Magnetic shielding and source-mass characterization in the ARIADNE axion experiment

Microwave Cavities and Detectors for Axion Research at LLNL - Aug 21-24th, 2018

Chloe Lohmeyer

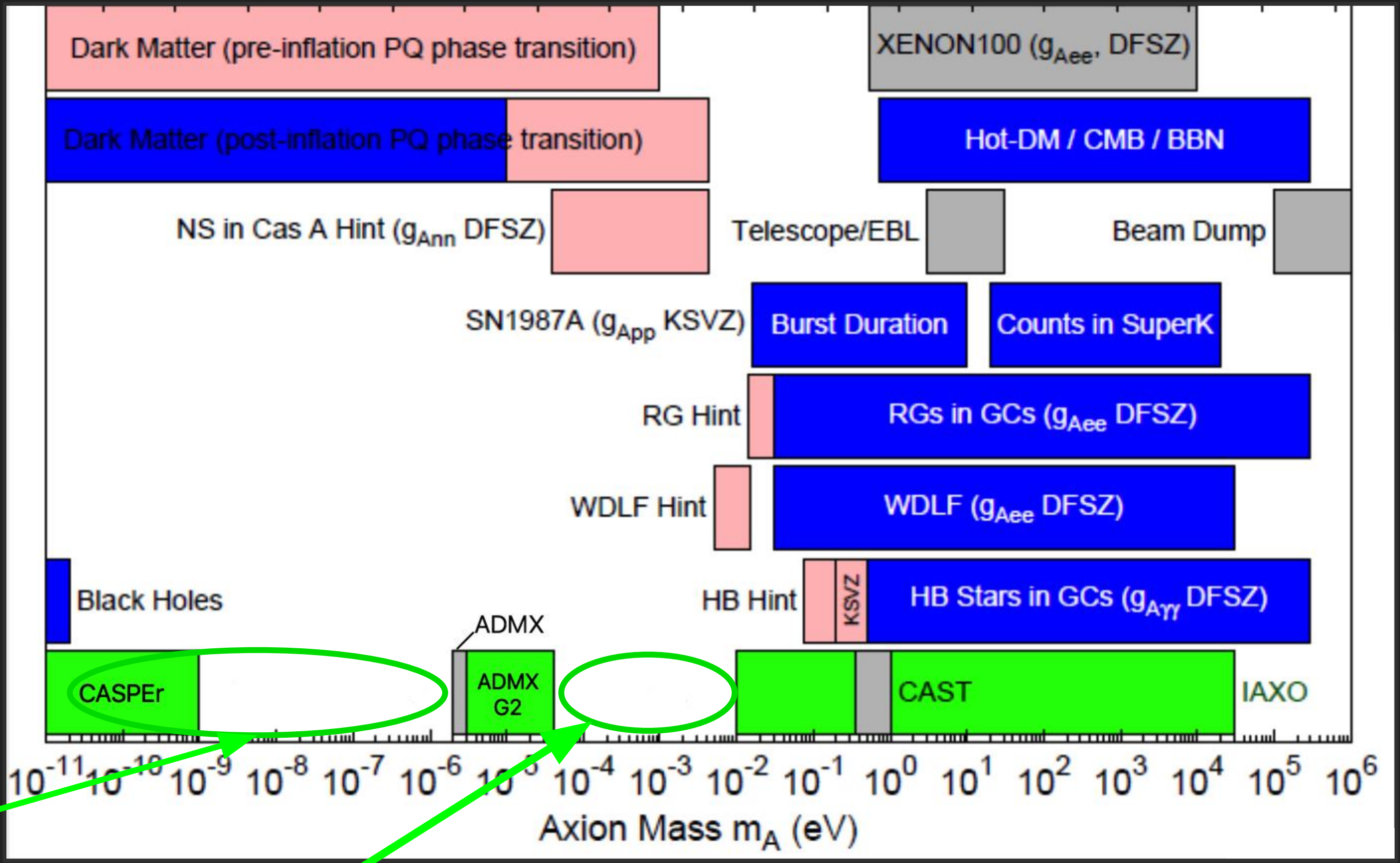
Axion Resonant InterAction DetectioN Experiment

Collaborators: Andrew Geraci (Northwestern), Asimina Arvanitaki (Perimeter), Aharon Kapitulnik (Stanford), Alan Fang (Stanford), Sam Mumford (Stanford), Josh Long (IU), Chen-Yu Liu (IU), Mike Snow (IU), Inbum Lee (IU), Justin Shortino (IU), Yannis Semertzidis (CAPP), Yun Shin (CAPP), Yong-Ho Lee (KRISS), Lutz Trahms (PTB), Allard Schnabel (PTB), Jens Voigt (PTB)

Grant No. PHY-1509176, 1510484, 1506508

Center for Fundamental Physics (CFP)

QCD Axion Parameter Space



DM Radio
LC Circuit
ABRACADABRA

ARIADNE

Adapted from http://pdg.lbl.gov/2015/reviews/rpp2015-rev-axions.pdf

Axion and ALP Searches

Source

Coupling

	Photons	Nucleons	Electrons
Dark Matter (Cosmic) axions	ADMX, HAYSTACK, DM Radio, LC Circuit, MADMAX, ABRACADABRA	CASPEr	QUAX
Solar axions	CAST IAXO		
Lab-produced axions	Light-shining-thru-walls (ALPS, ALPS-II)	ARIADNE	

Axion-exchange between nucleons

- Scalar Coupling $\propto \theta_{QCD}$

$$\mathcal{L} \supset \frac{\theta_{QCD}}{f_a} \mu \; a \bar{\psi} \psi$$

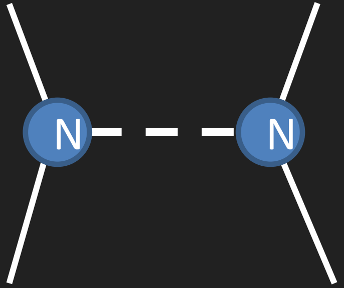
- Pseudoscalar coupling

$$\mathcal{L} \supset \frac{\partial_\mu a}{f_a} \bar{\psi} \gamma_\mu \gamma_5 \psi$$

In the non-relativistic limit:

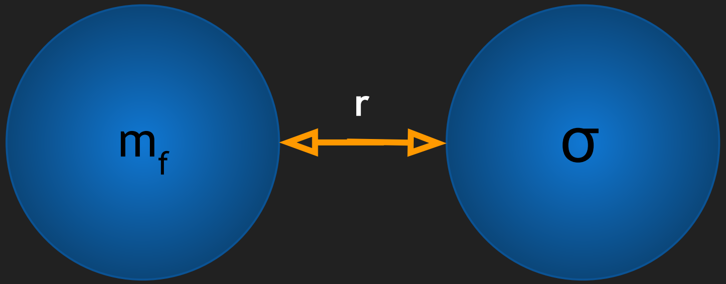
$$\mathcal{L} \supset \frac{\vec{\nabla} a}{f_a} \cdot \vec{\sigma}$$

Axion acts as a force mediator between nucleons



$(g_s^N)^2$	$g_s^N g_P^N$	$(g_p^N)^2$
Monopole-monopole	Monopole-dipole	Dipole-dipole

Spin-Dependent Forces



Monopole-Dipole Axion Exchange

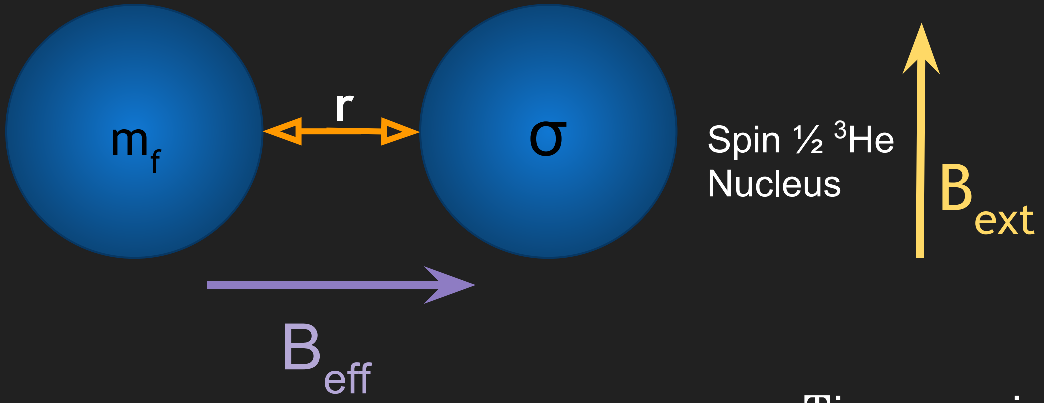
Fictitious magnetic field

$$U(r) = \frac{\hbar^2 g_s g_p}{8\pi m_f}\left(\frac{1}{r\lambda_a} + \frac{1}{r^2}\right)e^{-r/\lambda_a}(\hat{\sigma}\cdot\hat{r}) \equiv \mu \cdot B_{eff}$$

- Different from an ordinary magnetic field
- Does not couple to angular momentum
- Does not obey Maxwell's Equations
- Unaffected by magnetic shielding

A. Arvanitaki and A. Geraci, Phys. Rev. Lett. 113, 161801 (2014)

NMR for detection



$$U = \mu \cdot B_{\text{ext}}$$

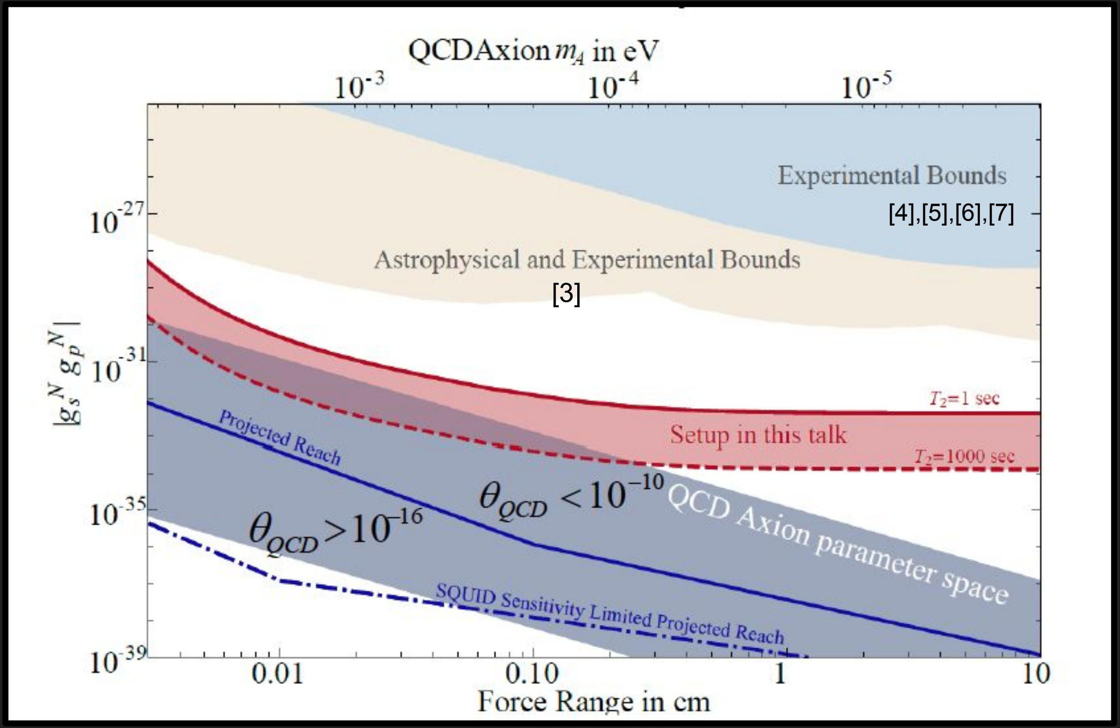
$$\omega = \frac{2\mu_N \cdot B_{\text{ext}}}{\hbar}$$

$$B_{eff} = B_{\perp}\cos(\omega t)$$

- Time varying B_{eff} drives spin precession
- This produces a transverse magnetization
- Magnetization can be detected using a SQUID

A. Arvanitaki and A. Geraci, Phys. Rev. Lett. 113, 161801 (2014)

Constraints and Sensitivity



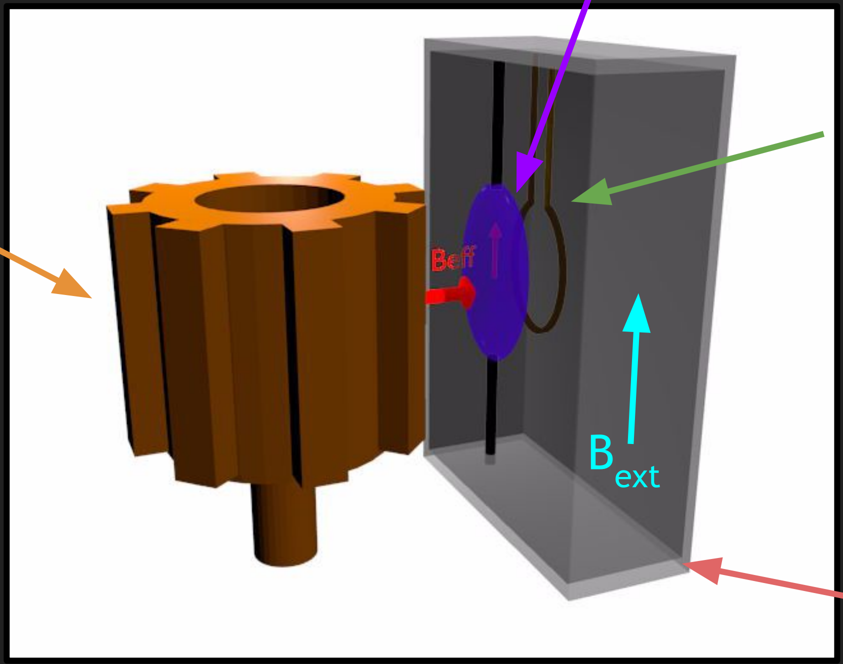
[3] G. Raffelt, Phys. Rev. D 86, 015001 (2012)] [4] G. Vasilakis, et. al, Phys. Rev. Lett. 103, 261801 (2009).
[5] K. Tullney,et. al. Phys. Rev. Lett. 111, 100801 (2013) **[6]** P.-H. Chu,et. al., Phys. Rev. D 87, 011105(R) (2013).
[7] M. Bulatowicz, et. al., Phys. Rev. Lett. 111, 102001 (2013).

Experimental Setup

Unpolarized tungsten source mass

Laser Polarized ^{3}He gas

SQUID pickup loop

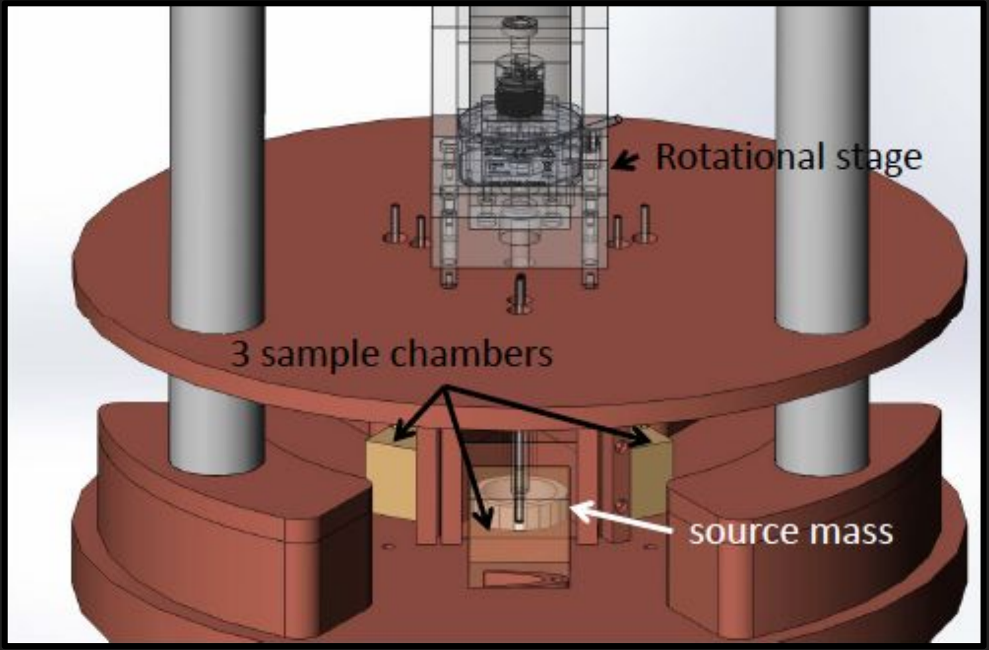


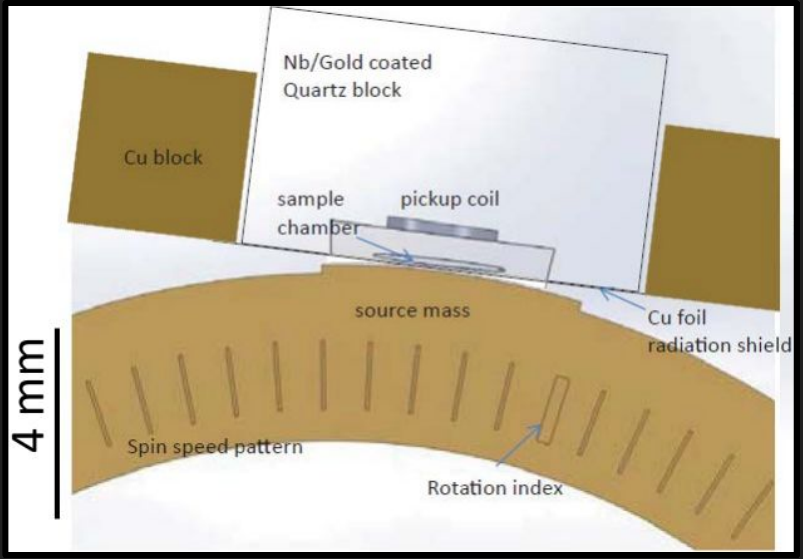
Superconducting Shielding

$$\omega = \frac{2\mu_N \cdot B_{\text{ext}}}{\hbar}$$

A. Arvanitaki and A. Geraci, Phys. Rev. Lett. 113, 161801 (2014)

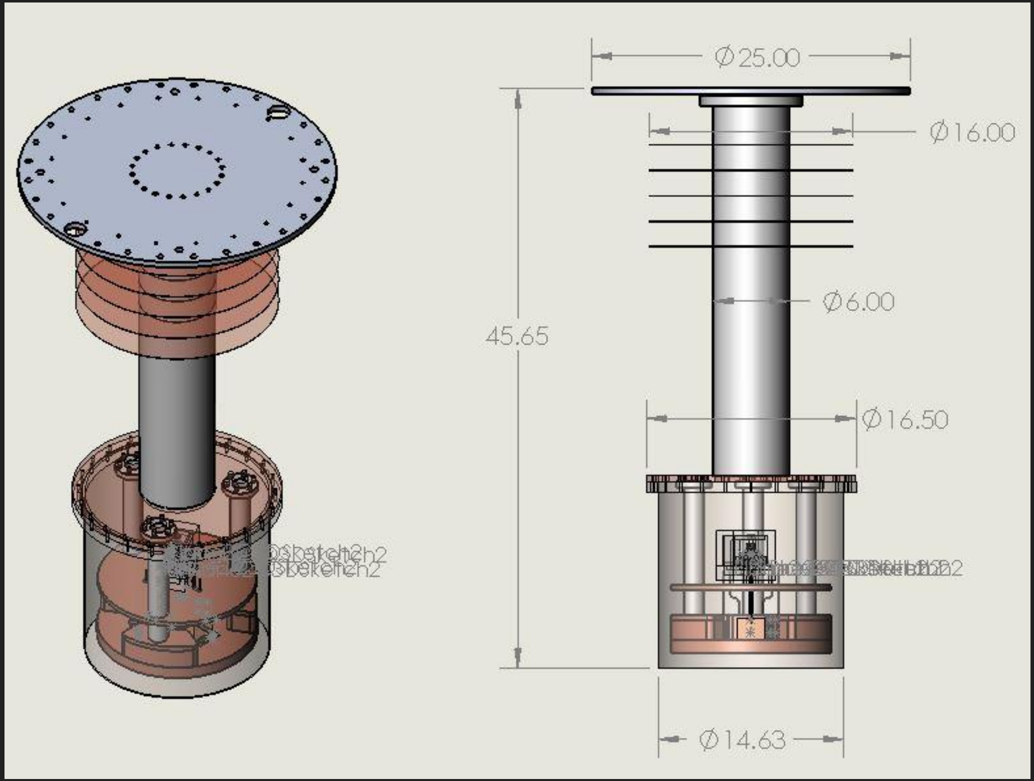
Experimental Parameters

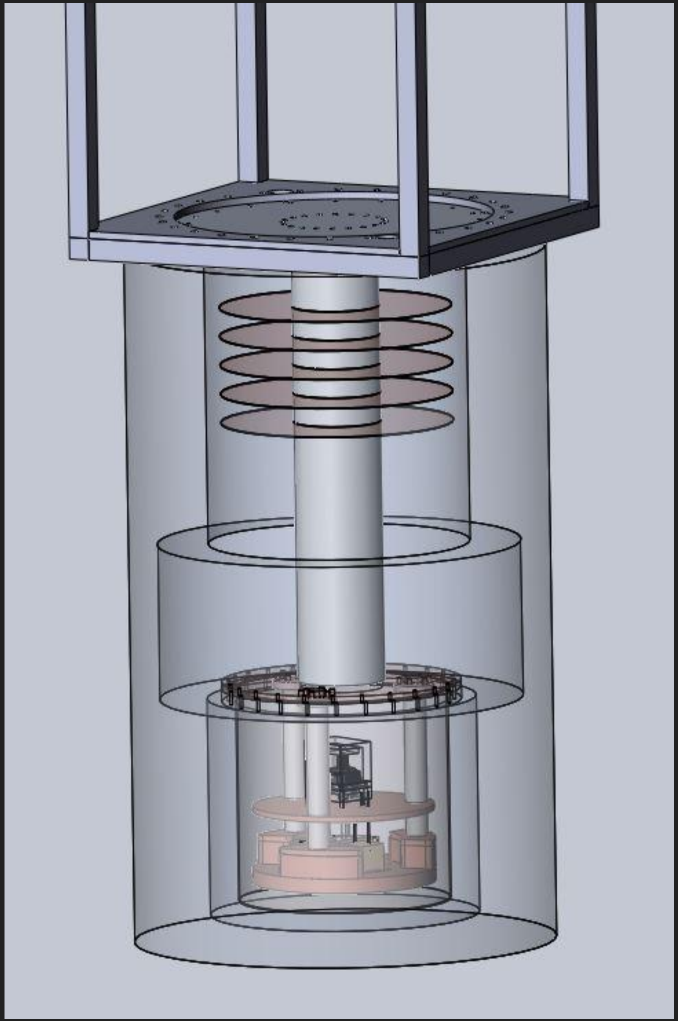




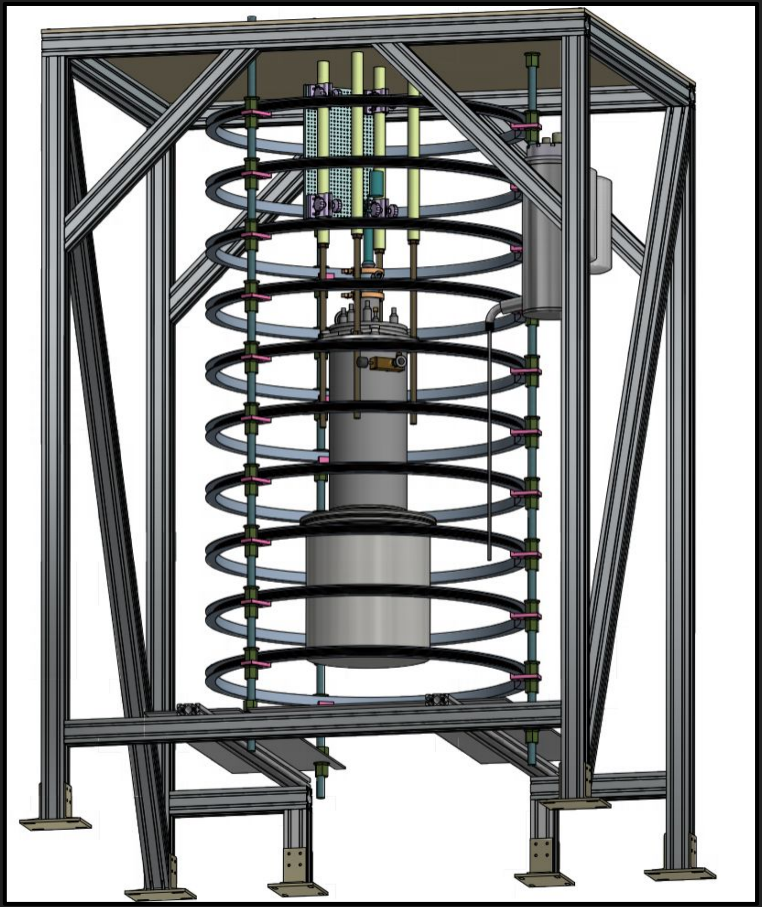
11 segments
100 Hz nuclear spin precession frequency
2 x 10^{21} / cc ^{3}He density
10 mm x 3 mm x 150 μm volume
Separation 200 μm
Tungsten source mass (high nucleon density)

Cryostat Design





IU Test Cryostat



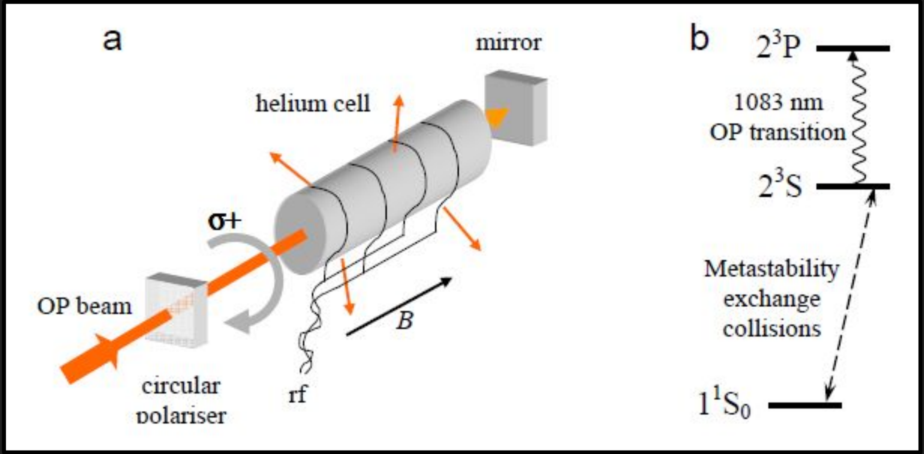
Hyperpolarized ^{3}He

- Ordinary magnetic fields cannot be used to reach near unity polarization

$$\exp[-\mu_N B / k_B T]$$

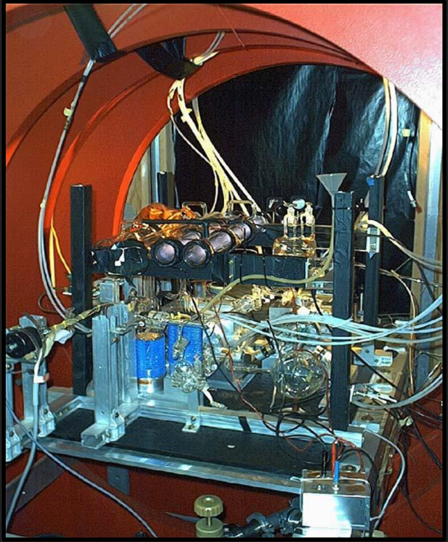
Optical pumping techniques

- Metastability exchange optical pumping



M Batz, P-J Nacher and G Tastevin, Journal of Physics: Conference Series **294** (2011) 012002

Indiana U. MEOP apparatus



Rev. Sci. Instrum. 76, 053503 (2005)

Experimental Challenges

Systematic Effect/Noise source	Background Level	Notes
Magnetic gradients	3×10^{-6} T/m	Limits T_2 to ~ 100 s
		Possible to improve w/shield geometry
Vibration of mass	10^{-22} T	For 10 μm mass wobble at ω_{rot}
External vibrations	5×10^{-20} T/$\sqrt{\mathrm{Hz}}$	For 1 μm sample vibration (100 Hz)
Patch Effect	$10^{-21}(\frac{V_{\mathrm{patch}}}{0.1\mathrm{V}})^2$ T	Can reduce with V applied to Cu foil
Flux noise in squid loop	2×10^{-20} T/$\sqrt{\mathrm{Hz}}$	Assuming $1\mu\Phi_0/\sqrt{\mathrm{Hz}}$
Trapped flux noise in shield	$7 \times 10^{-20} \frac{\mathrm{T}}{\sqrt{\mathrm{Hz}}}$	Assuming 10 cm^{-2} flux density
Johnson noise	$10^{-20}(\frac{10^8}{f})\mathrm{T}/\sqrt{\mathrm{Hz}}$	f is SC shield factor (100 Hz)
Barnett Effect	$10^{-22}(\frac{10^8}{f})$ T	Can be used for calibration above 10 K
Magnetic Impurities in Mass	$10^{-25} - 10^{-17}(\frac{\eta}{1\mathrm{ppm}})(\frac{10^8}{f})$ T	η is impurity fraction (see text)
Mass Magnetic Susceptibility	$10^{-22}(\frac{10^8}{f})$ T	Assuming background field is 10^{-10} T
		Background field can be larger if $f > 10^8$

Table 1: Table of estimated systematic error and noise sources, as discussed in the text. The projected sensitivity of the device is $3 \times 10^{-19}(\frac{1000\mathrm{s}}{T_2})^{1/2}\mathrm{T}/\sqrt{\mathrm{Hz}}$

A. Geraci et al., arXiv.1710.05413. Proceedings of the 2nd Axion Cavity and Detector Workshop (2017).

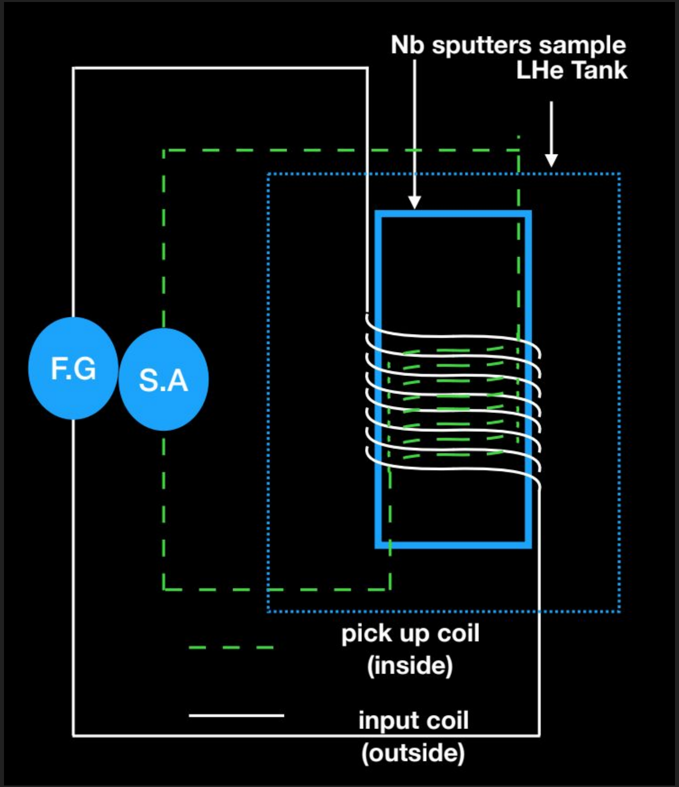
Thin Film Superconducting Shielding

- Shield out ordinary magnetic noise
- Sputtered Niobium on quartz tubes/different geometries for tests
- Tests of adhesion, Tc, shielding factor done by CAPP and Stanford collaborators

Younggeun Kim, Dongok Kim, Yun Chang Shin, Andrei Matlashov CAPP/IBS

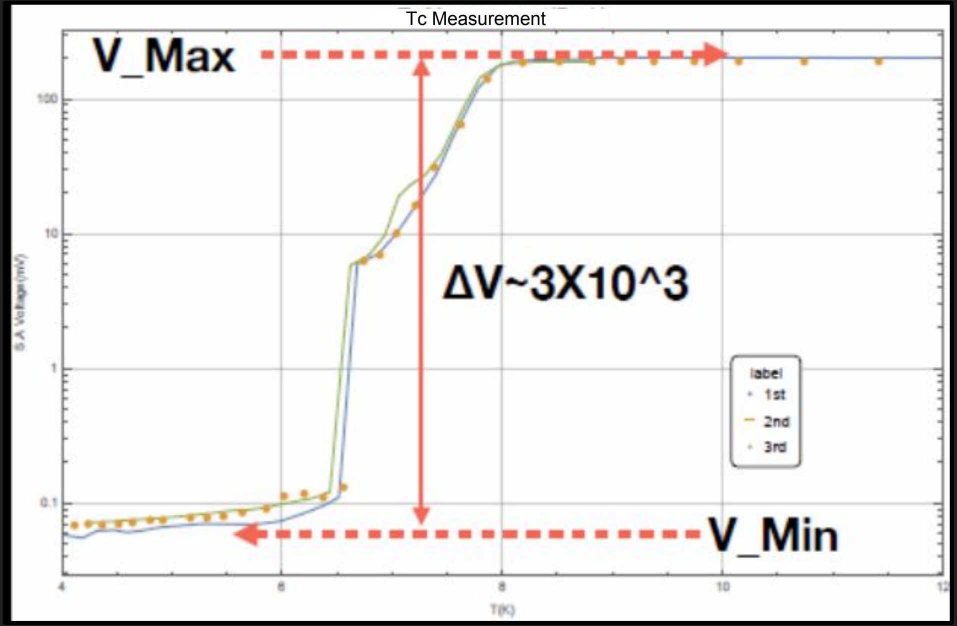
Thin Film Superconducting Shielding

- Measuring mutual inductance between inner and outer coils
- Place sample with coil in the liquid He dewar
- Found position where spectrum analyzer drops (where B field can no longer penetrate into the superconductor)



Younggeun Kim, Dongok Kim, Yun Chang Shin, Andrei Matlashov CAPP/IBS

Thin Film Superconducting Shielding



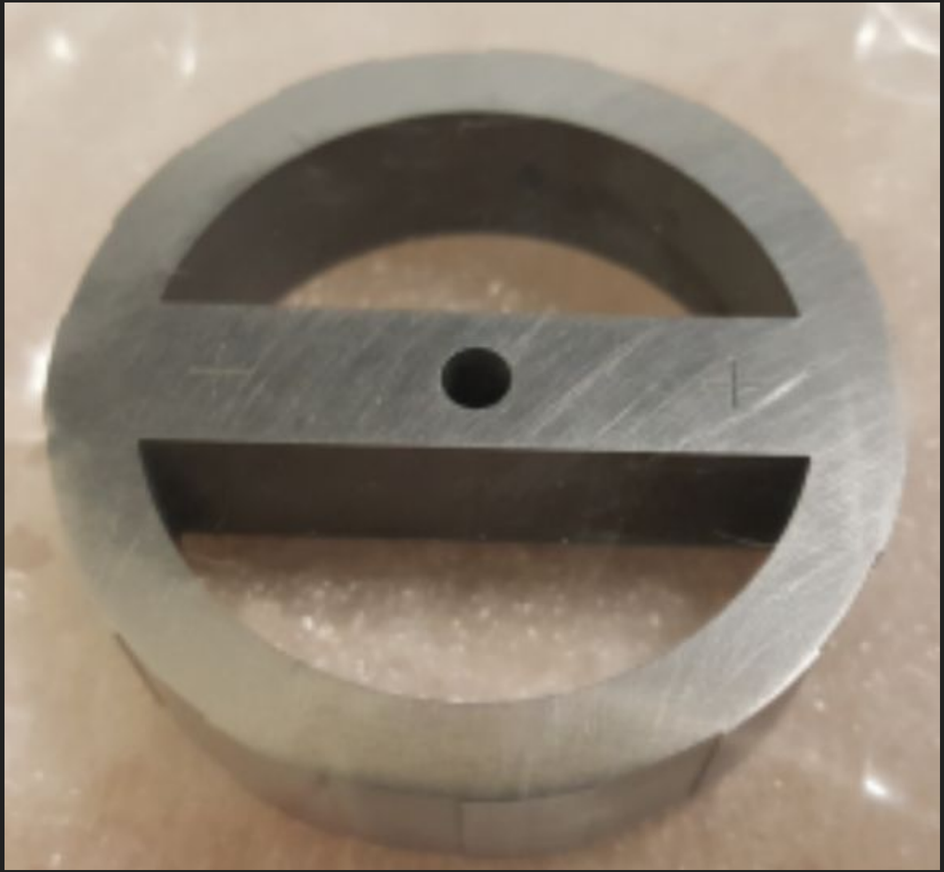
- With thin films between 250 nm to 1 micron, 7.25 < Tc < 7.5K

- Collaborators at Stanford will also be working towards optimizing Tc

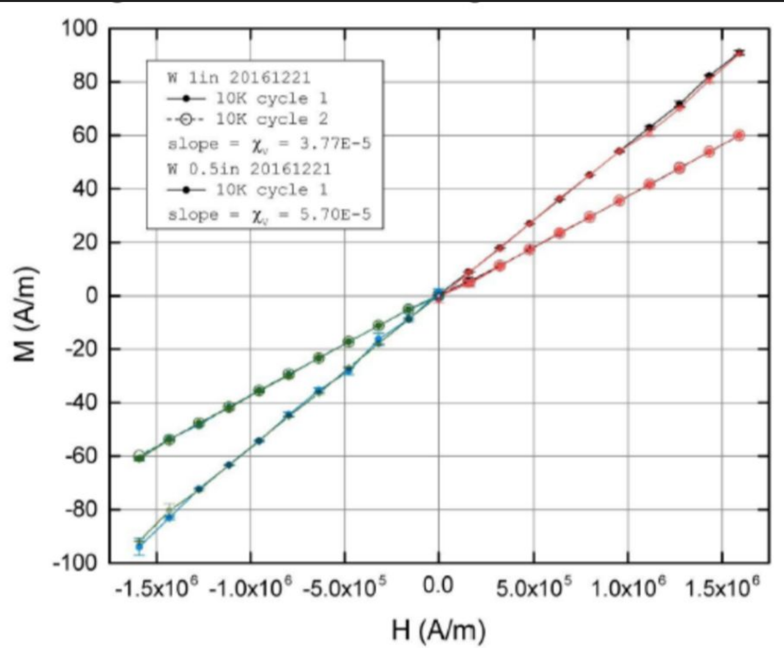
Younggeun Kim, Dongok Kim, Yun Chang Shin, Andrei Matlashov CAPP/IBS

Source Mass Prototype

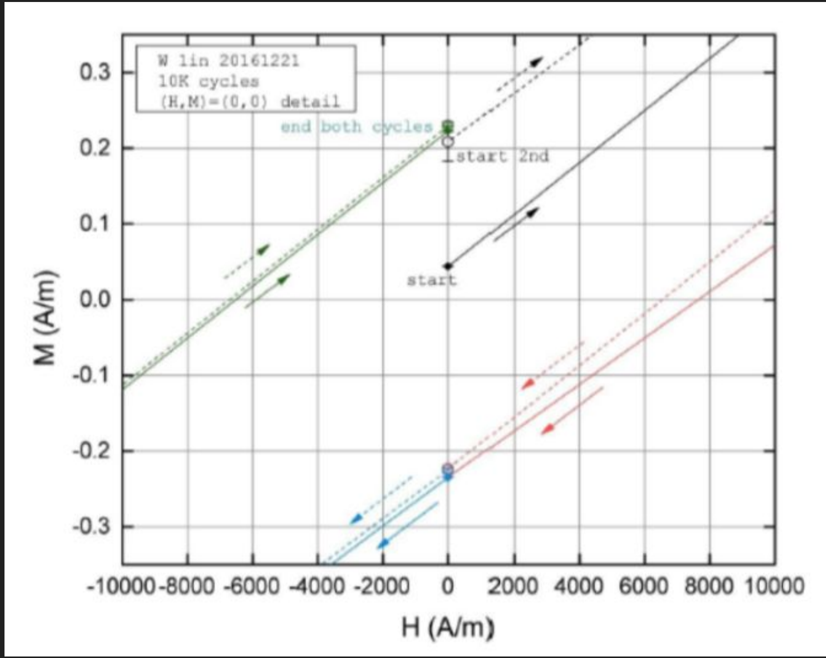
- Material: tungsten
- 11 segments
- 3.8 cm in diameter



Source Mass Characterization - Magnetic Impurities



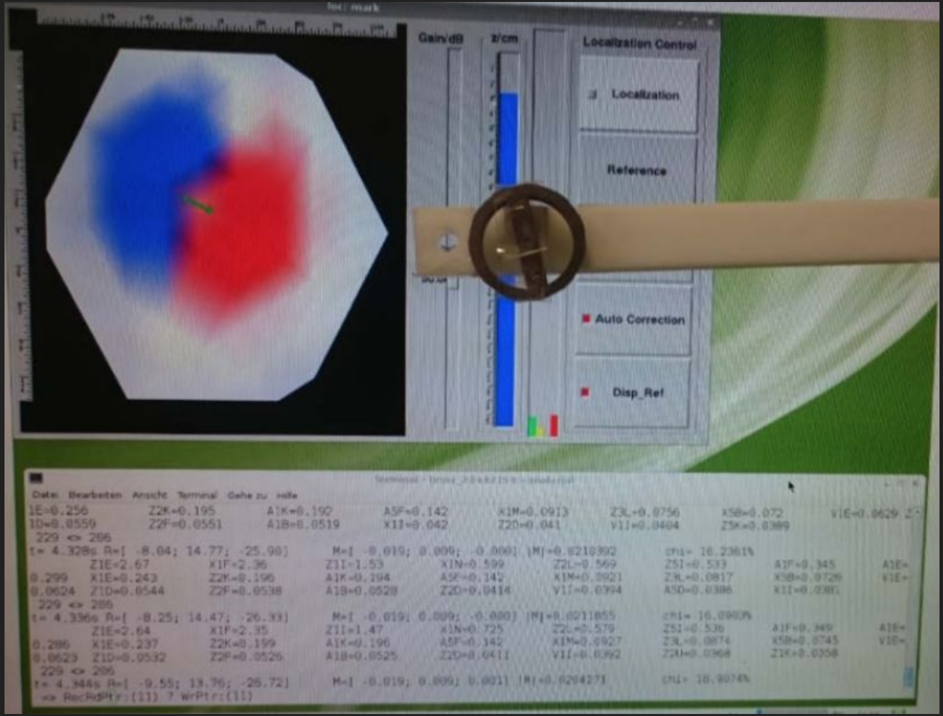
Magnetic impurity testing in Tungsten
using commercial SQUID magnetometer -- Indiana U



Magnetic impurities below 0.4 ppm

Source Mass Characterization

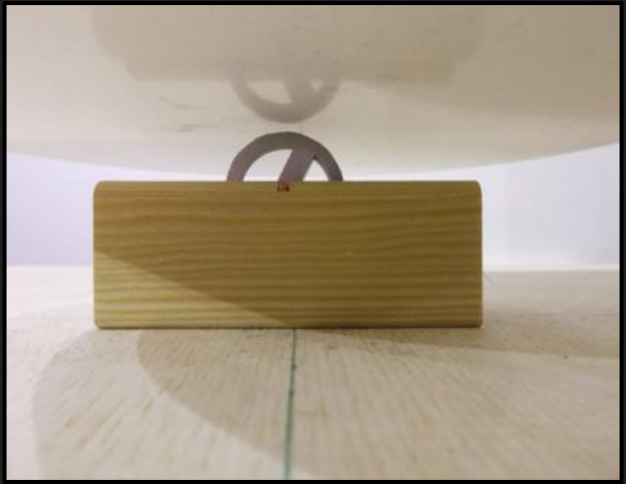
- Magnetized the wheel with a 30 mT magnet
- Wheel was brought under multichannel SQUID device in shielded room
- After degaussing, the magnetic moment is reduced by one order of magnitude to about 2 pT
- In addition, the wheel generates Johnson noise of some 1-1.5 pT (peak to peak)

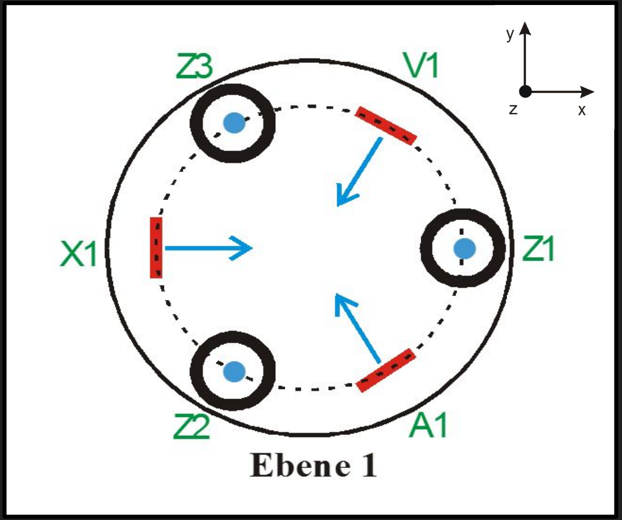


Lutz Trahms (PTB)

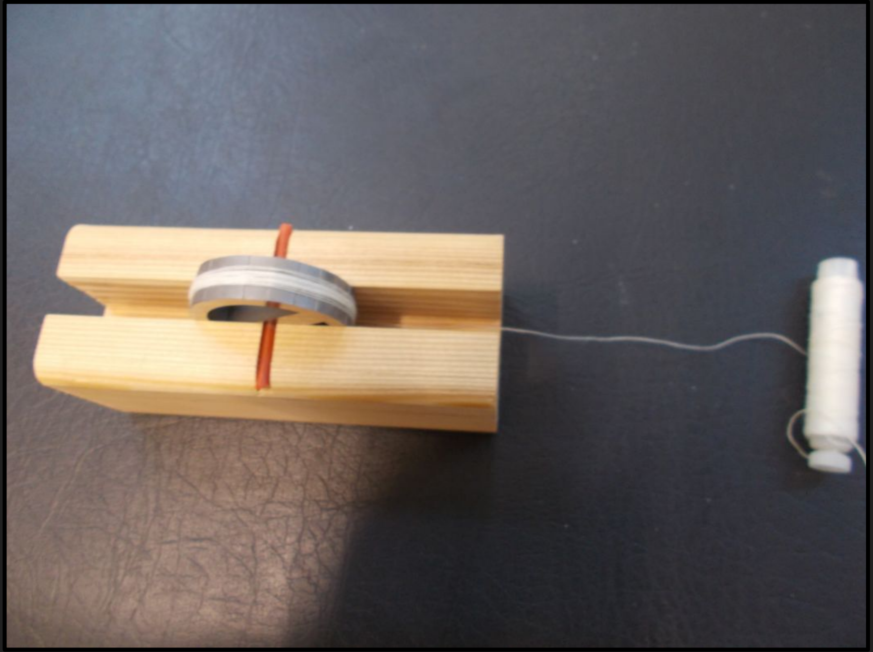
Source Mass Characterization

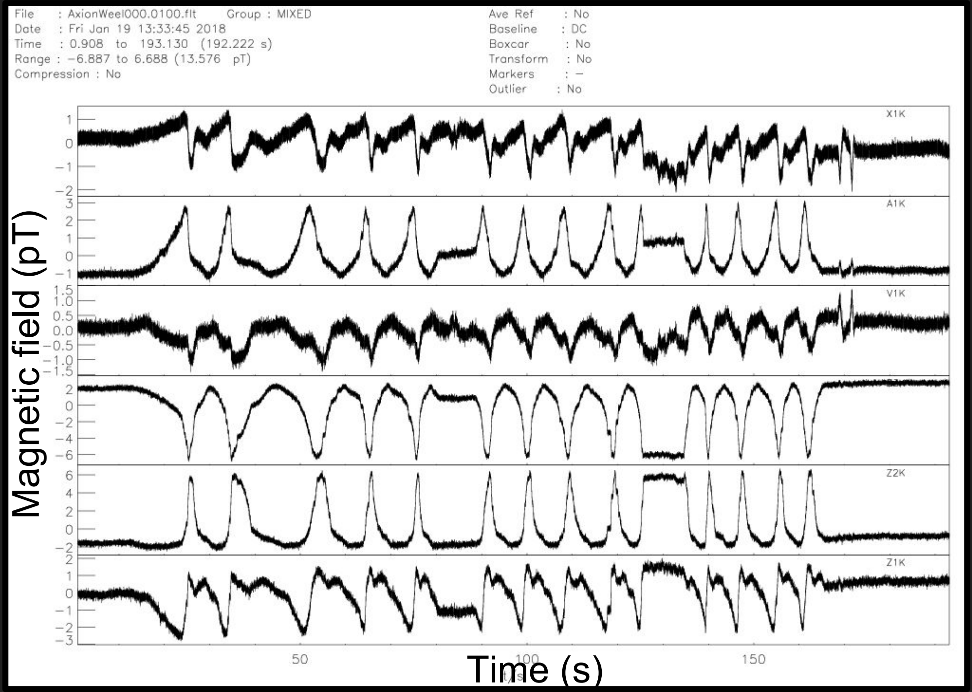
- Lowest measurement plane is shown here.
- Radius of the dotted circle is 16.667 mm.
- Wheel was adjusted in X direction and it was spinning around the Y-axis.
- All recordings were done with 250 Hz sampling rate.





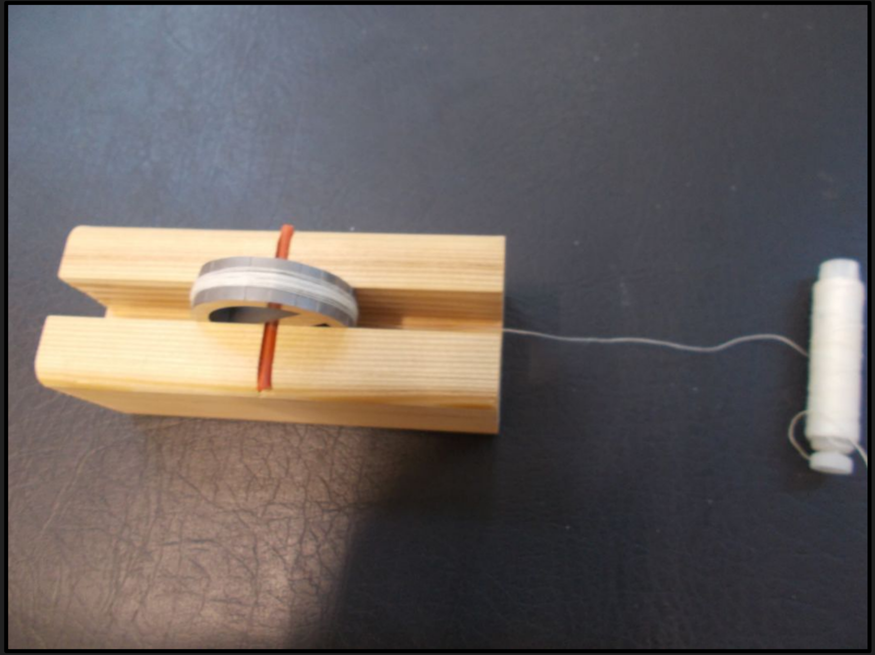
Source Mass Characterization - Before Degaussing

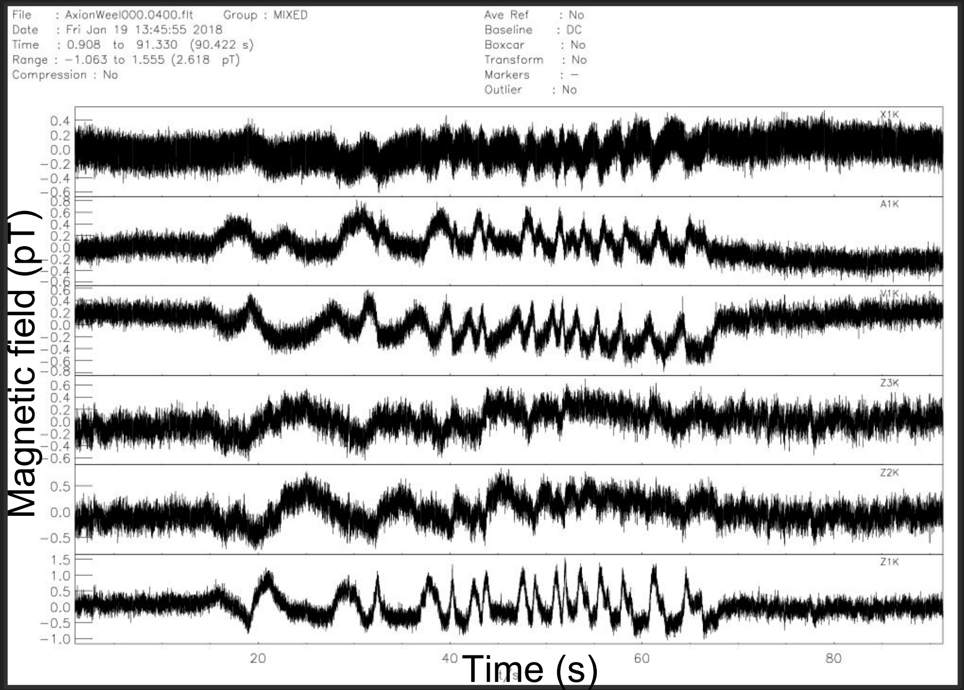




Lutz Trahms (PTB)

Source Mass Characterization - After Degaussing



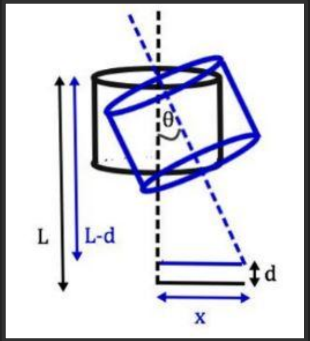


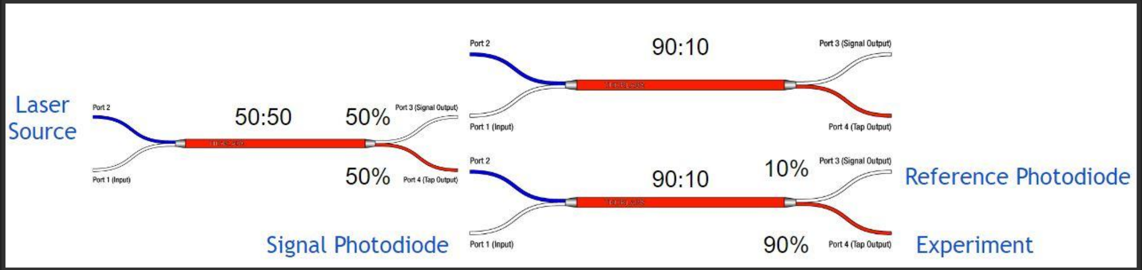
Rotated between 0.25Hz to 0.475Hz

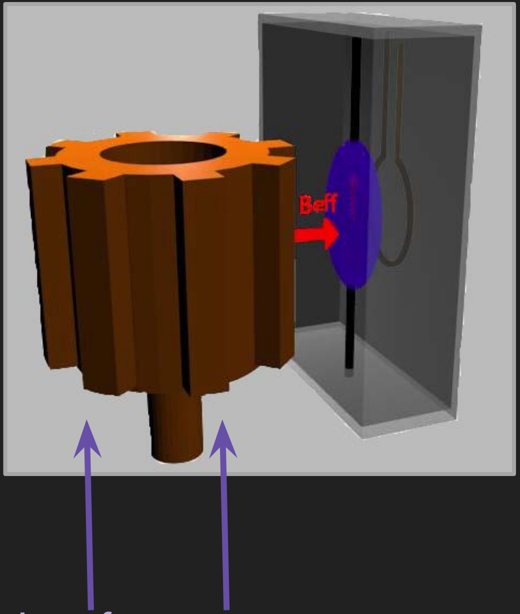
Lutz Trahms (PTB)

Rotational Stability

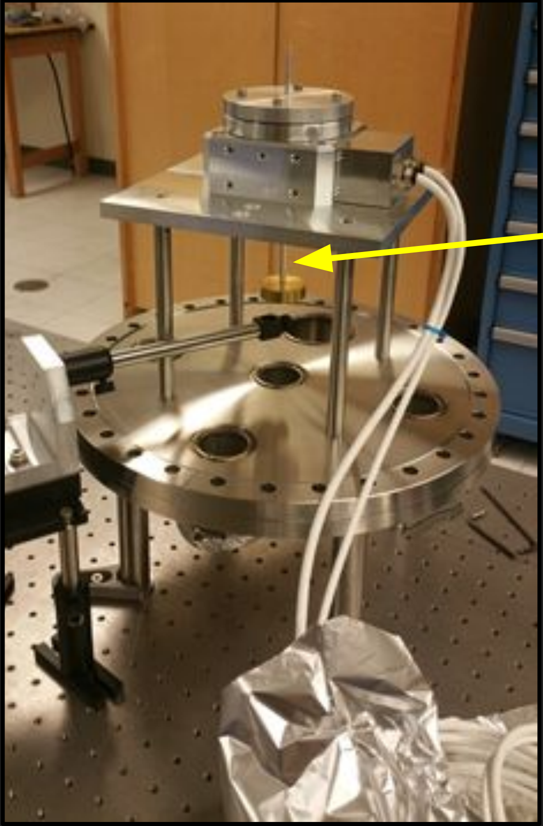
- Two interferometers pointed at bottom of sprocket
- Distance “d” is found
- Thus, wobble distance “x” can be found using geometry
- Distance Sensitivity 19 pm/√Hz

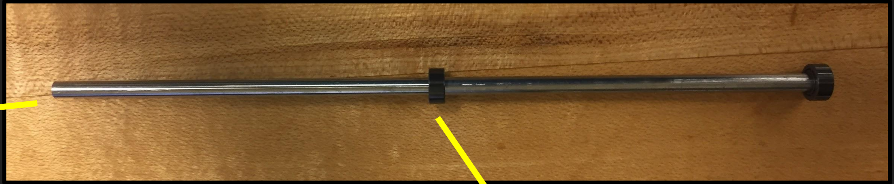






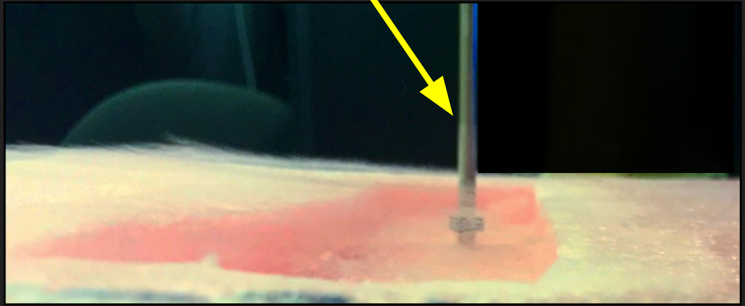
Test Mass Assembly





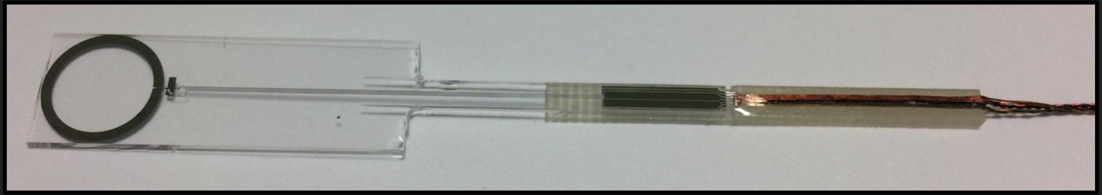
Rod details

Material: Ti6Al4V
Diameter: 5 ± .01mm
Length: 7.5 ± .1”
Ovality: < .0004"
Runout: < .0005"

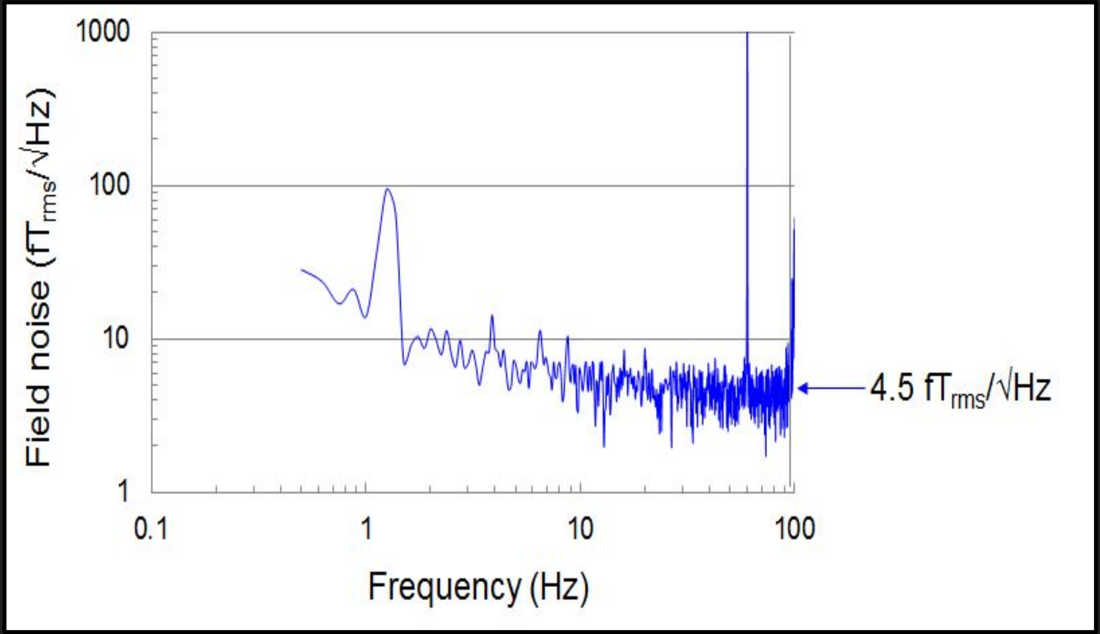


Original runout .0005" reduced to .0003" after bearing attachment

SQUID Development



Custom fabricated SQUID on quartz



Yong-Ho Lee (KRISS)

Field Noise from SQUID measured inside a magnetically shielded room

Future Plans

- Rotational stability testing (Northwestern)
- Improvements to thin film adhesion and Tc (CAPP/Stanford)
- Laser polarized 3He system tests (IU)
- 3He sample spheroidal cavity (Stanford)
- Cryostat building/assembly (Northwestern)
- Continuation of magnetic impurity testing (IU/PTB)
- Integration of SQUID system (KRISS)

Acknowledgements

Group Members (left to right): Chloe Lohmeyer, Andrew Geraci, Chethn Galla, Evan Weisman, Eduardo Alejandro, Cris Montoya

This research is supported by the National Science Foundation
(Grant No. PHY-1509176, 1510484, 1506508).

Questions

Extra Slides

Superconducting Magnetic Shielding

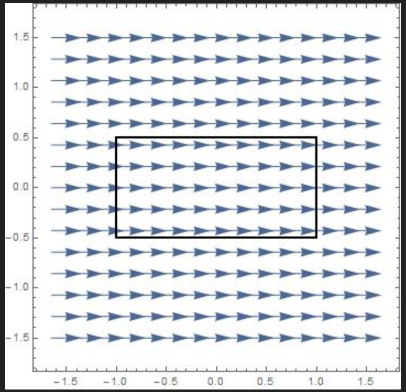
⟶ Essential to avoid Johnson noise

Meissner Effect

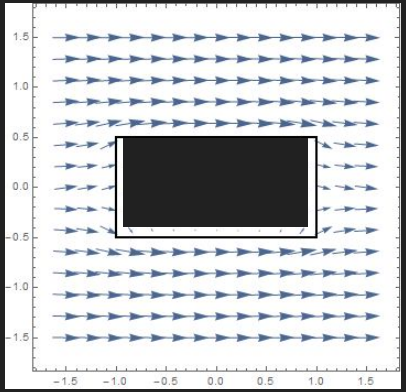
- No magnetic flux across superconducting boundary

Method of Images

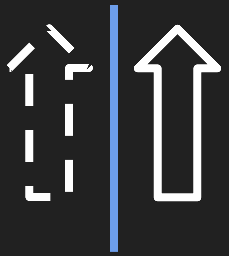
- Make “image currents” mirrored across the superconducting boundary



$T > T_c$



$T < T_c$

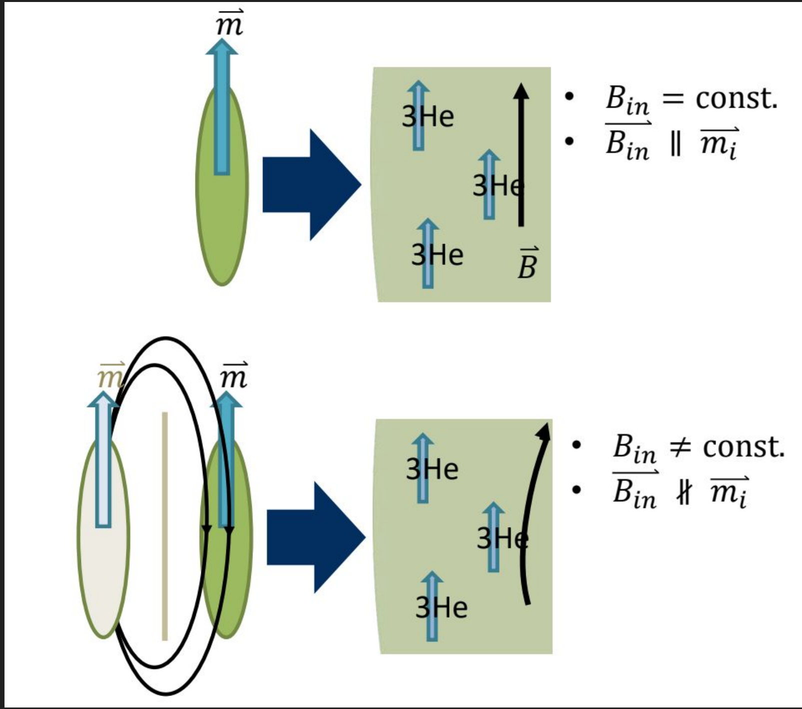


Dipole with image

The Problem of Unwanted Images

- ARIADNE uses magnetized spheroid
  - Constant interior field
- Magnetic shielding introduces "image spheroid"
  Interior field varies

$\longrightarrow$ variations in nuclear Larmor frequency



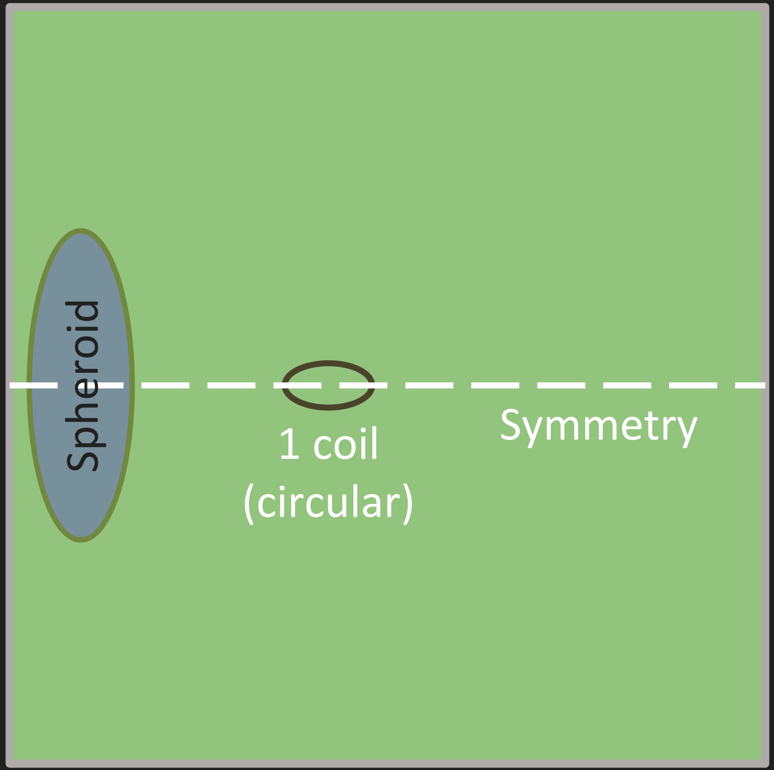
$\vec{B}$

$\vec{B}$

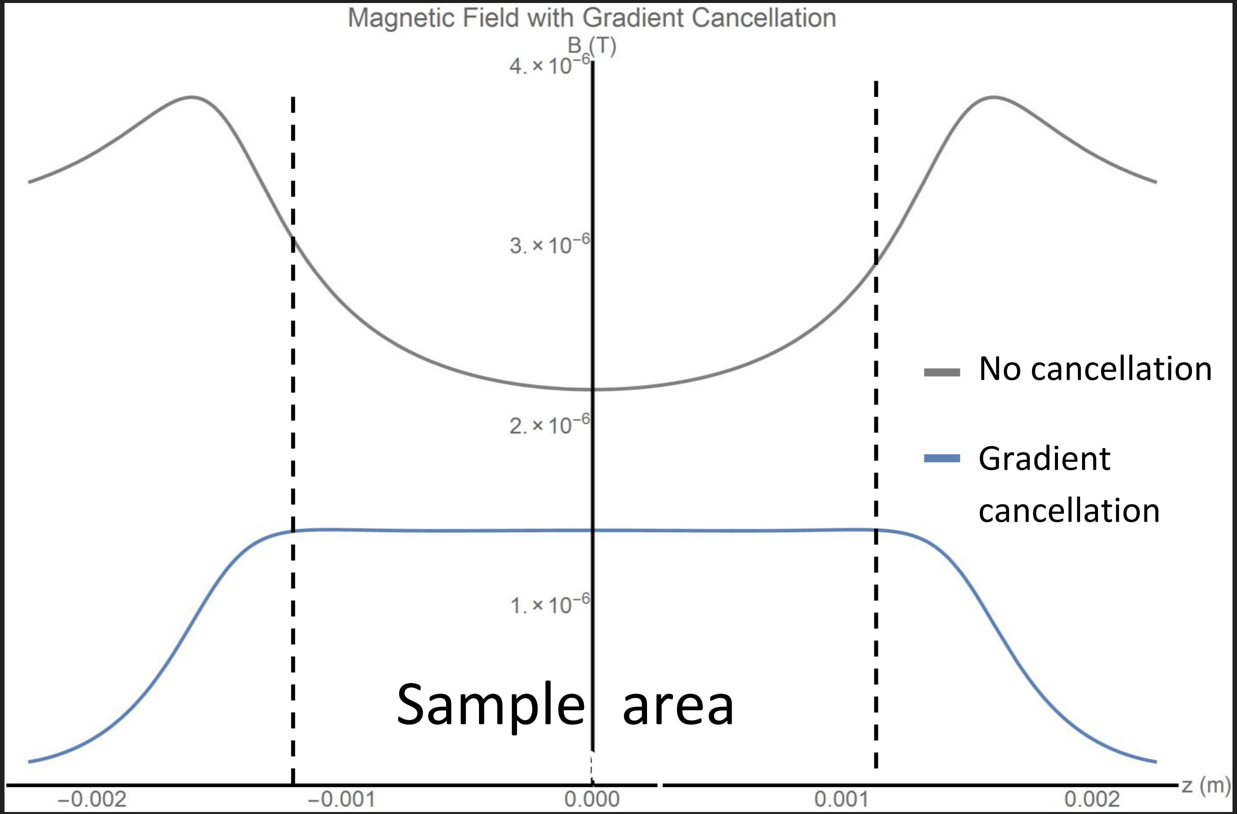
But want to drive entire sample on resonance

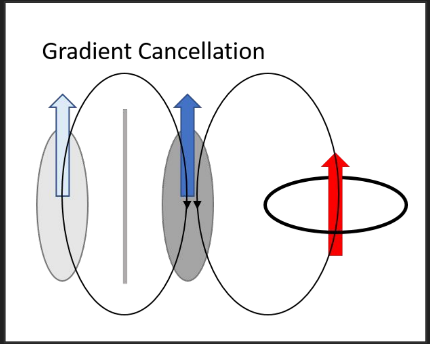
Flattening Solution

- 1 coil – simple configuration
- Expected field from spheroid ~1 μT
    - I on the 0.1 – 1 A range



Gradient Cancellation





98 times flatter

$I = 1.6$ A

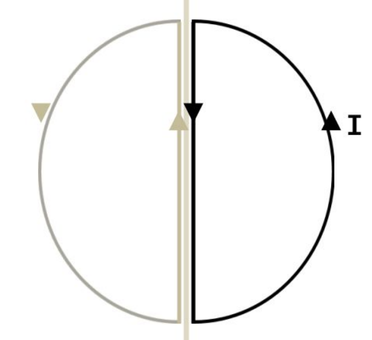
$s_{Frac} = 0.17\%$

enabling T_2 of ~100 s

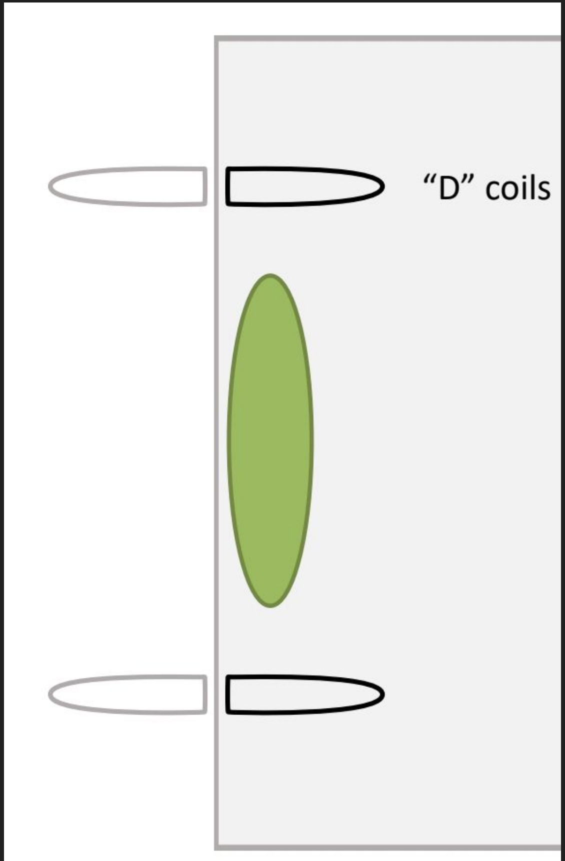
Tuning Solution – "D" Coils

- Tune field with Helmholtz coils
  - Helmholtz field only flat near the center
  - Geometry restrictions prevent the spheroid from being centered in traditional Helmholtz coils

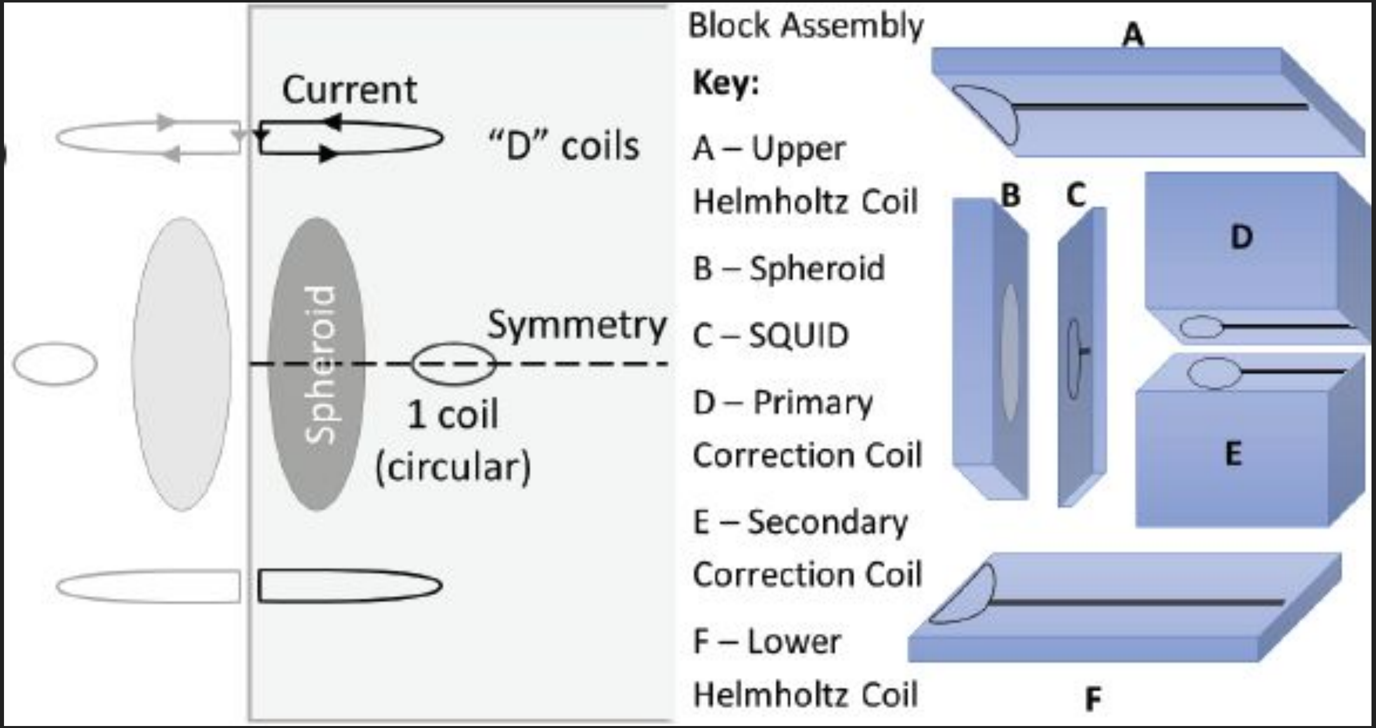
- "D" coils look like Helmholtz coils when their images are included
- Inner straight-line currents cancel
- Outer currents do not



One "D" coil and image (bird's eye view)

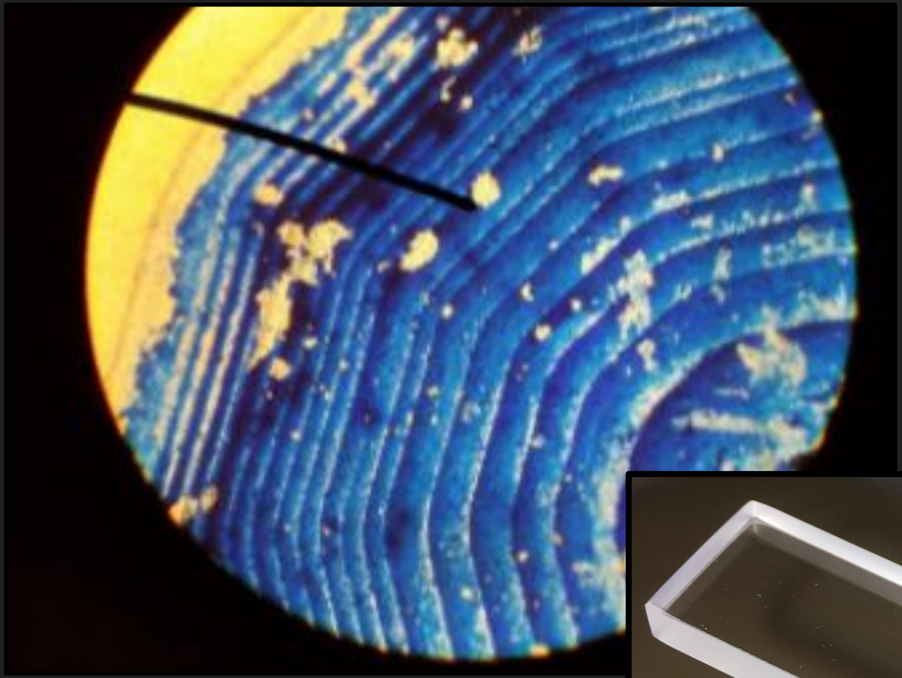


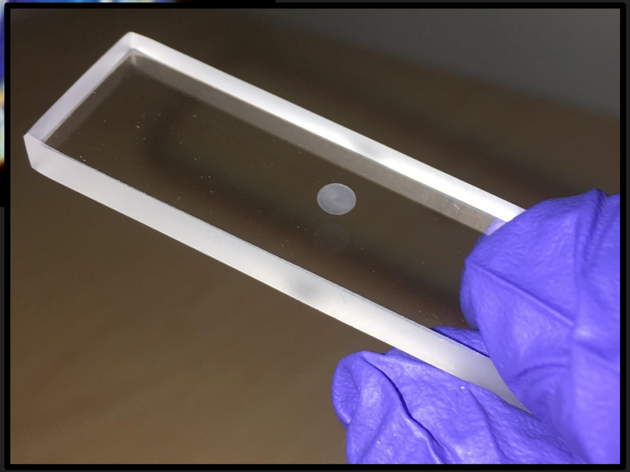
Quartz block assembly



Fabrication/polishing tests in process

Spheroidal Cavity for 3He





Rotational Stability