Magnetic Field Status

David Flay
Operational Readiness Review
October 2, 2017

Outline

- Introduction
  - Requirements for the Magnetic Field Measurements
  - Magnet Anatomy
  - Measuring and Calibrating the Magnetic Field
- Commissioning Run Overview
  - Highlights and Lessons Learned
- Summer Shimming: Fine-Tuning the Field
- Hardware Subsystems Status
  - Activities During Summer Shutdown
  - Preparedness for Running
- Summary

The Magnetic Field Team

- Laboratories: **FNAL**, **Argonne National Lab**
- Universities: **UWashington**, **UMichigan**, **UMass Amherst**, **UTexas-Austin**
- 4 postdocs: Joe Grange, Ran Hong, David Flay, Jimin George, Matthias Smith (transitioning over to INFN)
- 4 grad students: Rachel Osofsky, Alec Tewsley-Booth, Midhat Farooq, Alyssa Conway
- Scientists and Faculty: Peter Winter, Erik Swanson, Dave Kawall, Brendan Kiburg, Tim Chupp, Alejandro Garcia, Martin Fertl
- Interns: 3 undergraduates

Requirements for the Field Measurements

- Recall: $\omega_a \cong (e/m_\mu)a_\mu B$
- Using proton NMR, utilizing $\hbar\omega_p = 2\mu_p|\vec{B}|$ gives:

$$a_\mu = \frac{\omega_a}{\omega_p}\frac{\mu_p}{\mu_e}\frac{m_\mu}{m_e}\frac{g_e}{2}$$

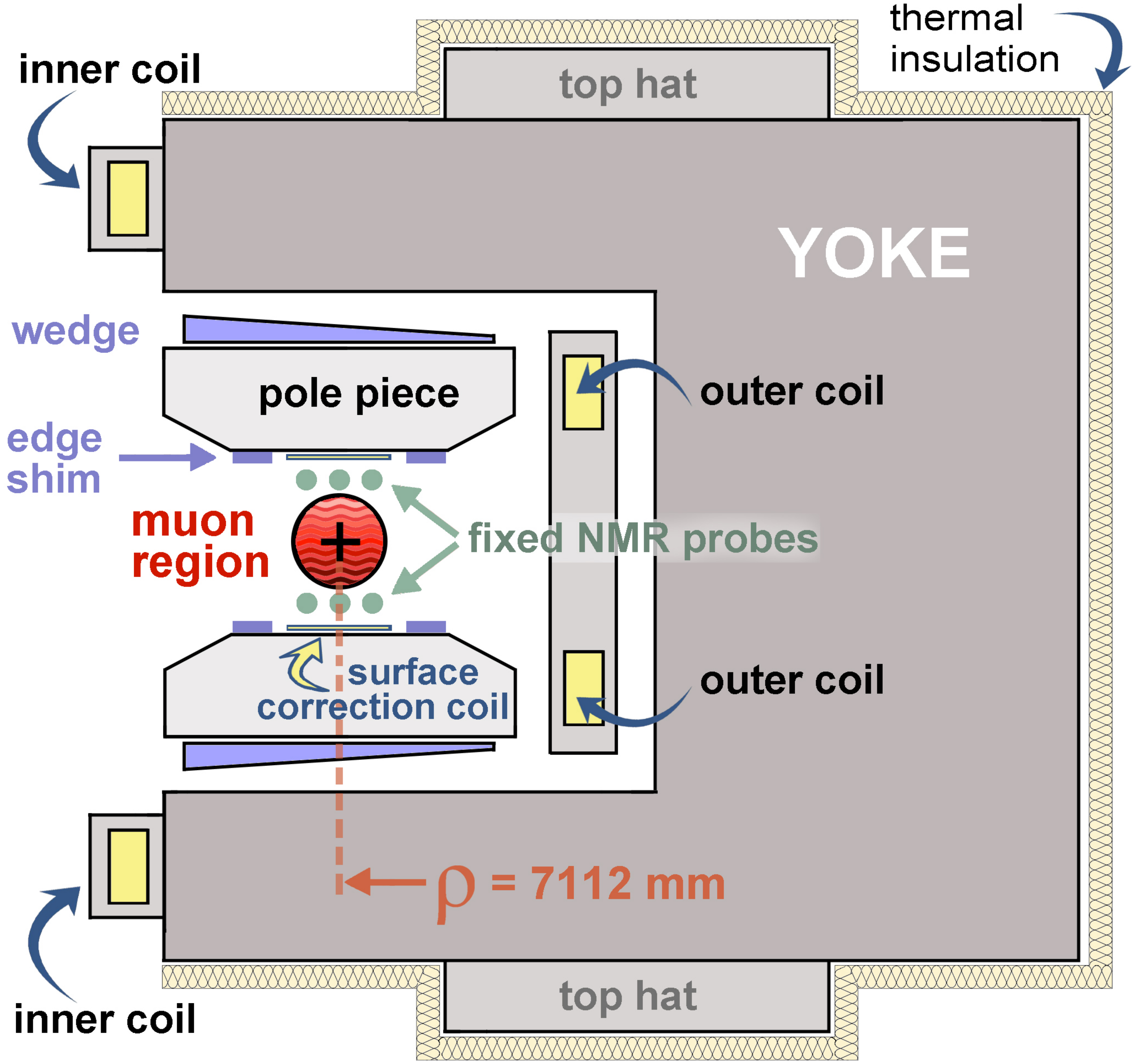
- We measure ω_a and ω_p separately
- Other ratios known to better than 25 ppb
- **Target: δa_μ = 140 ppb; 4-fold improvement over BNL**

- Need B in terms of the free-proton precession frequency ω_p
- $\omega_p \cong 2\pi \times 61.79$ MHz for B = 1.45 T
- Need to extract ω_p to better than 70 ppb (4.3 Hz)

Error Source	Allotted Uncertainty (ppb)
Trolley measurements	**30**
Trolley probe calibration	**30**
Fixed probe interpolation	**30**
Muon distribution convolution	**10**
Time-dependent external fields, others	**10**
Water probe calibration	**35**
Total	**70**

Magnet Anatomy

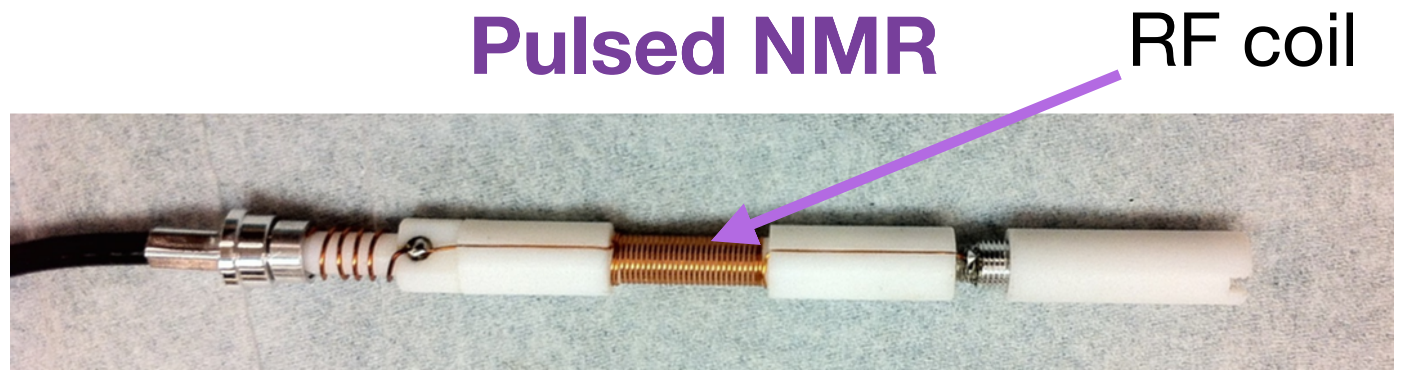
- B = 1.45 T (~ 5200 A)
  - Non-persistent current: fine-tuned in real time
- 12 C-shaped yokes
  - 3 upper and 3 lower poles per yoke
  - 72 total poles
- Shimming Knobs
  - Pole separation determines field: pole tilts, non-flatness affect uniformity
  - Top hats (30 deg effect, dipole)
  - Wedges (10 deg effect, dipole, quadrupole)
  - Edge shims (10 deg effect, dipole, quadrupole, sextupole)
  - Laminations (1 deg effect, dipole, quadrupole, sextupole)
  - Surface coils (360 deg effect, quadrupole, sextupole,…)

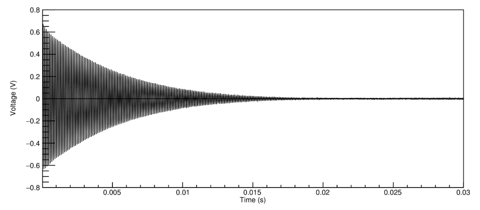


g-2 Magnet in Cross Section

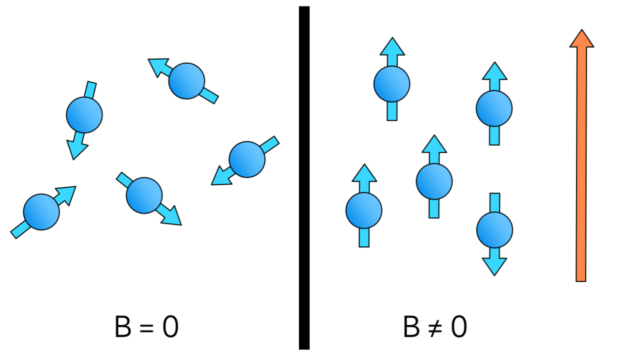
Measuring the Magnetic Field: Pulsed Systems

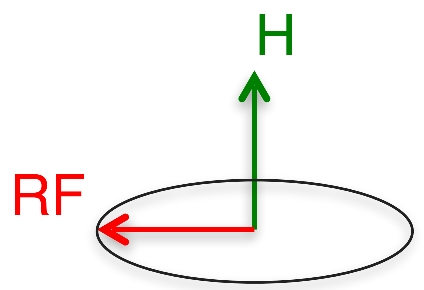
Pulsed NMR



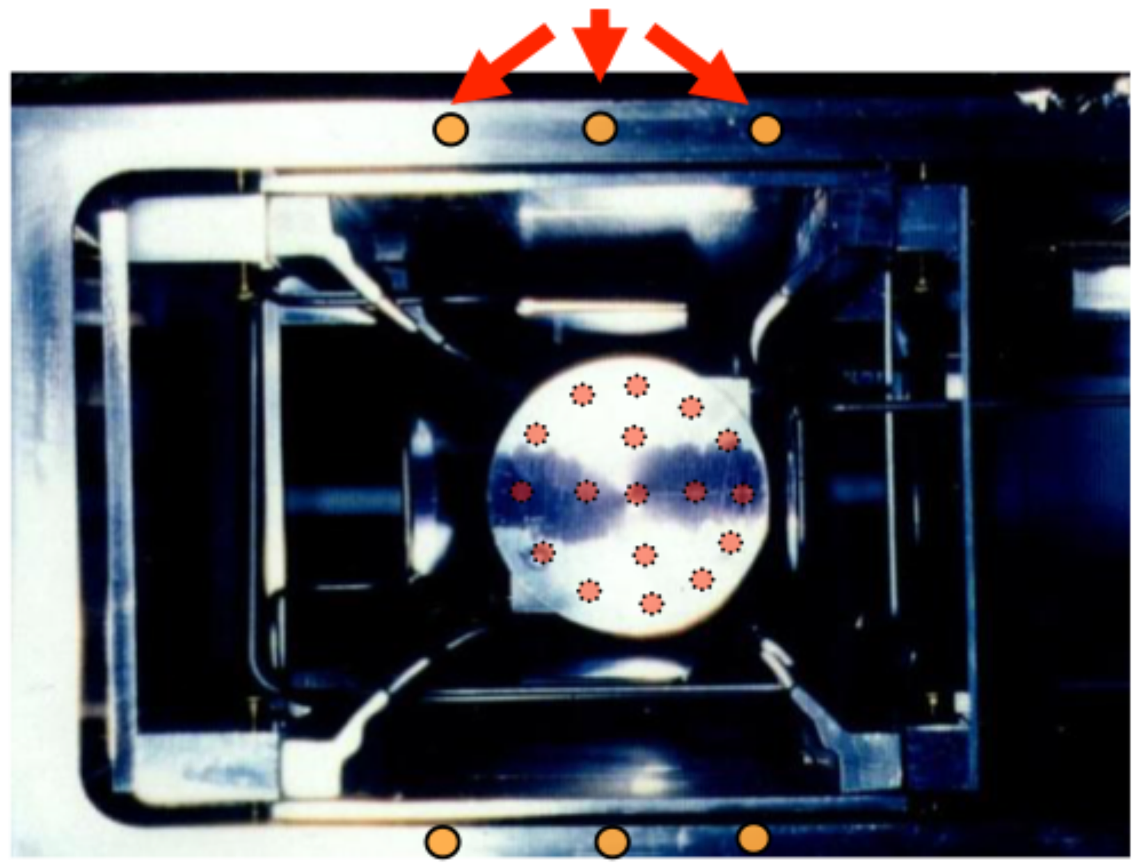


- Sample: petroleum jelly
- Deliver π/2 pulse to probe, induce & record the free-induction decay (FID)
- Extracted frequency precision: 10 ppb/FID



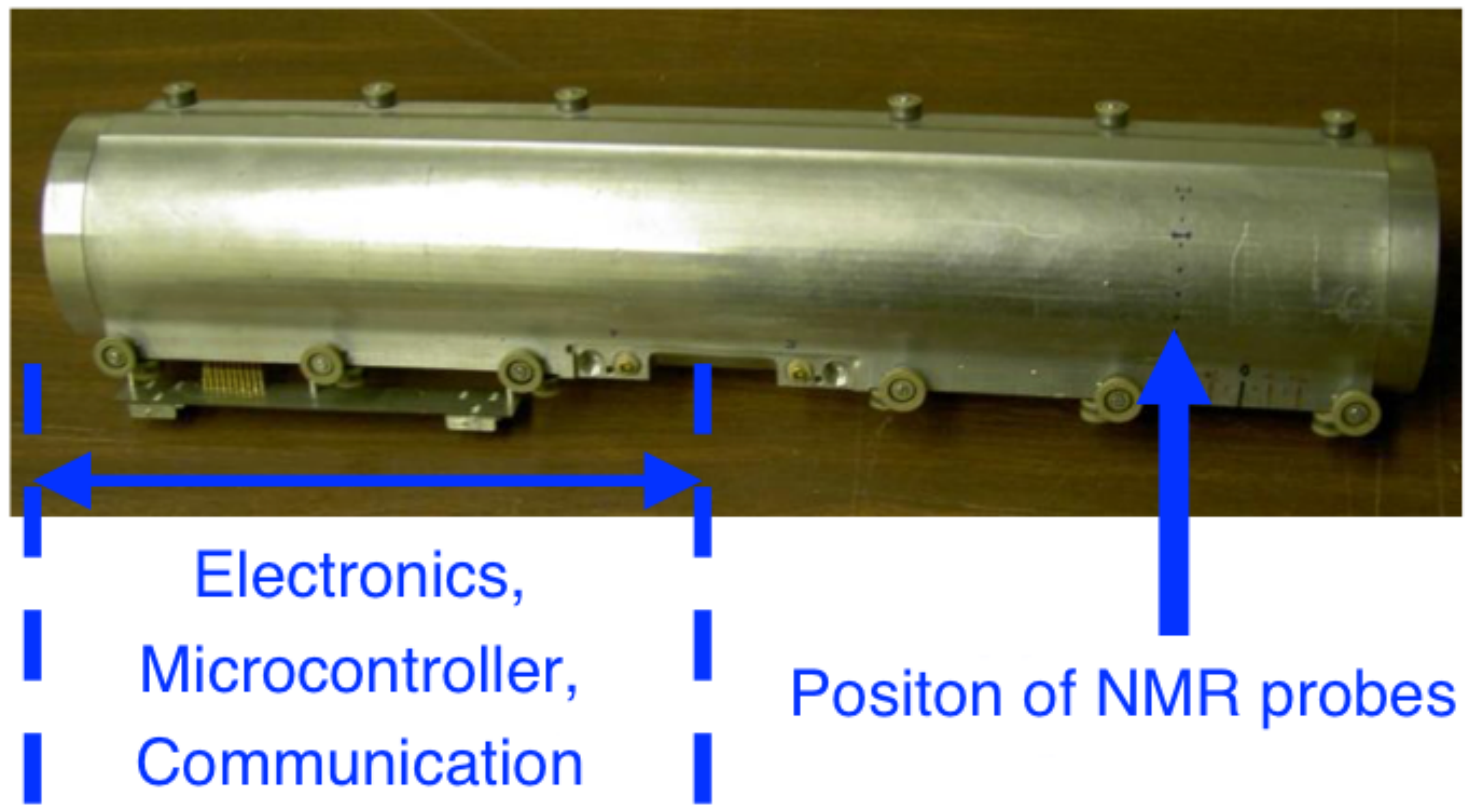


Fixed probes on vacuum chambers



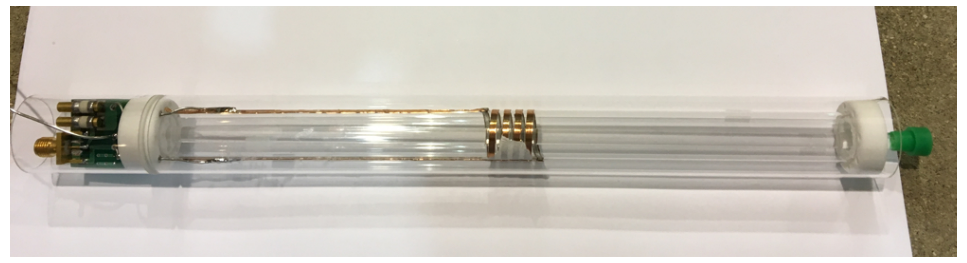
- Measure field while muons are in ring — probes **outside** storage region

Trolley matrix of 17 NMR probes

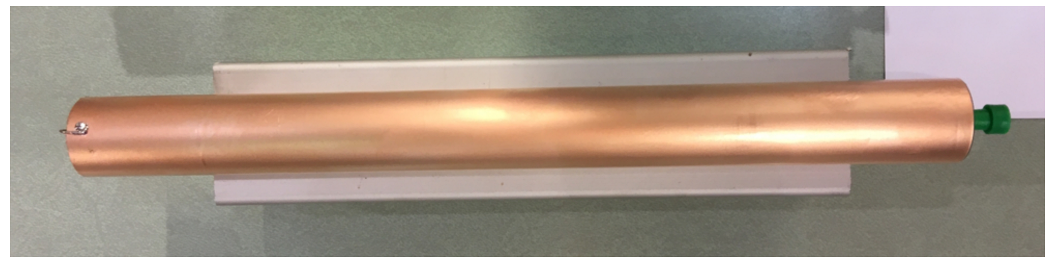


- Measure field in storage region during **specialized runs** when **muons are not being stored**

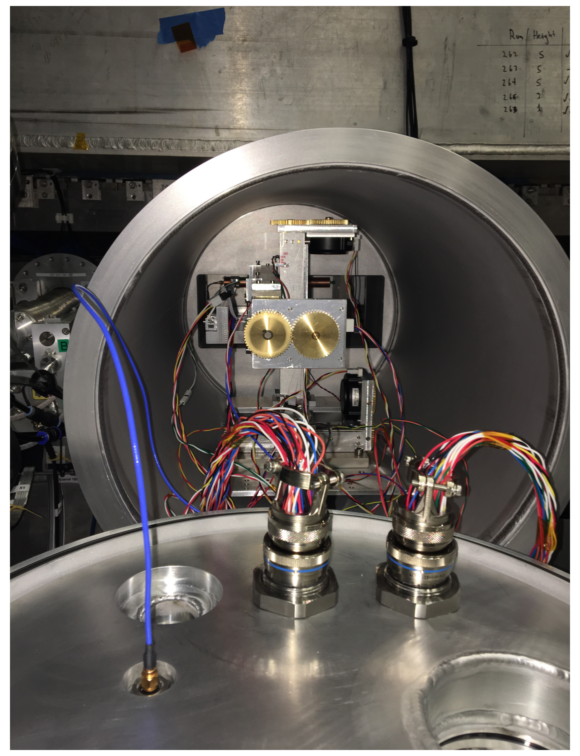
- **Trolley** probes **calibrated to free-proton Larmor frequency**
  - Calibrate trolley probes using a special probe that uses a water sample
  - Measurements in specially-shimmed region of ring

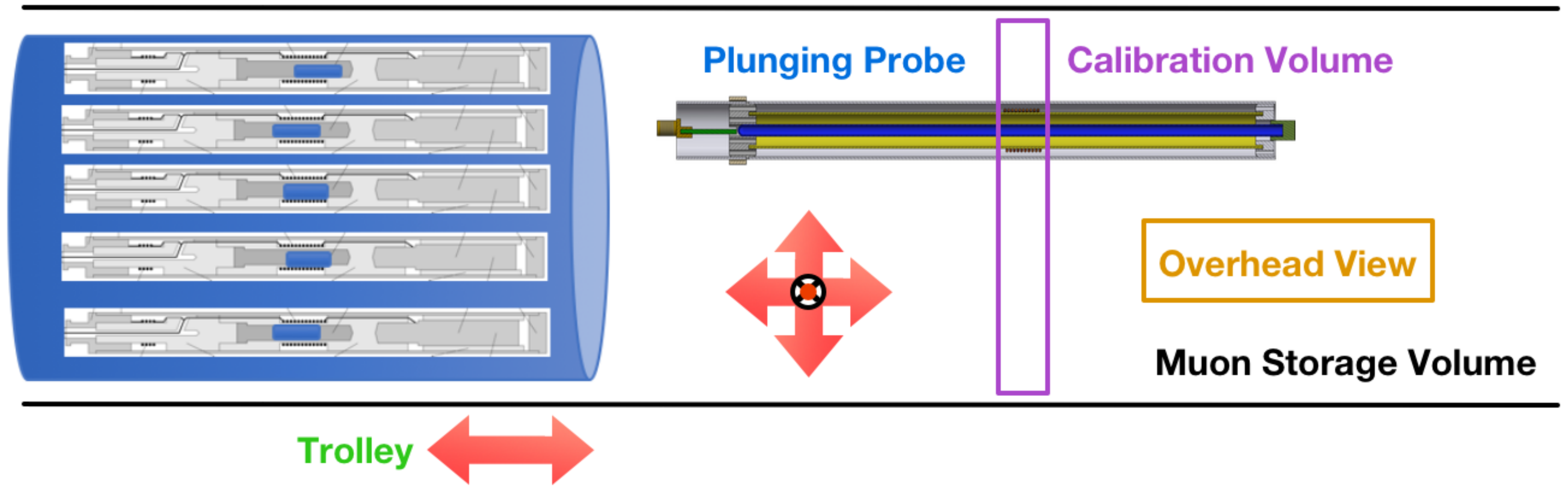


Plunging Probe internals



Probe w/ Cu shield

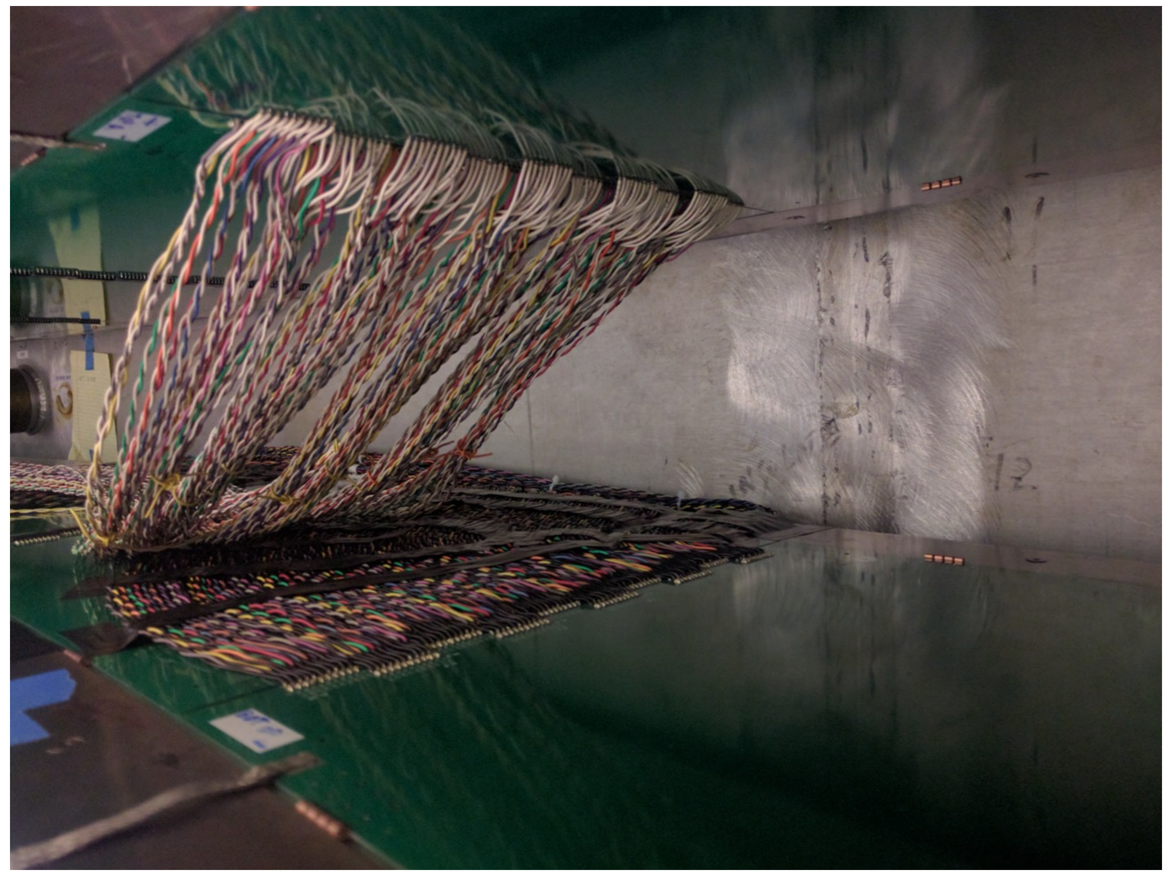


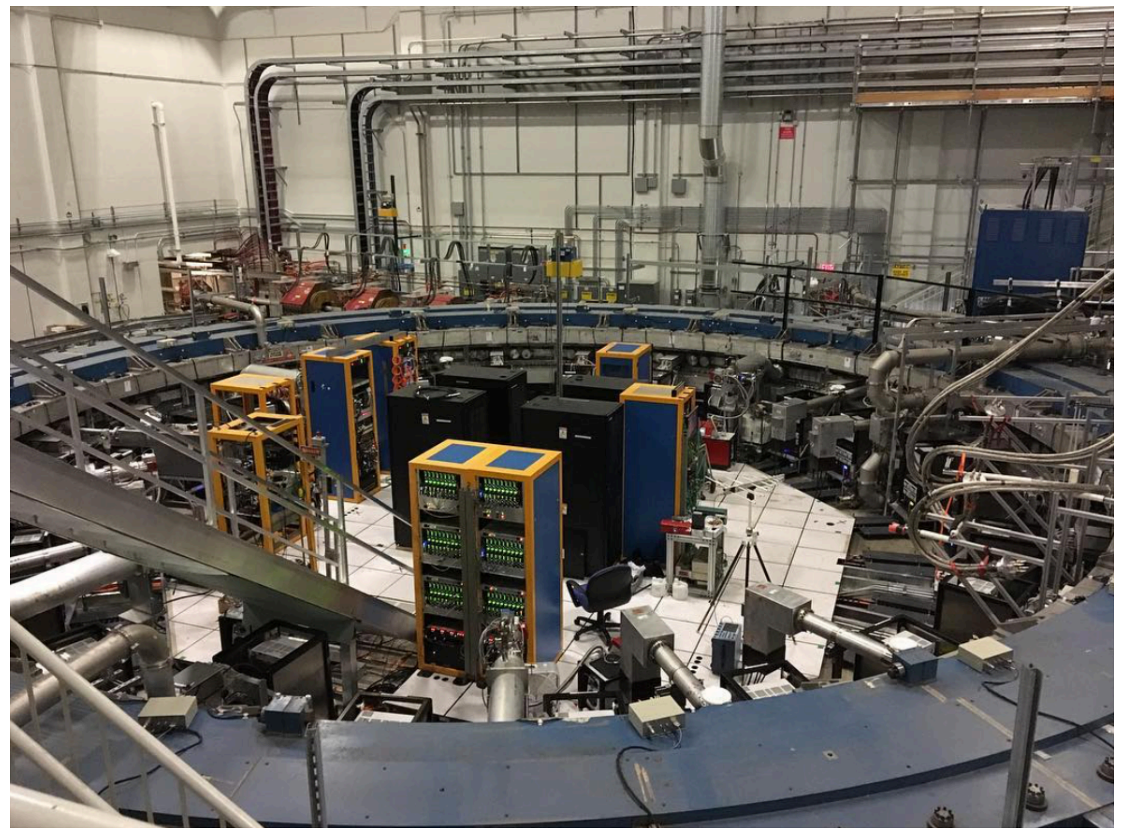


Auxiliary Field Systems

Surface Correction Coils

- Continuous PCB traces going around the ring on pole surfaces
- 100 concentric traces on upper poles, 100 on lower poles
- Current range: ± 2.5 A
- Used to cancel higher-order multipole moments in the magnetic field (on average)





Power Supply Feedback

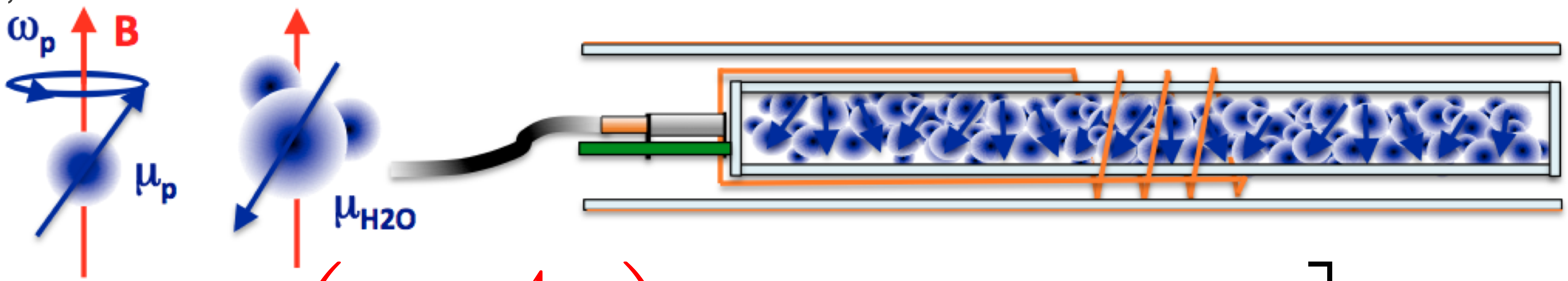
- Programmable current source with a range of ± 200 mA
- Uses data from **fixed probe** system to stabilize the field at a specified set point

Fluxgates

- Measure (x,y,z) components of transient fields in the hall
- Sensitive down to 10^{-9} T (DC or AC) fields
- Bandwidth up to 1 kHz

Calibrating the Magnetic Field

- In the experiment, need to extract ω_p; however, don't have free protons
  - Need a calibration
- Field at the proton differs from the applied field



$$\omega_p^{\text{meas}} = \left[1 - \sigma\left(H_2O, T\right) - \left(\varepsilon - \frac{4\pi}{3}\right)\chi\left(H_2O, T\right) - \delta_s\right]\omega_p^{\text{free}}$$

Protons in H_2O molecules, diamagnetism of electrons screens protons => local B changes

- σ = 25 680(2.5) x 10^{-9} at 25 deg C [Y. Neronov and N. Seregin, Metrologia **51**, 54 (2014)]

Magnetic susceptibility of water gives shape-dependent perturbation

- $\varepsilon = 4\pi/3$ (sphere), 2π (cylinder) when probe is perpendicular to B
- $\chi_{H_2O} \cong -720(2) \times 10^{-9}$ [J. Schenck, Med. Phys. **23**, 815 (1996)]

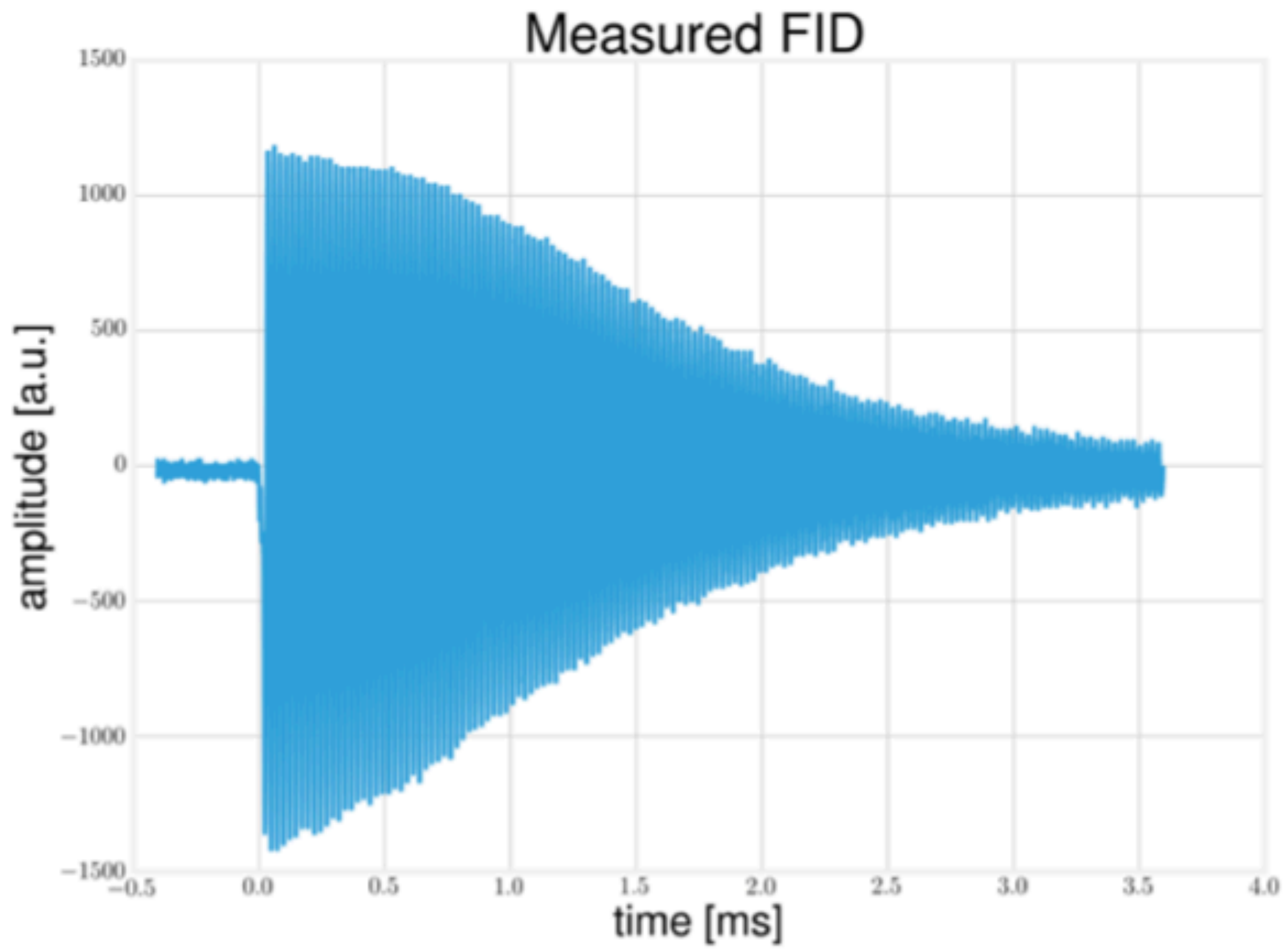
Magnetization of probe materials perturbs the field at site of protons

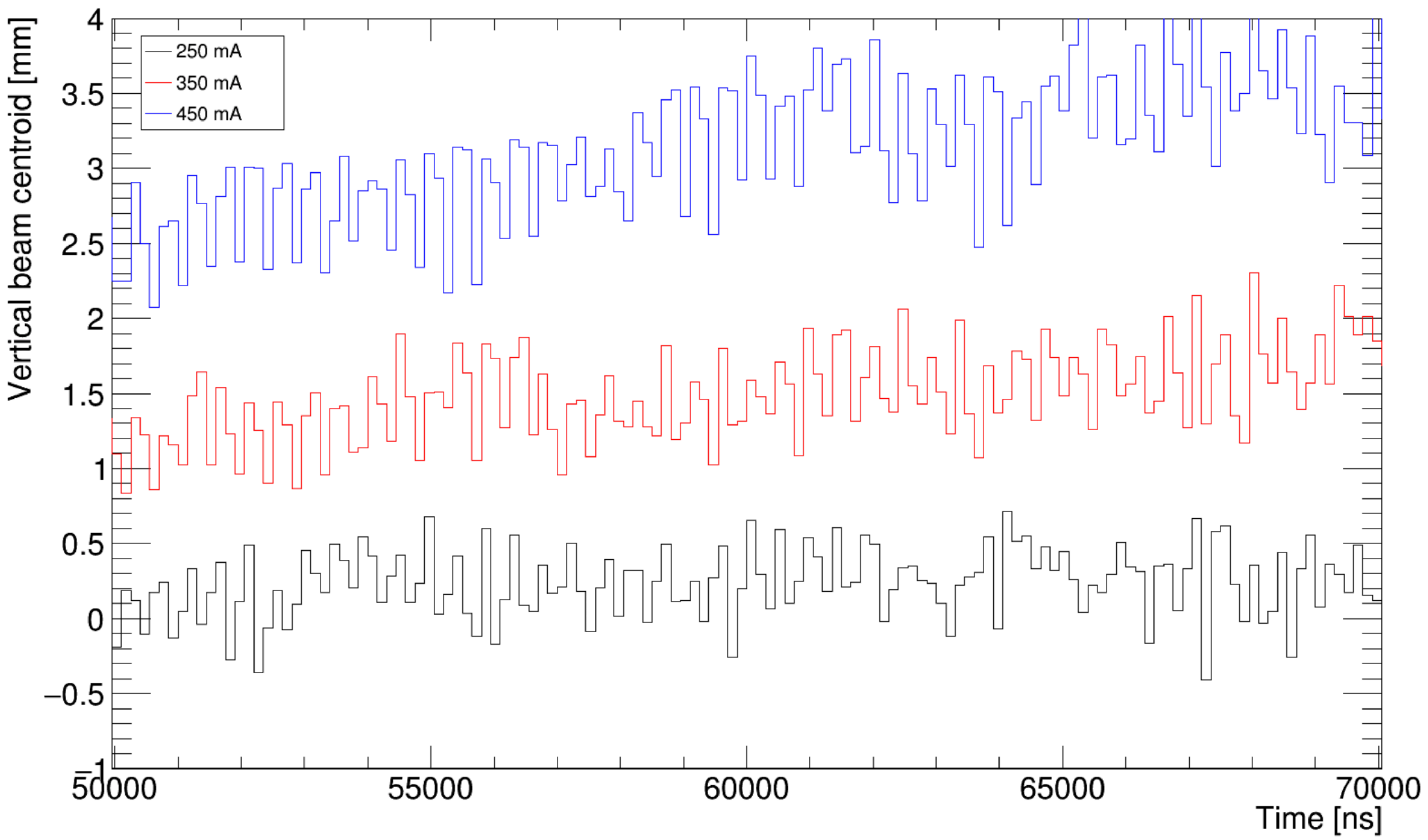
Goal: Determine total correction to ≤ 35 ppb accuracy

Commissioning Run Overview (1)

Highlights

- **Fixed probes:** Capable of reading out all 378 probes; ~ 80% with FIDs ≥ 500 µs
- Took 5 **trolley** runs
  - 1 full run, 4 partial runs



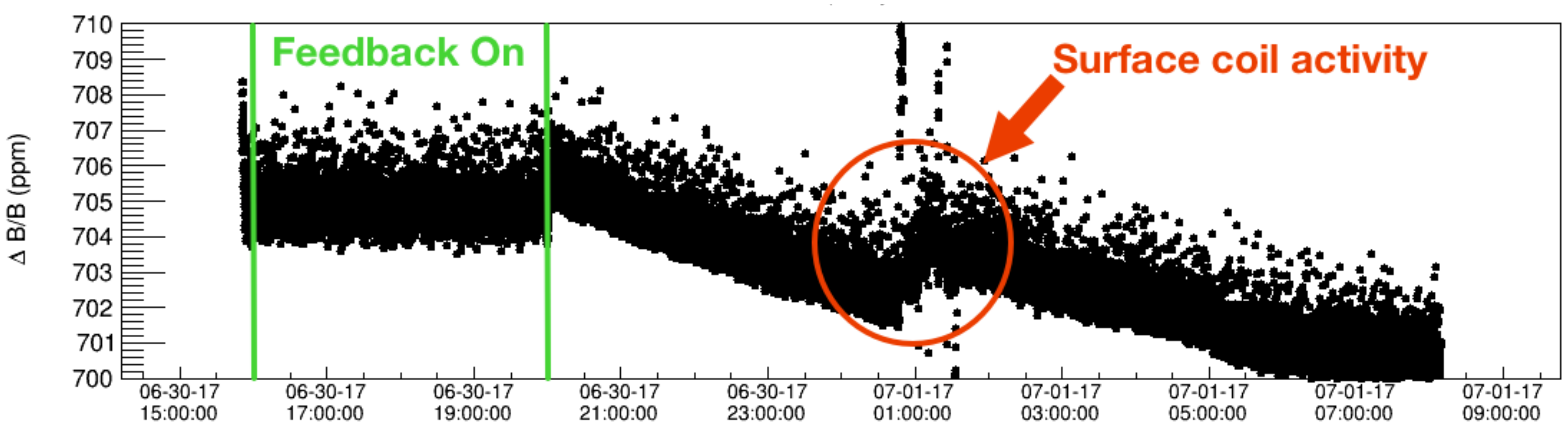


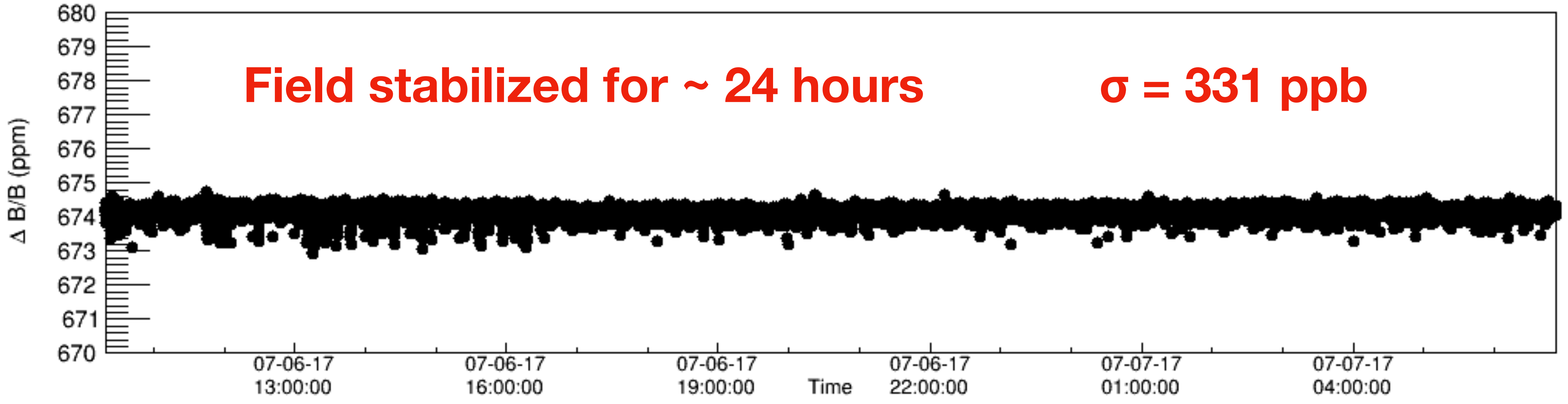
- Successful operation of **surface coils**
  - 2/3 of controller hardware installed
  - Generate radial field to control beam vertical position

Commissioning Run Overview (2)

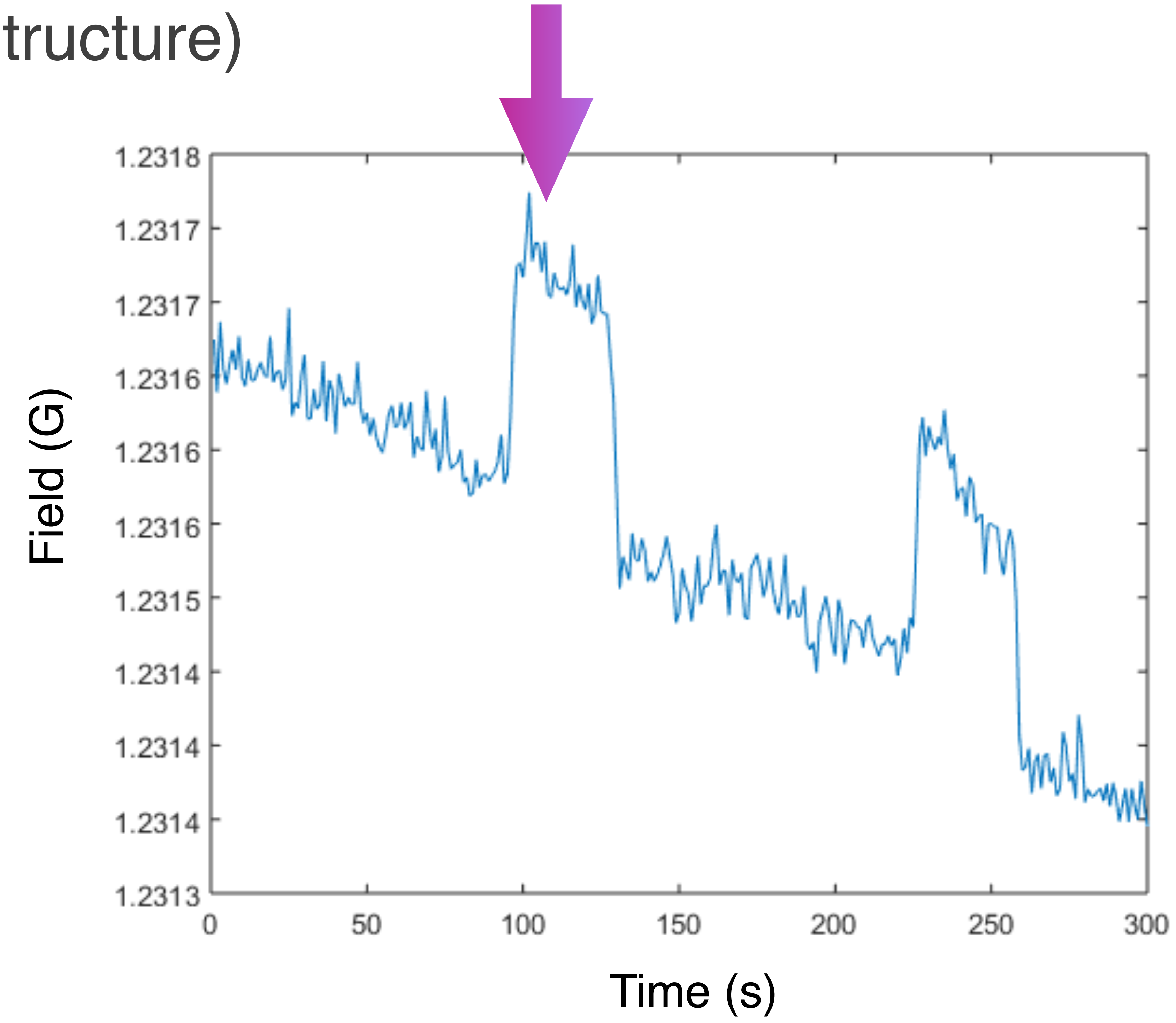
Highlights

- Learned how to utilize **power supply feedback** to stabilize the main field over long time scales





- **Fluxgates** detect transients in the hall
  - Correlated with field transients in storage volume
  - Observed regular field perturbation (130 sec structure)

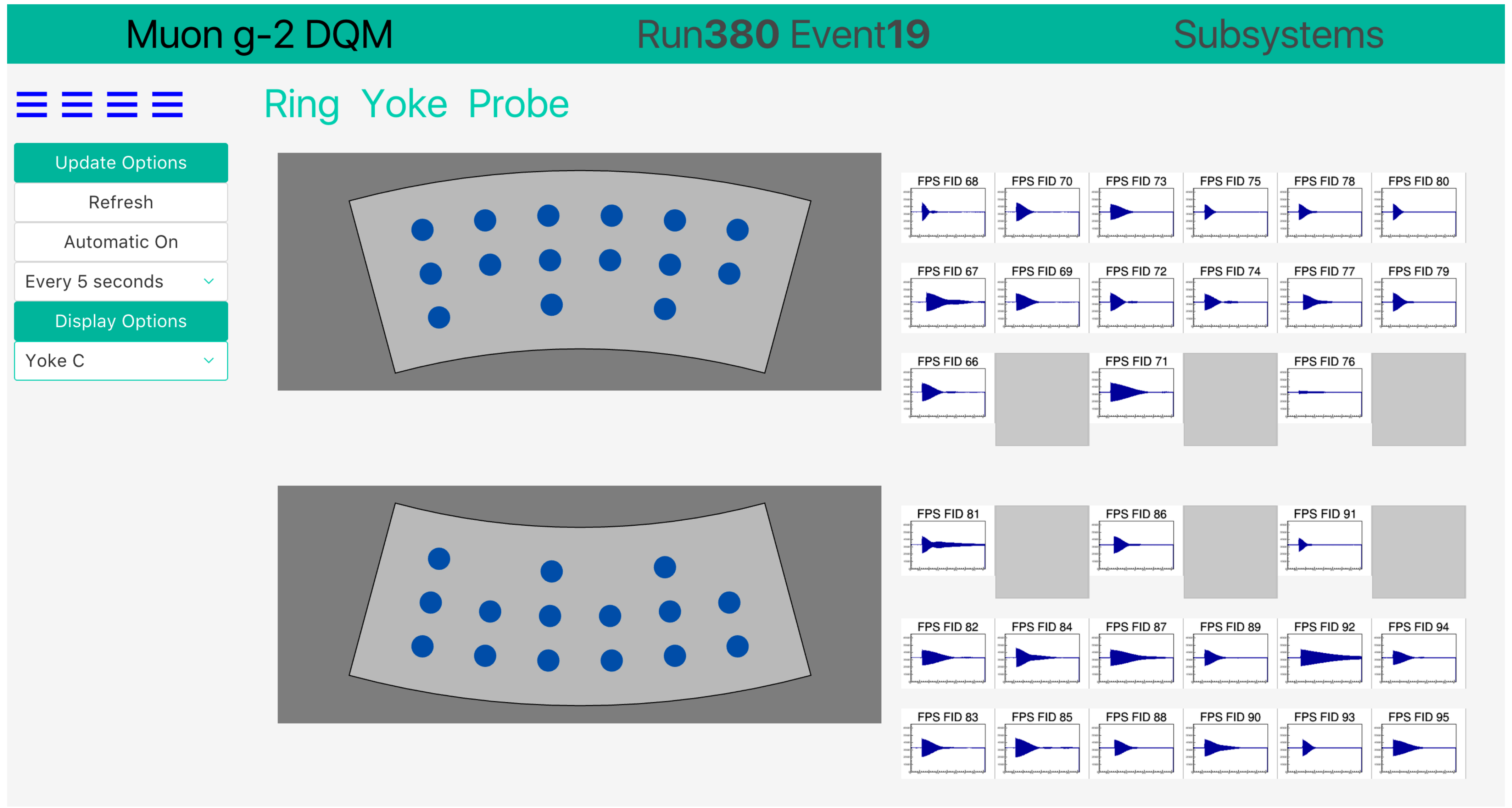


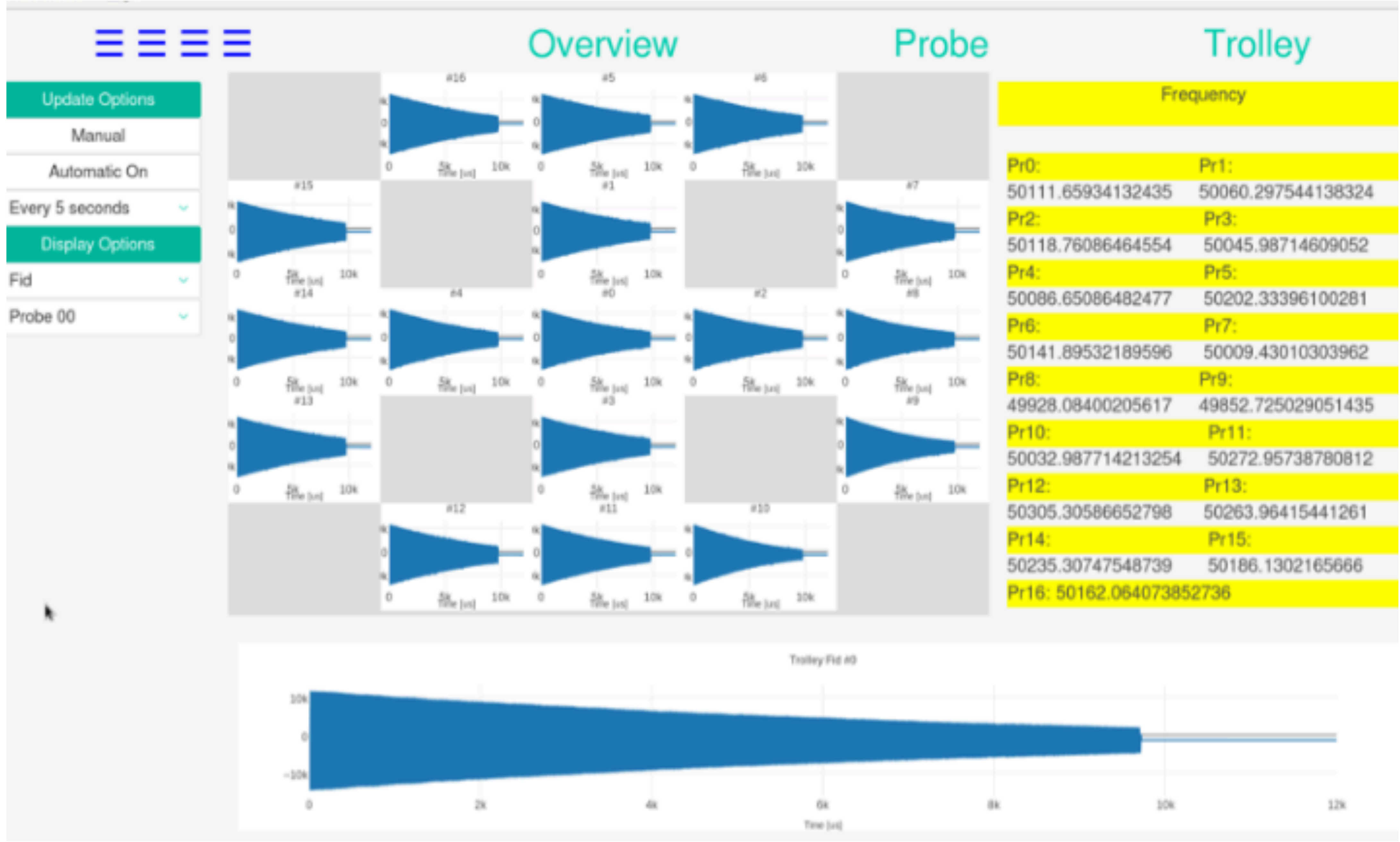
  - Working to identify, eliminate source; fallback is to utilize **PS feedback**

Commissioning Run Overview (3)

Highlights

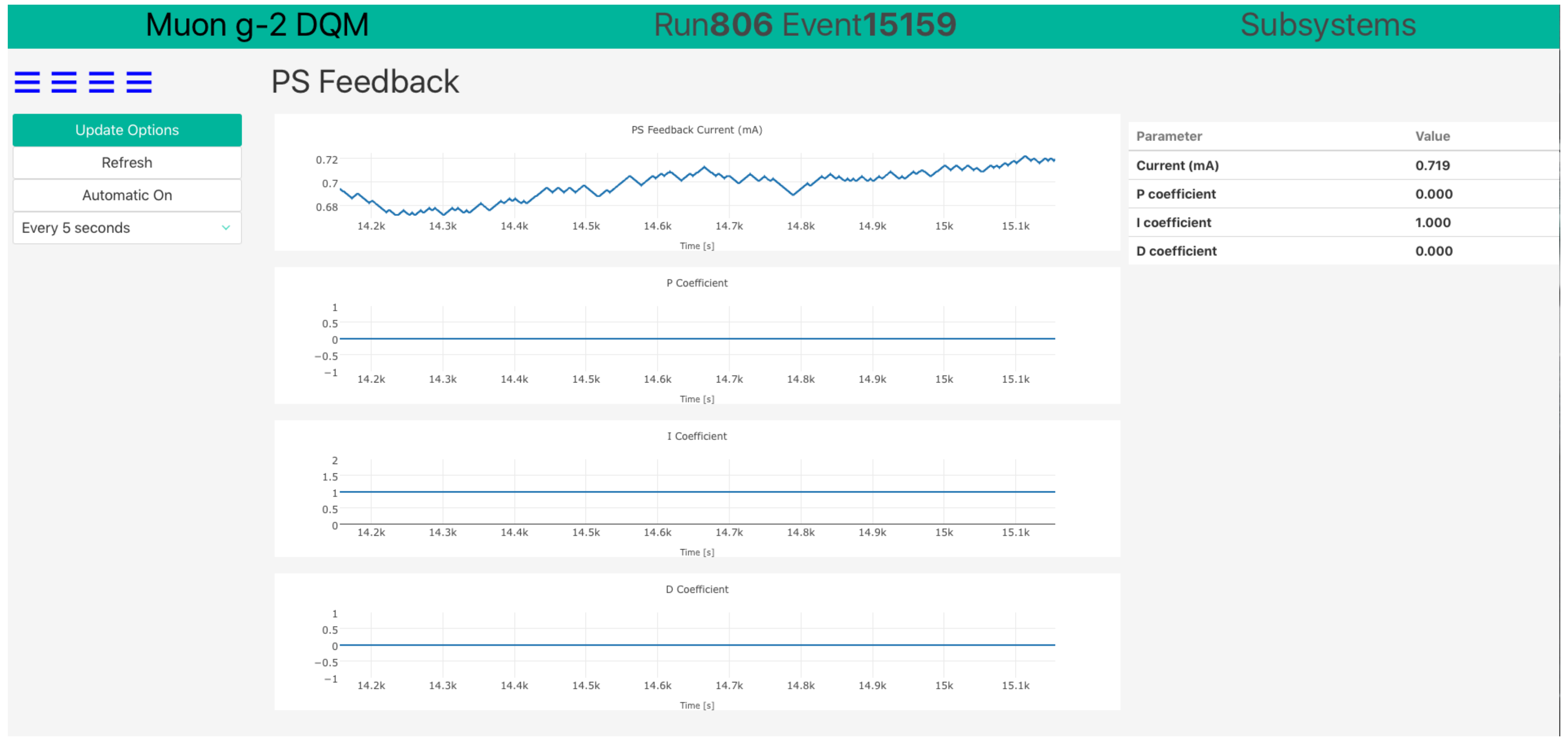
- **DQMs** mostly worked
  - **Trolley**, **fixed probes**, **PS feedback** operational
  - Demonstrated the ability to monitor data in real time





Frequency

Pr0: 50111.65934132435
Pr1: 50060.297544138324
Pr2: 50118.76086464554
Pr3: 50045.98714609052
Pr4: 50086.65086482477
Pr5: 50202.33396100281
Pr6: 50141.89532189596
Pr7: 50009.43010303962
Pr8: 49928.08400205617
Pr9: 49852.725029051435
Pr10: 50032.987714213254
Pr11: 50272.95738780812
Pr12: 50305.30586652798
Pr13: 50263.96415441261
Pr14: 50235.30747548739
Pr15: 50186.1302165666
Pr16: 50162.064073852736



Parameter	Value
Current (mA)	**0.719**
P coefficient	**0.000**
I coefficient	**1.000**
D coefficient	**0.000**

Commissioning Run Overview (4)

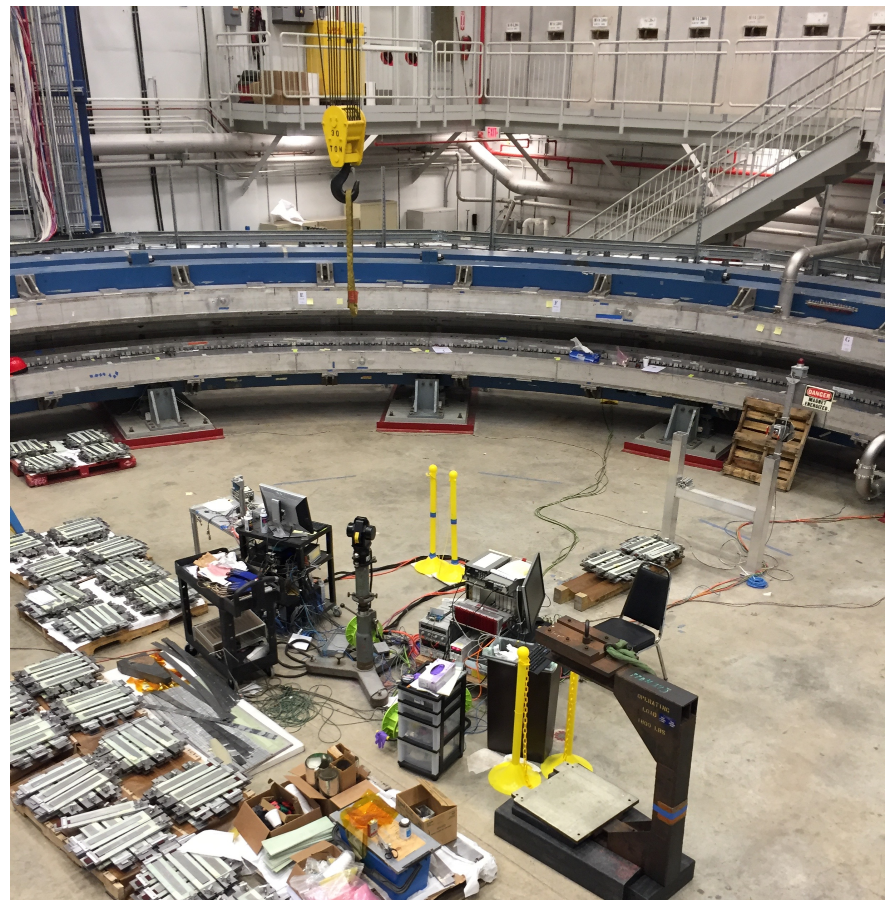
Problems & Lessons Learned

- **Trolley** motion problematic — motors driven outside recommended torque-RPM specs
  - Many incomplete runs, full circumference not mapped
- **Fixed probe** system encountered some hardware and software issues
  - Some (5 of 20) multiplexers failed: adjustable voltage in affected units exceeded an amplifier's spec; units pulled out and fixed
  - MIDAS Frontend and DQM crashed frequently: fixed by final week of run
- Did not get an opportunity to test out calibration procedure with **plunging probe** and **trolley**
  - Plunging probe DAQ was not installed
  - Tested plunging probe motion, failed — problem in assembly

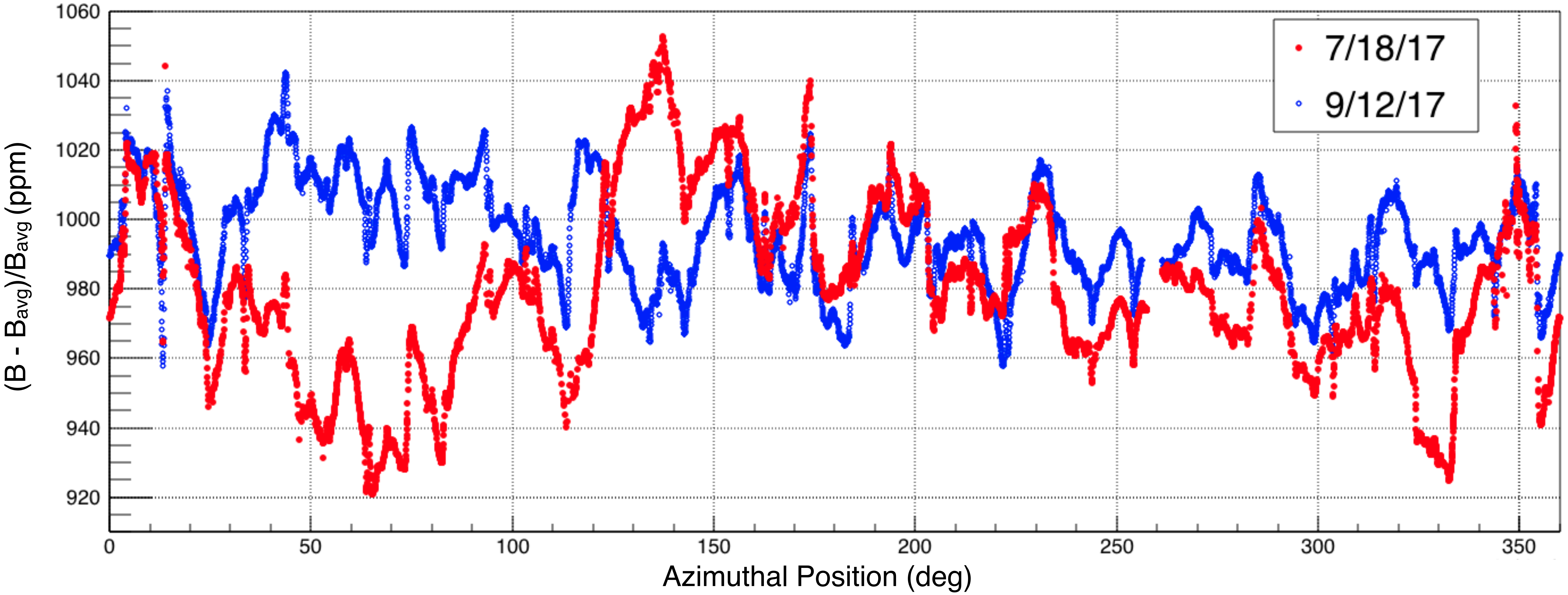
Summer Shimming: Fine-Tuning the Field (1)

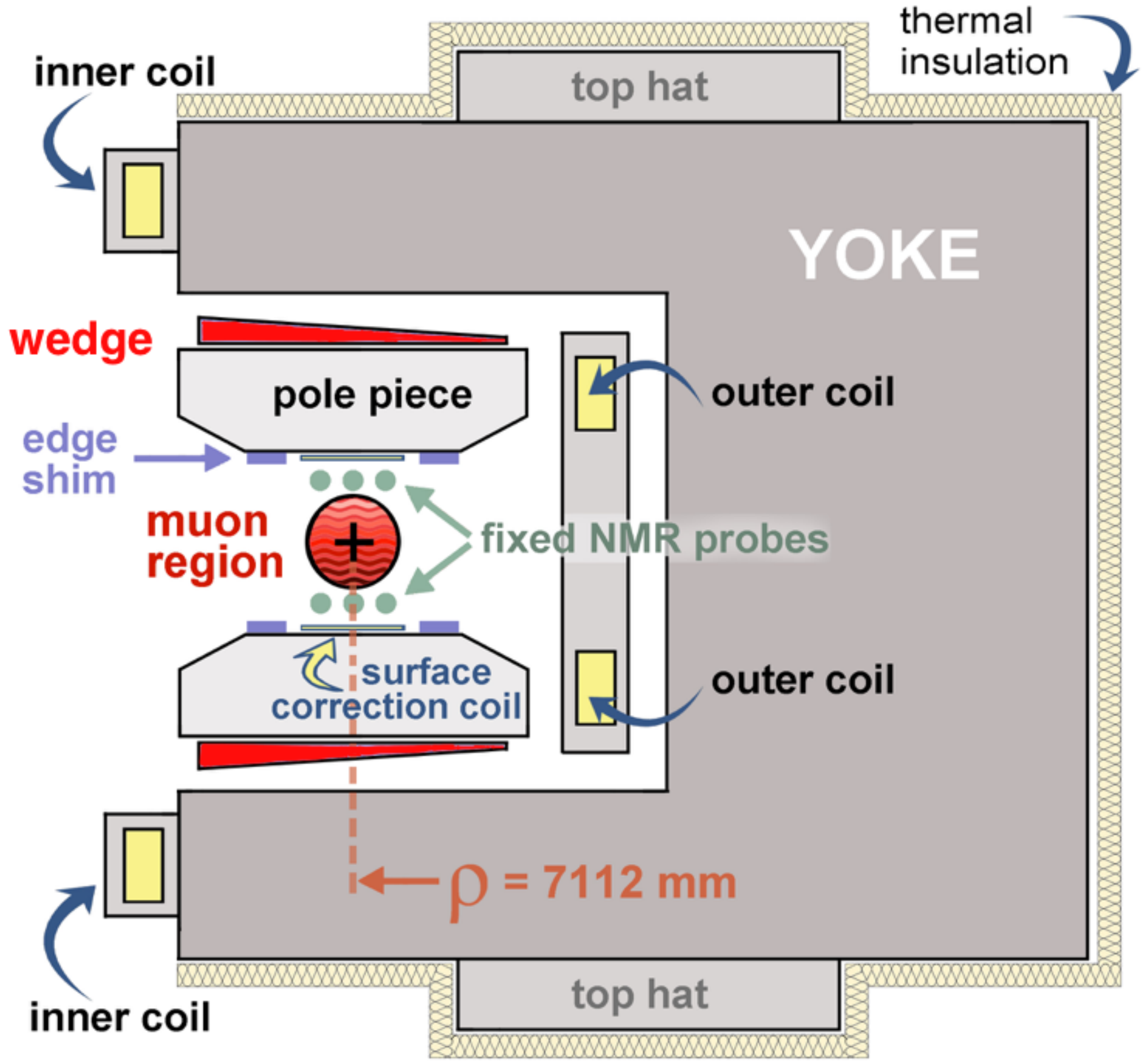
- Move wedges to reduce dipole variation around ring
- Field inhomogeneity 3x smaller than BNL

Wedge shims out of magnet during pole movements (before calorimeter installations)



Start of summer work → End of summer work





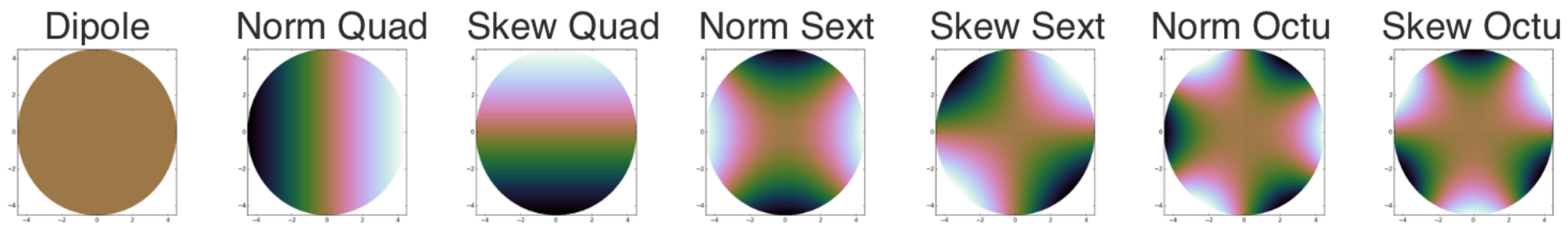
Summer Shimming: Fine-Tuning the Field (2)

- Surface coils adjusted according to measurements
- Utilize multipole decomposition of measured B:

$$B(x,y) = B(r,\theta) = B_0 + \sum_{i=1}^{n} \left(\frac{r}{r_0}\right)^i \left[a_i \cos(i\theta) + b_i \sin(i\theta)\right]$$

Radial dependence of coil currents for a given multipole

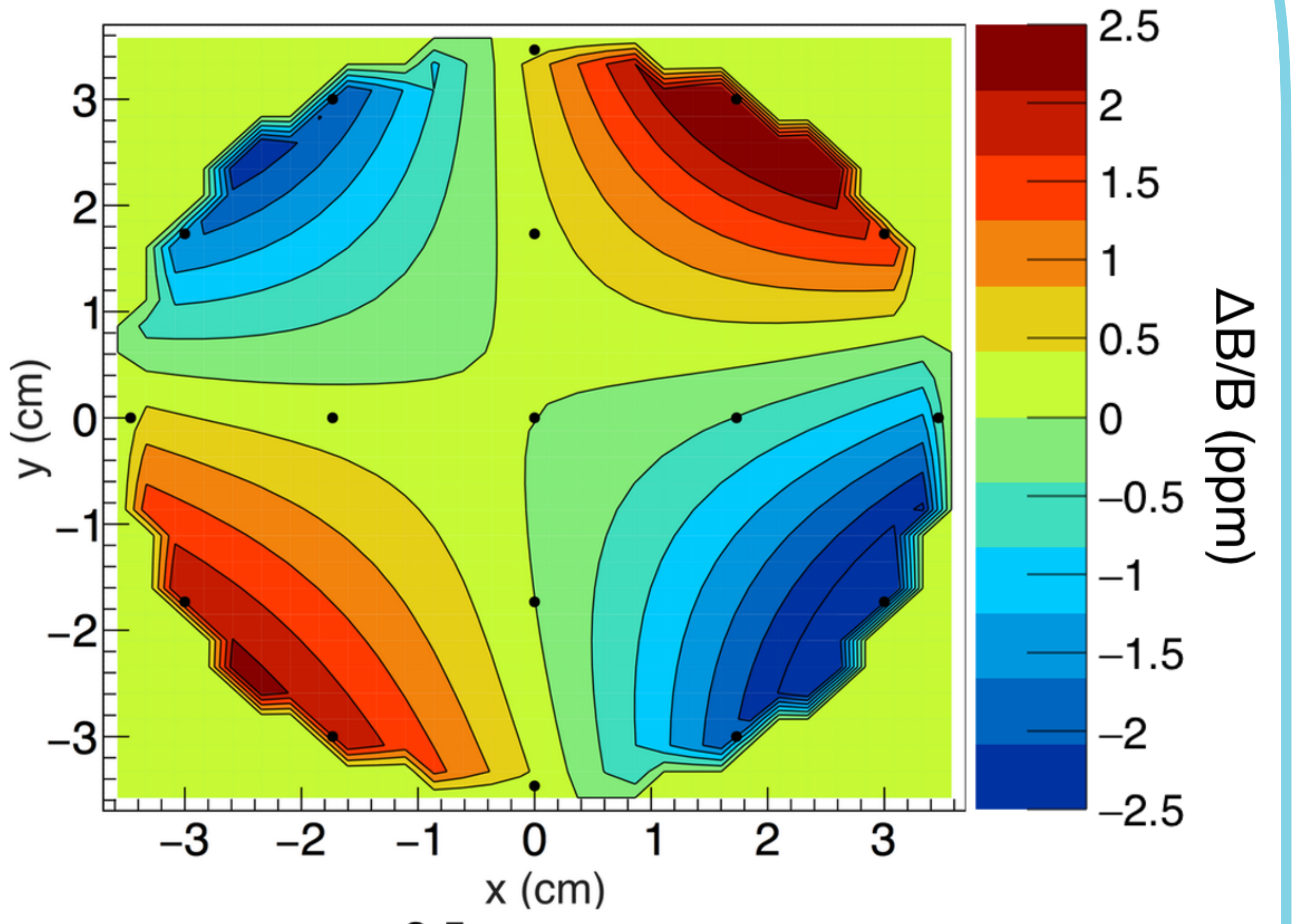
Multipole	Normal, Top	Normal, Bottom	Skew, Top	Skew, Bottom
Dipole	--	--	I	-I
Quadrupole	a	a	x	-x
Sextupole	ax	ax	x^2-a^2	$-x^2+a^2$
Octupole	$3ax^2-a^3$	$3ax^2-a^3$	x^3-3a^2x	$-x^3+3a^2x$
Decupole	ax^3-a^3x	ax^3-a^3x	$x^4+a^4-6a^2x^2$	$-x^4-a^4+6a^2x^2$

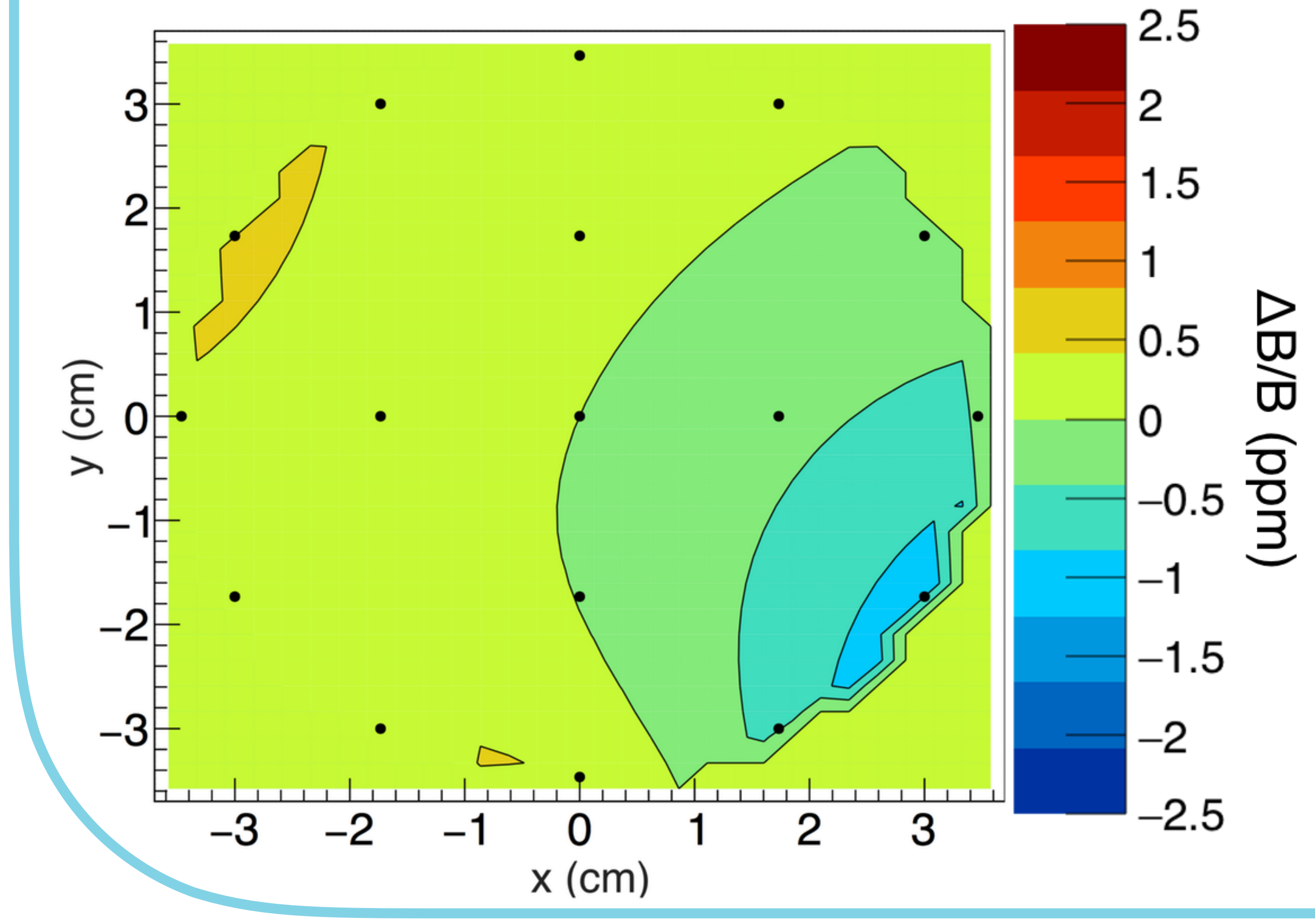


- Have mature tools to address inhomogeneities in the field
- Understand how things change on short (~ hours) and long (~ year) timescales
  - Know how to control uniformity

Azimuthally-averaged data

Non-optimized surface coils





Optimized surface coils

Fixed Probe System Status

Personnel

Matthias Smith, Jimin George

Summer Shutdown Work

- Remaining 15 multiplexers shipped back to UW for upgrades
- Working to improve trigger timing
  - FPGA-controlled triggering will be more robust than the current CPU-based triggering
- Sync field measurement to within a few ms of muon injection
- Frequency extraction algorithms being improved — crucial for **PS feedback**

Preparedness for Fall Run

- No additional hardware failures observed since commissioning
- **Will be ready**

Trolley System Status

Personnel

Ran Hong, Joe Grange

Summer Shutdown Work

- Commissioning run: motors driven improperly
  - Factor of 6 gear reduction so motors run at spec (60 RPM)
  - Thoroughly tested in air and vacuum, completed full trip around ring
- Currently back at ANL for calibration work
  - Finding NMR probe active volumes using MRI magnet gradient coils
  - Exercising calibration scheme with **plunging probe**

Preparedness for Fall Run

- **Will be ready**

Plunging Probe Status

Summer Shutdown Work

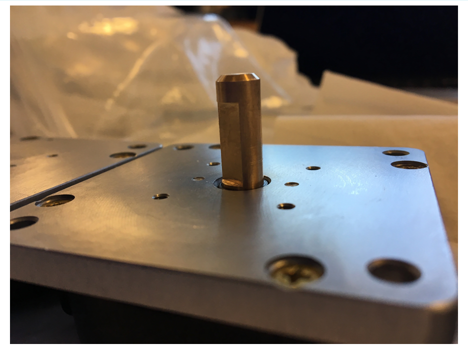
- 3D motion fixed and tested
- Installed DAQ
- Mapped field across muon storage area
  - Observed ~ 50 ppb/mm gradients
- Back at ANL for calibration studies
  - Measuring probe properties, compare with **trolley**

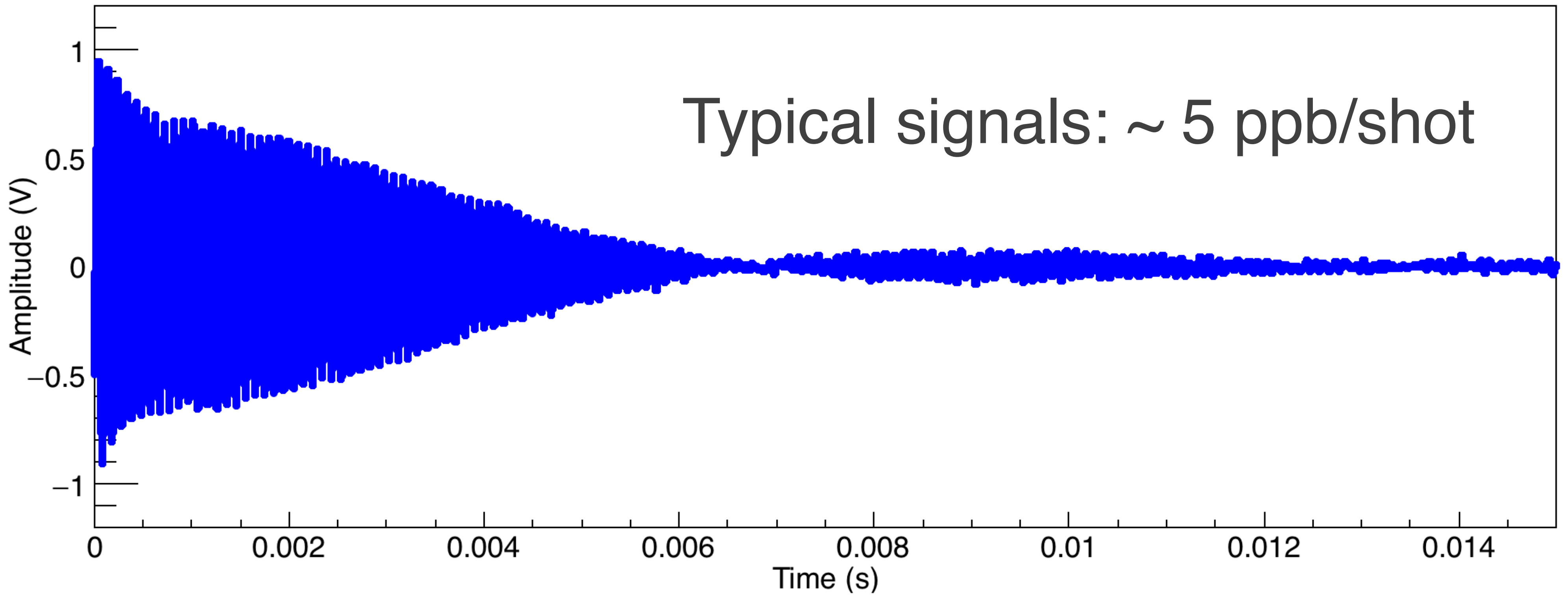
Preparedness for Fall Run

- **Will be ready**

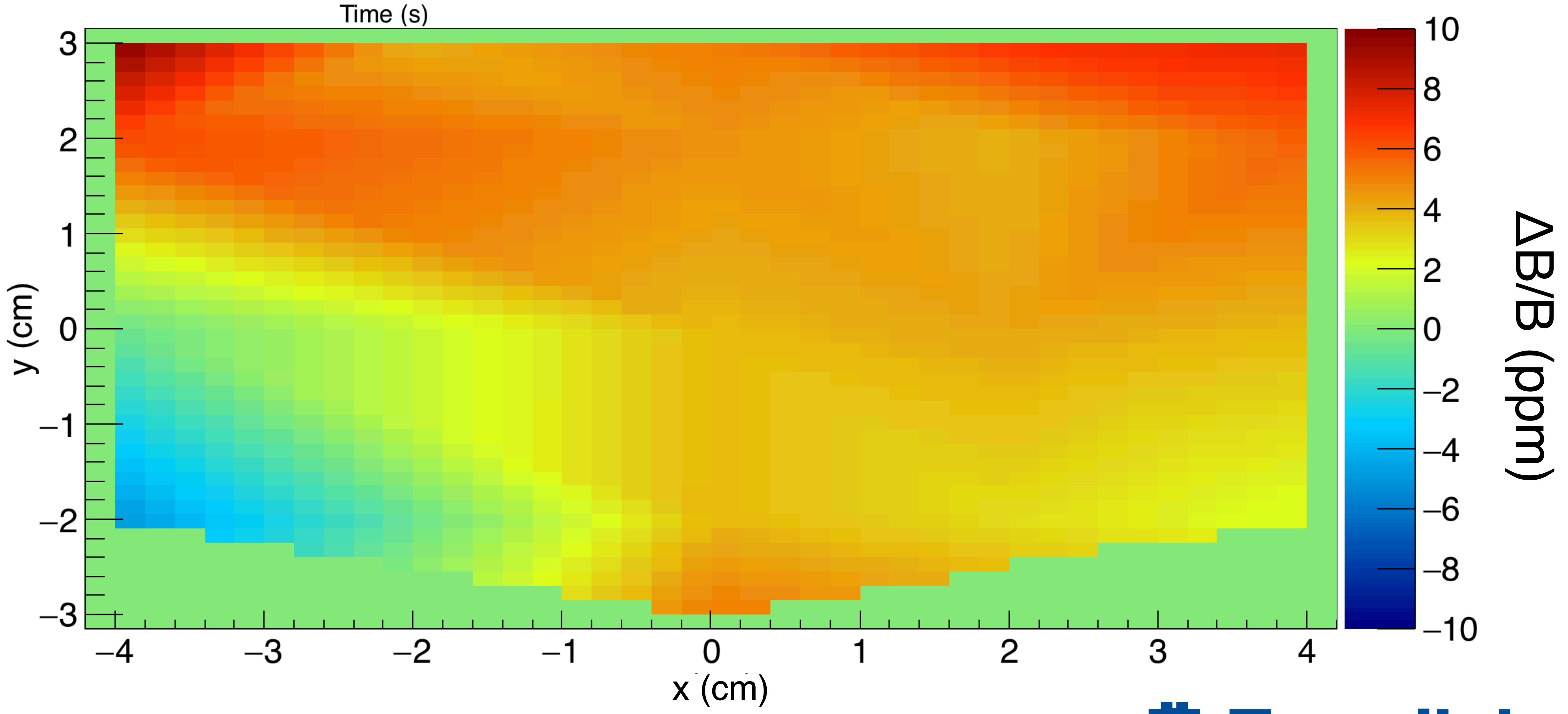
Personnel

David Flay





Typical signals: ~ 5 ppb/shot



Surface Coil Status

Personnel

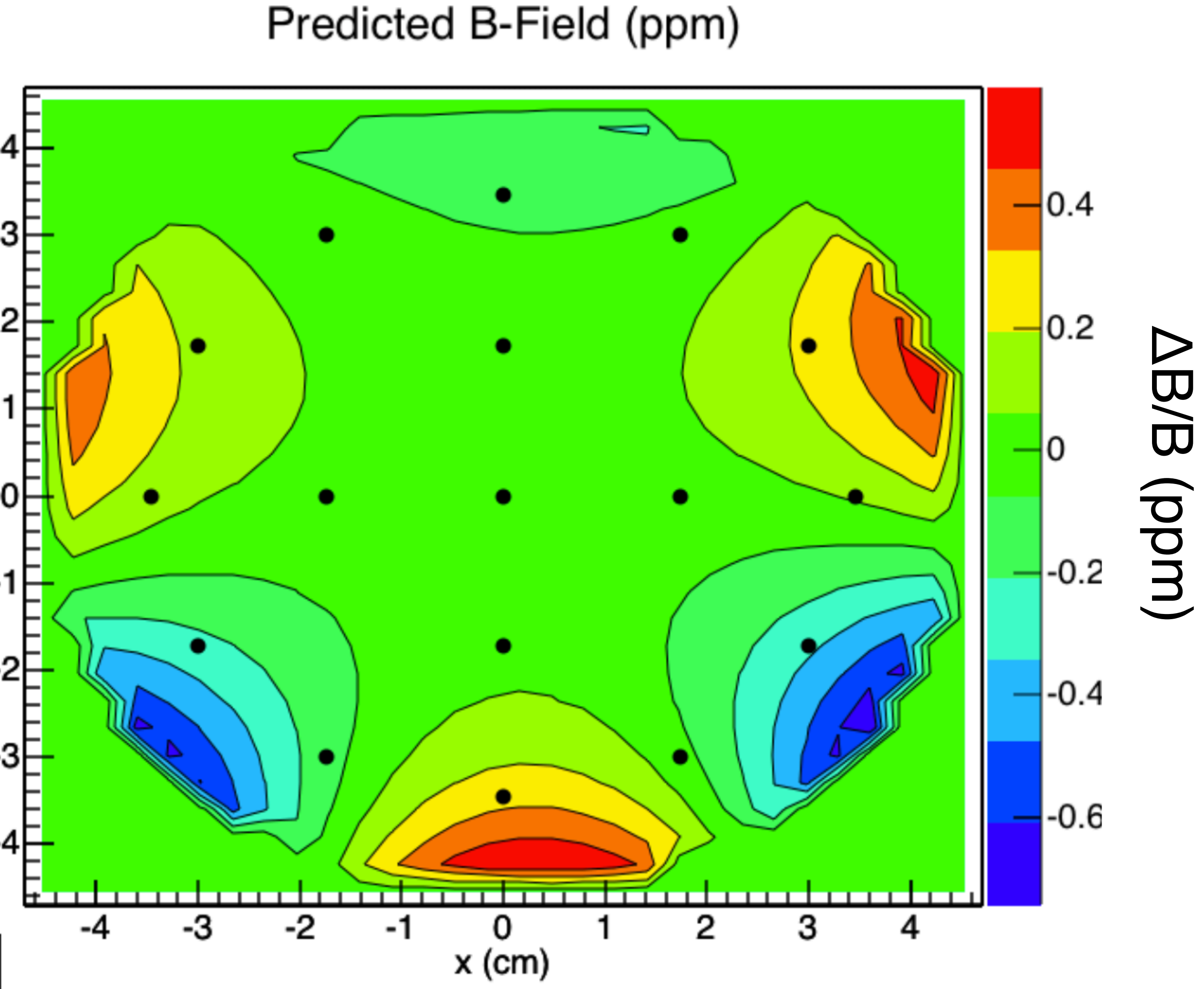
Rachel Osofsky, Brendan Kiburg

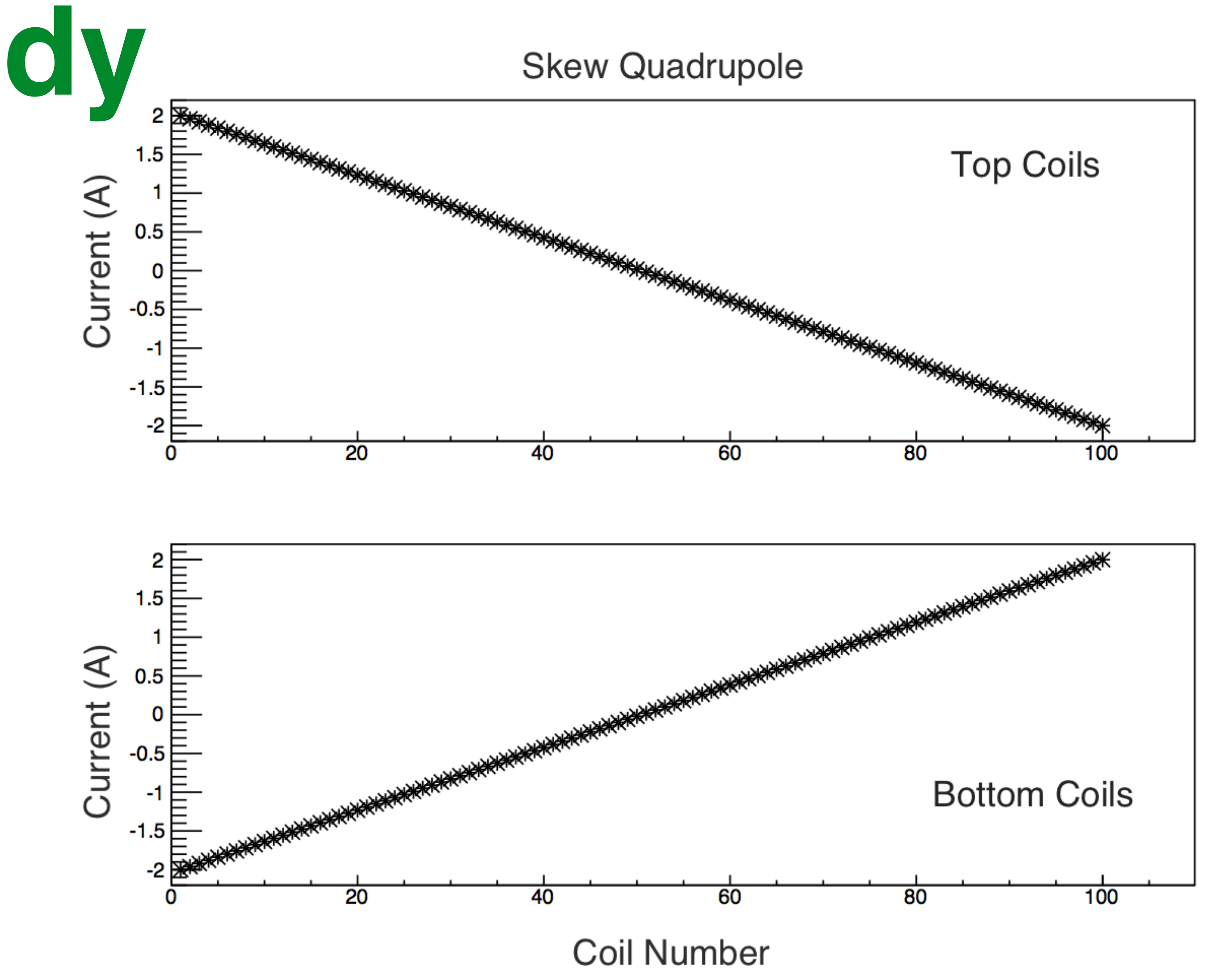
Summer Shutdown Work

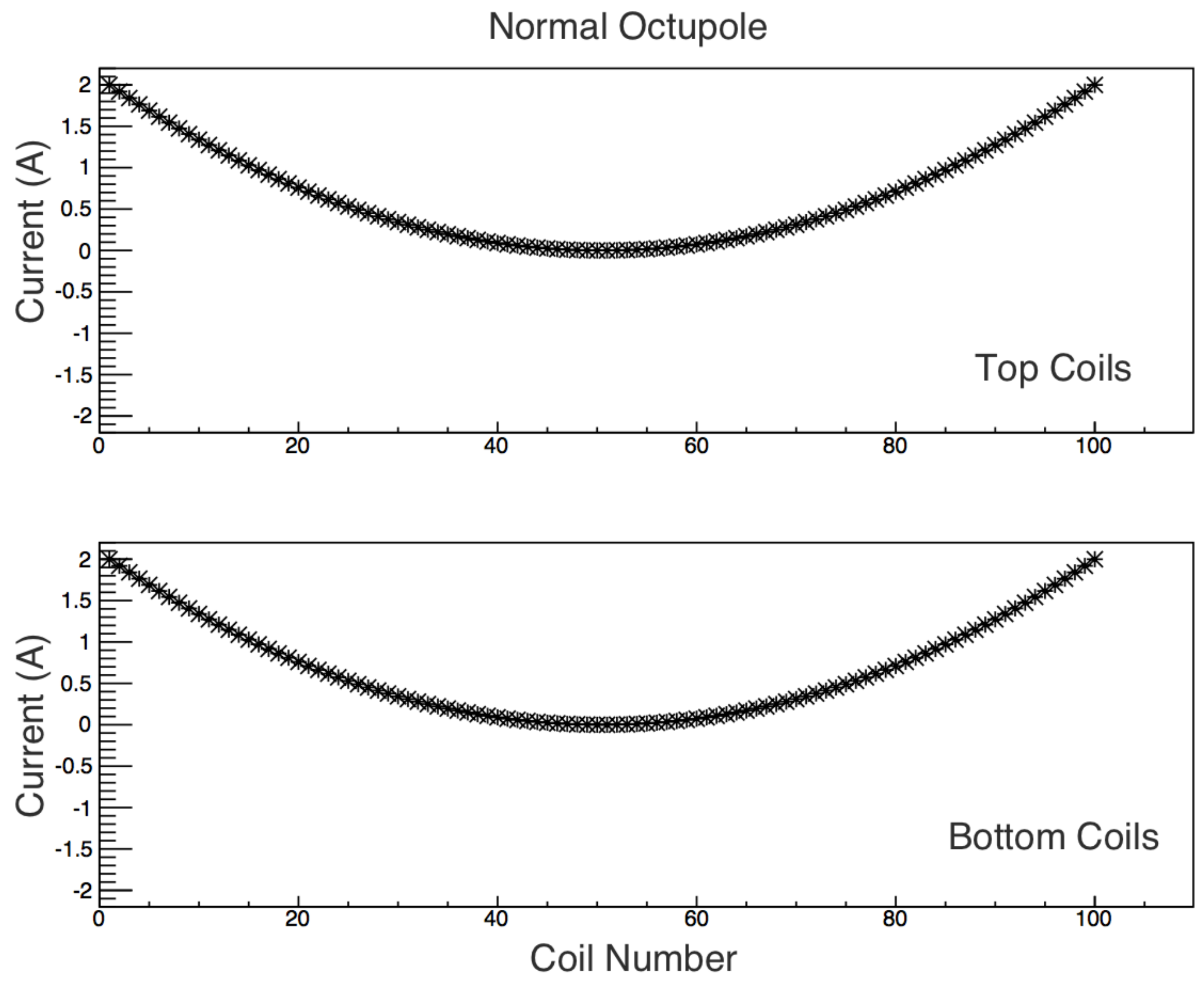
- Demonstrated how specific current configurations control individual multipole moments in the field
- Improvements to current configuration that cancels average higher-order multipoles

Preparedness for Fall Run

- **Will be ready**


Predicted B-Field (ppm)


Skew Quadrupole


Normal Octupole

Power Supply Feedback Status

Personnel

David Flay

Summer Shutdown Work

- No major work
- Updated DQM to display more information
  - Based on what we wanted to see during commissioning

Preparedness for Fall Run

- Ability to stabilize field to 100 ppb dependent upon improvements to **fixed probe** system
- **Will be ready**

Fluxgates Status

Personnel

Alec Tewsley-Booth

Summer Shutdown Work

- Final DAQ system installed
  - Tuning for optimal performance
- Took concurrent data with fixed probe system

Preparedness for Fall Run

- Need some tweaks to the DAQ
- Finalize the DQM development
- Determine final positions for the fluxgate devices
- **Will be ready**

Summary

- Magnetic field uniformity is in good shape
  - Homogeneity after vacuum chambers, calorimeter installations restored using well-understood knobs; ~ 3 times better than field at BNL, should meet all specs
- Most data-monitoring pages operational; bugs ironed out during commissioning run
- **Systems are just about ready for running**
  - Fixed probe multiplexers being upgraded; trigger timing being improved
  - Trolley and plunging probe coming back for reinstallation in mid to late October
  - Remaining data-monitoring software needed: surface coils, fluxgates

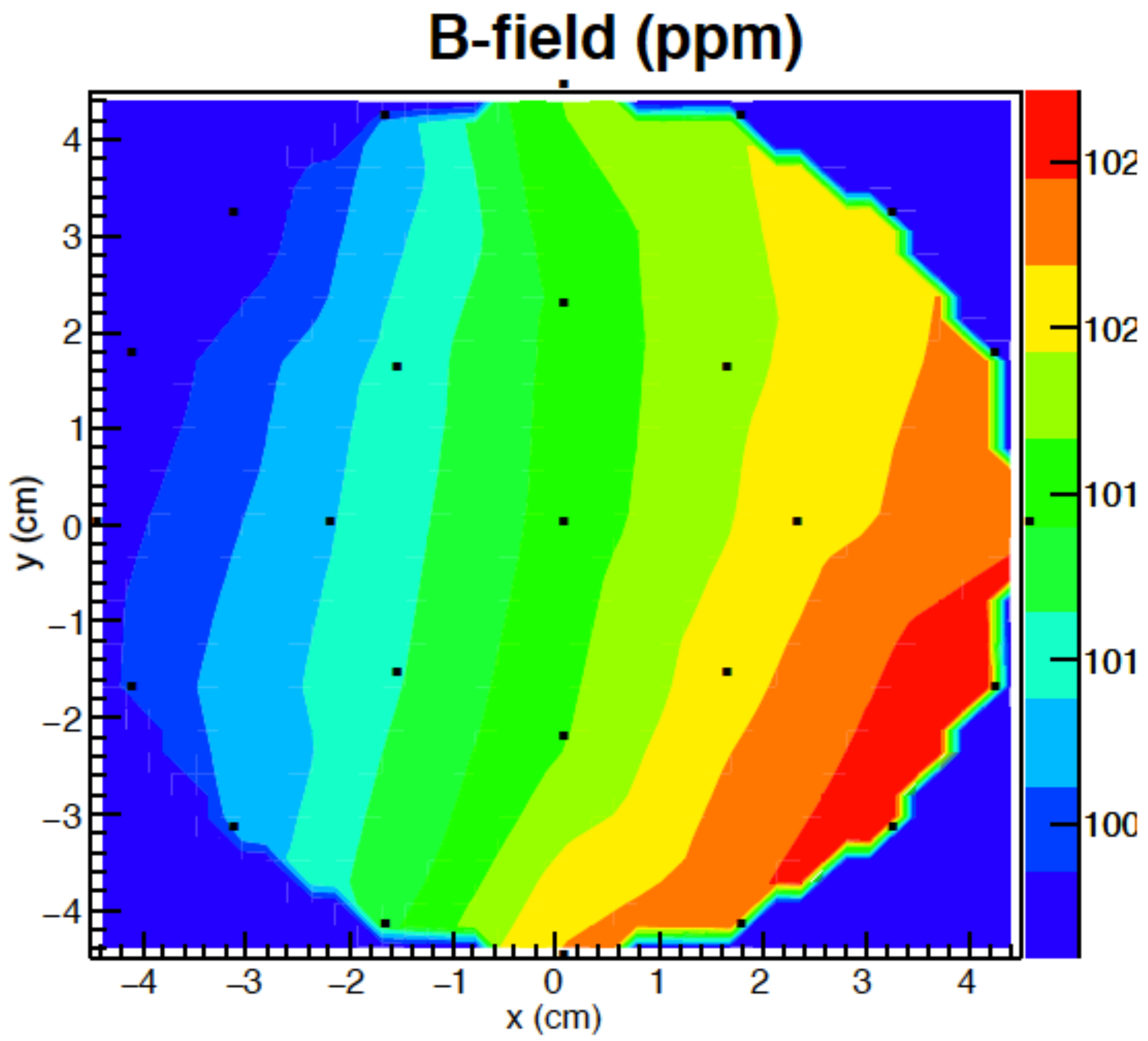
System	Ready?	Remaining Contingencies for Optimal Performance
Fixed Probes	✓	**Improved trigger timing**
Trolley	✓	**Improve probe-holding mechanism**
Plunging Probe	✓	**None**
Surface Coils	✓	**Operational DQM**
Power Supply Feedback	✓	**Improved frequency precision from fixed probes**
Fluxgates	✓	**Improved DAQ, operational DQM**

Backup

Multipole Decomposition of the Magnetic Field

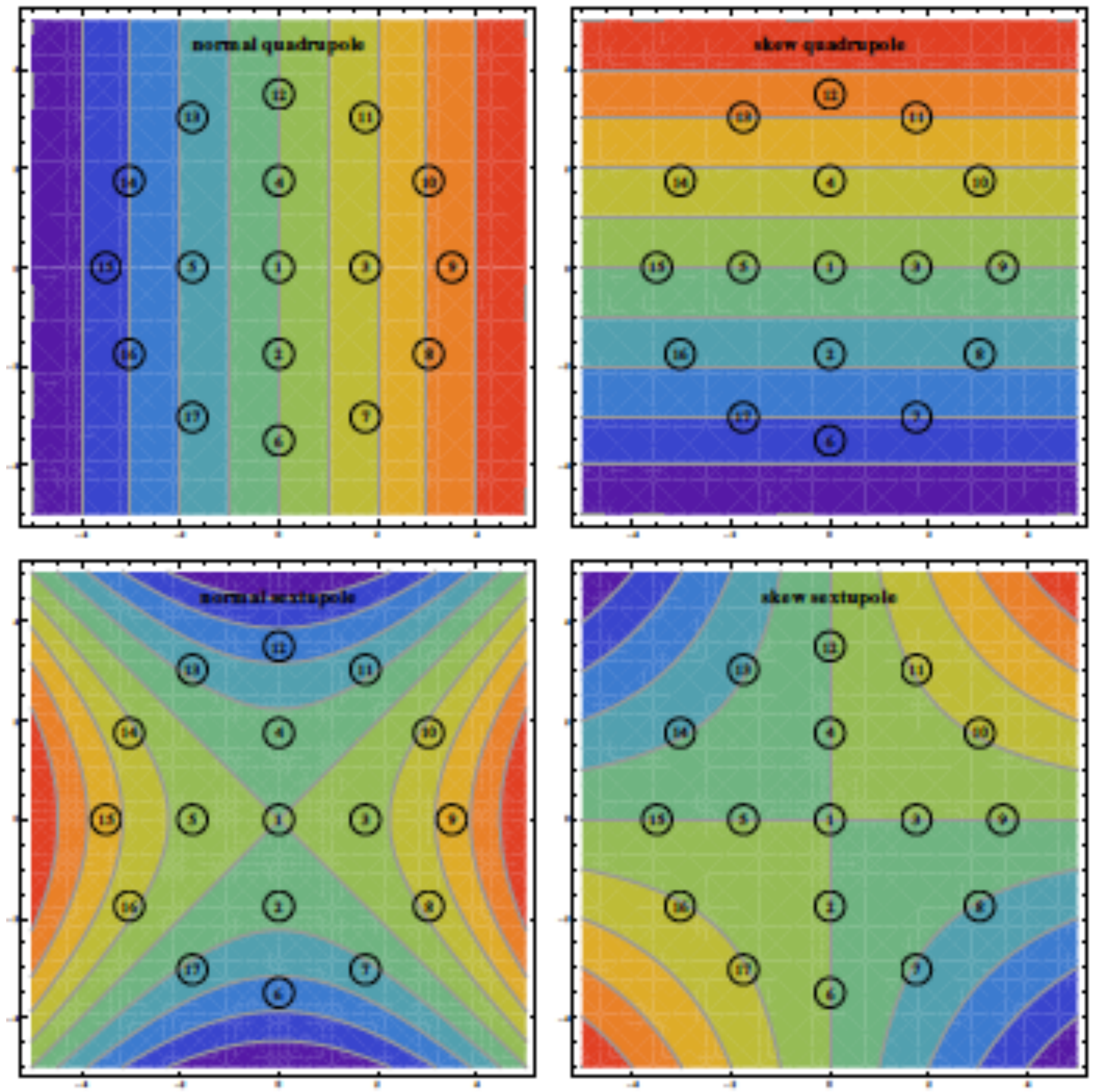
$$B(x,y) = B(r,\theta) = B_0 + \sum_{i=1}^{n} \left(\frac{r}{r_0}\right)^{i} \left[a_i \cos\left(i\theta\right) + b_i \sin\left(i\theta\right)\right]$$

- Sample at NMR probe locations
- Fit to sum of n orders of multipoles
  - a_i: normal terms
  - b_i: skew terms
- 2D approximation for small B_r, B_θ



Norm Quad

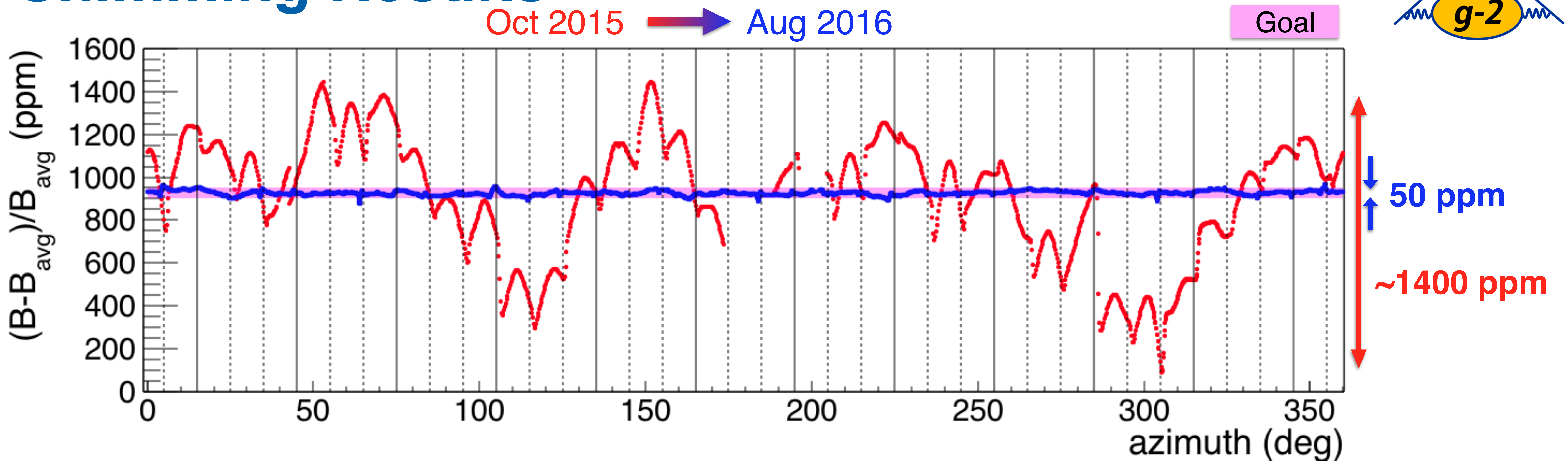
Skew Quad

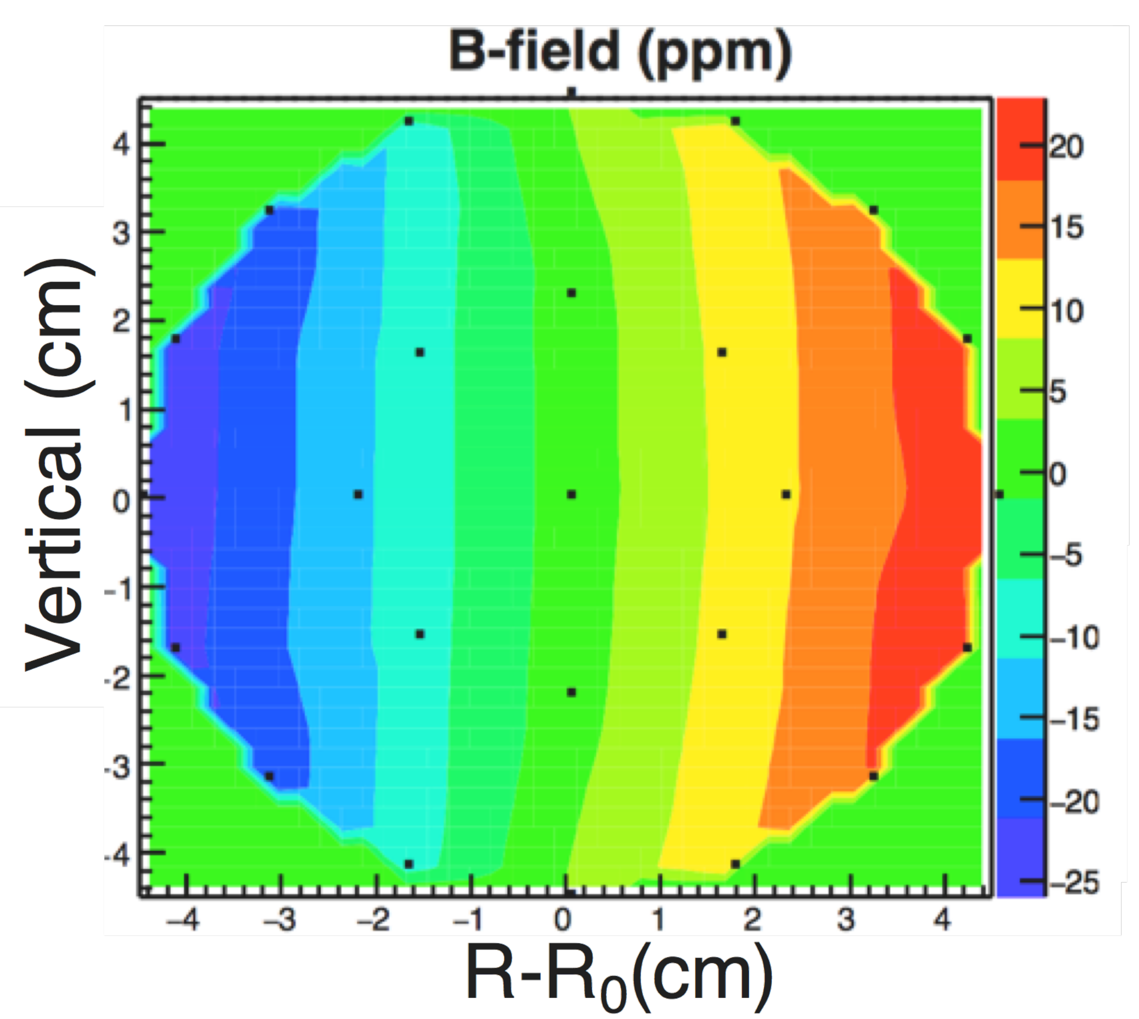


Norm Sext

Skew Sext

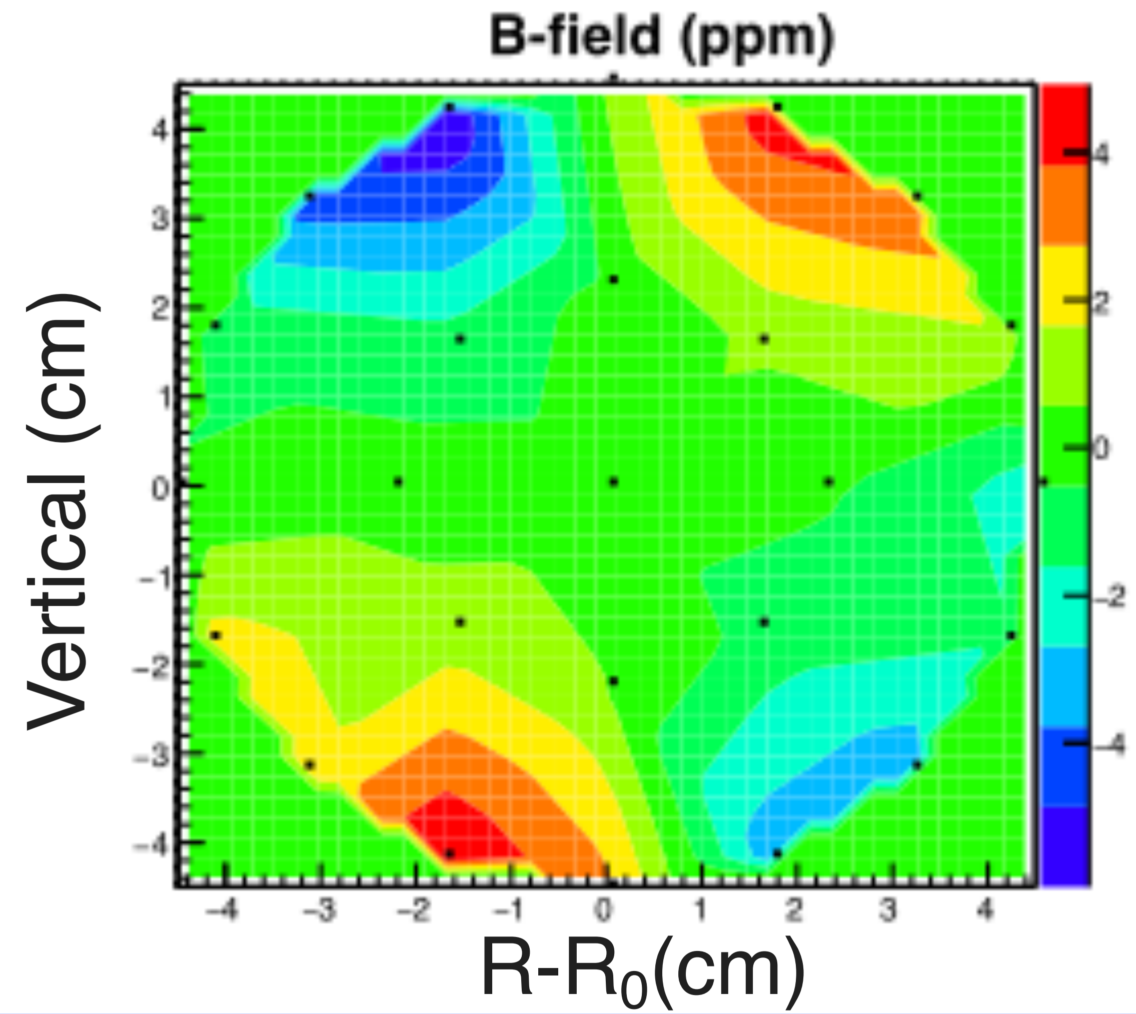
Rough Shimming Results





	Norm	Skew
Quad	25.13	-0.53
Sext	-1.99	-0.11
Octu	-1.16	-0.31
Decu	0.95	-0.07

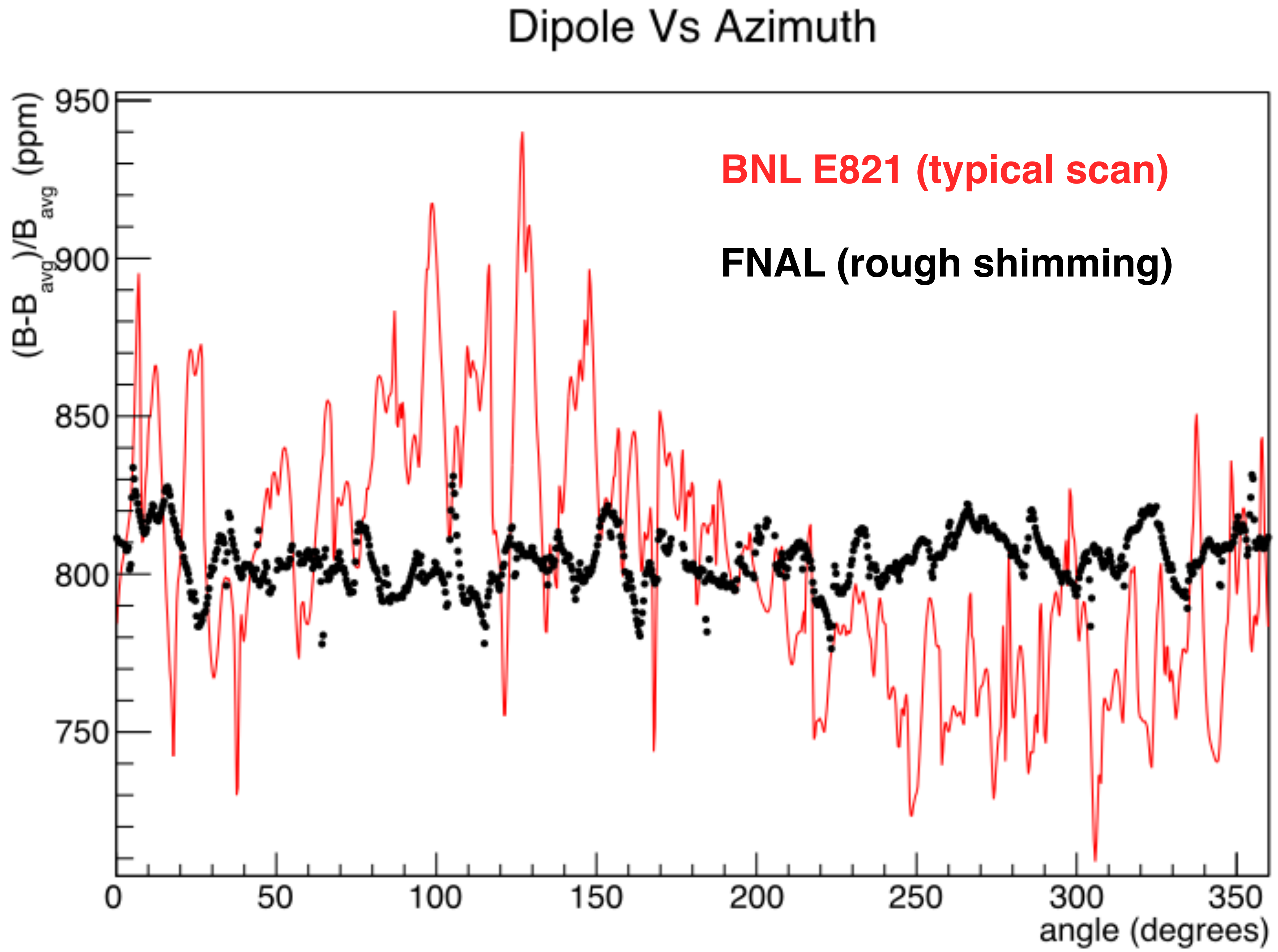
Oct 2015



	Norm	Skew
Quad	-0.02	-0.57
Sext	-0.70	3.84
Octu	-0.76	0.56
Decu	0.44	-1.61

Aug 2016

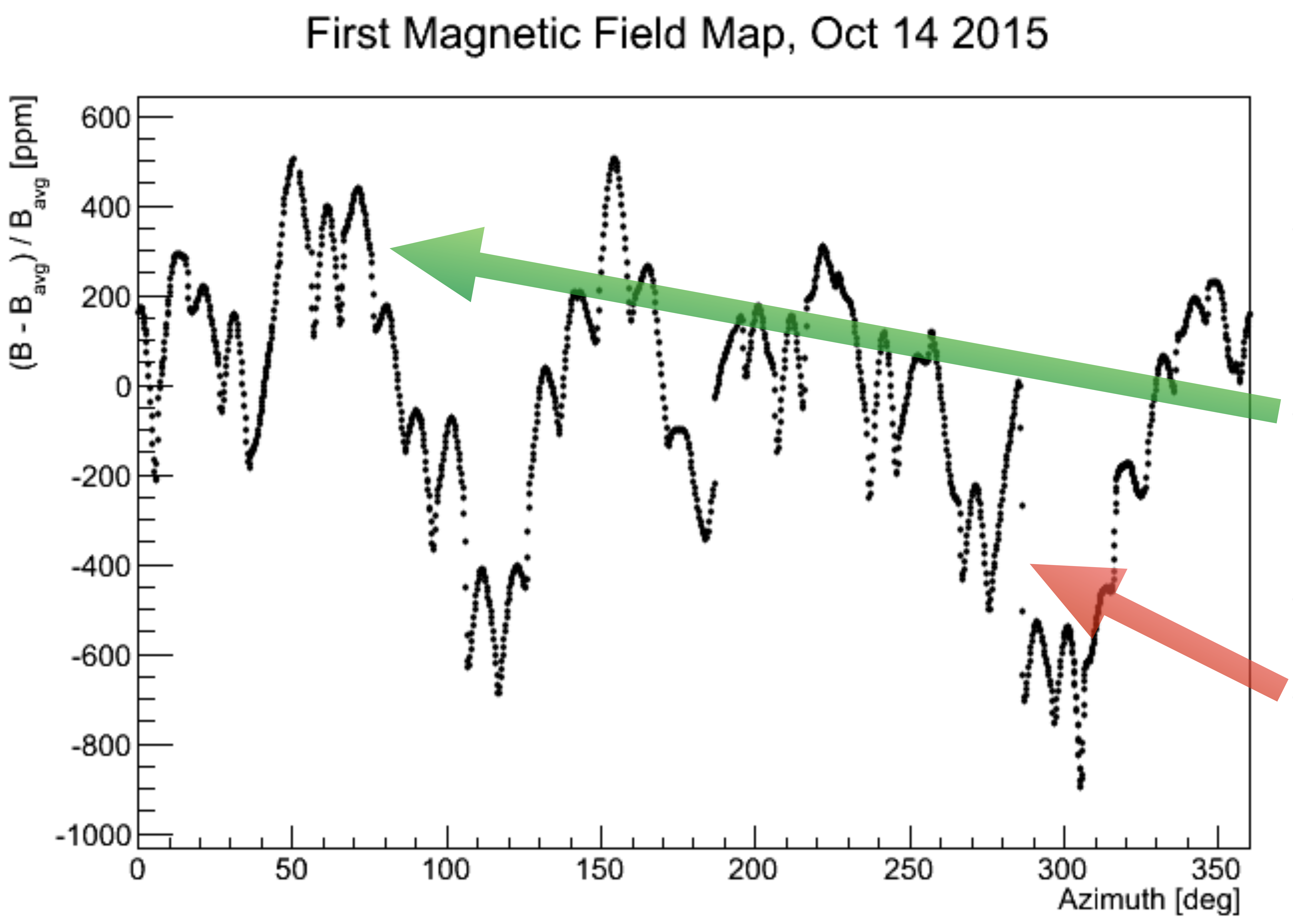
Magnetic Field Comparison: BNL E821 and FNAL E989

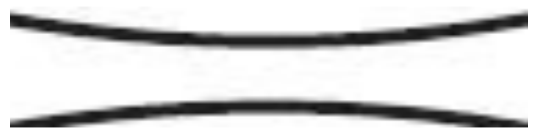


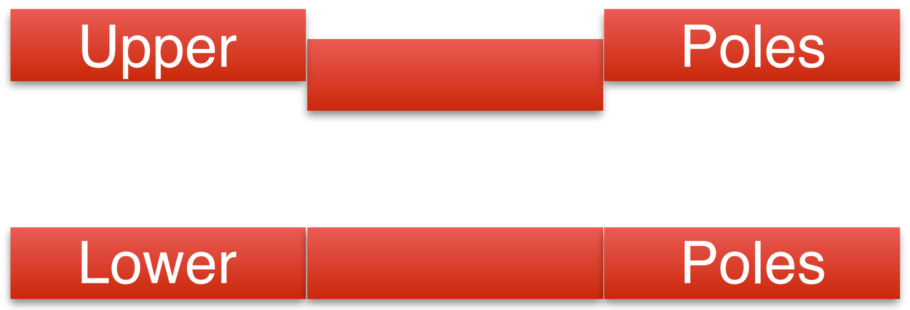
- Laminations very successful in reducing field variations

- BNL E821: 39 ppm RMS (dipole), 230 ppm peak-to-peak
- FNAL rough shimming: 10 ppm RMS (dipole), 75 ppm peak-to-peak

Magnetic Field Variations


First Magnetic Field Map, Oct 14 2015

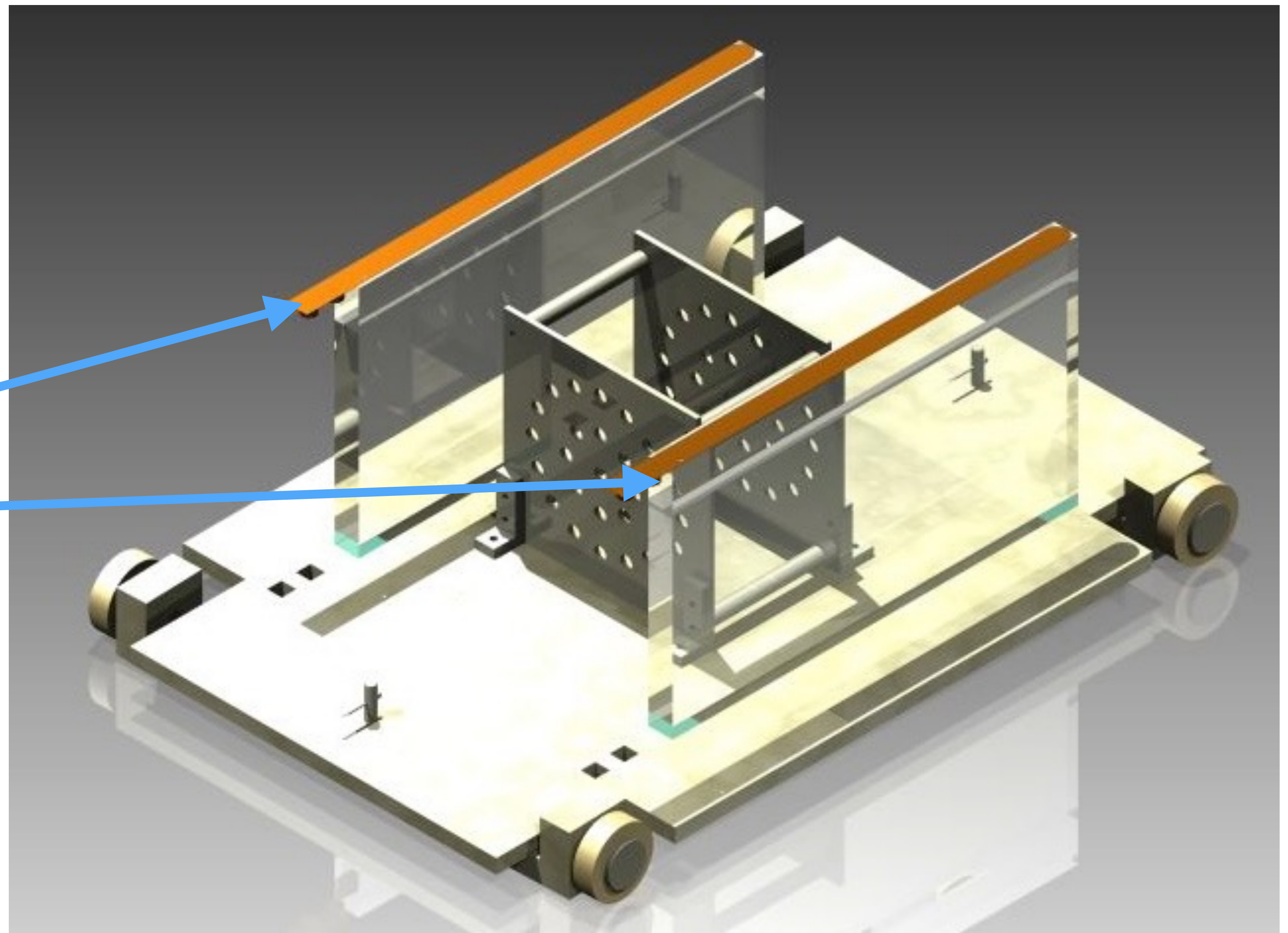
- Gradual drift from materials, pole gap changes
- 36 pairs of poles => 10-degree structure
- Pole shape: 
- Pole-to-pole discontinuities

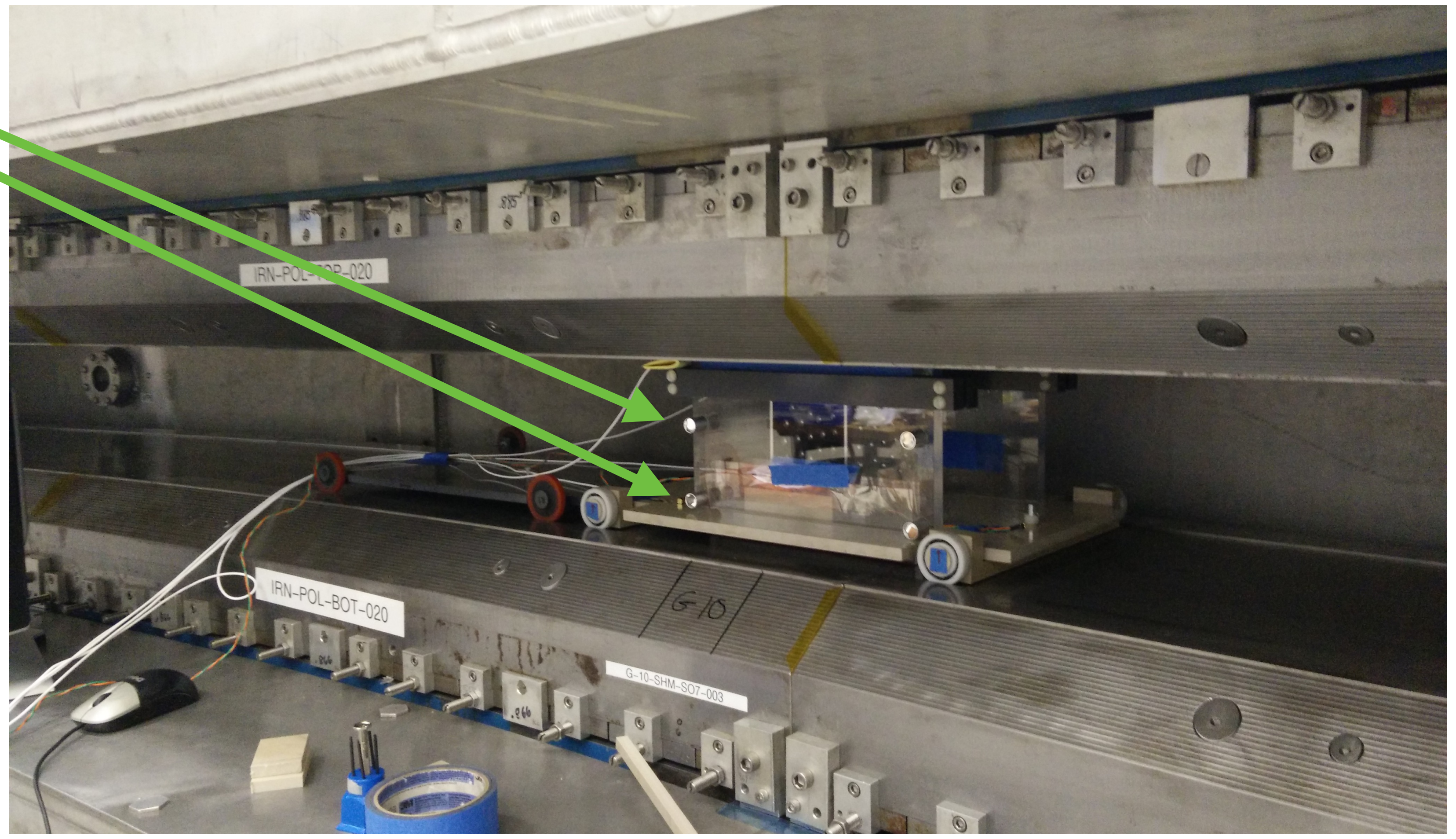

Upper Poles

Lower Poles

Measurement Tools: Rough Shimming

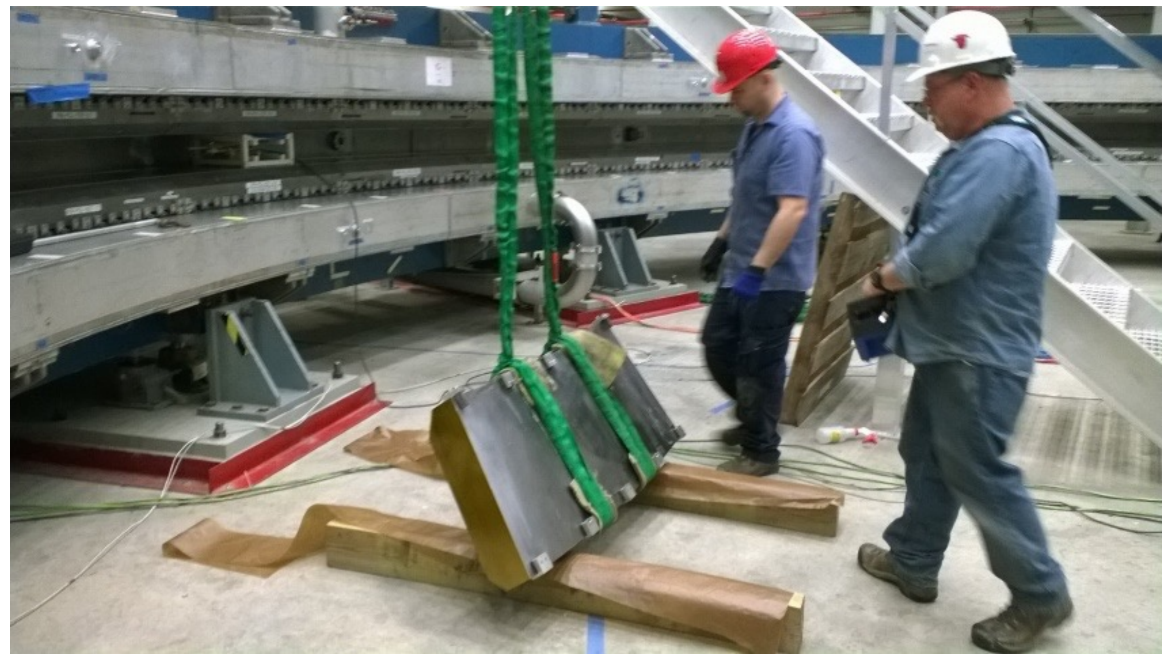
- Shimming Cart
  - Lattice of 25 NMR probes (field measurements
  - 4 **capacitive gap sensors** (pole-pole alignment/separation), 70-nm resolution
  - 4 **corner-cube retroreflectors** (position), ~ 25-µm resolution
- Laser Tracker
  - Cart position (r,ϕ,z)

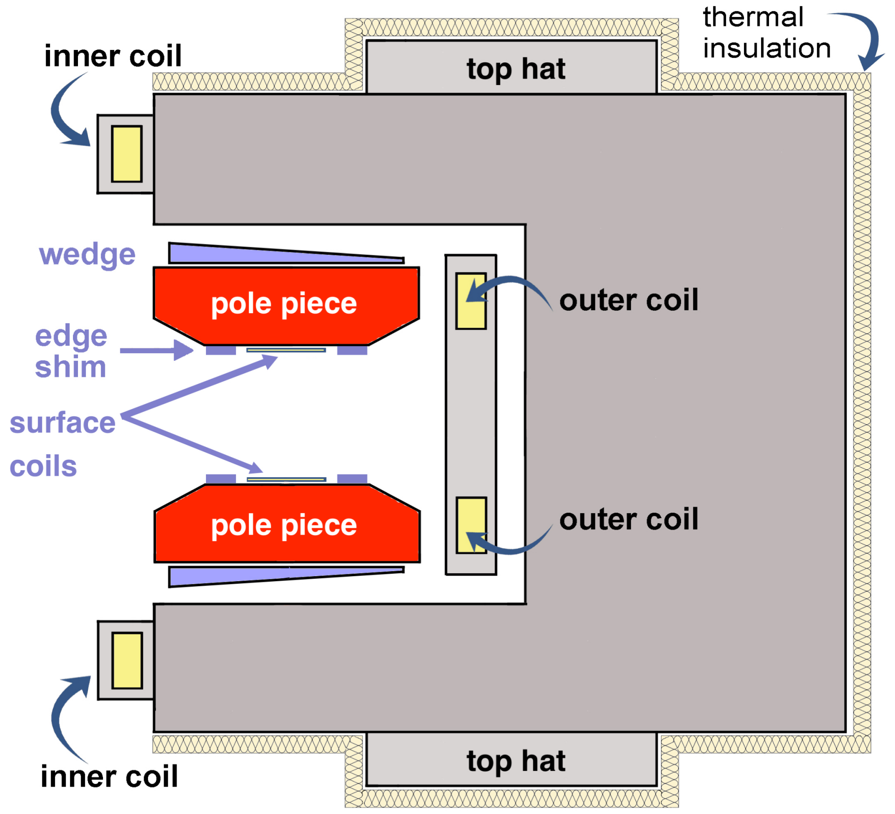




Rough Shimming: Pole Moves and Tilts

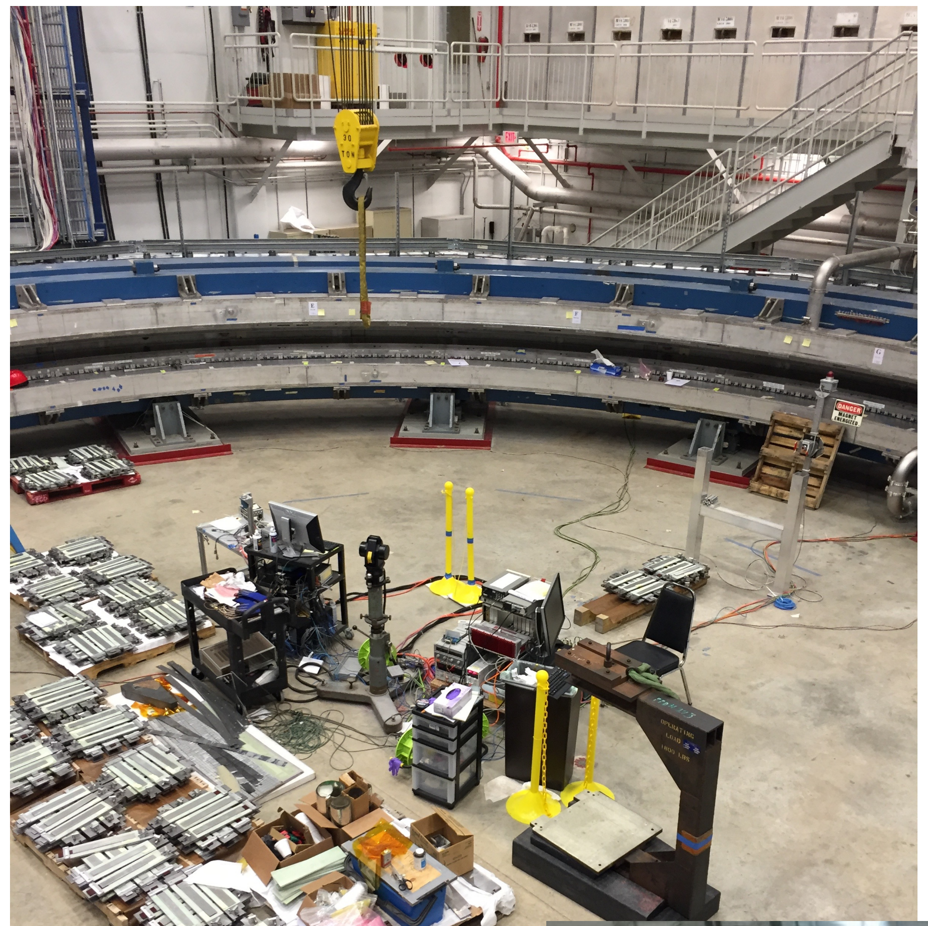
- Step and tilt discontinuities in pole surfaces yield large variations in the field
- To reduce/remove such effects, make adjustments to pole feet, which changes the magnet gaps and tilts
  - Use 0.001—0.010” thick steel shims
  - Requires removal of poles from the ring
- Informed by a computer model that optimizes the pole configurations
  - Requires global continuity between pole surfaces
  - Allows only thee adjacent poles to be moved at a time (preserves alignment)

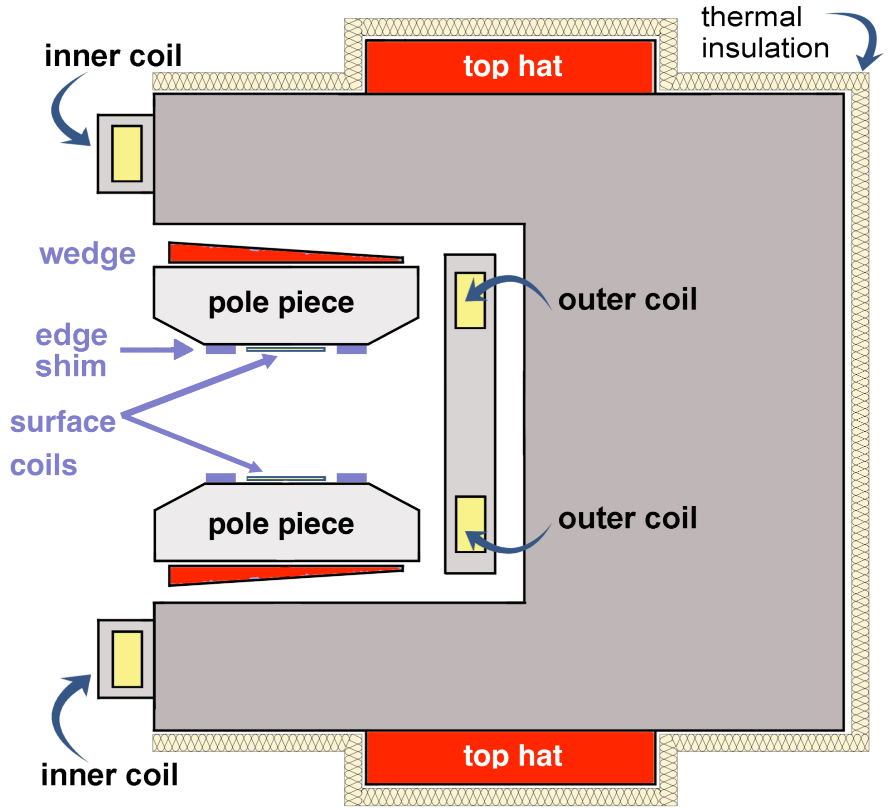


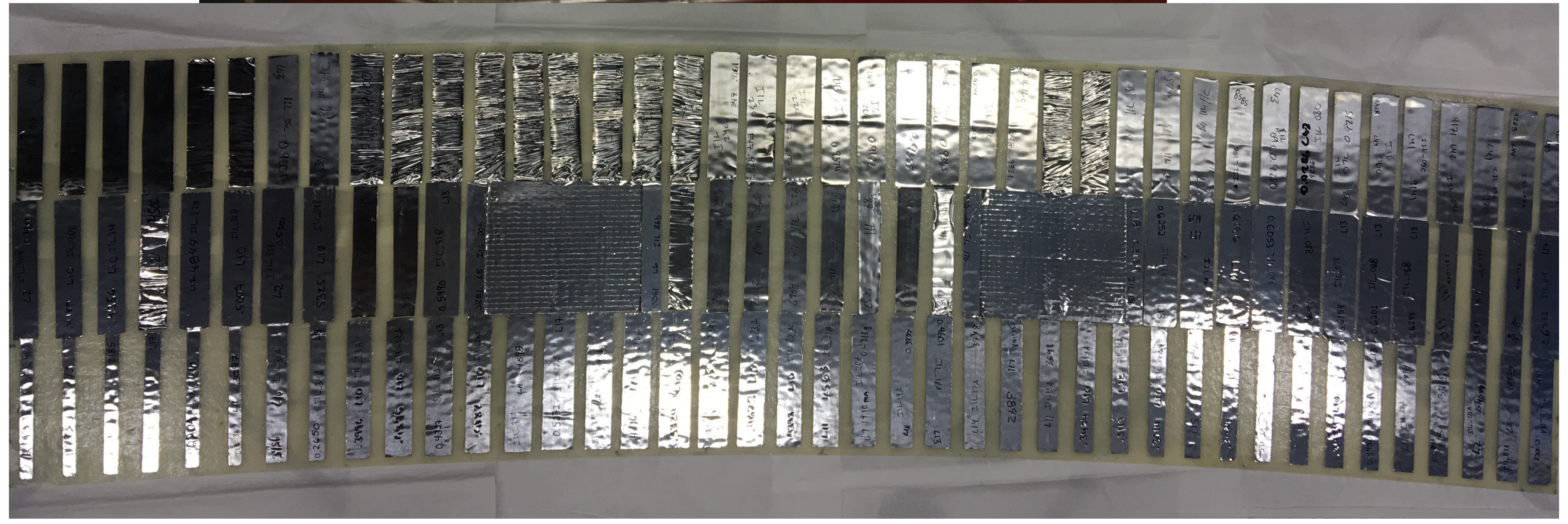


Rough Shimming: Tuning Out Small(er) Variations

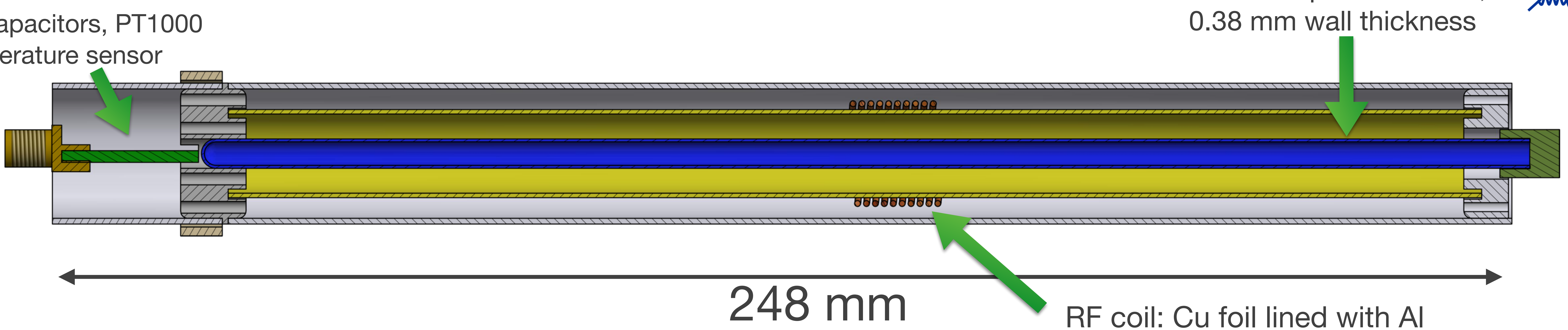
- **Calibrated shimming knobs**
  - 48 top hats
  - 864 wedges
  - ~8400 iron foils (on pole surfaces)
- **Coarse tuning:** top hat & wedge adjustments
  - Least-squares fit to field maps predicts top hat wedge positions
- **Fine tuning:** iron foils
  - Modeled as saturated dipoles in 1.45 T field
  - Computer code predicts foil width (mass) distribution to fill in the valleys of the field map
  - Radially-segmented distribution: control higher-order multipoles (quadrupole, sextupole,…)



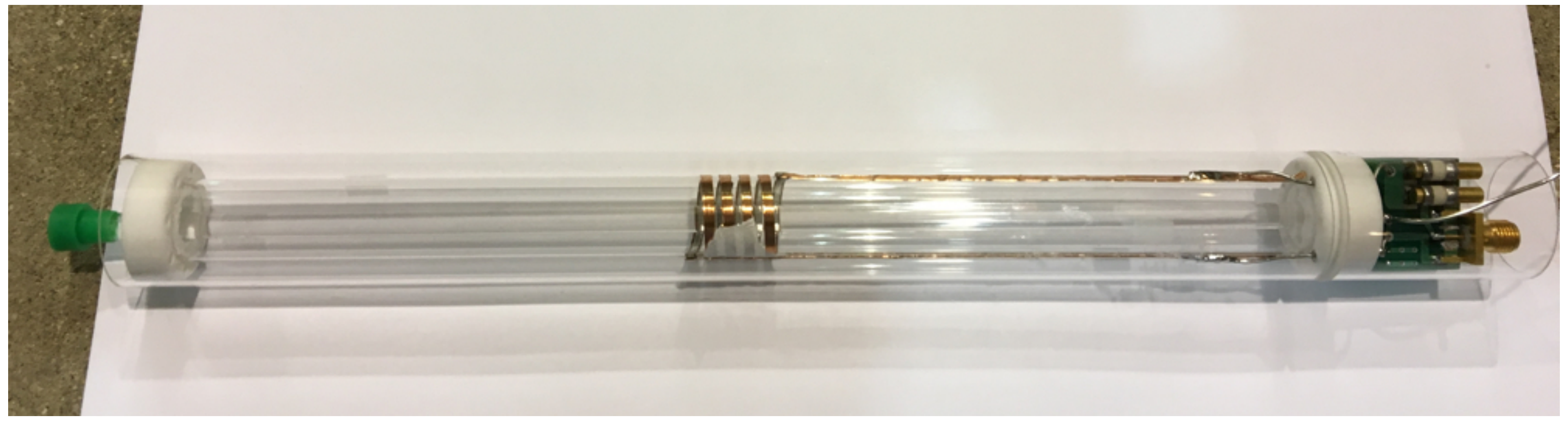


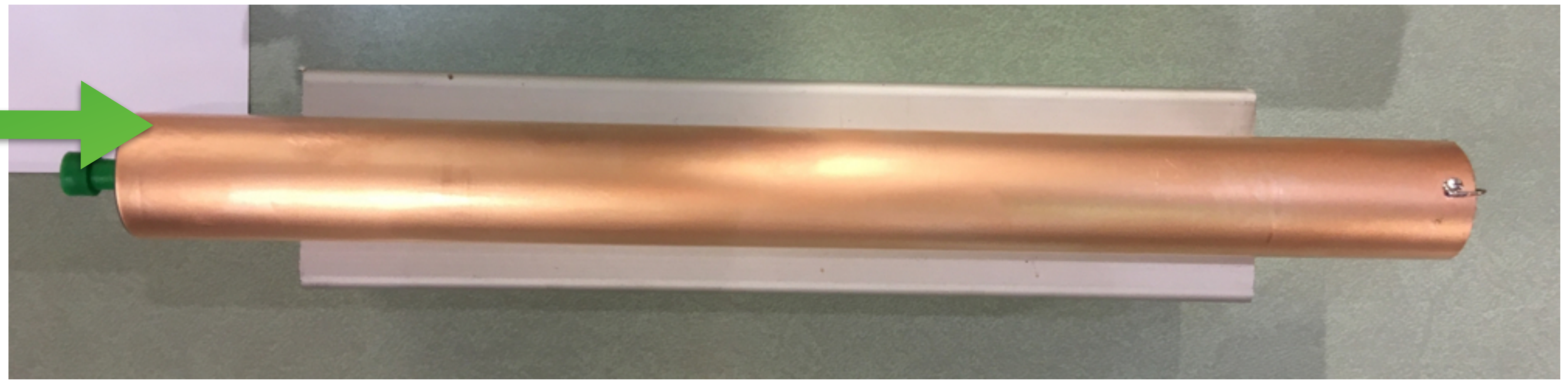


Plunging Probe Design



- Used to calibrate the **trolley** probes
- All-glass design: concentric high-precision glass cylinders
  - High degree of symmetry => minimizes field perturbations
- Macor endcaps ensures alignment of inner RF coil support
- Ground shield: 0.004” thick Cu foil
  - Stabilizes probe tune, reduces noise pickup
- Vacuum compatible





Plunging Probe 3D Translation Stage System

- The plunging probe will be in vacuum for the duration of the experiment in its own dedicated chamber
- 3D translation stage system moves the probe in and out of the storage volume for calibrating the trolley probes
- Characteristics
  - Motion in radial, azimuthal, vertical directions
  - High-precision encoder readout (~200-µm resolution)
  - Viewport for visual inspection

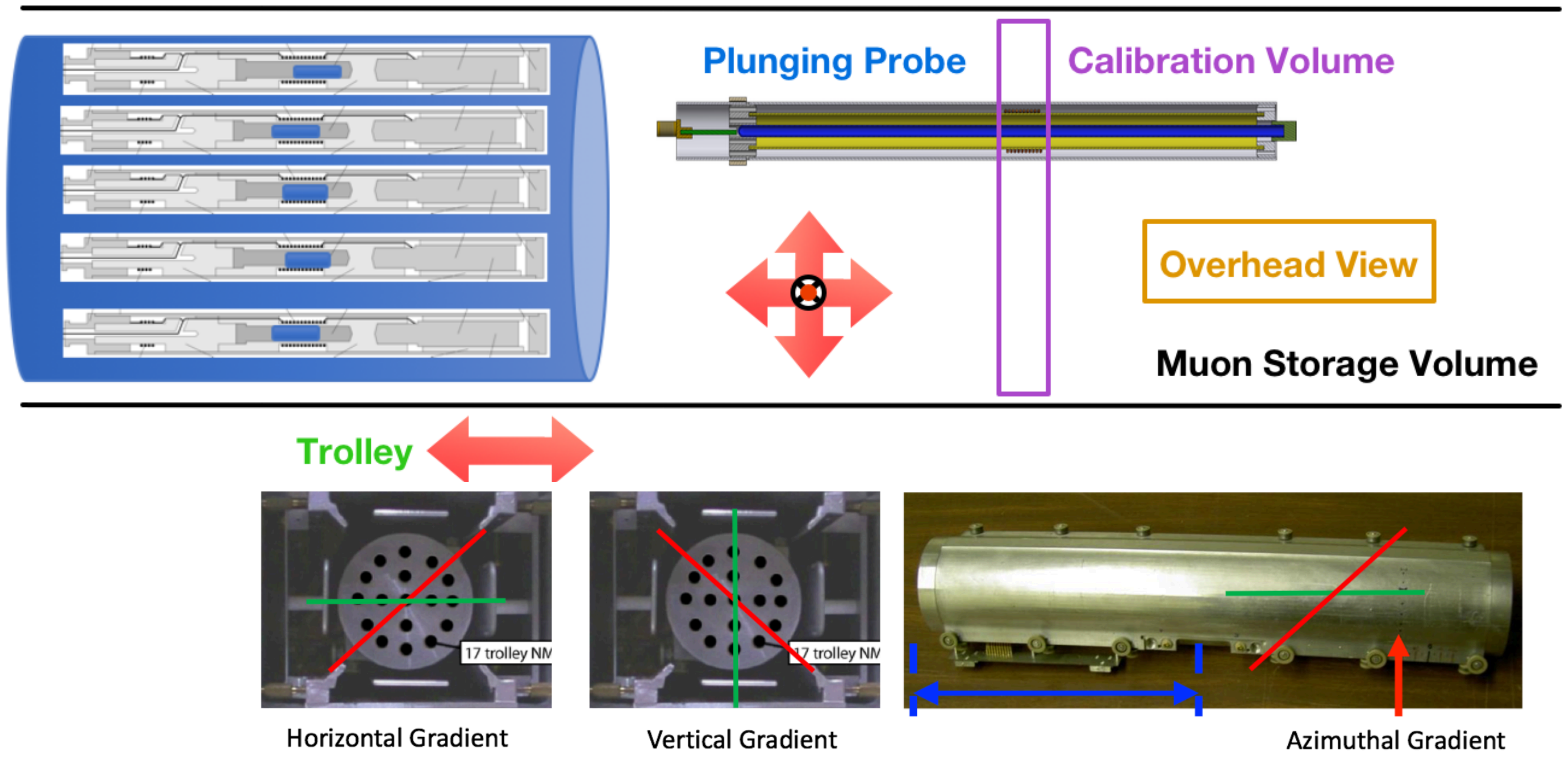
Calibration Scheme

Procedure

- Select trolley probe; use surface coils & azimuthal coils to reduce gradients to < 15 ppb/mm
- With x, y, z gradients imposed, Δω gives probe position
- Move plunging probe into volume; sweep through gradients and move plunging probe until Δω shape matches; record encoder counts

Active Shimming Needs

- Calibration region has gradients ~ 30—50 ppb/mm in azimuth
- Up to 150 ppb/mm in transverse (before surface coils)



Additional Shimming Knob: Azimuthal Coils

- Installed in early September 2016 before vacuum chamber installations