nEDMGroup

Minimizing Environmental Magnetic Field Sources for nEDM

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Background:

What is nEDM?

neutron Electric Dipole Moment

+2/3e (u-quark), -2(1/3e) (d-quarks) $\ell \longrightarrow \vec{d} = q\,\vec{l}$ (eq. 1)

How big is the nEDM?

Current Experimental Upper Bound:	vs.	Standard Model Prediction:
$d_n < 3\times10^{-26}$ e-cm		$d_n \approx 10^{-31}$ e-cm

Why do we care about something so small?

I. Possible Explanation to the Baryon Asymmetry Problem

The nEDM is a source of charge-parity symmetry violation

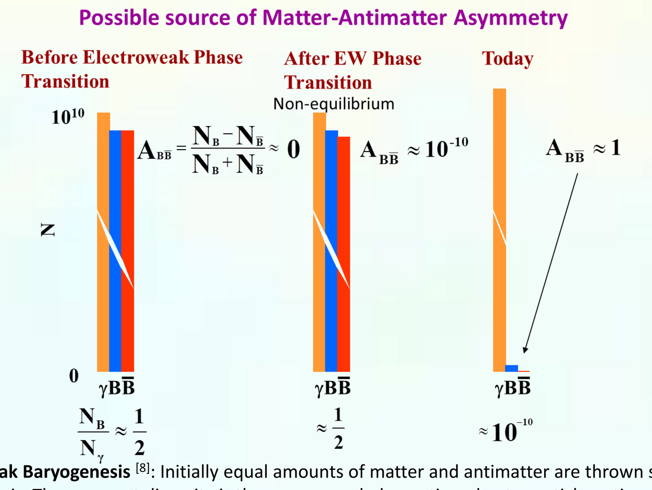
Sakharov Conditions

1. At least one B-number violating process.
2. C- and CP-violation
3. Interactions outside of thermal equilibrium.

Andrei Sakharov, "CP Symmetry Violation, C-Asymmetry, and Baryon Asymmetry of the Universe"

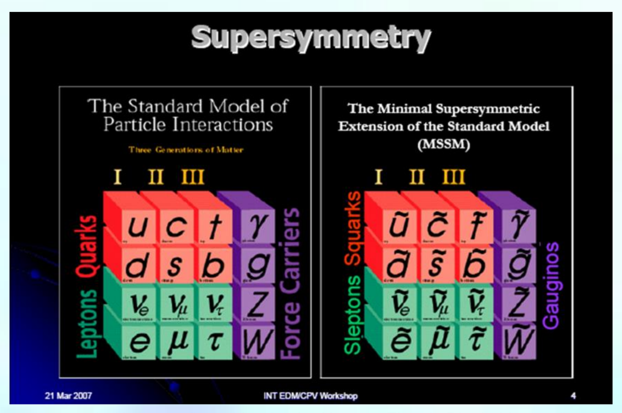
Electroweak Baryogenesis

Possible source of Matter-Antimatter Asymmetry



Electroweak Baryogenesis [8]: Initially equal amounts of matter and antimatter are thrown slightly off balance during Baryogenesis. The apparent disparity is then compounded over time due to particle-antiparticle annihilation.

II. Helps us determine the plausible theories extending beyond the standard Model

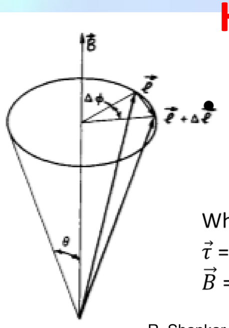


Brad Filippone, "Searching for the Neutron Electric Dipole Moment"

Which theories can we now falsify?

Which theories had we slepton?

How will you measure it?



- Precession of Angular Momentum:

$$\vec{\tau} = \frac{d\vec{l}}{dt} = \vec{\mu} \times \vec{B} = \gamma(\vec{l} \times \vec{B}) \quad \text{(eq. 2)}$$

Where:
$\vec{\tau}$ = torque, $\vec{l}$ = angular momentum, $\vec{\mu}$ = magnetic dipole moment,
$\vec{B}$ = magnetic field, γ = gyromagnetic ratio

R. Shankar, "Principles of Quantum Mechanics (Second Edition)"

- Larmor Frequency:

$$\omega_n = -2\frac{\mu_n B_0 \pm d_n E}{\hbar} \quad \text{(eq. 3)}$$

Where:
ω_n = precession frequency, μ_n = magnetic dipole moment, d_n = electric dipole moment,
B_0 = strength of magnetic holding field, E = strength of applied electric field, $\hbar$ = reduced Planck's constant

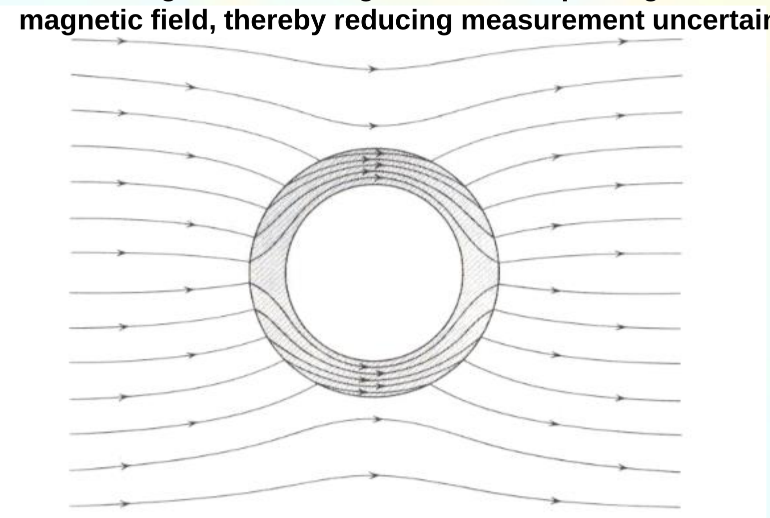
Pshh… Sounds Easy!

- Systematic Uncertainty from Geometric Phase Effect:

$$\delta\omega_n(\omega_0) = -\gamma^2\frac{E}{c}\left(\omega_0 \operatorname{Im}[G_y S_{yy}(\omega_0) + G_z S_{zz}(\omega_0)] + G_y\frac{L_y^2}{12} + G_z\frac{L_z^2}{12}\right) \quad \text{(eq. 4)}$$

Where:
$\delta\omega_n$ = frequency shift, γ = neutron gyromagnetic ratio, ω_0 = precession frequency due to holding field only,
c = speed of light, S_{ii} = position correlation function spectrum, L_j = length of measurement cell in j direction,
G_k = linear magnetic field gradient wrt k

We use magnetic shielding to minimize spatial gradients the magnetic field, thereby reducing measurement uncertainty:



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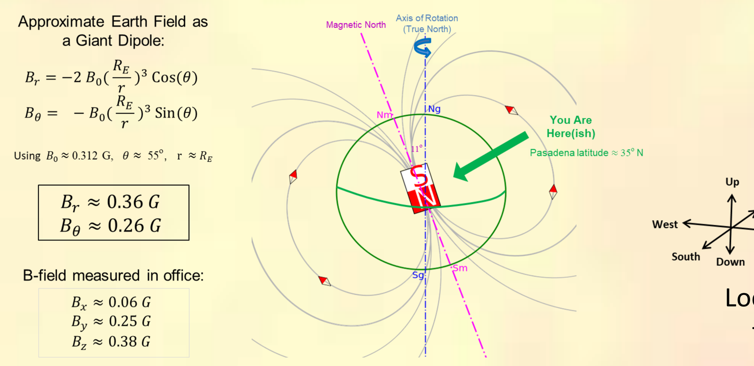
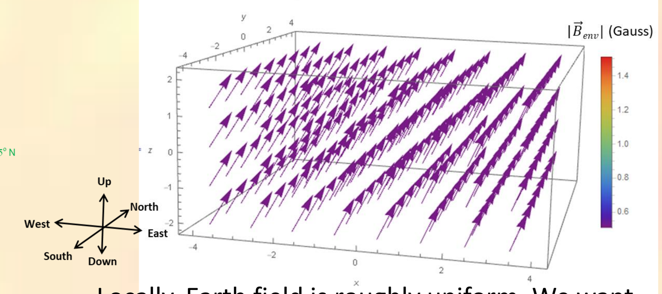
Materials with high magnetic permeability divert field lines away from the volumes they enclose.

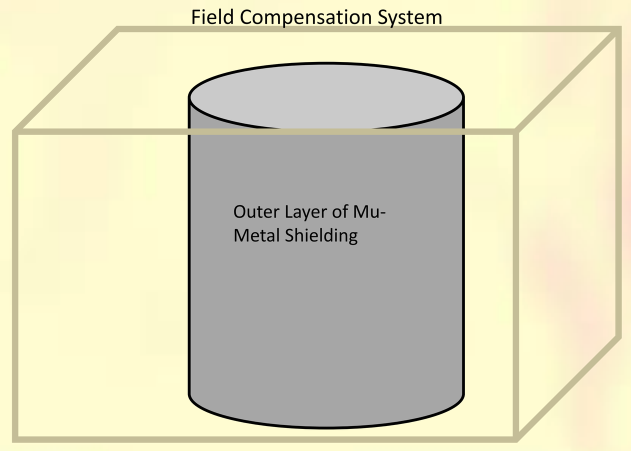
Field Compensation System (FCS)



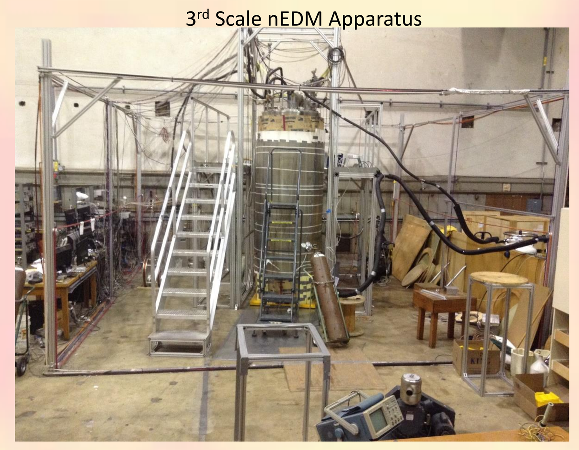


Locally, Earth field is roughly uniform. We want to offset this large constant field with FCS.

Field Compensation System

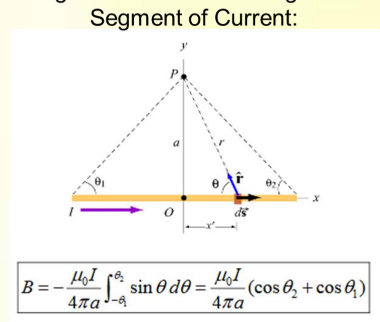


3rd Scale nEDM Apparatus

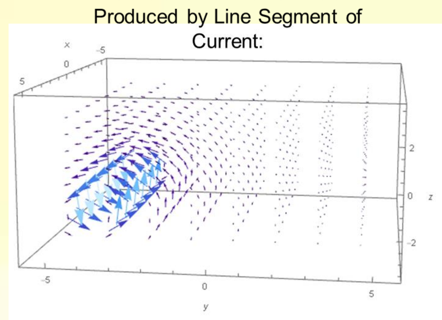


FCS Simulation with Mathematica:

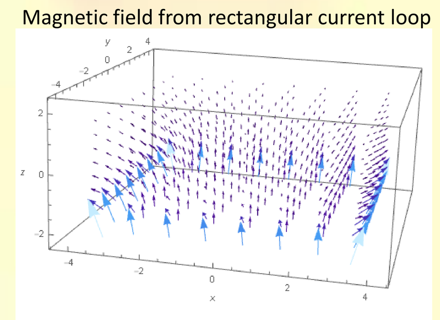
Magnetic Field from a Single Line Segment of Current:



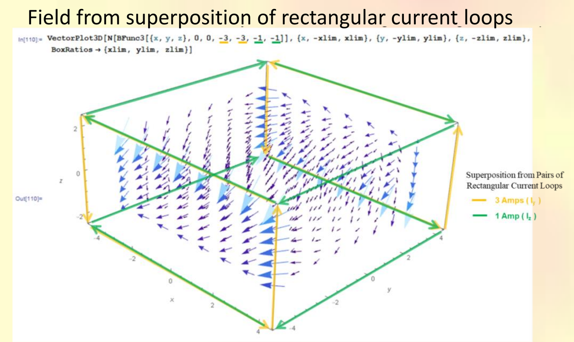
Simulation of Vector Field Produced by Line Segment of Current:

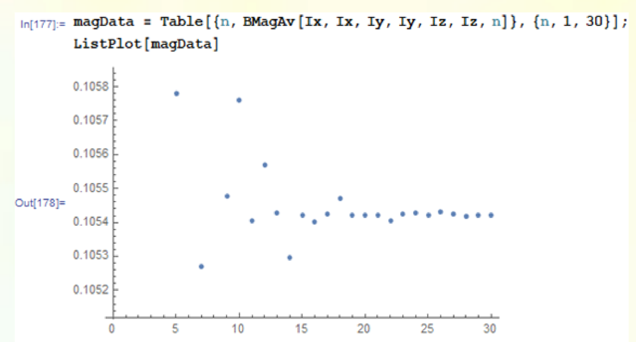


Magnetic field from rectangular current loop

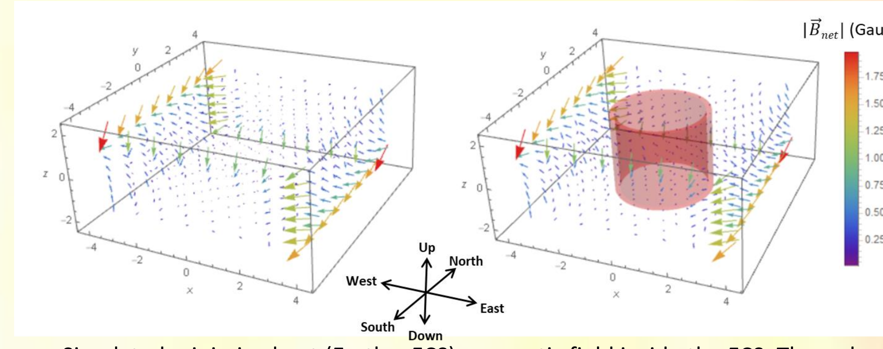


Field from superposition of rectangular current loops



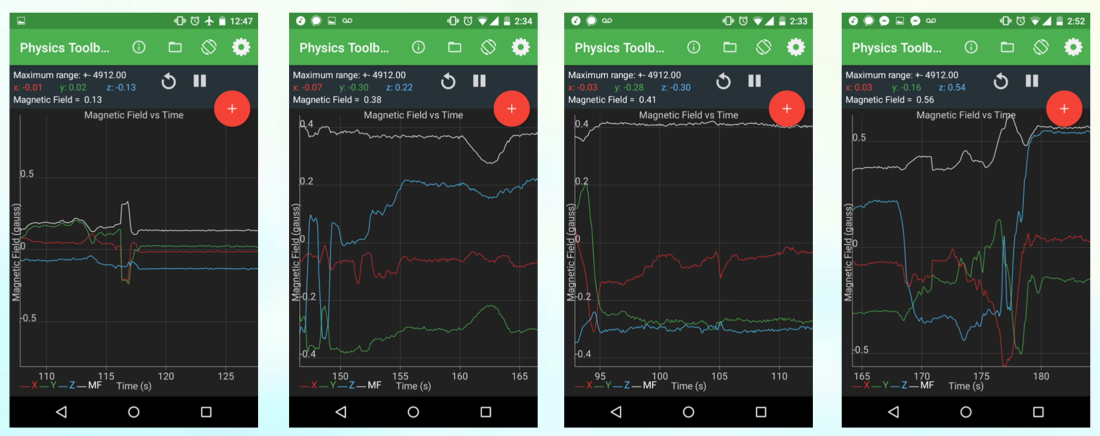


Average net B-field Magnitude as a function of the number of sample points (n). As n increases, the average converges to a stable estimate.

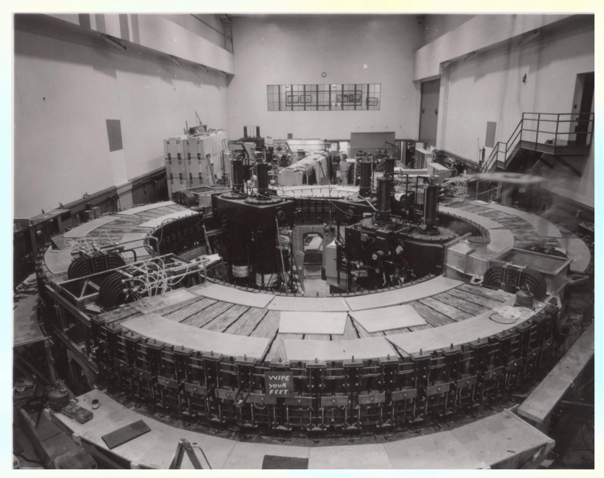


Simulated minimized net (Earth + FCS) magnetic field inside the FCS. The red cylinder, (right) represents the location of the Mu-Metal shielding.

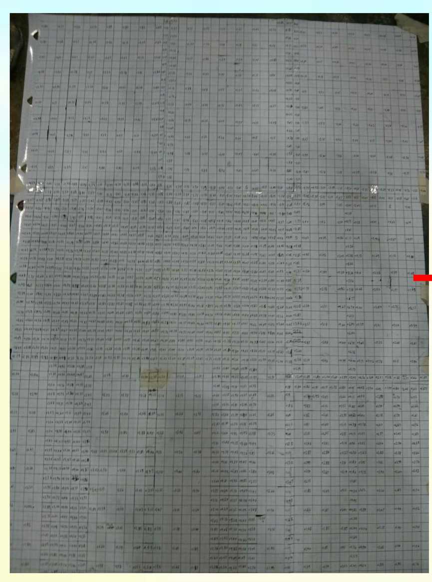
Floor Magnetization, Pt. 1



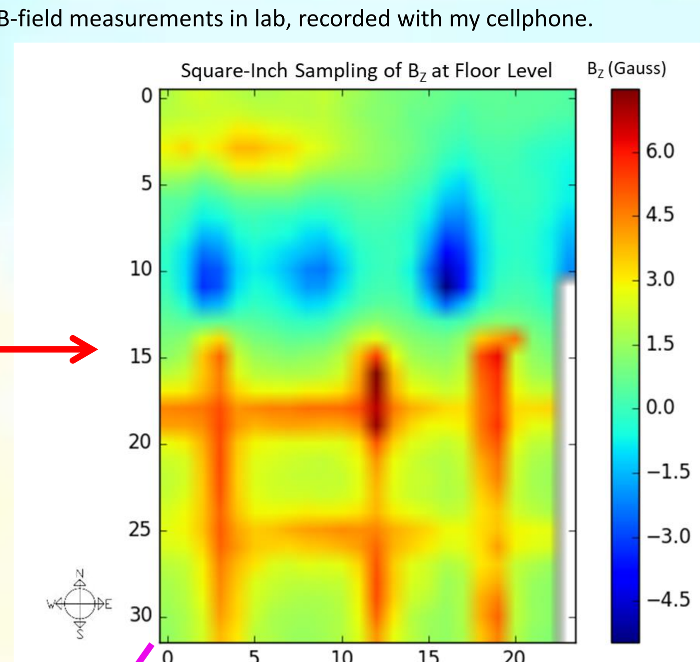
Environmental B-field measurements in lab, recorded with my cellphone.



Caltech Electron Synchrotron, circa ~1970

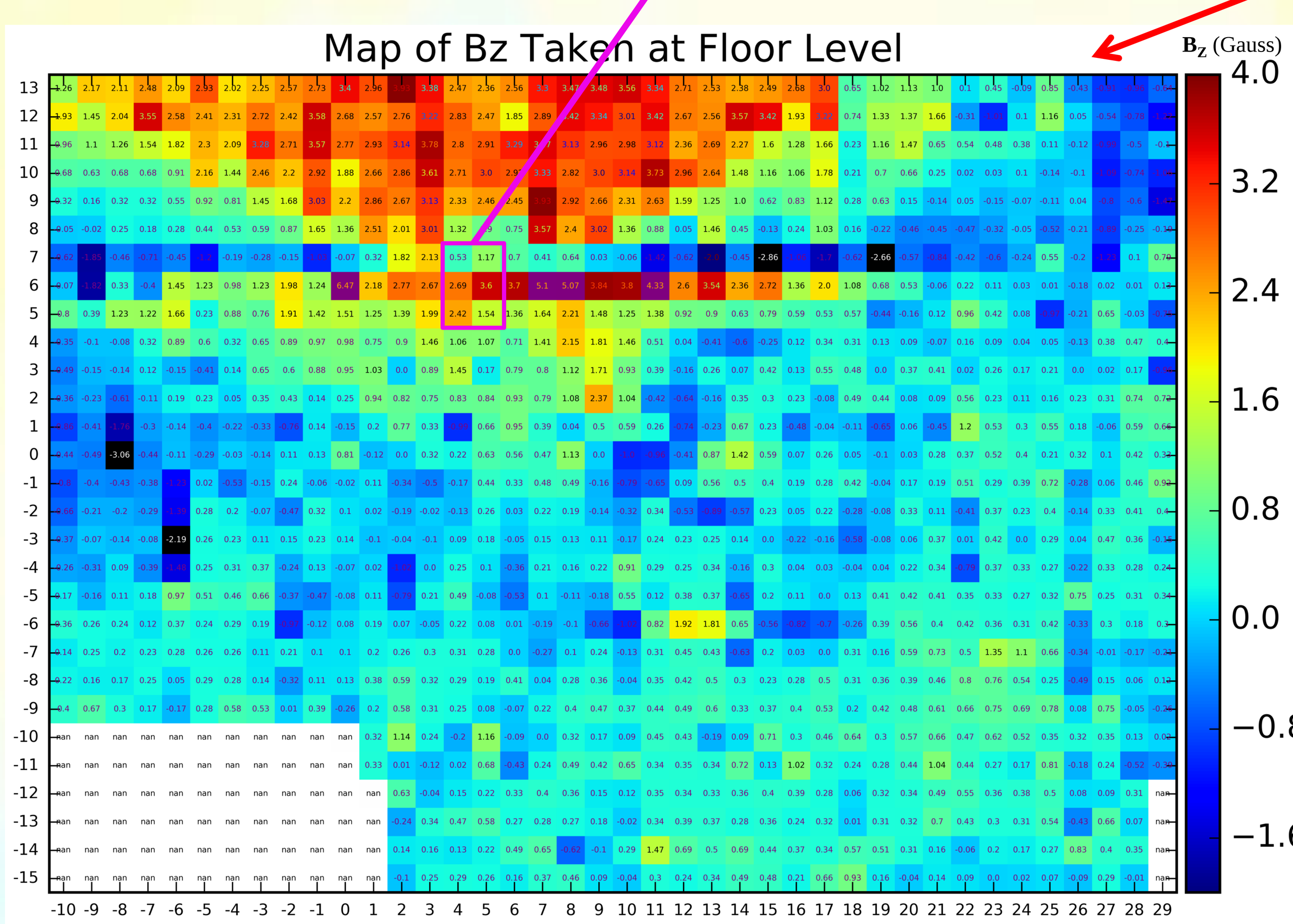


Gross-looking raw data

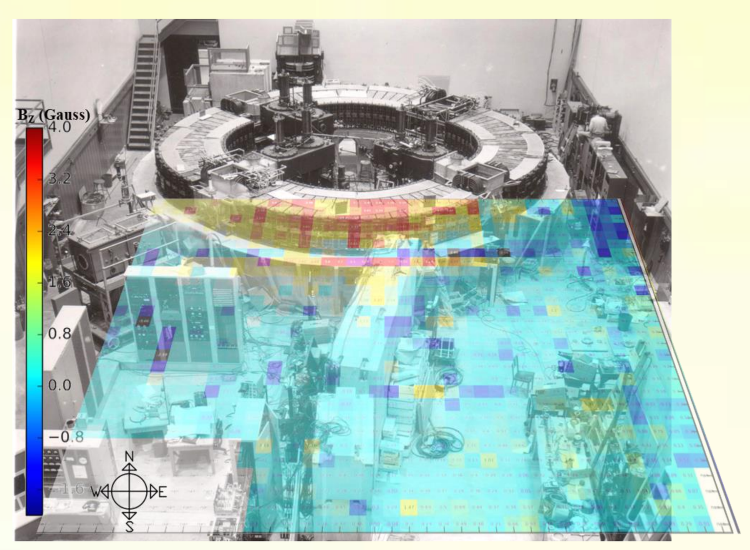


Floor field intensity map, with x and y axes are in inches.

Me marking off points to measure every square foot.

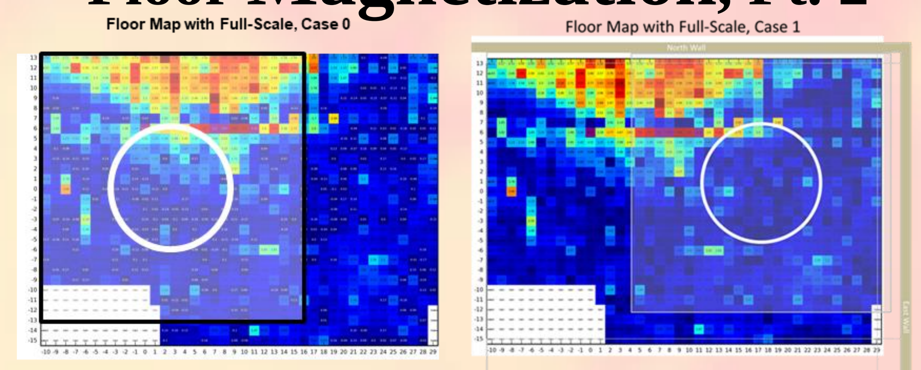


Floor field intensity map, with x and y in feet.

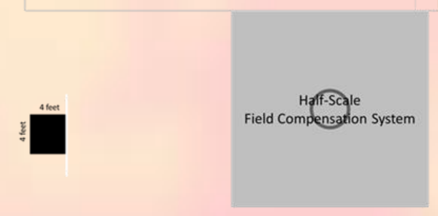


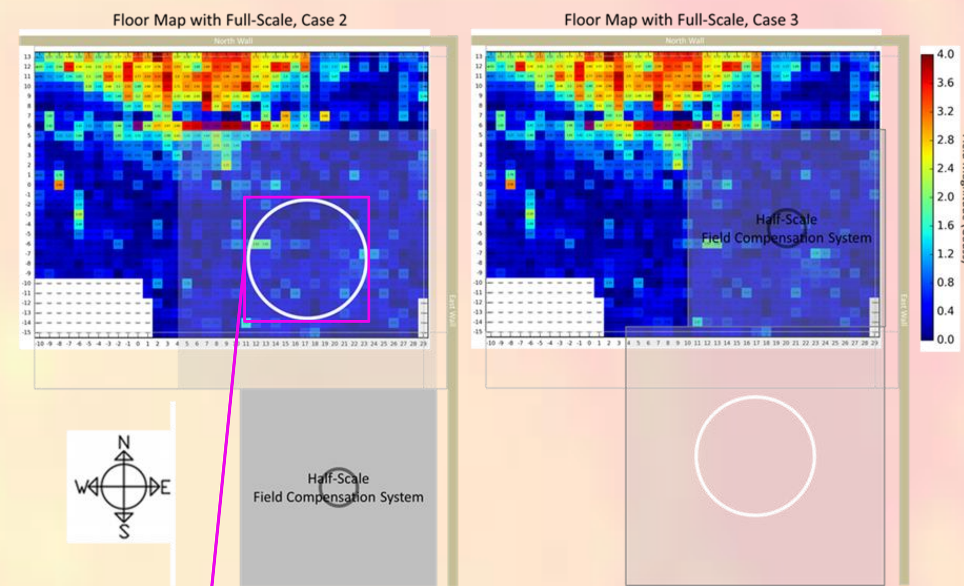
A (rough) projection of the Bz map onto the Synchrotron layout. The overlap is quite suggestive…

Floor Magnetization, Pt. 2



Possible floor layouts for the nEDM experiment. The big square and circle represent the full scale FCS and Mu-Metal shielding. The smaller square and circle correspond to the third-scale apparatus.

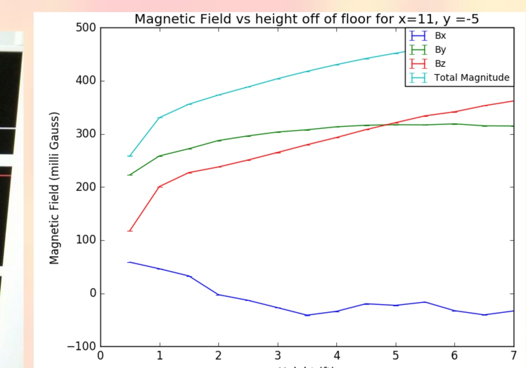




3D Field Mapping with Fluxgate Magnetometer

Three-axis fluxgate magnetometer, attached to a pole with every half-foot marked off.

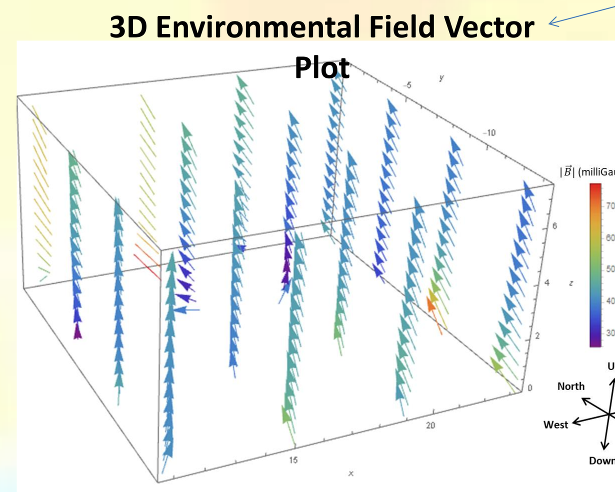
Example timestream of fluxgate data.



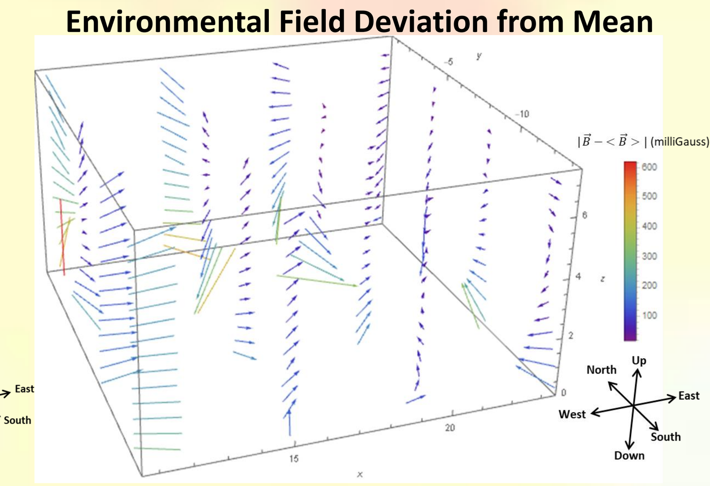
Magnetic field components as a function of height off floor.

By recording this type of data at 16 different (x,y) coordinates…

3D Environmental Field Vector Plot



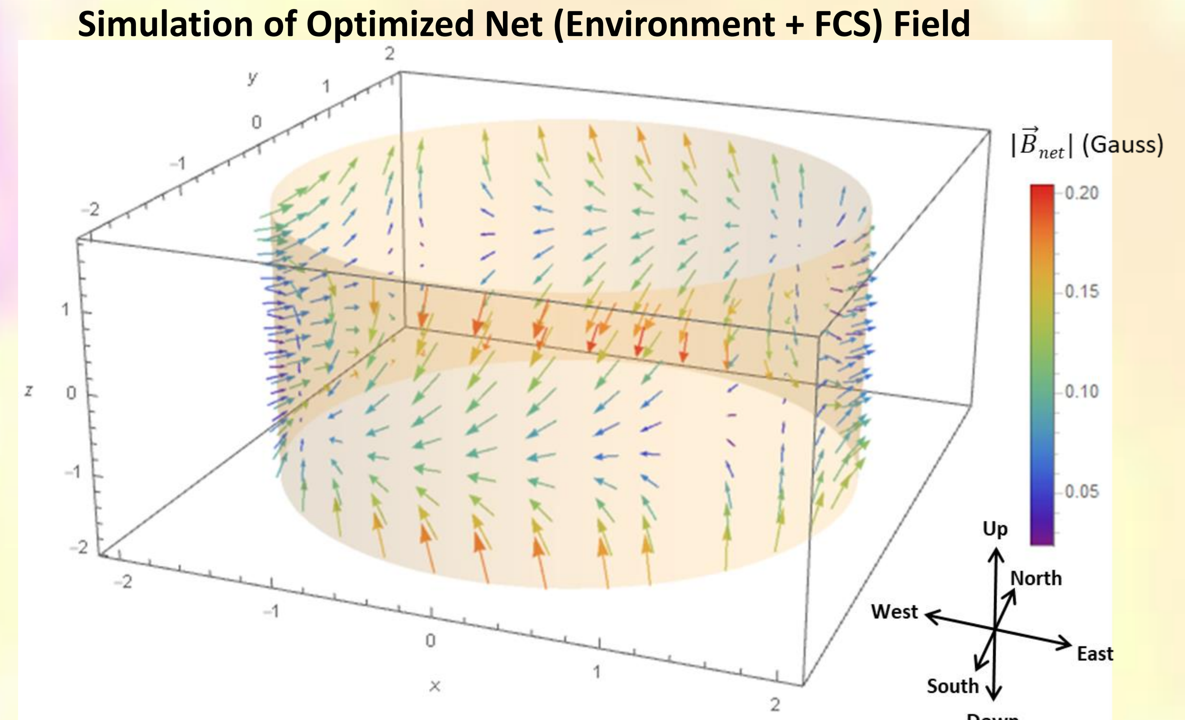
Environmental Field Deviation from Mean



Average B-field components as measured by fluxgate:	vs.	B-field measured in office:
$B_x \approx 0.01\,G$		$B_x \approx 0.06\,G$
$B_y \approx 0.26\,G$		$B_y \approx 0.25\,G$
$B_z \approx 0.32\,G$		$B_z \approx 0.38\,G$

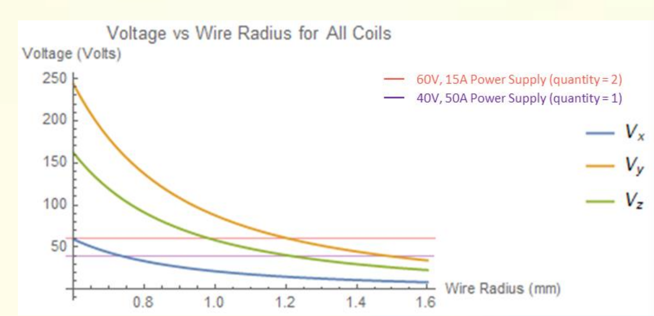
By approximating the "true" environmental field as it's (component-wise) average, I was able to use my FCS simulation to estimate the optimal FCS current response, as well as the resulting net field (which will need to be shielded by the Mu-Metal).

Simulation of Optimized Net (Environment + FCS) Field

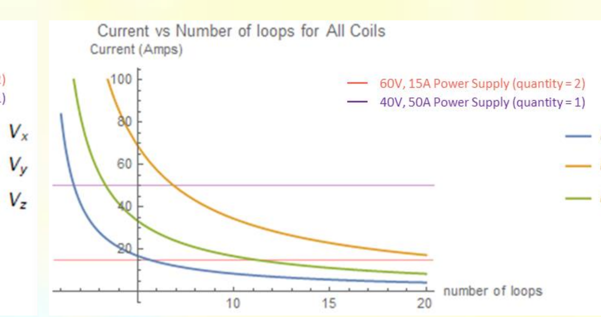


The net magnetic field, shown only along the surface of the shielding cylinder.

From the simulation, we estimate that the FCS will optimally minimize the environmental field if we run $\{I_x, I_y, I_z\} \approx \{83, 343, 166\}$ Amp-turns through the each loop component, respectively. Thus, we needed to select appropriate wire guages/ turn counts such that our power supplies were capable of running the Field Compensation System with optimal performance.



Voltage required to provide coils with necessary Amp-turns, as a function of wire radius.



Current required to provide coils with necessary Amp-turns, as a function of the number of loops.