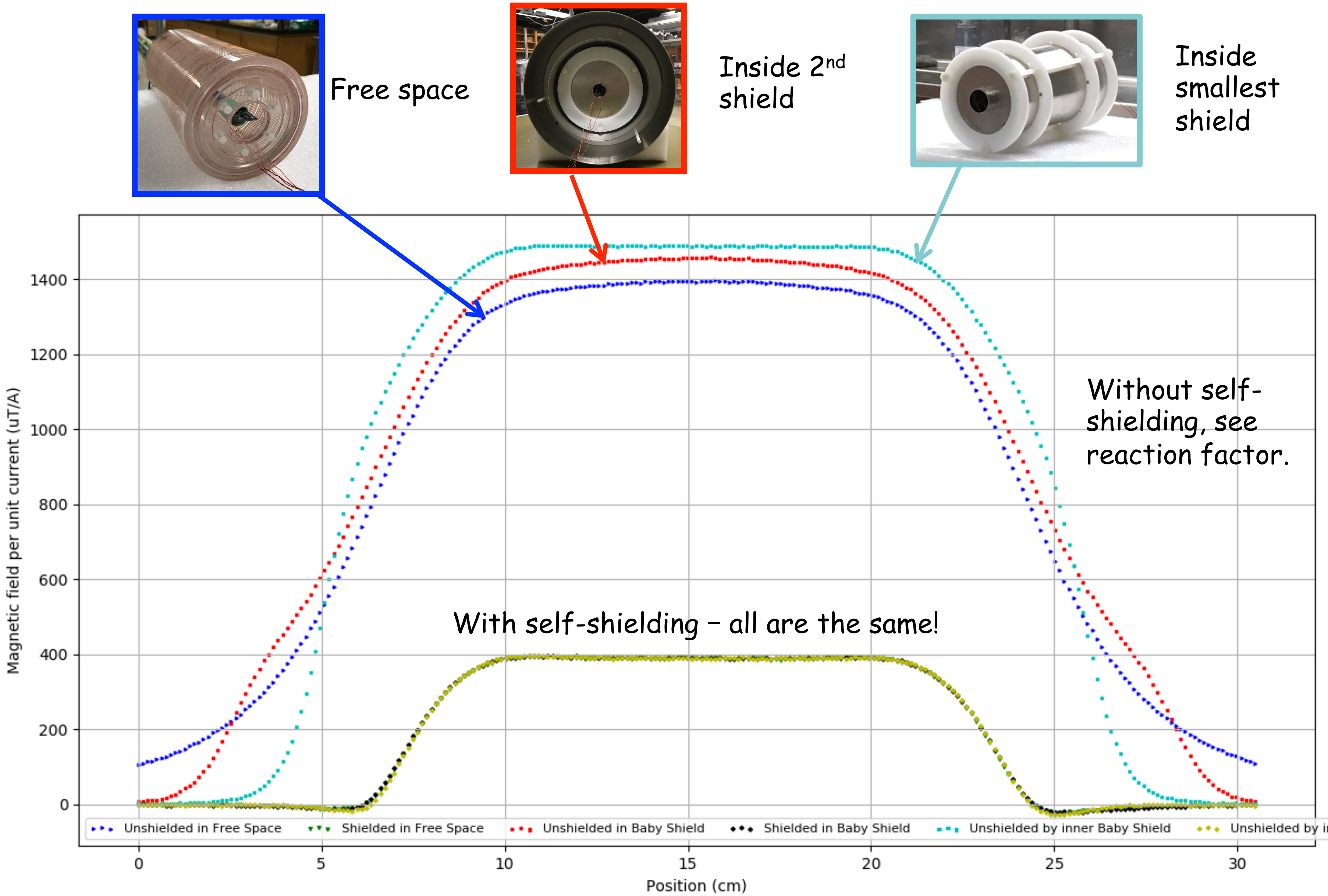


Field map outside cap – Bρ leakage field



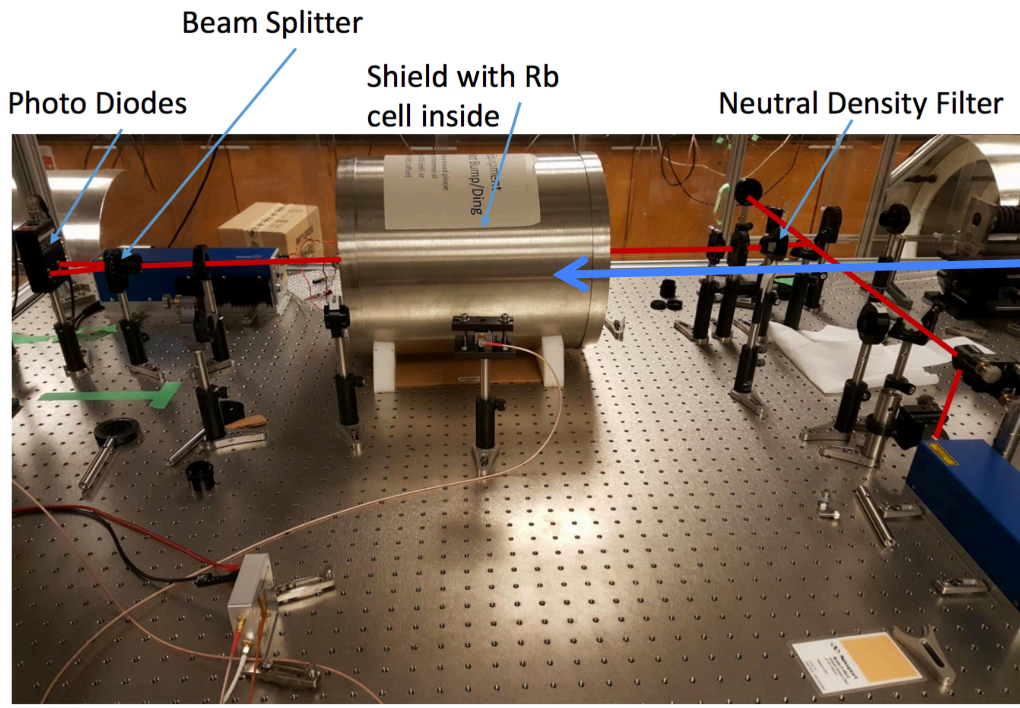


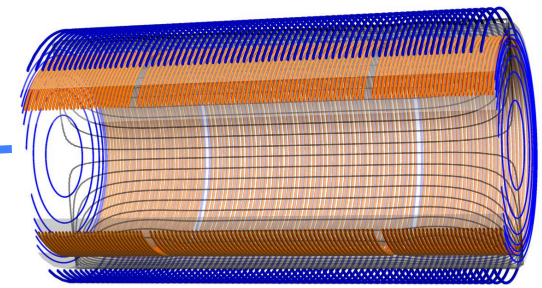
Field map along central axis inside passive shields



Next step – stability measurement via NMOR

Shield-coupled vs. self-shielded



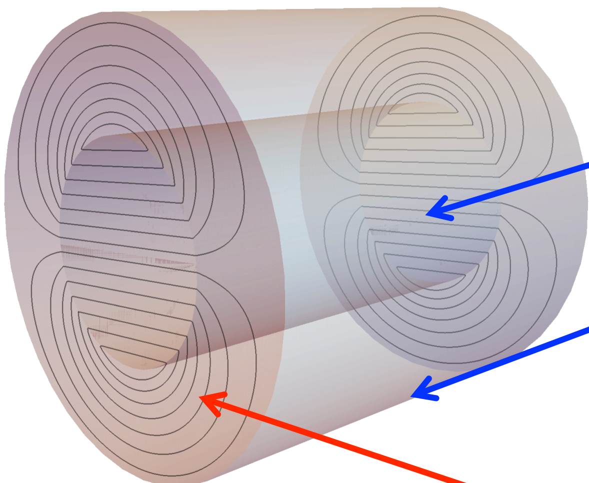


Temporal dependence
of reaction factor

NMOR apparatus at UW

- T Andalib et al, NIMA **867**, 139 (2017)

Design principle – self-shielded transverse coil



Analytic solution for sine-phi coil

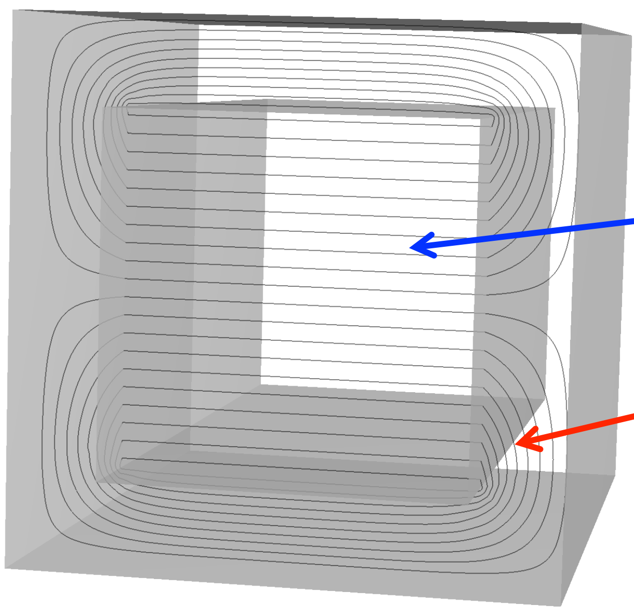
$$\boldsymbol{K}_a = K \sin\phi \; \Pi(-l, l) \; \hat{\boldsymbol{z}}$$

$$\boldsymbol{K}_b = -\left(\frac{a}{b}\right)^2 K \sin\phi \; \Pi(-l, l) \; \hat{\boldsymbol{z}}$$

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

- RA Beth, BNL-10143, US Pat 3466499 (1966)
- C Bidinosti et al, JMR **177**, 31 (2005)

Design principle – self-shielded box coil



Φ=0 externally

Numerical solution of Laplace Equation for <u>any</u> geometry and field profile

Specify Φ internally

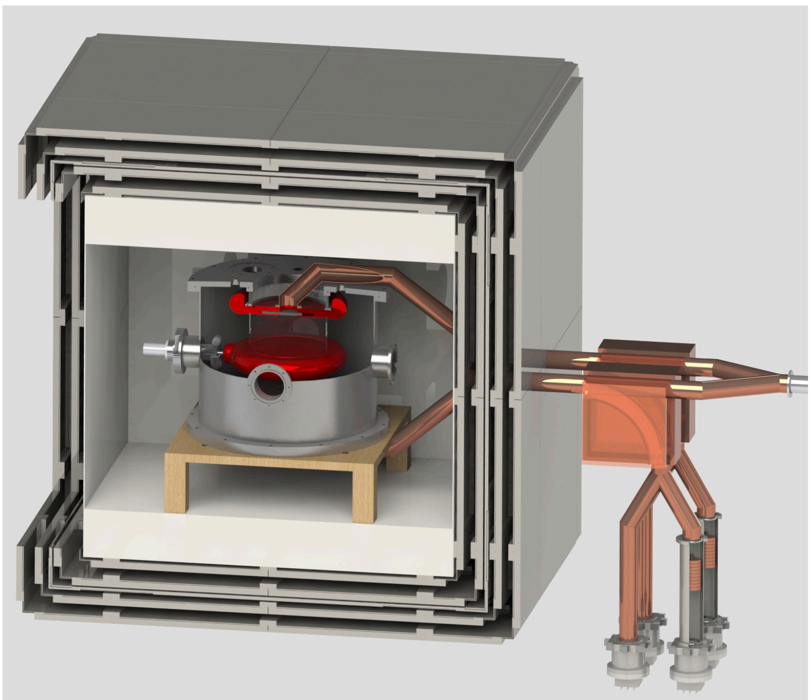
Solve $\nabla^2\Phi = 0$

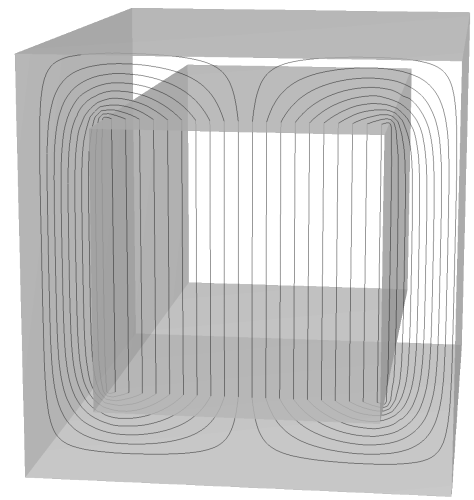
Contours of stream function give winding pattern

$$\psi \equiv \Delta\Phi$$

- C Crawford, U Kentucky

Design self-shielded box coil for Phase II





Self-shielded box coil
with removable end caps

Design self-shielded box coil for Phase II

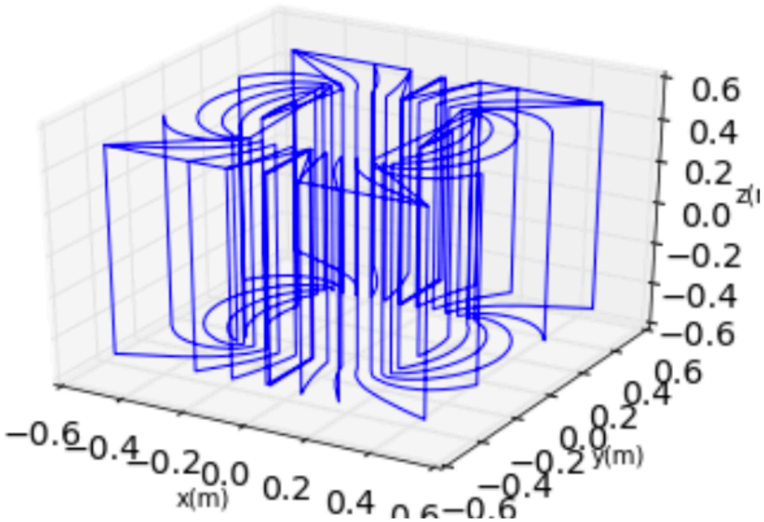


Figure 14: Full inner coil

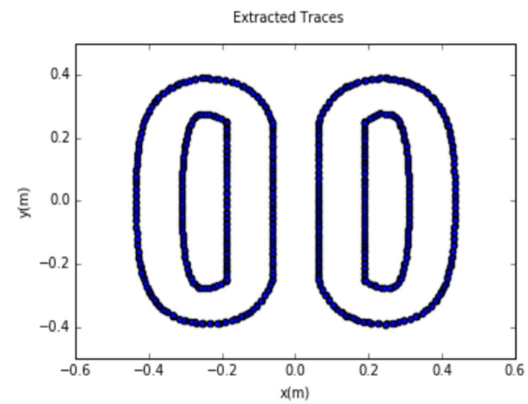
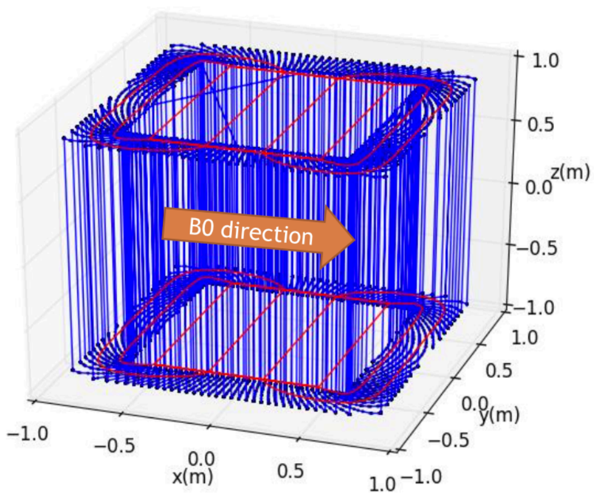
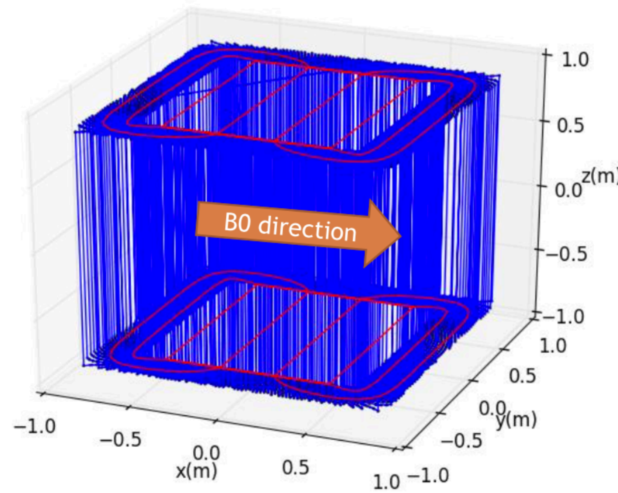


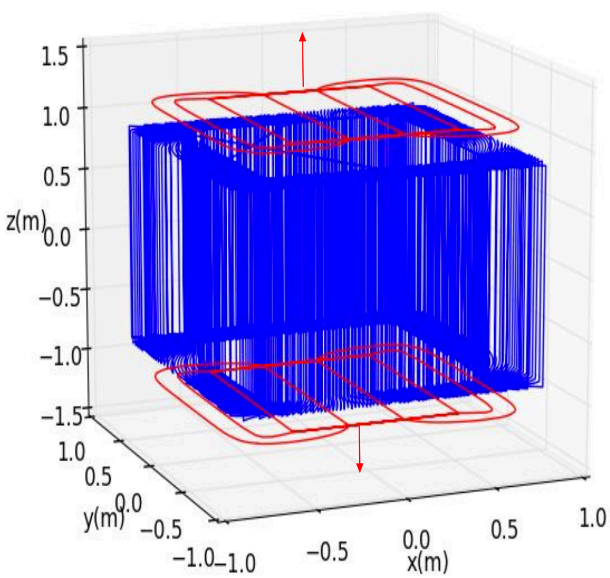
Figure 15: Outer removeable endcap

- R Burrough, UWinnipeg, 2017

Design self-shielded box coil for Phase II







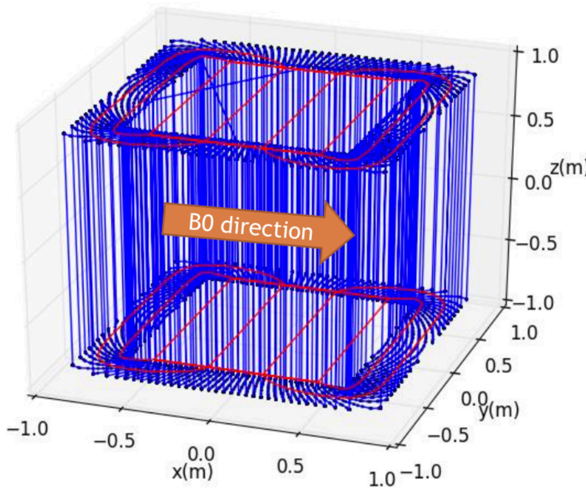
Want $\delta B \sim nT/m$

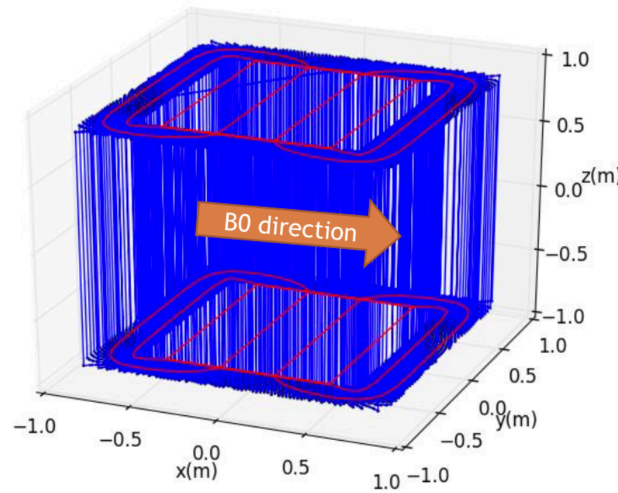
Explore:

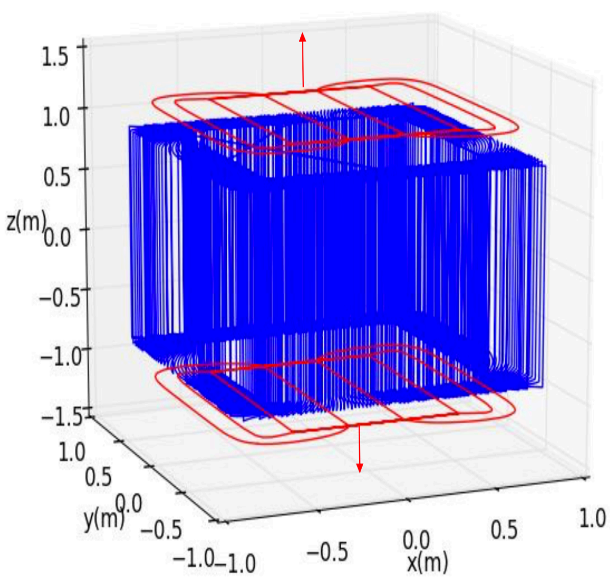
- dimensions
- number of turns
- wire displacements

- R Burrough, UWinnipeg, 2017

Design self-shielded box coil for Phase II







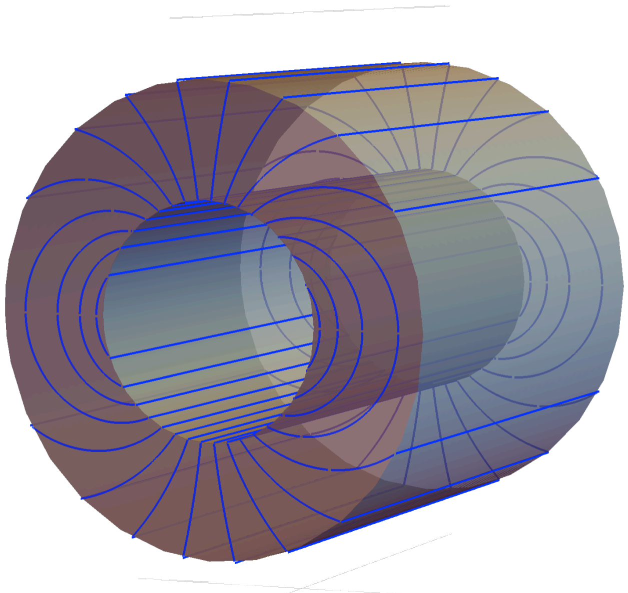
Challenges:

- Solve Laplacian in COMSOL
- Export and sort contour data in Python
- Biot-Savart calculation and analysis
- Presently time consuming

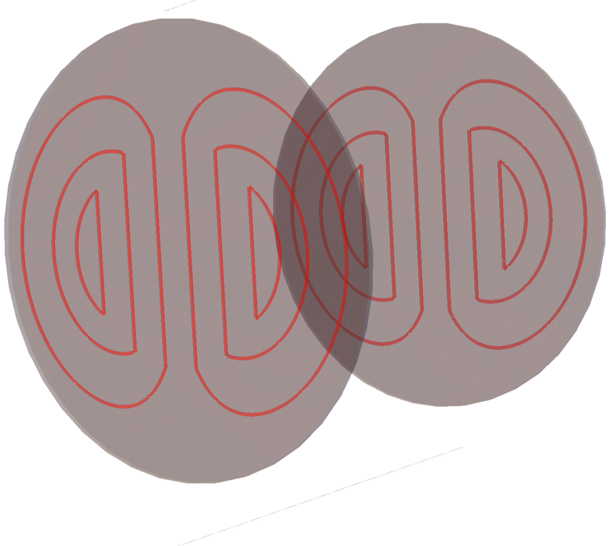
- R Burrough, UWinnipeg, 2017

Design self-shielded box coil for Phase II

Body



Caps

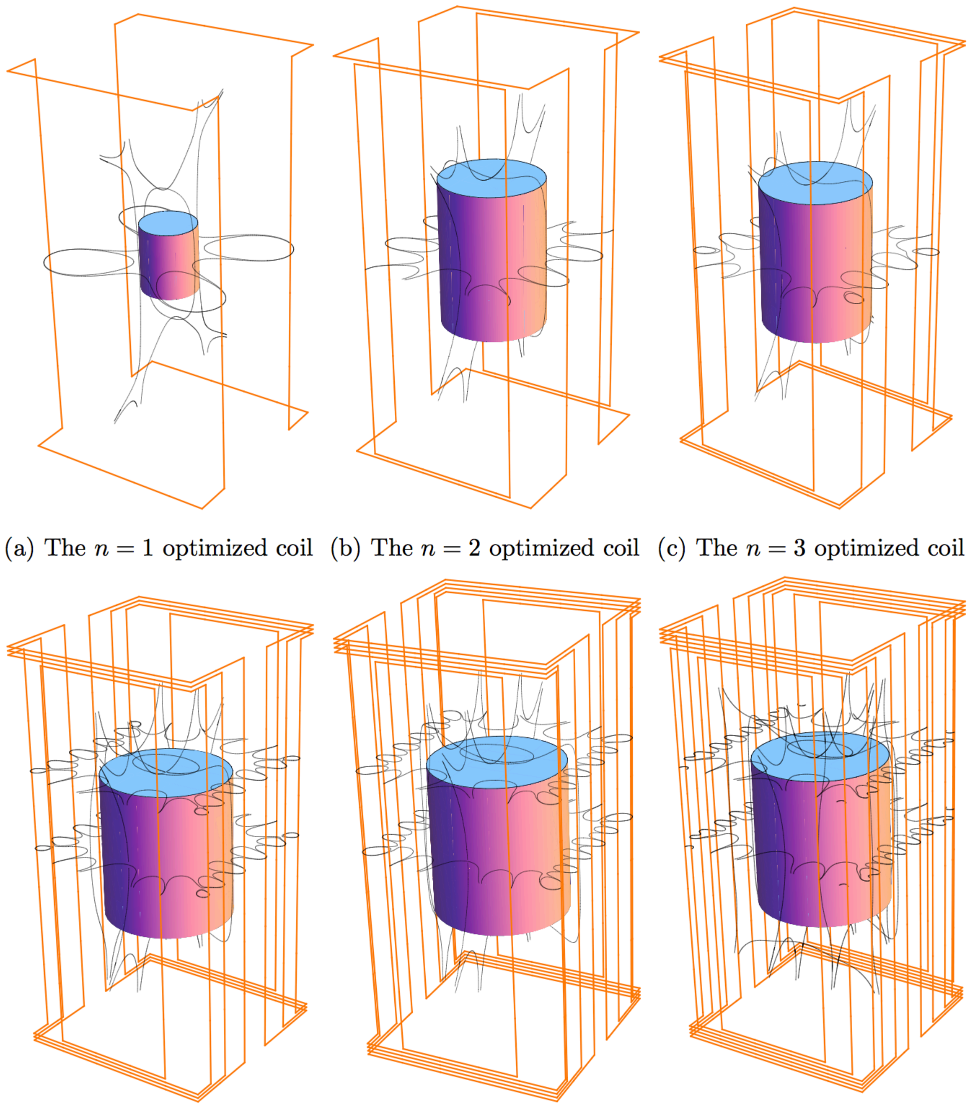


Return to analytic cylindrical model to get a better handle on parameter space (?)

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

e.g. use Mathematica for everything

Compensation coils for Phase I



(a) The $n = 1$ optimized coil (b) The $n = 2$ optimized coil (c) The $n = 3$ optimized coil

(d) The $n = 4$ optimized coil (e) The $n = 5$ optimized coil (f) The $n = 6$ optimized coil

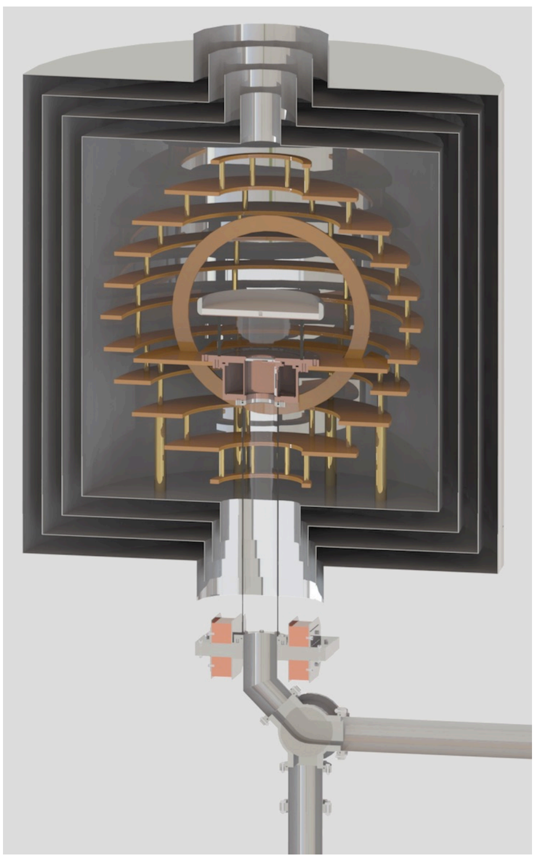
Optimization of square sine-phi coils

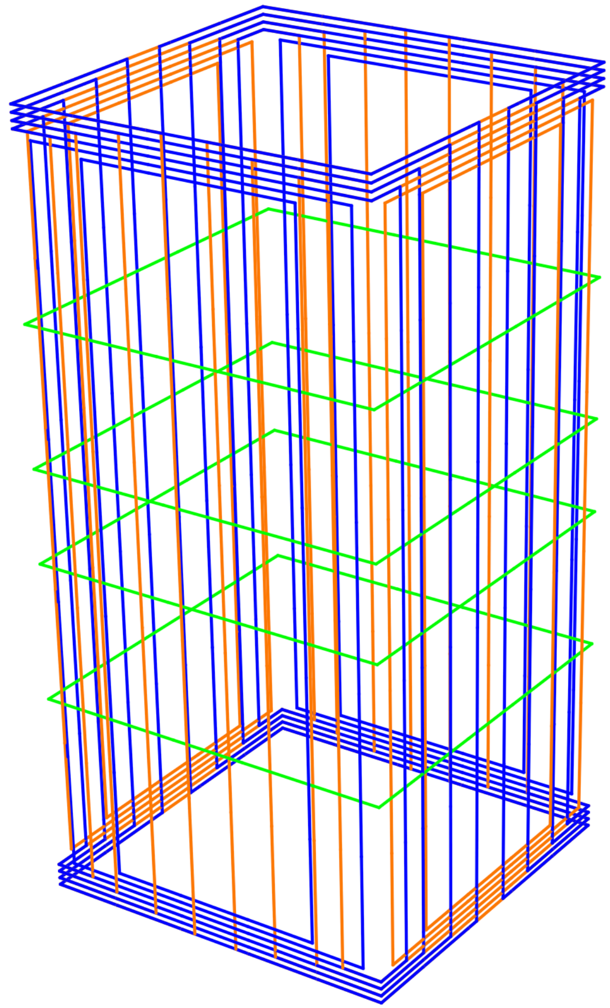
$$\left(\left|\frac{B_x - B_c}{B_c}\right| < 1\%\right) \bigcap \left(\left|\frac{|\vec{B}| - B_c}{B_c}\right| < 1\%\right)$$

Largest cylindrical volume fitting in region of δB < 1%

- C Loftson, UWinnipeg, 2013

Compensation coils for Phase I



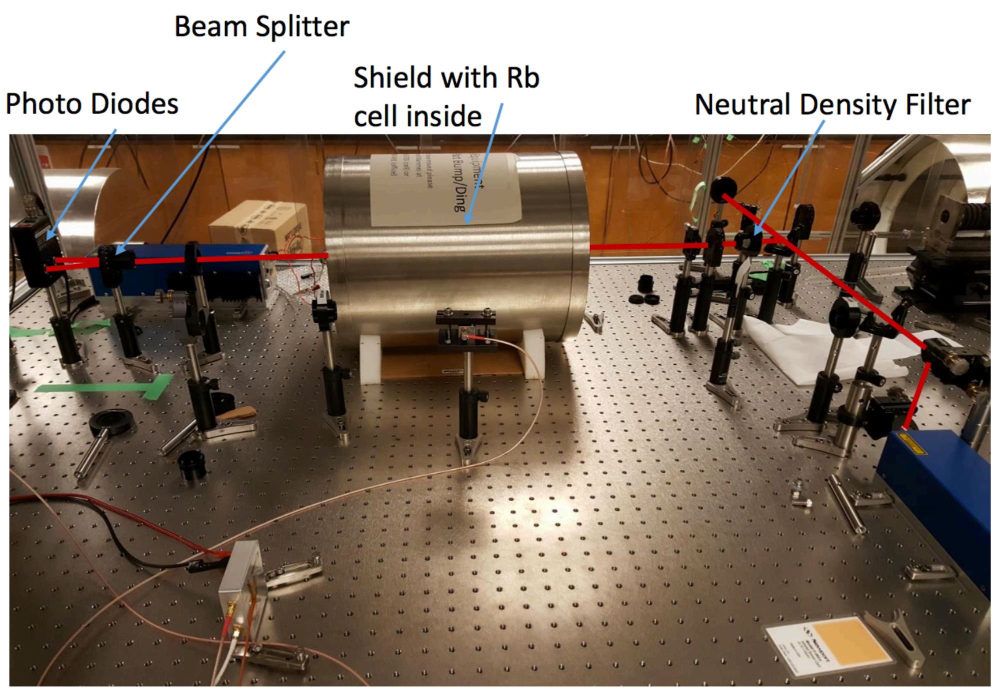


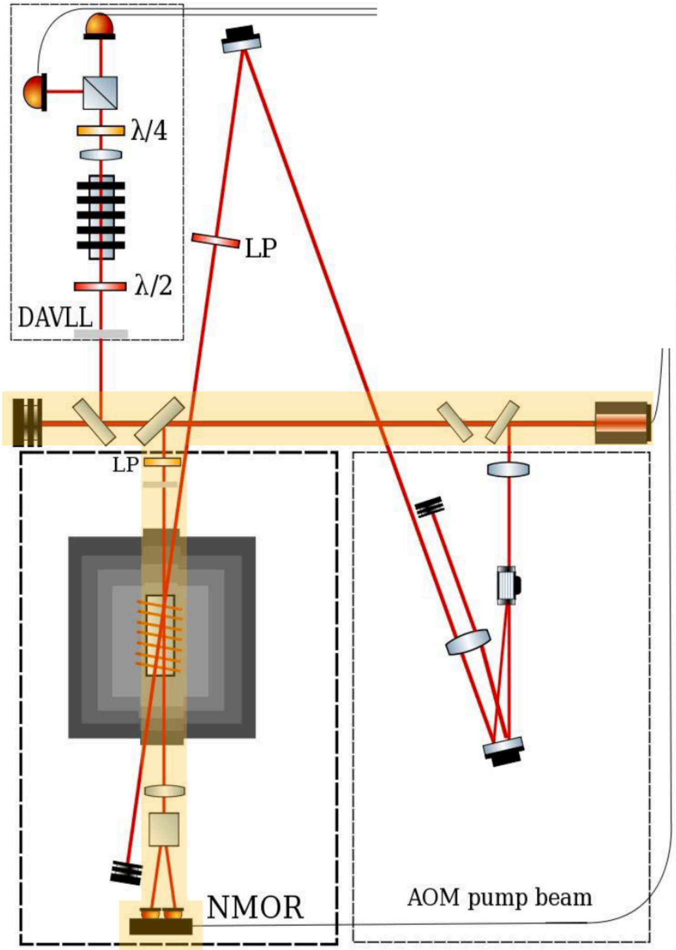
Square sine-phi coils:
Bx, By

Merritt-4 coil:
Bz

- C Loftson, UWinnipeg, 2013

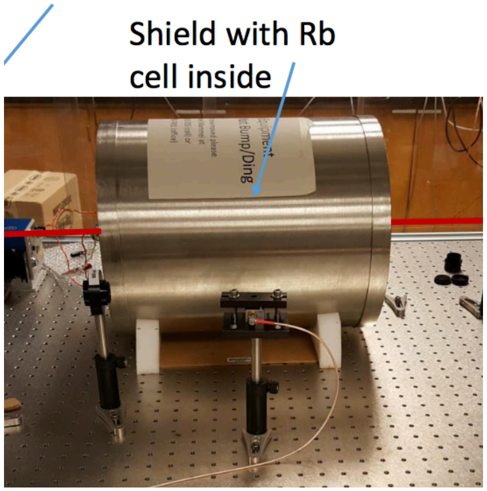
NMOR Studies at UWinnipeg

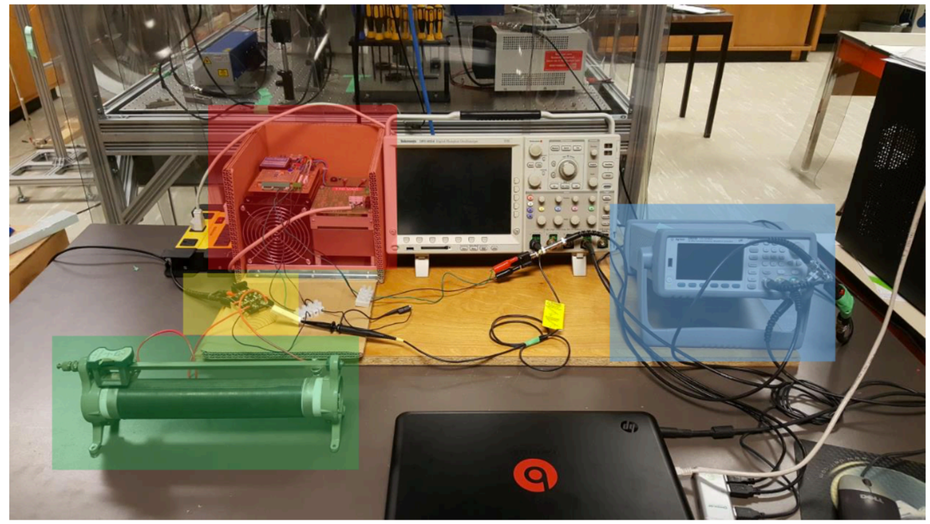


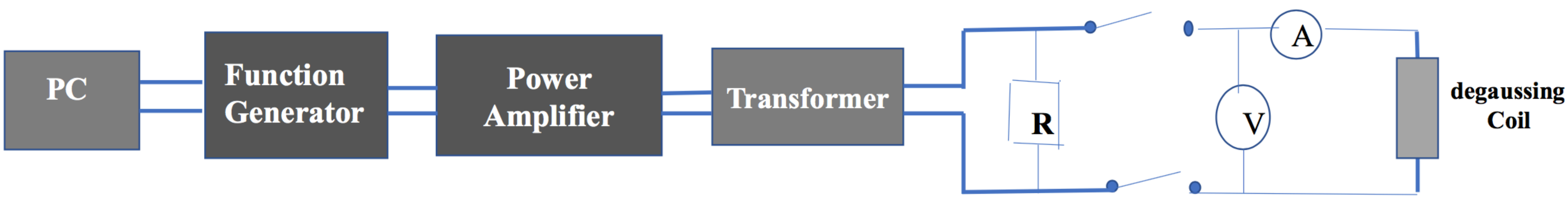


- J Martin et al, NIMA **778**, 61 (2015)

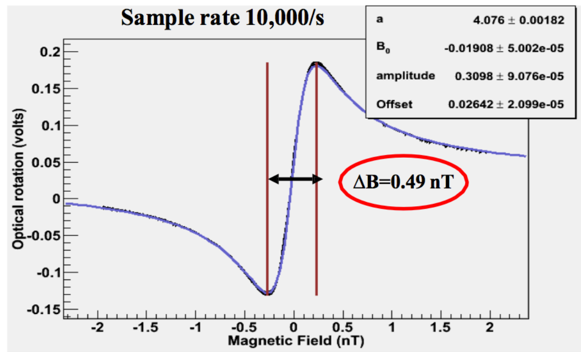
Degaussing

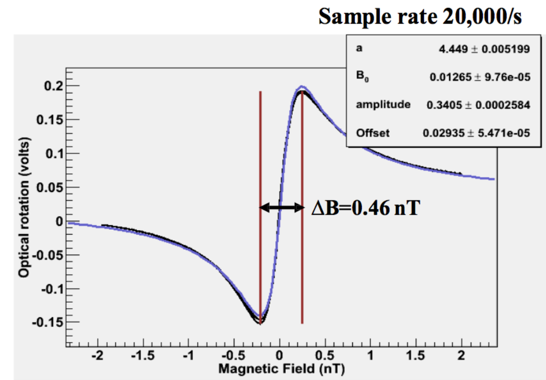

Shield with Rb
cell inside

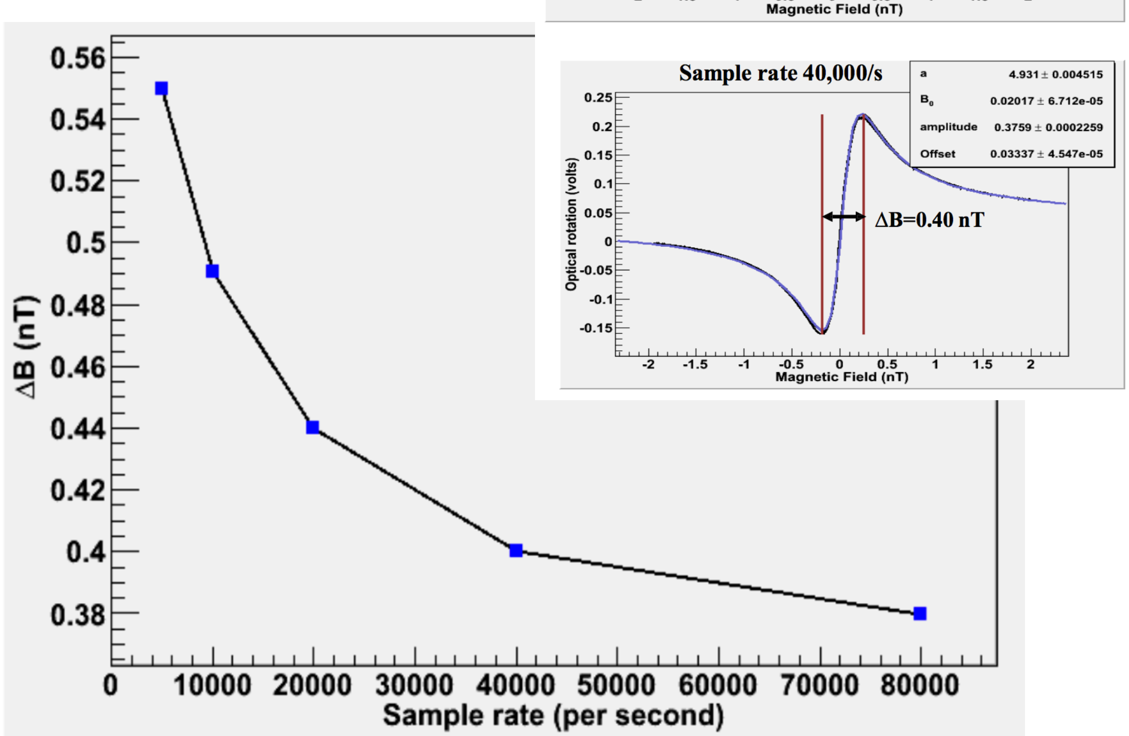


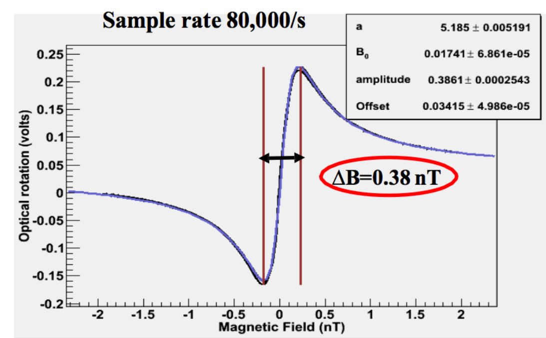

PC
Function Generator
Power Amplifier
Transformer
R
V
A
degaussing Coil

Degaussing





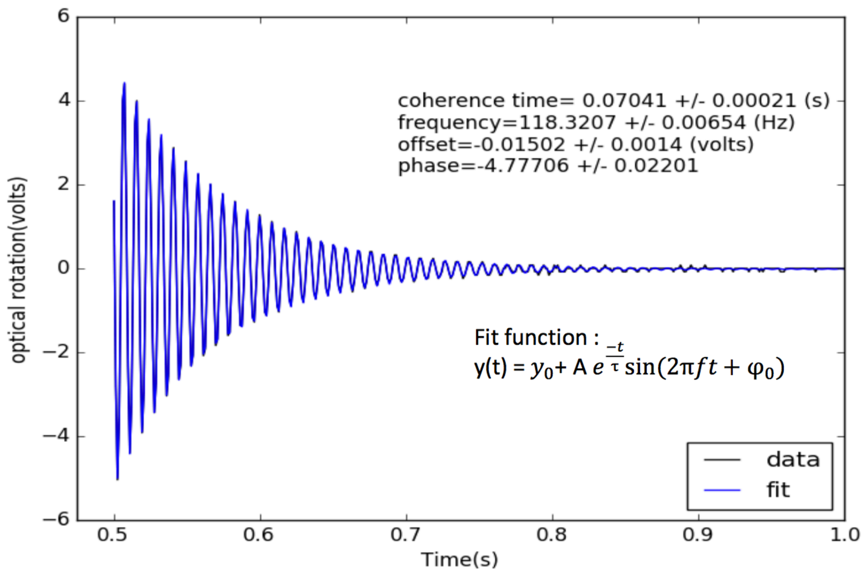




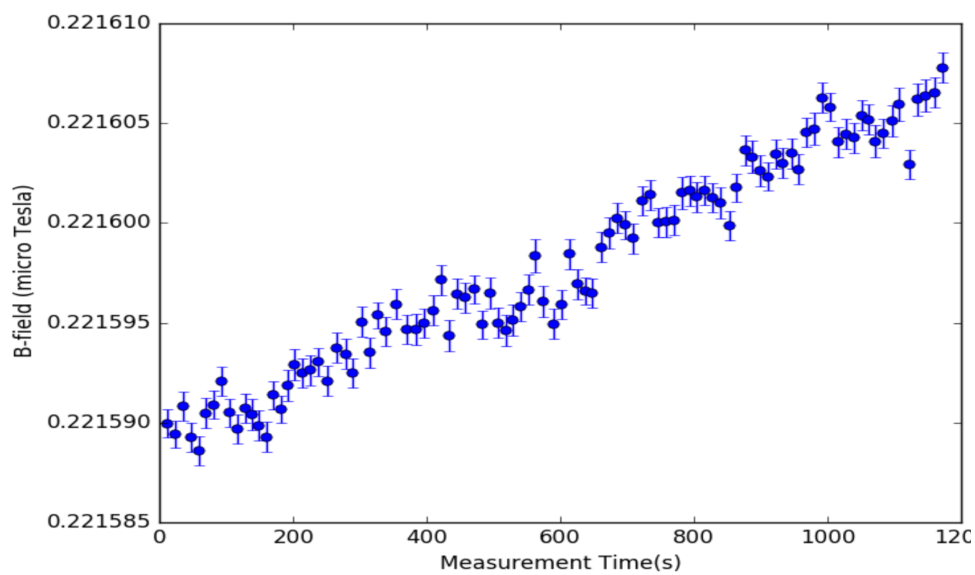
Work in progress!

Field Stability

Single FID at ~ 0.2uT



B(t) from repeat FIDs



Summary

- Designing, building, testing self-shielded B_0 coils
- Have ready design for compensation coils
- NMOR – for magnetometry and R&D tool

Thanks

Profs: R. Mammei, J. Martin

Students: J. Pu, R. Burrough, M. Anderson, T. Andalib, M. Das, M. Lang, C Loftson

Technicians: D. Ostapchuk

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