Design and testing of a novel birefringent device for Spin Echo angle coding

Low Energy Neutron Source

Paul Stonaha[1], V.R. Shah[1], A. Washington[1], B. Kirby[2], C.F. Majkrzak[2], B. Maranville[2], W. T. Lee[3], R. Pynn[1,3]

1 – Department of Physics at Indiana University Bloomington and the Low Energy Neutron Source at Indiana University Cyclotron Facility

2 – NIST Center for Neutron Research

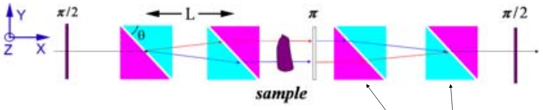
3 – Neutron Science Directorate, Oak Ridge National Lab, Oak Ridge TN.

This work was supported by the Department of Energy Office of Basic Energy Science. (Grant # ER46279)

Theory

Spin Echo Scattering Angle Measurement (SESAME) is a sensitive interference technique for measuring neutron diffraction. The technique uses pairs of magnetic fields with triangular cross-sections, which each produce Larmor precession proportional to the distance that the neutron is from the center of the neutron beam. For two such pairs, the amount of precession is proportional to the in-plane path angle. This property allows one to infer, from the final polarization, the scattering angle off of a sample.

- This technique is known to work for well defined field boundaries, as shown in the adjacent figure.



- When travelling through a magnetic field at speed v, the magnetic moment of a neutron will precess about the field by a Larmor phase equal to:

$$\varphi = \frac{\gamma}{v}\int\left|\overline{B}\right|dx$$

γ = gyromagnetic ratio of neutron

- In the absence of scattering, any Larmor phase picked up in the first half of the instrument will be canceled in the second.
- Any neutron that scatters from the sample will experience a net non-zero Larmor phase.
- The final Larmor phase of a neutron is dependent only on the scattering angle off of the sample, not on the neutron's initial trajectory.

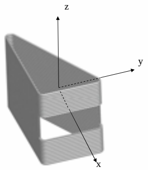
Partially assembled triangular solenoids. Mu-metal completes the magnetic circuit.

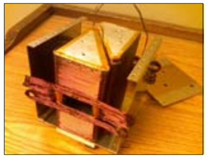
Motivation for Gapped Triangles

- A neutron passing from the solenoid to the guide field region "sees" an abrupt change in magnetic field direction, which may depolarize the beam.
- Each field boundary contributes a layer of aluminium wire, decreasing overall beam intensity.

Solution:

- Introduce a gap into the leading face of each triangular solenoid.

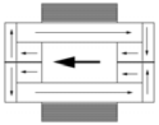




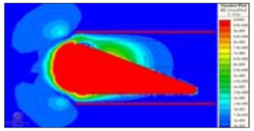
- Does this produce aberrations in the Larmor phase that do not cancel in the full SESAME setup?

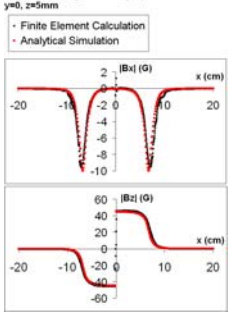
Symmetric Cancelation of Larmor Phase Aberrations

The gapped triangular solenoids were modeled analytically, using a Heavyside function to model an infinite solenoid, and the Biot-Savart law to model a series of current sheets to simulate the gaps (below left).



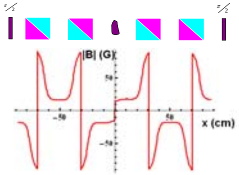
Finite-element calculations (FEC) were carried out as well (right). These calculations take into account the effects of mu-metal surrounding the triangular solenoids. The results of analytic simulation match the FEC within the solenoid pair (far right). Therefore, we believe that the results of the analytical simulation accurately represent the actual fields.





The final polarization of a neutron beam is given by $P = \langle \cos(\varphi) \rangle = \left\langle \cos\left(\frac{\gamma}{v}\int\left|\overrightarrow{B}(x,y,z)\right|dx\right)\right\rangle$

We can integrate **B** for the analytical model through a full SESAME setup (see figure right) to determine the final neutron polarization. These simulations show a loss of polarization through the setup of <0.0001% for a 2 x 2cm beam with ± 1° divergence.

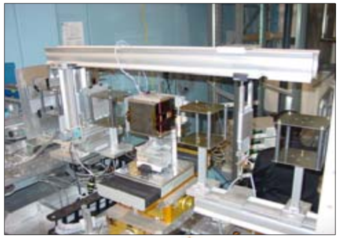


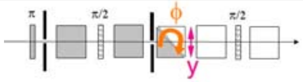
Integration of the analytical function can also determine variations in Larmor phase for scattering from a sample. The variation in Larmor phase over a 1° divergent beam, scattering by 1° from a sample, is only ~5%.

i.e. Larmor phase aberrations due to gaps are largely cancelled by symmetry.

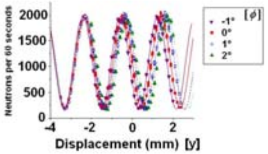
Testing on AND/R

A gapped solenoid pair installed on the AND/R instrument at the NCNR is shown below.





The solenoid pair was energized with 5 Amps, giving an internal field of ~45Gauss. Single spin-state intensity was measured as the solenoid pair was translated across a 50 micron-wide beam. This was repeated for 4 angles (see image left, results below). The frequency of the intensity vs. displacement remained constant as the triangle pair was translated.



The intersection of the intensity curves for the 4 angles indicates the location of the physical center of the triangle pair (~-4mm in above figure). The results of the experiment showed that the aberrations produced by the gapped solenoid pair are within error of the analytical simulations. In fact, these aberrations were also within error of what one would expect with non-gapped triangular solenoids, demonstrating the minimal impact of the gap on the field-integral of a pair (see table right).

	$\frac{dI}{dy}$ $\phi=0°$	$\frac{d^2I}{d\phi dy}$ y=0 mm, $\phi=0°$	$\frac{d^2I}{d\phi^2}$ y=0 mm, $\phi=0°$
Ungapped Model	14.1194	-0.3874	0.00000
Complete Model	14.1194	-0.3883	0.00000
NIST Data	14.1449 ± 0.1383	-0.3835 ± 0.0568	-0.12466 ± 0.24158

Summary

- **Experiments have confirmed that the gapped triangular solenoids can be accurately modeled using Biot-Savart law.**
- **Although the fields of gapped and ungapped triangle pairs differ, the phase aberrations produced by the gaps cancel out through the entire SESAME setup. The decrease in the spin-echo polarization due to the gaps is calculated to be < 0.0001% for a 4cm^2 beam with ± 1° divergence.**
- **The overall field integral is proportional to the scattering angle from the sample, and the constant of proportionality varies by ~5% across a 2 x 2cm beam.**
- **The use of gapped solenoids will allow for the development of a beam line accommodating a large (2 x 2cm) and divergent (± 1°) neutron beam for SESAME.**