Precision Magnetic Field Calibration for the Muon g-2 Experiment at Fermilab

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On Behalf of the Muon g-2 Collaboration

New Perspectives, Fermilab
June 5—6, 2017

Outline

Introduction

- Measuring the Muon Anomaly
- Measuring the Magnetic Field in g-2

Calibration of the Magnetic Field

- Relating the Observed NMR Frequency to the Free-Proton Precession Frequency

Calibration Hardware

- Data Acquisition System
- The Calibration “Plunging” Probe
- 3D Translation Stage System

Summary

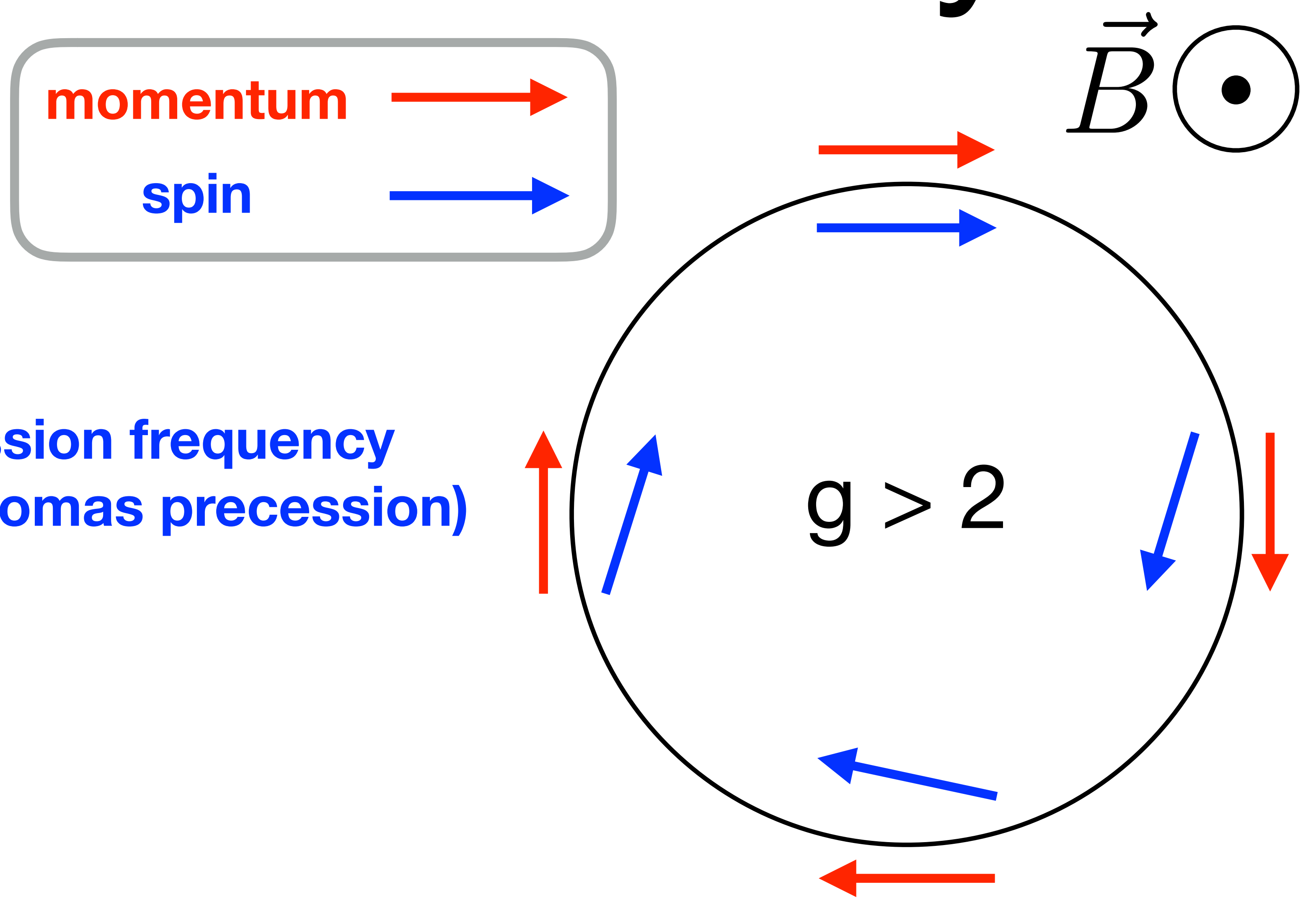
Introduction: Measuring the Muon Anomaly

- Inject polarized muon beam (from pion decay) into ring

$$\vec{\omega}_C = -\frac{e}{\gamma m}\vec{B}$$ cyclotron frequency

- Measure **difference** between spin precession and cyclotron frequencies

$$\vec{\omega}_S = -\frac{e}{\gamma m}\vec{B}\left(1 + \gamma a_\mu\right)$$ spin precession frequency (Larmor, Thomas precession)



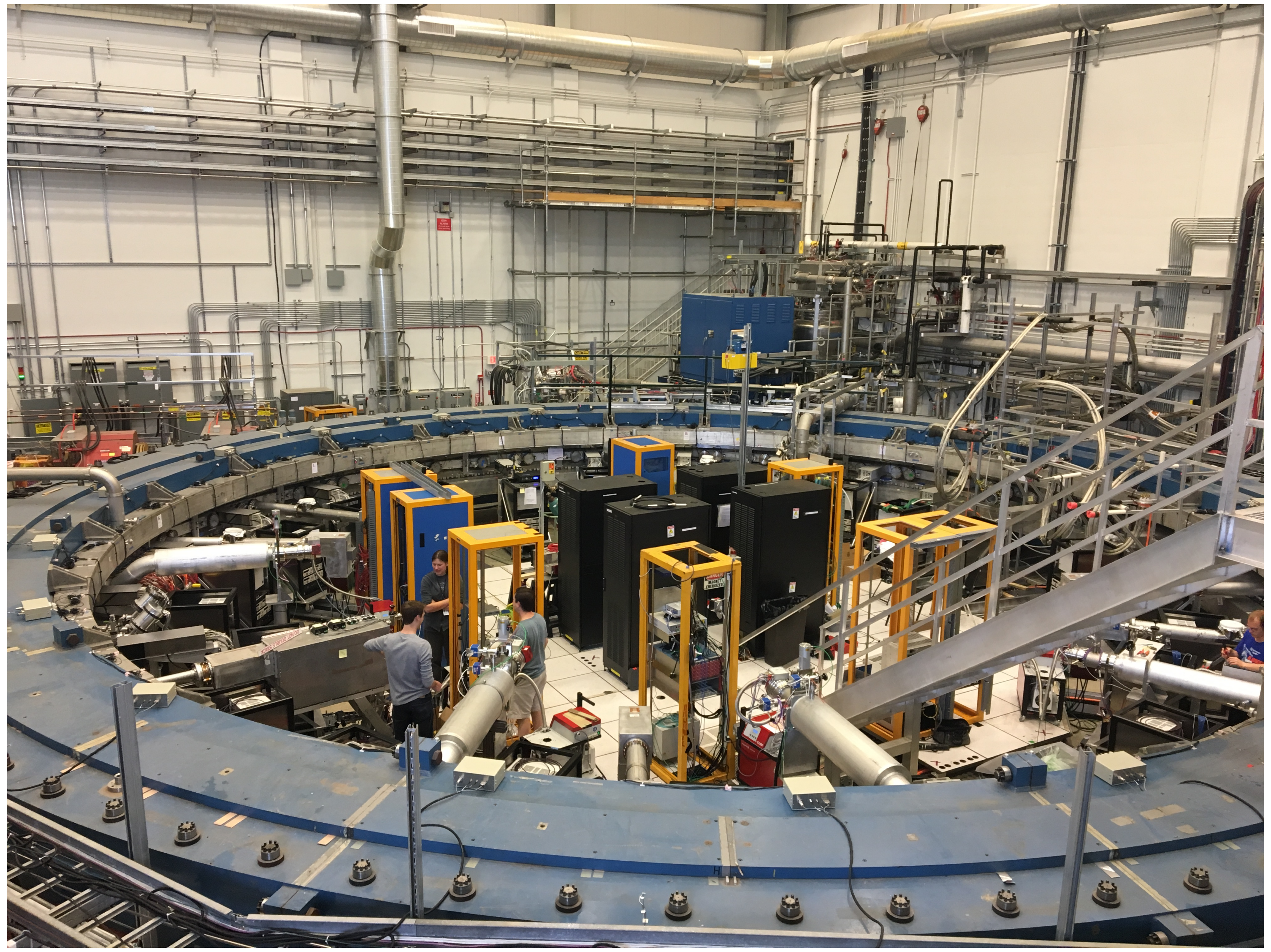
- If g = 2, $\omega_a = 0$

$$\vec{\omega}_a \equiv \vec{\omega}_S - \vec{\omega}_C$$

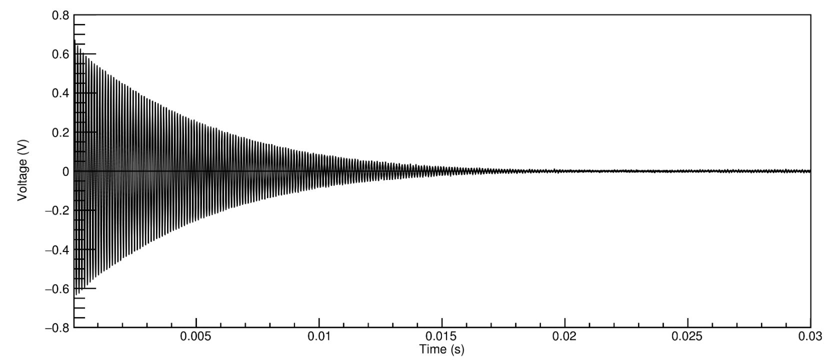
- g ≠ 2, $\omega_a \cong (e/m_\mu)a_\mu B$
- Using $\hbar\omega_p = 2\mu_p|\vec{B}|$:

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

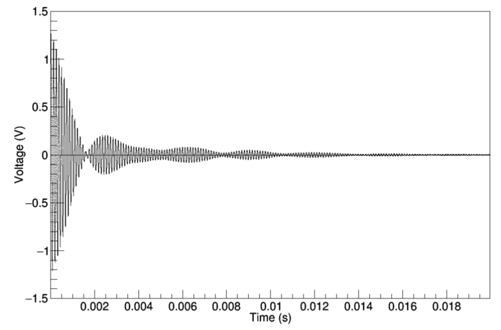
- We measure ω_a and ω_p separately
- Other ratios known to better than 25 ppb
- **Target: δa_μ = 140 ppb; 4-fold improvement over BNL**



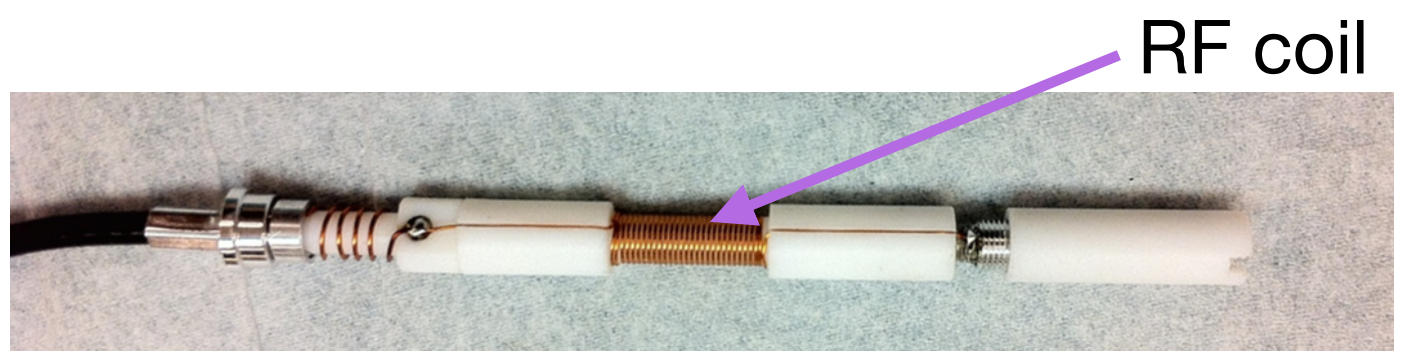
- Need B in terms of the free-proton precession frequency ω_p
- $\omega_p \cong 2\pi$ x 61.79 MHz for B = 1.4513 T
- Need to extract ω_p to better than 70 ppb



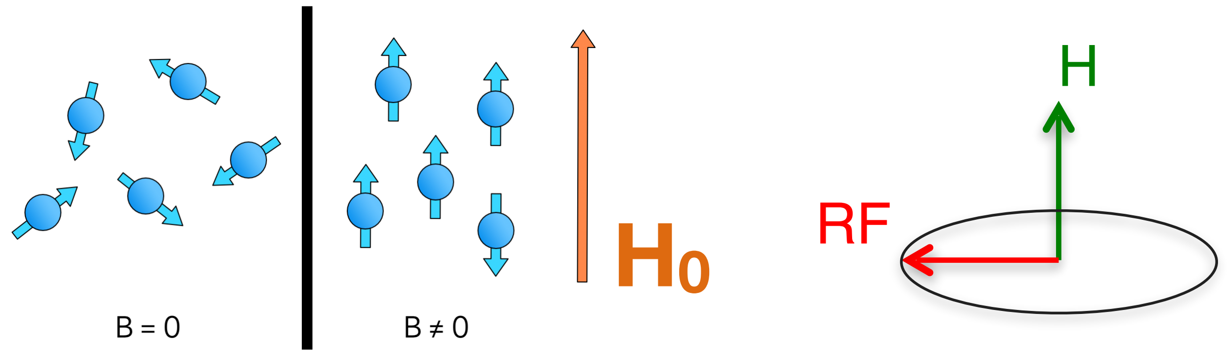
Measuring ω_p in-situ



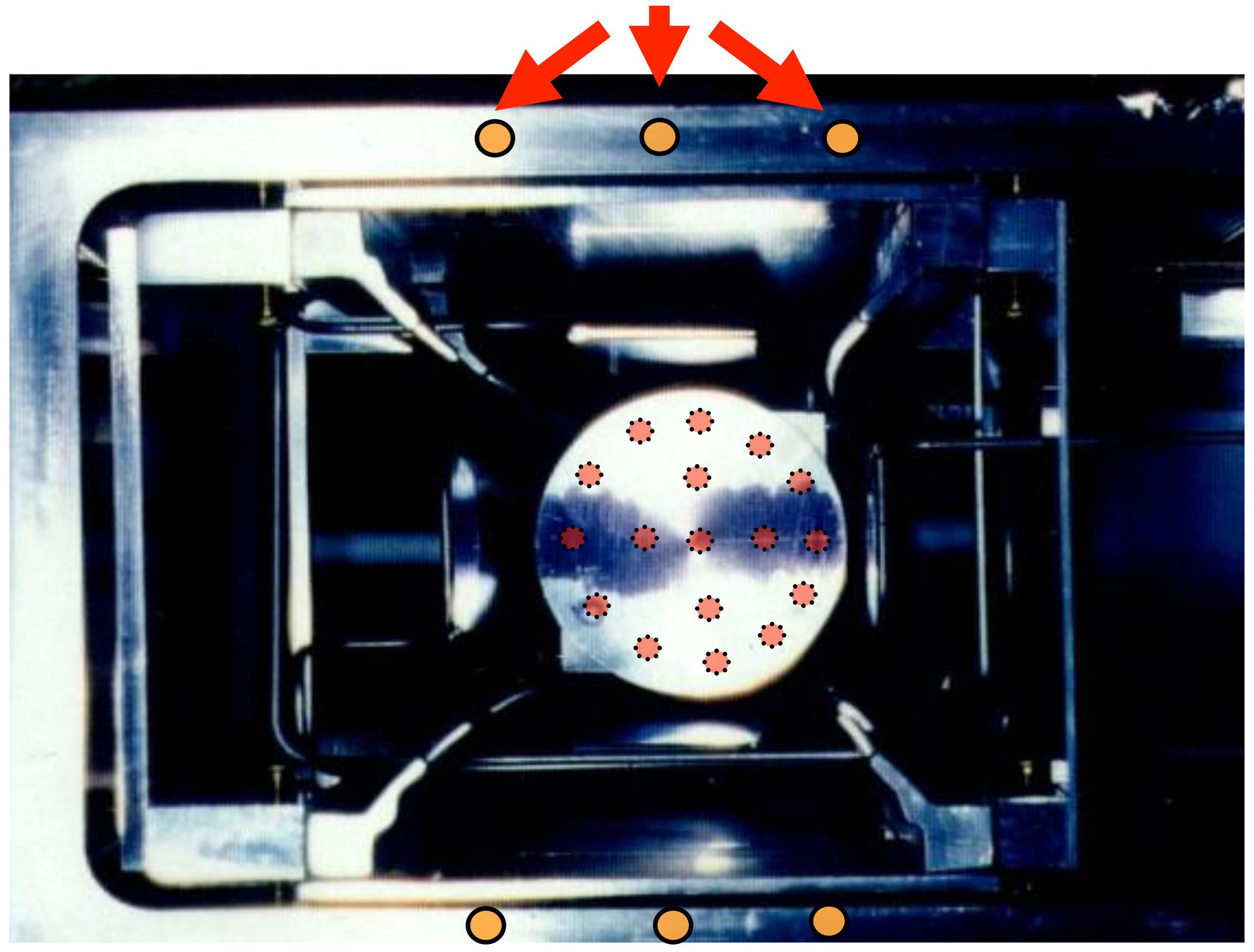
Pulsed NMR



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

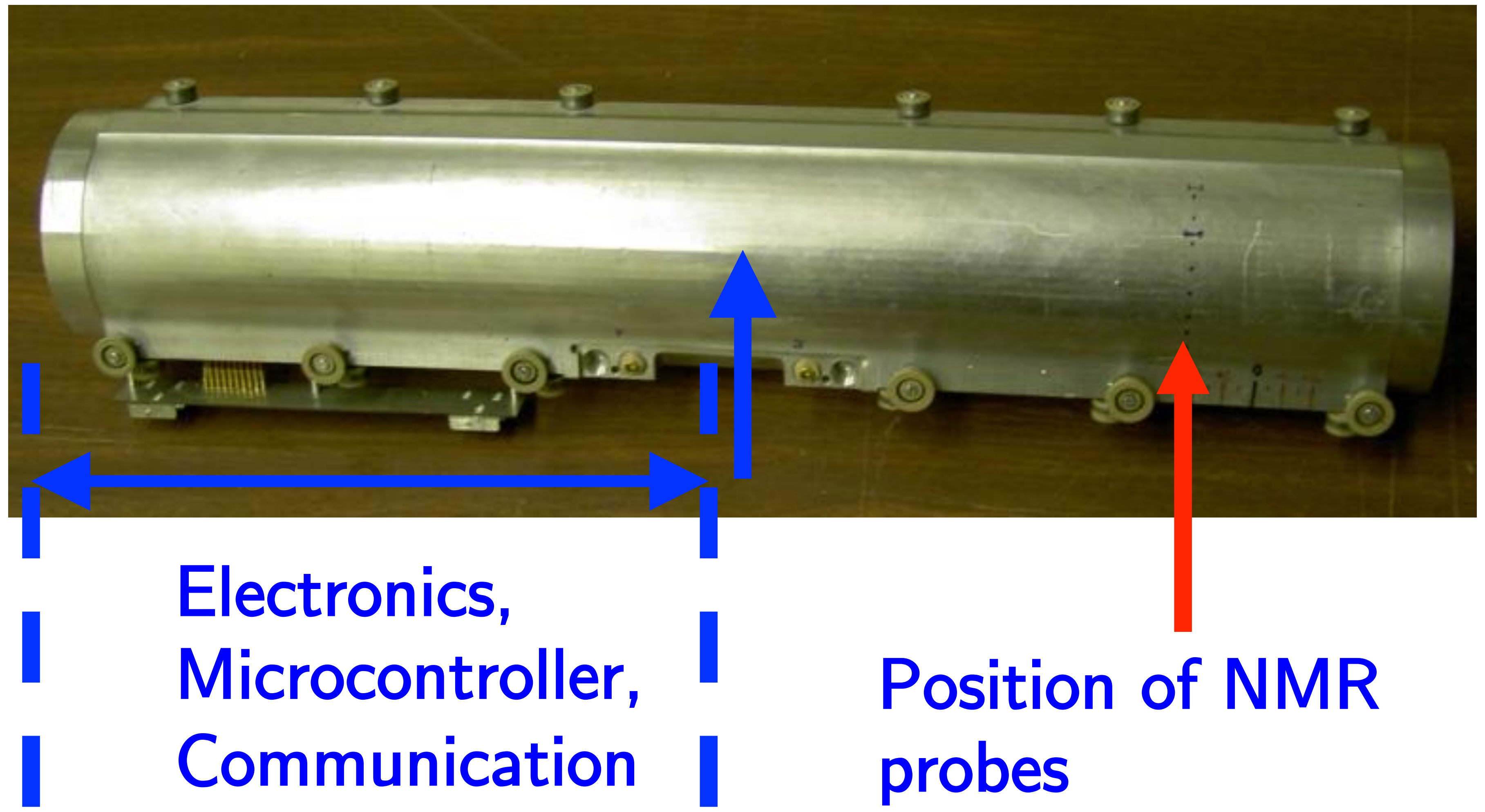


Fixed probes on vacuum chambers



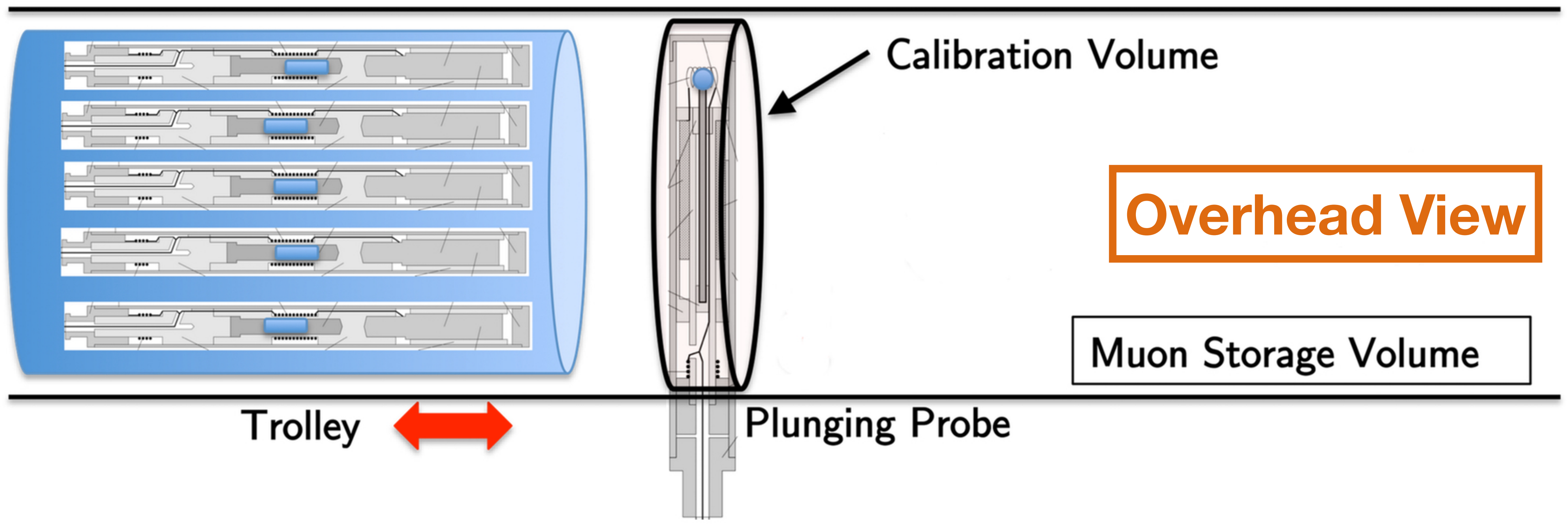
- Measure field while muons are in ring — probes **outside** storage region

Trolley matrix of 17 NMR probes



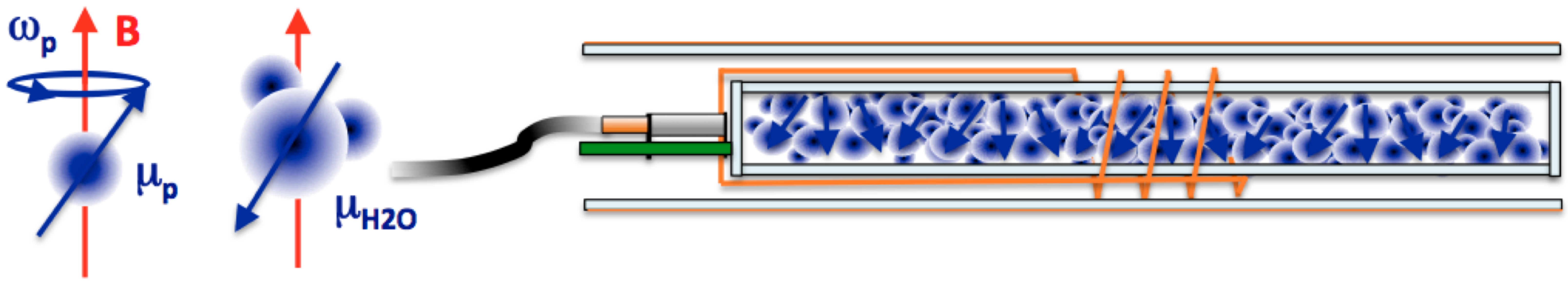
- Measure field in storage region during **specialized runs** when **muons are not being stored**

- **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



Calibration of the Magnetic Field

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



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

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 $\chi_{H_2O} \cong$ -719 x 10^{-9} gives shape-dependent perturbation

- $\varepsilon = 4\pi/3$ (sphere), 2π (cylinder) when probe is perpendicular to B

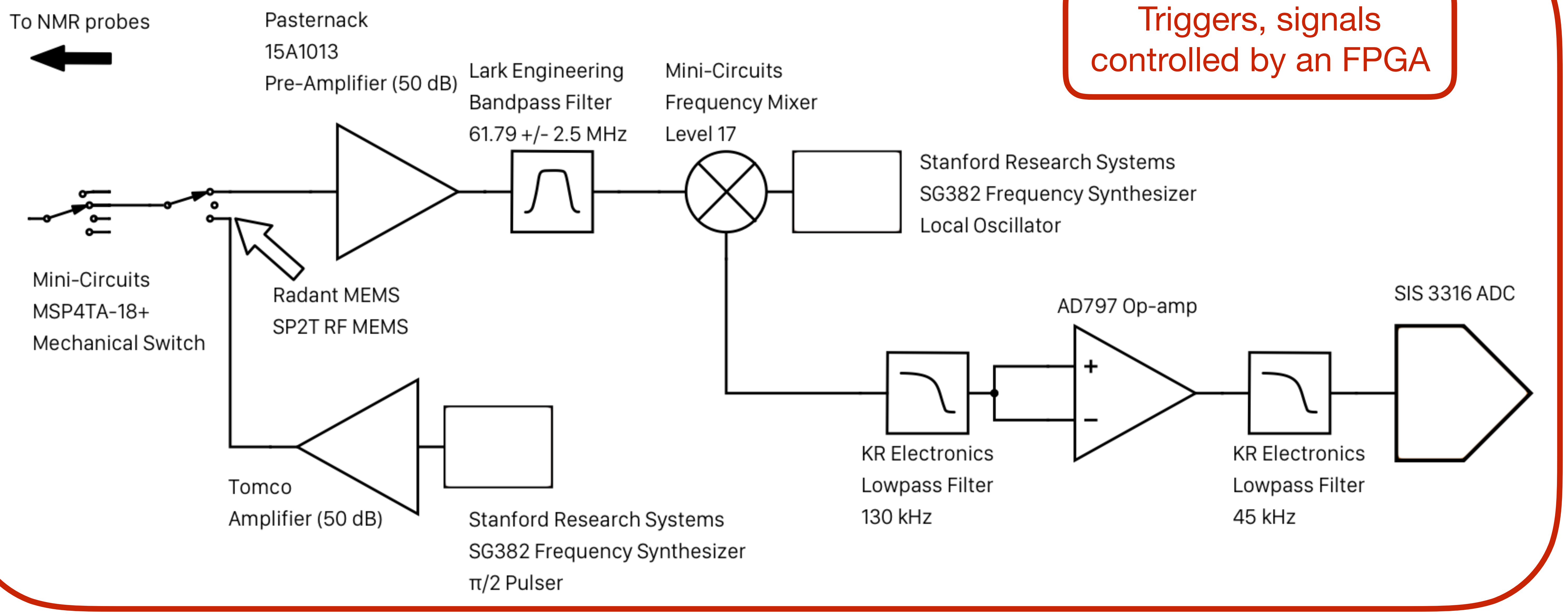
Magnetization of probe materials perturbs the field at site of protons

Future: Why ^{3}He?
- $\sigma(^3He)$ precisely calculated
- $\chi_{^3He}$ smaller than water

Goal: Determine total correction to ≤ 35 ppb accuracy

Data Acquisition System

System Schematic



Triggers, signals controlled by an FPGA

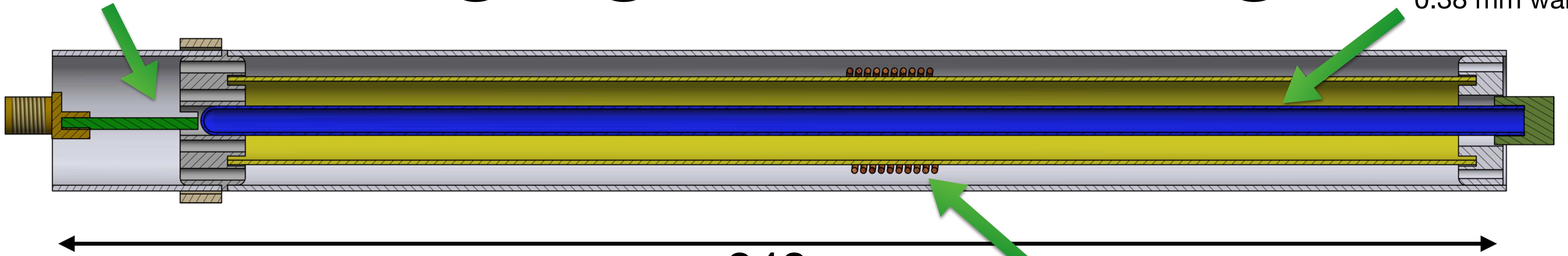
Performance Capabilities

- High SNR: ~ 1500/1
- ± 45 kHz (±750 ppm) bandwidth
- ≤ 1 ppb shot resolution

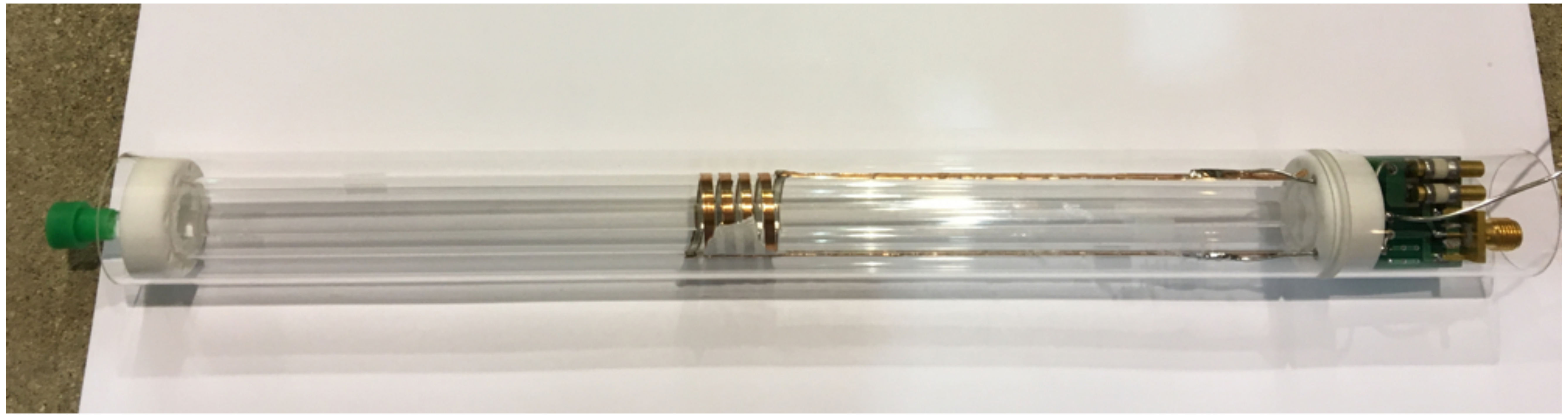
DAQ Highlights

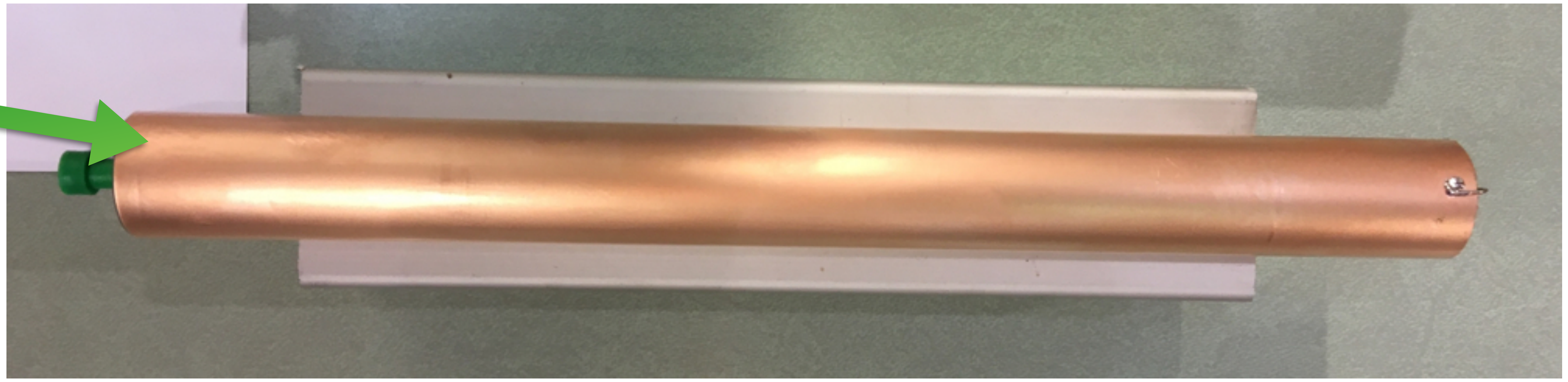
- Operational since early 2015
- Extremely stable: >99.99% successful over 6000+ runs, including long runs (12 hours)
- Used for numerous studies across g-2
  - Perturbations of various components of NMR probes, trolley system, collimators, surface coils, etc.
  - Used in the shimming of the ANL MRI test magnet
- Analysis software works hand-in-hand with system

Plunging Probe Design



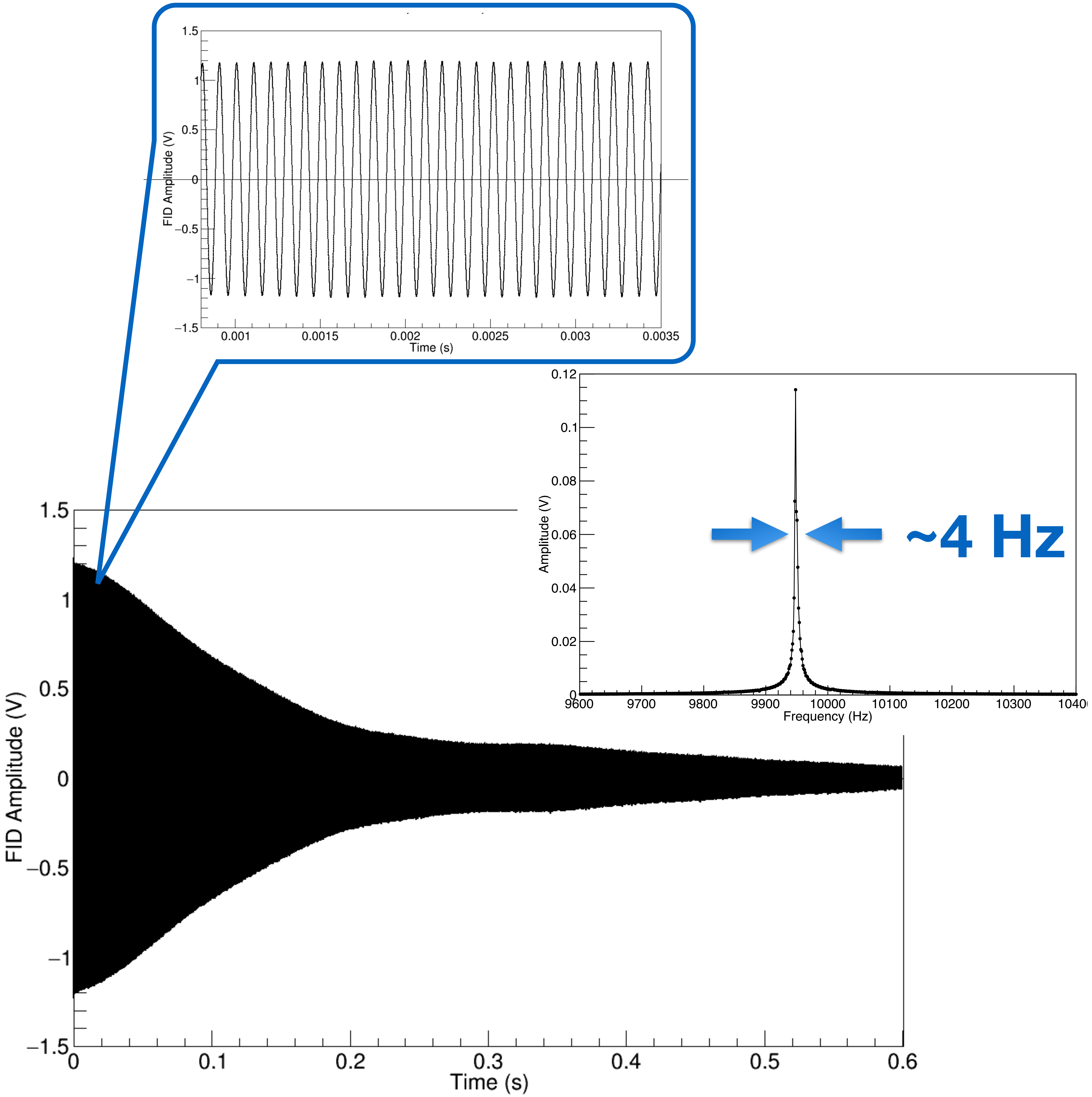
- Used to calibrate the trolley NMR probes
- All-glass design: concentric high-precision glass cylinders
  - High degree of symmetry => minimizes field perturbations
- Macor endcaps ensures alignment of inner RF coil support
- Ground shield: 4-mil thick Cu foil
  - Stabilizes probe tune, reduces noise pickup
- Vacuum compatible
- All machining, glass cutting done at ANL

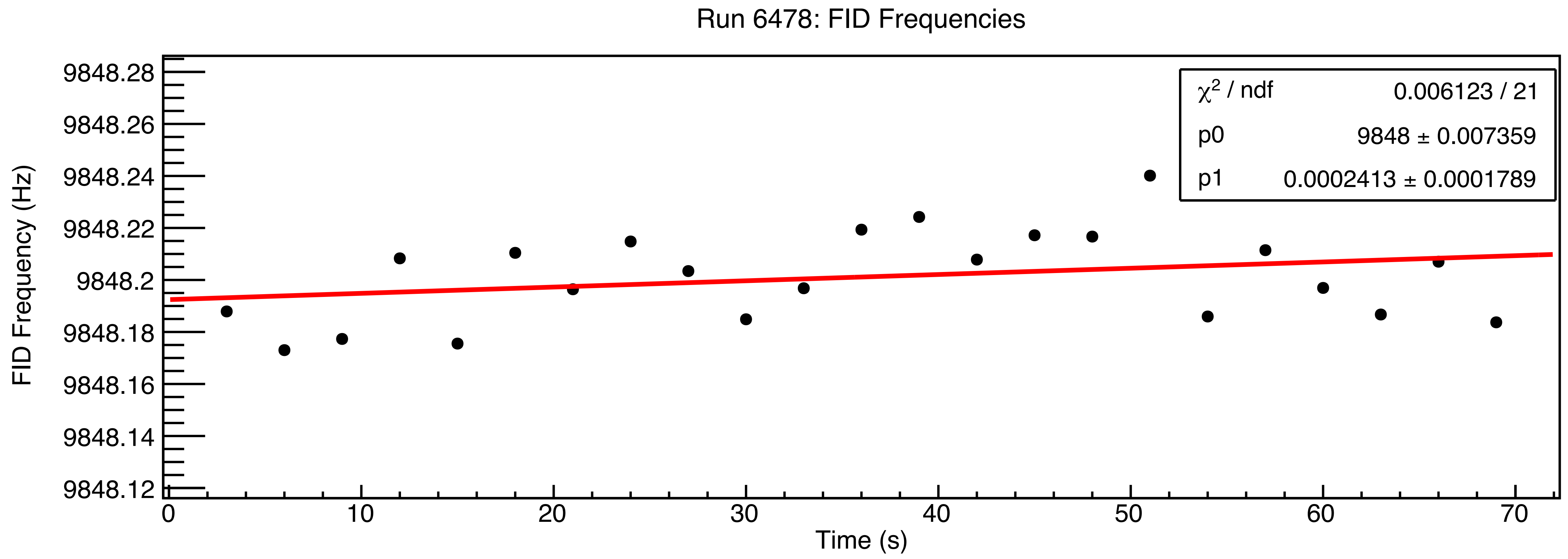


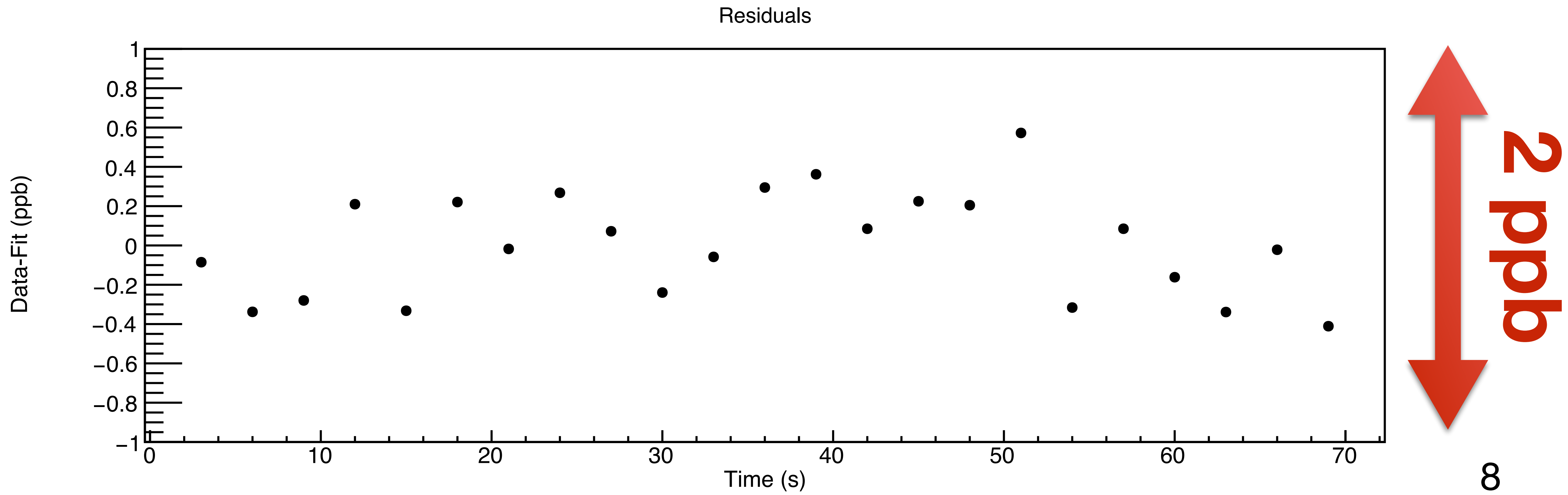


Plunging Probe Performance

- Amplitudes of ~ 1.2 V; S/N ~ 1000
- Signals at least 600 ms long
- Very high resolution (**≤ 250 ppt**)

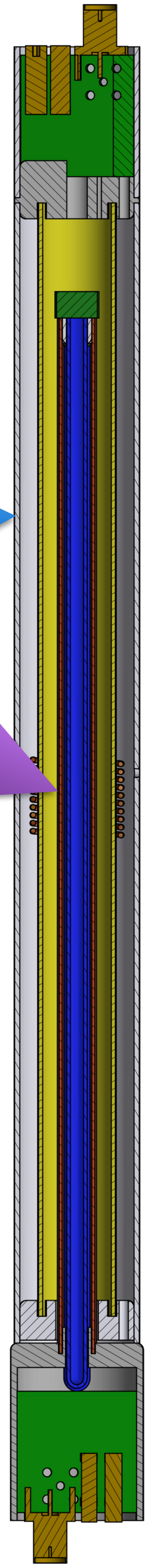


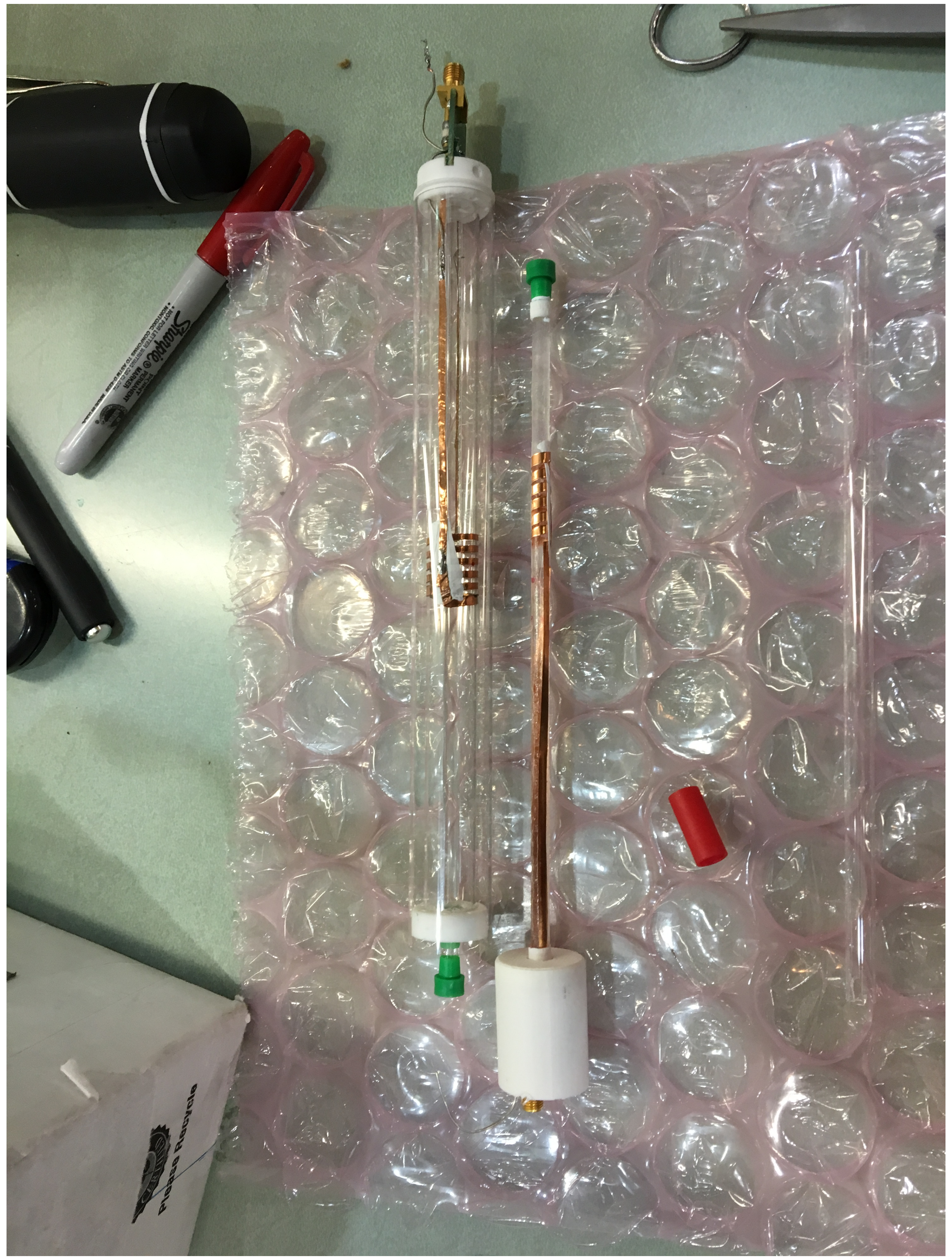


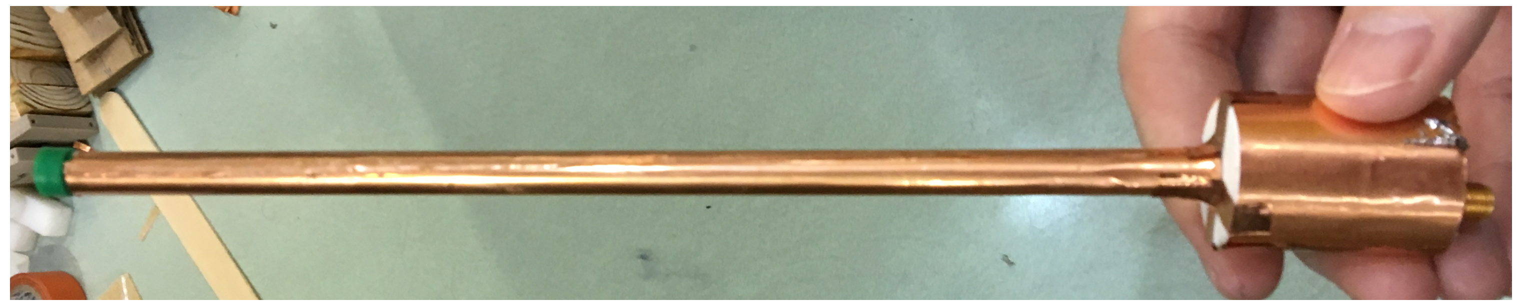


Characterizing the Plunging Probe

- In order to quantify the field perturbations, we need a special probe that can fit inside the plunging probe
- **Test probe** specifications
  - All-glass structure
  - 7.5 mm OD
  - 5 mm OD water sample
  - Same electronics, RF coil as plunging probe
- **How to quantify perturbations?**
  - Probe assembly: Measure the field with the test probe while inserted in the plunging probe, and not inserted; difference gives perturbation
  - Components: Measure the field with and without the component next to a probe
    - Measured components: glass shell (4 ppb), capacitors (< 1 ppb), temperature sensors (< 1 ppb)
- **Which measurements to make?**
  - How much of a perturbation does the plunging probe give? Is it consistent with individual material measurements? (**probe structure**, δ_s)
  - Field dependence on rotations about its central or transverse axes?
    - Shows build quality/sensitivity to alignment (**shape factor**, ε)



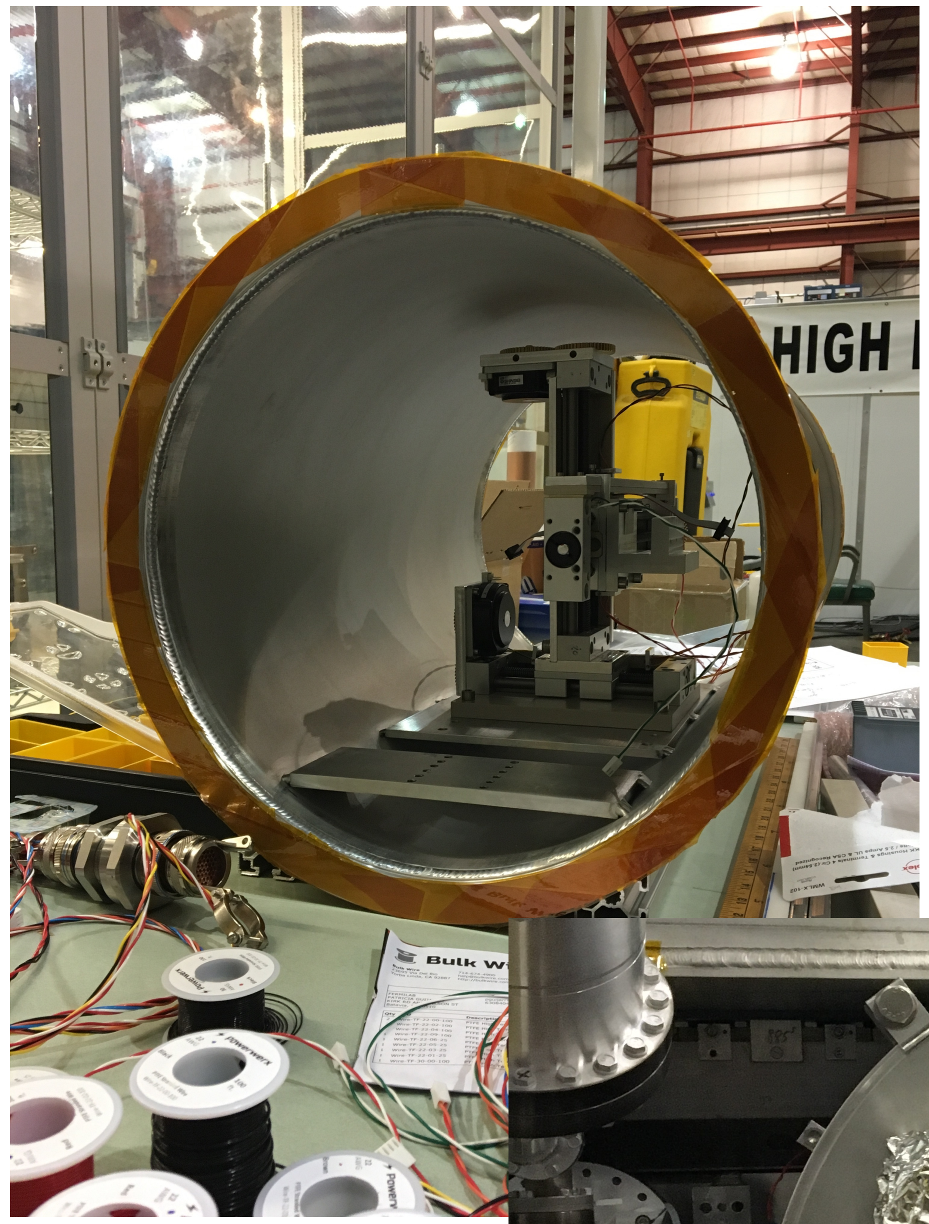


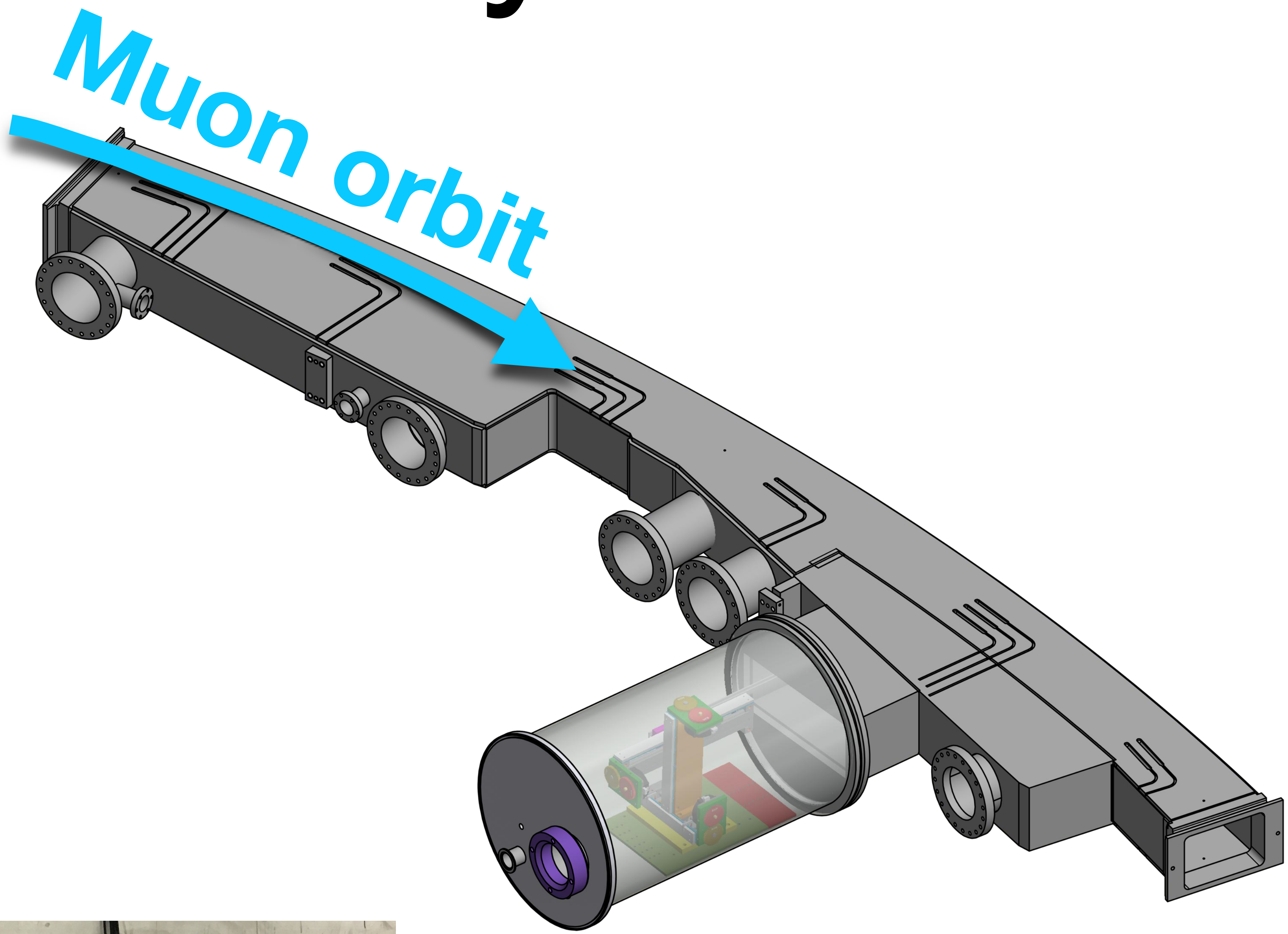


Plunging Probe 3D Translation System

- 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
  - Position is readout by high-precision inductive linear encoders (6.7 counts/mm)
    - Cross-checked with Rasperry-Pi Camera installed in the chamber
  - Viewport welded onto flange for visual inspection of system
  - Additional backup port for testing/inspection

Designed, machined, and assembled at ANL





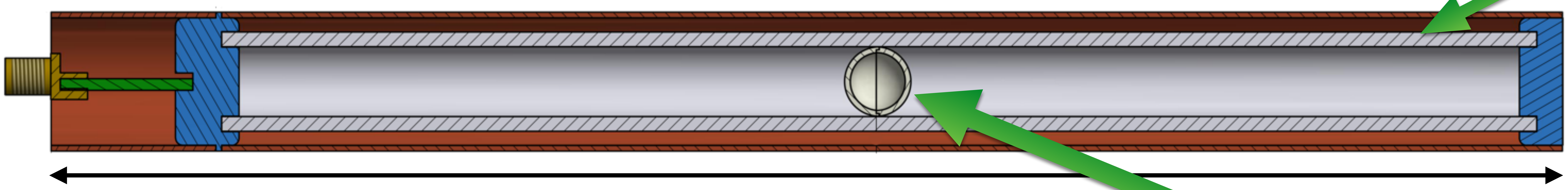
Installed in MC-1 on 5/25

Summary

- Magnetic field calibration: calibrate the trolley probes to a specially-designed water-based NMR probe whose magnetic properties have been precisely determined
- Plunging probe designed to have a minimal magnetic footprint, high resolution
  - Perturbation of components: at most ~ 3—4 ppb (each)
  - Excellent performance: S/N ~ 1000:1, resolution ≤ 250 ppt
- Plunging probe system recently installed in MC-1
- What's Next?
  - Transport DAQ system to MC-1, exercise full operation of the calibration system in-situ
  - Continue calibration studies (after engineering run)

Backup

Spherical Probe Design

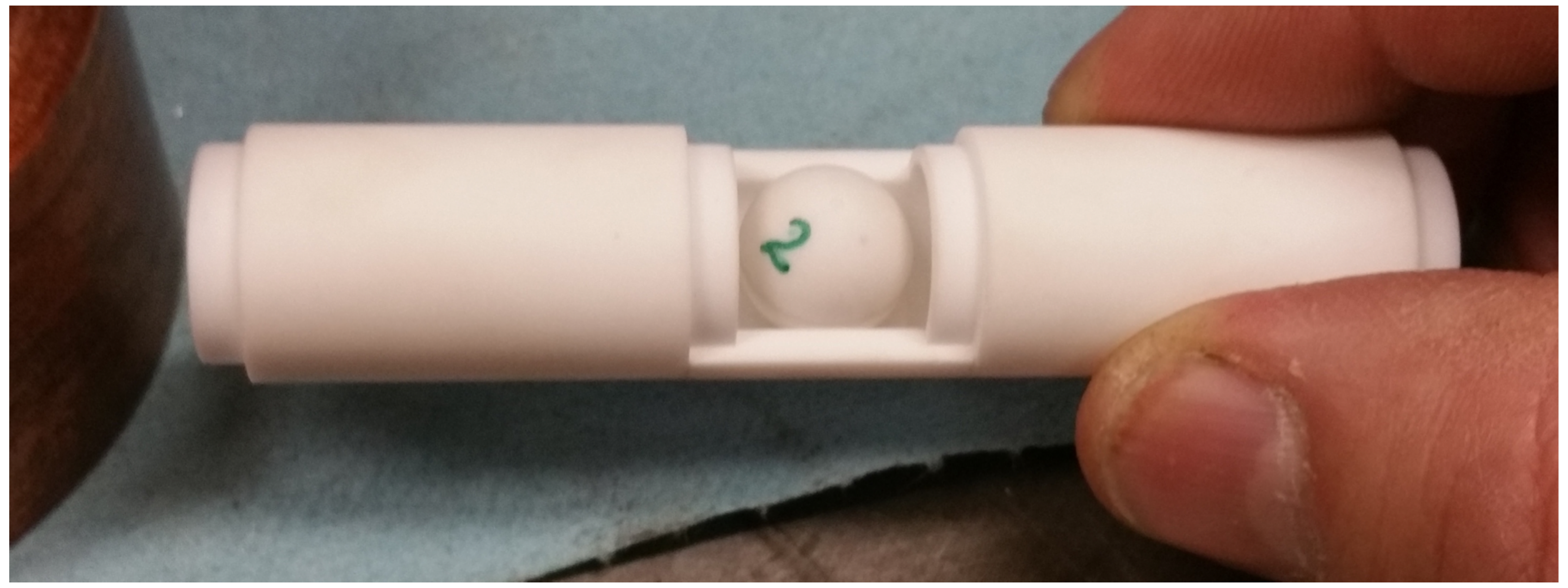


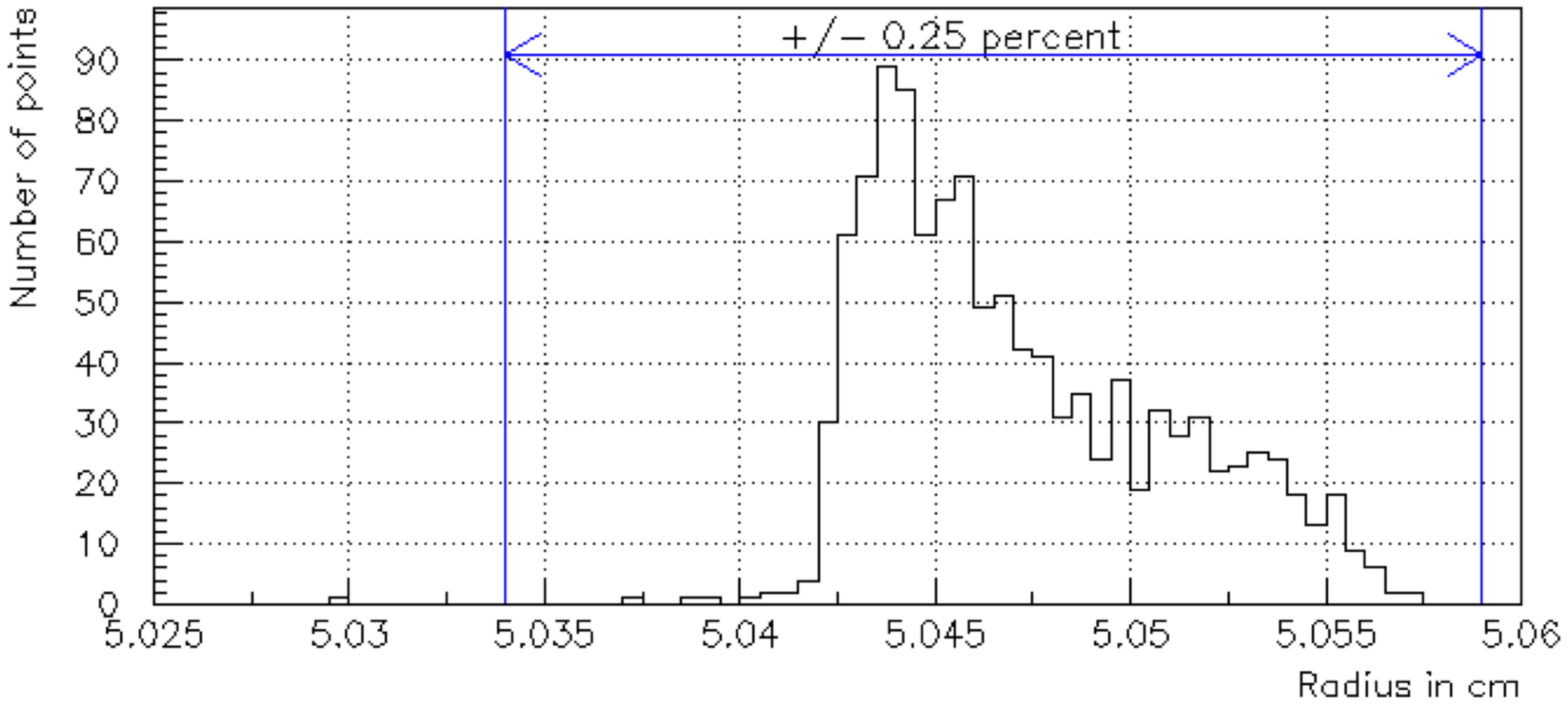
RF coil support: macor tube

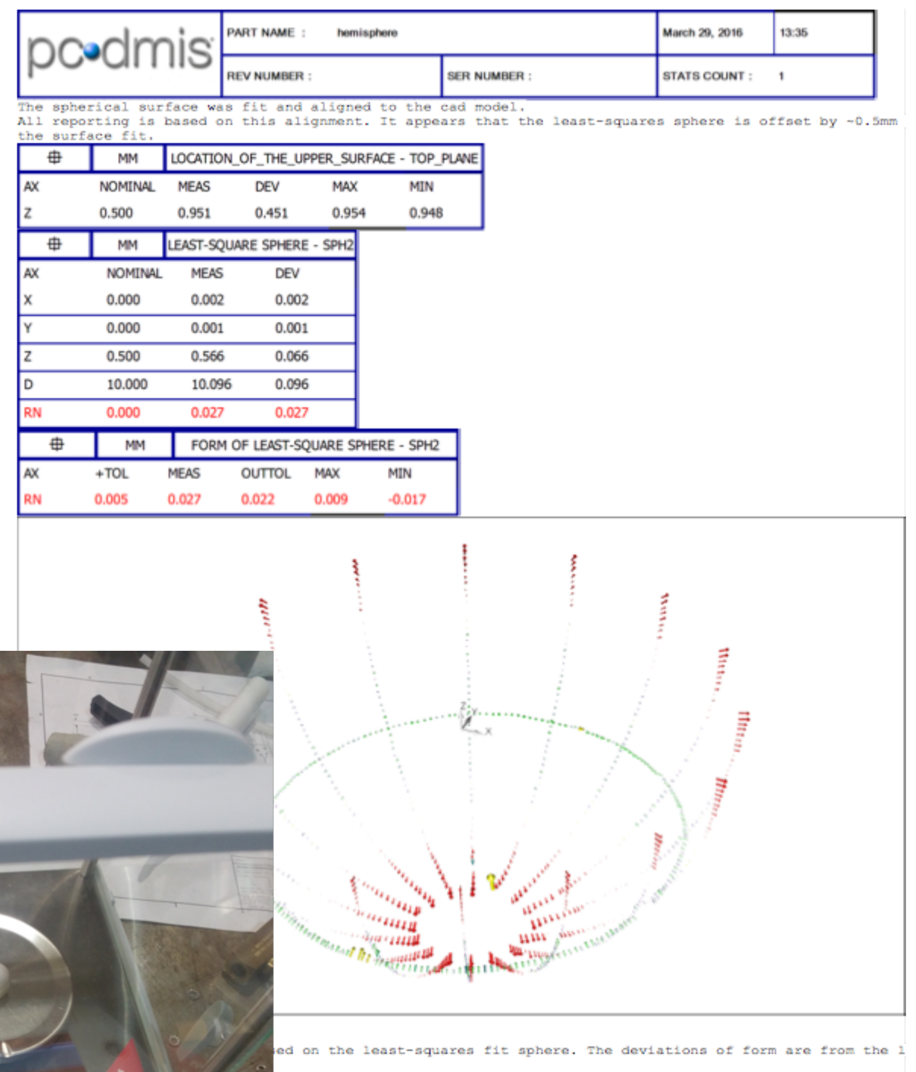
248 mm

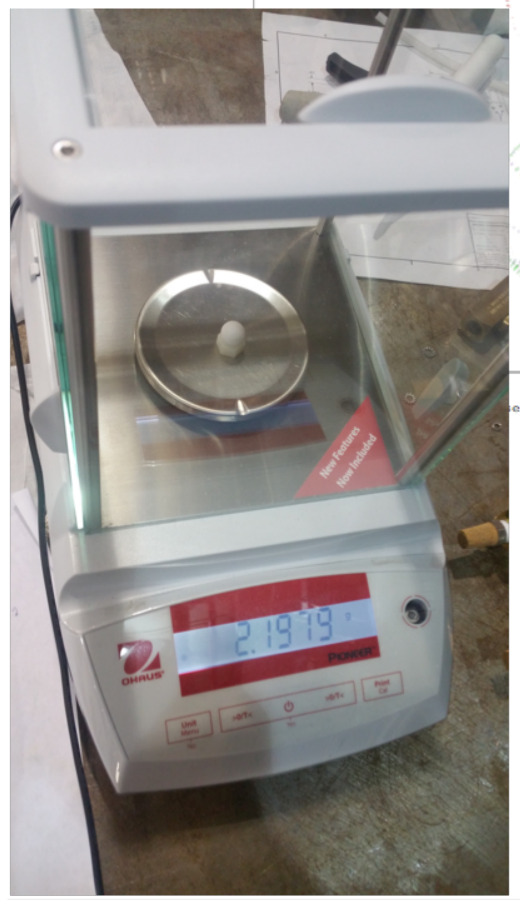
Water sample:
12 mm OD, 10 mm ID sphere

- Used to cross-calibrate the plunging probe
- Design: macor cylindrical shell, spherical water sample
- Uses similar parts as seen in plunging probe: RF coil, outer shell, endcaps, electronics, etc
- Sphericity of macor hemispheres measured using CMM at FNAL
  - Highly spherical: < 15 ppb sphericity correction
- One set of hemispheres filled with water and sealed; no water loss in weeks









Test Magnet at Argonne

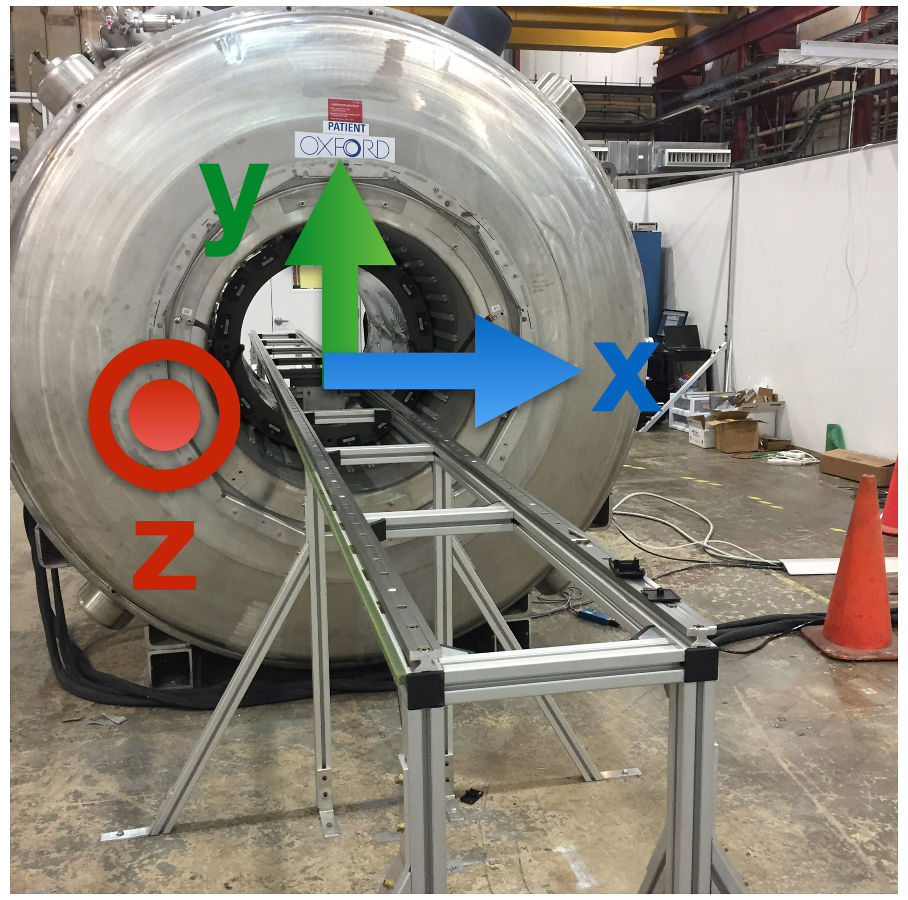
- Acquired an MRI solenoid magnet from SF for the absolute calibration work (April 2014)
- Cooled and powered as of summer 2015
- Fields up to 4 T; we operate at ~ 1.45 T
- Built-in shimming kit
  - **Passive:** two sets of removable pockets where iron pieces may be placed
  - **Active:** linear (x, y, z) and higher-order (~ x^2, y^2, z^2) coils; have a Bruker power supply for powering (up to 10 A)

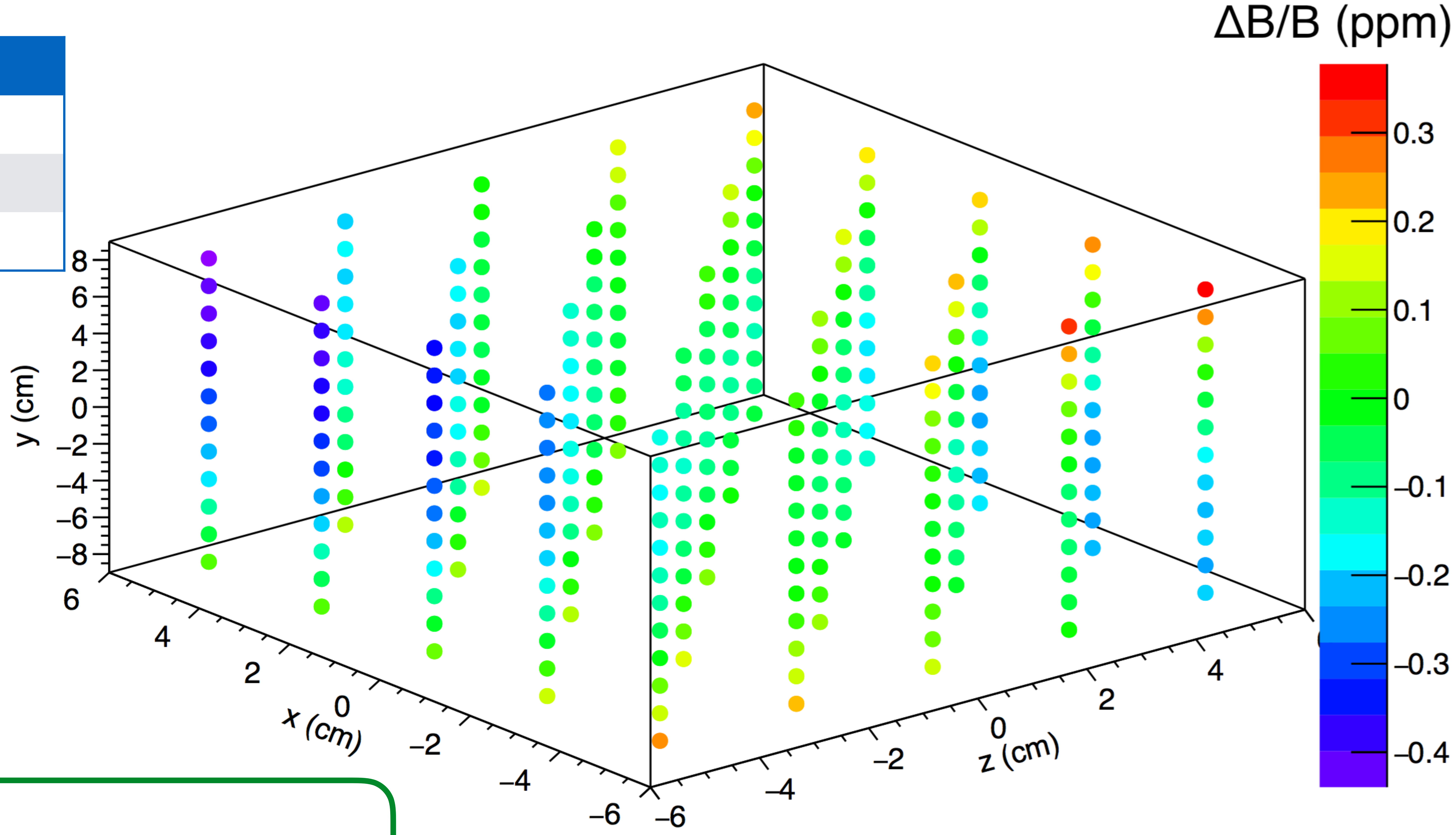
- Since we're using it for the commissioning and systematic studies of the calibration probes (and trolley system), we need to shim this magnet to be highly uniform (~ 1 ppb/mm)

$$dB = \sqrt{\left(\frac{\partial B}{\partial x}\right)^2 dx^2 + \left(\frac{\partial B}{\partial y}\right)^2 dy^2 + \left(\frac{\partial B}{\partial z}\right)^2 dz^2 + \left(\frac{\partial B}{\partial T}\right)^2 dT^2 + \left(\frac{\partial B}{\partial t}\right)^2 dt^2}$$

Field Homogeneity Using Linear Shim Coils

Coil	Current (mA)
x	-20
y	110
z	-68





700 ppb peak-to-peak variation of the field **over 12 x 16 x 12 cm^3** volume

Calibration Systematic Studies

- Field perturbations from probe materials
- “Radiation damping”-induced field shifts
- Dipolar field contribution from precessing proton spins
- Field from currents induced in probe shield
- Magnetic images of the probe in the pole faces of the magnet
- Field inhomogeneity effects on frequency extraction
- RF coil inhomogeneity
- Oxygen effects, including amount of dissolved oxygen in water sample
- Temperature effects
- Effects of misalignment and rotational asymmetries in the probes
- Sensitivity to RF pulse power/duration/tip angle
- Fidelity/frequency dependence of electronics and frequency extraction algorithms on known input signals

ω_p, ω_a Improvements

Reduce ω_p systematic uncertainties by a factor of 2.5

- Better run conditions (e.g., temperature stability, more time to shim magnetic field to high uniformity, smaller muon beam profile)
- Many hardware and software improvements

E821 Error	Size [ppm]	Plan for the E989 $g-2$ Experiment	Goal [ppm]
Absolute field calibrations	0.05	Special 1.45 T calibration magnet with thermal enclosure; additional probes; better electronics	0.035
Trolley probe calibrations	0.09	Absolute cal probes that can calibrate off-central probes; better position accuracy by physical stops and/or optical survey; more frequent calibrations	0.03
Trolley measure-ments of B_0	0.05	Reduced rail irregularities; reduced position uncer-tainty by factor of 2; stabilized magnet field during measurements; smaller field gradients	0.03
Fixed probe interpolation	0.07	More frequent trolley runs; more fixed probes; better temperature stability of the magnet	0.03
Muon distribution	0.03	Additional probes at larger radii; improved field uniformity; improved muon tracking	0.01
Time-dependent external B fields	–	Direct measurement of external fields; simulations of impact; active feedback	0.005
Others	0.10	Improved trolley power supply; trolley probes extended to larger radii; reduced temperature effects on trolley; measure kicker field transients	0.05
Total	0.17		0.07

Reduce ω_a systematic uncertainties by a factor of 3

- Tackling major systematic uncertainties with knowledge gained from E821, improved hardware
- Environmental improvements by changing run conditions (e.g., no hadronic flash)

E821 Error	Size [ppm]	Plan for the E989 $g-2$ Experiment	Goal [ppm]
Gain changes	0.12	Better laser calibration; low-energy threshold; temperature stability; segmentation to lower rates; no hadronic flash	0.02
Lost muons	0.09	Running at higher n-value to reduce losses; less scattering due to material at injection; muons reconstructed by calorimeters; tracking simulation	0.02
Pileup	0.08	Low-energy samples recorded; calorimeter segmentation; Cherenkov; improved analysis techniques; straw trackers cross-calibrate pileup efficiency	0.04
CBO	0.07	Higher n-value; straw trackers determine parameters	0.03
E-Field/Pitch	0.06	Straw trackers reconstruct muon distribution; better collimator alignment; tracking simulation; better kick	0.03
Diff. Decay	0.05[1]	better kicker; tracking simulation; apply correction	0.02
Total	0.20		0.07