The Muon g-2 Experiment at Fermilab

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on Behalf of the Muon g-2 Collaboration

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Fermilab

U.S. DEPARTMENT OF ENERGY

Outline

Introduction

- The Magnetic Moment and the g-factor
- The Anomalous Magnetic Moment
- Current Status: Theory and Experiment

Experiment Overview

- Moving the ring
- Storing Muons
- Measuring the Anomaly

The Magnetic Field

- Magnet Geometry
- Shimming the Magnet
- Absolute Calibration

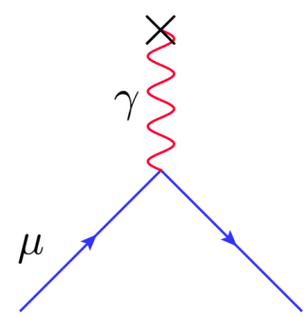
Summary

- Outlook: Where Are We and What's to Come?

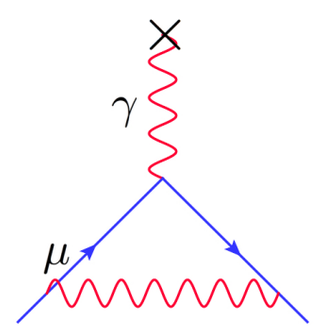
The Magnetic Moment

$$\vec{\mu} = g\frac{q}{2m}\vec{s}$$

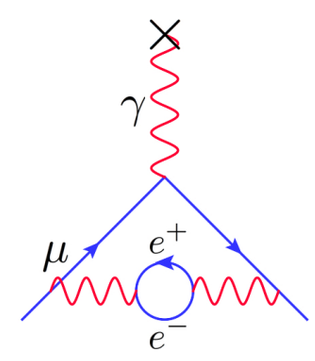
- Magnetic moment connected to spin via dimensionless g-factor
- Dirac: g = 2 for s = 1/2 particles (1928)
- g for electron found to differ from 2 in hyperfine structure experiments on hydrogen (Kusch, Foley 1948)
  - Anomalous contribution a_e
  - Interpretation: Schwinger's QED calculation of $a_e = \alpha/2\pi$ (1948)
  - Radiative corrections from virtual particles in loops



Dirac



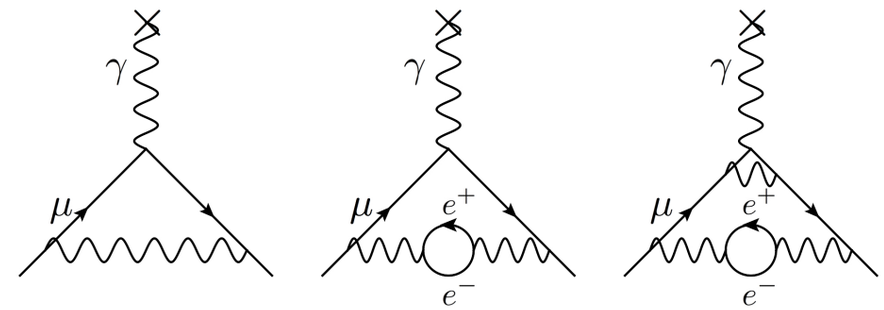
Schwinger O(α)



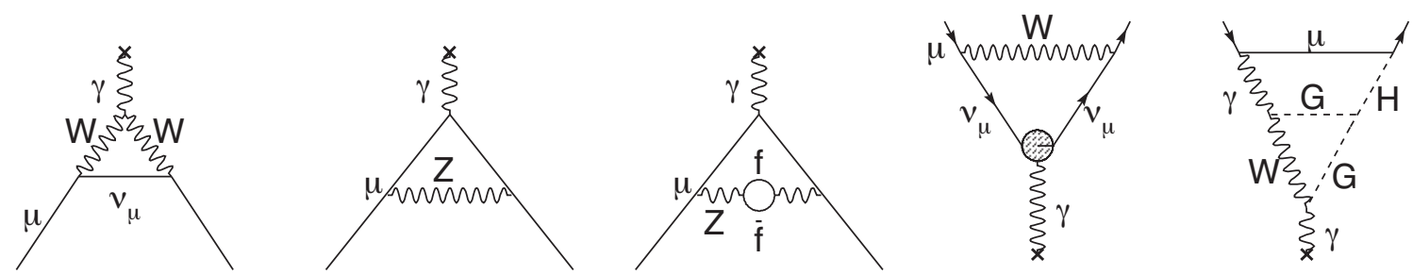
Vacuum polarization $O(\alpha^2)$

SM Contributions to a_μ

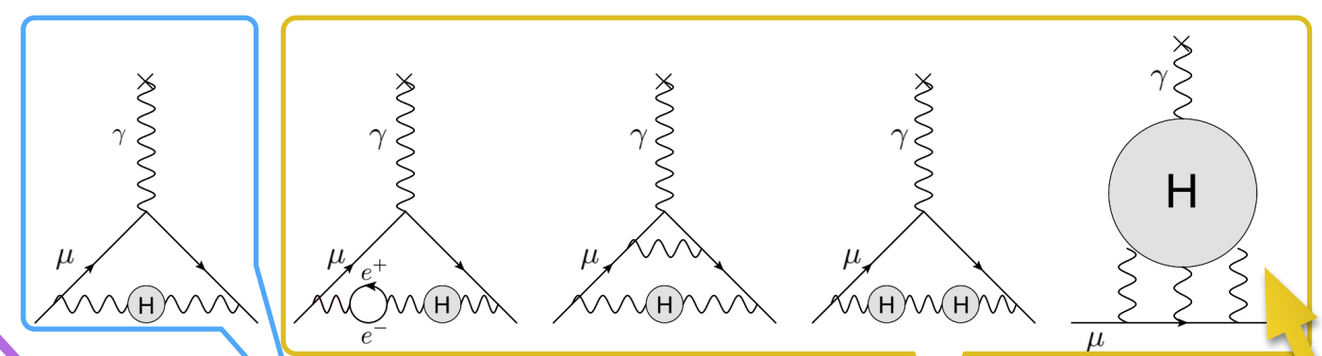
$$g_\mu \equiv 2\left(1 + a_\mu\right)$$



QED



EW



QCD

hadronic lowest order

hadronic higher order

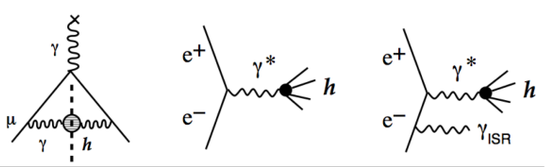
hadronic light-by-light

Contributions from **quantum electrodynamics**, **electroweak**, and **quantum chromodynamics**

SM Contributions to a_μ

Source	Value (x 10^{-11})	Uncertainty (x 10^{-11})	Reference
QED	116584718.951	0.080	Kinoshita et al., 2012
EW (1 loop)	194.8	–	
EW (2 loop)	-41.2	1	Czarnecki, Marciano, Stöckinger et al., 2013
HVP (LO)	**6923**	**42**	Davier et al., 2011
HVP (LO)	**6949**	**43**	Hagiwara et al., 2011
HVP (HO)	-98.4	0.7	Hagiwara et al., 2011
HLbL	105	26	Prades et al., 2010
Total	**116591802**	**49 (420 ppb)**	
	116591828	**50 (430 ppb)**	

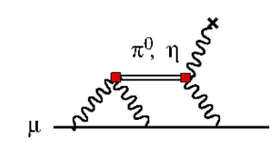
HVP (LO): Lowest-Order Hadronic Vacuum Polarization

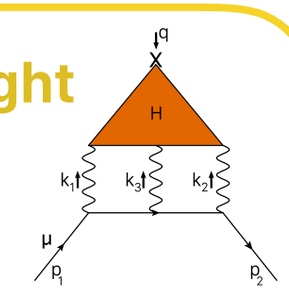


$$a_\mu^{\rm HVP} \cong \frac{1}{4\pi^3}\int_{4m_\pi^2}^{\infty} K(s)\sigma(e^+e^- \to \text{hadrons})ds$$

- **Critical input** from e^+e^- colliders (data from SND, CMD3, BaBar, KLOE, Belle, BESIII) , $\delta a_\mu^{\rm HVP}$ ~ 0.7%; extensive physics program in place to reduce $\delta a_\mu^{\rm HVP}$ to ~ 0.3% in coming years
- **Progress on the lattice:** Calculations at physical π mass; goal: $\delta a_\mu^{\rm HVP}$ ~ 1—2% in a few years (cross-check with e^+e^- data)

HLbL: Hadronic Light-by-Light





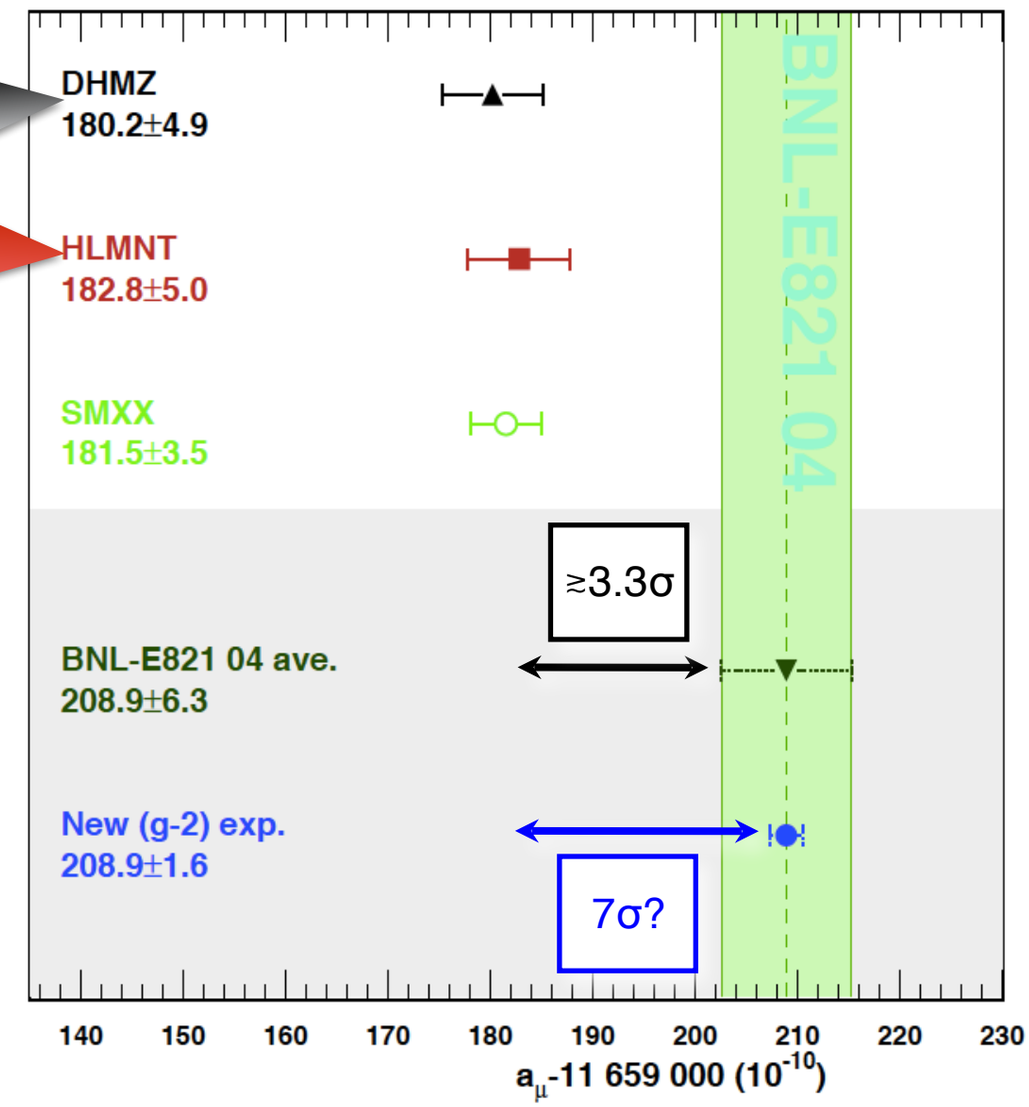
- Model dependent: based on χPT + short-distance constraints (operator product expansion)
- Difficult to relate to data like HVP (LO); γ* physics, π^0 data (BESIII, KLOE) important for constraining models
- **Theory Progress:** New dispersive calculation approach; extend the lattice (finite volume, disconnected diagrams); Blum et al. optimistic (see his talk, Plenary VI)

Current Status

a_μ (Exp) - a_μ (SM) = 287 ± 80 (3.6σ)

a_μ (Exp) - a_μ (SM) = 261 ± 80 (3.3σ)

Blum et al., arXiv:1311.2198



- **Disagreement** between experiment and theory
  - Deviation is large compared to EW contribution, uncertainty on hadronic terms
  - Not at discovery threshold (5σ)
  - **Due to new physics?**
    - **SUSY, TeV-scale models, dark photon...**
- **Improvements** on both theory and experiment sides
  - **Experiment:** more statistics, reduce systematics
  - **Theory:** reduce uncertainties (HVP, HLbL)

Uncertainty Source δa_μ	Status 2016 (ppb)	Projected after E989 (ppb)
HVP	360	215
HLbL	225	225
Total Theory	420	310
Total Experiment	540	**140**

Experiment Overview

The Muon g-2 Collaboration

33 institutions, 150 members

Domestic Universities

- Boston
- Cornell
- Illinois
- James Madison
- Kentucky
- Massachusetts
- Michigan
- Michigan State
- Mississippi
- Northern Illinois University
- Northwestern
- Regis
- Virginia
- Washington
- York College

National Labs

- Argonne
- Brookhaven
- Fermilab

Italy

- Frascati
- Roma 2
- Udine
- Pisa
- Naples
- Trieste

China

- Shanghai

The Netherlands

- Groningen

Germany

- Dresden

Russia

- Dubna
- Novosibirsk

England

- University College London
- Liverpool
- Oxford

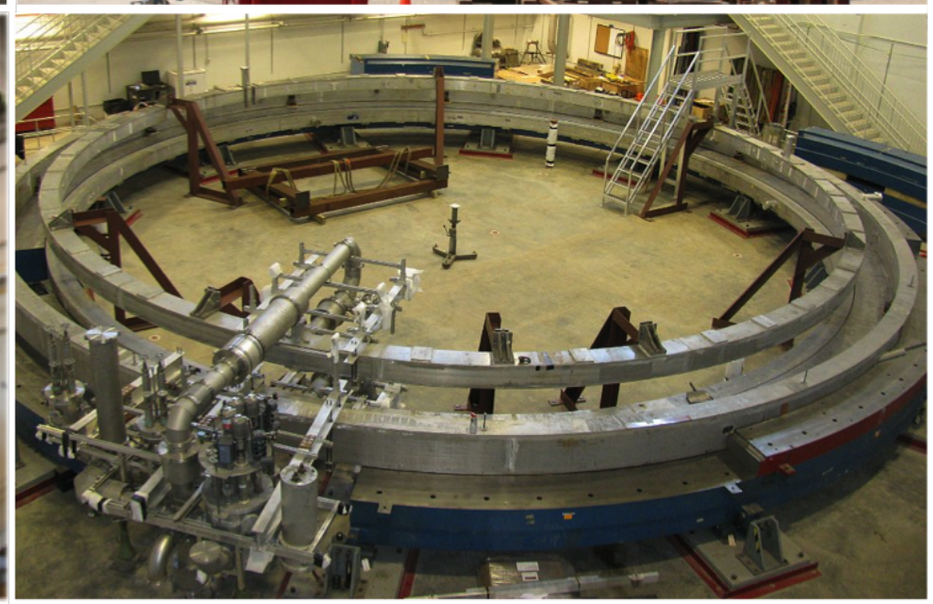
Korea

- KAIST

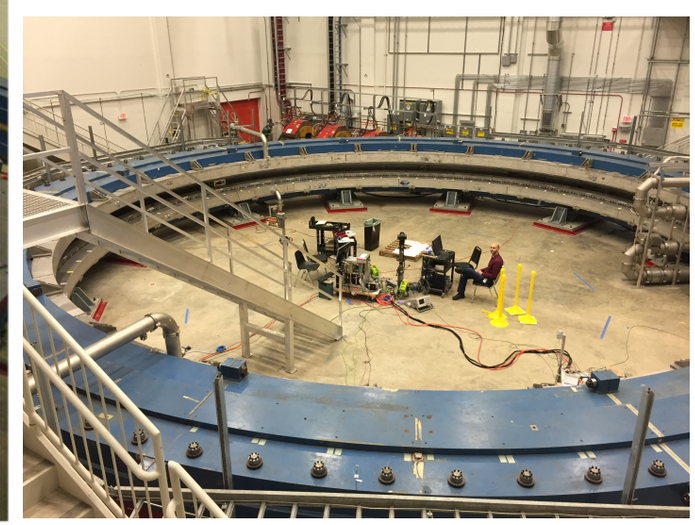
- D. W. Hertzog, Co-Spokesperson
- B. L. Roberts, Co-Spokesperson
- C. Polly, Project Manager

The Big Move

Relocating the Ring from BNL to FNAL



- June 2013—June 2015
- Ring deconstructed at BNL, transported by barge/flatbed trailer
- Reassembled at FNAL



Ring successfully cooled and powered to 1.45 T in September 2015 — remarkable achievement!

Muon Beam:
From Protons to Muons

Recycler

- Rebunches 8 GeV protons from booster

Target Station

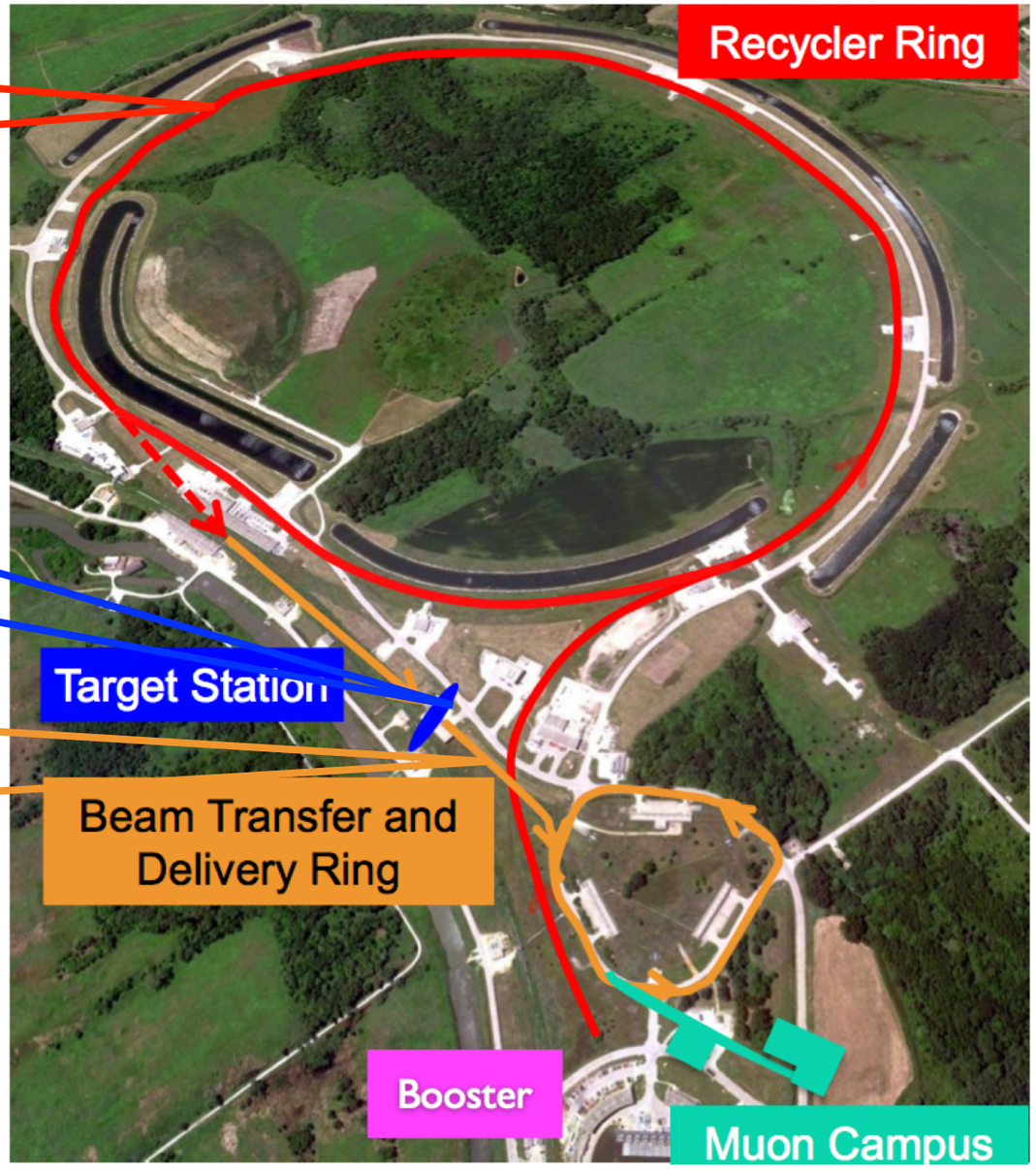
- Protons impinge upon Inconel target
- Focusing lens captures pions

Beam Transfer and Delivery

- Straight section: capture muons from forward-decaying pions (polarized)
- Remove protons by time-of-flight
  - Reduce number of pions and protons in ring

Characteristics

- Fill storage ring 16 times/1.4 sec (2x muons/fill compared to BNL)
- Expect 21x more statistics than BNL

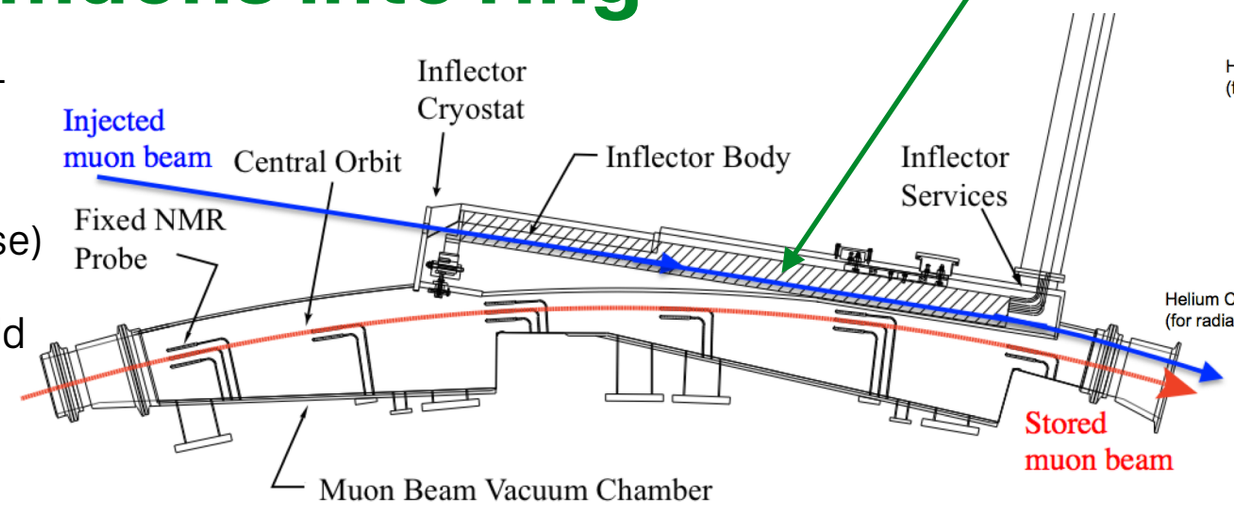


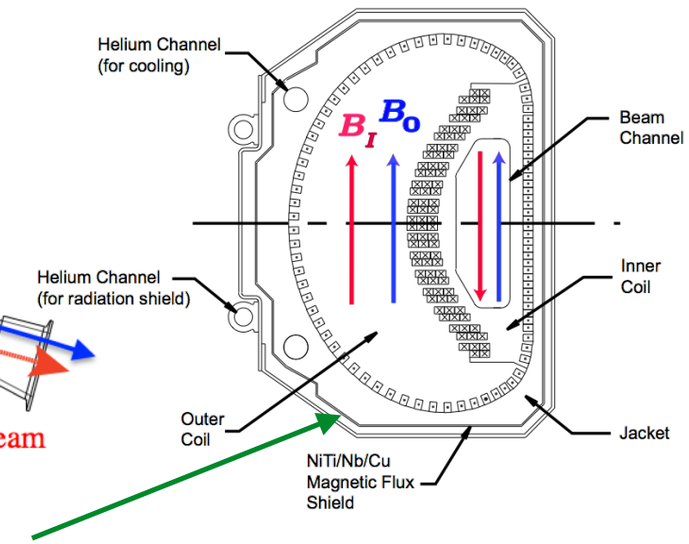
Muon Storage Technique

Inflector: Getting muons into ring

- Outside ring: B = 0 T, inside: B = 1.45 T
- Need to cancel field in order to get muons in (strong deflection otherwise)
- No perturbation to field outside shield
- Double-cos θ superconducting inflector from BNL E821
- New inflector design with higher transmission under development

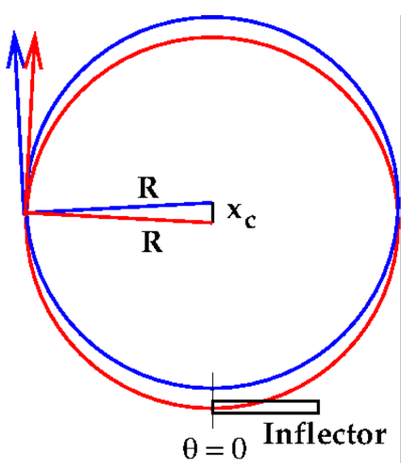
Energizing coils cancels the field in the beam channel

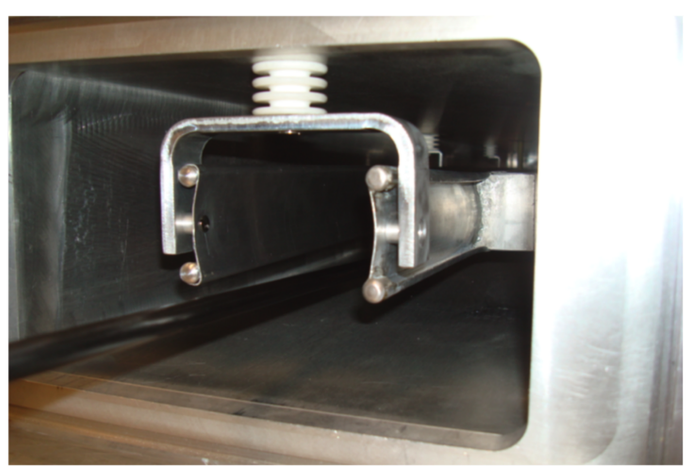




Eddy currents in passive superconducting shield prevents flux leakage

Kicker: Moving muons onto closed orbit

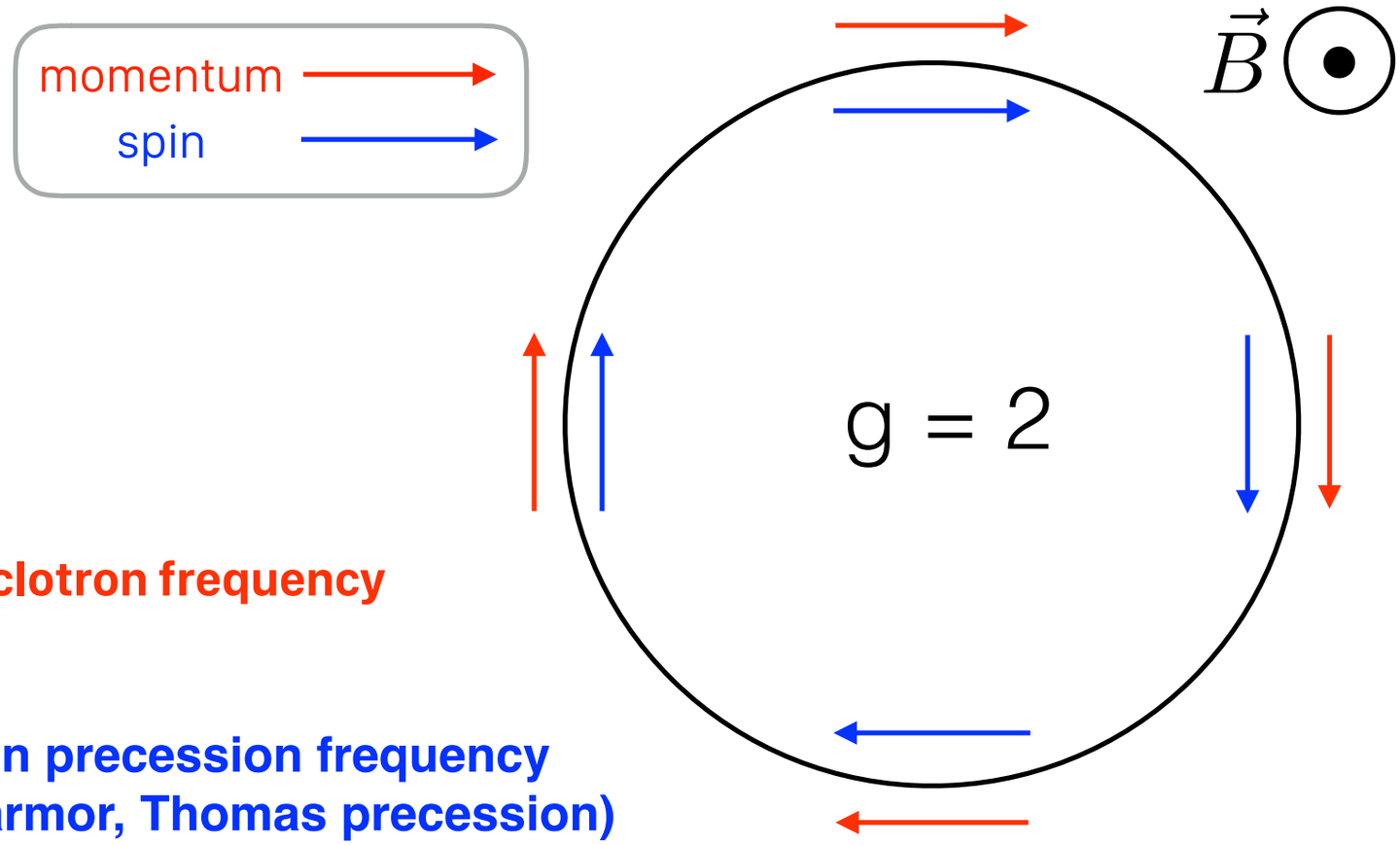




- After inflector, muons enter storage region at r = 77 mm outside central closed orbit
- Muons cross ideal orbit 90 deg. later in azimuth, angle is off by 10.8 mrad
- Need 14 mrad kick (includes effects from multiple scattering, momentum spread)
- Temporarily reduce field by 280 G over 5.1 m
- Operating time: < 149 ns at f = 100 Hz
- Characteristics: 3 x 1.7 m stripline kickers, Blumlein PFN

Measuring a_μ

- Inject polarized muon beam (from pion decay) into ring
- Measure **difference** between spin precession and cyclotron frequencies



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

cyclotron frequency

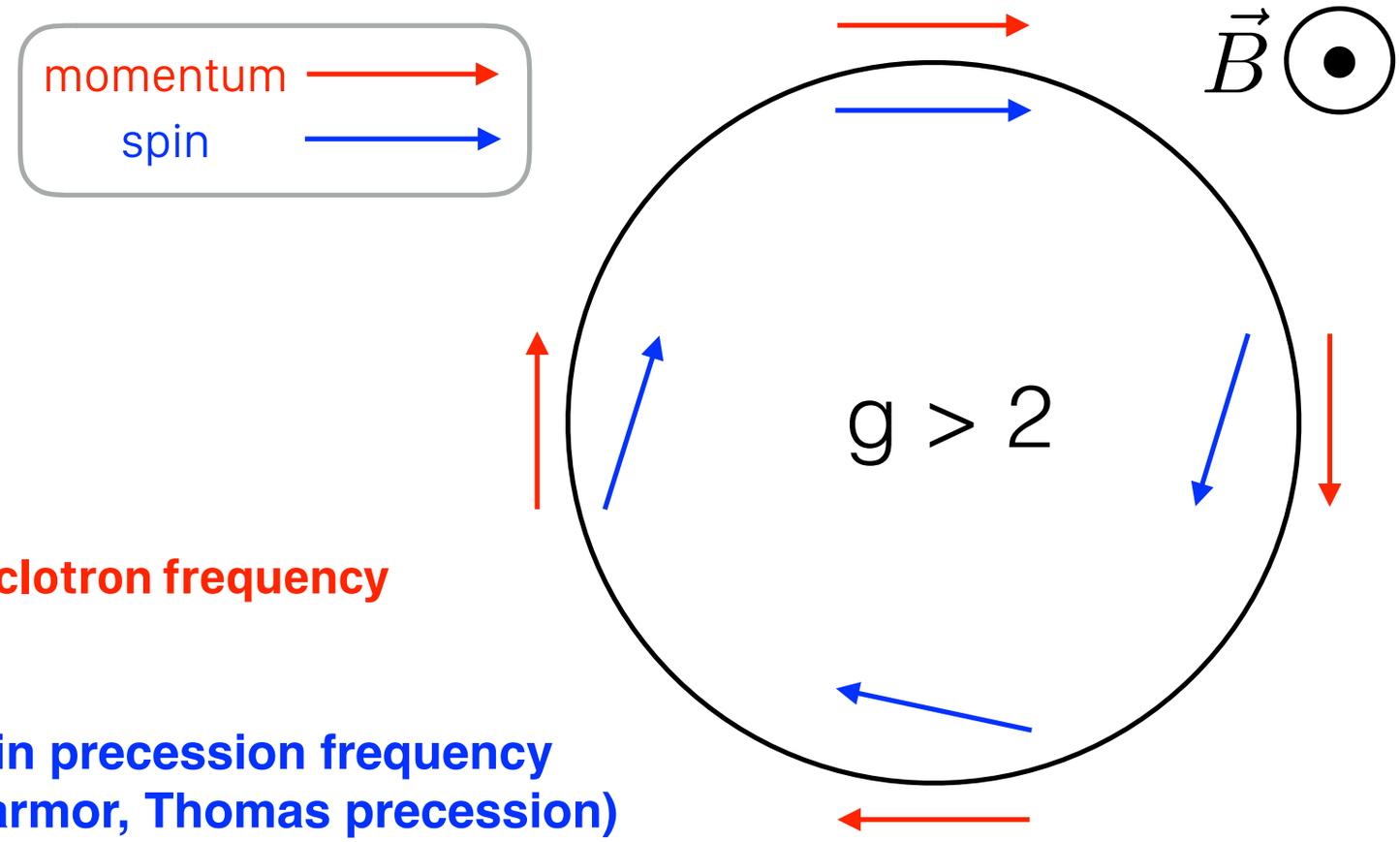
$$\vec{\omega}_S = -\frac{e}{\gamma m}\vec{B}$$

spin precession frequency (Larmor, Thomas precession)

- If g = 2, difference of spin precession and cyclotron frequencies is zero

Measuring a_μ

- Inject polarized muon beam (from pion decay) into ring
- Measure **difference** between spin precession and cyclotron frequencies



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

cyclotron frequency

$$\vec{\omega}_S = -\frac{e}{\gamma m}\vec{B}\left(1+\gamma a_\mu\right)$$

spin precession frequency (Larmor, Thomas precession)

0 for γ = 29.3 (p = 3.1 GeV)

$$\vec{\omega}_a \equiv \vec{\omega}_S - \vec{\omega}_C = -\frac{e}{m}\left[a_\mu \vec{B} - \left(a_\mu - \frac{1}{\gamma^2-1}\right)\frac{\vec{\beta}\times\vec{E}}{c}\right]$$

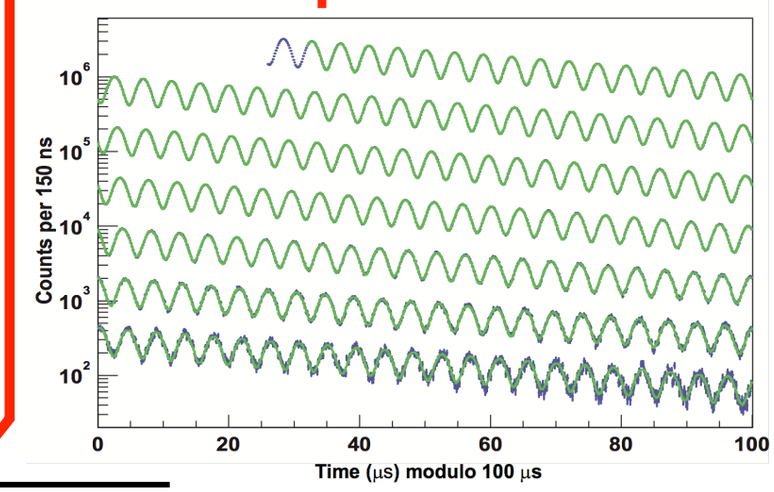
E-field vertical focusing allowed at p = 3.1 GeV (higher-order a_μ contribution cancelled)

Measuring a_μ

Re-write B-field in terms of free-proton precession frequency ω_p:

$$a_\mu = \frac{\omega_a/\omega_p}{\mu_\mu/\mu_p - \omega_a/\omega_p}$$

Measure muon decay to positrons

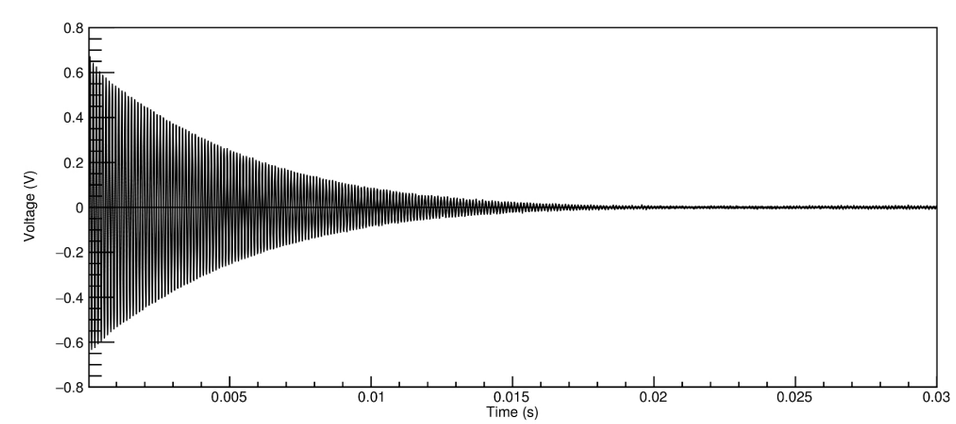


Muonium hyperfine experiments

25 ppb contribution to a_μ

(see Yasuhiro Ueno's talk, Beyond SM Parallel VI)

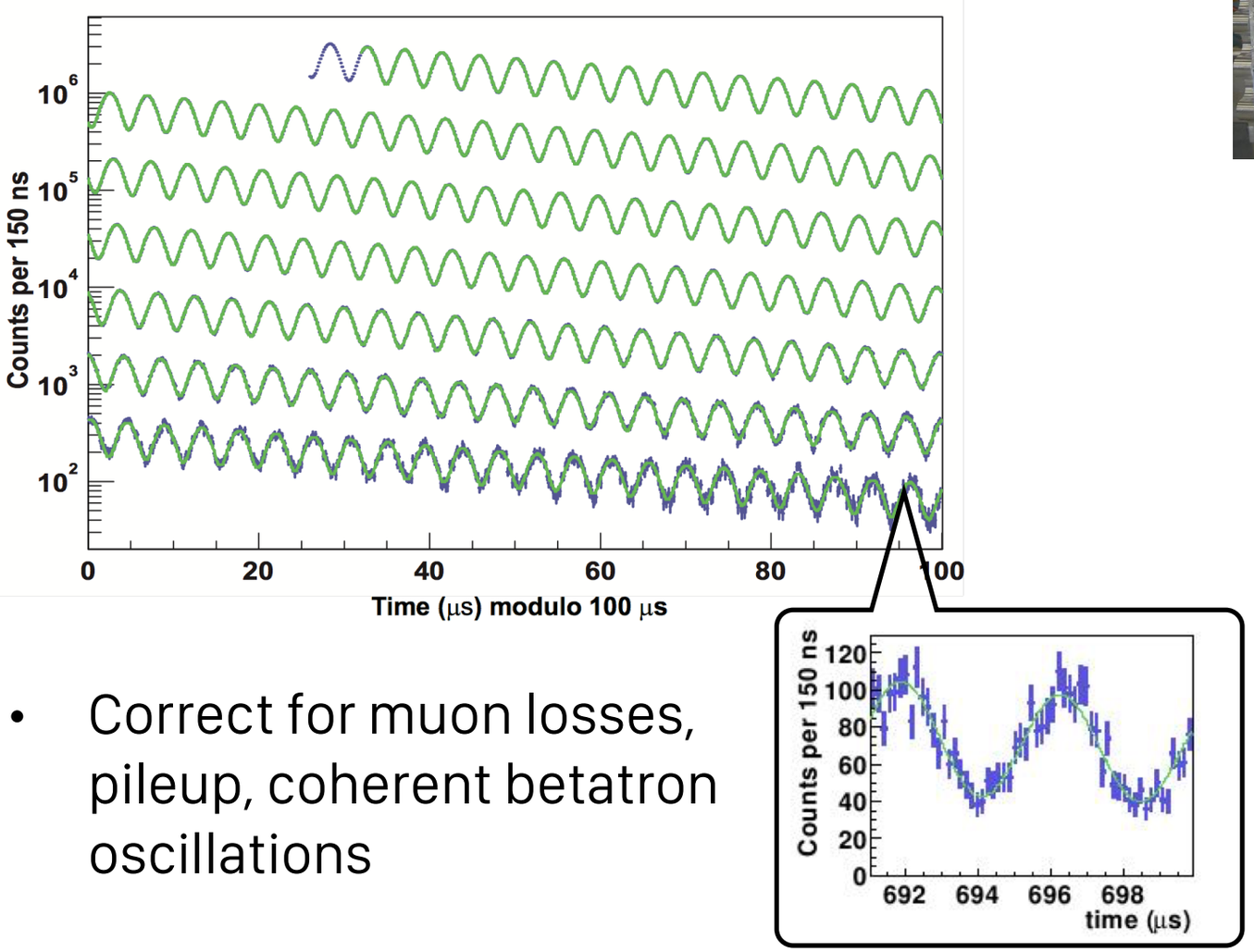
NMR measurements on proton samples



Measuring ω_a

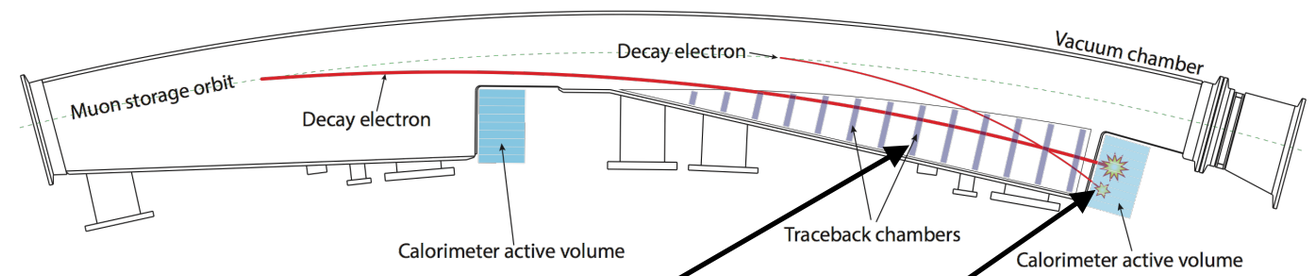
- Self-analyzing decay: $\mu^+ \to e^+ \bar{\nu}_\mu \nu_e$
  - e^+ emitted preferentially along muon spin
- Results in sinusoidally-oscillating energy deposition in calorimeters

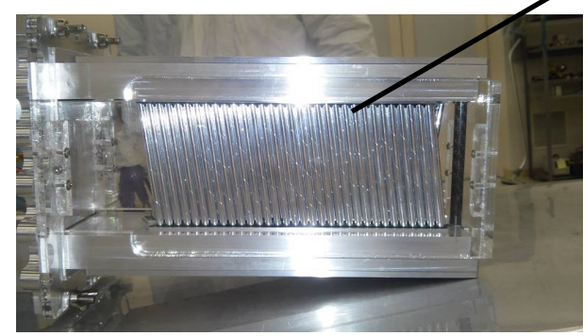
$$N(t) = N_0 e^{-t/\tau} \left[1 + A \cos\left(\omega_a t + \phi\right)\right]$$

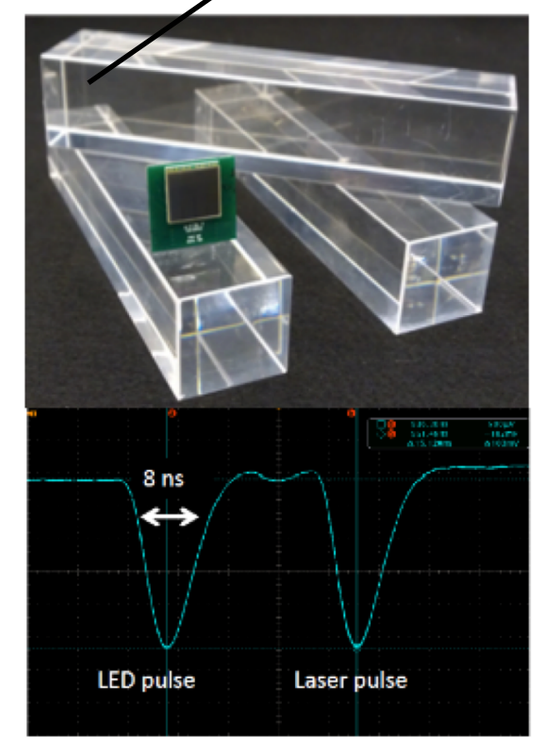


- Correct for muon losses, pileup, coherent betatron oscillations

Top view of vacuum chamber (1 of 12)





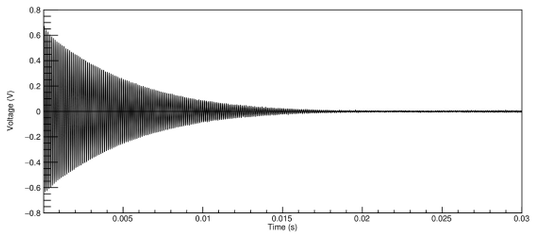


3 tracker systems

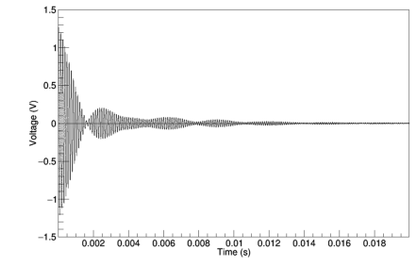
- 1500-channel straw trackers
- Reconstruct muon distribution from e^+ trajectories

24 calorimeters

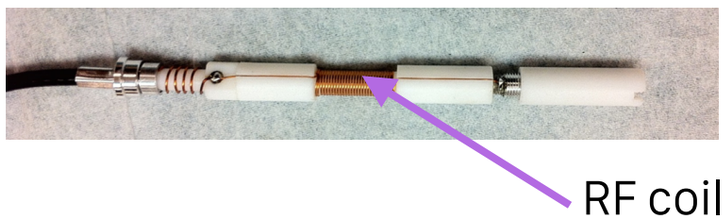
- 6 x 9 PbF_2 crystal arrays
  - fine segmentation, good timing resolution; low sensitivity to pileup
  - readout by SiPMs
- New electronics/DAQ, 800 MHz WFDs
- Laser calibration: 10^{-4}/hr gain stability demonstrated



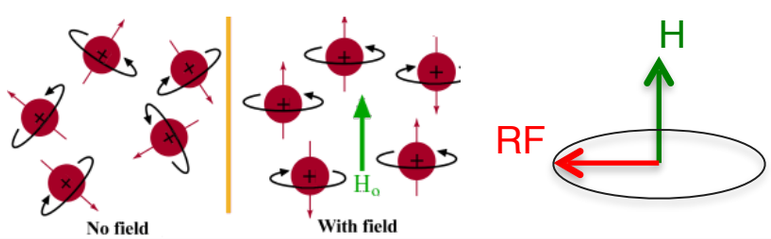
Measuring ω_p



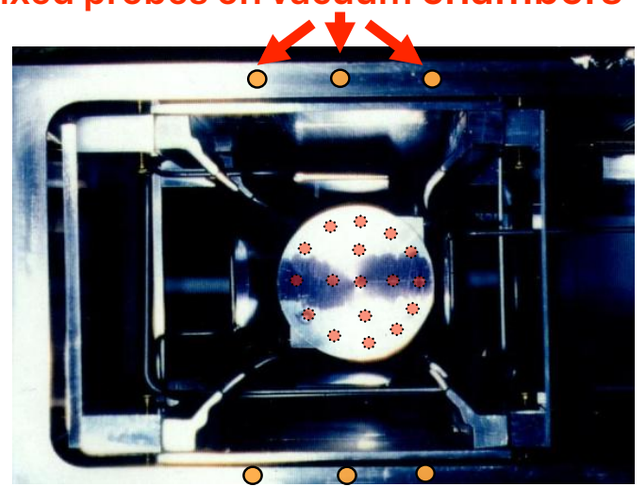
Pulsed NMR



- Sample: petroleum jelly
- Deliver π/2 pulse to probe, induce & record FID
- Extracted frequency precision: 10 ppb/FID

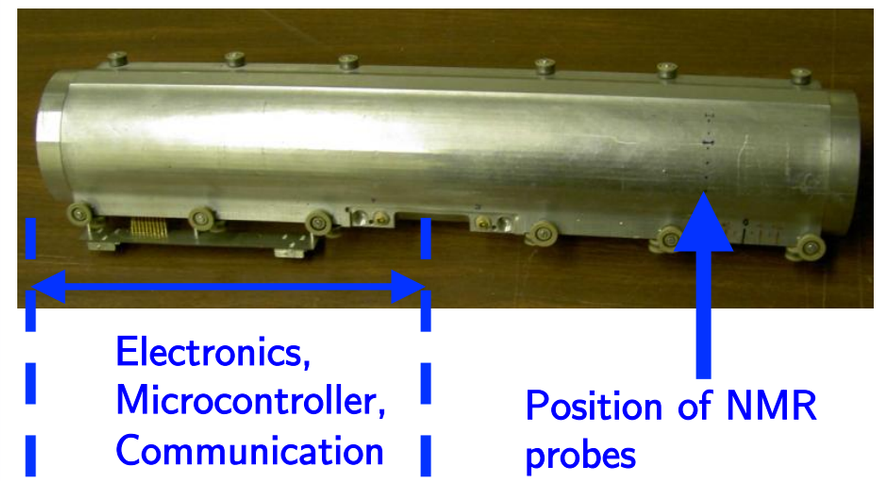


Fixed probes on vacuum chambers



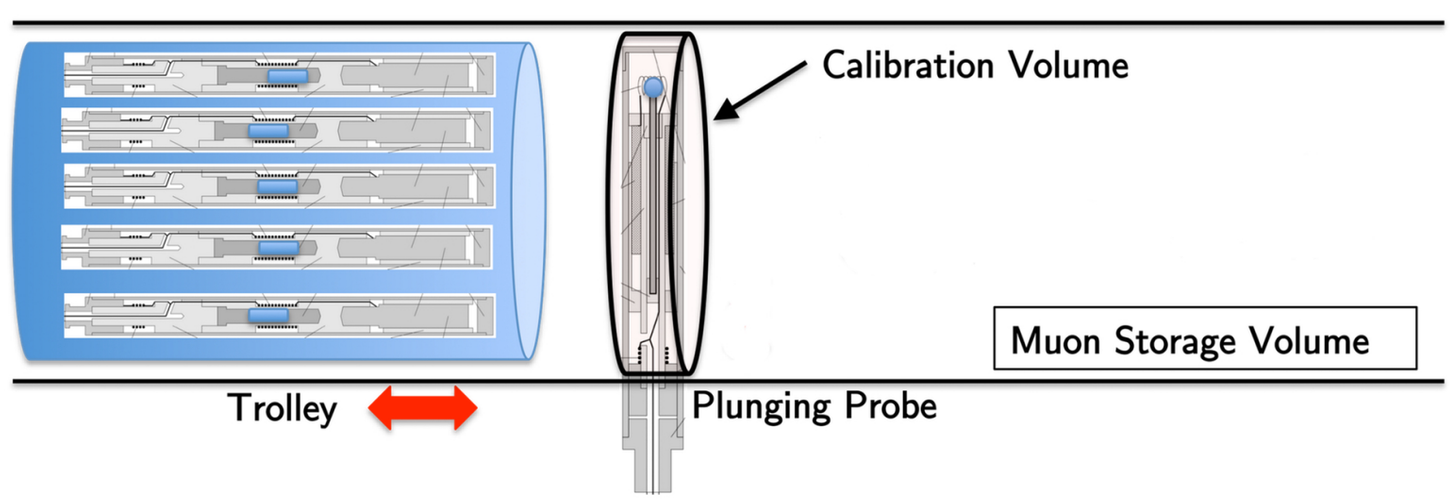
- Measure field while muons are in ring — probes **outside** storage region

Trolley with matrix of 17 NMR probes



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

- **Fixed** & **trolley** probes **calibrated to free proton Larmor frequency**
  - Absolute calibration probes using a water sample
  - Measurements in specially-shimmed region of ring



ω_a, ω_p Improvements

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)

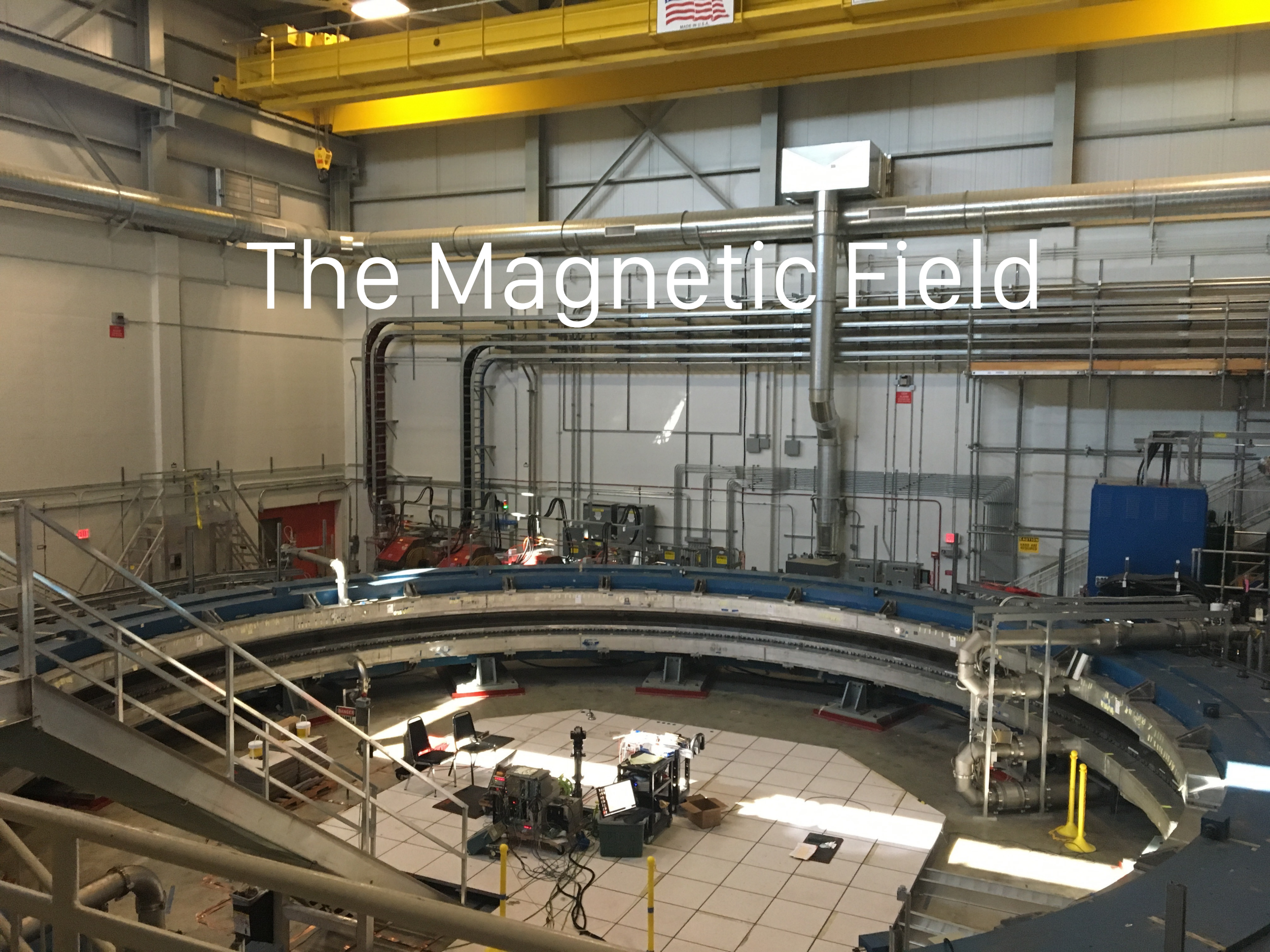
E821 Error	Size [ppm]	Plan for the E989 $g-2$ Experiment	Goal [ppm]
Gain changes	0.12	Better laser calibration; low-energy threshold; temperature stability; segmentation to lower rates; no hadronic flash	0.02
Lost muons	0.09	Running at higher n-value to reduce losses; less scattering due to material 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

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 measurements of B_0	0.05	Reduced rail irregularities; reduced position uncertainty 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_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

The Magnetic Field



Magnet Anatomy

B = 1.4513 T (~5200 A)

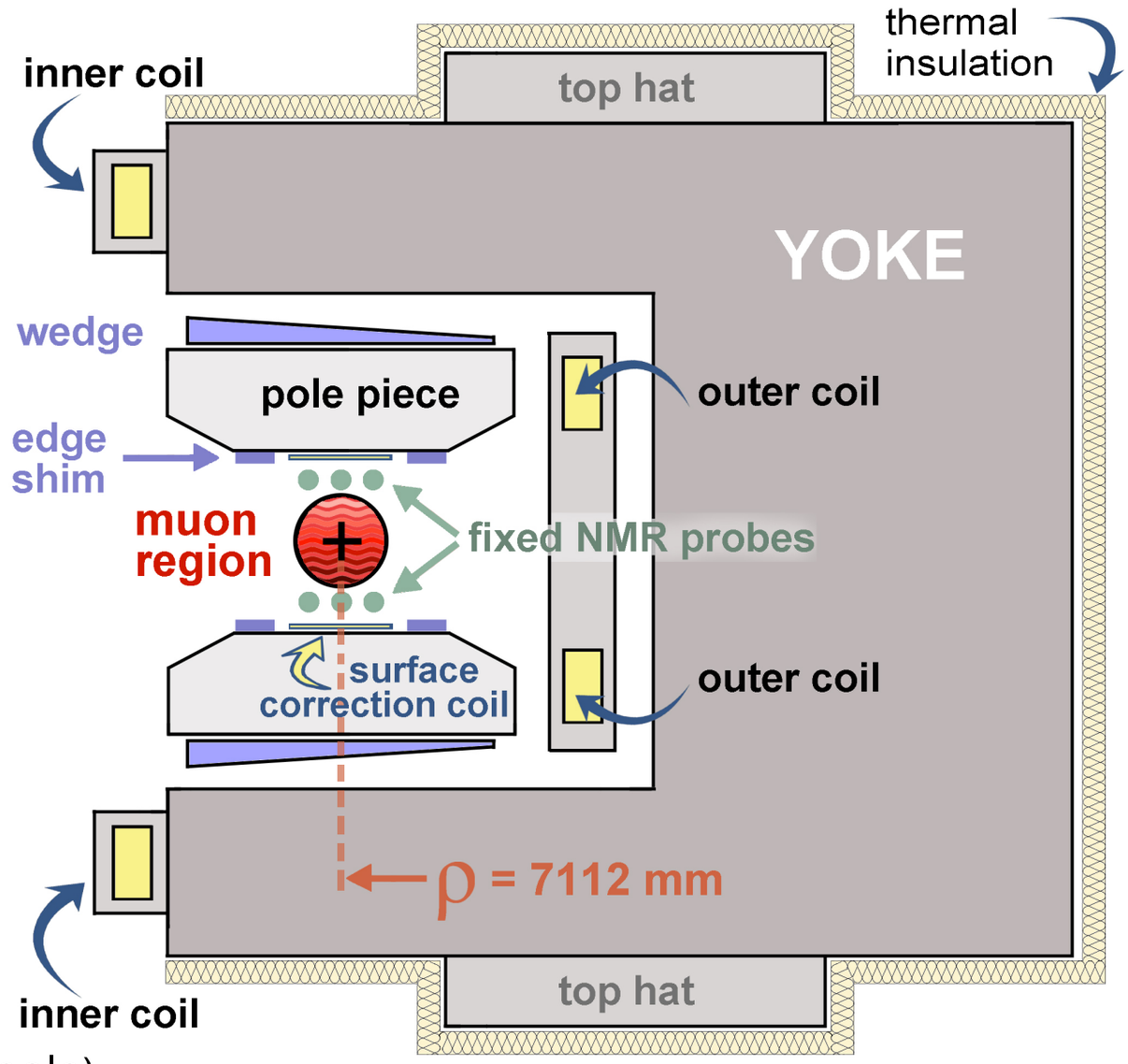
- Non-persistent current: fine-tuning of field in real time

12 C-shaped yokes

- 3 poles per yoke
- 72 total poles

Shimming knobs

- Poles: shape field
- Top hats (30 deg,dipole)
- Wedges (10 deg, dipole, quadrupole)
- Edge shims (360 deg, quadrupole, sextupole)
- Laminations (360 deg, dipole, quadrupole, sextupole)
- Surface coils (360 deg, quadrupole, sextupole,...)



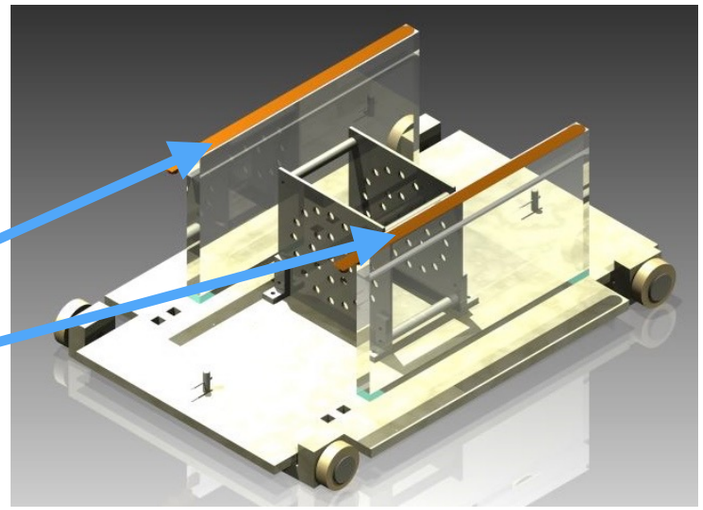
g-2 Magnet in Cross Section

Measurement Tools

Rough Shimming

Shimming cart

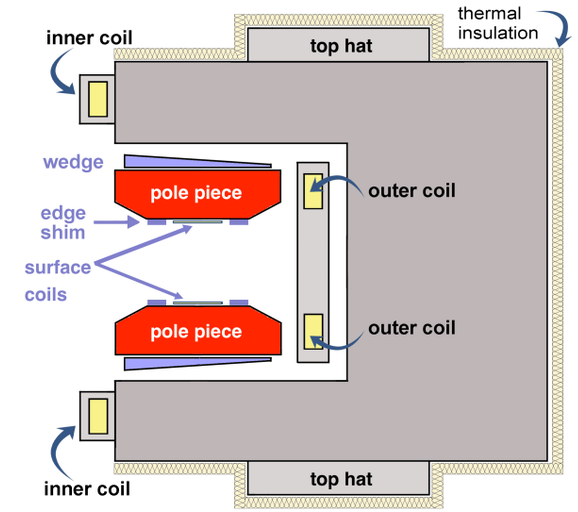
- Lattice of 25 NMR probes (field measurements)
- 4 capacitive gap sensors (pole-pole alignment/ separation), 70-nm resolution
- 4 corner-cube retroreflectors (position), ~25 μm resolution



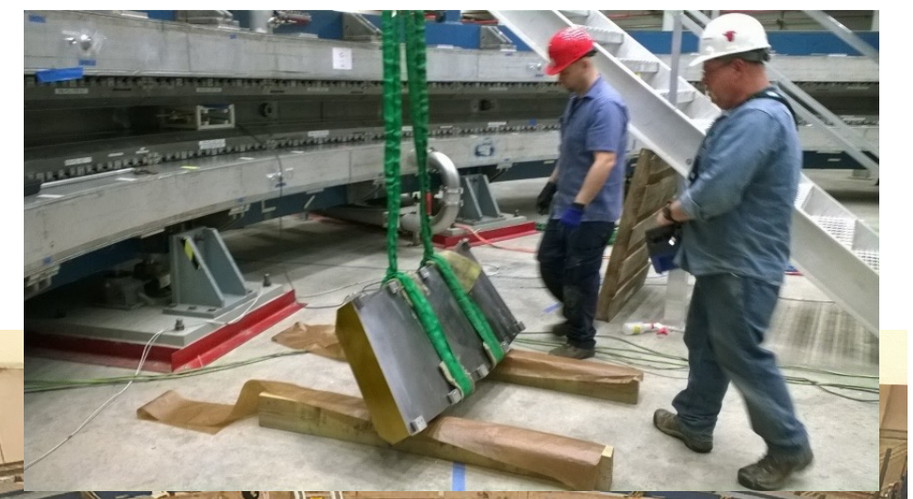
Laser tracker

- Cart position (r, φ, z)

Pole Moves and Tilts



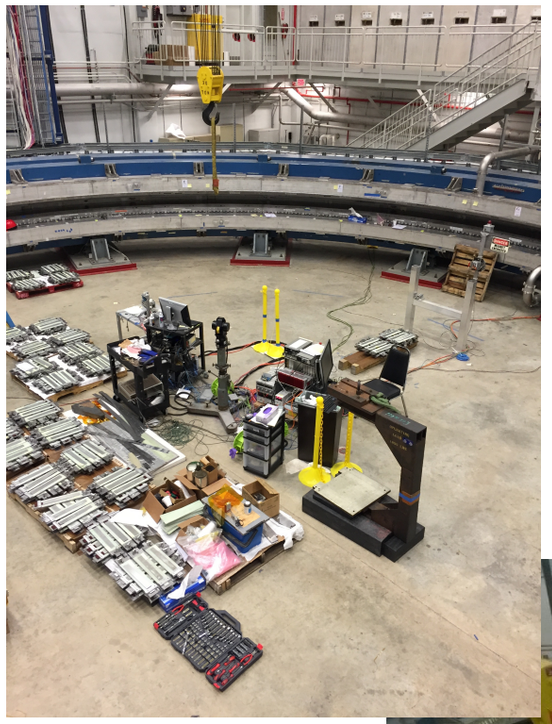
- Step and tilt discontinuities in pole surfaces yield large variations in the field
- To reduce/remove such effects, make adjustments to pole feet, which changes the magnet gaps and tilts
  - Use 0.001—0.010” thick shims
  - Requires removal of poles from the ring
- Informed by a computer model that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

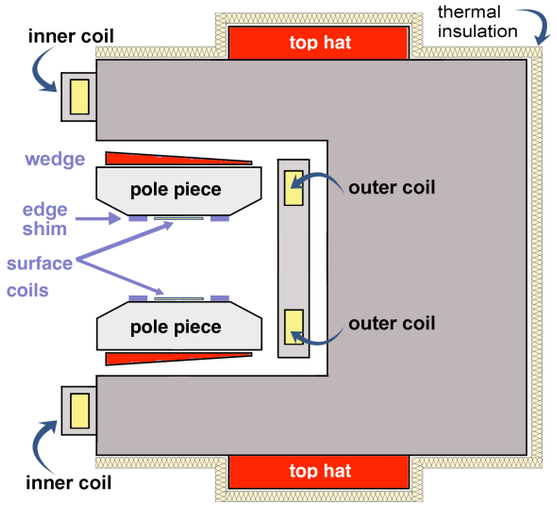


Tuning Out Small(er) Variations

Calibrated shimming knobs

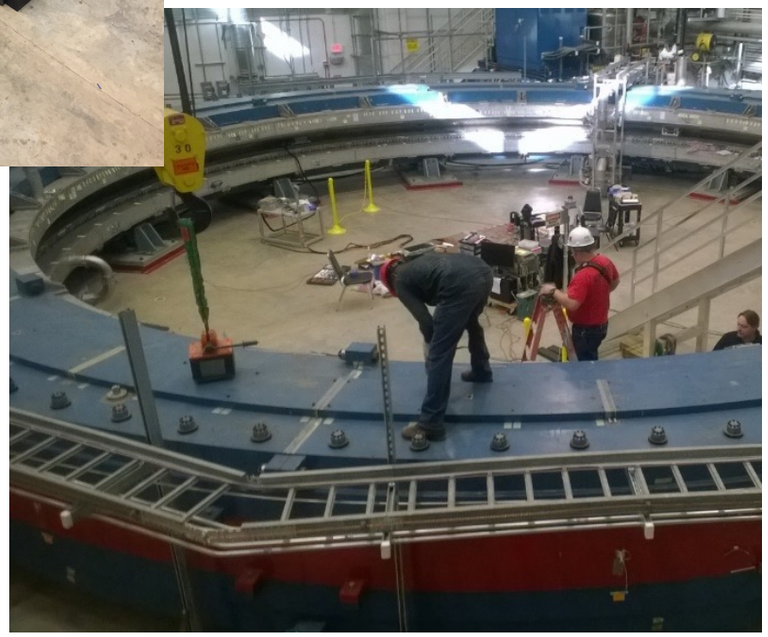
- 48 top hats
- 864 wedges
- ~8400 iron foils (on pole surfaces)





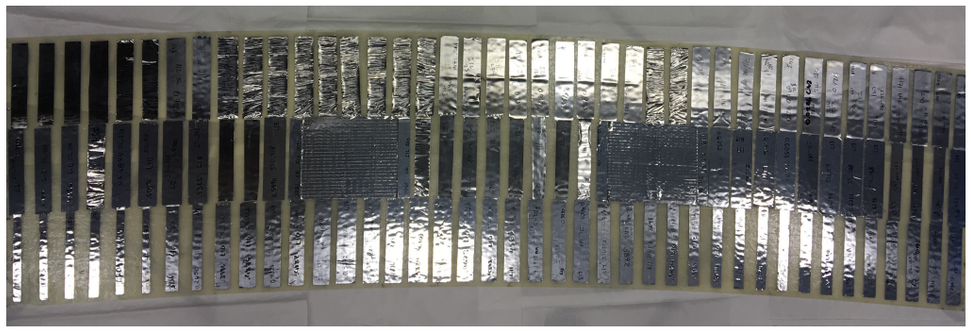
Coarse tuning: top hat & wedge adjustments

- Least-squares fit to field maps predicts top hat and wedge positions

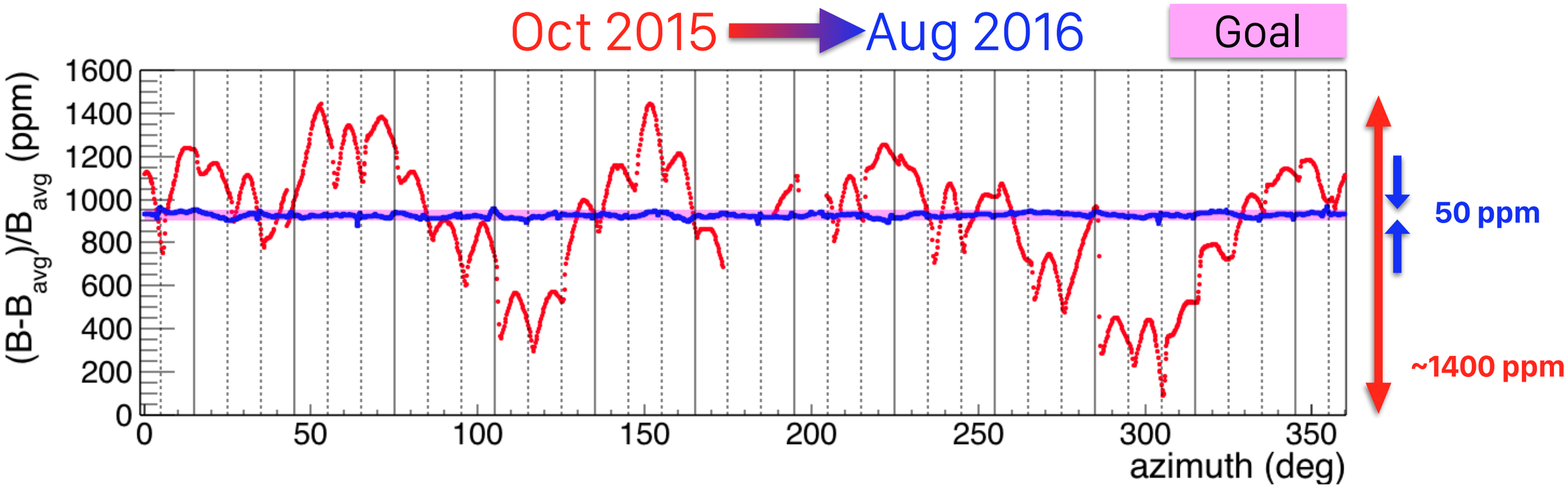


Fine tuning: iron foils

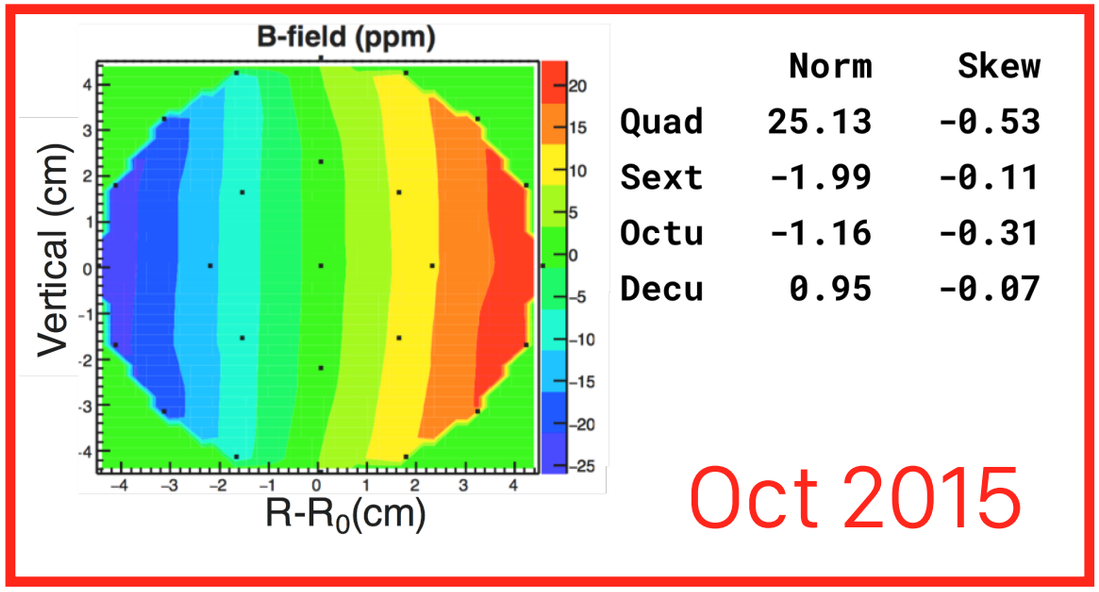
- Modeled as saturated dipoles in 1.45 T field
- Computer code predicts foil width (mass) distribution to fill in the valleys of the field map
- Radially-segmented distribution: control higher-order multipoles (quadrupole, sextupole,...)



Rough Shimming Results

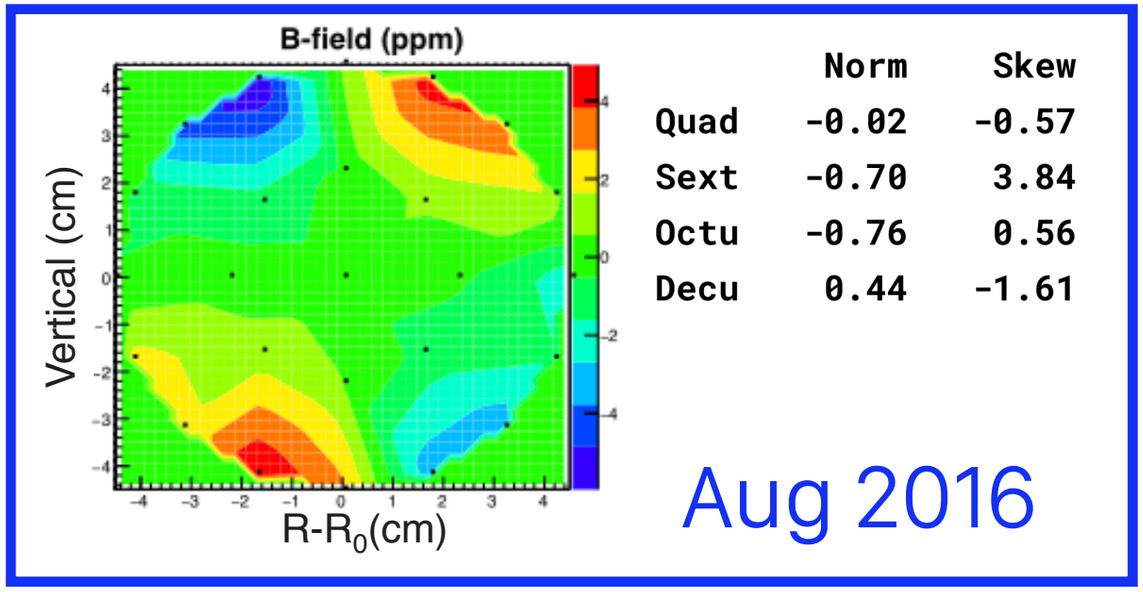


Azimuthally-Averaged Map



	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

Absolute Calibration

- In the experiment, need to extract ω_p, but we don't have free protons — need a calibration

- Field at the location of a proton differs from the applied field:

$$
\begin{aligned}
B_{\text{meas}} &= (1-\delta_t)B \\
&= \left[1-\sigma\left(\mathrm{H_2O}, T\right)-\delta_b-\delta_p-\delta_s\right]B
\end{aligned}
$$

Paramagnetic ion cont.

Diamagnetic shielding

Bulk diamagnetic shape $(\varepsilon - 4\pi/3)\,\chi$

Probe structure

- Carefully-constructed probes
  - Studying build quality and magnetic footprint of materials
  - Pure water sample
- Goal: reduce the uncertainty from 50 ppb (E821) to 35 ppb

Table: Systematic uncertainties for the E821 absolute calibration probe. Data from Nucl. Instrum. Meth. **394**, 349 (1997).

Projections

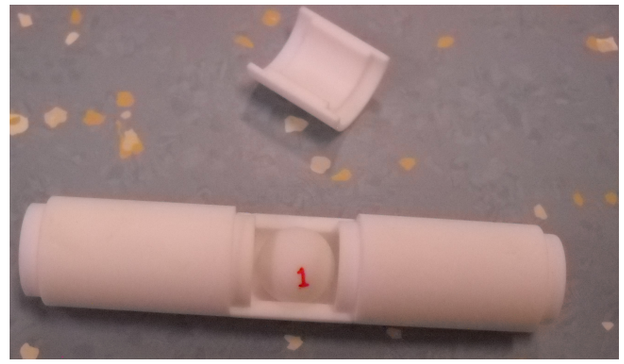
Source of Error	Uncertainty (ppb)
NMR detection and measurement	15 → **5**
Field homogeneity	10
Materials outside the probe	15
Water/sample holder shape	15 → **10**
Probe materials	10
Diamagnetic shielding (H_2O)	14 → **2.5**
Temperature	10 → **5**
Total	34

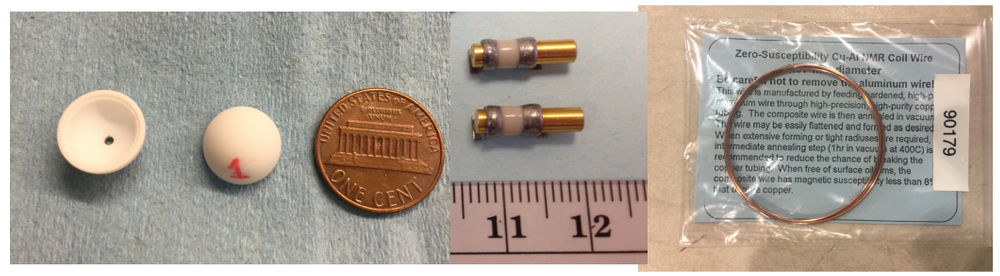
Metrologia **51**, 54 (2014)

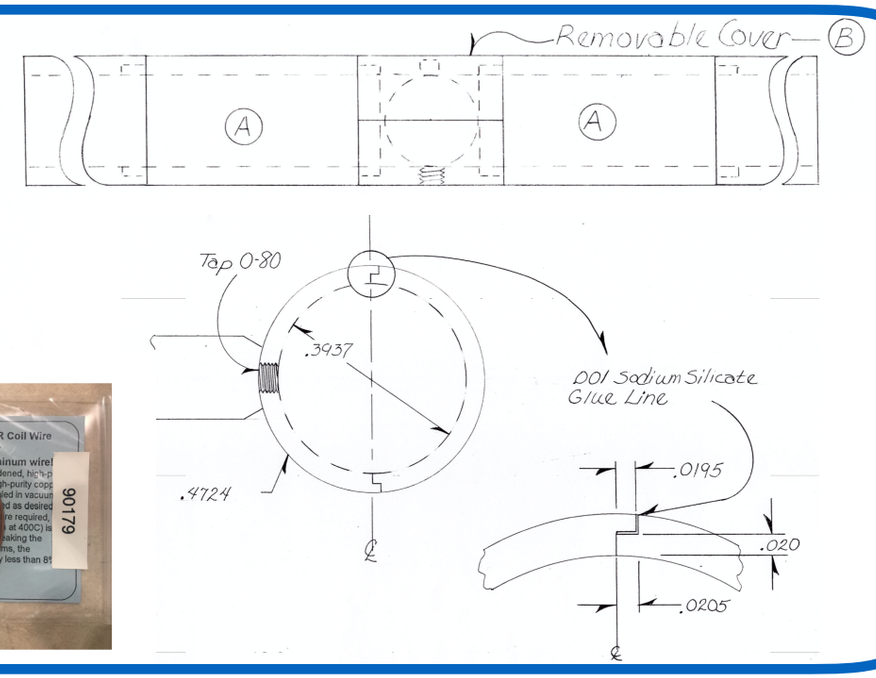
Probe Design

Absolute Probe

- Probe made from macor
- Geometry: spherical sample holder encased in cylindrical tube
- Circuitry: non-magnetic RF coil, capacitors
- Calibrates the **plunging probe**



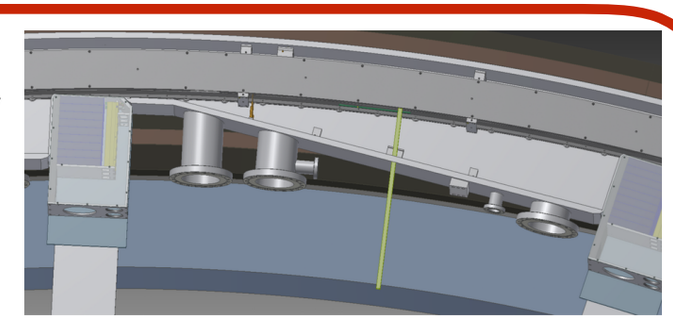


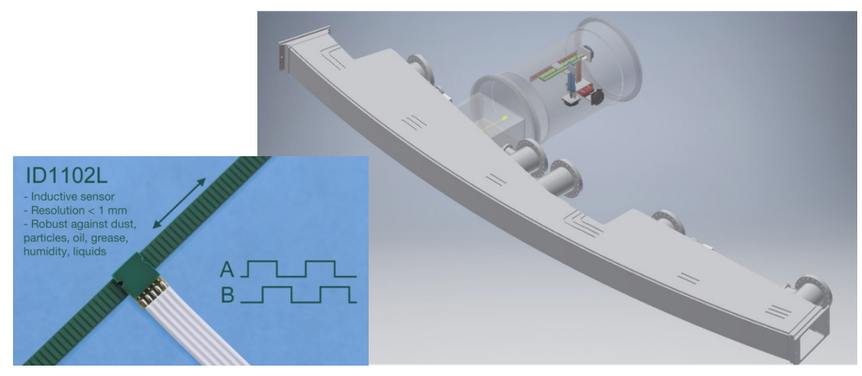


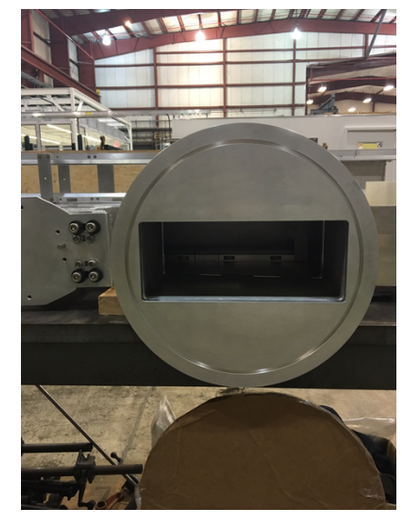
Plunging probe

- **Calibrates** the trolley probes and fixed probes
- Geometry: cylindrical tube
- Operates in vacuum
- Materials: glass, non-magnetic RF coil, capacitors
- Galil controller directs motion (x, y, z), cross-checked by high-res photographs
  - Positional accuracy < 1 mm (inductive linear encoder)

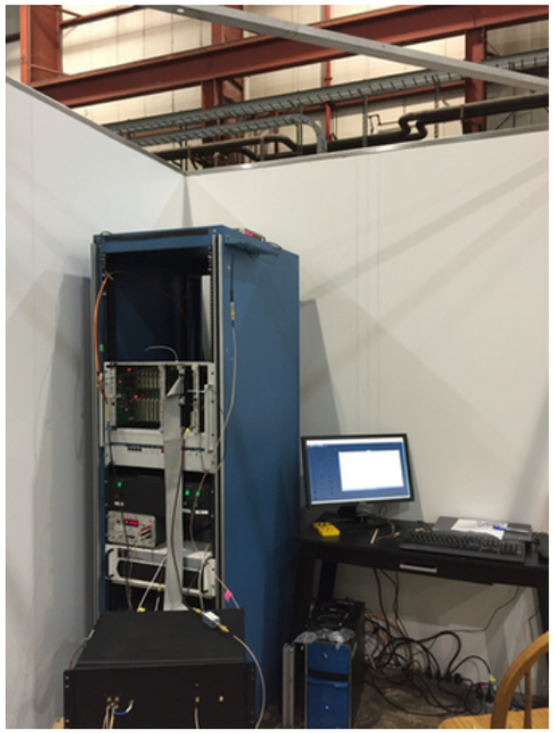
- **Coverage in ring:** 5 cm azimuthally, 11 cm vertically, 20–25 cm radially
- **Location in ring:** 6 o'clock position
- **Vacuum chamber** has been scalloped, rectangular extension welded on and slot cut (BU/FNAL)





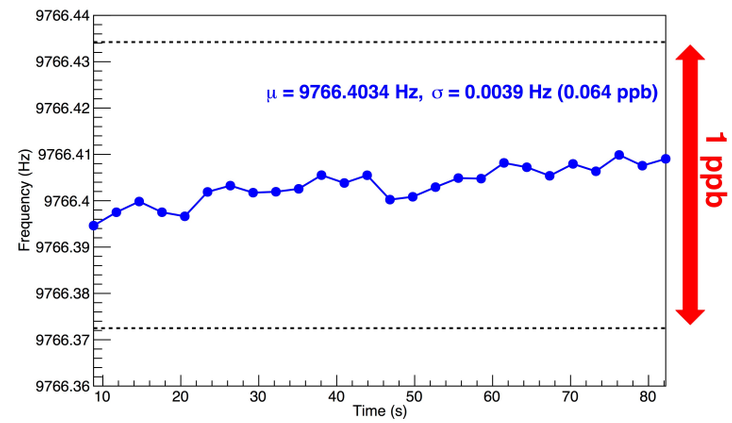


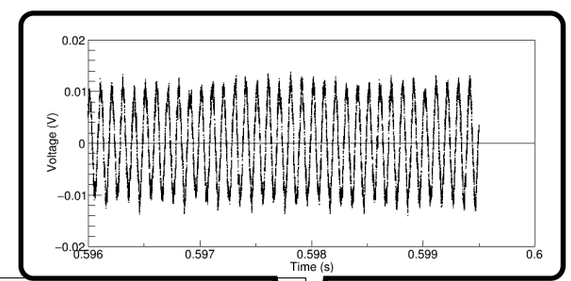
Instrumentation at Argonne

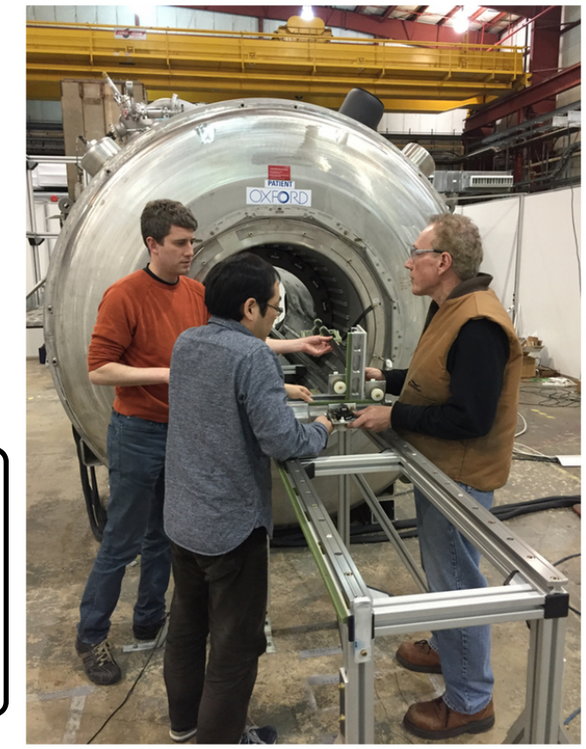


DAQ Characteristics

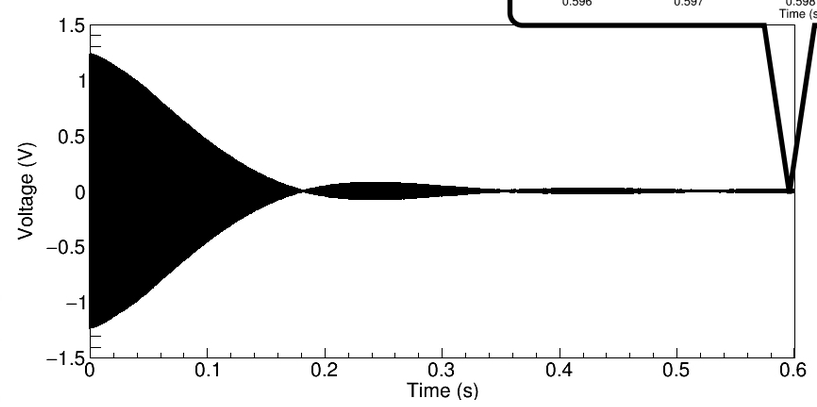
- Bandwidth: 61.79 MHz ± 50 kHz (833 ppm)
- Amplitude: ~ 1 V at t ~ 0
- RMS Noise: ~ 1 mV
- S/N: ~ 1000 at t ~ 0
- Resolution: < 1 ppb

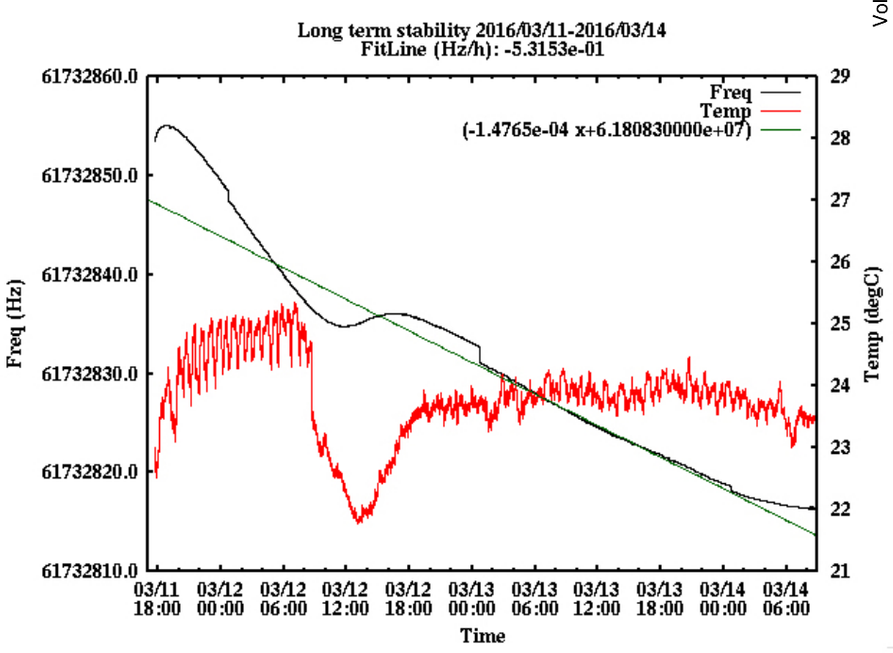


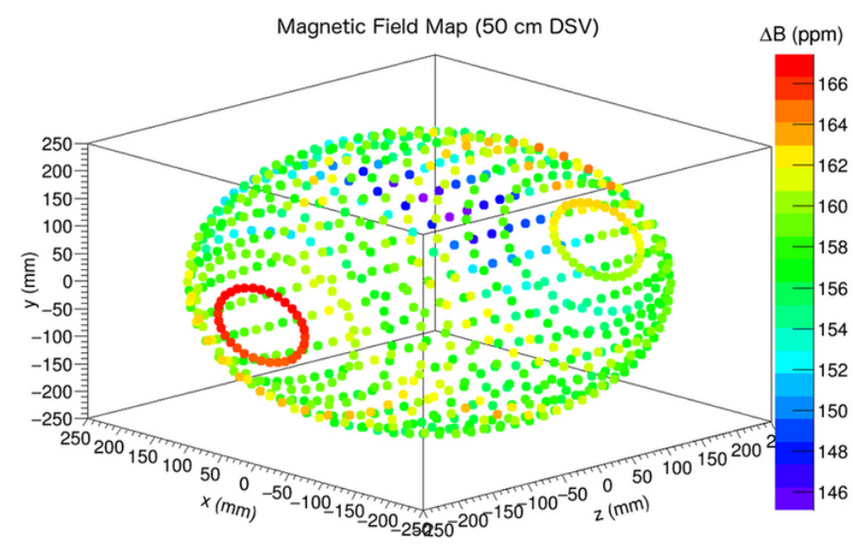




Absolute Calibration DAQ



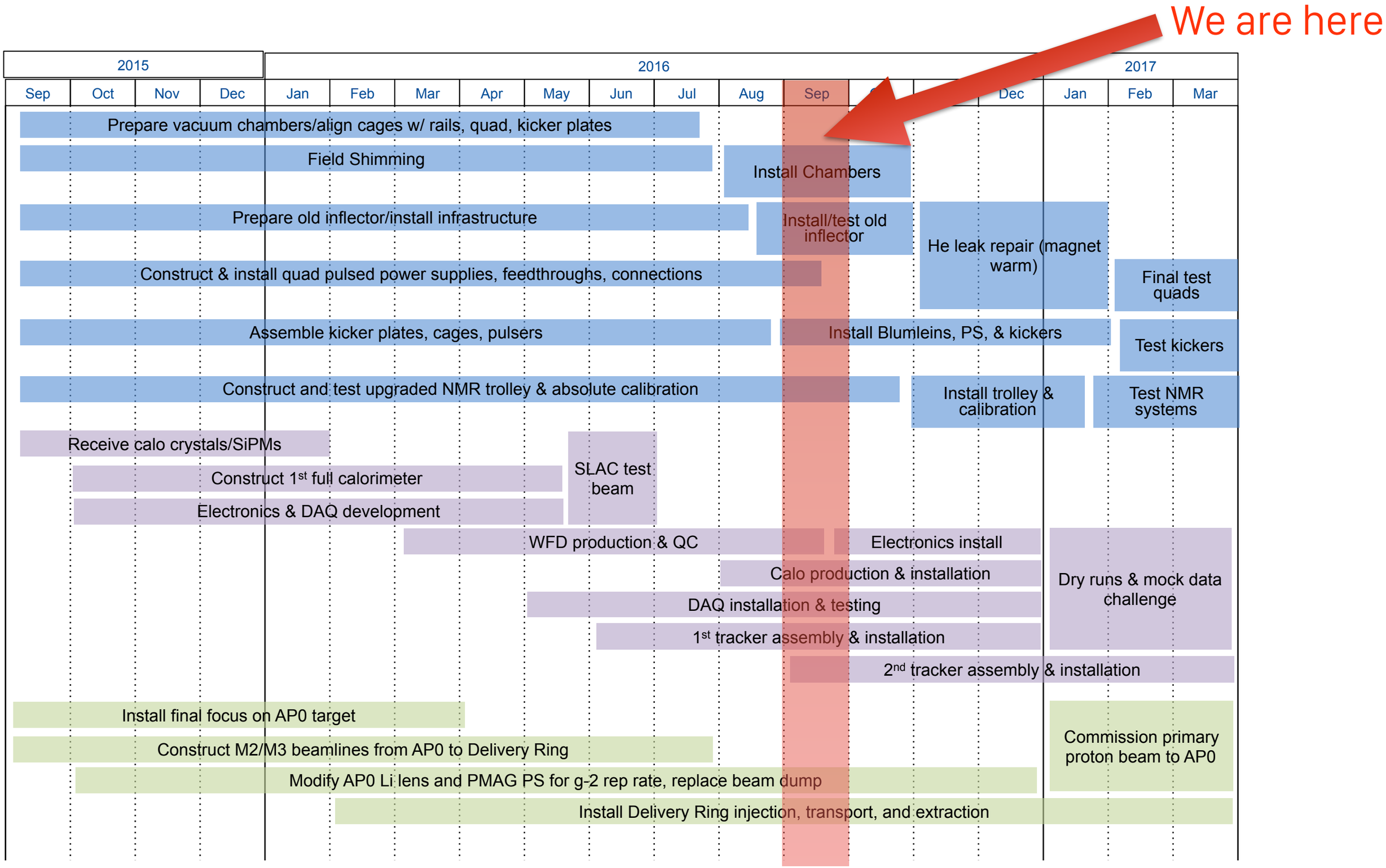




Magnet Details

- **Characteristics:** MRI solenoid, persistent current, 68-cm bore
- **Uniformity:** Shimmed to 13 ppm peak-to-peak over a 50-cm diameter spherical volume (DSV)
- **Stability:** Field drift ~ 9 ppb/hr

Approximate Project Timeline

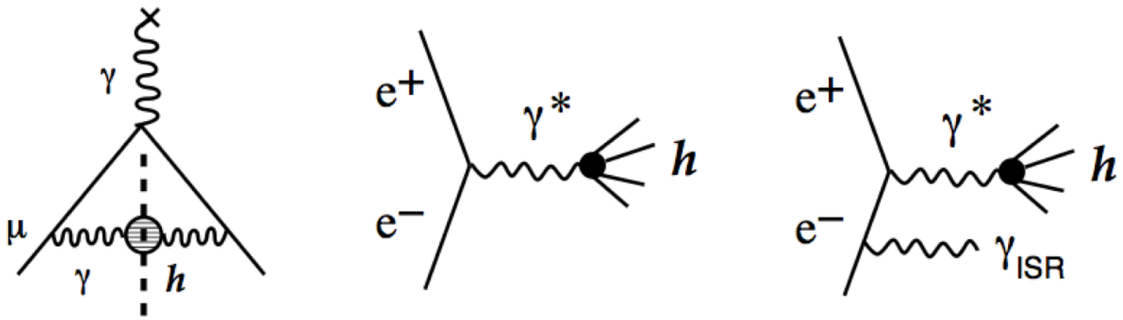


Summary

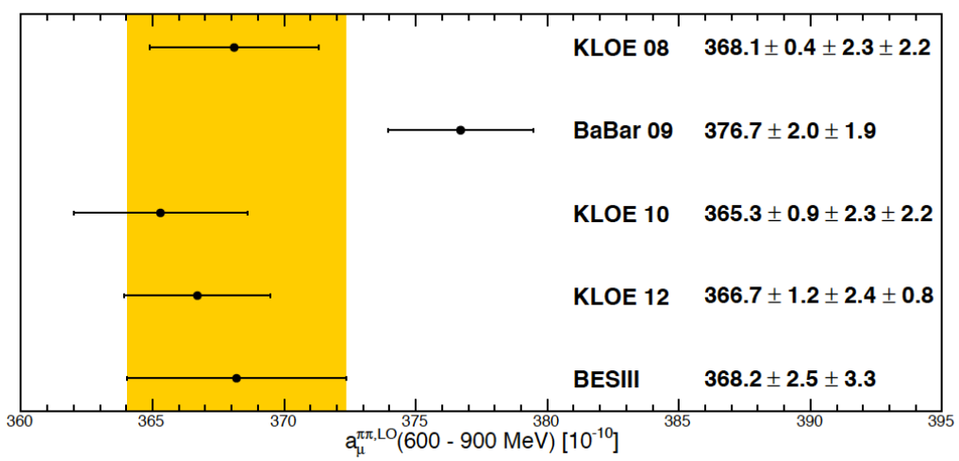
- The experiment will measure the muon's anomalous magnetic moment to a precision of 140 ppb — a fourfold improvement over BNL E821
- Magnet disassembled at BNL, transported to FNAL and is operational at 1.45 T as of September 2015
- Rough-shimming stage of magnetic field is complete
  - Field variations reduced to 50 ppm peak-to-peak around the ring — factor of 2 better than E821
- Absolute calibration effort well underway: probe design, construction, and material studies all progressing
- Project on pace to take physics data in fall/winter 2017
  - Much to do in the meantime! Calorimeter construction, vacuum chamber installation, simulations, radial & AC magnetic field studies, DAQ stress-testing, ...

Backup

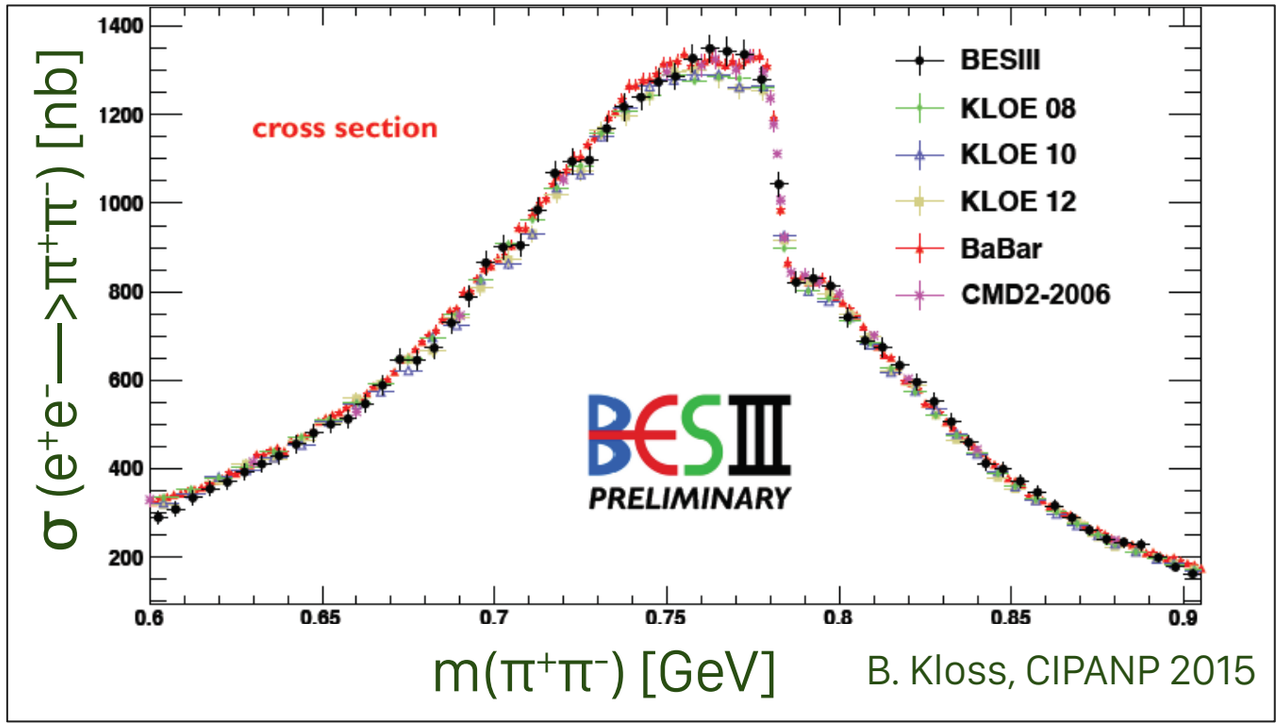
Hadronic Vacuum Polarization



- **Critical input to HVP** from e^+e^- colliders (SND, CMD3, BaBar, KLOE, Belle, BESIII)
- **BESIII:** 3x more data available, luminosity measurement improvements
- **VEPP-2000:** Aiming for 0.3% (fractional) uncertainty by 2017; radiative return + energy scan
- **CMD3:** Will measure up to 2 GeV (energy scan, ISR — good cross check)

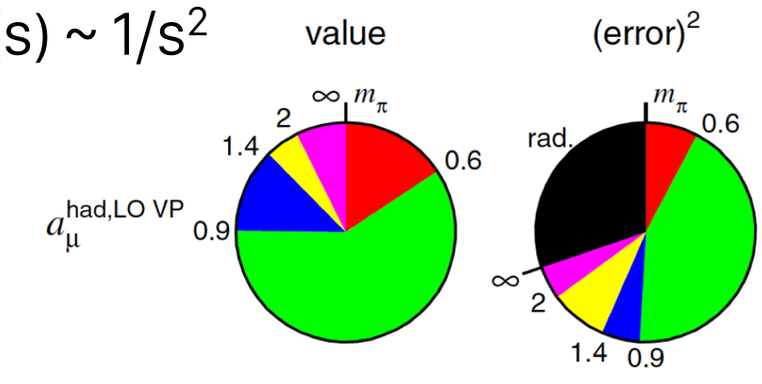


σ (600-900 MeV)



$$a_\mu^{\mathrm{HVP}} \cong \frac{1}{4\pi^3}\int_{4m_\pi^2}^{\infty} K(s)\sigma(e^+e^- \to \mathrm{hadrons})ds$$

Kernel function K(s) ~ $1/s^2$

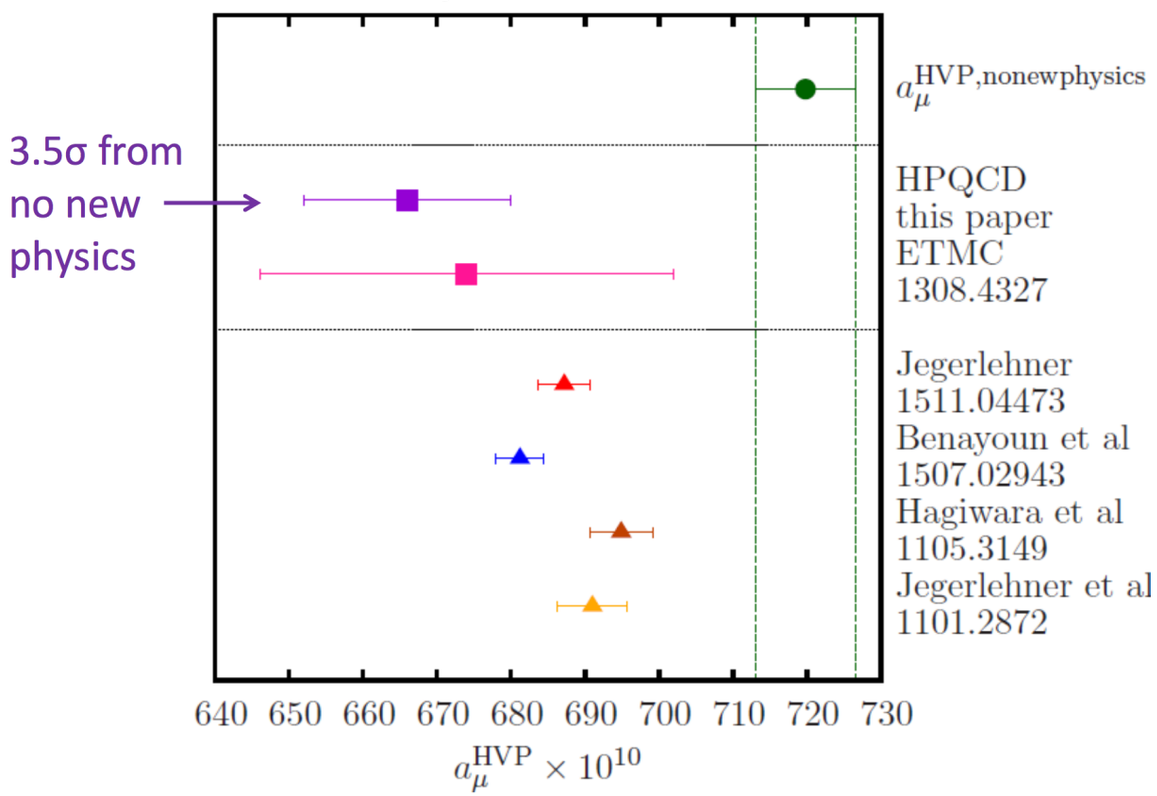


- **Lattice calculations** of a_μ^{HVP} to 1% possible, 30% for HLbL in 3—5 years

Theoretical Progress
Lattice Calculations for g-2

Lattice QCD has been making **tremendous progress**

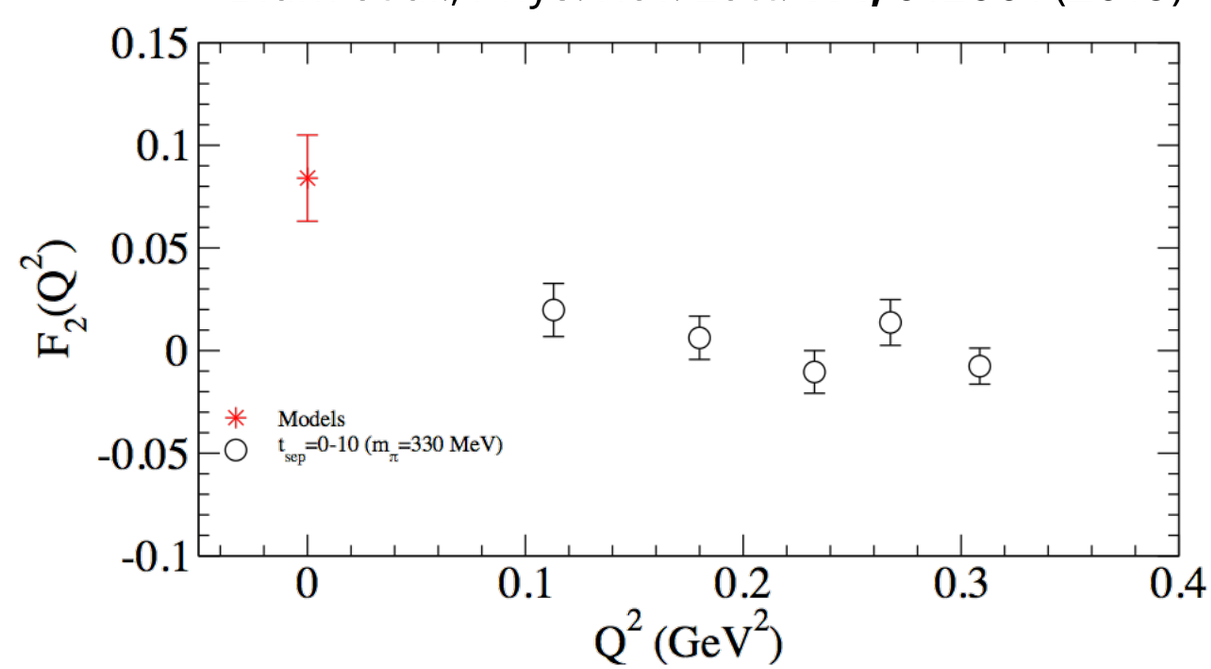
Chakraborty (ICHEP 2016)



- **HVP (LO)** calculations are converging; expect to be competitive with $e^+ e^-$

- **Initial attempts** to calculate **HLbL** by factorizing QED component

Blum et al., Phys. Rev. Lett. **114,** 012001 (2015)



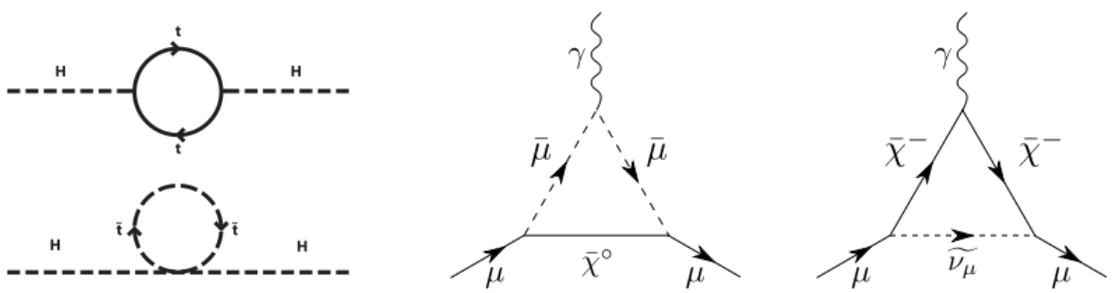
Lattice results for HVP (LO) and HLbL will have a profound impact

Motivation to Measure a_μ

- **Sensitivity to new physics**
  - SUSY [tan β, sgn(μ)] — difficult to measure at LHC
  - MSSM, UED (1D) , Littlest Higgs: similar signatures at LHC, distinguishable by Δa_μ
  - TeV-scale models
  - Dark matter
- Sensitive to flavor- and CP-conserving, chirality-flipping, loop-induced contributions
- **Independent & complementary to LHC physics**
  - Most LHC observables are chirality-conserving; complementary low-energy precision observables are CP-violating (EDMs) or flavor-violating (CLFV)
- CLFV μ–>e process depends upon mass and coupling strength of new physics (many unknowns) ; a_μ can determine nature of new physics
- Sensitive to leptonic couplings; b- and K-physics sensitive to hadronic couplings
- **Can discern between theories** that predict large/small Δa_μ
- Agreement with SM would be interesting too…

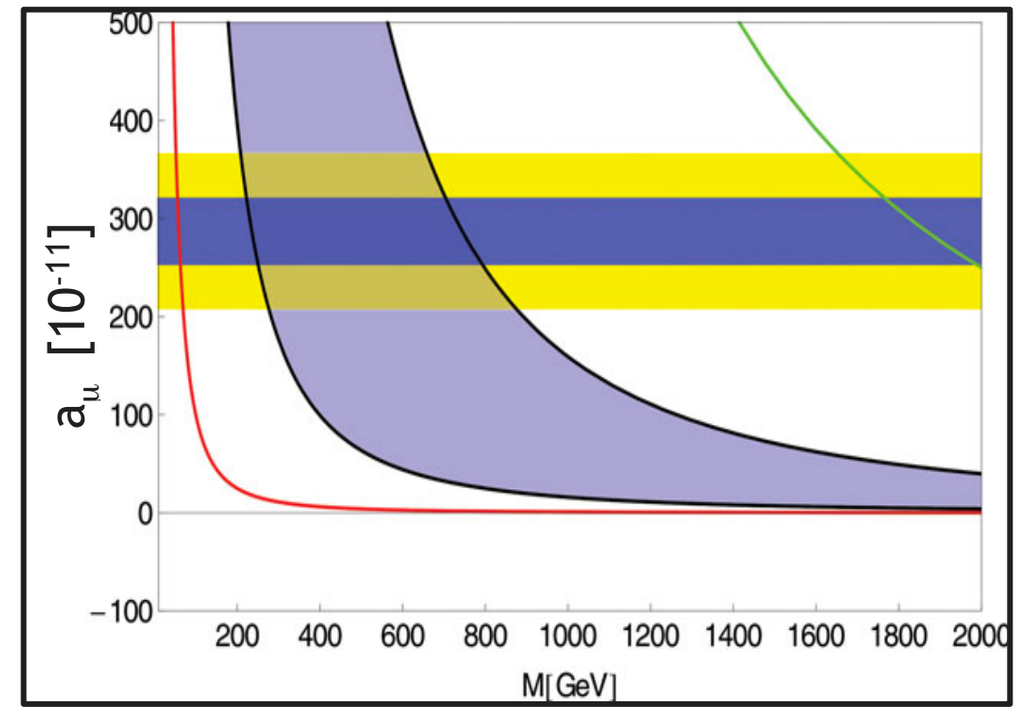
Physics Beyond SM?
SUSY, TeV-scale Models

- Higgs measured at the LHC to be ~125 GeV
- Theory: Higgs should acquire much heavier mass from loops with heavy SM particles (e.g., top quark)
  - **Supersymmetry: new class of particles** that enters such loops and **cancels this contribution**



- **Complementary to direct searches at the LHC**
  - Sensitivity to sgn(μ), tan(β)
  - Contributions to a_μ arise from charginos, sleptons
  - LHC searches sensitive to squarks, gluinos

Improved precision on a_μ will continue to constrain (or validate!) the energy scale of new models



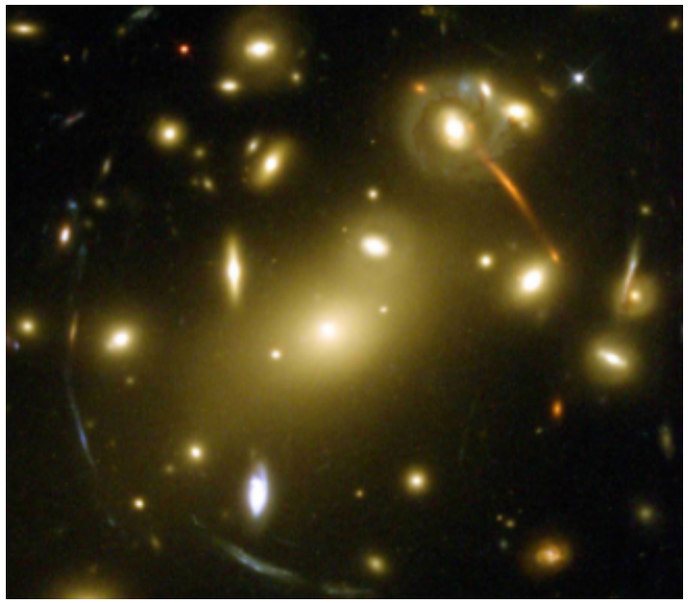
D. Hertzog, Ann. Phys. (Berlin), 2015, courtesy D. Stockinger

Z′, W′, UED, Littlest Higgs
- Assumes typical weak coupling

Radiative muon mass generation

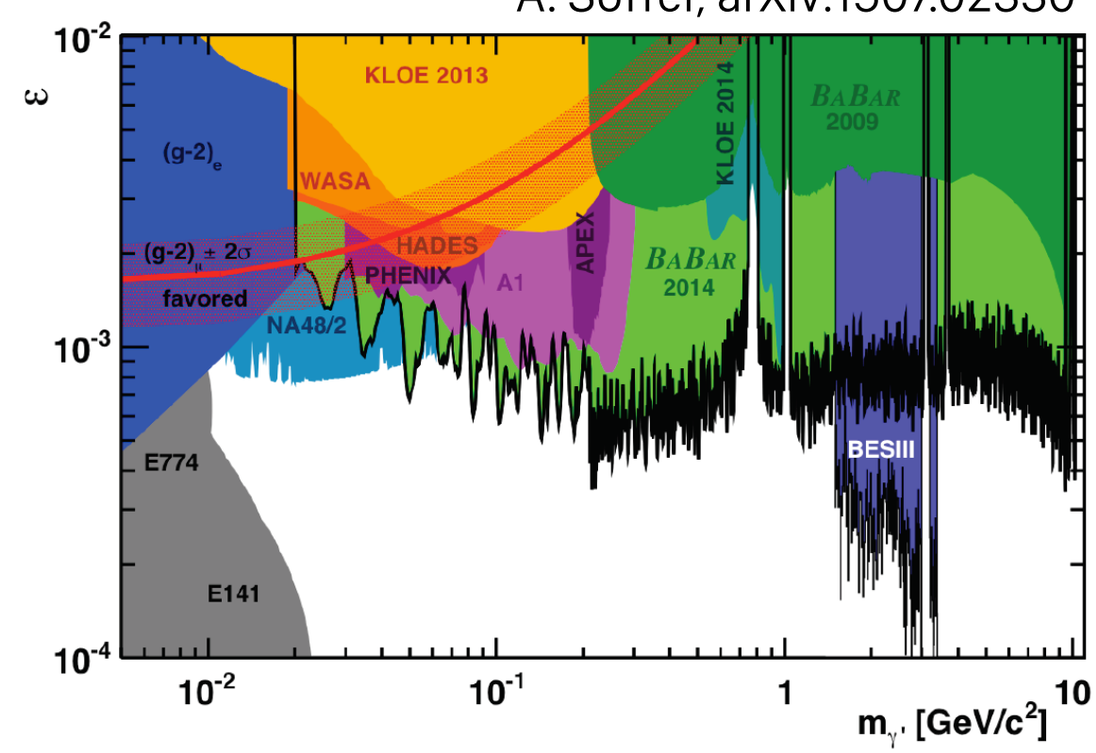
Unparticles, Extra Dimension Models, SUSY (tan β = 5 to 50)

Physics Beyond the SM? Dark Matter

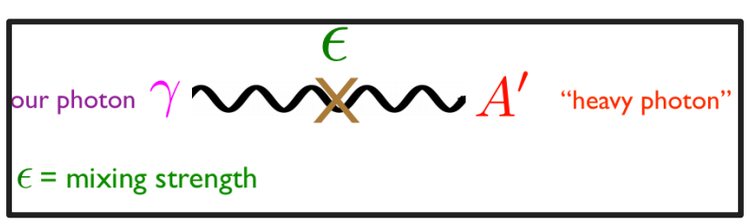


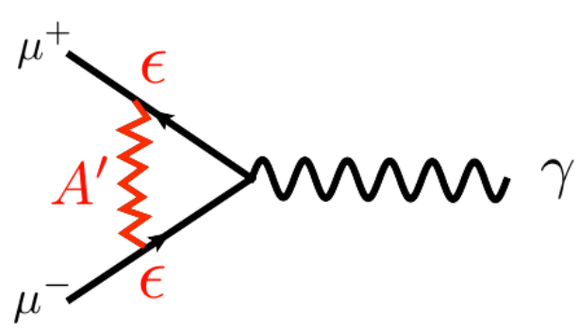
- **Dark photon** could impact the muon's magnetic moment
- Many direct-detection searches underway

A. Soffer, arXiv:1507.02330



- **Cosmological observations** (galaxy rotation curves, lensing) point to much **more mass in the universe** than expected
- Many **theories** to explain dark matter
- **A new U(1)' symmetry: dark photon A'**





ω_a Statistics

Concern for achieving required statistics

- **Need 21x more** statistics than BNL E821
- **Need 85x improvement** in integrated beam coming from many other factors

Item	Estimate
Protons per fill on target	10^{12} p
Positive-charged secondaries with $dp/p = \pm 2\%$	4.8×10^7
π^+ fraction of secondaries	0.48
π^+ flux entering FODO decay line	$> 2 \times 10^7$
Pion decay to muons in 220 m of M2/M3 line	0.72
Muon capture fraction with $dp/p < \pm 0.5\%$	0.0036
Muon survive decay 1800 m to storage ring	0.90
Muons flux at inflector entrance (per fill)	4.7×10^4
Transmission and storage using $(dp/p)_\mu = \pm 0.5\%$	0.10 ± 0.04
Stored muons per fill	$(4.7 \pm 1.9) \times 10^3$
Positrons accepted per fill (factors 0.15 x 0.63)	444 ± 180
Number of fills for 1.8×10^{11} events	$(4.1 \pm 1.7) \times 10^8$ fills
Time to collect statistics	(13 ± 5) months
Beam-on commissioning	2 months
Dedicated systematic studies periods	2 months
Net running time required	17 ± 5 months

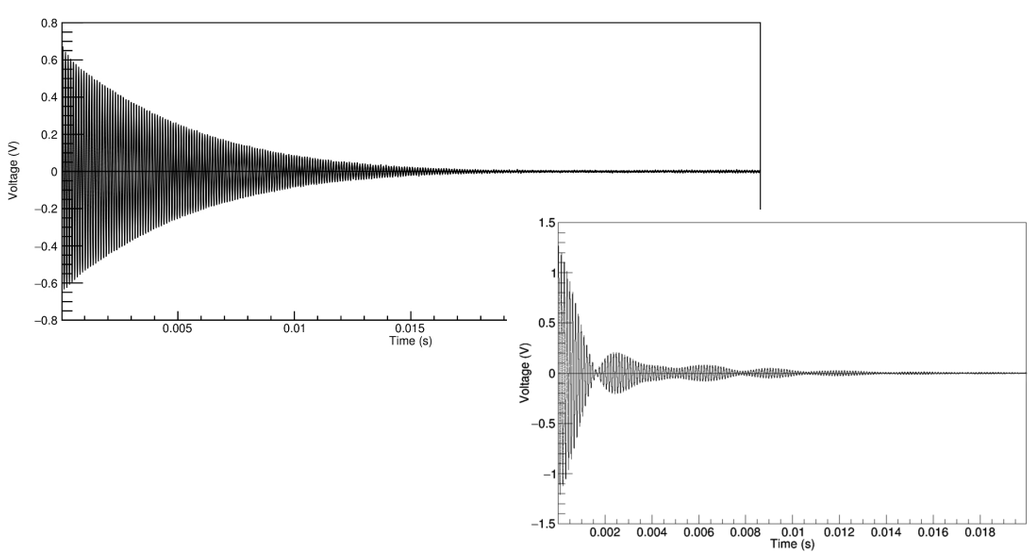
Ratio of beam powers **BNL**/**FNAL**:

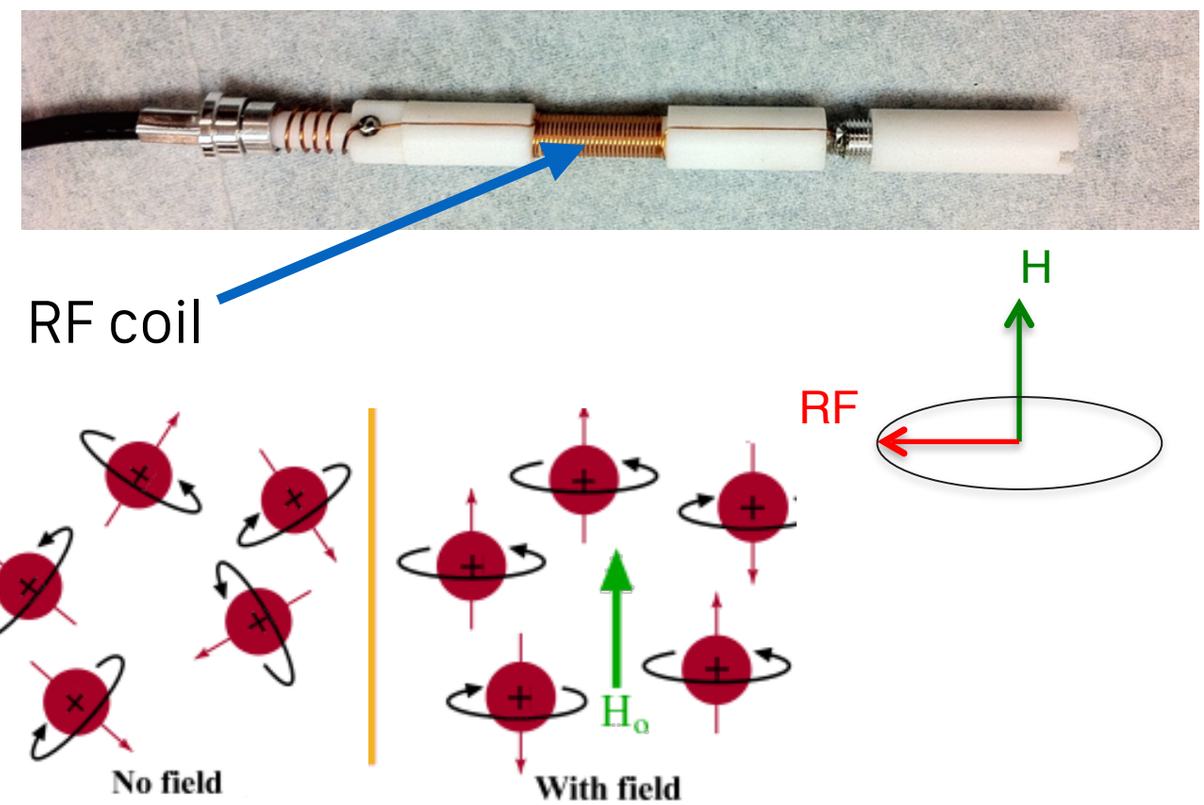
$$\frac{4\text{x}10^{12}\ \text{protons/fill x (12 fills/2.7 sec) x 24 GeV}}{1\text{x}10^{12}\ \text{protons/fill x (16 fills/1.3 sec) x 24 GeV}} = 4.3$$

Reduced beam power

Measuring the Field

- To measure the field, utilize pulsed **nuclear magnetic resonance** (NMR) on proton sample (petroleum jelly)
  - Larmor precession frequency proportional to field magnitude, gyromagnetic ratio
  - Record the free-induction decay (FID) signal
  - Extracted frequency precision: 10 parts per billion (ppb)/FID



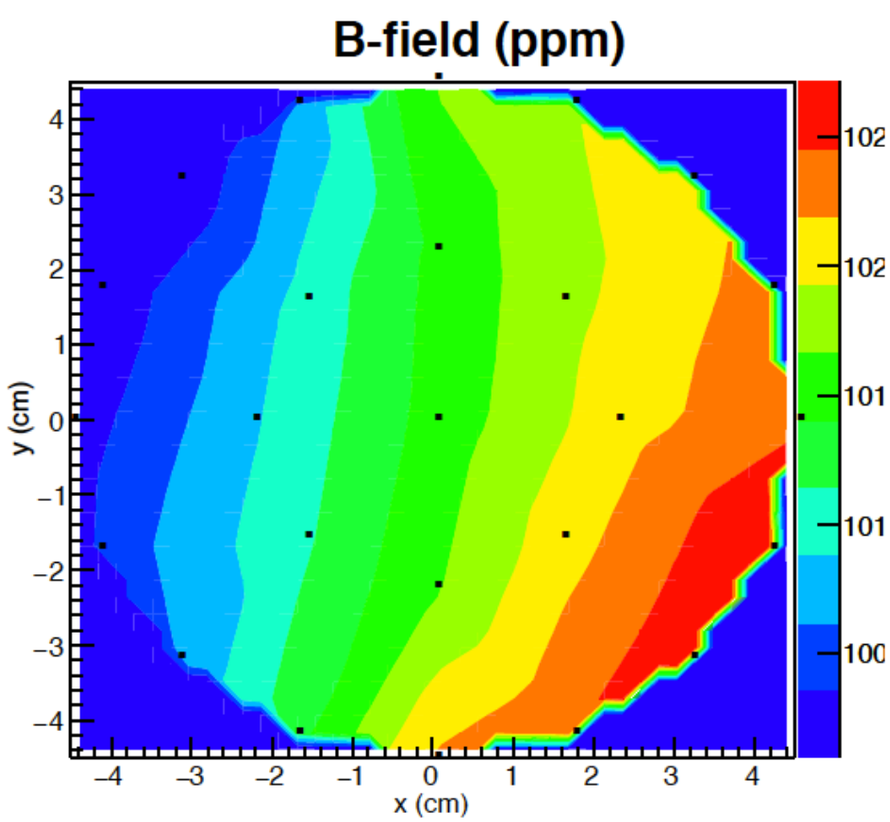


- Deliver π/2 pulse to probe, induce FID
- Precessing spins induce EMF in RF coil — this signal is amplified, mixed down to kHz and digitized
- Envelope of FID tells us about gradients in the field

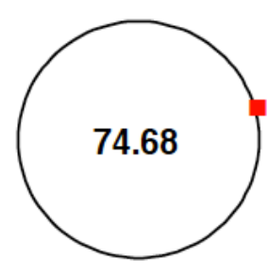
Magnetic Field
Multipole Decomposition

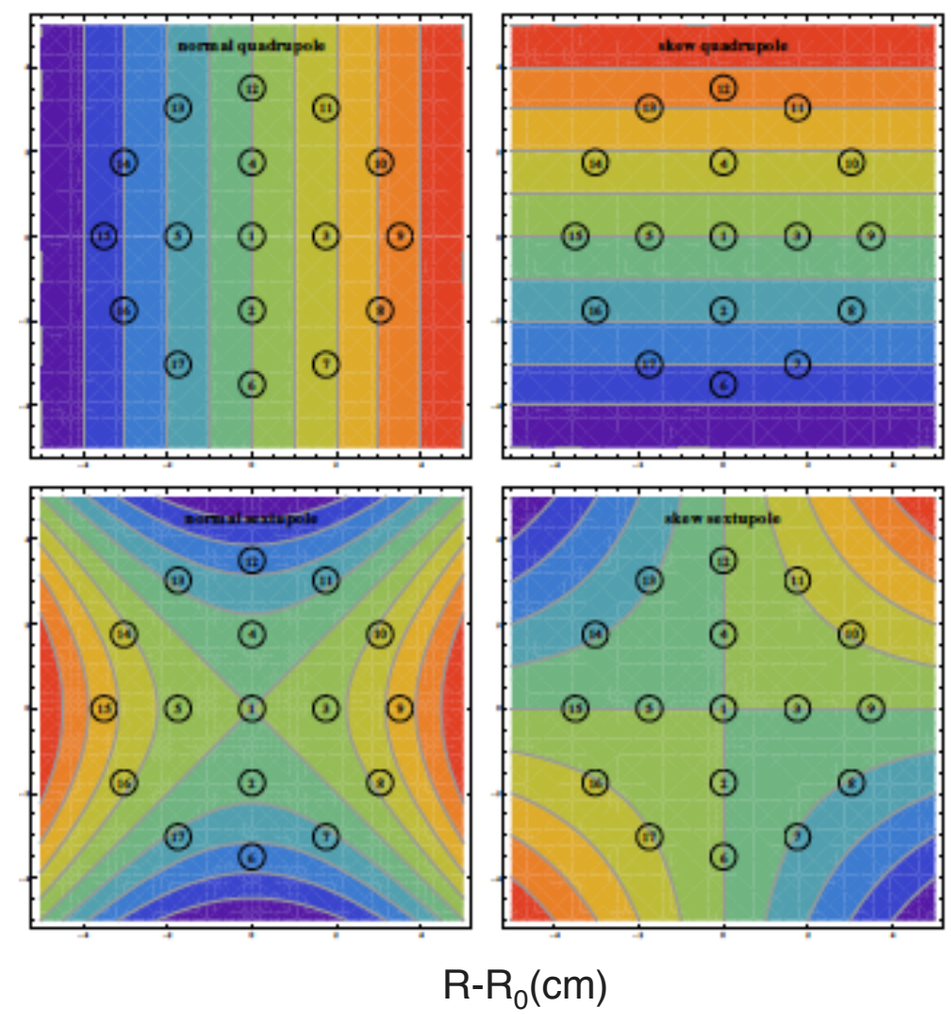
$$B(x,y) = B(r,\theta) = B_0 + \sum_{i=1}^{n} \left(\frac{r}{r_0}\right)^i \left[a_i \cos(i\theta) + b_i \sin(i\theta)\right]$$

- Sample at NMR probe locations
- Fit to sum of n-orders of multipoles
- 2D approximation for small B_r, B_θ

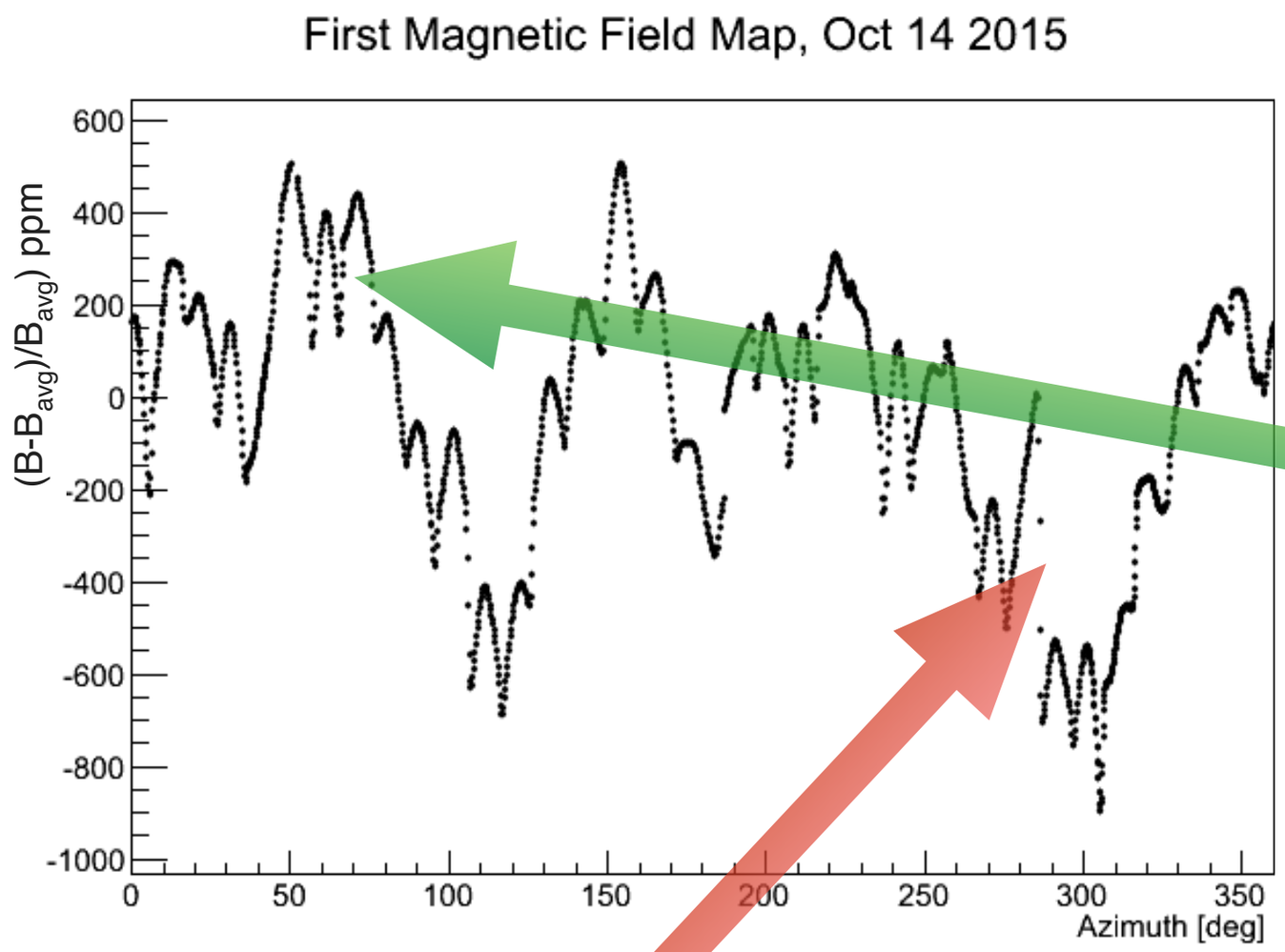


	Norm	Skew
Quad	12.56	-3.18
Sext	-2.23	-0.06
Octu	-1.43	-0.58
Decu	1.33	-0.31
Dipole	1014.9	



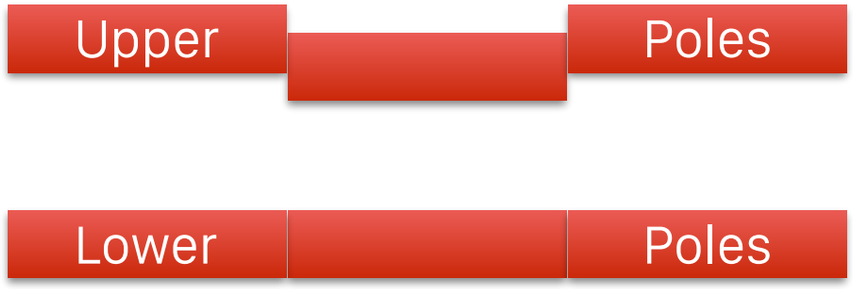


Magnetic Field Variations



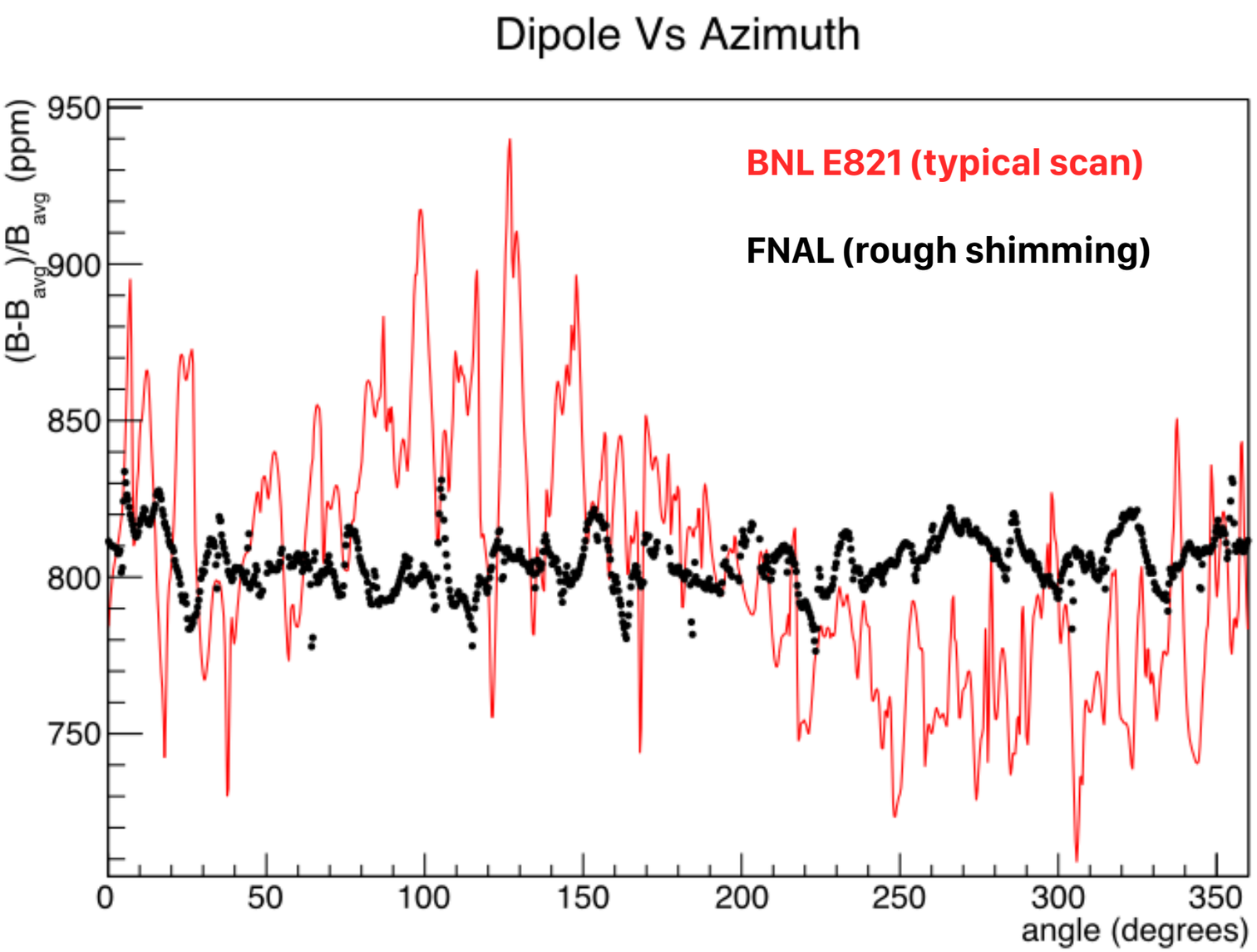
- **Gradual drift** from materials, pole gap changes
- **36 pairs of poles** => 10 degree structure
- Pole shape: 

- **Pole-to-pole discontinuities**



Magnetic Field Comparison

BNL E821 and FNAL E989



Status:

- Laminations very successful in reducing field variation
- Vacuum chamber installations proceeding

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

Absolute Calibration Procedure

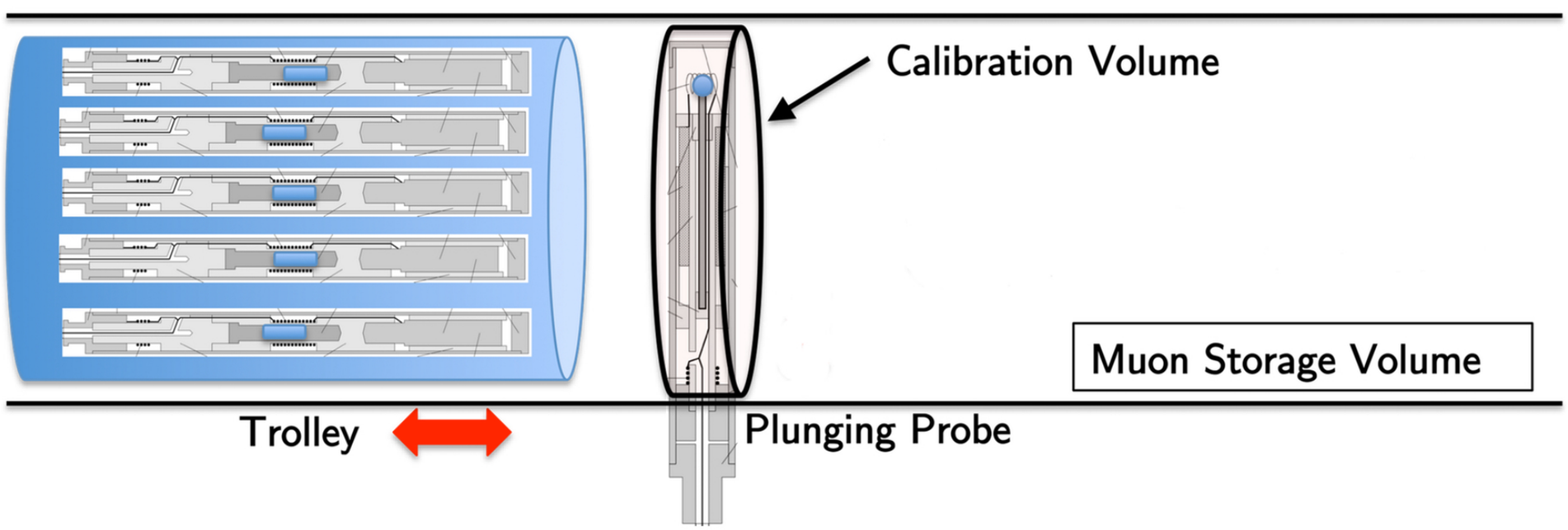
- During the experiment, **specialized runs** will be taken to **transfer** the **plunging probe** measurements to the **trolley** and **fixed** probes

    1. Move trolley into position, take measurements

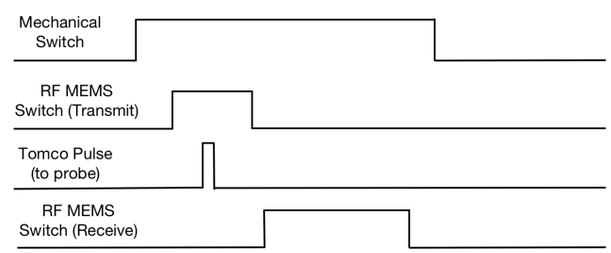
    2. Pull trolley far away; move plunging probe to a given trolley probe position, take measurements (repeat for each probe)

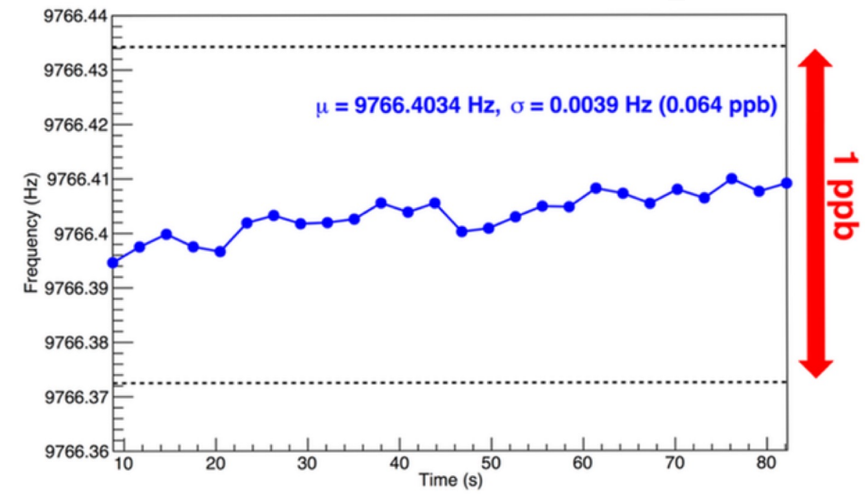
    3. Measurements made in specially-shimmed region in the ring

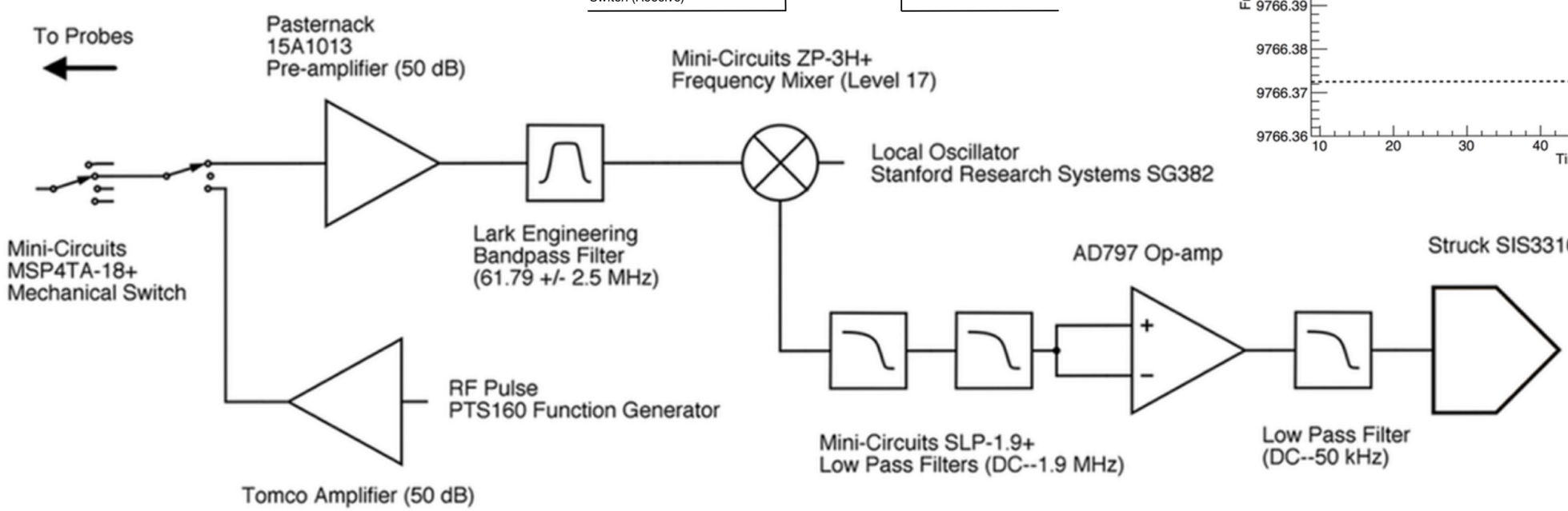
    4. Calibration accounts for probe materials perturbing the field and magnetic images

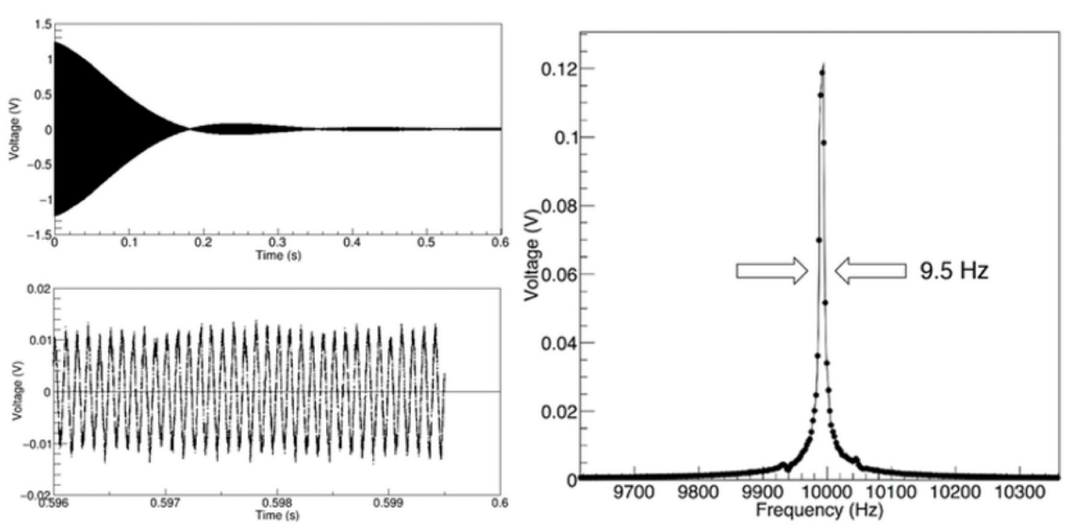


Absolute Calibration DAQ









System Characteristics

- Bandwidth: 61.79 MHz ± 50 kHz (833 ppm)
- Amplitude: ~ 1 V at t ~ 0
- RMS Noise: ~ 1 mV
- S/N: ~ 1000 at t ~ 0
- Resolution: < 1 ppb

Absolute Calibration

Material Studies

- Need to quantify field perturbations due to materials used in probes
- Measurements for many components have been performed
  - zero-χ wire: 4 ppb
  - capacitors: 3 ppb
  - super glue: 1 ppb
  - BNL probe: 45 ppb
    - Accounts for: aluminum shell, full probe, rotational symmetry
- Will do similar studies for new probes