Compensation of Magnetic Fields at the TRIUMF nEDM Experiment

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(For TUCAN Collaboration)

WNPPC
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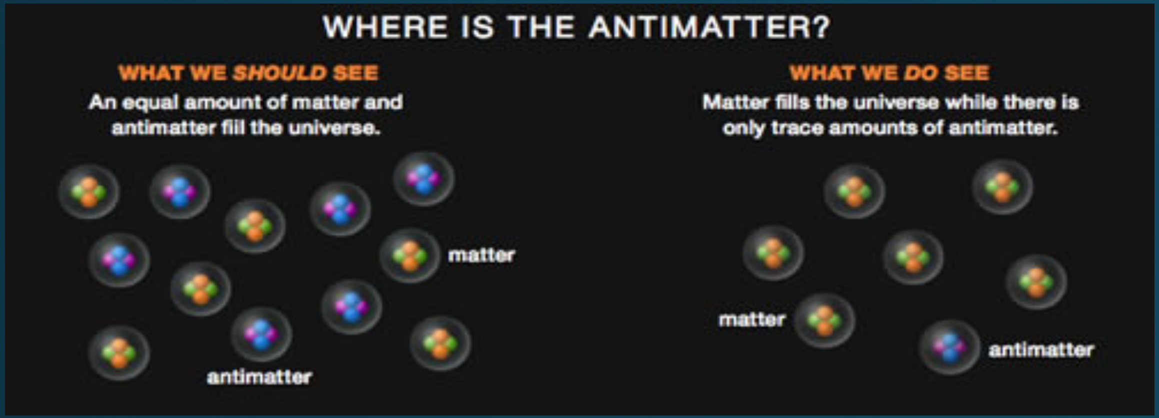
University of Manitoba

The University of Winnipeg

Motivation Behind nEDM Experiment



From https://todaysnews2.blogspot.ca/2015/09/matter-and-antimatter-are-mirror-images.html

Sakharov Conditions (1967) for Baryogenesis

- Baryon number violation
- C and CP violation
- Departure from thermodynamic equilibrium

Andrei Sakharov

Experimentally[1] , $\eta = \frac{\eta_B - \eta_{B'}}{\gamma} = 6 * 10^{-10} \frac{excess\ baryons}{photon}$

Standard Model fails to explain. Reason : Not enough CP violation.

Requires

- Additional CP violation near TeV scale

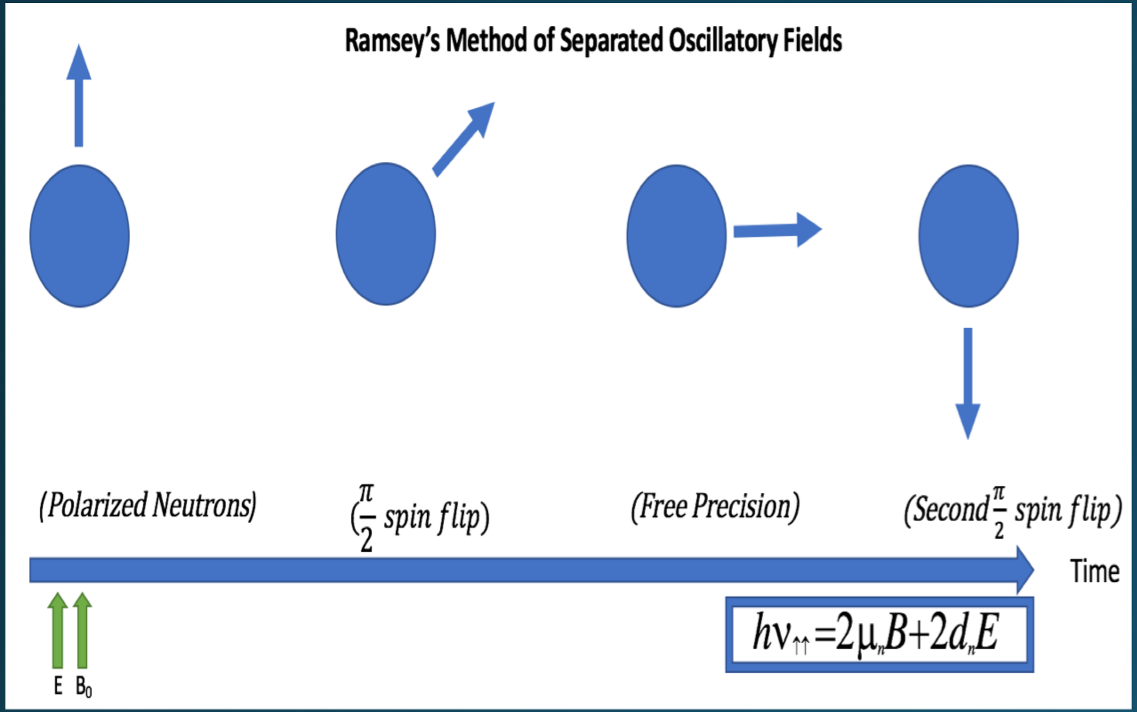
In turn ,

- Generating a nEDM to be 10^{-26} - 10^{-28} e-cm .

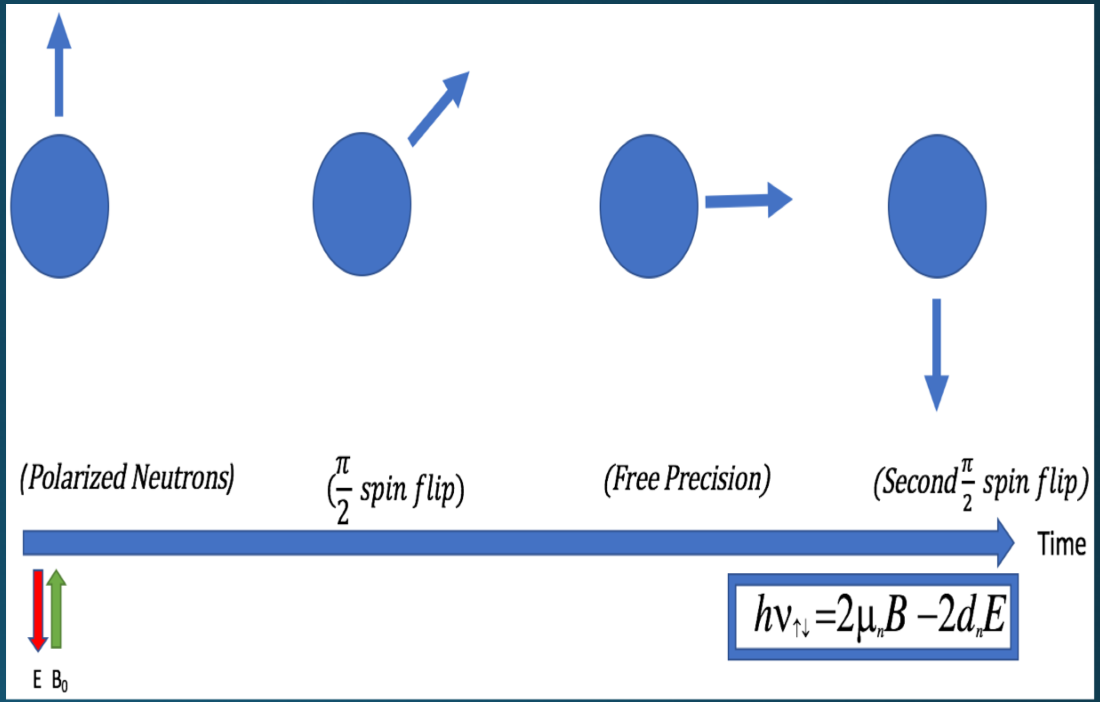
- The current best upper limit[2] set by Sussex/RAL/ILL nEDM experiment is 3.0×10^{-26} e-cm.
- The nEDM experiment at TRIUMF is aiming at the 10^{-27} e-cm sensitivity level.

1. V.Barger et al. Phys.Lett. B 566 , 8(2003).
2. J. M. Pendlebury et al.Phys. Rev. D 92, 092003(2015).

How To Measure nEDM?



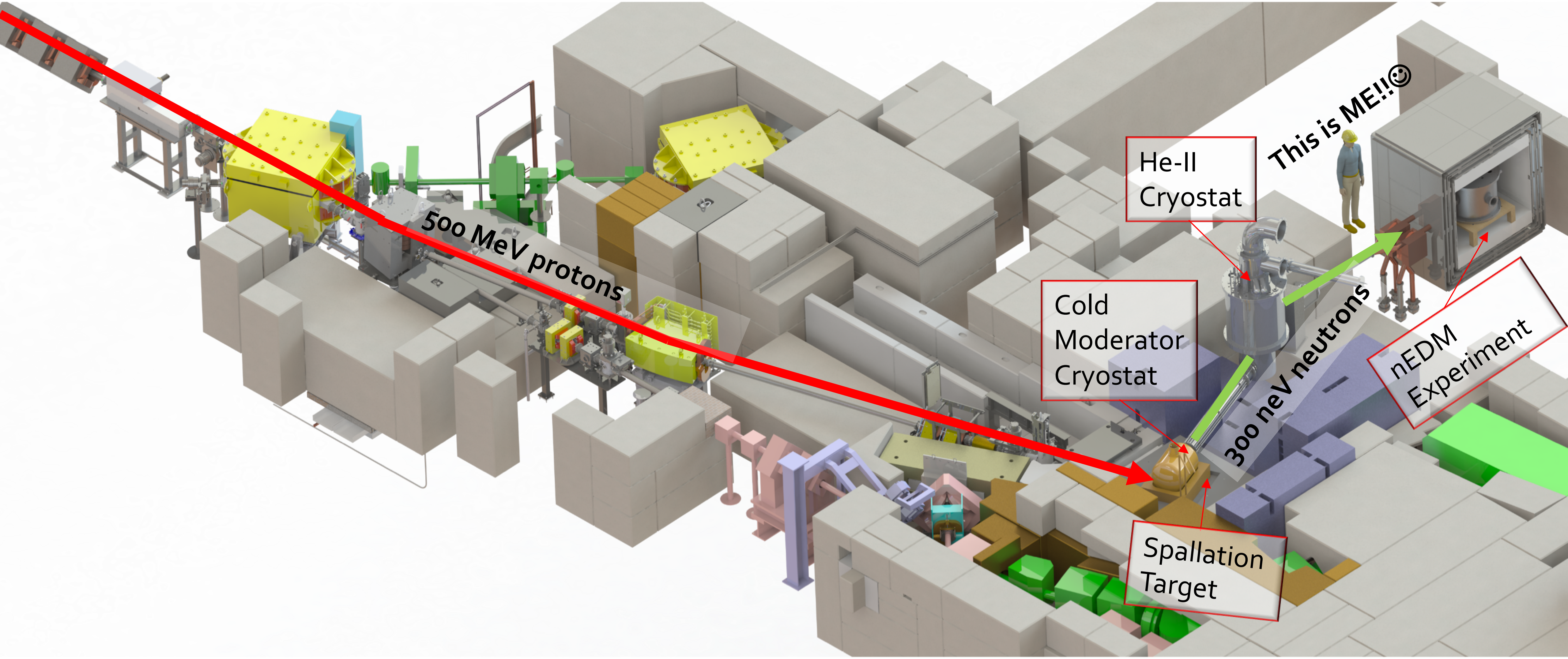
Repeat



Now, if the magnetic field is very stable and homogeneous ,

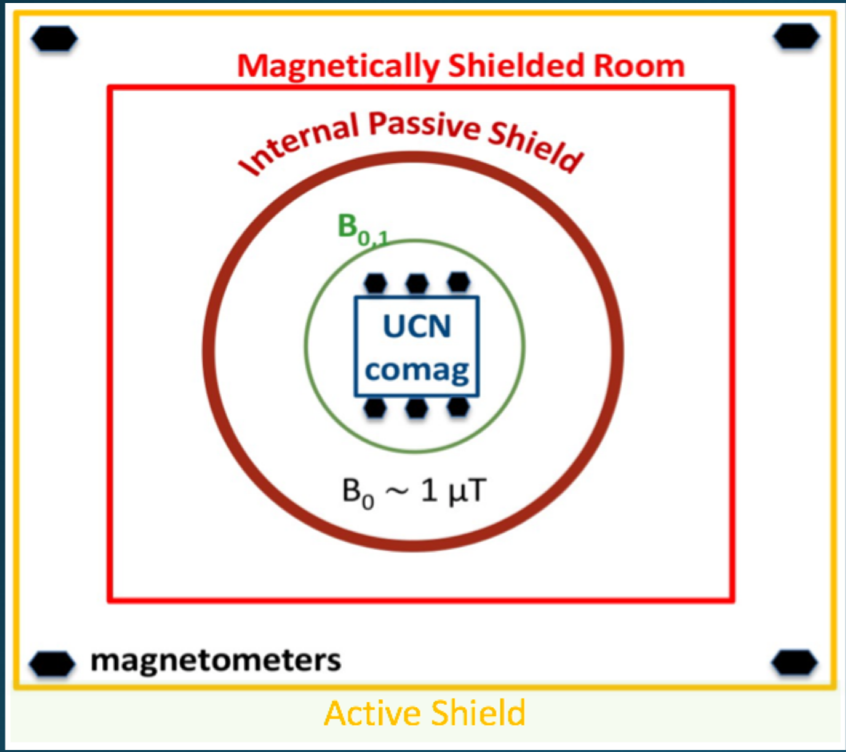
$$d_n = \frac{h(\nu_{\uparrow\uparrow} - \nu_{\uparrow\downarrow})}{4E}$$

The UCN Facility at TRIUMF

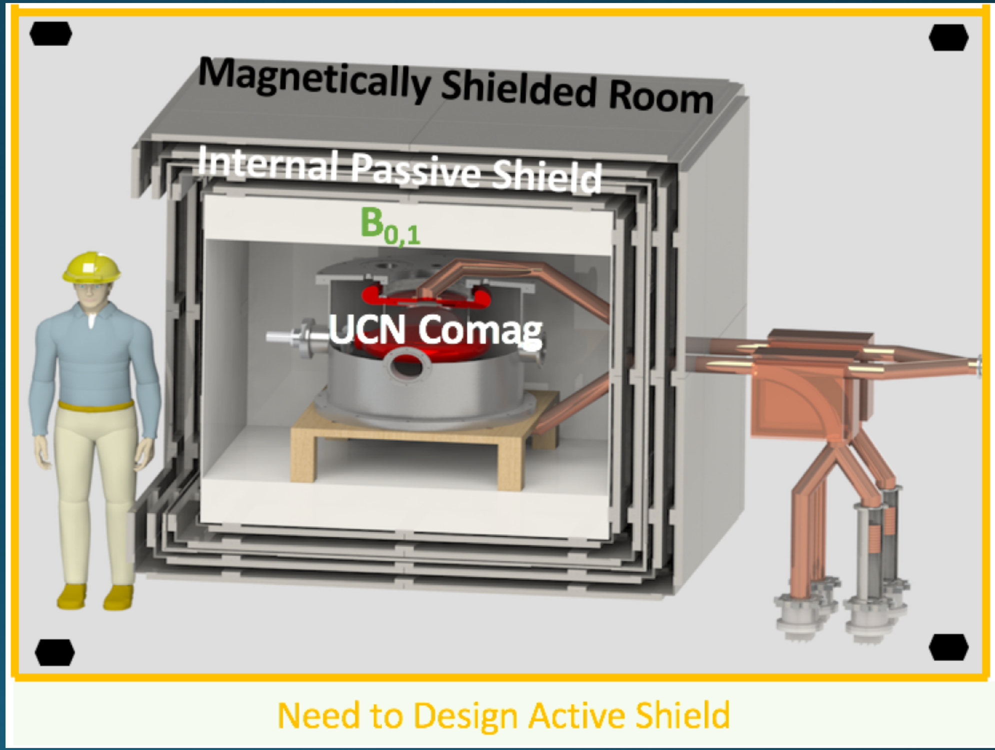


Magnetic Field Compensation System

nEDM experiment requirements- **B_0**= 1 μT, **Stability** < pT & **Homogeneity** < nT/m



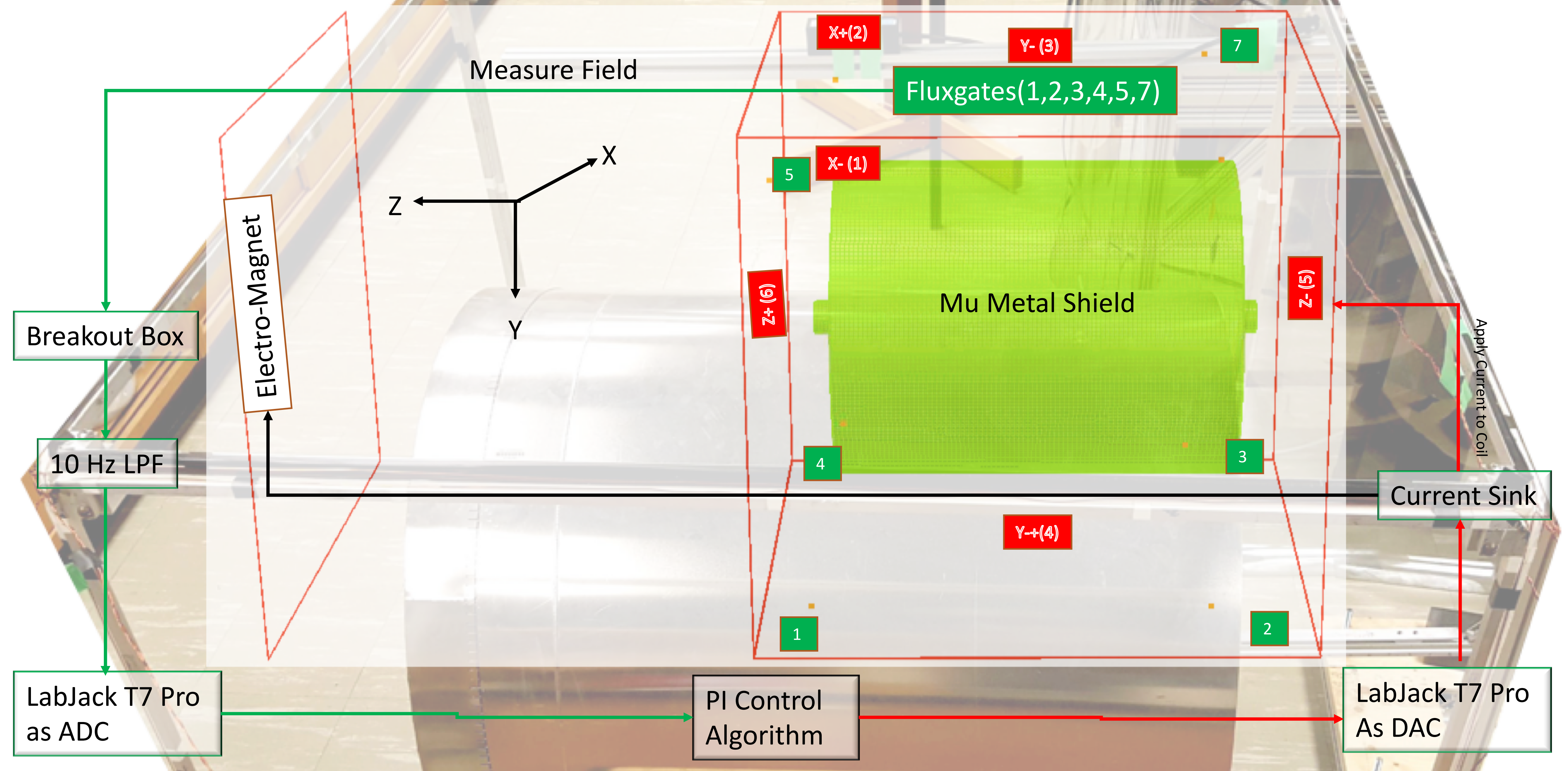
$B_{ext} \approx 400\ \mu T$



Active shield goals-

- Stability of field surrounding MSR ≤ 100 nT.
- Reduce 400 μT background (avoid saturation).
- Ability to open the door without magnetizing internal layers.

Prototype Active Magnetic Field Compensation System at U of Winnipeg



Multi-Dimensional Control

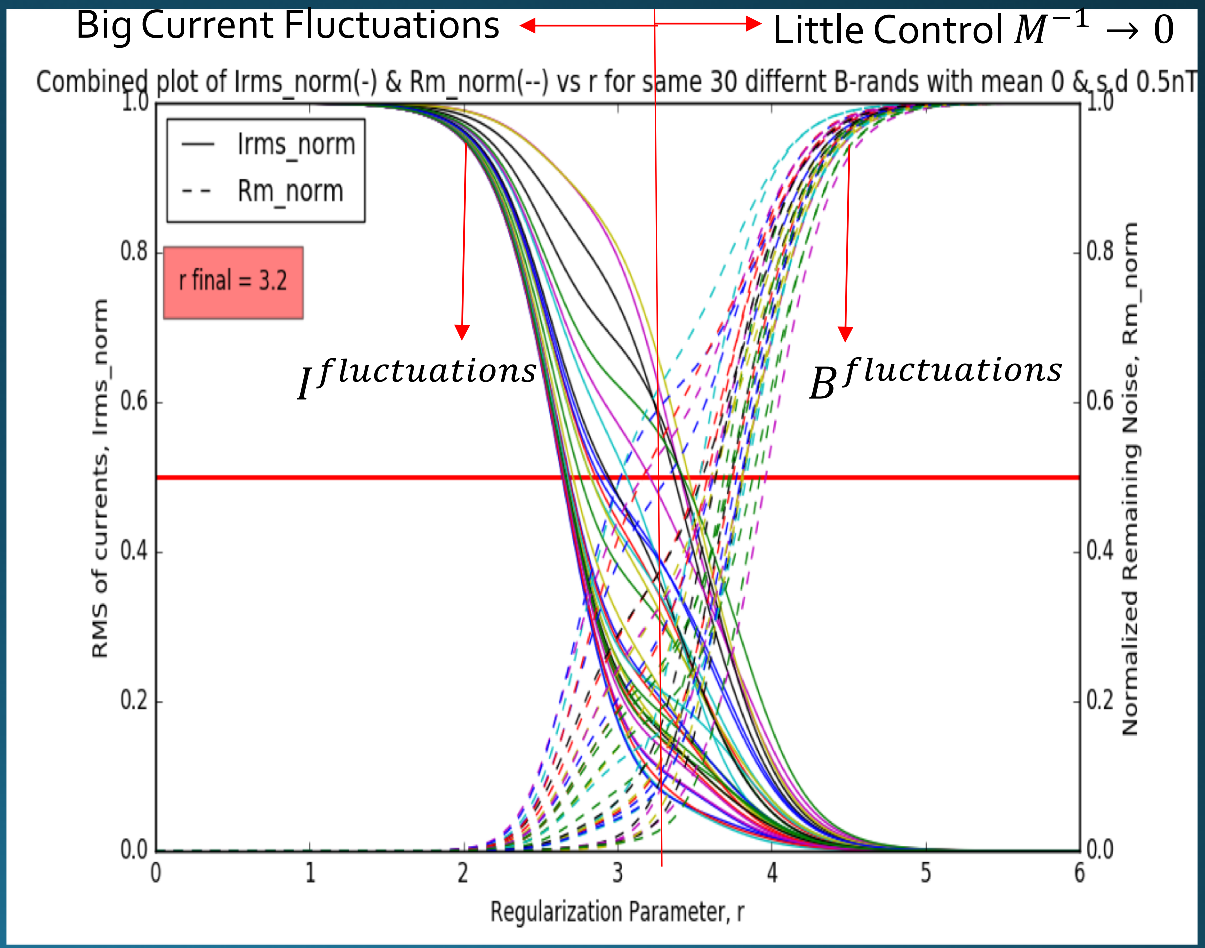
$$B_k^{coils} = \sum_j M_{kj}.I_j \;\rightarrow\; \Delta I_j = \sum_j M_{jk}^{-1}.(B_k^{goal} - B_k^{meas})$$

❖ Problem

- ➢ Inverse of non-square matrix.
- ➢ Wildly varying currents and poor control away from sensor positions.

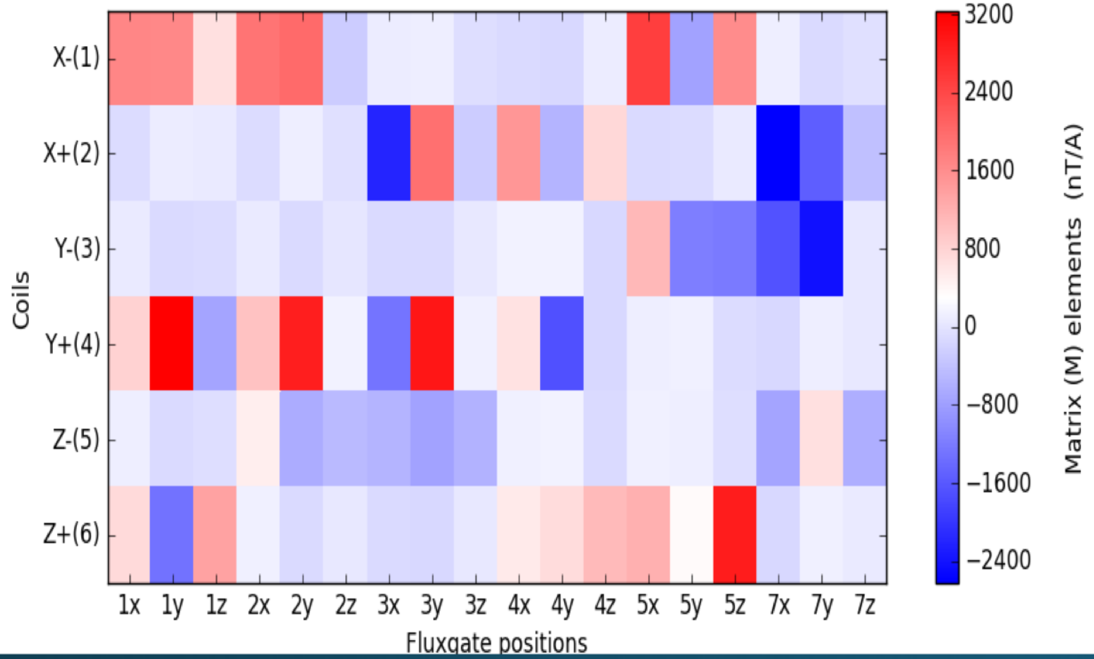
❖ Solution*

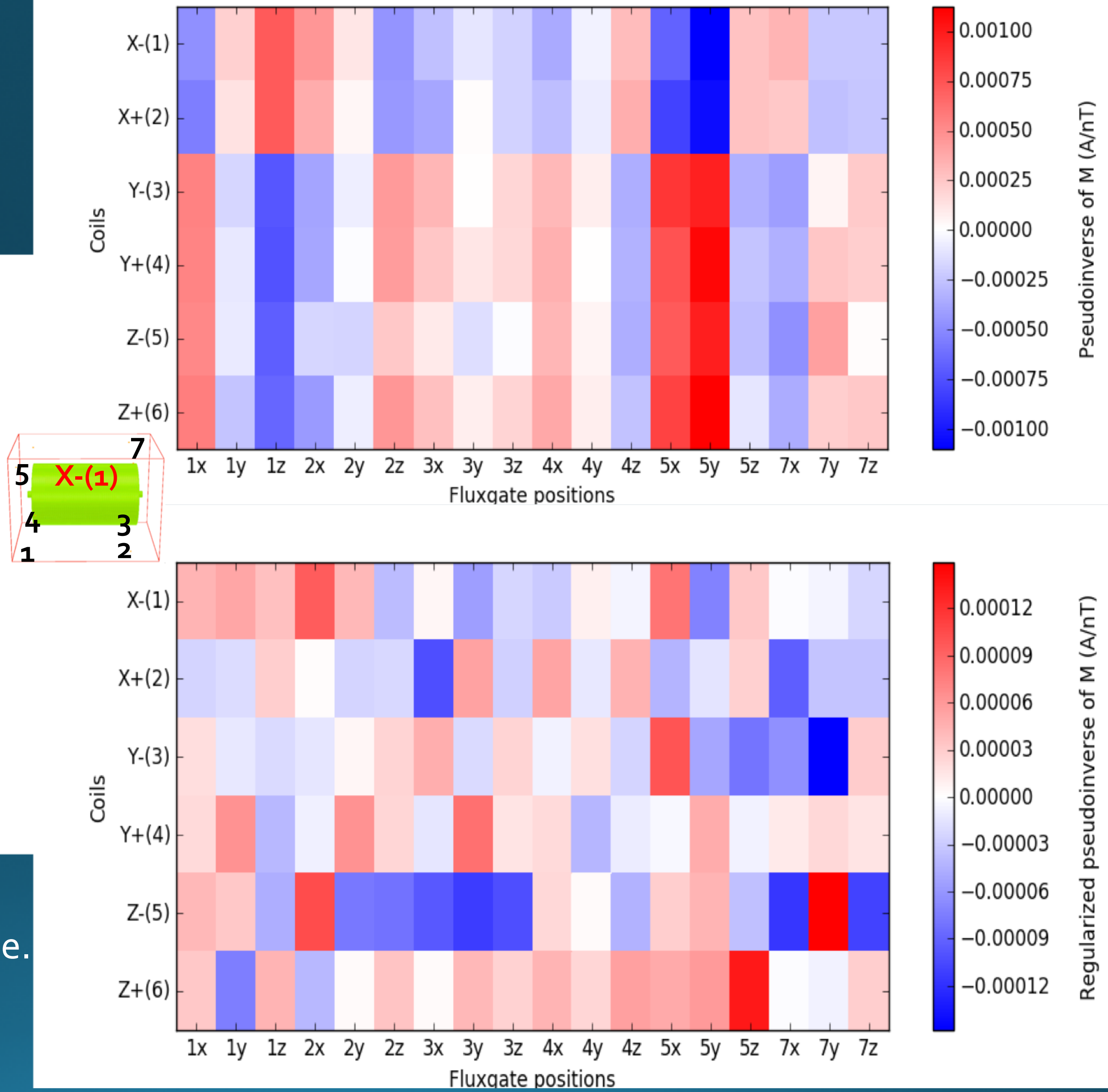
- ➢ Use pseudoinverse with Tikhonov regularization.
- ➢ Regularization Parameter, r
  - $r \rightarrow -\infty$ means non regularized (big current fluctuations).
  - $r \rightarrow +\infty$ means $M^{-1} \rightarrow 0$ (no control).



*B. Franke, Doctoral Theses, ETH-Zürich (2013).

Matrix of Proportionality Factors





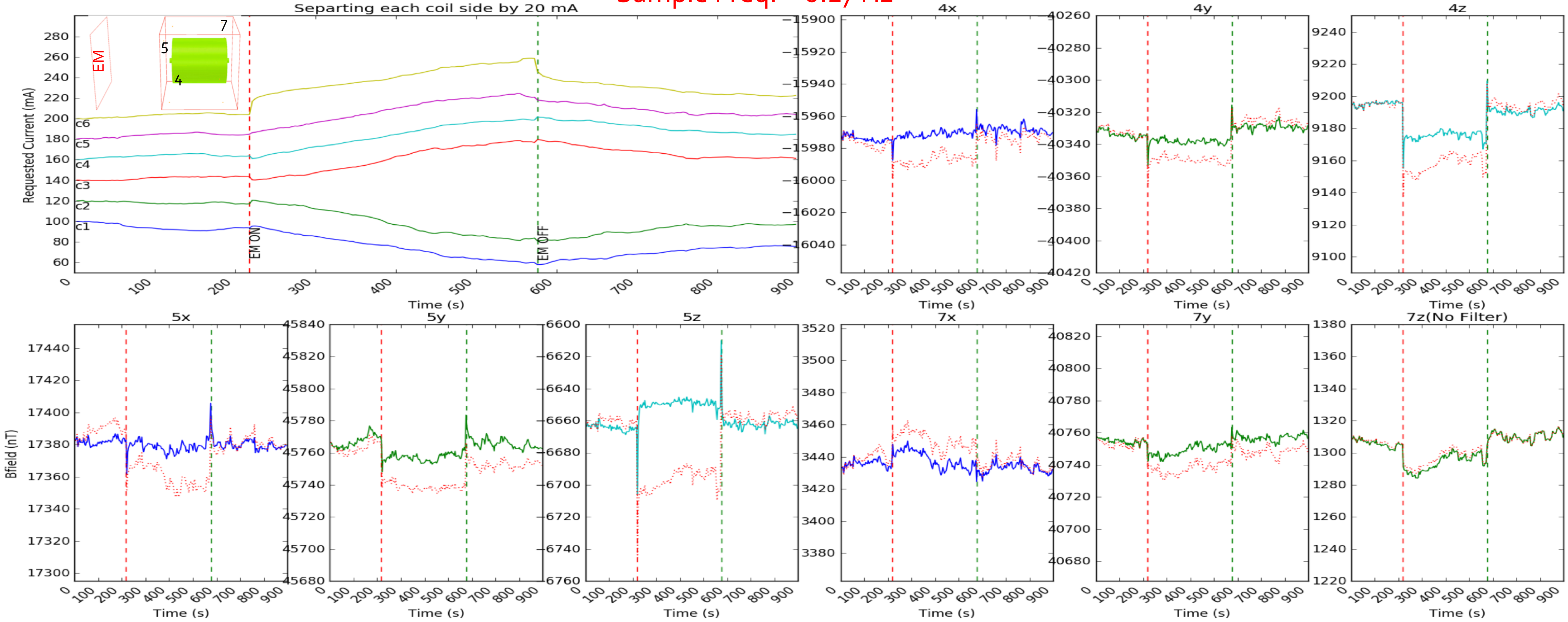
- e.g. last 3 values of 5y in M while inverse-
  - Produce huge current fluctuations in pseudoinverse.
  - Regularized one compensate to give best result.

Multi-Dimensional Control Results

- $B_k^{meas} = B_k^{uncomp} + B_k^{coils}$

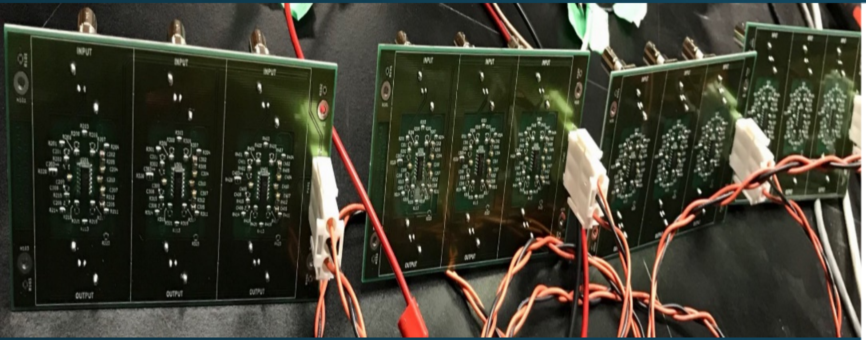
For resIndex 12(21.8 bits, 5.7 uV, 66.2 ms/sample), r=3.1, p=0.05, i=0.8, sample time = 3.72 s & sample freq.=0.27 Hz - Here Bmeas = Solid Line & Buncomp = Dashed

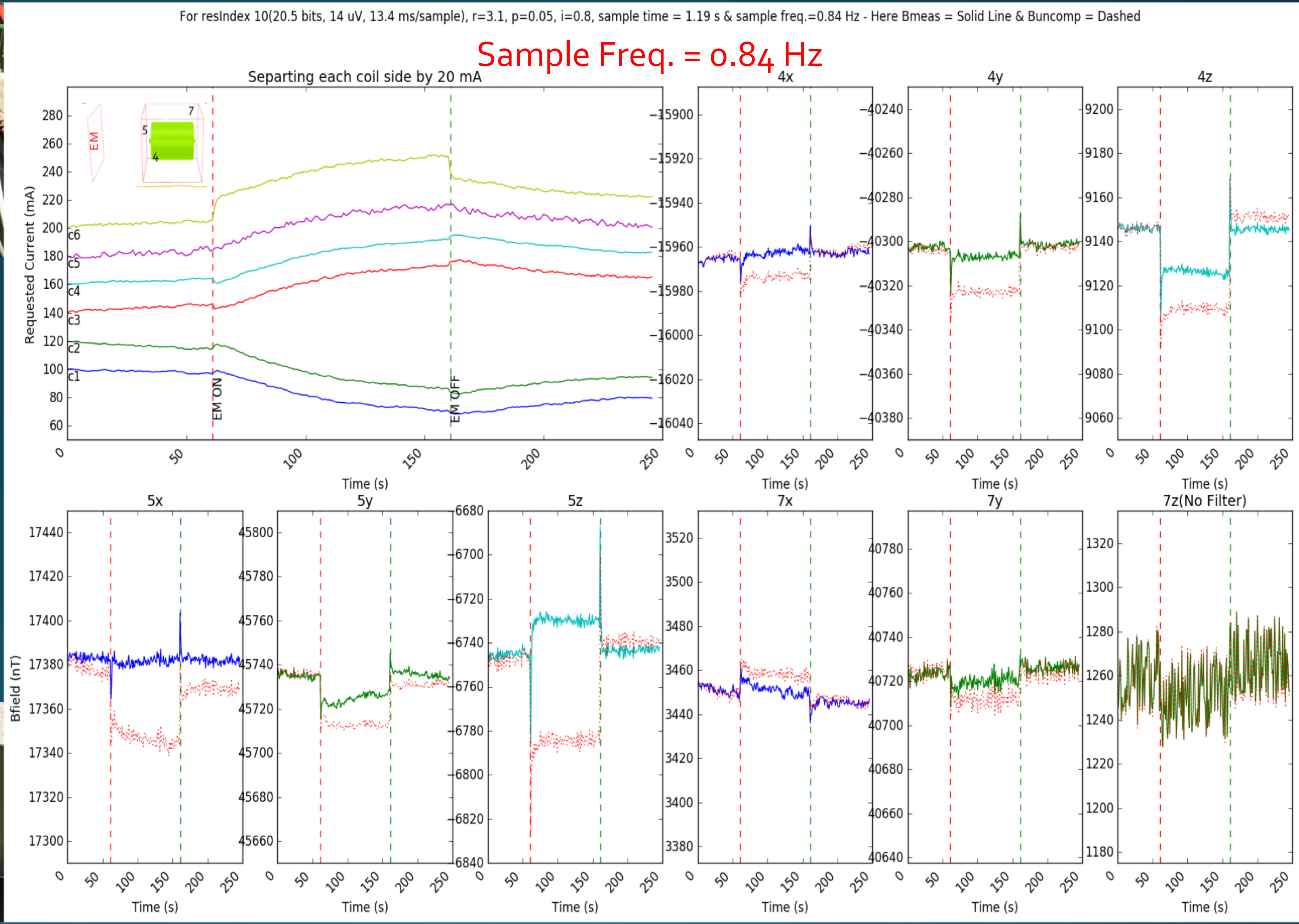
Sample Freq. = 0.27 Hz



*All sensor results are in backup slide#19

Importance of Filter



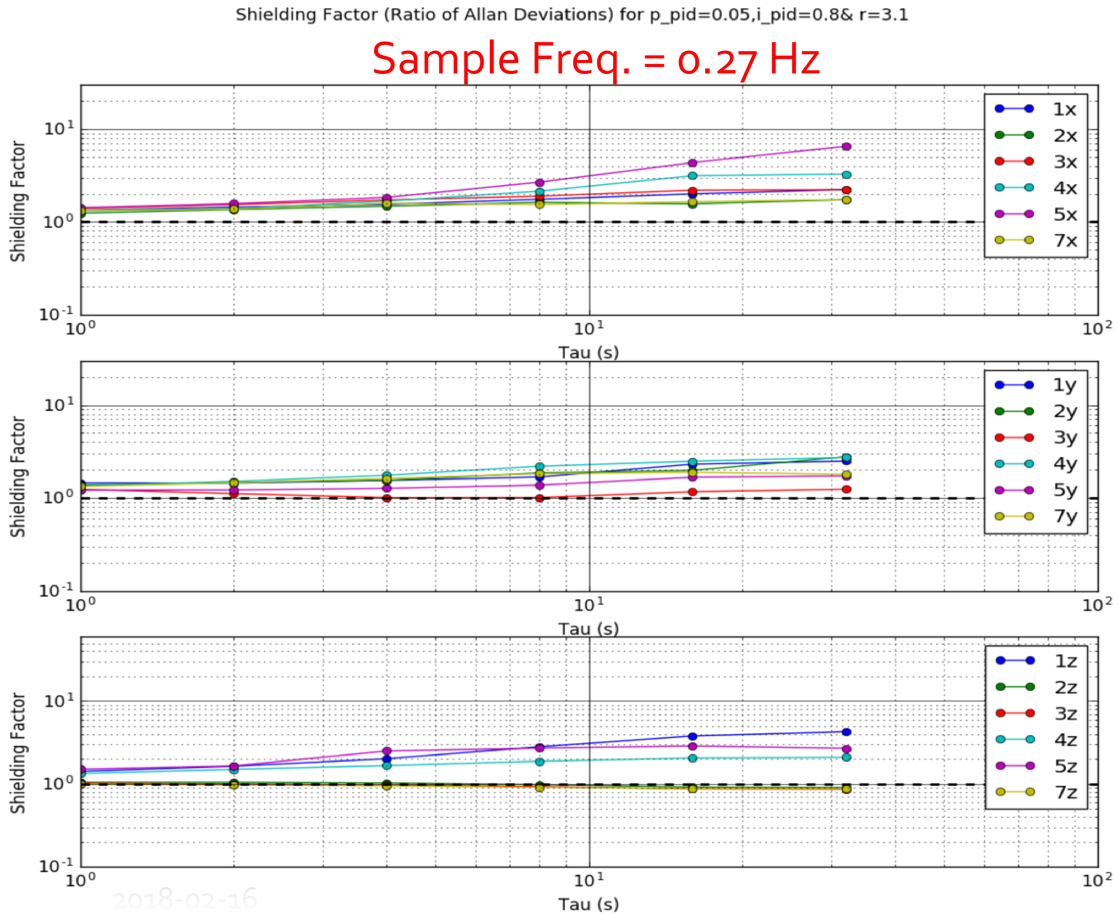


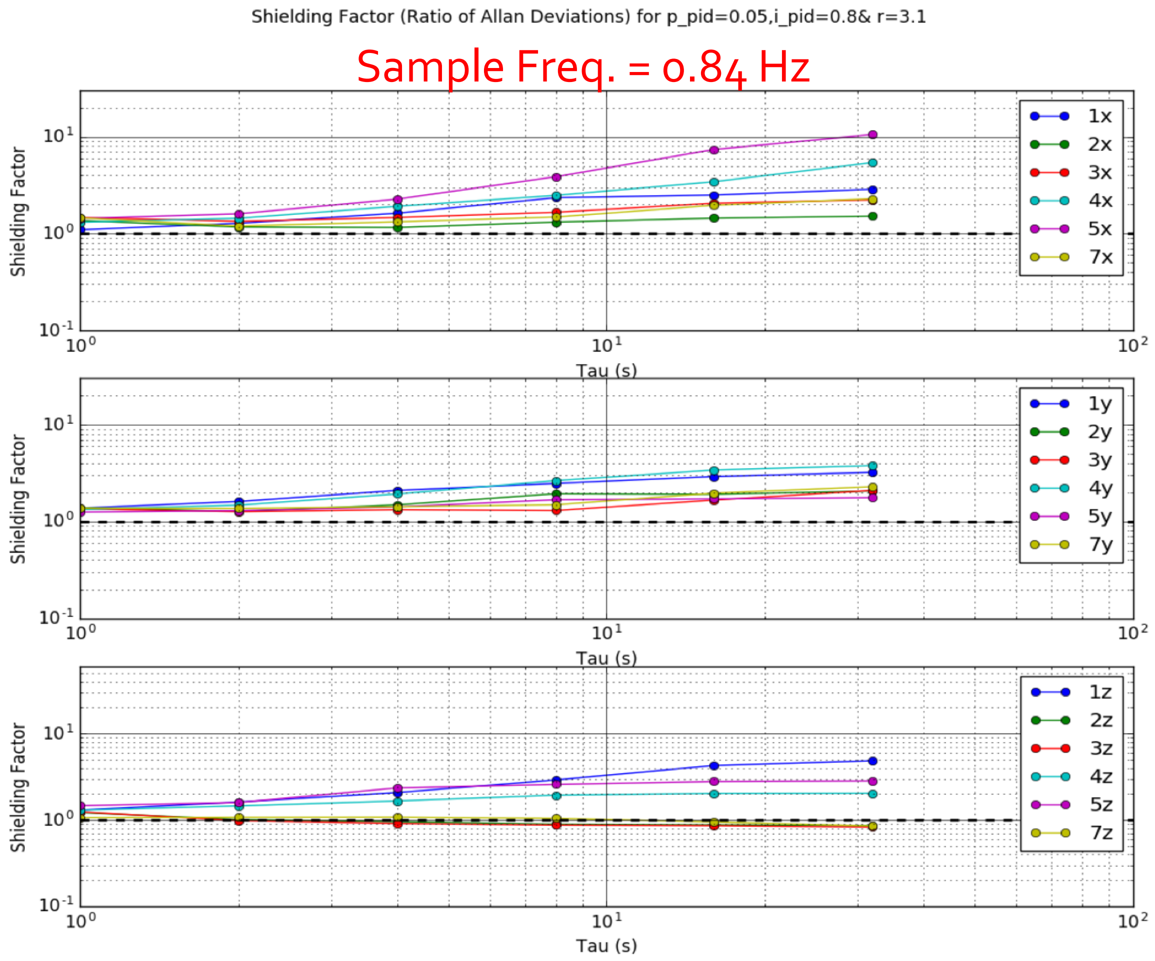
- ❖Specifications:
  - ➢Gain: 1 V/V
  - ➢Passband: -3dB at 10Hz
  - ➢Stopband: -60dB at 100Hz
- ❖ Advantages :
  - ➢ Increase the sampling frequency rate.

*All sensor results are in backup slide#20

Quantifying the Results

- Allan Deviation, $\sigma_{ADEV} = \sqrt{\frac{1}{2} < (y_{n+1} - y_n)^2 >}$
  - ➢ y_n - n^{th} average over τ.
- Shielding Factor , $S_k(\tau) = \frac{\sigma_{ADEV}(B_k^{uncomp})}{\sigma_{ADEV}(B_k^{meas})}$





*Shielding Factor > 1 indicates success.

Next Steps

- Optimize the system to get best results out of it.

- The steps -
  - Find the best tuning process (ongoing).
  - Build an analog filter and increase the sampling frequency rate (done).
  - Find the best positions of the fluxgates (ongoing).

- Finally, the optimized system will be compared with a simulated result (target – CAP Congress in June).

Conclusion

- Non-zero nEDM tests T-symmetry, new physics violating CP symmetry.
- TRIUMF nEDM sensitivity 10^{-27} e-cm.
- nEDM experiment requires very stable (< pT) and homogeneous (< nT/m) magnetic field.
- Need suitable active magnetic compensation system.
- Prototype system at UW gives reasonable level of compensation.
- We are working on to have better result.

Thank You

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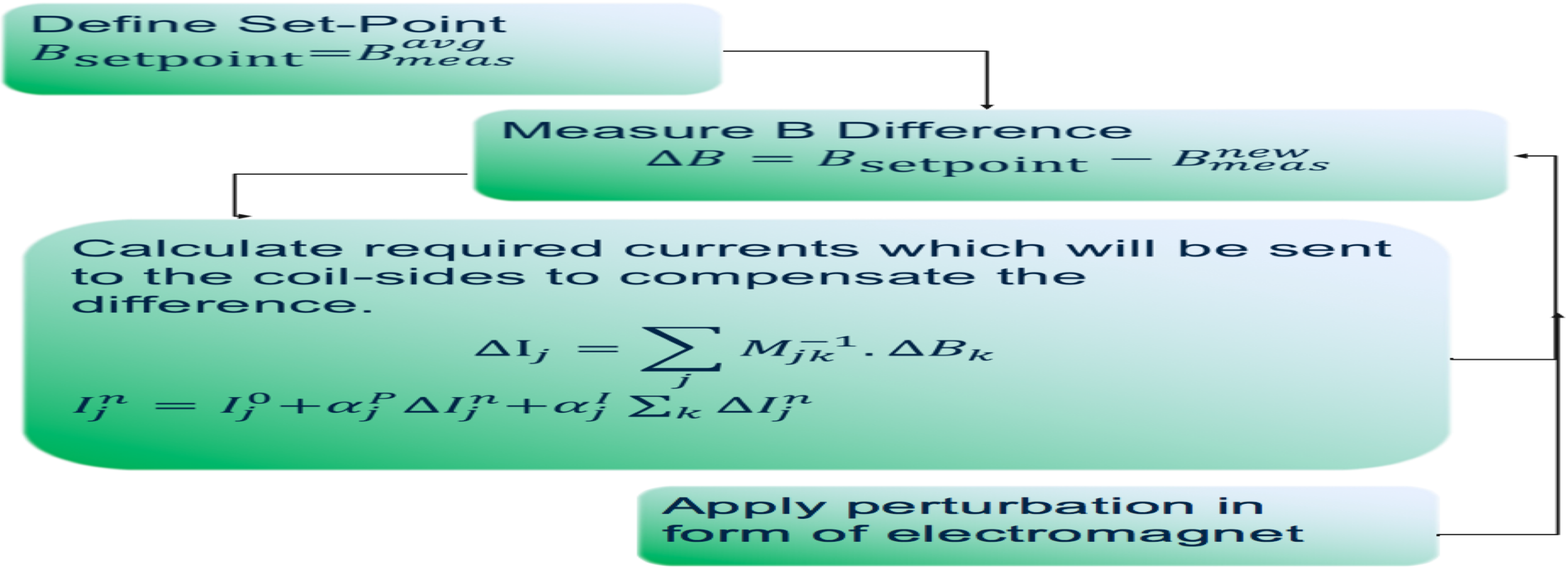
Back Up Slides

Method

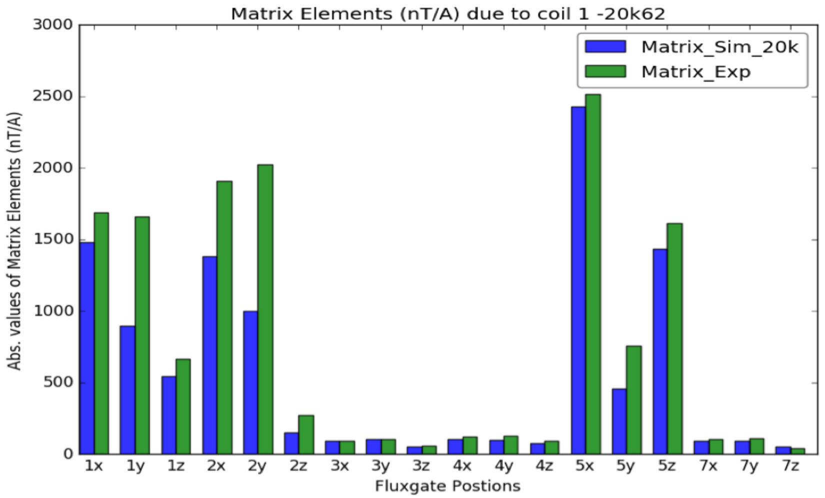


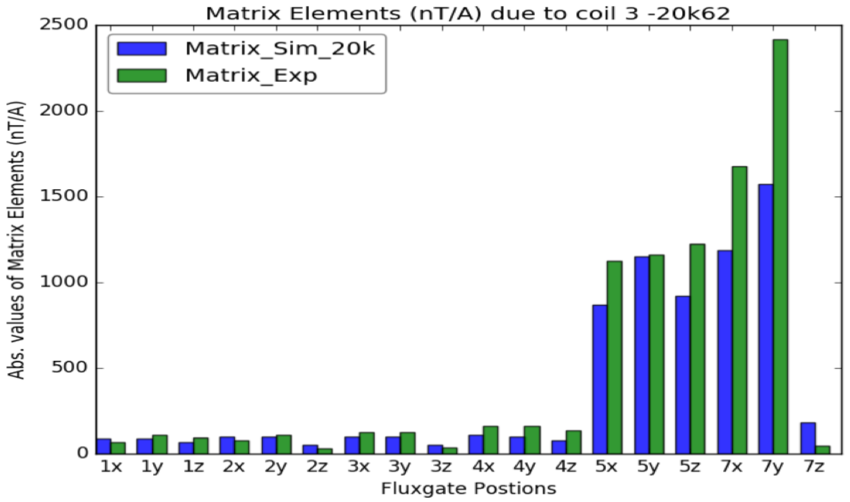
Flow chart of the whole process. Here, M (nT/A) is the matrix of proportionality factors.

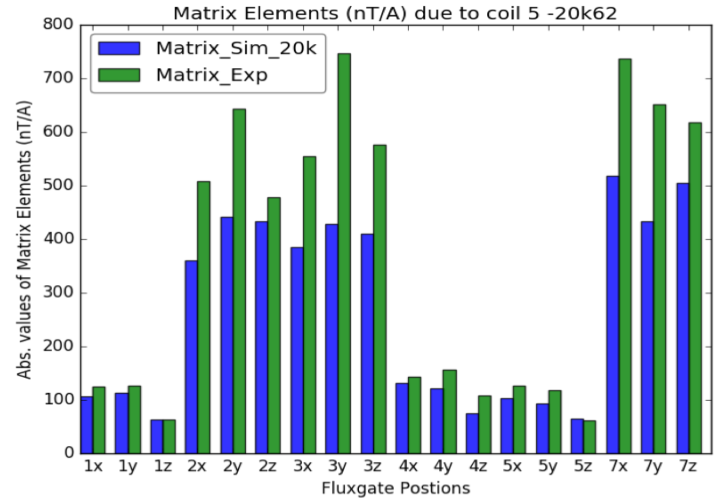
Monte Carlo Method To Find M^{-1}

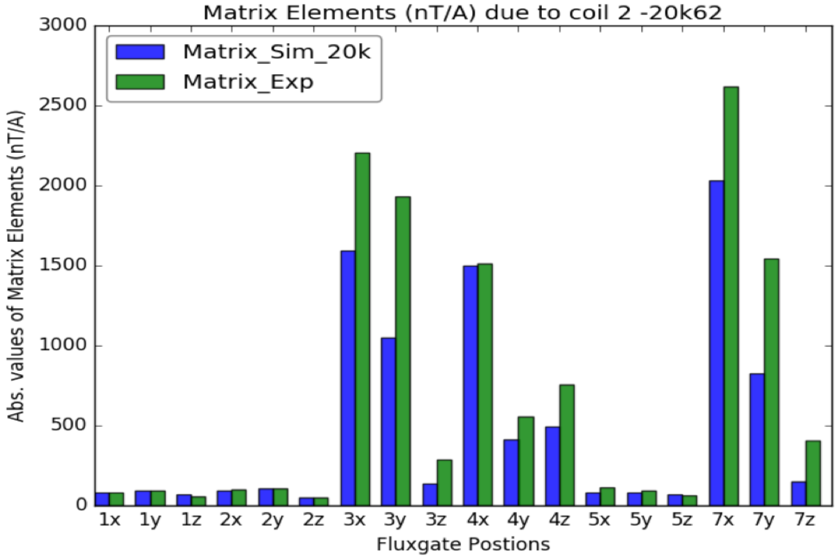
1. Generate Random B^{rand} at sensors.
2. Calculate $I_j^{sim}(r) = \sum_k (M_{jk}^{-1}(r))^{reg} . (-B^{rand})$ and $(I_j^{sim}(r))_{rms}$
3. Calculate $B_k'(r) = B_k^{rand} + \sum_j M_{kj} . I_j^{sim}(r)$
4. Define $R_m = \frac{(B')_{rms}}{(B_k^{rand})_{rms}}$
5. Normalize $(I_j^{sim}(r))_{rms}$ & R_m and determine r_{final}

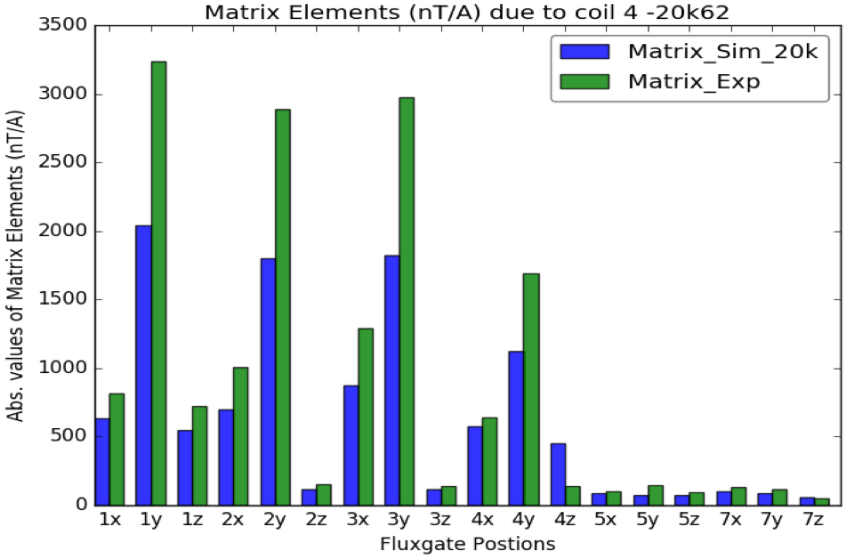
Comparison with Simulation

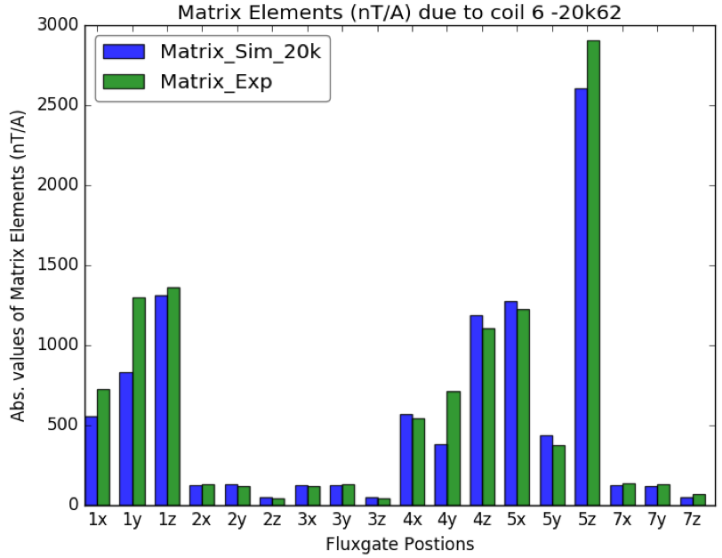












Multi-Dimensional Control Results

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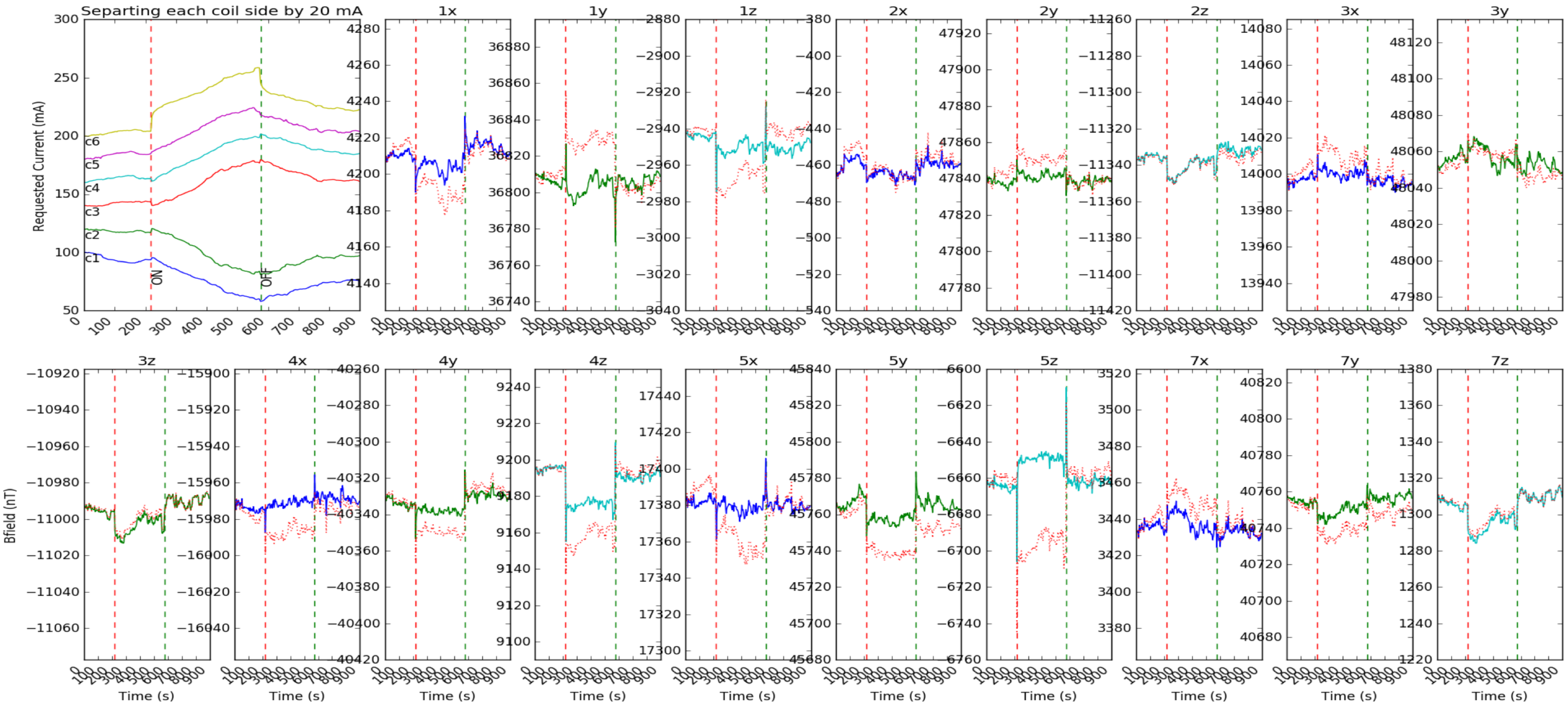
Sample Freq. = 0.27 Hz



Multi-Dimensional Control Results (Contd.)

For resIndex 10(20.5 bits, 14 uV, 13.4 ms/sample), r=3.1, p=0.05, i=0.8, sample time = 1.19 s & sample freq.=0.84 Hz - Here Bmeas = Solid Line & Buncomp = Dashed

Sample Freq. = 0.84 Hz