Design and Performance of a Superconducting RF Neutron Spin Flipper

For application to Neutron Resonance Spin Echo (NRSE) scattering techniques

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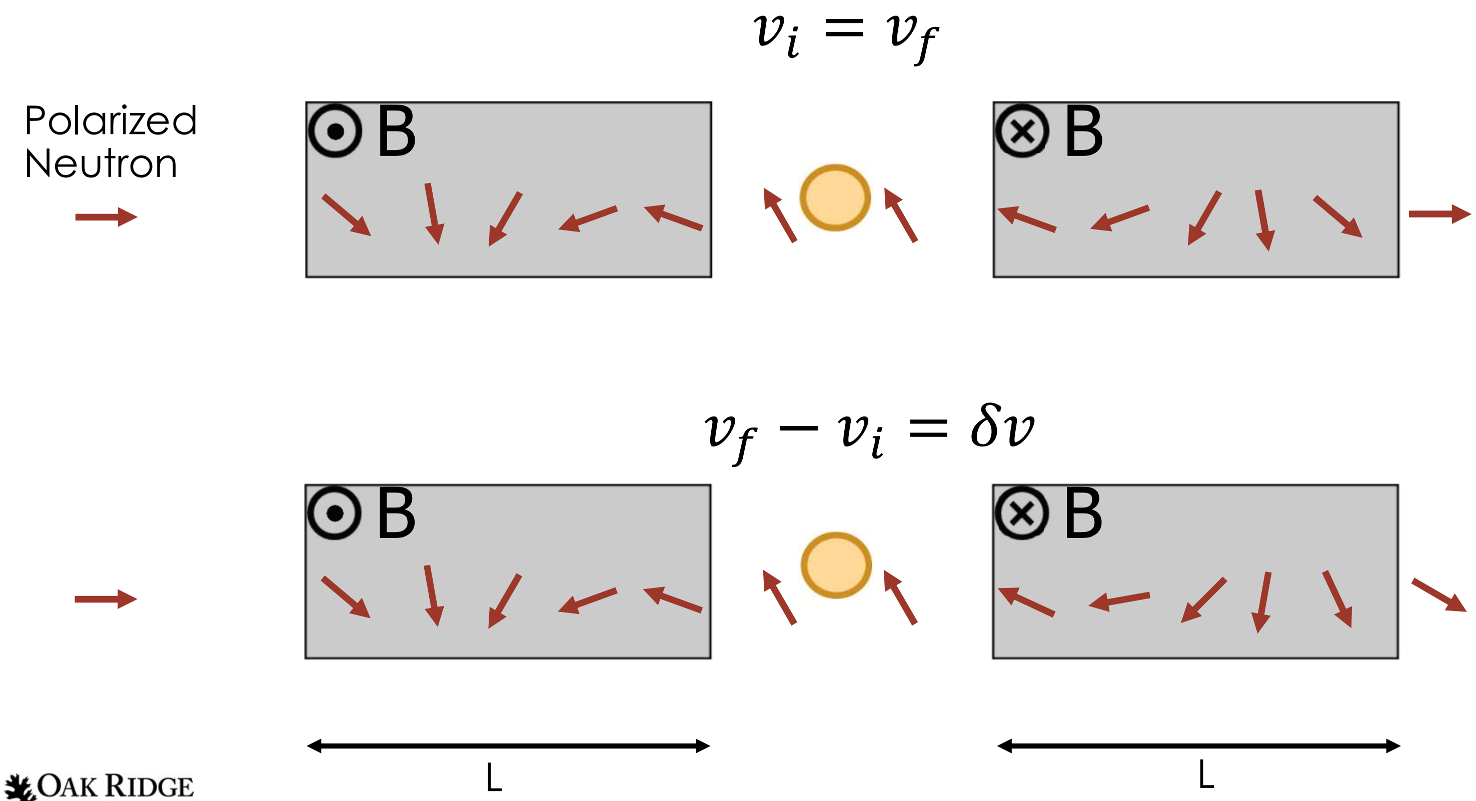
ORNL is managed by UT-Battelle, LLC for the US Department of Energy

Outline

- Neutron resonance spin echo motivation
- Adiabatic RF spin flip method
- Device design
- Spin flip efficiency results
- Measurement of self-cancellation of Larmor phase aberrations

Neutron Spin Echo (NSE): Using Larmor precession to encode energy in spin phase

Spin phase: $\phi = \gamma \int B\, dt$



$$v_i = v_f$$

$$v_f - v_i = \delta v$$

Use a spin analyzer to measure the phase

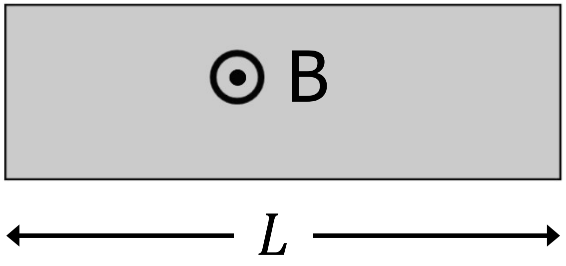
$$I \propto \cos(\Delta E\ \tau /\ \hbar)$$

Energy scale set by spin echo time:

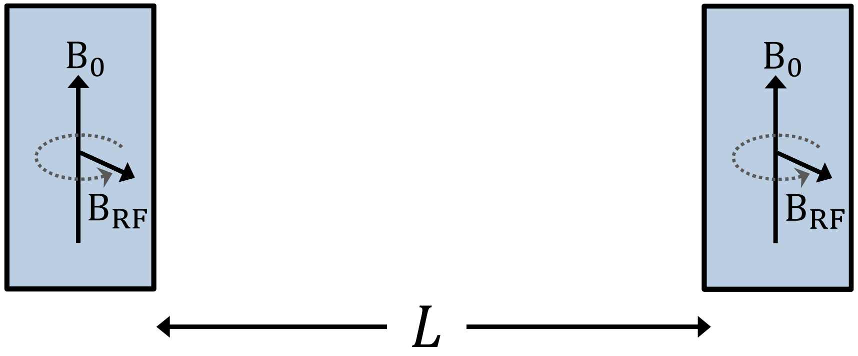
$$\tau = \frac{m^2 \gamma B\ L\ \lambda^3}{2\pi h^2}$$

Neutron Resonance Spin Echo (NRSE)

Replace long, DC field…



with separated RF spin flippers



Advantages to NRSE:

1. Factor of 2 increase in resolution for same length spectrometer and same static field
2. Can stack RF flippers to multiply the spin echo time (Bootstrap method)
3. Can vary the spin echo time by changing the spacing between the RF flippers
4. Stability is based on function generator frequency rather than DC supply
5. Can be used in Modulated Intensity with Zero Effort (MIEZE), allowing magnetic samples and more complicated sample environments

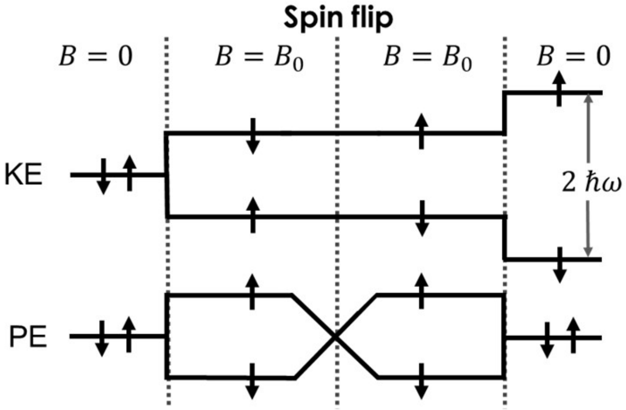
How NRSE works

Static magnetic field: $\vec{B}_0$ ↑

Incident neutron polarized perpendicular: $\vec{P}$ →

Can write spin as superposition: $\Psi = \frac{1}{\sqrt{2}}\left[\psi_\uparrow + \psi_\downarrow\right]$ ↑ $\psi_\uparrow = \begin{pmatrix}1\\0\end{pmatrix}$ ↓ $\psi_\downarrow = \begin{pmatrix}0\\1\end{pmatrix}$

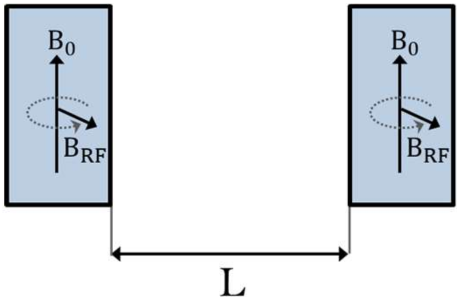
A spin flip imparts an energy difference between the spin states



Time-dependence of spin states:

$$\psi_{\uparrow(\downarrow)} \propto e^{iE_{\uparrow(\downarrow)}t/\hbar} \qquad \vec{P}(t) = \cos(\phi(t))$$

A second spin flip will undo the energy splitting



Velocity is encoded in the phase:

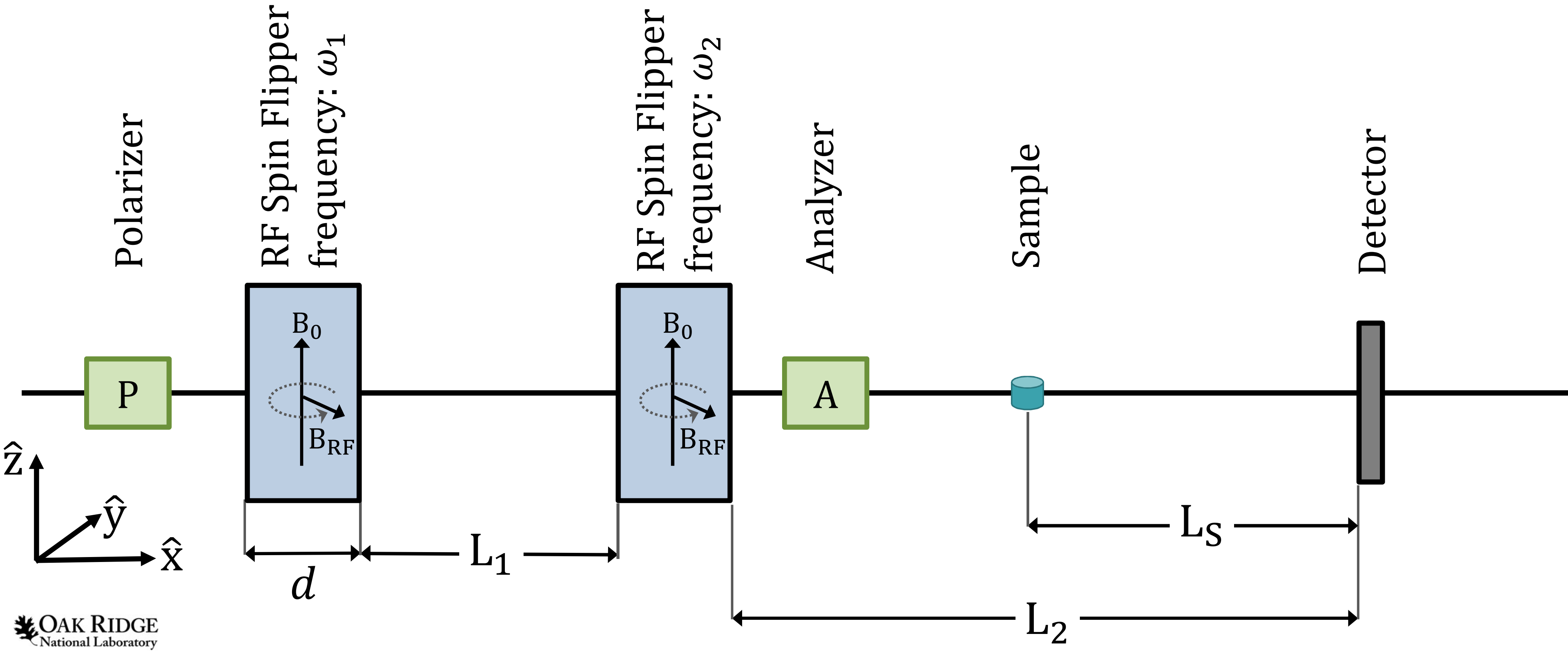
$$\phi = 2\omega L/v + \phi_f$$

Where ω is the frequency of the spin flipper, v the neutron velocity, and ϕ_f a phase accumulated inside the spin flipper

MIEZE

All spin manipulation performed before sample.

Produces an intensity modulation in time measured at the detector: $I(t) = I_0 + \mathrm{I_A}\cos(2\Delta\omega t + \phi_0)$



MIEZE Measurement

Tune frequencies based on RF flipper distances to detector: $\frac{\omega_2}{\omega_1} = (L_1 + L_2)/L_2$

Tune the spin-echo length: $\tau_{MIEZE} = \frac{\Delta\omega\, m^2 \lambda^3 L_S}{h^2}$

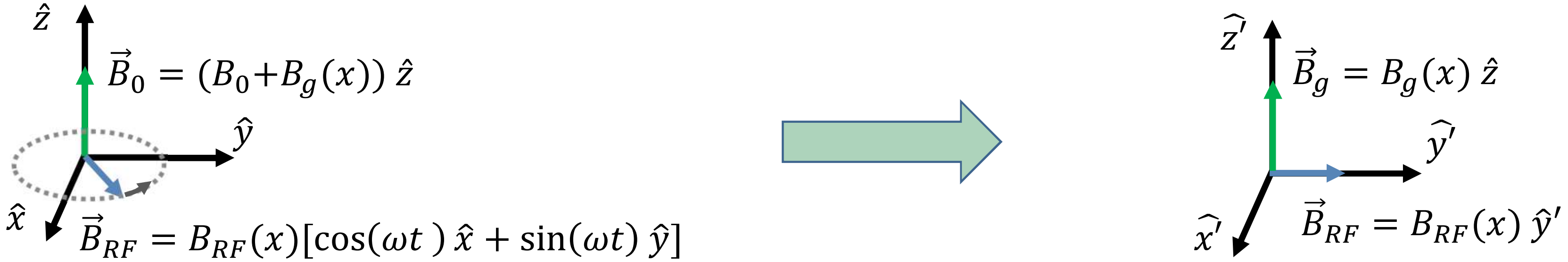
Measure the contrast: $\mathrm{C} = \frac{I_A}{I_0} = \frac{\int S(\boldsymbol{Q},\omega)\cos(\omega\tau_{MIEZE})d\omega}{\int S(\boldsymbol{Q},\omega)d\omega} = \frac{S(\boldsymbol{Q},\tau)}{S(\boldsymbol{Q},0)}$ $I(t) = I_0 + \mathrm{I_A}\cos(2\Delta\omega t + \phi_0)$

(where ω here is the quasi-elastic energy transfer)

This can be measured as a function of momentum transfer Q by fitting the contrast in spatial bins on detector

Adiabatic Spin Flip

Consider fields shown, transformed into the frame co-rotating at $\omega = \omega_0 = \gamma B_0$



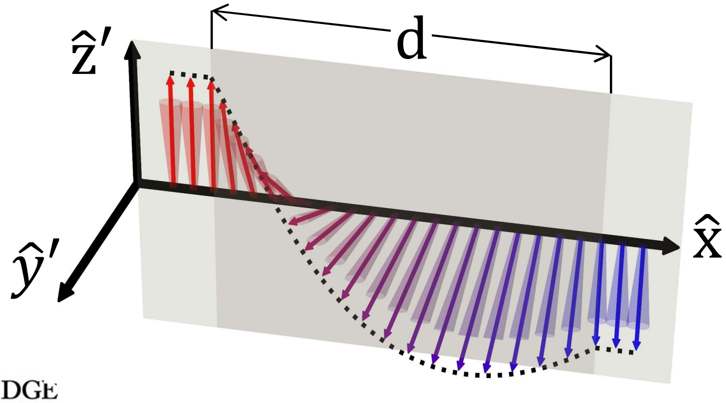
$$\vec{B}_0 = (B_0 + B_g(x))\,\hat{z}$$

$$\vec{B}_{RF} = B_{RF}(x)[\cos(\omega t)\,\hat{x} + \sin(\omega t)\,\hat{y}]$$

$$\vec{B}_g = B_g(x)\,\hat{z}$$

$$\vec{B}_{RF} = B_{RF}(x)\,\hat{y}'$$

The spin follows the field in the rotating frame.



Assuming fields have the form:

$$B_g = A\,cos(\pi x/d) \qquad B_{RF} = A\,sin(\pi x/d)$$

Grigoriev et al, Phys. Rev. A 64 (2001) 013614.

Adiabaticity parameter:

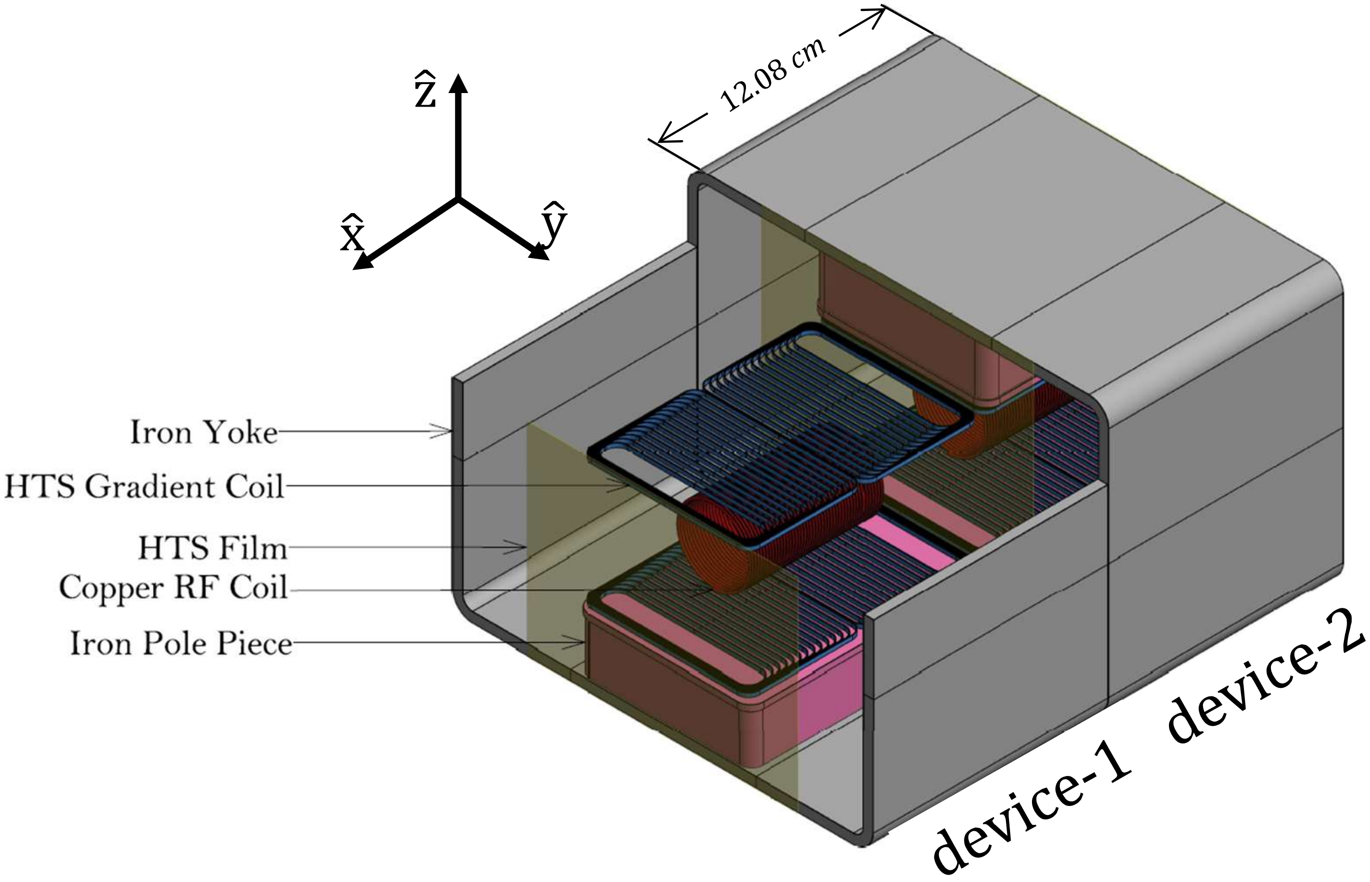
$$k = \frac{\gamma d A}{\pi v} \gg 1$$

Spin flip efficiency is independent of wavelength once k >> 1

Superconducting spin flipper design

- General overview
- B_0 and Gradient coil
- RF coil

General design



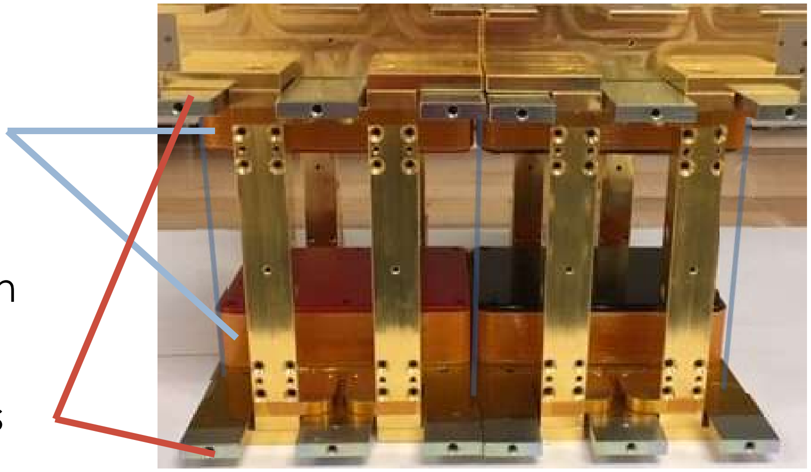
Most of support structure is made of oxygen free copper for high thermal conductivity and uniform thermal expansion

Two spin-flippers separated with HTS films to allow for “Bootstrap” configuration

B_0 Coil

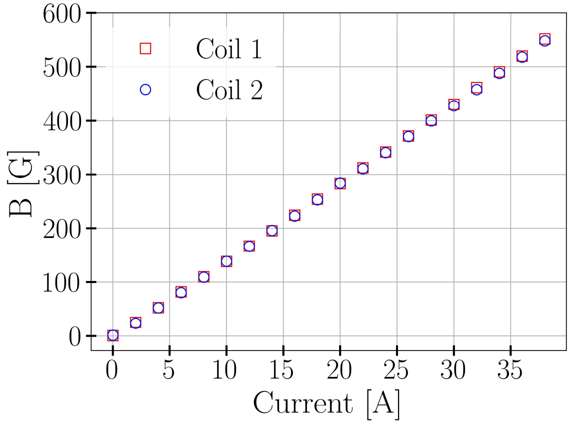
48-turns of HTS wire on each iron pole

Low-carbon steel flux return yoke (side plates removed)

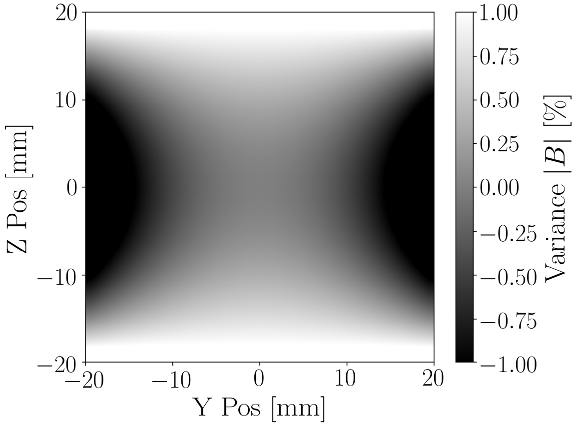


HTS films mounted on each side of coil

Field at center of coils

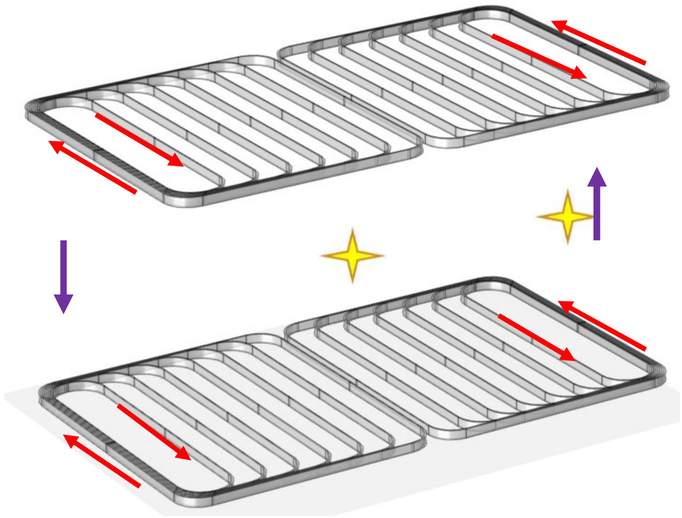


Simulated field variance (x=0)



Gradient Coil

Current direction indicated

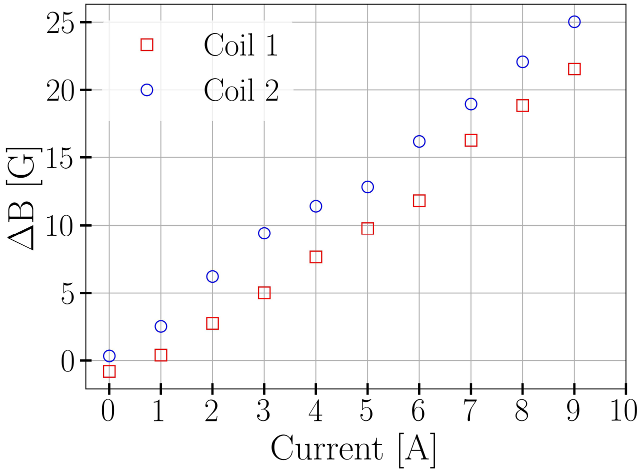


✦ Measurement locations.

Measured gradient ≈ 0.675 G A^{-1} cm^{-1}

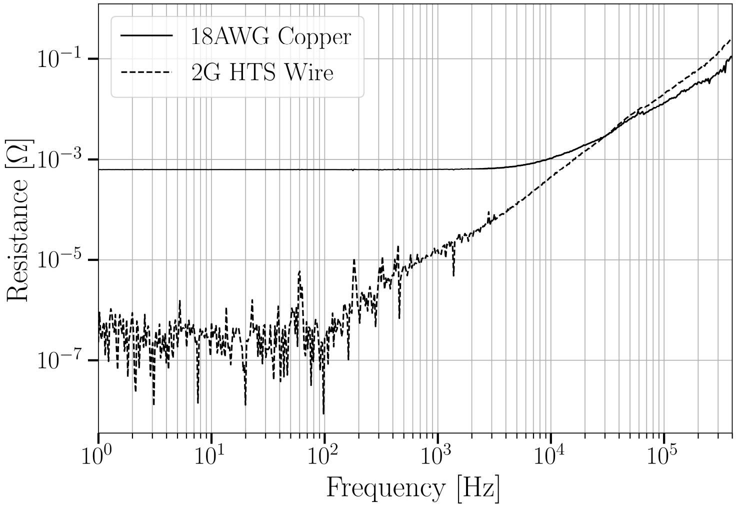
HTS wire wound on Cu form

Calibration measurement

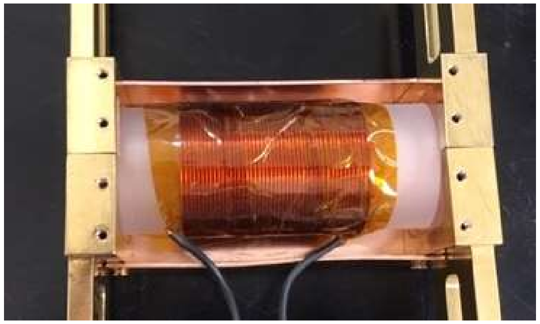


RF Coil design

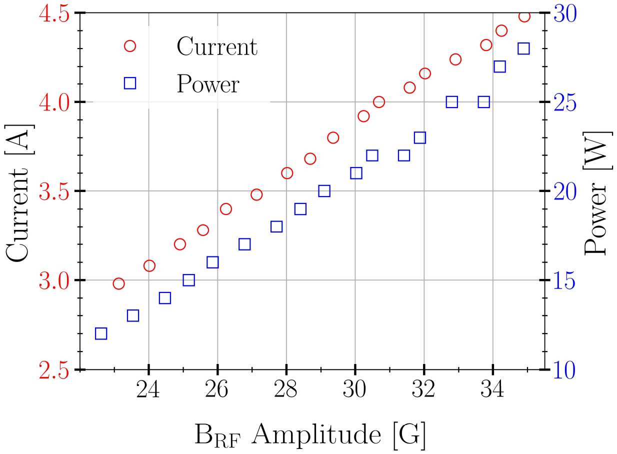
HTS tape is not superconducting at high frequencies



47-turn 18AWG Cu solenoid



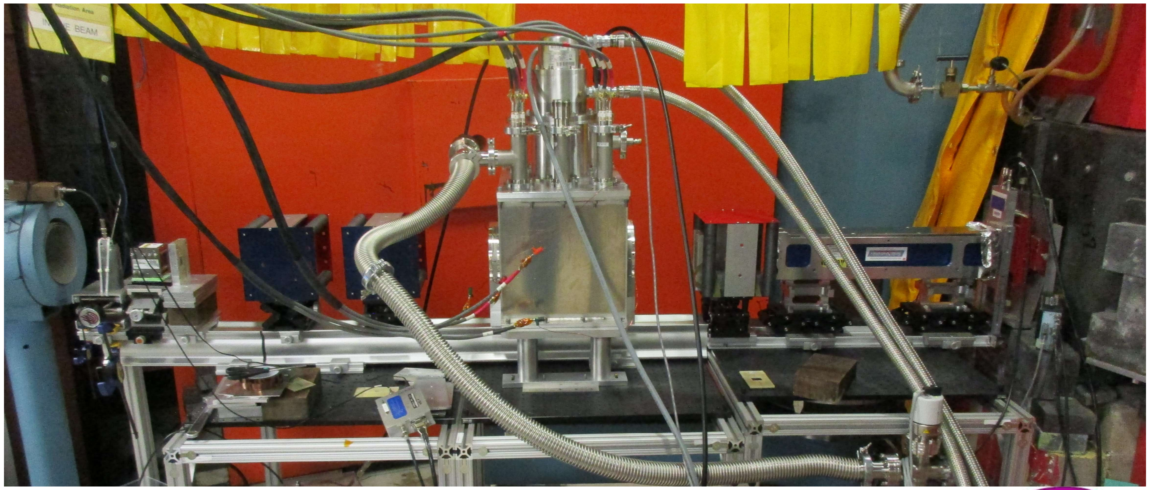
Field in a single coil.
Pair of coils wired in series

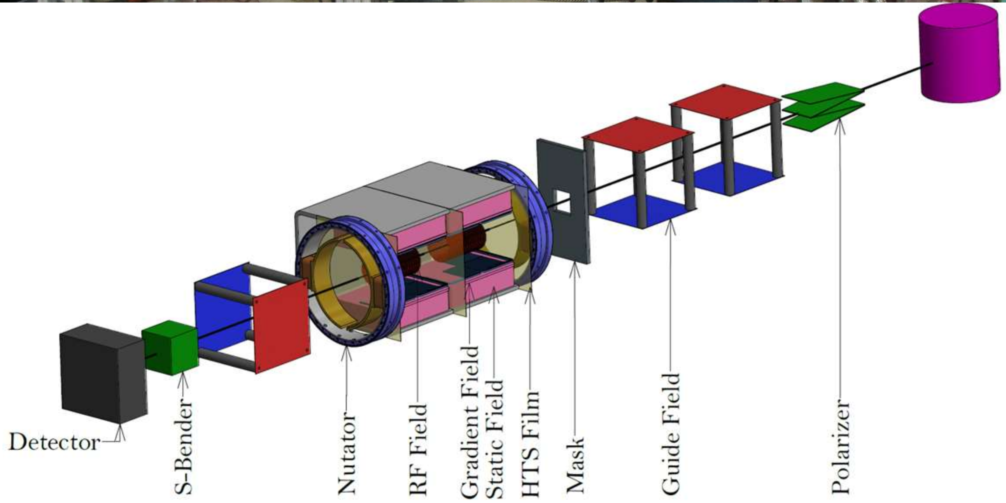


Test Results from Missouri University Research Reactor (MURR)

- Setup at MURR 2XC
- Spin flip efficiency
- Time modulations
- Phase cancellation

Setup on MURR beamline 2XC



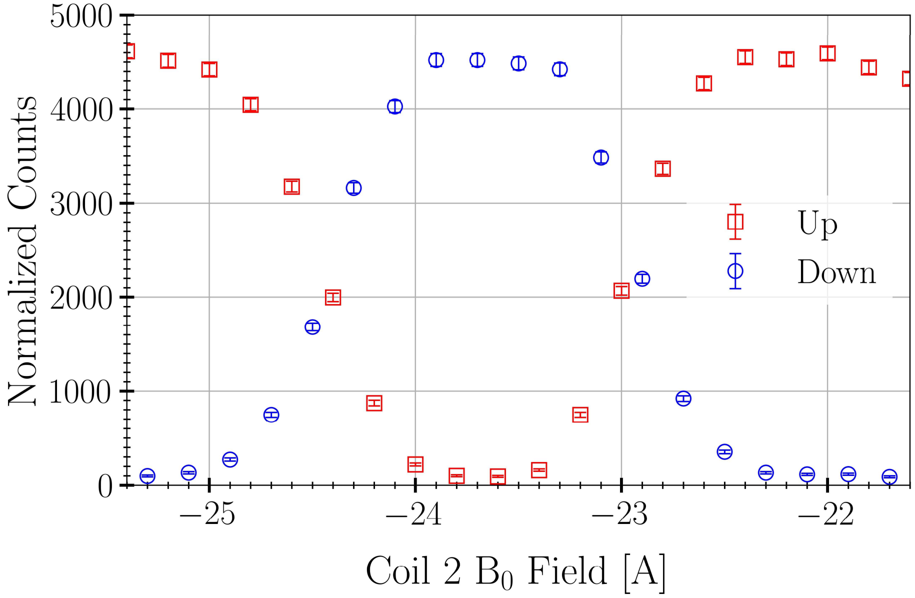


Spin flip efficiency: adiabatic 1MHz

Procedure:

1. Set B_{RF} (peak) and B_{grad} (at entrance) to ~ 25G
2. Scan B_0 to find the resonance peak
3. Repeat for other spin flipper

Bootstrap adiabatic spin flip



Polarization bootstrap double-spin flip (normalized to raw beam polarization):

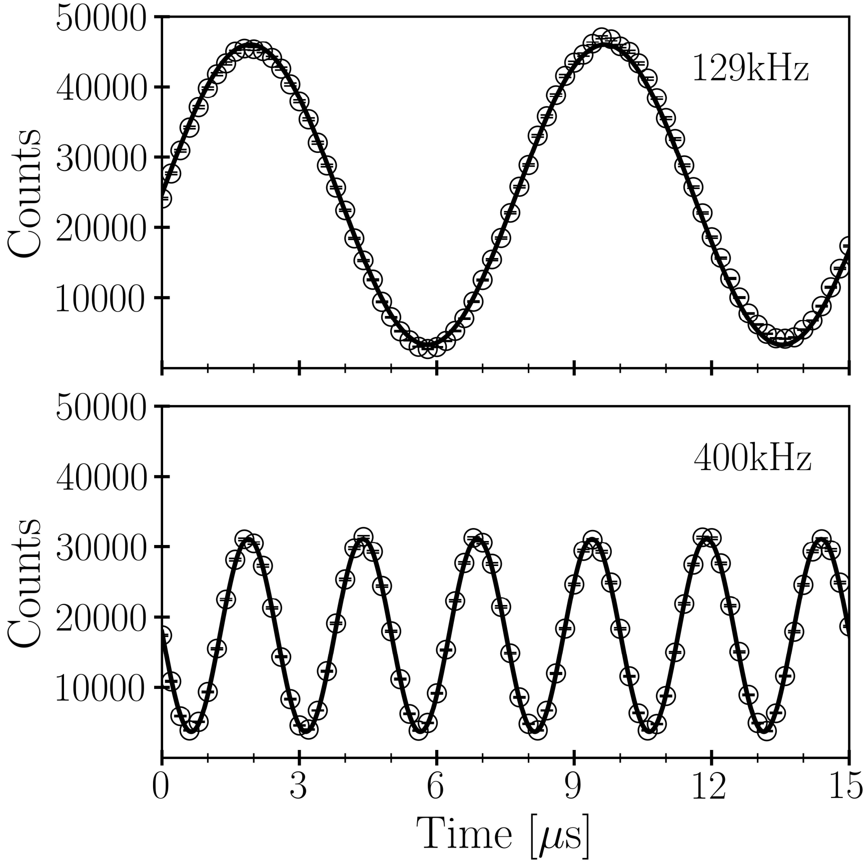
97.9%

Time modulations

Same setup, but switching ^{3}He detector with Anger camera

Ran individual spin-flippers in MIEZE mode to remove wavelength dispersion effects

Signal: $I(t) \propto \cos(2\Delta\omega t)$



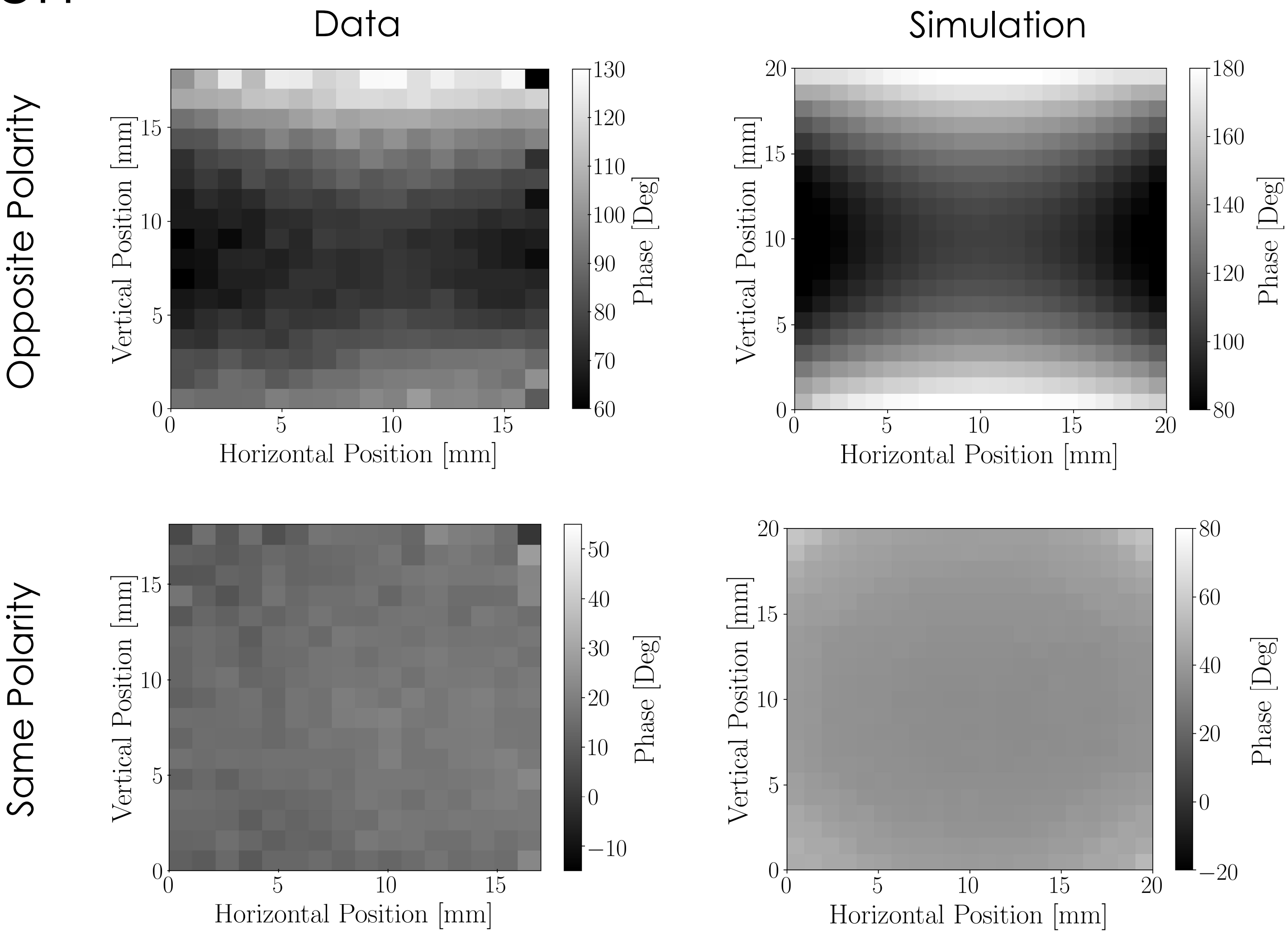
$f_1 = 200kHz$
$f_2 = 264.8kHz$

$f_1 = 615kHz$
$f_2 = 815kHz$

Phase cancellation

Fit time modulation in spatial bins across detector surface

Expectation: some self cancellation when appropriate gradient coil relative polarity



Summary

- Developed a bootstrap RF neutron spin flipper with HTS technology with high spin flipping efficiency
- Have shown self cancellation of phase aberration as predicted by appropriate gradient coil polarity

Future: 2nd device built and currently performing validation tests. Planned MIEZE-SANS measurement of skyrmion dynamics at HFIR development beamline CG4B

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