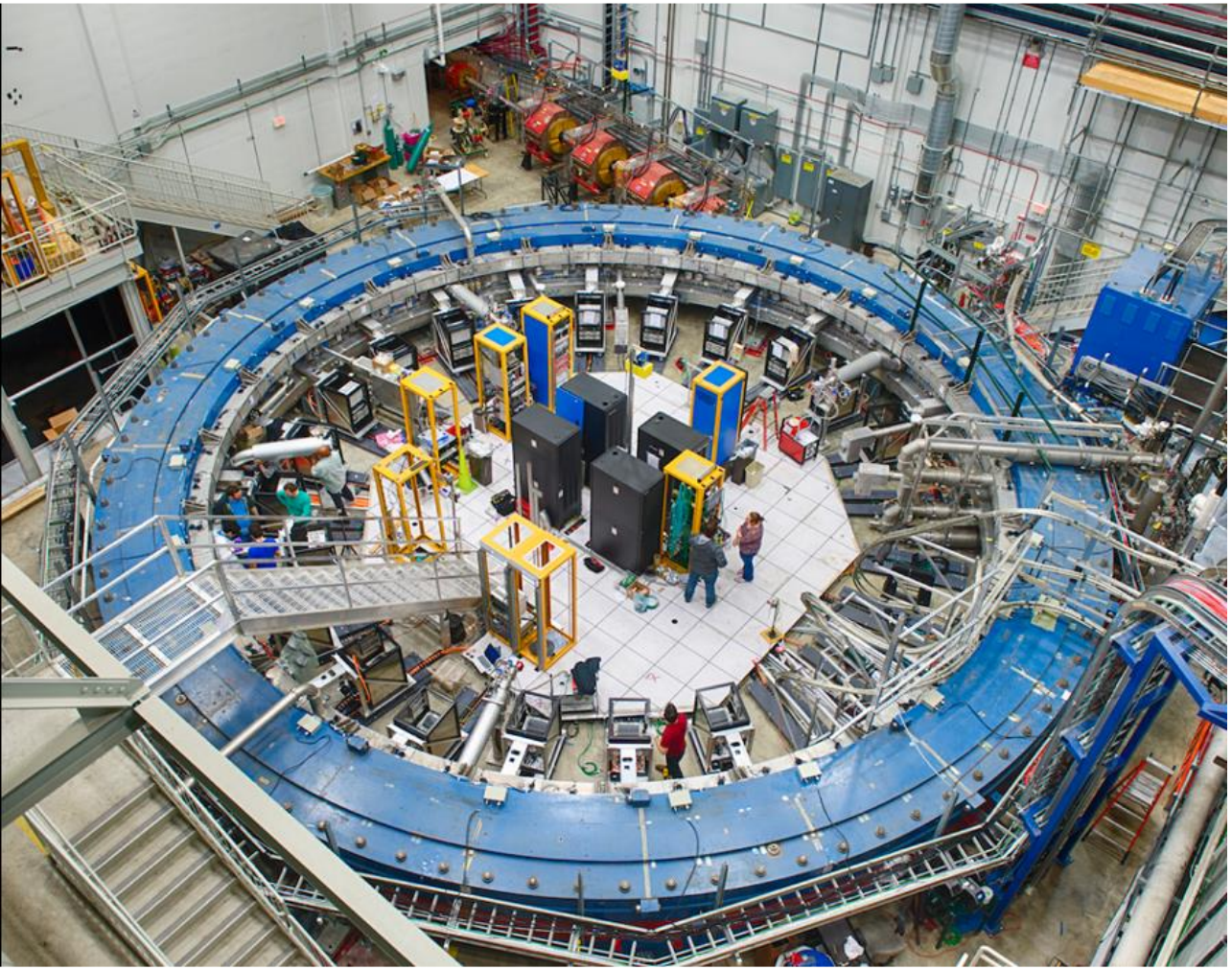


Improved understanding of the magnetic field in the Muon g-2 experiment

René Reimann for the Muon g-2 collaboration

WIN 2025

Brighton, June 10th, 2025

PRISMA+ Cluster of Excellence
Precision Physics, Fundamental Interactions and Structure of Matter

μ g-2

JOHANNES GUTENBERG UNIVERSITÄT MAINZ
JG|U

Muon magnetic anomaly

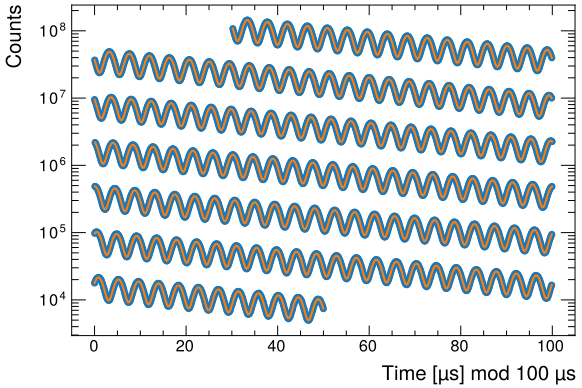
Experimental Result

Joe Price
Mon 9:30 AM

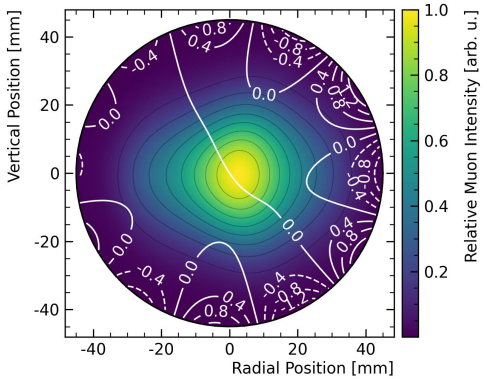
Theory Prediction

Christop Lehner
Mon 10:00 AM

muon anomalous spin-precession frequency



$$a_\mu \equiv \frac{g-2}{2} = \frac{\omega_a}{\tilde{B}} \frac{m_\mu}{e} =$$



+ correction terms

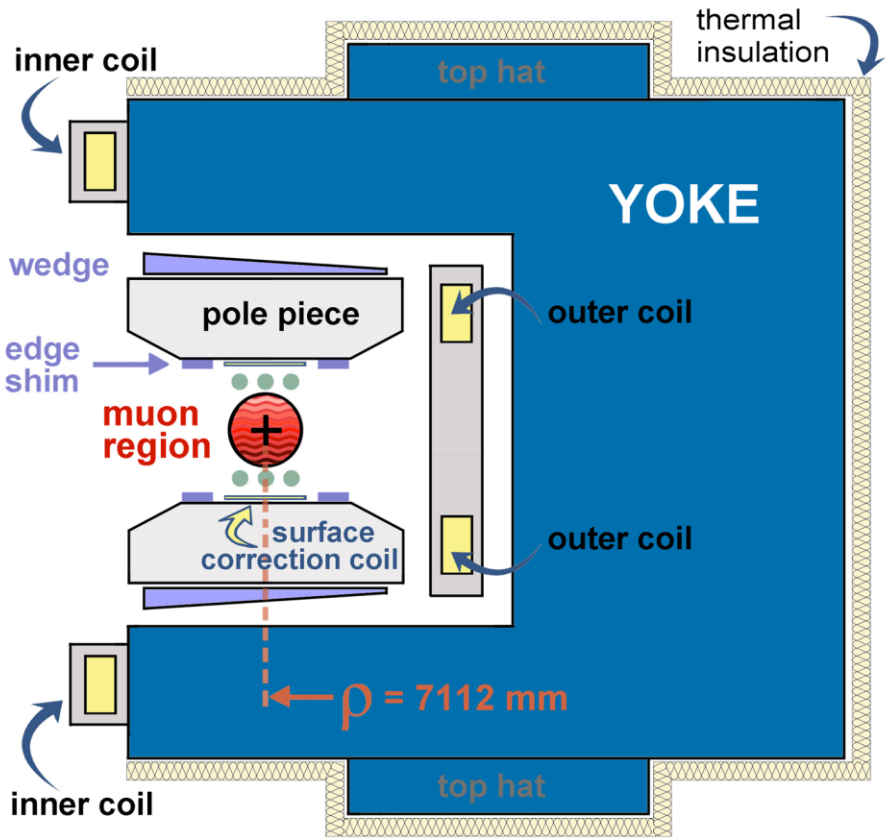
magnetic field experienced by muons

previous talk

Yonghau Zeng

this talk

Magnetic Storage Ring

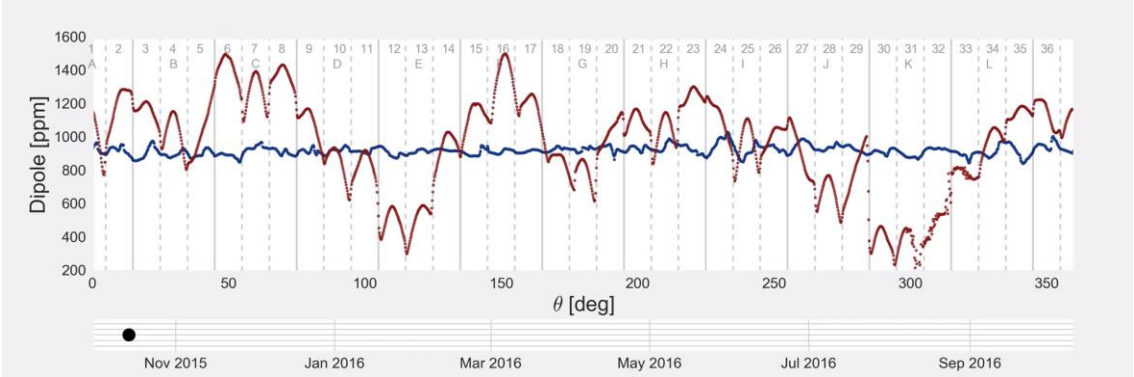


Muon storage ring creates homogeneous 1.45 T magnetic field

- C-shaped iron yoke
- Field generated by 4 super-conducting coils & iron
- Storage ring radius 7.112 m
- Shaped by adjusting pole piece & shim positions

Online magnetic field adjustments:

- Keep the field as **uniform** as possible
  - active shimming
- Keep the field as **stable** as possible
  - power supply feedback & temperature stabilization



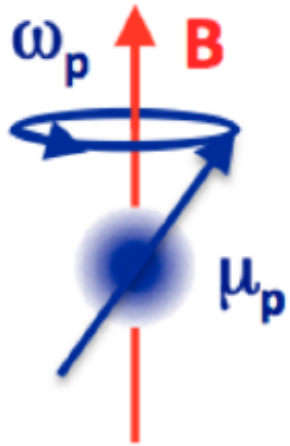
Nuclear Magnetic Resonance (NMR)

- Measure magnetic field in terms of **proton spin precession frequency**

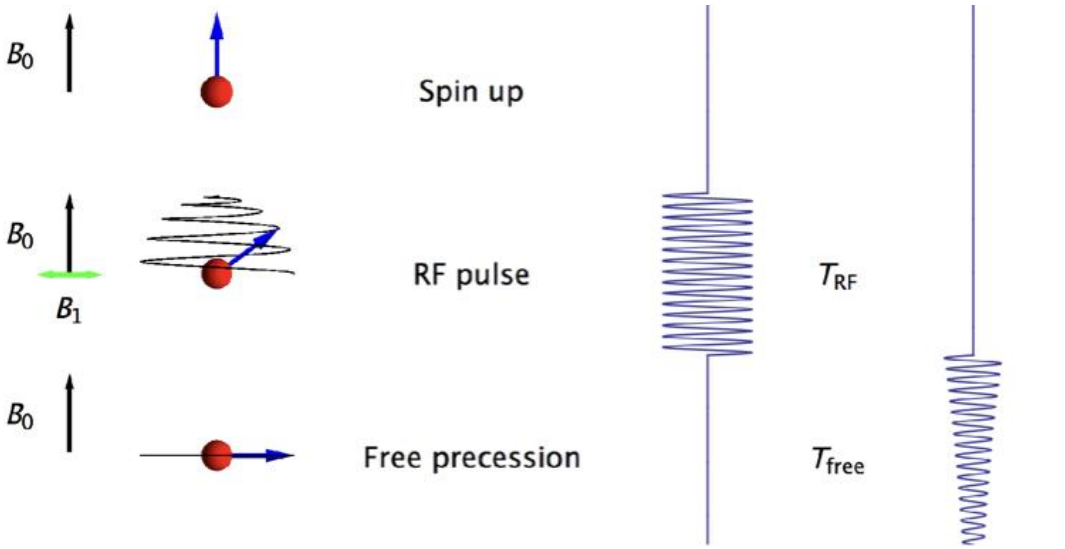
$$\omega'_p = \gamma'_p B$$

- γ'_p: gyromagnetic ratio of shielded **protons in a spherical water sample @ 25°C**

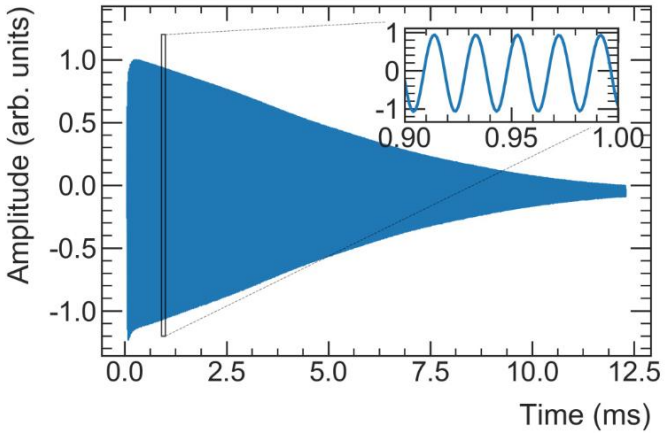
$$\gamma'_p/2\pi = 42.576\,385\,43(17)\,\mathrm{MHz/T}$$



pulsed NMR



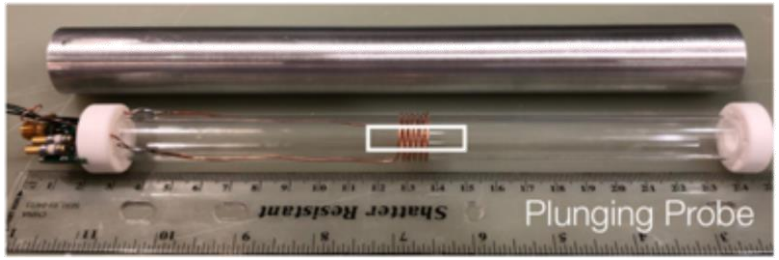
Free Induction Decay Signal



frequency at t=0
field average over active volume

Magnetic Field Sensor Systems

Absolute Calibration



1 NMR probes

absolute calibrated

twice per year

Spatial Mapping

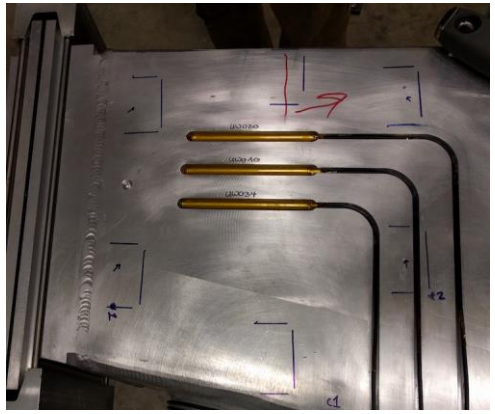
17 NMR probes

pulled through ring

every few days

measures spatial field dist.
in storage region

Tracking over Time



378 NMR probes

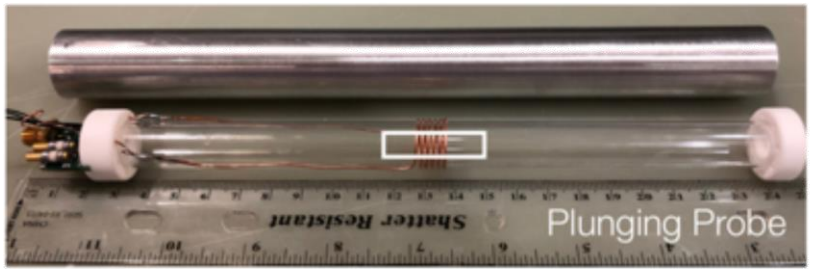
72 azimuthal locations
in vacuum chamber wall

24/7

measures field drift

Absolute Magnetic Field Calibration

Absolute water NMR probe



- Cylindrical ultra-pure water sample
- Designed to minimize material effects
- Correction for cylinder shape 1503.4 ppb (largest correction)

New Cross-Calibration

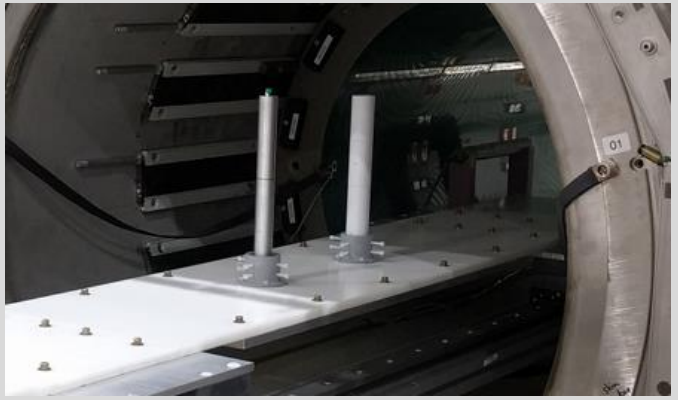
in Argonne National Laboratory MRI magnet

Absolute ^{3}He NMR probe

Hyper-polarized ^{3}He NMR probe

Consistency at 1.7σ

J-PARC Muon g-2/EDM probe

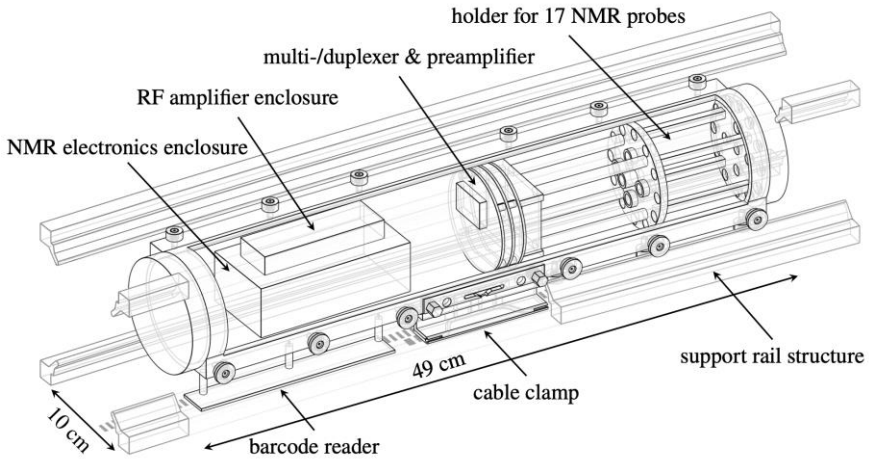


Cylindrical ultra pure water continuous wave NMR probe

Last 2 out of 4 cross-calibration in good agreement
→ *add 25 ppb uncertainty*

Independent determinations of absolute magnetic field

Calibration Transfer



- Transfer of calibration to trolley twice a year with automated procedure to each trolley probe

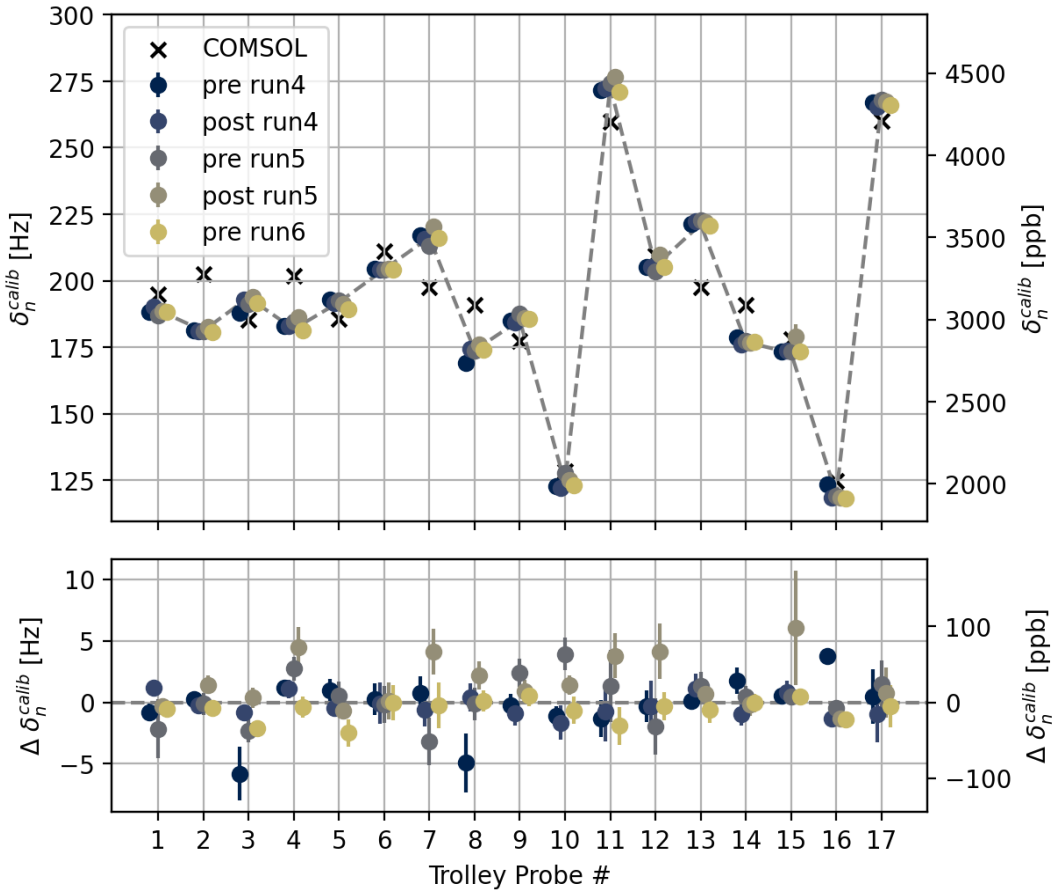
$$\omega'_n(T_r) = \omega_n^{tr}\left(1 + \delta_n^{calib}\right)$$

- *In-situ* swapping of probes

$$\delta_n^{calib} = \left(1 + \delta^{abs} + \delta_n^{trans} + \delta_n^{env}\right)$$

- Additional correction due to environmental effects, e.g. material effect of the other probe

Calibration Transfer



no significant variation over time observed

- Transfer of calibration to trolley twice a year with automated procedure to each trolley probe

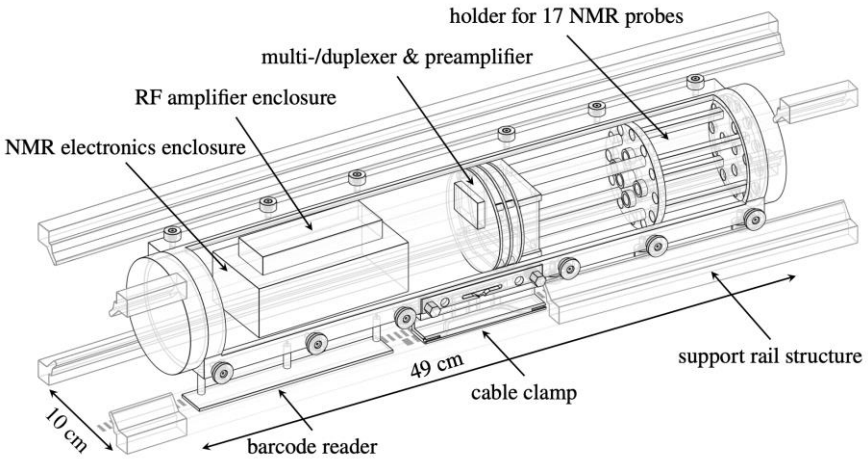
$$\omega_n'(T_r) = \omega_n^{tr}\left(1 + \delta_n^{calib}\right)$$

- *In-situ* swapping of probes

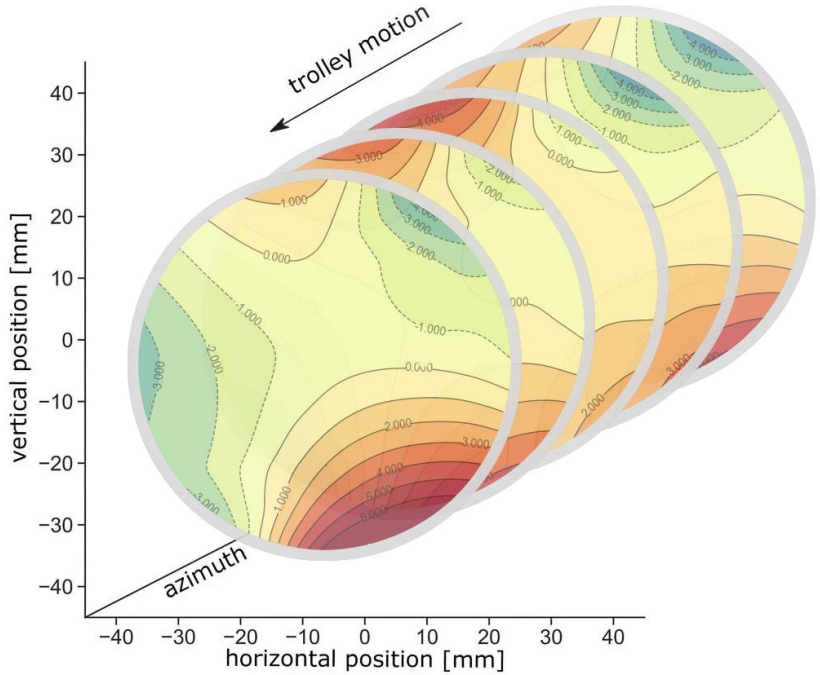
$$\delta_n^{calib} = \left(1 + \delta^{abs} + \delta_n^{trans} + \delta_n^{env}\right)$$

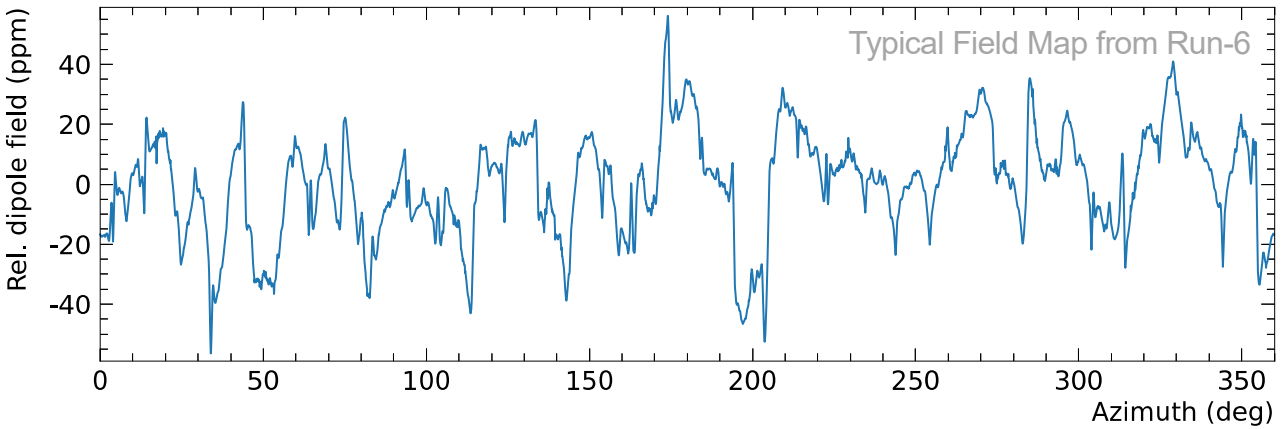
- Additional correction due to environmental effects, e.g. material effect of the other probe

Magnetic Field Maps

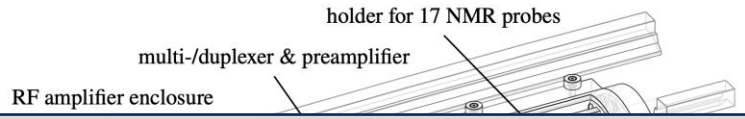


- Trolley pulled through the ring every few days
- 194 trolley maps just for production data (many more for systematic studies)
- Can only measure while muons are not present



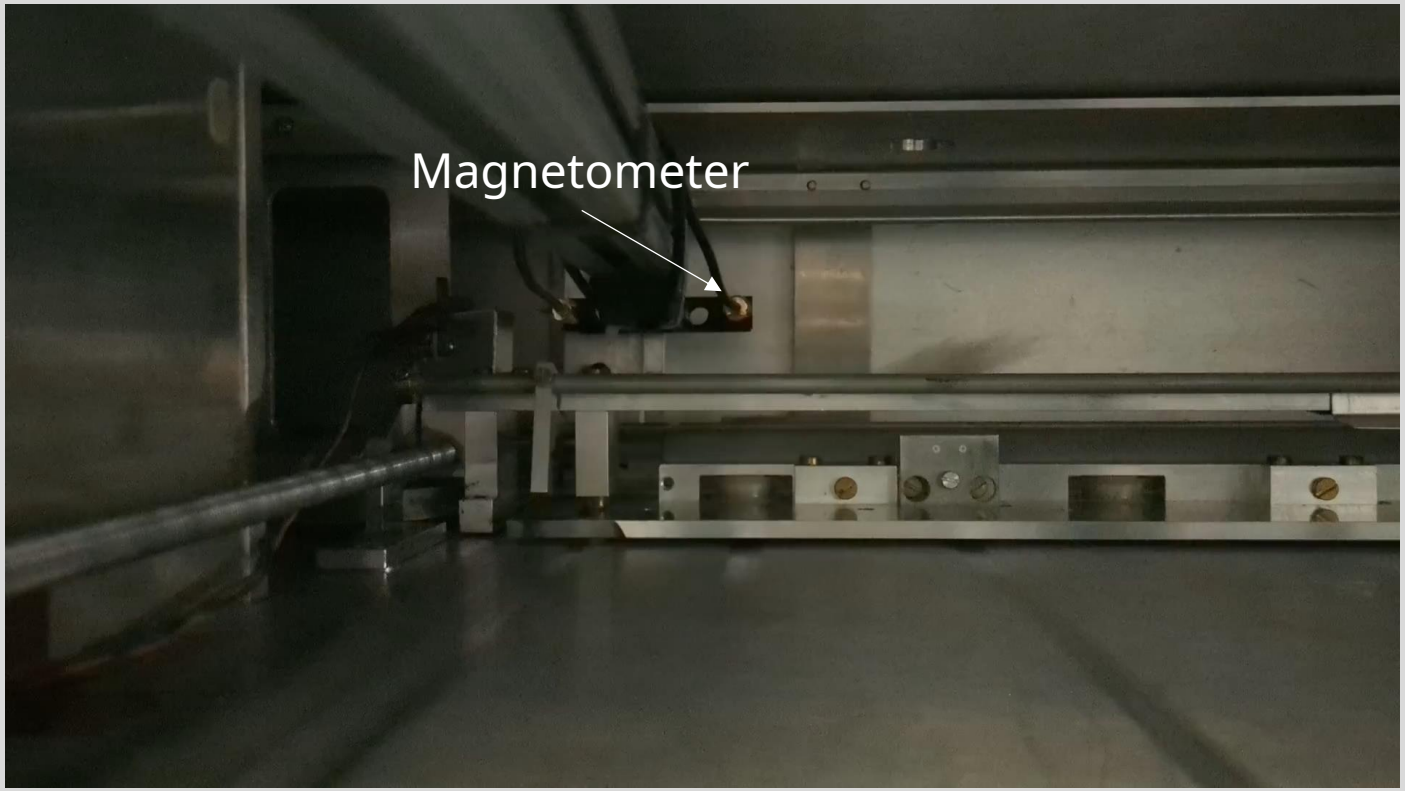


Magnetic Field Maps



- Trolley pulled through the ring every few days

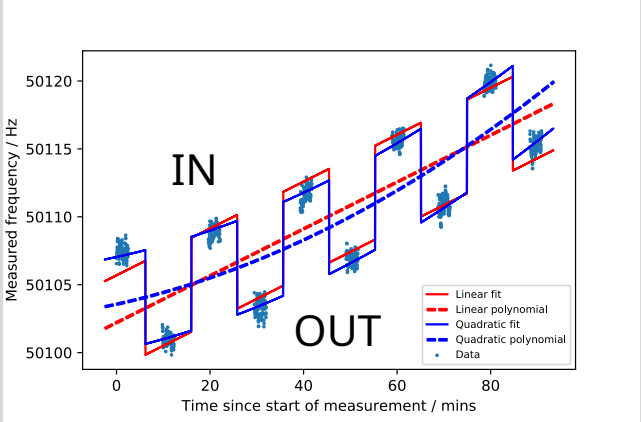
New Systematics Measurement



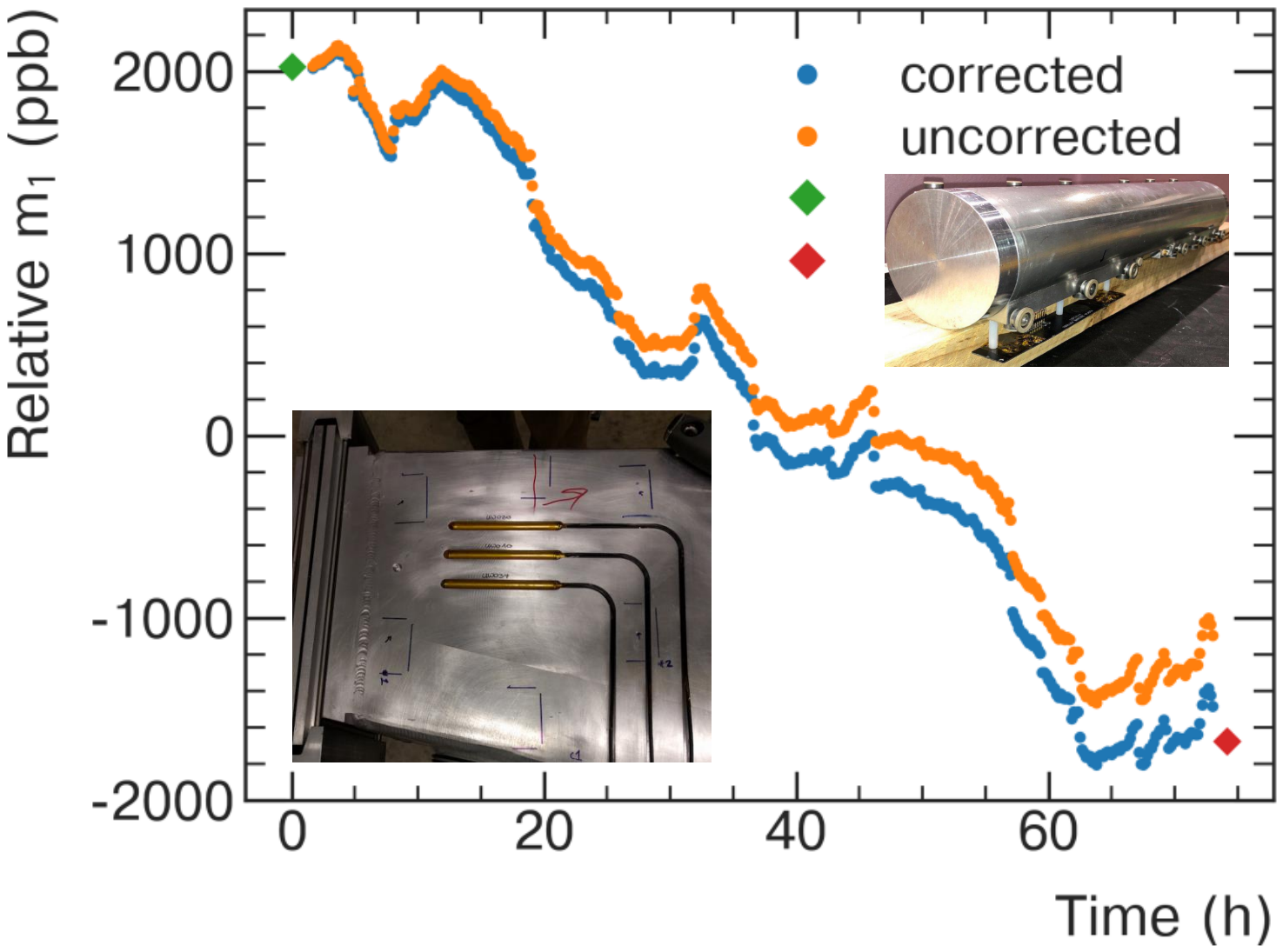
Material effect of trolley garage frame

Before from simulation only

Uncertainty reduced
22ppb → 2ppb



Magnetic field tracking



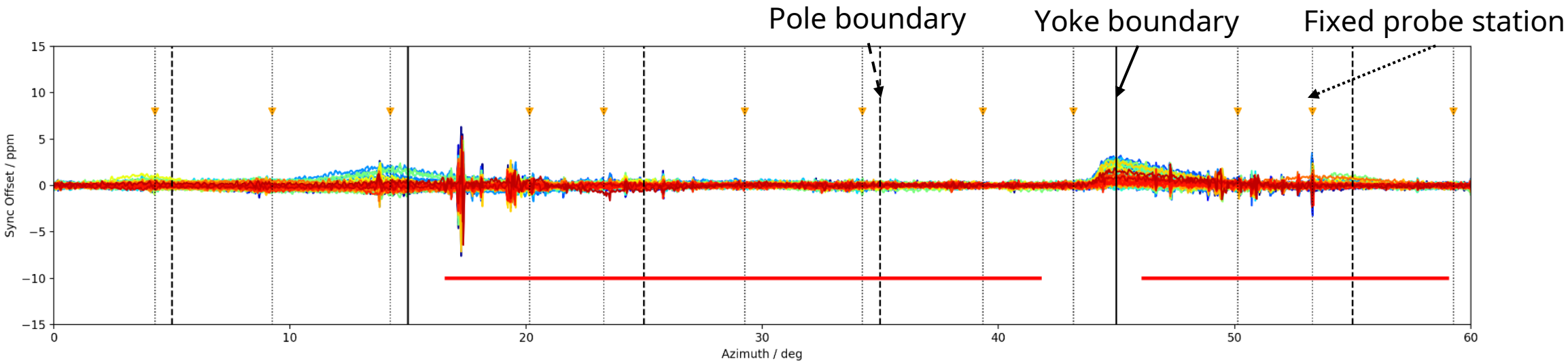
track magnetic field drift
at 72 azimuthal locations

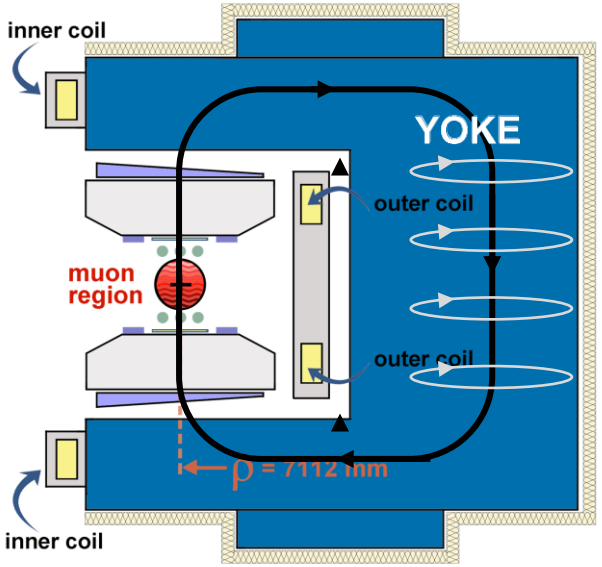
tie to magnetic field maps
(single or double ended)

untracked
field drift

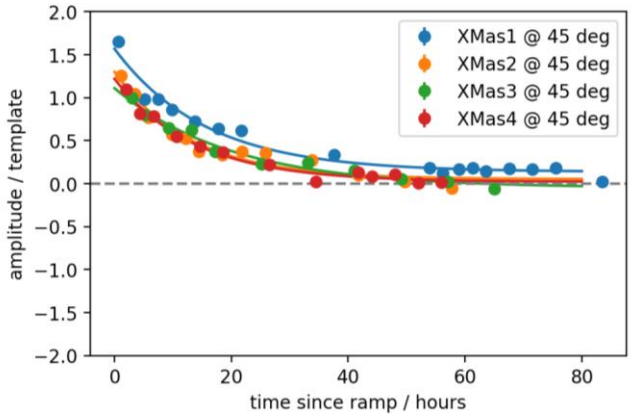
estimate tracking uncertainty

Untracked magnetic field changes



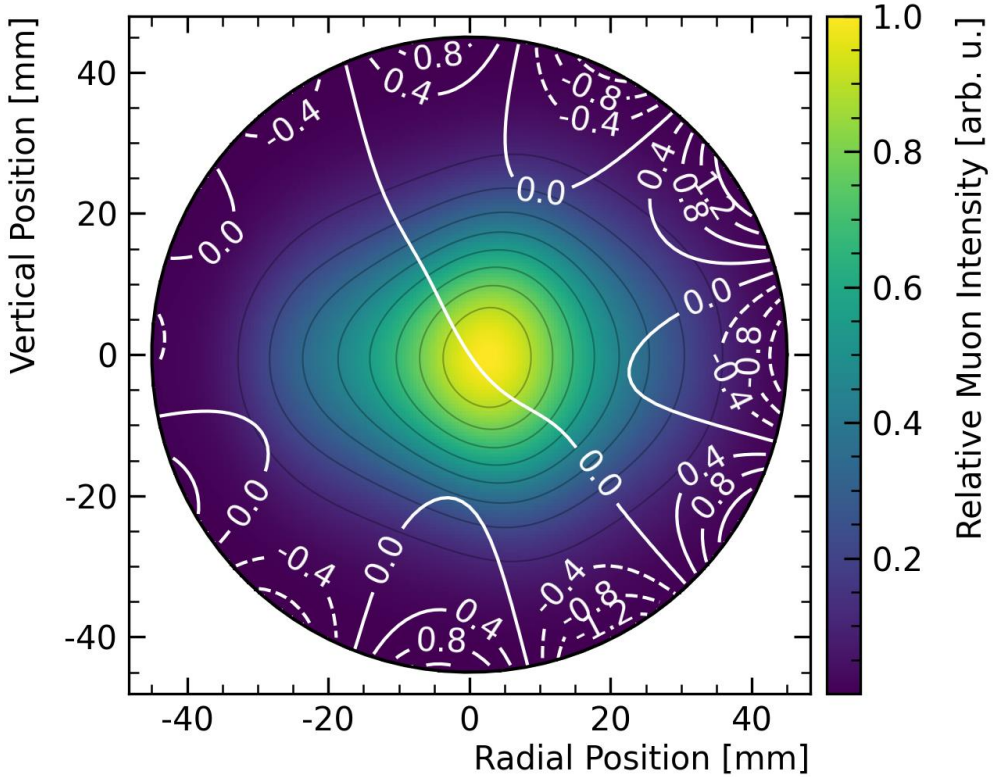


- Magnet ramp induces eddy currents in yoke
- Eddy currents differently at yoke boundaries → not tracked
- Untracked magnetic field changes have
  - consistent shape at all yoke boundaries
  - consistent time behavior over several ramps



Muon weighted magnetic field

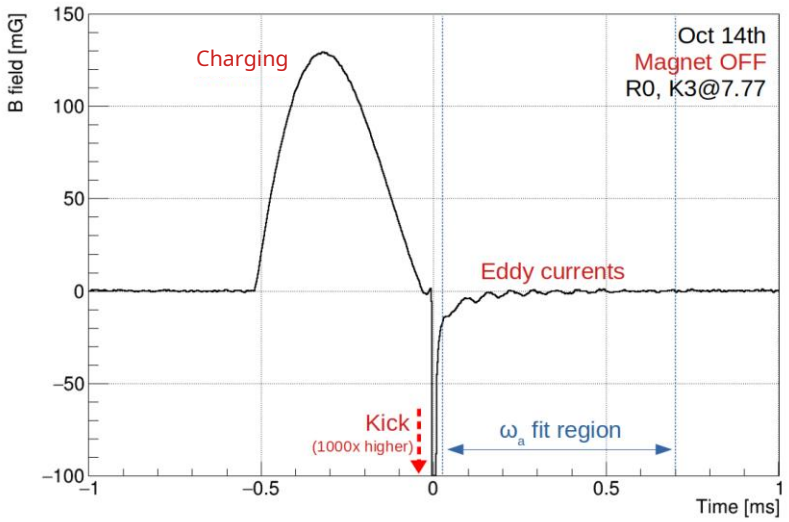
magnetic field seen by the muons

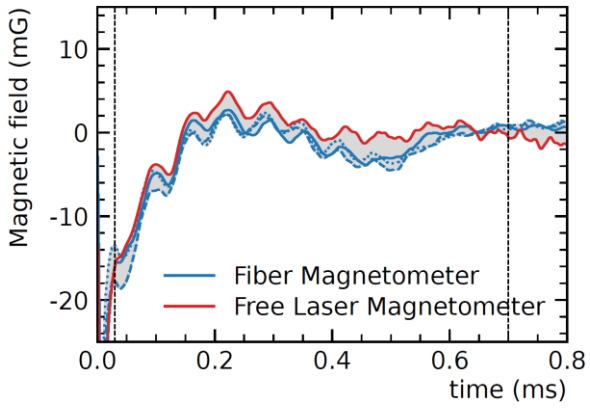


Muon distribution determined
by tracker data & beam dynamics simulation

Kicker Transient Magnetic Field

- Kicker used to place beam on storage orbit

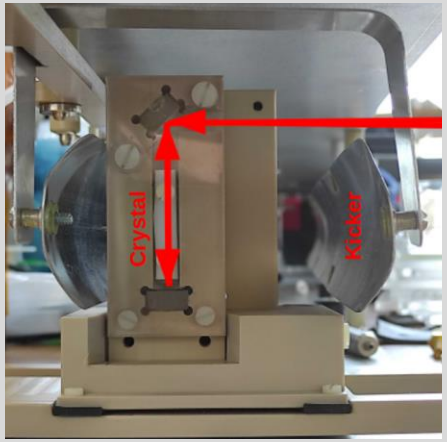




- Kick pulse induces eddy currents
- Synchronized with beam injections
- **Measurement based on Faraday rotation** in TGG crystal

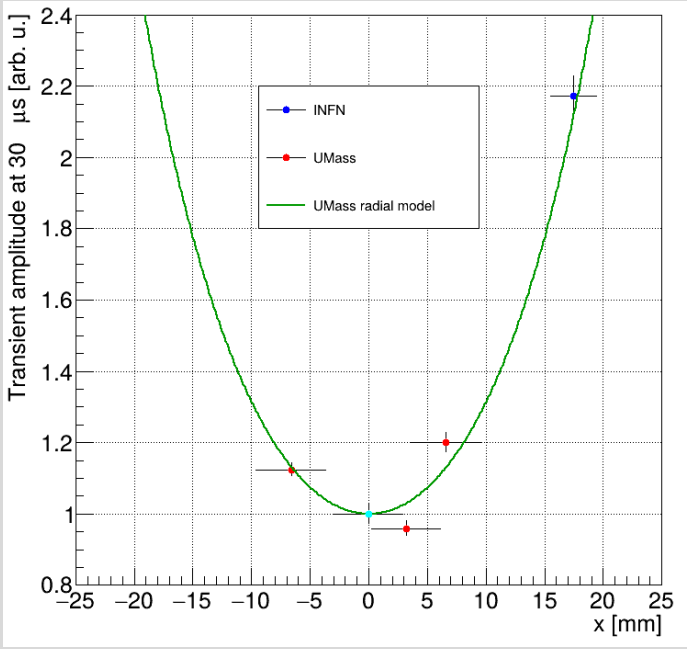
Fiber magnetometer

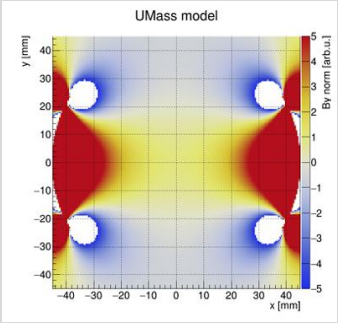
Free laser magnetometer

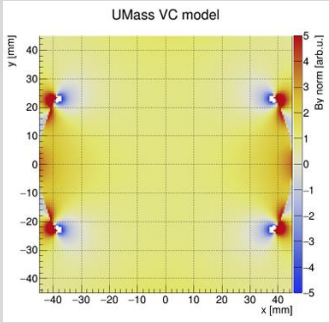


Kicker Transient Magnetic Field

New spatial model







New measurement point at r=+17.5mm

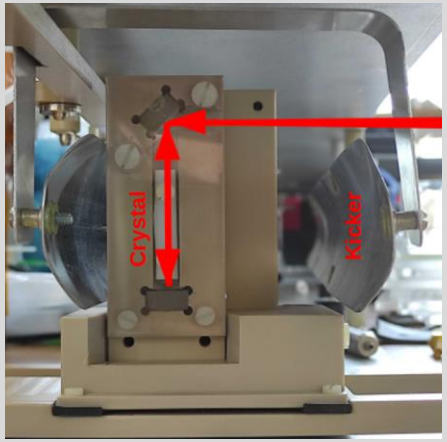
Observed strong radial dependence

Eddy currents in kicker plates & vacuum chambers modify spatial model

Analytic model & studied with mock setup

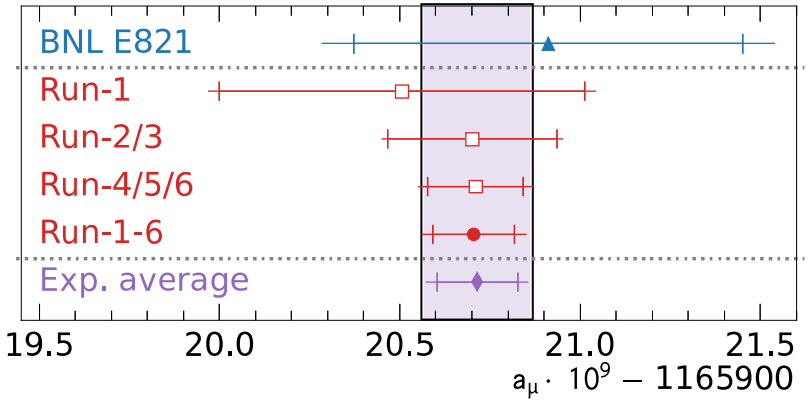
Fiber magnetometer

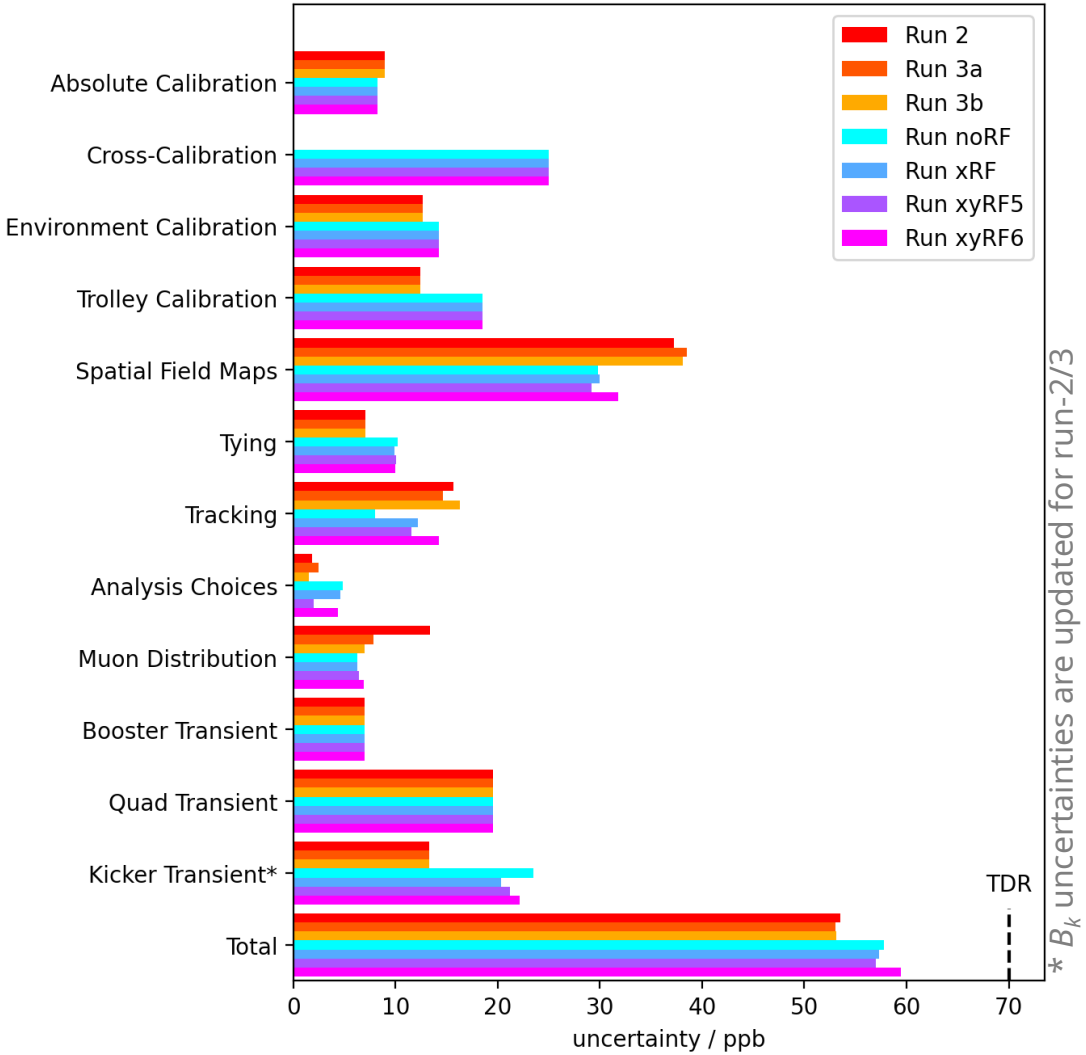
Free laser magnetometer



Conclusion

- Three magnetic sensor systems based on NMR
  - for absolute calibration
  - for spatial mapping
  - for 24/7 tracking
- Most systematic uncertainties were already excellent in run-2/3 publication
- Several additional devices, systematic studies, cross-checks & cross-calibrations
- Magnetic field systematic of 56 ppb surpassed TDR design goal of 70 ppb
- Key for





Thanks to the funding agencies

- Deutsche Forschungsgemeinschaft (Germany)
- European Union's Horizon 2020
- PRISMA+ Cluster of Excellence
- Department of Energy (USA)
- National Science Foundation (USA)
- Istituto Nazionale di Fisica Nucleare (Italy)
- Science and Technology Facilities Council (UK)
- Royal Society (UK)
- Leverhulme Trust (UK)
- Strong 2020 (EU)
- National Natural Science Foundation of China
- MSIP, NRF and IBS-R017-D1 (Republic of Korea)

PRISMA+ Cluster of Excellence
Precision Physics, Fundamental Interactions and Structure of Matter

Backup

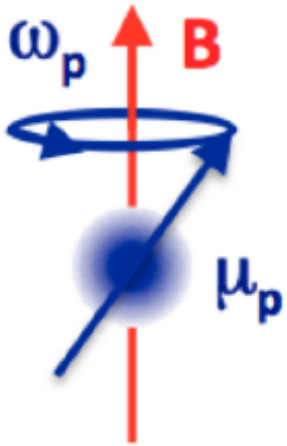
Nuclear Magnetic Resonance (NMR)

- Measure magnetic field in terms of **proton spin precession frequency**

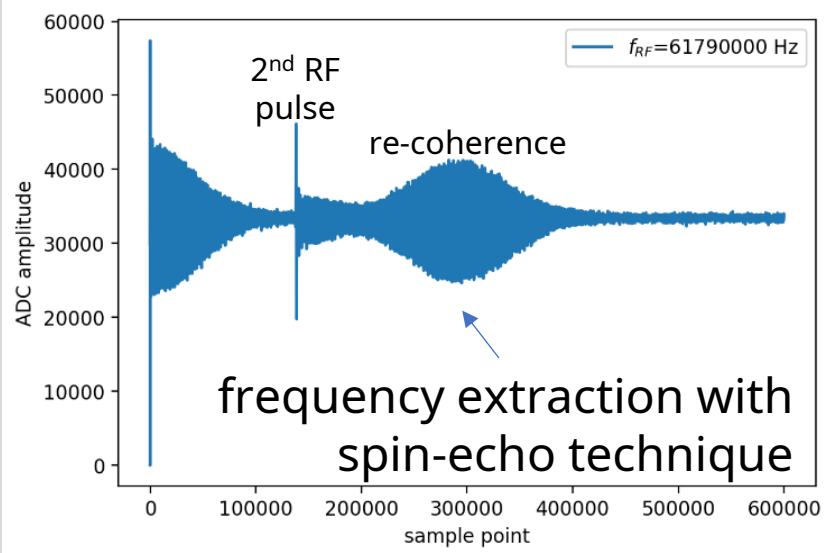
$$\omega'_p = \gamma'_p B$$

- γ'_p: gyromagnetic ratio of shielded **protons in a spherical water sample @ 25°C**

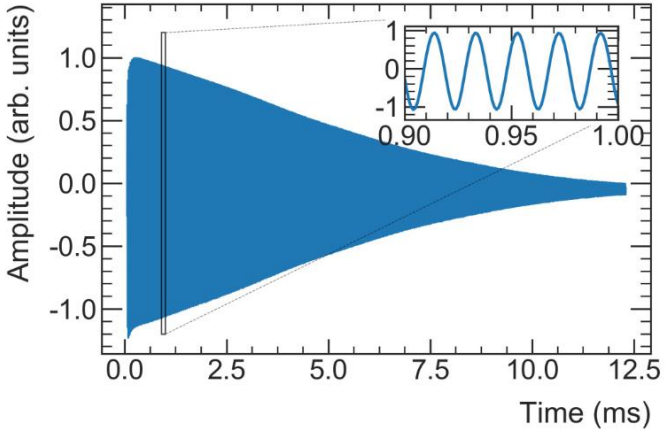
$$\gamma'_p/2\pi = 42.576\,385\,43(17)\ \mathrm{MHz/T}$$



New Cross-Check



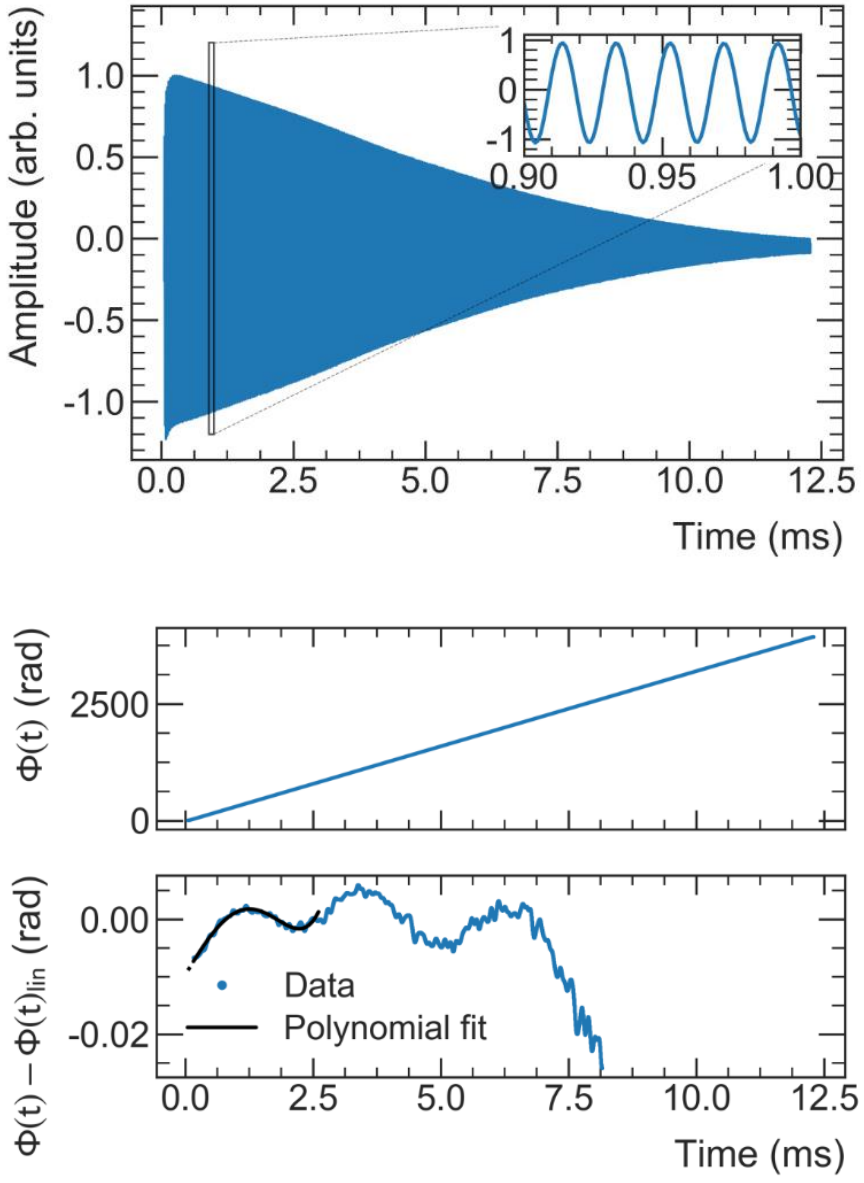
Free Induction Decay Signal



frequency at t=0
field average over active volume

Free Induction Decay

- At 1.45 T field proton spin precession frequency if about 61.79 MHz
- Mixed down frequency to ~50kHz for digitization
- Free induction decay signal oscillates at Lamor frequency
- Decoherence of spins in sample lead to envelop decay
- Using Hilbert transformation to extract phase
- Frequency is given by slope of phase at time t=0
- Subtract template → measure field differences

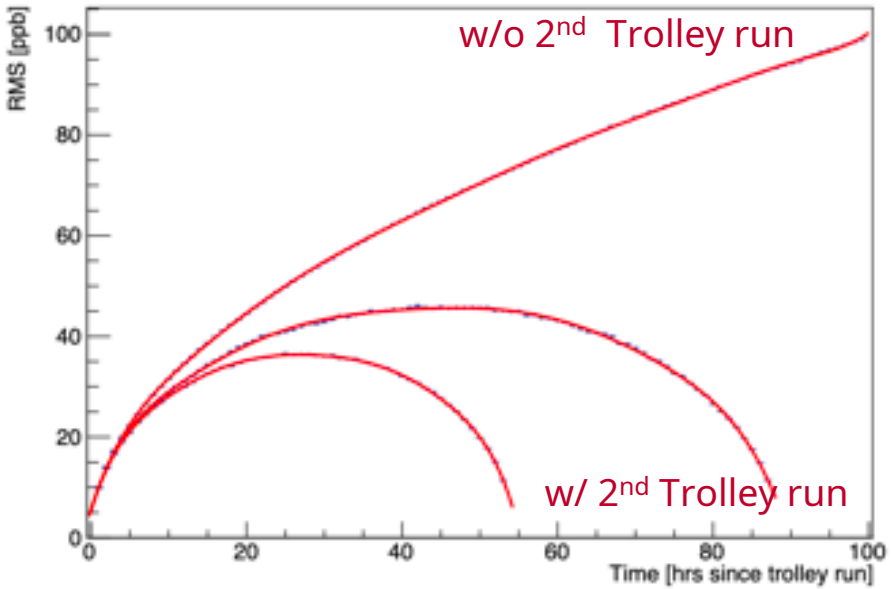


Tracking Uncertainty

Characterization of untracked magnetic field changes

Random Walk Model

Fixed Probes do not track higher order moments field changes



Magnetic field uncertainty time dependent

New Model

Observed untracked magnetic field changes not dependent on time

Magnetic field changes dominated by trolley measurement effects, e.g. motion

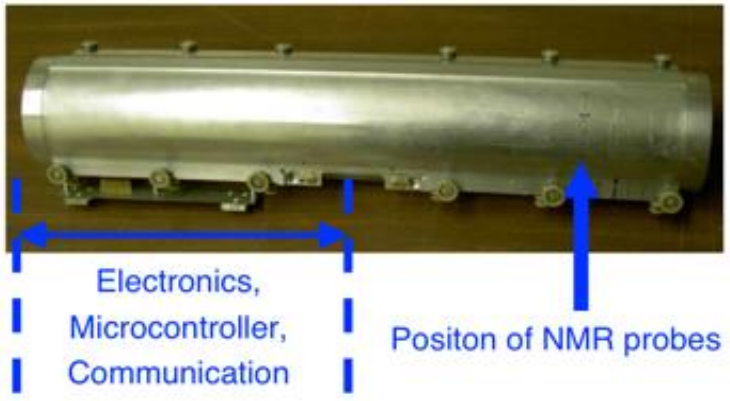
Magnetic field uncertainty time independent

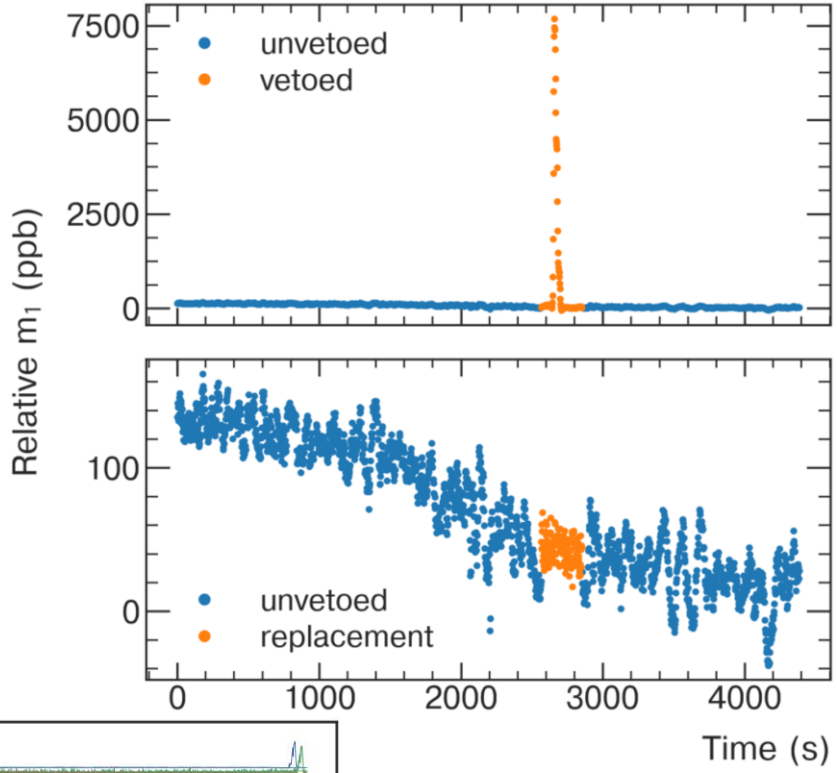
Both models give consistent uncertainties

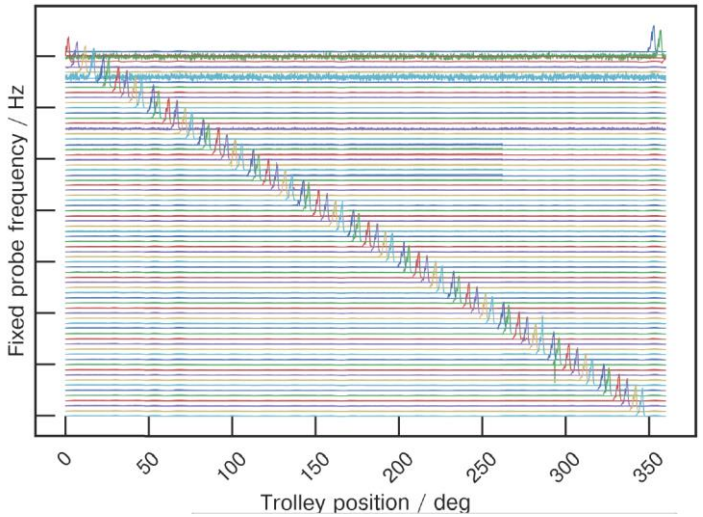
Both models reduce with additional magnetic field maps

Trolley Footprint Removal

Phys. Rev. A **103**, 042208 (2021)







- trolley electronics disturbs field (footprint)
- veto measurements
- interpolate from neighboring probes

Comparison Analysis Teams

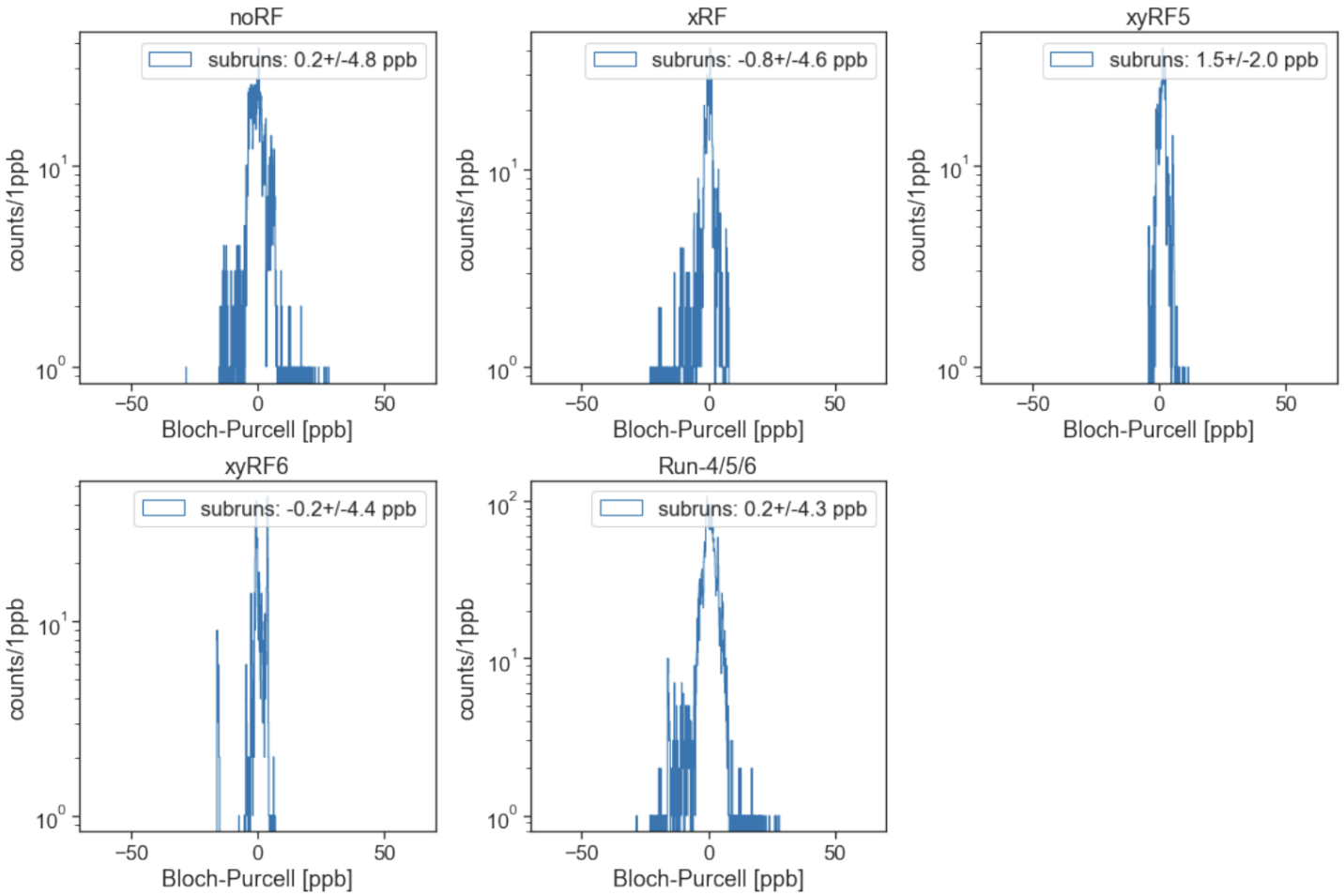


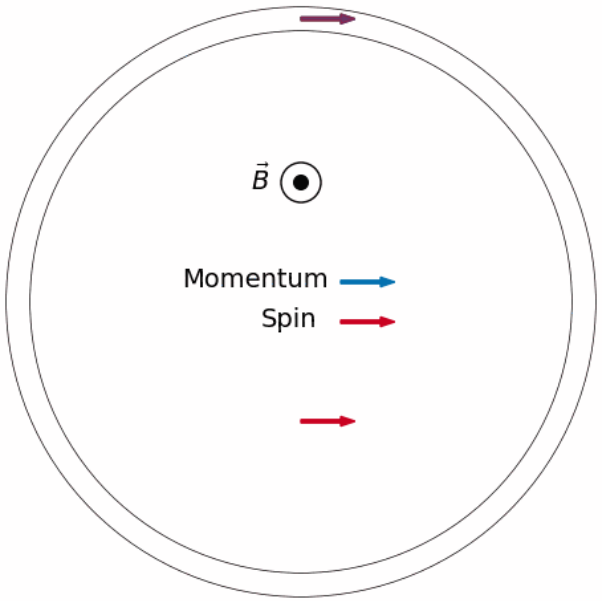
Figure 26: $\tilde{\omega_p}'$ differences between Bloch-Purcell per run-group for the different datasets.

Muon in a homogeneous magnetic field

Cyclotron Motion

centrifugal force = Lorentz force

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



Spin Precession

magnetic moment and field couple

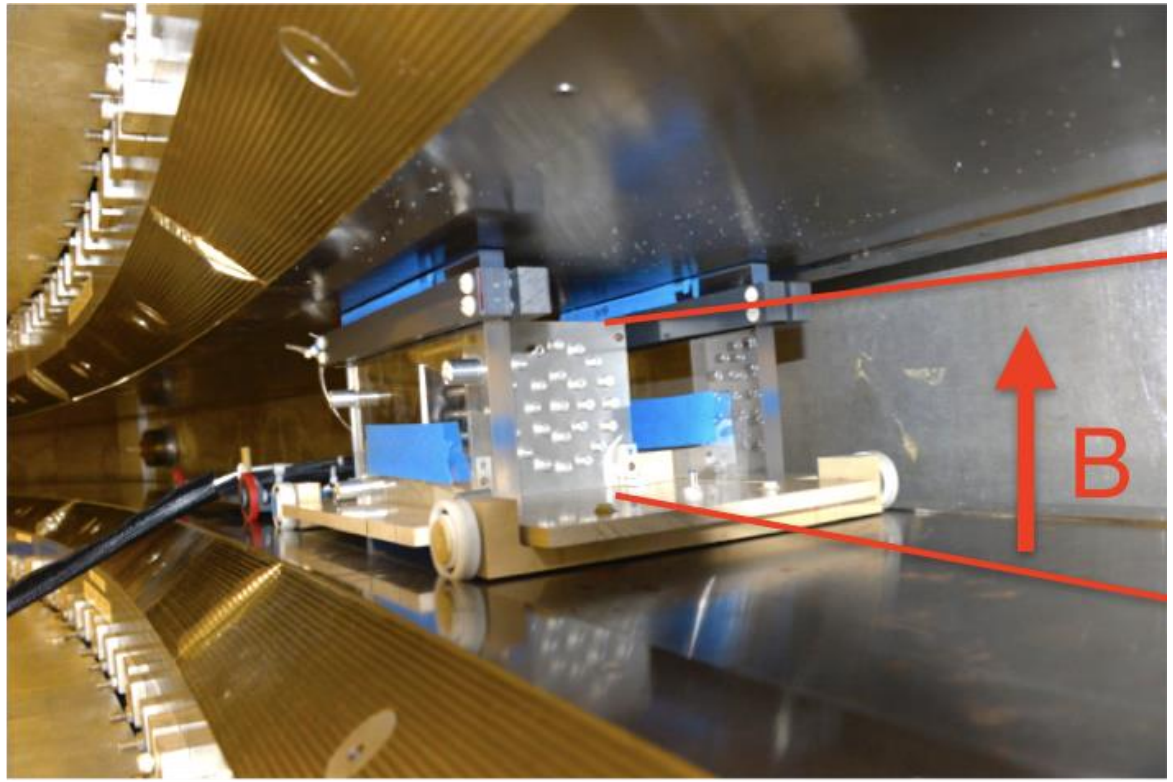
$$\vec{\omega}_S = -g\frac{e}{2m}\vec{B} - (1-\gamma)\frac{e}{\gamma m}\vec{B}$$

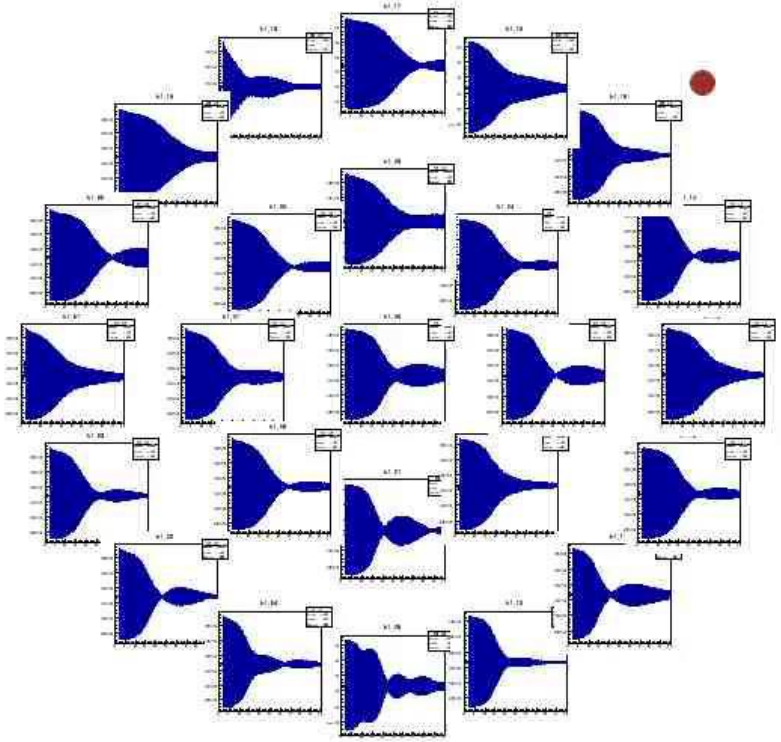
$$\underbrace{\omega_s - \omega_c}_{\omega_a} = g_\mu \frac{e}{2m_\mu}B - \frac{e}{m}B = \underbrace{\frac{g_\mu - 2}{2}}_{a_\mu}\frac{e}{m_\mu}B$$

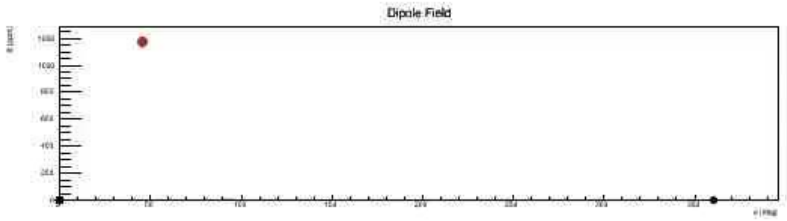
anomalous spin-precession frequency

anomalous magnetic moment

Shimming trolley



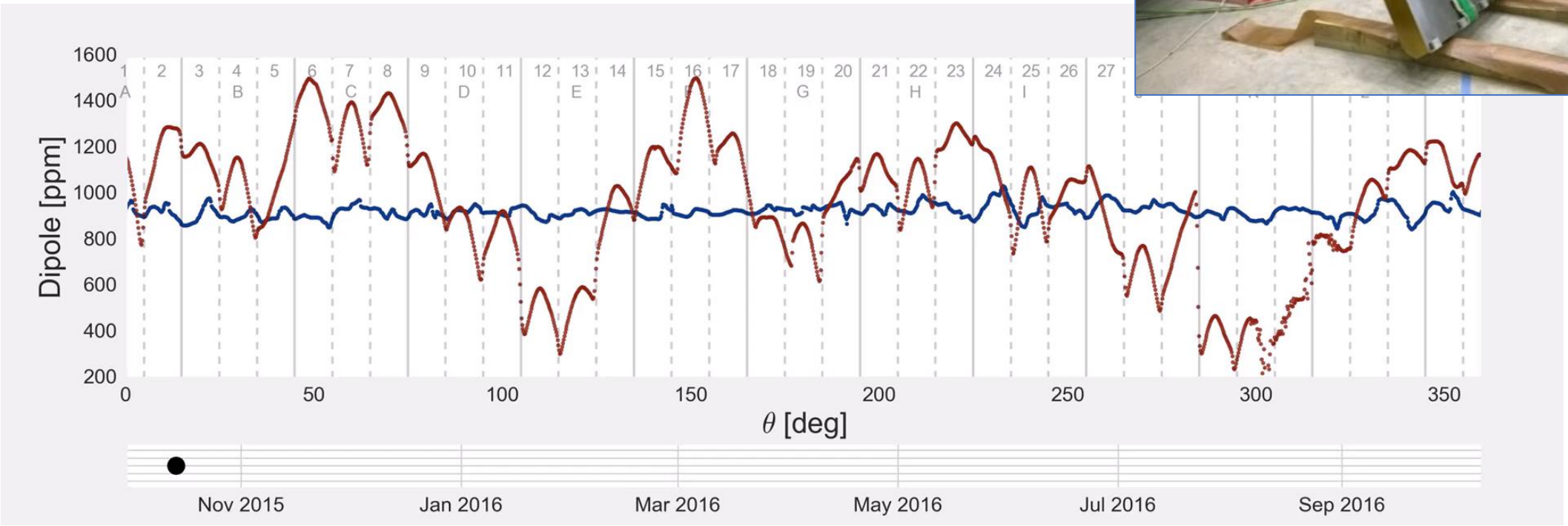




- 25 NMR probes on movable platform
- Used to measure field while assembly

Getting a homogeneous field

First adjust height and tilt of pole pieces

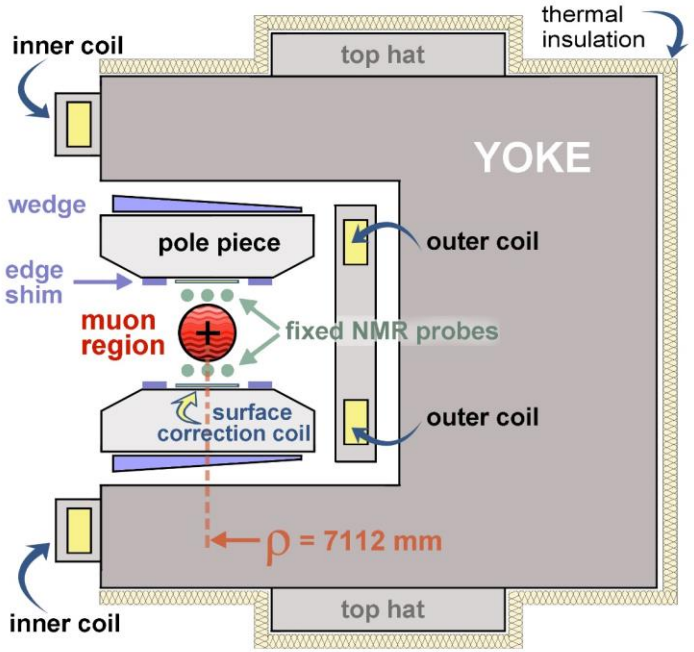


Getting a homogeneous field

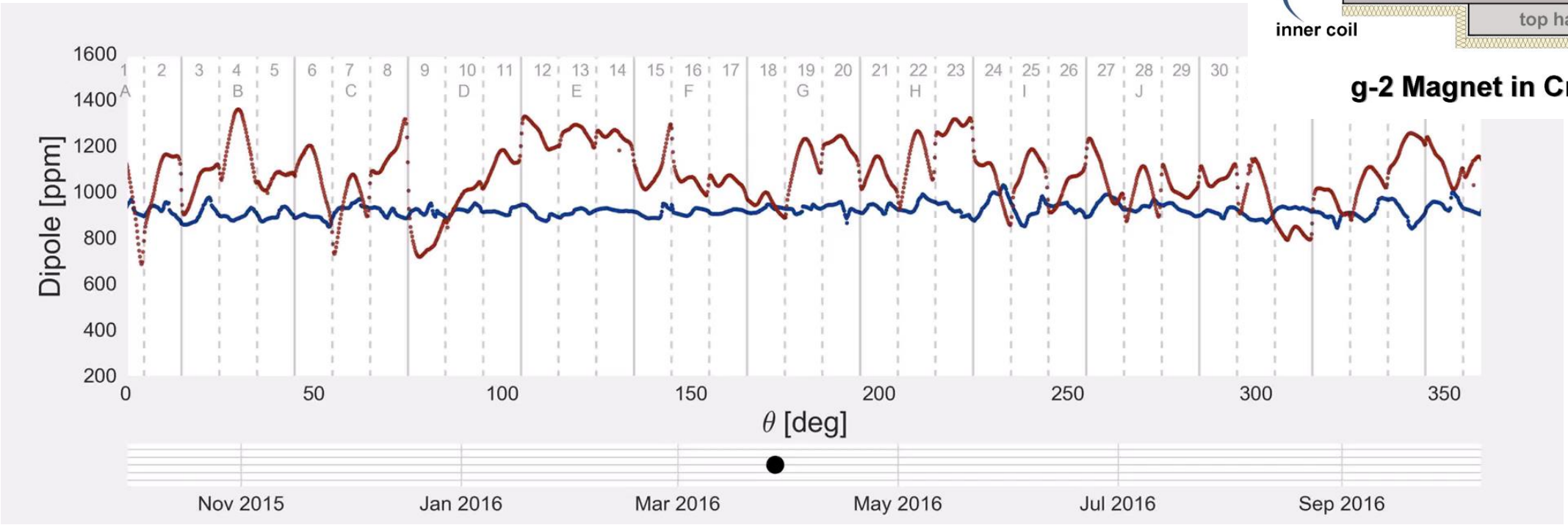
Second top hats and wedge shims

Top hats gap changes effective permeability in the magnetic circuit

Radial position of wedges to adjust dipole and compensate quadrupole

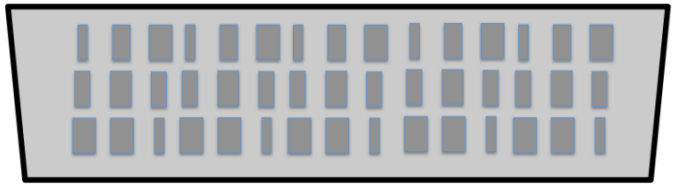


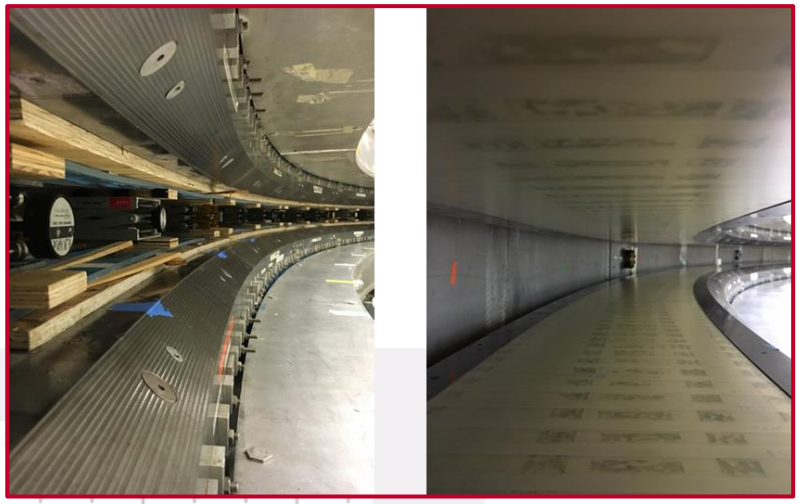
g-2 Magnet in Cross Section

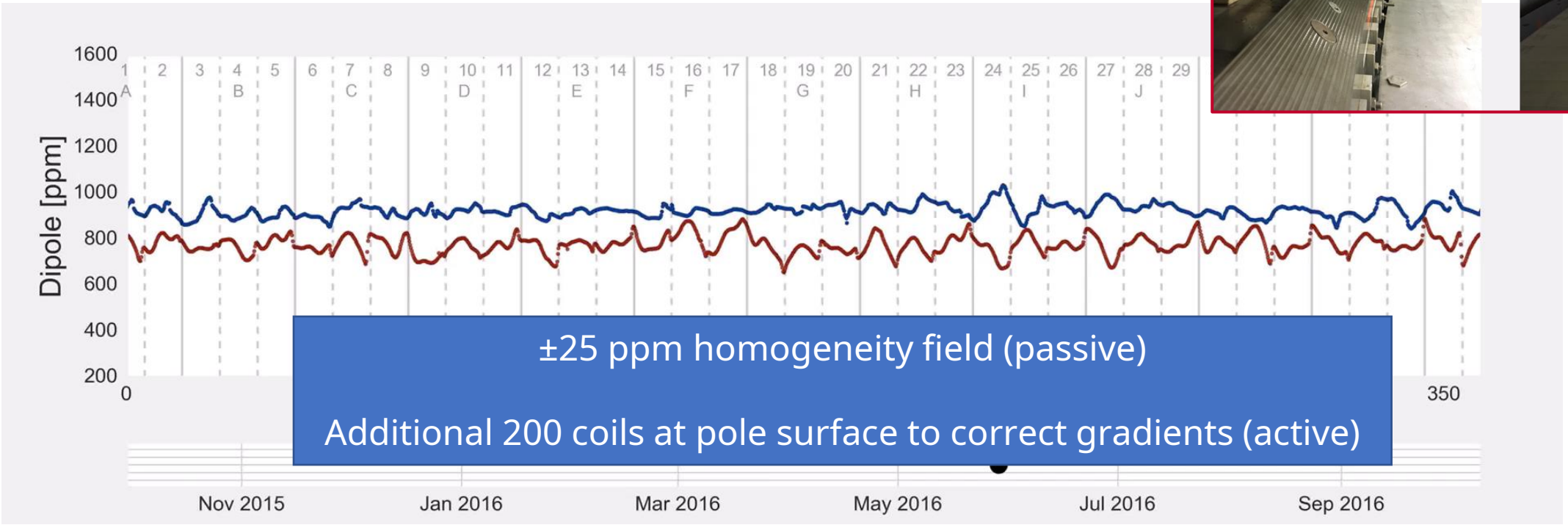


Getting a homogeneous field

Add IR laser cut iron foils



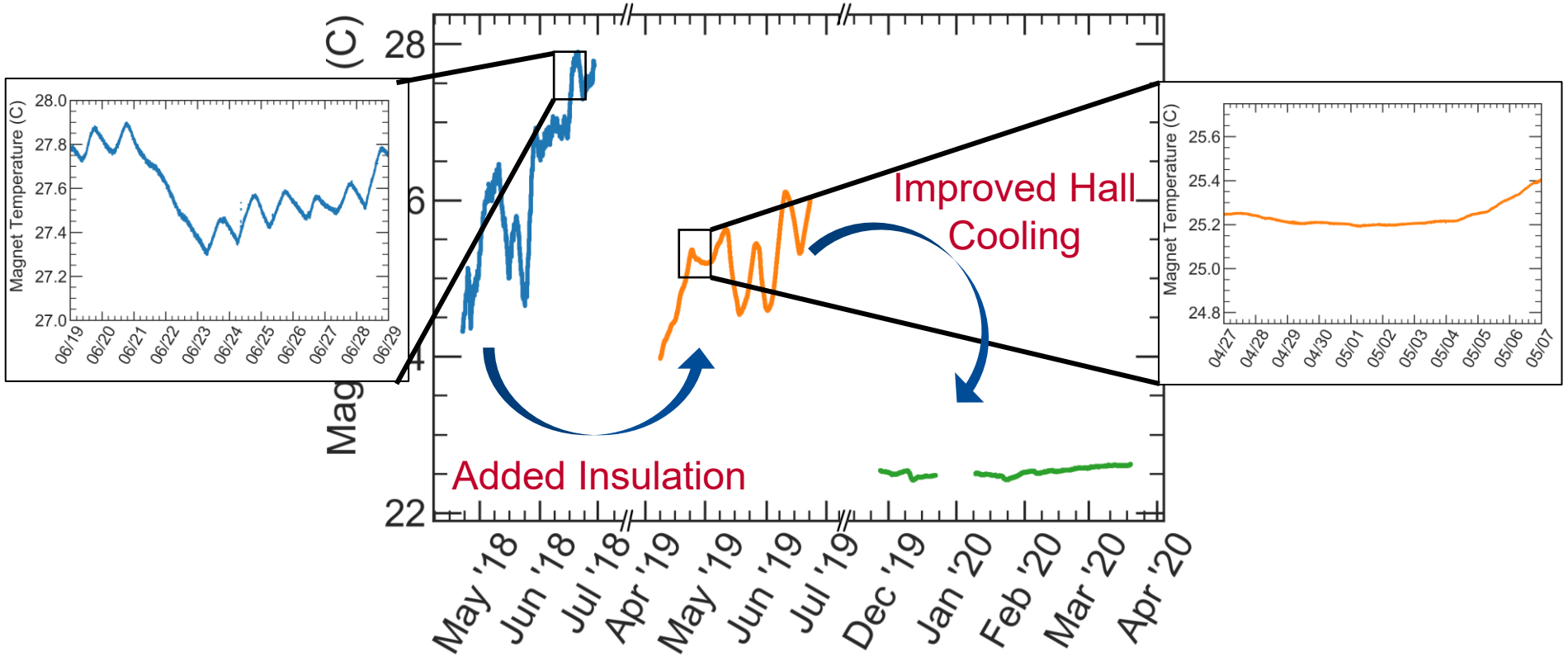


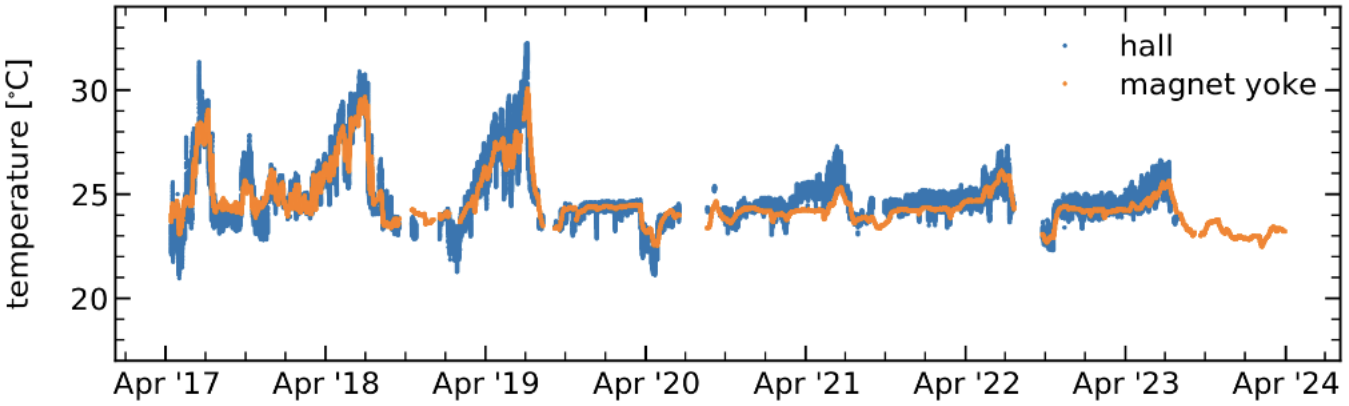


±25 ppm homogeneity field (passive)

Additional 200 coils at pole surface to correct gradients (active)

Magnetic field stability





Determination of a_μ

$$R'_\mu(T_r) = \omega_a \,/\, \tilde{\omega}'_p(T_r)$$

this measurement

$$a_\mu = R'_\mu(T_r)\frac{m_\mu}{e}\frac{2\mu'_p(T_r)}{\hbar}$$

general expression

$$a_\mu = R'_\mu(T_r)\frac{\mu'_p(T_r)}{\mu_e(H)}\frac{\mu_e(H)}{\mu_e}\frac{m_\mu}{m_e}\frac{g_e}{2}$$

previous publications

$$a_\mu = R'_\mu(T_{r,2})\frac{\mu'_p(T_{r,2})}{\mu_h(^3\mathrm{He})}\frac{\mu_h(^3\mathrm{He})}{\mu_N}\frac{\mu_N}{\mu_e}\frac{m_\mu}{m_e}\frac{g_e}{2}$$

new water to ^{3}He results

$$a_\mu = R'^{,\mathrm{He}}_\mu(T_r)\frac{\mu_{^3\mathrm{He}}}{\mu_N}\frac{\mu_N}{\mu_e}\frac{m_\mu}{m_e}\frac{g_e}{2}$$

using ^{3}He directly