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Simulation of the Ultra-Cold Neutron Spin Analyzer Foil

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Abstract

Faculty of Science
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Simulation of the Ultra-Cold Neutron Spin Analyzer Foil

by Sean HANSEN-ROMU

Liberated neutrons that travel at kinetic energies of ~ 100 neV with average temperatures of 3.5 mK are called Ultra-Cold Neutrons (UCNs) and they reflect off of material surfaces if the surface possesses a Fermi potential larger than the kinetic energy. The property of being able to be held in a material trap as well as the Zeeman splitting as a result of the magnetic moment of the neutron allow for Nuclear Magnetic Resonance (NMR) type experiments to test the existence of a neutron electric dipole moment(nEDM). The polarization and neutron count can be improved through multi detector design for the neutron electric dipole moment experiment in order to improve the increasingly more precise limit of the nEDM. Since the spin flipper is important in measuring the coherence of polarized neutrons the magnetic field of the spin analyzer foil was simulated in Opera with the goal of a design for the prototype for the spin analyzer. The simulation was tested against real life measurements of the field gradients of the spin analyzer at the Research Center for Nuclear Physics (RCNP), in Osaka, Japan. The results of the RCNP comparison reveals that the BH curve choice for stainless steel was a wrong one, since it was acting like a return yoke, altering the magnetic character of the foil more than an non-magnetic material should, qualitatively. Future work on Monte Carlo simulations to process the results of the Opera Simulation is required.

Acknowledgements

First I would like to express my gratitude and thanks to my supervisor, Dr. Blair Jamieson. It is because of him that I had the opportunity to work on research during the summer and chose to do my honours thesis in physics. I would also like to thank my honours committee. Also, I am thankful for NSERC for their USRA program that provided summer research funding which allowed me to learn to code for the first time, vital to working on this thesis about simulations. Finally, thanks to my family and friends who have supported me throughout my university career.

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Abbreviations

AFP	**A**diabatic **F**ast **P**assage
EDM	**E**lectric **D**ipole **M**oment
nEDM	**n**eutron **E**lectric **D**ipole **M**oment
RCNP	**R**esearch **C**entre for **N**uclear **P**hysics
SA	**S**pin **A**nalyzer
SF	**S**pin **F**lipper
TRIUMF	**TRI**-**U**niversity **M**eson **F**acility
UCN	**U**ltra-**C**old **N**eutron

Physical Constants

Neutron gyromagnetic ratio	γ_n	$=$	$1.832\ 471\ 79(43) \times 10^{8}\ \mathrm{s}^{-1}\ \mathrm{T}^{-1}$
Neutron magnetic moment	μ_n	$=$	$-0.966\ 236\ 47(23) \times 10^{-26}\ \mathrm{J\ T}^{-1}$
Planck's Constant	$\hbar$	$=$	$1.054\ 571\ 726(47) \times 10^{-34}\ \mathrm{J\ s}$

Symbols

d	electric dipole moment	e cm
E	energy	neV
V_F	potential energy	neV
$\vec{B}$	magnetic field	T
$\vec{E}$	electric field	N C^{-1}
$\vec{H}$	magnetic field in material	A/m

ω	angular frequency	rad s^{-1}
ν	angular frequency	rad s^{-1}
μ	magnetic permeability	N A^{-2}
μ_N	magnitude of neutron's magnetic moment	N m T^{-1}
$\vec{\mu}$	magnetic moment	N m T^{-1}

Chapter 1

Introduction

1.1 Motivation

The neutron electric dipole moment (nEDM) experiment is a precision measurement that has gone through many iterations in the ever more precise search for the nEDM [1].

The statistical uncertainty in the measurement of nEDM experiment σ_d is given by [1]:

$$\sigma_d = \frac{\hbar}{2\alpha E T\sqrt{N}} \quad , \tag{1.1}$$

where α is visibility of the Ramsey central fringe, E is the electric field, N is the neutron count, and T is the time that the neutrons spend in coherence [1]. Here the polarization efficiency is strongly related to the visibility of the Ramsey fringe α, which has an inverse relationship with the error σ_d . This effect has a greater impact on the error when compared to the neutron count N, which as an inverse square root relation with the nEDM error σ_d.

Simultaneous measurements of the neutrons would increase both neutron count N from minimization of losses and a more optimal design of the spin flipper and spin analyzer would increase α thereby reducing the error in the measurement of the nEDM.

TRIUMF, Canada's subatomic laboratory, has approved the UCN project which is slated to produce UCN densities of 50 000 UCN/cm^3, the worlds largest [2]. The future inaugural experiment with this high density source is the nEDM so work is going into the design phase of each part of the experiment.

1.2 Thesis work

This thesis looks at Spin Analyzer (SA) and Spin Flipper (SF) design and simulates the magnetic field of the SA in Opera [3], as well as examining a brief overview of the ultra-cold neutrons (UCNs) and the nEDM. In order to design the adiabatic fast passage spin flipper, a magnetic field gradient is required. The Opera field simulation is being used to design the SA to have the desired field gradient for the SF.

Chapter 2

Background

2.1 Ultra Cold Neutrons

UCNs are free neutrons at temperatures below 3.5 mK, which correspond to an average speed of less than 8 m/s [1]. The kinetic energy of UCNs at this energy scale is less than 330 neV. Neutrons on this energy scale interact with the strong, gravitational and the electromagnetic forces at enegies comparable to the kinetic energy. It is because the interaction with these forces occur at energies comparable to UCNs that the UCNs are easily manipulated. The electromagnetic force interaction changes the kinetic energy of the UCN by 60 neV/T. The interaction with gravity alters velocity by 100 neV/T [1].

It is because of the low kinetic energy of the UCNs that they are interacting with matter below the threshold for which the strong force interaction is described by the Fermi potential, V_F [1, 13]. This constant potential V_F is given by:

$$V_F = \frac{2\pi\hbar^2}{m} na \tag{2.1}$$

where n is the number density in the matter, a is the bound coherent nuclear scattering length, and m is the mass of the neutron.

The bound coherent nuclear scattering length a is the low energy limit of a potential arbitrary potential that has the same low energy properties as a solid sphere potential of radius a [6].

The Fermi potential V_F is responsible for reflection of a neutron with a material boundary when the equation below is satisfied.

$$E \sin^2\theta \leq V_F \tag{2.2}$$

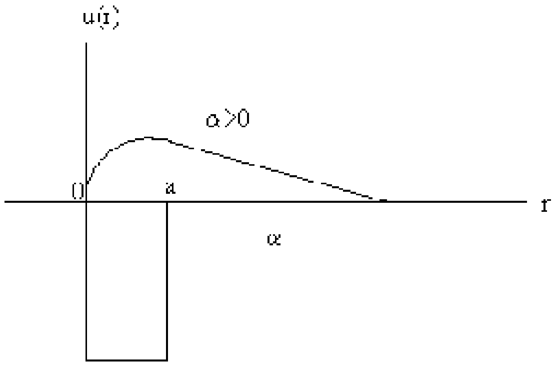

FIGURE 2.1: Scattering limit of the radial finite-square well that has scatting length a [6]

Here θ is the angle of incidence of the neutron to the material, E is the kinetic energy and V_F is the Fermi potential. For all kinetic energies E less than that of the potential V_F, equation 2.2 is satisfied and will reflect the neutron regardless of the angle of incidences. That is as long as:

$$E \leq V_F \tag{2.3}$$

Reflection always occurs. This allows for the storage and transport of UCNs.

Additionally UCNs interaction with the electromagnetic and strong force allows for the trapping of UCNs with magnetic and material traps respectively. Gravitational interaction is responsible for UCNs following parabolic paths.

2.2 Neutron Electric Dipole Moment Experiment

An EDM classically is a measure of the separation of charge and is defined by:

$$\vec{d} \equiv \int \vec{x} q\left(\vec{x}\right) d^3\vec{x} \tag{2.4}$$

Where $\vec{d}$ is an EDM vector, $\vec{x}$ is a displacement and $q\left(\vec{x}\right)$ is a charge distribution. The neutron is electrically neutral overall, however if the charge distribution is such that there is asymmetry between positive and negative charges it will result in an EDM [11]. The classical definition of the EDM may not describe the phenomenon correctly, as the nEDM is considered to be a quantum effect resulted from the electric dipole of the constituent quarks of the neutron.

Why the nEDM important is because a high nEDM can provide clues about physics beyond the Standard Model, see Section 2.3 for more information.

If the neutron has an EDM in addition to its intrinsic magnetic moment then its motion will be described by the Hamiltonian $\mathcal{H}$ of a particle in an electric field $\vec{E}$ and magnetic field $\vec{H}$, which is given by:

$$\mathcal{H} = -(d_n\, \vec{I} \cdot \vec{E} + \mu_N\, \vec{I} \cdot \vec{B})/I \tag{2.5}$$

Where d_n is the magnitude of an electric dipole, μ_N is the magnitude of the magnetic moment, $\vec{H}$ is the applied magnetic field, and $\vec{I}/I$ is the unit vector parallel with the intrinsic spin of the particle [12]. In the nEDM measurement the magnetic field and the electric field are applied either parallel or anti-parallel.

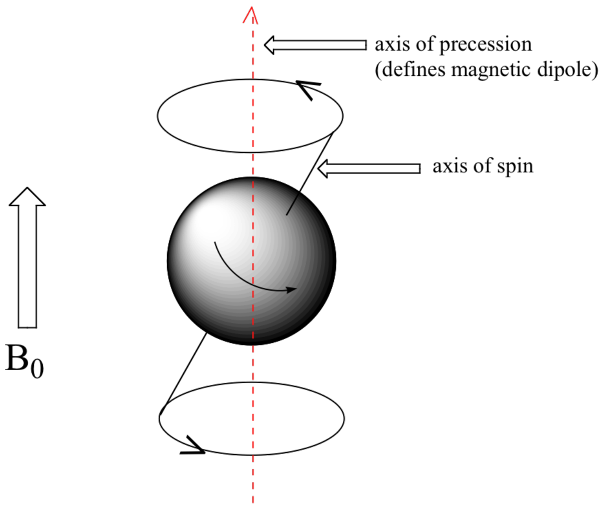

FIGURE 2.2: The magnetic dipole moment in the presence of a magnetic field processes around the field vector [7]

The rotation of the magnetic moment, in Fig. 2.2, goes as the Larmor frequency γ defined by:

$$\omega = \gamma H \tag{2.6}$$

where γ is the gyromagnetic ration of the particle precessing about the magnetic field H. If an oscillating magnetic field is acting on this system, the manipulation of the bulk magnetization is possible. A perpendicular RF coil is typically is used in Nuclear Magnetic Resonance (NMR) to measure the frequency and decay times of the magnetization.

Looking at equation 2.5 a particle in only a magnetic field follows only:

$$\mathcal{H} = -\mu_N\, (\vec{I}/I) \cdot \vec{B} \tag{2.7}$$

For a particle in a constant magnetic field $\vec{B} = B_0\ \hat{k}$ the equation 2.7 has eigenvalues of the spin I_z component. The allowed energies are then[12]:

$$E = -\mu_N / I\ B_0\ m, \qquad m = -I, I+1, \ldots, I-1, I \tag{2.8}$$

The neutron is a baryon with spin $I = 1/2$ and spin eigenvalue $m = -1/2,\ 1/2$. This means that the allowed energies are split into two energy levels with a separation of $\gamma_N \hbar H_0$ since the magnetic moment is given by:

$$\vec{\mu_N} = \gamma \hbar \vec{I} \tag{2.9}$$

Where γ_N is the gyromagnetic ratio of the neutron. The splitting of the energy levels is called Zeeman energy splitting[12]. Just like the Zeeman energy levels the electric dipole moment in the presence of an electric field further alters the levels of energy depending on the direction of magnitude relative to electric field.

UCNs are used for the nEDM experiment because of the NMR technique used to measure the magnetic moment has a reduced error because of the random directional velocity distribution of the UCN gas held in storage. This is because using a mono directional neutron beam at higher temperatures can be misaligned to the plates generating the electric and magnetic fields. This misalignment will give rise to a magnetic field via:

$$\vec{B} = \frac{1}{c} \vec{v} \times \vec{E} \tag{2.10}$$

Where the $\vec{v}$ is the average velocity of the neutron beam and $\vec{E}$ is the electric field generated by the plate [11]. The generated magnetic field will give rise to a false nEDM. UCNs are used because the random nature of trapped neutrons reduce the systematic error and the average velocity is zero which significantly reduce this error [11]. The interaction time between the electric and magnetic fields is increased when using UCNs in storage cells to perform the NMR experiment. As a result the sensitivity of the experiment is raised from acquiring larger phase changes from reversing the direction $\vec{E}$ field [11].

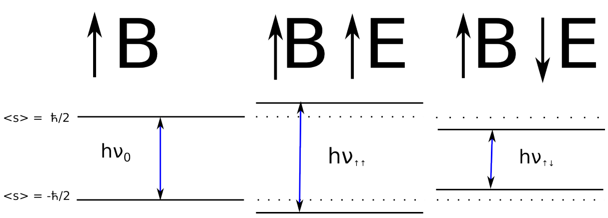

FIGURE 2.3: The shift in energy levels of the allowed neutrons of Zeeman split levels via spin directional dependent interaction of the EDM to the electric field. **Image based on [9]*

The nEDM measures the shift of the Zeeman energy levels of neutrons in a magnetic and electric field. It does this through low field NMR imaging and is measured through:

$$d_N = \frac{h\left(\nu_{\uparrow\uparrow} - \nu_{\uparrow\downarrow}\right)}{4E} \tag{2.11}$$

where $\nu_{\uparrow\uparrow}$ is the frequency of the energy levels of where the magnetic holding field B_0 is parallel to the electric field E, and $\nu_{\uparrow\downarrow}$ is the frequency of the energy level with the magnetic and electric field in anti-parallel configuration as in Fig. 2.3.

The nEDM experiment uses a nuclear magnetic resonance sequence named the Ramsey Sequence that is method of separating frequencies via NMR. The Ramsey fringe uses four points on the central fringe. The Ramsey fringe is sown in Figure 2.5.

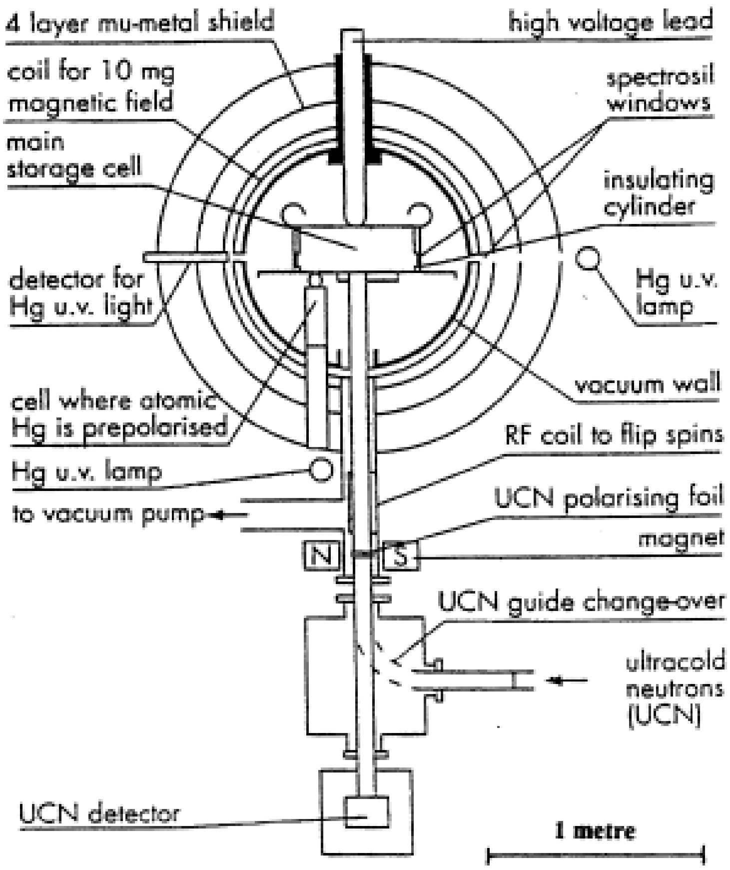

FIGURE 2.4: Experiment setup at ILL of the neutron electric dipole moment.[8]

TRIUMF's flagship experiment using the developing source of UCNs is the nEDM experiment using the highest densities in the world [2]. The initial experimental setup will be similar to the ILL experimental setup in Fig. 2.4 is many respects. The mu-metal layers shield the neutrons from earth's magnetic field, the magnetic field from the TRIUMF cyclotron magnets, and other magnetic noise in the vicinity of the experiment. UCNs will be transported to a storage cell where the Ramsey sequence will be performed for a given frequency near the Ramsey resonance frequency. The polarized neutrons are then allowed fall after the experiment is performed and the polarizing foil in Fig. 2.4 doubles as the SA in our experiment allowing on of the spin states of the neutrons to get counted in the neutron detector.

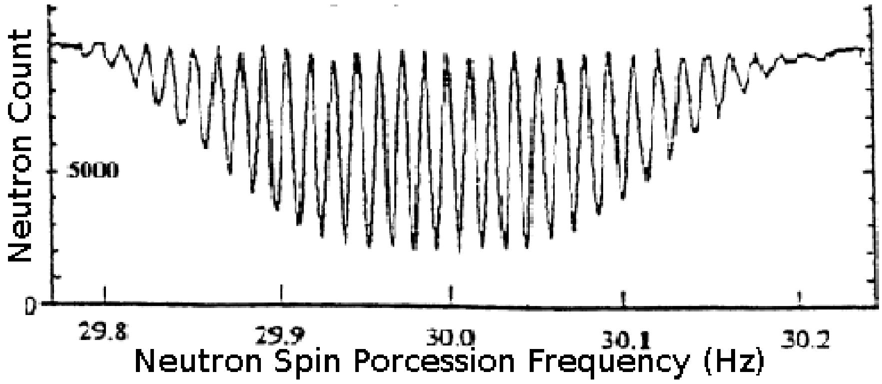

FIGURE 2.5: Neutron electric dipole moment Ramsey interference pattern at ILL.[8]

The nEDM measure uses four points on the Ramsey interference pattern on the central fringe to measure the frequency shift disscussed by Fig. 2.3 and equation (2.11).

2.3 CP Violation

The nEDM is predicted by that Standard Model on the order 10^{-32} e cm [4]. The existence of an nEDM could ultimately lead to physics beyond that of the Standard Model since theories predict a larger value. The existence of an EDM could explain the baryogenesis of the universe through CP violation [11].

2.4 Spin Analyzer

Using nuclear magnetic resonance (NMR) a particle with a magnetic moment $\vec{\mu}$ in a magnetic field $\vec{H}$ gives rise to an interaction energy according to the Hamiltonian, $\mathcal{H}$ [12]:

$$\mathcal{H} = -\vec{\mu} \cdot \vec{H}. \tag{2.12}$$

Additionally, UCNs at the boundary of a magnetized surface will experience the Fermi surface potential.

The change in energy the neutron undergoes as it passes through a surface that is magnetized is modelled with an effective potential via:

$$V_{eff} = V_F \mp \mu_N \ B \quad , \tag{2.13}$$

with '$\mp$' for the spin up and down states modifying the Fermi potential. This gives rise to an effective Fermi potential V_{eff} for the polarized neutrons. From equation (2.2) with the new Fermi potential from equation (2.13) if the neutrons have kinetic energy on par with the unmodified Fermi potential with large surface magnetization, then neutrons that experience less of a potential will transmit through the material, while neutrons that experience more modified Fermi potential will reflect.

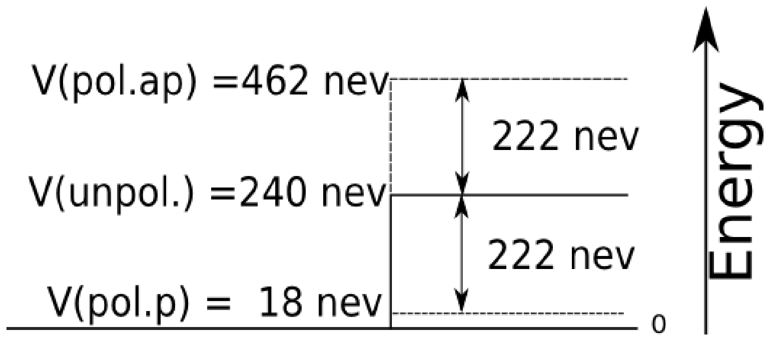

FIGURE 2.6: The spin analyzer has different Fermi potentials for polarized anti-parallel (ap) or parallel (p) spins to surface magnetization compared un-magnetized materials. Fermi potentials given here are for pure iron at saturation point which is approximately 2 T.

The multi-spin analyzer simultaneously measure the spins of the neutrons in order to increase efficiency due to losses from depolarization and up scattering between measuring gated measurement. The sequential spin analyzer is ineffective as losses are occurring during collection time of on spin state over the other.

Polarized neutrons will enter the multi-spin analyzer device (shown if Fig. 2.8) and fall into one either the left detector or the right detector, with SF on or off respectively. From there if the neutrons spin is anit-aligned to surface magnetization then the particle is reflected and will go through the SF region again where it will flip to the initial spin state and have the opportunity to quickly travel through the other SA foil via reflections on the surface. If the particle was in alignment with the surface magnetization the neutron will pass through, as described in Fig. 2.6.

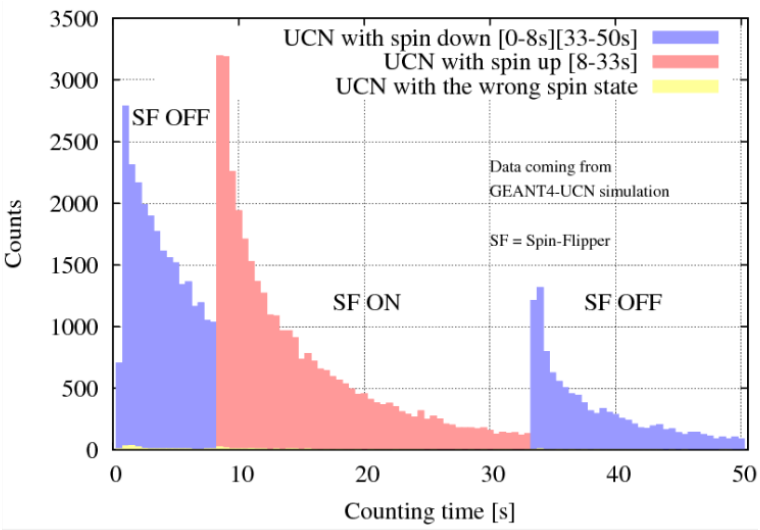

FIGURE 2.7: The single sequential spin analyzer simulation by Victor Hélaine to demonstrate the inefficiency of the sequential method [14].

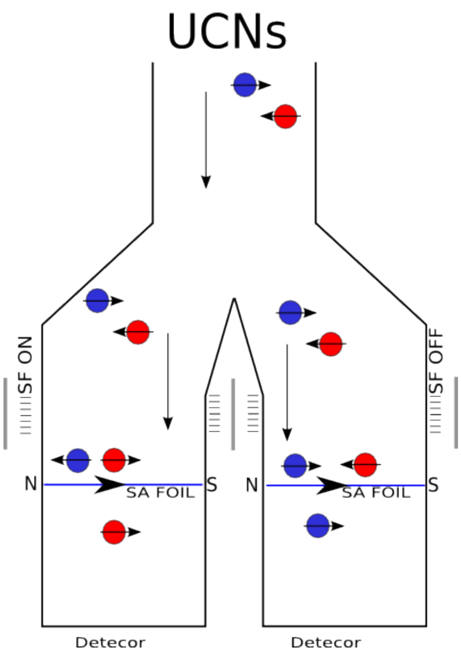

FIGURE 2.8: The multi-spin analyzer used two spin flippers and two SA foils in its design.

2.5 Spin Flipper

The spin flipper (SF) is a device that reverses the neutrons spins from parallel to anti-parallel and vice versa. It does this through adiabatic fast passage (AFP). It does so using the adiabatic condition on and effective rotating magnetic field.

2.5.1 Adiabatic Theorem

Adiabatic theorem states that the angle of magnetization makes with the direction of the changing magnetic field $\vec{H}$ will remain constant, as long as the variation is time is sufficiently slow [5].

The time varying equation for a general magnetic field is given by:

$$\frac{d\vec{H}}{dt} = \vec{\omega} \times \vec{H} + \nu\vec{H} \tag{2.14}$$

Where both the vector $\vec{\omega}$ and the scalar ν are frequencies [5]. According to Abragam the motion of a moving frame S' with the z-axis continuously aligned to the direction of the magnetic field $\vec{H}$ and moving in a rotation about the axis $\vec{\omega}$ will have a magnetization $\vec{M}$ according to:

$$\frac{\partial\vec{M}}{\partial t} = \gamma\vec{M} \times (\vec{H}_eff) \tag{2.15}$$

Where the $\vec{H}_{eff}$ is the effective field in a rotating frame of reference. Here the rotation $\vec{\omega}$ is about the z-axis, coincidence to the magnetic field $\vec{H}$, so that this frame only the z-component of the magnetic field is non-zero.

$$\vec{H}_{eff} = \vec{H} + \frac{\vec{\omega}}{\gamma} \tag{2.16}$$

The magnetization $\vec{M}$ is related to the sum of the magnetic moments $\vec{d}$ in a given volume V:

$$\vec{M} = \sum \vec{d_i}/V \tag{2.17}$$

If the magnitude of the frequency of the rotating frame ω is small compared to $|\gamma H|$ then M_x and M_y are sinusoidal functions with frequency ω_0 given by:

$$\omega_0(t) = -\gamma H(t) \quad \text{the adiabatic approximation.} \tag{2.18}$$

The magnetization of the M_z is given by

$$\frac{\partial M_z}{\partial t} = M_x\omega_y - M_y\omega_x \quad . \tag{2.19}$$

Integrating equation (2.19) from $t = 0$ to long time T, the change in magnetization becomes:

$$\Delta M_z = \int_0^T [M_x(t)\omega_y(t) - M_y(t)\omega_x(t)]\, dt. \tag{2.20}$$

If we assume the adiabatic condition that the rotational frame $\vec{\omega}$ is negligible in frequency on the order of $|\gamma H|$, which is:

$$|\vec{\omega}| \ll |\omega_0| = |\gamma H| \tag{2.21}$$

$$\frac{|\vec{\omega}|}{|\gamma H|} \ll 1 \tag{2.22}$$

then the integration introduces a $1/\omega_0$ term from the sinusoidal magnetization functions. This is equivalent to $1/|\gamma H|$ from equation (2.18).

$$|\Delta M_z| = |\frac{1}{\gamma H}[M_y(t)\omega_y(t) + M_x|(t)\omega_x(t)|_0^T. \tag{2.23}$$

because there is a sign change on one of the sinusoidal magnetization functions. Since the sinusoidal functions have a theoretical maximum value of M, then for time T the change becomes:

$$|\Delta M_z| \sim \frac{|M\omega|}{|\gamma H|} \ll M \tag{2.24}$$

Which is the adiabatic theorem. Equation (2.24) says that M_z will remain constant, as a result of the change being small for long time T. [5]

2.5.2 Adiabatic Fast Passage

Abragam [5] and Holley[13] describe adiabatic fast passage classically from the case of a magnetic moment in a rotating field $\vec{H_0} + \vec{H_1}$. Where the holding field $\vec{H_0}$ is being slowly varied [5, 13]. And the rotating field $\vec{H_1}$ has frequency ρ. The effective field in the rotating then defined by:

$$H_{eff} = \sqrt{H_1^2 + [(\rho/\gamma) - H_0]^2} \tag{2.25}$$

$$\vec{H_{eff}} = vecH_1 + [(\vec{\rho}/\gamma) - \vec{H_0} \tag{2.26}$$

which makes the change of effective field becomes:

$$\frac{d\vec{H_{eff}}}{dt} = \cos\theta \frac{\dot{H_0}}{H_{eff}}\vec{H_{eff}} + \sin\theta \frac{\dot{H_0}}{H_{eff}}\vec{n} \times \vec{H_{eff}} \tag{2.27}$$

where $\vec{n}$ is the unit normal vector of the cross of $\vec{H}_0$ and $\vec{H}_1$ and θ is the angular separation between the magnetization vector and the rotating field H_1. Comparing Equation 2.27 to 2.14 and relating to the adiabatic condition yields:

$$\dot{H}_0 \ll \frac{\gamma H_e^2}{\sin\theta} \quad . \tag{2.28}$$

This AFP condition is strongest on resonance and yields:

$$\dot{H}_0 \ll \gamma H_e^2 \quad . \tag{2.29}$$

The use of the adiabatic theorem also predicates that the ω have frequencies that are not close to γH_e [5, 13] .

As you approach resonance the magnitude and direction of the effective field changes but if the AFP condition is met then the magnitude will continue to precess around the effective field in the rotating frame [12]. According to equation (2.25) at resonance the effective field will only have a value of H_1 and will be pointing along $\vec{H}_1$ in the rotating frame. Sweeping through resonance has the effect of inverting the magnetization [12].

In addition to this the the following time condition has to be met.

$$\tau = \frac{|H_1|}{|\dot{H_{eff}}|} \quad . \tag{2.30}$$

Equation 2.30 states that the time duration of the passage through resonance will be a small fraction of period of rotation [5]. This time condition is where the fast in AFP comes from.

For the spin flipper device, specifically, for contentious velocity of thin neutron gas particles there is the necessity of a monotonic gradient in the holding field to in effect sweep through resonance slowly with the monotonic gradient and the quadratic acceleration to form the time varying holding field [13]. This sweep will go from far off resonance through resonance to the other side in order for AFP to occur at different locations as made necessary by the velocity distribution.

Chapter 3

Opera Simulation

3.1 Magnetic Field Simulations

Opera is a finite element analysis software that can solve problems involving magnetostatics that produces numerical solutions [3]. The magnetic field character of the SA foil and its fringe field is important to the SA and the SF design so the field was simulated in Opera.

Additionally, a field map is necessary for accurate simulation of the transport of neutrons through regions that contains a magnetic field from the SA for future work using Monte Carlo Simulations.

3.1.1 Geometries

Several preliminary geometries were chosen to test the design of the SA foil. Primarily of concern was the method of magnetization, be it magnets or coil. Neodymium was choice for the magnets, shown in teal in Fig. 3.1, and a simple race track design was chosen for the coil shown in red in Fig. 3.2.

The boundary condition (BC) of Maxwell's equations of magnetic fields next to a large thin plane gives the geometry required. The Maxwell equation is [10]:

$$\oint \vec{B} \cdot d\vec{S} = 0 \quad , \tag{3.1}$$

the specific boundary conditions of is that from one surface to another the normal component must be continuous while the tangential component need not be continuous across the boundary.

This means for a thin piece of metal the saturation point is not as readily reached along the normal than the transverse component. This is due to the need of the smooth BCs at the normal. The thin foil acts as a concentrating yoke along the transverse but not in the normal direction [10]. This also has to do with the requirement of the magnetic permeability $\mu_p er$ being a contentious function over the region of space where the differential forms of Maxwell's equations are defined.

An iron return yoke was used to control magnetic fringe fields. The yoke is shown blue in Fig. 3.1 and green in Figs. 3.2 and 3.4.

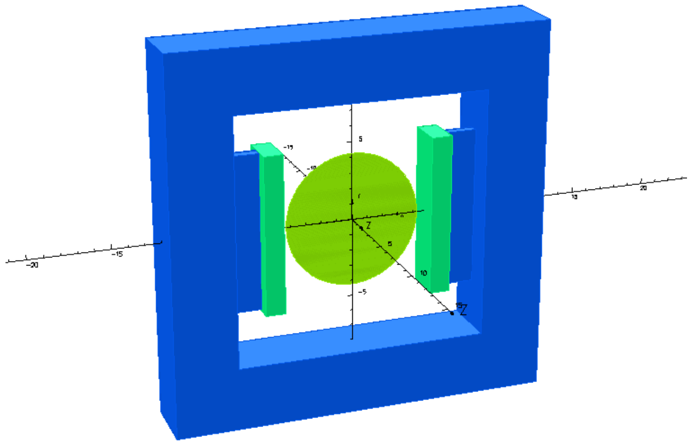

FIGURE 3.1: Geometry of the spin analyzer using neodymium magnets to saturate the iron foil (shown in green) simulated in Opera.

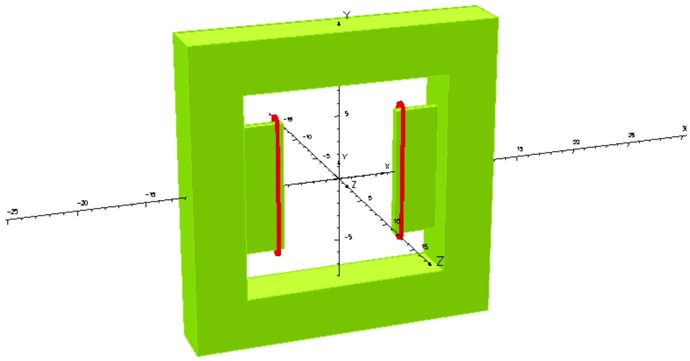

FIGURE 3.2: Geometry of the spin analyzer using thin racetrack coil to saturate the iron foil (hidden) simulated in Opera.

To get an understanding of coil design and how the performance of the simulation compares to the real world we simulated the SA design of the RCNP nEDM experiment setup (shown in figure 3.3 and 3.4).

The choice of axes for all simulations was z-direction was normal to the foil, with the magnetization axes the x-axis and thus leaving the normal to these to axes to be the y-direction. Note

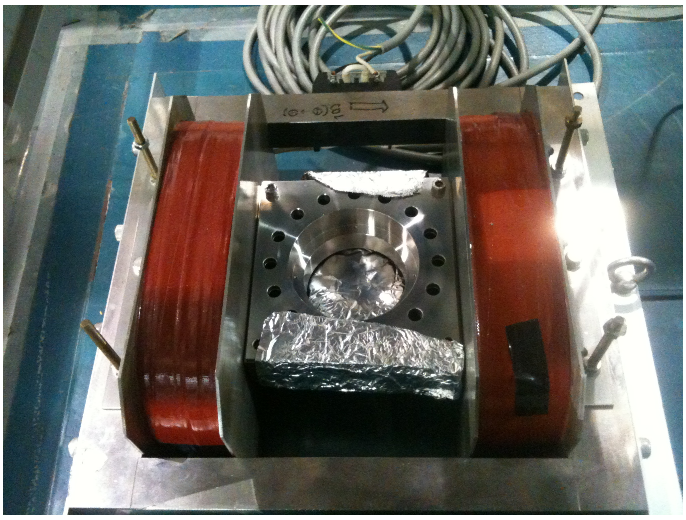

FIGURE 3.3: Geometry of the RCNP spin analyzer setup (Photo from Edgard Pierre), simulated in Opera with the iron thin foil not shown .

this is contrary to the RCNP measurements which defined there axes to be the y-axis is normal of foil, the z-axis is the magnetization axis and the x-axis is perpendicular to those two.

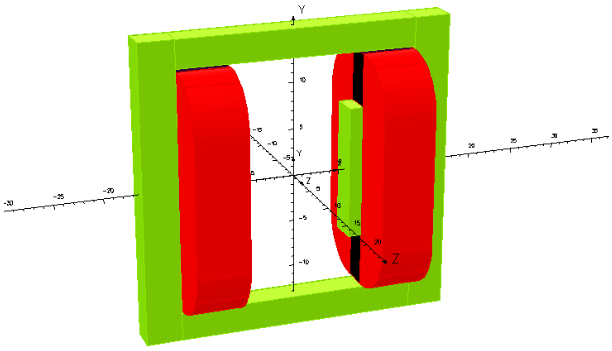

FIGURE 3.4: Geometry of the spin analyzer using the the RCNP setup simulated in Opera with the thin foil and stainless steel foil hold not shown.

3.2 Outline of Work done

The simulated of the geometries in Opera was accomplish using command interface scripts (.comi or .co scripts). Thin iron foils alongside the foil holder had difficultly meshing due to thin geometry errors and size of the cell changing size rapidly. The solution to the messing problem was a cylindrical shell on axis with foil performing function of cut plane.

The BH curves were defined according to Fig. 3.5 in the Opera simulation.

Parameters of the RCNP coil were unknown and had to be calculated from simulation. It is however known that the thin foil was made of sputtered iron onto aluminum. Using current

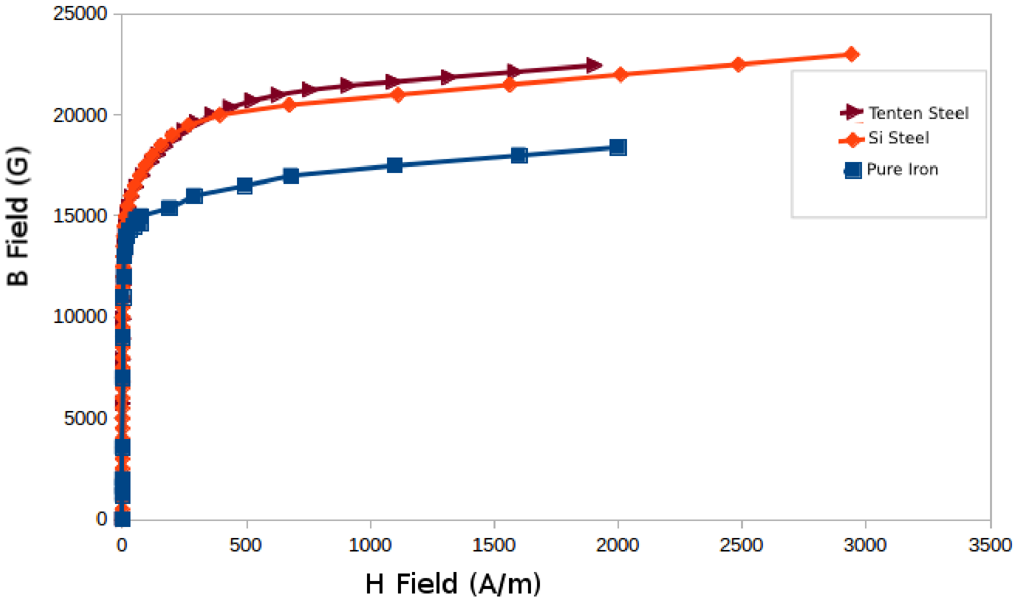

FIGURE 3.5: The BH curve used in simulation for: (i) Pure iron in blue. (ii) Silicone Steel in orange. (iii) Tenten steel shown in dark red.

values of the coil and magnetization of the air without the foil holder the current density required was calculated.

Qualitatively inspected the simulated surface magnetization to gauge the saturation of the thin iron foil. Looked at fringe field along axes of the RCNP simulation and to compared to the RCNP field data to get an idea of how realistic the Opera simulations are.

3.3 Results

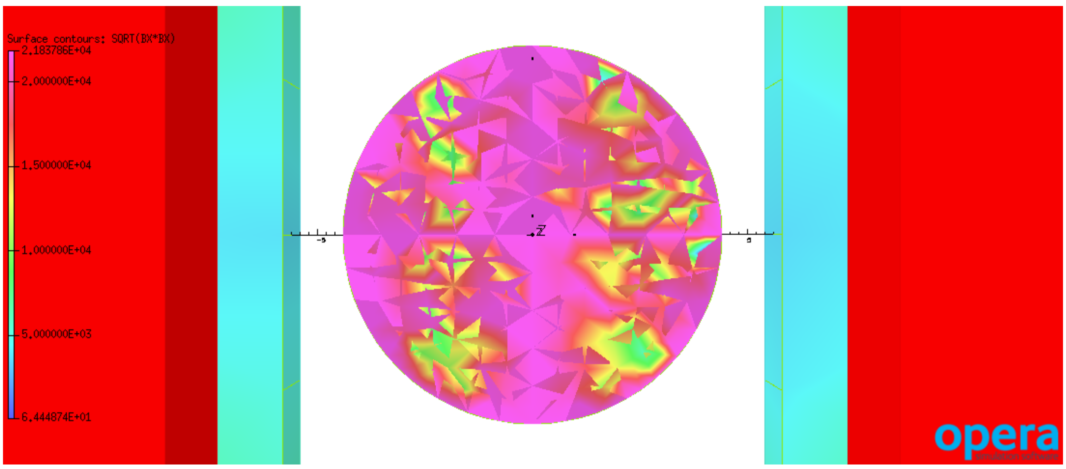

FIGURE 3.6: The magnitude of the surface magnetization of B_x in Gauss as a function of z-direction measured in mm of the RCNP SA design without the stainless steel foil holder. The bright red bar on either side of the foil is just the material colour of coils listed as conductors in Opera.

In Fig. 3.6 the surface magnetization of the analyzer foil was not completely saturated at 2 T, leaving vertical unsaturated bars along the surface of the foil splitting it into three regions.

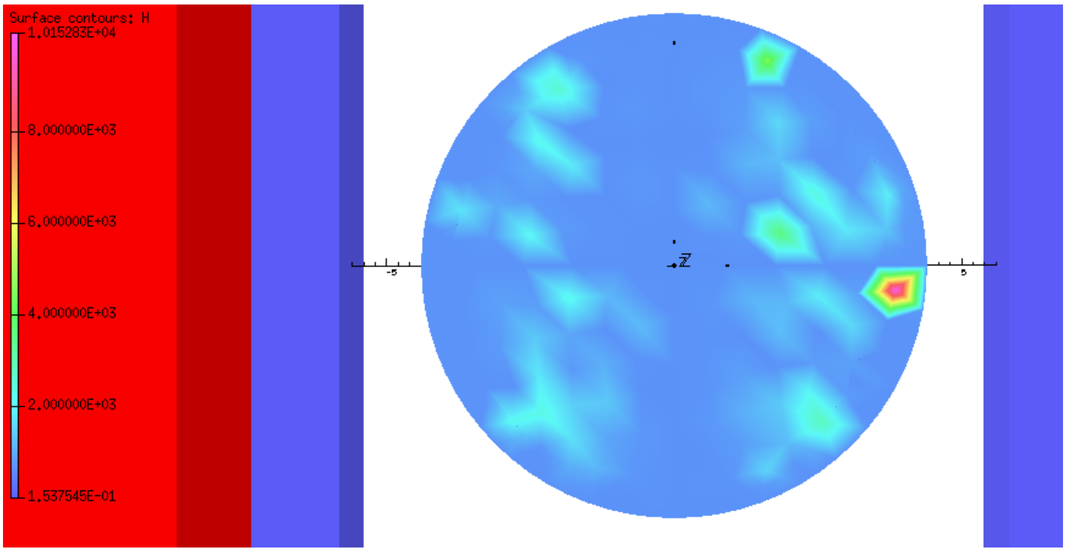

FIGURE 3.7: The magnitude of the surface magnetization of B_x in Oersted simulated without a foil-holder.

In Fig. 3.7 the surface magnetization H also exhibits the non-uniformity of the vertical bars. The changes in H are

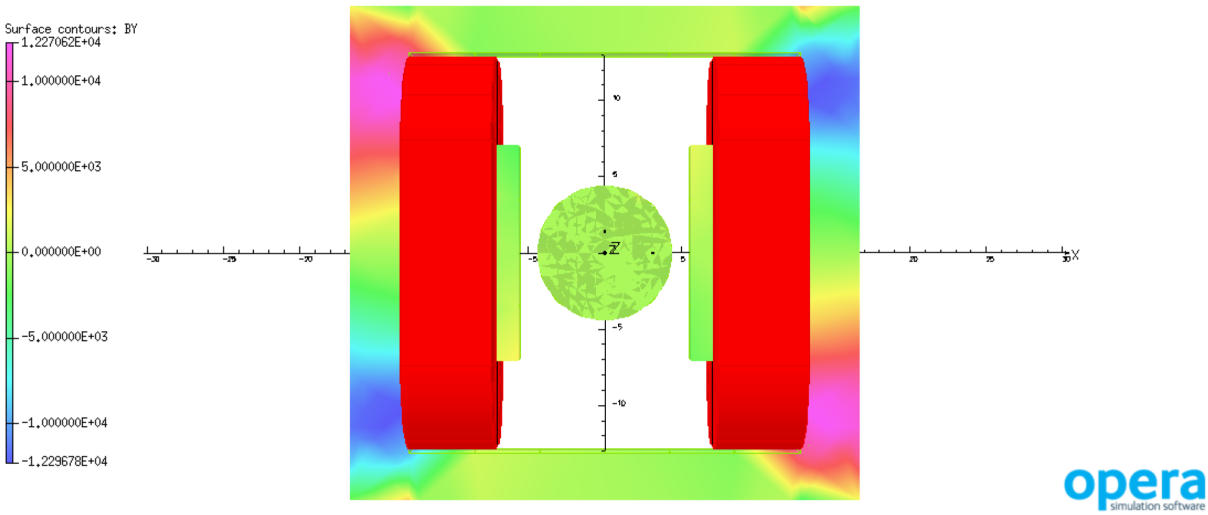

FIGURE 3.8: Surface magnetization in B_y direction of the RCNP spin Analyzer simulation. The magnetization is measured in Gauss and the postion is measure in mm.

In figure 3.8 there is no determinable difference in the surface magnetization in the B_y direction, being near zero.

A comparison of the RCNP geometry simulations against real life measurements of magnetic field normal to the spin analyzer foil.

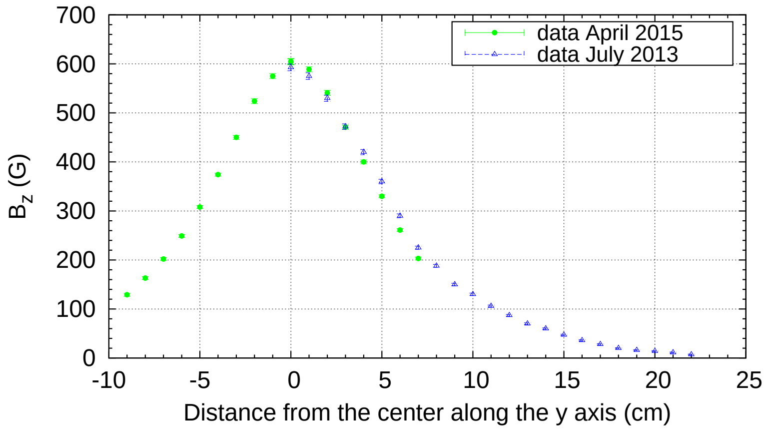

FIGURE 3.9: A scan of magnetic magnitude as a function of vertical distance from foil centre location. This is in the B_z direction in our coordinate choice, but in B_y in RCNPs coordinated choice (Data from Edgard Pierre) .

In Fig. 3.9 the magnetization goes to zero near 20 cm away form the center of the foil, but the simulation (shown in blue Fig. 3.10) goes towards zero closer at 10 cm. This is most likely a result of the choice of BH curve of the steel to be more magnetic than intended.

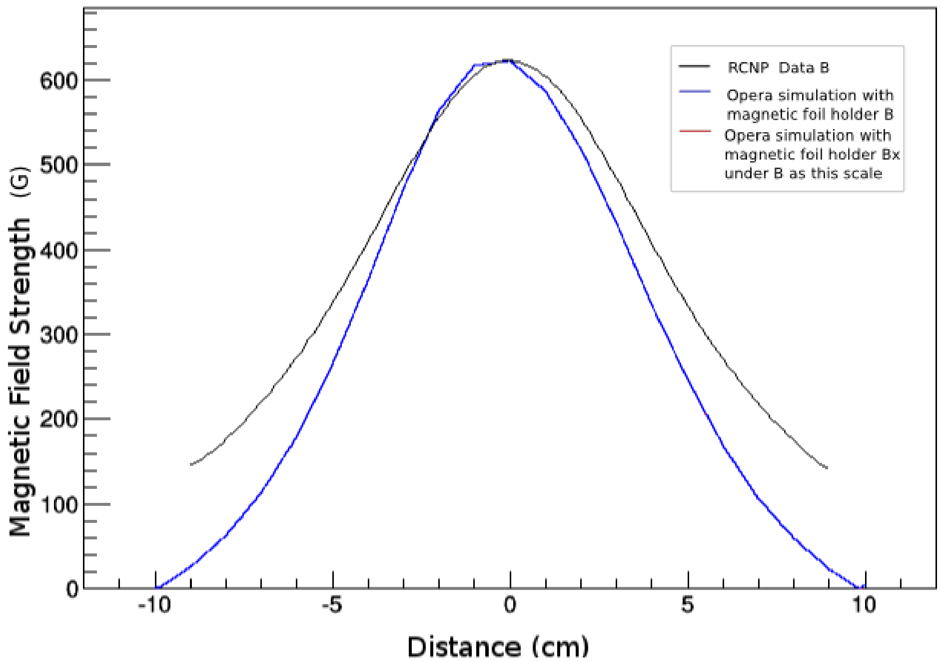

FIGURE 3.10: The scan of the magnetic field as a function of vertical distance from the center of the spin analyzer. Black is a measurement from the RCNP geometry without the stainless steel foil holder (Data from Edgard Pierre). Blue and Red are simulations of the magnitude of the magnetic field and the B_x component of the field, respectively as a function of position along the z-direction with foil holder (Blue and Red appear overlaid).

In Fig. 3.10 the RCNP coil data was used to determine the current density of the coil. This was done by running the simulation multiple times with different current densities. An initial guess was used; for the current density of the coil and then changed based on a linear interpolation until the field value simulated matched that of the measurement to the 1 G level. The simulated coil was determined to have approximately 500 turns and a wire diameter of 0.2 mm.

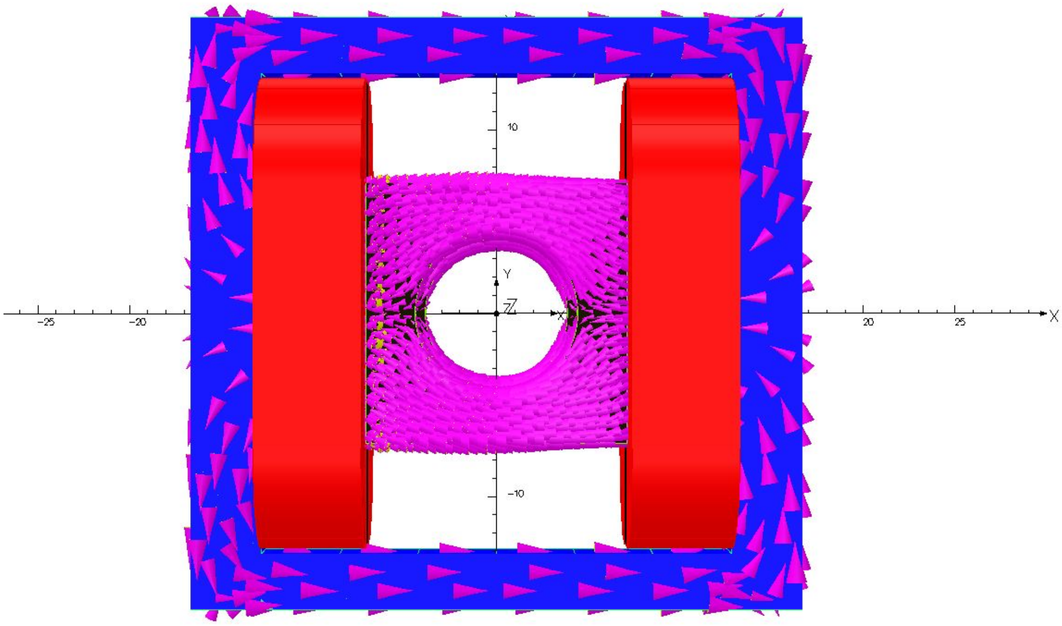

Figure 3.11: Each cell face has the unit vector of the magnetization direction on the surface. The foil holder has magnetization vectors that bow outwards.

In Fig. 3.10 the black line shows the measurement of the magnetic field as a function of z, when the foil holder and the foil are not present. We see that the blue curve from the Opera simulation is a little asymmetric about zero. This asymmetry is due to the foil holder, leading to the belief that the foil holder should be non-magnetic stainless steel. The fact that the RCNP field maps were made without the foil holder in place while in the calculations assumed there was one when we predicted that the foil had 500 turn of 0.2 mm wire diameter means that the current density used in teh simulation will need to be re-tuned.

Chapter 4

Conclusion and Future Work

4.1 Conclusion

Three simulations have been prepared for use in Opera to test the magnetization of the thin iron foil for. One geometry uses neodymium magnets, the second a thin race track coil and the third uses the geometry of the RCNP analyzer foil RCNP geometry. The RCNP simulation can correctly simulate the magnetic field when there is no stainless steel foil holder and no SA foil. Further investigations of the non-uniformity in the magnetic saturation of the thin iron foil seen in the simulation needs to be carried out.

4.2 Future Work

Looking further to using the geometry and write a Monte Carlo that simulates 1D neutrons with 3D spins that simultaneously checks if the adiabatic condition is followed as it travels along a path and calculated the probability of reflection/transmission at the SA foil.

We can use the aforementioned Monte Carlo to calculate the evolution of spin along the SF portion, by checking the magnetization and the changing monotonic B_1 field making sure the adiabatic fast passage conditions are met, using the velocity of decent to calculated the modulated B_1 to make sure the spin conditions are met.

Testing the magnetic fields against the simulated Monte Carlo with a velocity distribution will ensure that each UCN will undergo a spin flip at the SF and correctly be reflected or transmitted by the SA foil.

There are three main future steps i the design of teh SA and SH. The first step once the static field map is complete, is to design the SF RF coil and pick their frequency so that spin flipping occurs. The second step is to simulated teh field of the SF coils. Finally these simulated fields can be used in a neutron spin tracking code to estimate the efficiency of the combined SA and SF system.

Additionally the multi-spin analyzer system needs to be simulated. Simulating the leakage and cross effect of the opposite detector and opposite spin analyzer will have to be addressed in the future.

Further simulations would include tests using 100% polarized neutrons dropped from the holding cell through the SF and the SA can be used to test the efficiency in more detail than simple spin tracking. Once hardware is developed and built, measurements with polarized UCN can be done to verify the simulated efficiency of the SF-SA combination.

Appendix A

Opera Simulation Macro Files

Iron Foil Magnetized by Magnets

fe_foil_magnets_ver2.co

```
GUIOPTIONS set CONSOLEVIEW=yes

CYLINDER Name='foil' X0=0 Y0=0 Z0=-.00005 X1=0 Y1=0 Z1=+.00005 -TUBE SHAPECONTROL=SIMPLE
     MAJORRADIUS=4.25 MINORRADIUS=4.25 TOPRADIUS=4.25 SIDES=2 MATERIALLABEL='Fe'
/CYLINDER Name='Cylinderinner' X0=0 Y0=0 Z0=-2 X1=0 Y1=0 Z1=2 -TUBE SHAPECONTROL=SIMPLE
    MAJORRADIUS=9 MINORRADIUS=9 TOPRADIUS=9 SIDES=2 MATERIALLABEL='Air' LEVEL=11

 BLOCK Name='Block1' X0=4.75 Y0=-5.08 Z0=1.27 X1=4.75+1.27 Y1=5.08 Z1=-1.27
    MATERIALLABEL='Nd'
 BLOCK Name='Block2' X0=-4.75 Y0=-5.08 Z0=1.27 X1=-4.75-1.27 Y1=5.08 Z1=-1.27
    MATERIALLABEL='Nd'

PICK OPTION=ADD PROPERTY=UniqueName LABEL='Block1'
PICK OPTION=ADD PROPERTY=UniqueName LABEL='Block2'
CELLDATA OPTION=MODIFY MATERIALLABEL='Nd' POTENTIAL=Default ELEMENTTYPE=Linear LEVEL=10
    VOLUMELABEL='xdirected' SIZE=1 ELEMSHAPEPREF=HEXORPRISM
PICK OPTION=ADD PROPERTY=UniqueName LABEL='foil'
CELLDATA OPTION=MODIFY MATERIALLABEL='Fe' POTENTIAL=Default ELEMENTTYPE=Linear LEVEL=12
    SIZE=1 ELEMSHAPEPREF=HEXORPRISM



CYLINDER Name='Cylinderouter' X0=0 Y0=0 Z0=-6 X1=0 Y1=0 Z1=6 -TUBE SHAPECONTROL=SIMPLE
    MAJORRADIUS=12 MINORRADIUS=12 TOPRADIUS=12 SIDES=2 MATERIALLABEL='Air' LEVEL=5

PICK OPTION=ADD PROPERTY=UniqueName LABEL='Cylinderouter'
CELLDATA OPTION=MODIFY MATERIALLABEL='Air' POTENTIAL=Default ELEMENTTYPE=Linear LEVEL=10
     SIZE=1 ELEMSHAPEPREF=HEXORPRISM
```

```
/BLOCK Name='cutplane' X0=0 Y0=-12 Z0=-12 X1=0 Y1=12 Z1=12 MATERIALLABEL='Air'
/ BLOCK Name='cutplane2' X0=-12 Y0=0 Z0=-12 X1=12 Y1=0 Z1=12 MATERIALLABEL='Air'
/$close

/FILL TOL=1.0E-08

BLOCK Name='Yoke1' X0=6 Y0=-5 Z0=-0.3 X1=8 Y1=+5 Z1=0.3 MATERIALLABEL='steel' LEVEL=10
BLOCK Name='YokeEnd' X0=8 Y0=-8 Z0=-2 X1=12 Y1=+8 Z1=2 MATERIALLABEL='steel'
BLOCK Name='YokeSide' X0=0 Y0=8 Z0=-2 X1=12 Y1=12 Z1=2 MATERIALLABEL='steel'
PICK OPTION=ADD PROPERTY=Name LABEL='YokeSide' | TRANSFORM OPTION=COPY KEEP=YES TYPE=
    ROTATE ROTU=1 ROTV=0 ROTW=0 ANGLE=180 COUNT=1
PICK OPTION=ADD PROPERTY=Name LABEL=Yoke1 | PICK OPTION=ADD PROPERTY=Name LABEL=YokeEnd
    | PICK OPTION=ADD PROPERTY=Name LABEL=YokeSide |TRANSFORM OPTION=COPY TYPE=ROTATE
    ROTU=0 ROTV=0 ROTW=1 ANGLE=180 COUNT=1

PICK OPTION=ADD PROPERTY=Name LABEL=Yoke1 | PICK OPTION=ADD PROPERTY=Name LABEL=YokeEnd
    | PICK OPTION=ADD PROPERTY=Name LABEL=YokeSide | COMBINE OPERATION=UNION +REGULAR

/$close


BACKGROUND OPTION=SET SHAPE=BLOCK SCALEX=3 SCALEY=3 SCALEZ=3   XYSYMMETRYPLANE=NO
    YZSYMMETRYPLANE=NO ZXSYMMETRYPLANE=NO ROTZNUM=1


mODEL CREATE
MESH SIZE=5 NORMALTOL=10 SURFACETOL=0.0 TOLERANCE=1.0E-08 TYPE=PREFERMOSAIC
FILL TOL=1.0E-08
BHDATA OPTION=NEW  LABEL='Nd_mag' | BHDATA OPTION=LOAD LABEL=Nd_mag FILE=/opt/vf/
    Opera_17/bh/ndfebo1t.bh
BHDATA OPTION=NEW  LABEL='tenten' | BHDATA OPTION=LOAD LABEL=tenten FILE=/opt/vf/
    Opera_17/bh/tenten.bh
BHDATA OPTION=NEW  LABEL='SI_STEEL' | BHDATA OPTION=LOAD LABEL=SI_STEEL FILE=/home/
    hansenr/SiSteel.bh
BHDATA OPTION=NEW  LABEL='pure_Fe' | BHDATA OPTION=LOAD LABEL=pure_Fe CGS=NO FILE=/home/
    hansenr/pureFe.bh
/data from the program FERMI



MATERIALS PICK 'steel'
MATERIALS OPTION=MODIFY MULINEARITY=NONLINEAR MUANISOTROPY=ISOTROPIC BH='SI_STEEL'
MATERIALS OPTION=MODIFY MULINEARITY=NONLINEAR MUANISOTROPY=ISOTROPIC BH='SI_STEEL'

MATERIALS PICK 'Fe'
MATERIALS OPTION=MODIFY MULINEARITY=NONLINEAR MUANISOTROPY=ISOTROPIC BH='pure_Fe'
MATERIALS OPTION=MODIFY MULINEARITY=NONLINEAR MUANISOTROPY=ISOTROPIC BH='pure_Fe'
```

```
MATERIALS UNPICK 'Fe' | MATERIALS PICK 'Nd'
MATERIALS OPTION=MODIFY MULINEARITY=NONLINEAR MUANISOTROPY=ISOTROPIC BH='Nd_mag'
MATERIALS OPTION=MODIFY MULINEARITY=NONLINEAR MUANISOTROPY=ISOTROPIC BH='Nd_mag'
VOLUME PICK 'xdirected'
VOLUME OPTION=MODIFY THETA=90 PHI=0 PSI=90
/$close
ANALYSISDATA OPTION=SET PROGRAM=TOSCAMAGN LINEAR=NO NLITERTYPE=NEWTON NITERATIONS=21
    TOLERANCE=1.0E-05 HX=0 HY=0 HZ=0 RHS=ADAPTIVE POTENTIALCUT=YES USEDEFORMEDMESH=NO

SOLVERS SOLVENOW=YES SAVEMODEL=YES, | SOLVERS OPTION=TEST FILE='10
    micron_fe_foil_comi_test9' UNITS=CGS ELEMENT=MIXED SURFACE=CURVED | COMMENT CLEAR=YES
     TYPE=DBTITLE | SOLVERS OPTION=OVERWRITE
```

Iron Foil Magnetized by Coil

fe_foil_coil_ver3.co

```
GUIOPTIONS set CONSOLEVIEW=yes

/CYLINDER Name='foil' X0=0 Y0=0 Z0=-.00005 X1=0 Y1=0 Z1=+.00005 -TUBE SHAPECONTROL=
    SIMPLE MAJORRADIUS=4.25 MINORRADIUS=4.25 TOPRADIUS=4.25 SIDES=2 MATERIALLABEL='Fe'
/CYLINDER Name='Cylinderinner' X0=0 Y0=0 Z0=-2 X1=0 Y1=0 Z1=2 -TUBE SHAPECONTROL=SIMPLE
    MAJORRADIUS=9 MINORRADIUS=9 TOPRADIUS=9 SIDES=2 MATERIALLABEL='Air' LEVEL=11

 /BLOCK Name='Block1' X0=4.75 Y0=-5.08 Z0=1.27 X1=4.75+1.27 Y1=5.08 Z1=-1.27
    MATERIALLABEL='Nd'
 /BLOCK Name='Block2' X0=-4.75 Y0=-5.08 Z0=1.27 X1=-4.75-1.27 Y1=5.08 Z1=-1.27
    MATERIALLABEL='Nd'

/PICK OPTION=ADD PROPERTY=UniqueName LABEL='Block1'
/PICK OPTION=ADD PROPERTY=UniqueName LABEL='Block2'
/CELLDATA OPTION=MODIFY MATERIALLABEL='Nd' POTENTIAL=Default ELEMENTTYPE=Linear LEVEL=10
     VOLUMELABEL='xdirected' SIZE=1 ELEMSHAPEPREF=HEXORPRISM
/PICK OPTION=ADD PROPERTY=UniqueName LABEL='foil'

/CELLDATA OPTION=MODIFY MATERIALLABEL='Fe' POTENTIAL=Default ELEMENTTYPE=Linear LEVEL=12
     SIZE=1 ELEMSHAPEPREF=HEXORPRISM


BLOCK Name='Yoke1' X0=4.5 Y0=-5 Z0=-0.3 X1=8 Y1=+5 Z1=0.3 MATERIALLABEL='steel' LEVEL=10
BLOCK Name='YokeEnd' X0=8 Y0=-8 Z0=-2 X1=12 Y1=+8 Z1=2 MATERIALLABEL='steel'
BLOCK Name='YokeSide' X0=0 Y0=8 Z0=-2 X1=12 Y1=12 Z1=2 MATERIALLABEL='steel'
PICK OPTION=ADD PROPERTY=Name LABEL='YokeSide' | TRANSFORM OPTION=COPY KEEP=YES TYPE=
    ROTATE ROTU=1 ROTV=0 ROTW=0 ANGLE=180 COUNT=1
```

```
PICK OPTION=ADD PROPERTY=Name LABEL=Yoke1 | PICK OPTION=ADD PROPERTY=Name LABEL=YokeEnd
    | PICK OPTION=ADD PROPERTY=Name LABEL=YokeSide |TRANSFORM OPTION=COPY TYPE=ROTATE
    ROTU=0 ROTV=0 ROTW=1 ANGLE=180 COUNT=1

PICK OPTION=ADD PROPERTY=Name LABEL=Yoke1 | PICK OPTION=ADD PROPERTY=Name LABEL=YokeEnd
    | PICK OPTION=ADD PROPERTY=Name LABEL=YokeSide | COMBINE OPERATION=UNION +REGULAR




STRAIGHT OPTION=NEW -KEEP WIDTH=0.2 THICKNESS=0.2 H1=10 INCIRCUIT=NO CIRCUITELEMENT=
    CURD=400 TOLERANCE=0 DRIVELABEL='Default Drive' LCNAME='Global coordinate system'
    XCEN2=5 YCEN2=-5 ZCEN2=0.5 THETA2=90 PHI2=90 PSI2=180 RXY=0 RYZ=0 RZX=0 SYMMETRY=1
    MODELCOMPONENT=NO
STRAIGHT OPTION=NEW -KEEP WIDTH=0.2 THICKNESS=0.2 H1=10 INCIRCUIT=NO CIRCUITELEMENT=
    CURD=-400 TOLERANCE=0 DRIVELABEL='Default Drive' LCNAME='Global coordinate system'
    XCEN2=5 YCEN2=-5 ZCEN2=-0.5 THETA2=90 PHI2=90 PSI2=180 RXY=0 RYZ=0 RZX=0 SYMMETRY=1
    MODELCOMPONENT=NO

STRAIGHT OPTION=NEW -KEEP WIDTH=0.2 THICKNESS=0.2 H1=10 INCIRCUIT=NO CIRCUITELEMENT=
    CURD=400 TOLERANCE=0 DRIVELABEL='Default Drive' LCNAME='Global coordinate system'
    XCEN2=-5 YCEN2=-5 ZCEN2=0.5 THETA2=90 PHI2=90 PSI2=180 RXY=0 RYZ=0 RZX=0 SYMMETRY=1
    MODELCOMPONENT=NO
STRAIGHT OPTION=NEW -KEEP WIDTH=0.2 THICKNESS=0.2 H1=10 INCIRCUIT=NO CIRCUITELEMENT=
    CURD=-400 TOLERANCE=0 DRIVELABEL='Default Drive' LCNAME='Global coordinate system'
    XCEN2=-5 YCEN2=-5 ZCEN2=-0.5 THETA2=90 PHI2=90 PSI2=180 RXY=0 RYZ=0 RZX=0 SYMMETRY=1
    MODELCOMPONENT=NO

ARC OPTION=NEW -KEEP WIDTH=0.2 THICKNESS=0.2 R1=0.4 ANGLE=180 INCIRCUIT=NO
    CIRCUITELEMENT= CURD=400 TOLERANCE=0 DRIVELABEL='Default Drive' LCNAME='Global
    coordinate system' XCEN2=-5 YCEN2=-5 ZCEN2=-0.5 THETA2=90 PHI2=-90 PSI2=90 RXY=0 RYZ
    =0 RZX=0 SYMMETRY=1 MODELCOMPONENT=NO
PICK OPTION=TOGGLE TYPE=COND N=5
TRANSFORM OPTION=COPY KEEP=NO TYPE=ROTATE ROTU=1 ROTV=0 ROTW=0 ANGLE=180 COUNT=1


ARC OPTION=NEW -KEEP WIDTH=0.2 THICKNESS=0.2 R1=0.4 ANGLE=180 INCIRCUIT=NO
    CIRCUITELEMENT= CURD=400 TOLERANCE=0 DRIVELABEL='Default Drive' LCNAME='Global
    coordinate system' XCEN2=5 YCEN2=-5 ZCEN2=-0.5 THETA2=90 PHI2=-90 PSI2=90 RXY=0 RYZ=0
     RZX=0 SYMMETRY=1 MODELCOMPONENT=NO
PICK OPTION=TOGGLE TYPE=COND N=7
TRANSFORM OPTION=COPY KEEP=NO TYPE=ROTATE ROTU=1 ROTV=0 ROTW=0 ANGLE=180 COUNT=1


CYLINDER Name='Cylinderouter' X0=0 Y0=0 Z0=-100 X1=0 Y1=0 Z1=100 -TUBE SHAPECONTROL=
    SIMPLE MAJORRADIUS=20 MINORRADIUS=20 TOPRADIUS=20 SIDES=2 MATERIALLABEL='Air' LEVEL=5

PICK OPTION=ADD PROPERTY=UniqueName LABEL='Cylinderouter'
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CELLDATA OPTION=MODIFY MATERIALLABEL='Air' POTENTIAL=Default ELEMENTTYPE=Linear LEVEL=5
    SIZE=1 ELEMSHAPEPREF=HEXORPRISM


/BLOCK Name='cutplane' X0=0 Y0=-12 Z0=-12 X1=0 Y1=12 Z1=12 MATERIALLABEL='Air'
/ BLOCK Name='cutplane2' X0=-12 Y0=0 Z0=-12 X1=12 Y1=0 Z1=12 MATERIALLABEL='Air'
/$close

/FILL TOL=1.0E-08

BACKGROUND OPTION=SET SHAPE=BLOCK SCALEX=3 SCALEY=3 SCALEZ=3   XYSYMMETRYPLANE=NO
    YZSYMMETRYPLANE=NO ZXSYMMETRYPLANE=NO ROTZNUM=1


MODEL CREATE
MESH SIZE=5 NORMALTOL=10 SURFACETOL=0.0 TOLERANCE=1.0E-08 TYPE=PREFERMOSAIC
FILL TOL=1.0E-08

/BHDATA OPTION=NEW  LABEL='Nd_mag' | BHDATA OPTION=LOAD LABEL=Nd_mag FILE=/opt/vf/
    Opera_17/bh/ndfebo1t.bh

BHDATA OPTION=NEW  LABEL='tenten' | BHDATA OPTION=LOAD LABEL=tenten FILE=/opt/vf/
    Opera_17/bh/tenten.bh
BHDATA OPTION=NEW  LABEL='SI_STEEL' | BHDATA OPTION=LOAD LABEL=SI_STEEL FILE=/home/
    hansenr/SiSteel.bh
BHDATA OPTION=NEW  LABEL='pure_Fe' | BHDATA OPTION=LOAD LABEL=pure_Fe CGS=NO FILE=/home/
    hansenr/pureFe.bh
/have to get new data (or smooth it out with a fit)



MATERIALS PICK 'steel'
MATERIALS OPTION=MODIFY MULINEARITY=NONLINEAR MUANISOTROPY=ISOTROPIC BH='SI_STEEL'
MATERIALS OPTION=MODIFY MULINEARITY=NONLINEAR MUANISOTROPY=ISOTROPIC BH='SI_STEEL'

MATERIALS PICK 'Fe'
MATERIALS OPTION=MODIFY MULINEARITY=NONLINEAR MUANISOTROPY=ISOTROPIC BH='pure_Fe'
MATERIALS OPTION=MODIFY MULINEARITY=NONLINEAR MUANISOTROPY=ISOTROPIC BH='pure_Fe'



/MATERIALS UNPICK 'Fe' | MATERIALS PICK 'Nd'
/MATERIALS OPTION=MODIFY MULINEARITY=NONLINEAR MUANISOTROPY=ISOTROPIC BH='Nd_mag'
/MATERIALS OPTION=MODIFY MULINEARITY=NONLINEAR MUANISOTROPY=ISOTROPIC BH='Nd_mag'
/VOLUME PICK 'xdirected'
/VOLUME OPTION=MODIFY THETA=90 PHI=0 PSI=9

ANALYSISDATA OPTION=SET PROGRAM=TOSCAMAGN LINEAR=NO NLITERTYPE=NEWTON NITERATIONS=21
    TOLERANCE=1.0E-05 HX=0 HY=0 HZ=0 RHS=ADAPTIVE POTENTIALCUT=YES USEDEFORMEDMESH=NO
```

```
SOLVERS SOLVENOW=YES SAVEMODEL=YES, | SOLVERS OPTION=TEST FILE='10
    micron_fe_nofoil_coil3_ver2_comi_test1' UNITS=CGS ELEMENT=MIXED SURFACE=CURVED |
    COMMENT CLEAR=YES TYPE=DBTITLE | SOLVERS OPTION=OVERWRITE
```

RCNP Spin Analyzer

RCNP_analyzer.co

```
/GUIOPTIONS set CONSOLEVIEW=yes
/SELECT AUTOUPDATE=CLOSEWINDOW

/foil
/CYLINDER Name='foil' X0=0 Y0=0 Z0=-.00005 X1=0 Y1=0 Z1=+.00005 -TUBE SHAPECONTROL=
    SIMPLE MAJORRADIUS=4.4 MINORRADIUS=4.4 TOPRADIUS=4.4 SIDES=2 MATERIALLABEL='Fe' LEVEL
    =10

//stainless steel foil holder
/BLOCK Name='FoilHolder' X0=7.0 Y0=7.0 Z0=2.0 X1=-7.0 Y1=-7.0 Z1=-2.0
/CYLINDER Name='HoleThrough' X0=0 Y0=0 Z0=-4.5 X1=0 Y1=0 Z1=4.5 -TUBE SHAPECONTROL=
    SIMPLE MAJORRADIUS=3.9 MINORRADIUS=3.9 TOPRADIUS=3.9 SIDES=2 MATERIALLABEL='Steel'
/PICK OPTION=ADD PROPERTY=UniqueName LABEL='FoilHolder' | PICK OPTION=ADD PROPERTY=
    UniqueName LABEL='HoleThrough'
/COMBINE OPERATION=SUBTRACT +REGULAR
/CYLINDER Name='HoleHalf' X0=0 Y0=0 Z0=-0.00005 X1=0 Y1=0.0 Z1=4.5 -TUBE SHAPECONTROL=
    SIMPLE MAJORRADIUS=4.4 MINORRADIUS=4.4 TOPRADIUS=4.4 SIDES=2
/PICK OPTION=ADD PROPERTY=UniqueName LABEL='FoilHolder' | PICK OPTION=ADD PROPERTY=
    UniqueName LABEL='HoleHalf'
/COMBINE OPERATION=SUBTRACT +REGULAR
/BLOCK Name='YokeSlot' X0=5.6 Y0=-7.5 Z0=-1.5 X1=7.0 Y1=7.5 Z1=1.5
/PICK OPTION=ADD PROPERTY=UniqueName LABEL='FoilHolder' | PICK OPTION=ADD PROPERTY=
    UniqueName LABEL='YokeSlot'
/COMBINE OPERATION=SUBTRACT +REGULAR
/BLOCK Name='YokeSlot2' X0=-5.6 Y0=-7.5 Z0=-1.5 X1=-7.0 Y1=7.5 Z1=1.5
/PICK OPTION=ADD PROPERTY=UniqueName LABEL='FoilHolder' | PICK OPTION=ADD PROPERTY=
    UniqueName LABEL='YokeSlot2'
/COMBINE OPERATION=SUBTRACT +REGULAR

/return yoke
BLOCK Name='Yoke' X0=5.6 Y0=7.0 Z0=1.5 X1=12.7 Y1=-7.0 Z1=-1.5 MATERIALLABEL='Fe'
BLOCK Name='Yoke-01' X0=12.7 Y0=-16.0 Z0=1.5 X1=16.5 Y1=16.0 Z1=-1.5 MATERIALLABEL='Fe'
PICK OPTION=ADD PROPERTY=UniqueName LABEL='Yoke' | PICK OPTION=ADD PROPERTY=UniqueName
    LABEL='Yoke-01'
COMBINE OPERATION=UNION +REGULAR
PICK OPTION=ADD PROPERTY=UniqueName LABEL='Yoke'|TRANSFORM OPTION=COPY KEEP=YES TYPE=
    REFLECT NU=1 NV=0 NW=0 COUNT=1
PICK OPTION=TOGGLE PROPERTY=UniqueName LABEL='Yoke'
```

```
BLOCK Name='Yoke-02' X0=-12.7 Y0=16.0 Z0=1.5 X1=12.7 Y1=13.0 Z1=-1.5 MATERIALLABEL='Fe'
PICK OPTION=ADD  PROPERTY=UniqueName LABEL='Yoke-02'|TRANSFORM OPTION=COPY KEEP=YES TYPE
    =REFLECT NU=0 NV=1 NW=0 COUNT=1
PICK OPTION=TOGGLE PROPERTY=UniqueName LABEL='Yoke-02'

/coil
STRAIGHT OPTION=NEW -KEEP WIDTH=5.6 THICKNESS=5.6 H1=14 INCIRCUIT=NO CIRCUITELEMENT=
    CURD=116.6 TOLERANCE=0 DRIVELABEL='Default Drive' LCNAME='Global coordinate system'
    XCEN2=9.85 YCEN2=-7.0 ZCEN2=4.35 THETA2=90 PHI2=90 PSI2=180 RXY=-1 RYZ=1 RZX=0
    SYMMETRY=1 MODELCOMPONENT=NO
ARC OPTION=NEW -KEEP WIDTH=5.6 THICKNESS=5.6 R1=0.1 ANGLE=90 INCIRCUIT=NO CIRCUITELEMENT
    = CURD=116.6 TOLERANCE=0 DRIVELABEL='Default Drive' LCNAME='Global coordinate system'
     XCEN2=9.85 YCEN2=7 ZCEN2=4.35 THETA2=90 PHI2=90 PSI2=-90 RXY=-1 RYZ=1 RZX=-1
    SYMMETRY=1 MODELCOMPONENT=NO
STRAIGHT OPTION=NEW -KEEP WIDTH=5.6 THICKNESS=5.6 H1=2.9 INCIRCUIT=NO CIRCUITELEMENT=
    CURD=116.6 TOLERANCE=0 DRIVELABEL='Default Drive' LCNAME='Global coordinate system'
    XCEN2=9.85 YCEN2=9.85 ZCEN2=1.45 THETA2=180 PHI2=90 PSI2=-90 RXY=0 RYZ=1 RZX=-1
    SYMMETRY=1 MODELCOMPONENT=NO

/CYLINDER Name='Cylinderinner' X0=0 Y0=0 Z0=-2 X1=0 Y1=0 Z1=2 -TUBE SHAPECONTROL=SIMPLE
    MAJORRADIUS=9 MINORRADIUS=9 TOPRADIUS=9 SIDES=2 MATERIALLABEL='Air' LEVEL=11

 /BLOCK Name='Block1' X0=4.75 Y0=-5.08 Z0=1.27 X1=4.75+1.27 Y1=5.08 Z1=-1.27
    MATERIALLABEL='Nd'
 /BLOCK Name='Block2' X0=-4.75 Y0=-5.08 Z0=1.27 X1=-4.75-1.27 Y1=5.08 Z1=-1.27
    MATERIALLABEL='Nd'

/PICK OPTION=ADD PROPERTY=UniqueName LABEL='Block1'
/PICK OPTION=ADD PROPERTY=UniqueName LABEL='Block2'
/CELLDATA OPTION=MODIFY MATERIALLABEL='Nd' POTENTIAL=Default ELEMENTTYPE=Linear LEVEL=10
     VOLUMELABEL='xdirected' SIZE=1 ELEMSHAPEPREF=HEXORPRISM

/PICK OPTION=ADD PROPERTY=UniqueName LABEL='foil'
/CELLDATA OPTION=MODIFY MATERIALLABEL='Fe' POTENTIAL=Default ELEMENTTYPE=Linear LEVEL=12
     SIZE=1 ELEMSHAPEPREF=Tetrahedral

/PICK OPTION=ADD PROPERTY=UniqueName LABEL='FoilHolder'
/CELLDATA OPTION=MODIFY MATERIALLABEL='steel' POTENTIAL=Default ELEMENTTYPE=Linear LEVEL
    =12 SIZE=1 ELEMSHAPEPREF=Tetrahedral


/$close

CYLINDER Name='Cylinderouter' X0=0 Y0=0 Z0=-10 X1=0 Y1=0 Z1=10 -TUBE SHAPECONTROL=SIMPLE
     MAJORRADIUS=4.4 MINORRADIUS=4.4 TOPRADIUS=4.4 SIDES=2 MATERIALLABEL='Air' LEVEL=5

PICK OPTION=ADD PROPERTY=UniqueName LABEL='Cylinderouter'
CELLDATA OPTION=MODIFY MATERIALLABEL='Air' POTENTIAL=Reduced ELEMENTTYPE=Linear LEVEL=10
     SIZE=1 ELEMSHAPEPREF=None
```

```
CYLINDER Name='Cylinder' X0=0 Y0=0 Z0=-20 X1=0 Y1=0 Z1=20 +TUBE SHAPECONTROL=TUBE
    MAJORRADIUS=20 MINORRADIUS=20 TOPRADIUS=20 THICKNESS=0 SIDES=2 MATERIALLABEL='Air'

BLOCK Name='cutplane' X0=0 Y0=-20 Z0=-20 X1=0 Y1=20 Z1=20 MATERIALLABEL='Air'
BLOCK Name='cutplane2' X0=-20 Y0=0 Z0=-20 X1=20 Y1=0 Z1=20 MATERIALLABEL='Air'
/$close

/FILL TOL=1.0E-08

BACKGROUND OPTION=SET SHAPE=BLOCK SCALEX=3 SCALEY=3 SCALEZ=3   XYSYMMETRYPLANE=NO
    YZSYMMETRYPLANE=NO ZXSYMMETRYPLANE=NO ROTZNUM=1

///
MODEL CREATE
MESH SIZE=5 NORMALTOL=10 SURFACETOL=0.0 TOLERANCE=1.0E-08 TYPE=PREFERMOSAIC
FILL TOL=1.0E-08

/BHDATA OPTION=NEW  LABEL='Nd_mag' | BHDATA OPTION=LOAD LABEL=Nd_mag FILE=/opt/vf/
    Opera_17/bh/ndfebo1t.bh
BHDATA OPTION=NEW  LABEL='tenten' | BHDATA OPTION=LOAD LABEL=tenten FILE=/opt/vf/
    Opera_17/bh/tenten.bh
BHDATA OPTION=NEW  LABEL='SI_STEEL' | BHDATA OPTION=LOAD LABEL=SI_STEEL FILE=/home/
    hansenr/SiSteel.bh
BHDATA OPTION=NEW  LABEL='pure_Fe' | BHDATA OPTION=LOAD LABEL=pure_Fe CGS=NO FILE=/home/
    hansenr/pureFe.bh
/have to get new data (or smooth it out with a fit)



/MATERIALS PICK 'steel'
/MATERIALS OPTION=MODIFY MULINEARITY=NONLINEAR MUANISOTROPY=ISOTROPIC BH='tenten'
/MATERIALS OPTION=MODIFY MULINEARITY=NONLINEAR MUANISOTROPY=ISOTROPIC BH='tenten'

MATERIALS PICK 'Fe'
MATERIALS OPTION=MODIFY MULINEARITY=NONLINEAR MUANISOTROPY=ISOTROPIC BH='pure_Fe'
MATERIALS OPTION=MODIFY MULINEARITY=NONLINEAR MUANISOTROPY=ISOTROPIC BH='pure_Fe'


/MATERIALS UNPICK 'Fe' | MATERIALS PICK 'Nd'
/MATERIALS OPTION=MODIFY MULINEARITY=NONLINEAR MUANISOTROPY=ISOTROPIC BH='Nd_mag'
/MATERIALS OPTION=MODIFY MULINEARITY=NONLINEAR MUANISOTROPY=ISOTROPIC BH='Nd_mag'
/VOLUME PICK 'xdirected'
/VOLUME OPTION=MODIFY THETA=90 PHI=0 PSI=90
/$close
ANALYSISDATA OPTION=SET PROGRAM=TOSCAMAGN LINEAR=NO NLITERTYPE=NEWTON NITERATIONS=21
    TOLERANCE=1.0E-05 HX=0 HY=0 HZ=0 RHS=ADAPTIVE POTENTIALCUT=YES USEDEFORMEDMESH=NO
```

```
SOLVERS SOLVENOW=YES SAVEMODEL=YES, | SOLVERS OPTION=TEST FILE='RCNP_coil_test12' UNITS=
    CGS ELEMENT=MIXED SURFACE=CURVED | COMMENT CLEAR=YES TYPE=DBTITLE | SOLVERS OPTION=
    OVERWRITE
/END
/Yes
```

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