PRECISION CROSS-CALIBRATION OF THE NMR CALIBRATION PROBES FOR THE J-PARC MUON G-2/EDM, J-PARC MUSEUM, AND FNAL MUON G-2 EXPERIMENTS AT THE ANL 4T MAGNET FACILITY

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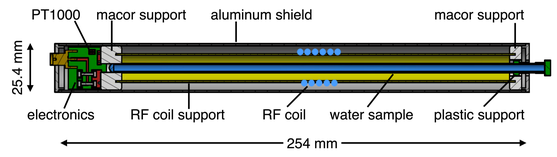
Motivation

- The measurement of the muon anomalous magnetic moment a_μ is a precision test of the Standard Model and an indirect search for New Physics.
- The Muon g-2 (E989) collaboration at Fermilab has published the most precise measurement of the muon anomalous magnetic moment with an uncertainty of 460 ppb in 2021, leading to a world average that deviates by 4.2 standard deviations from the Standard Model prediction provided by the Muon g-2 Theory Initiative.
- The complementary Muon g−2/EDM experiment (E34) at Japan Proton Accelerator Research Complex (J-PARC) is under construction.

$$a_\mu = \frac{\omega_a}{\tilde{\omega}'_p(T_r)} \frac{\mu'_p(T_r)}{\mu_e(H)} \frac{\mu_e(H)}{\mu_e} \frac{m_\mu}{m_e} \frac{g_e}{2}$$

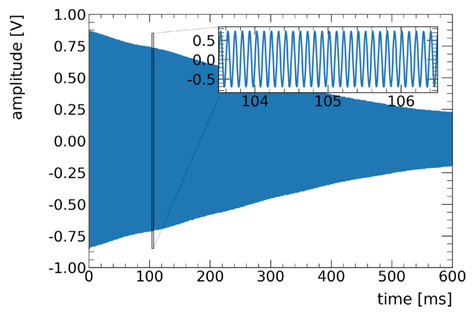
- Both experiments use nuclear magnetic resonance (NMR) probes to measure the magnetic field in terms of the precession frequency of the protons.
- **Goal: cross-calibration of the NMR calibration probes on the 30 ppb level at 1.45T, 1.7T, and 3.0T**

Fermilab Calibration Probe

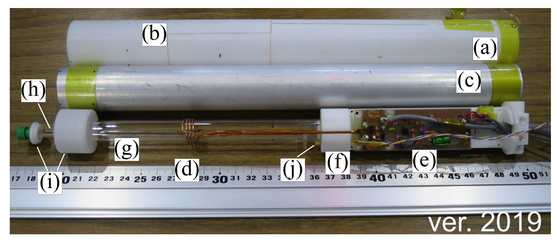


Pulsed NMR

Schematic drawing of the calibration probe used to calibrate the trolley probe measurements.

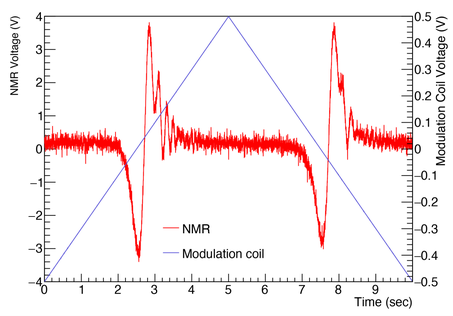


J-PARC Calibration Probe



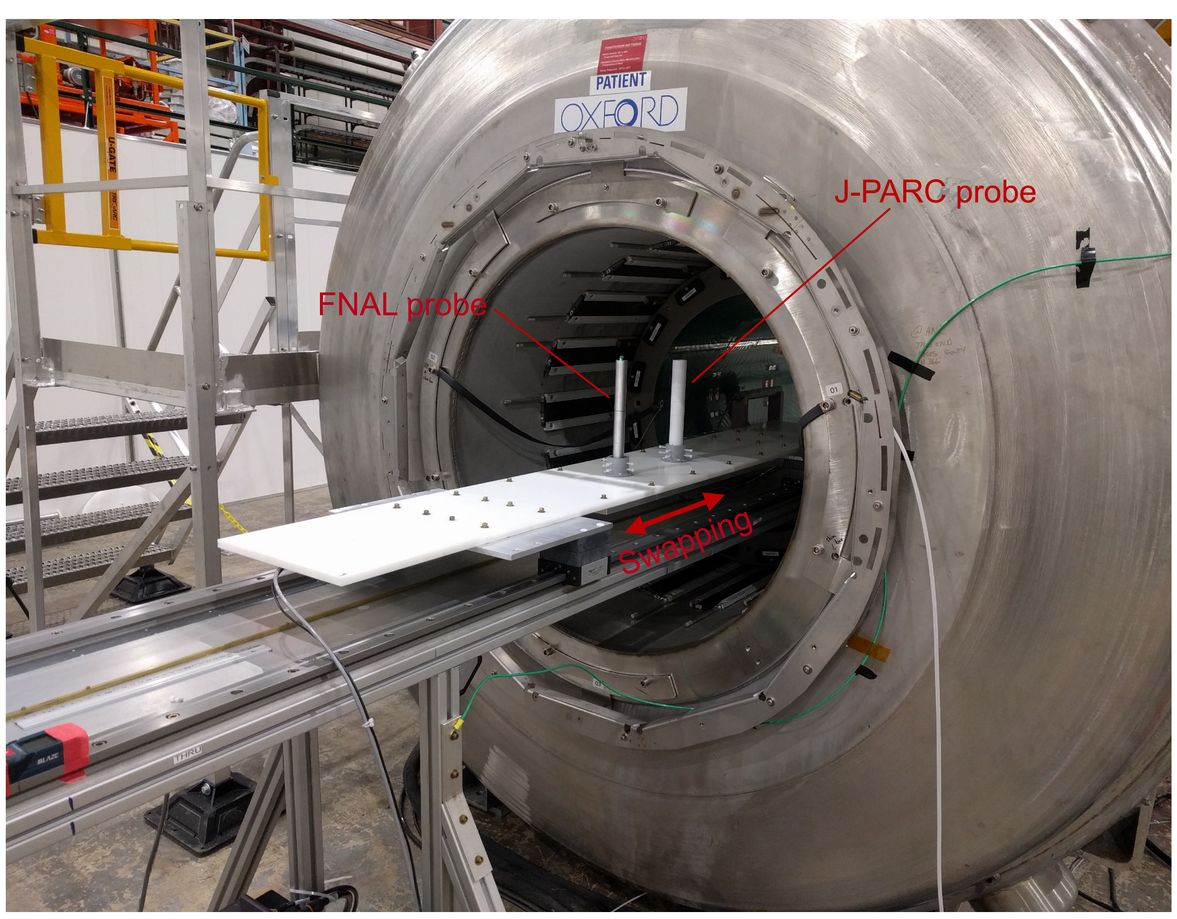
Continuous Wave NMR

(a) Teflon pipe, (b) Modulation coil, (c) Aluminum pipe, (d) RF coil, (e) Readout board, (f) Board holder, (g) d: 14mm glass cylinder, (h) d: 5mm glass cylinder

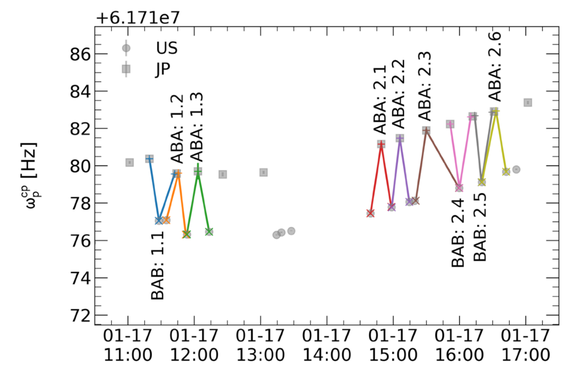


Facility

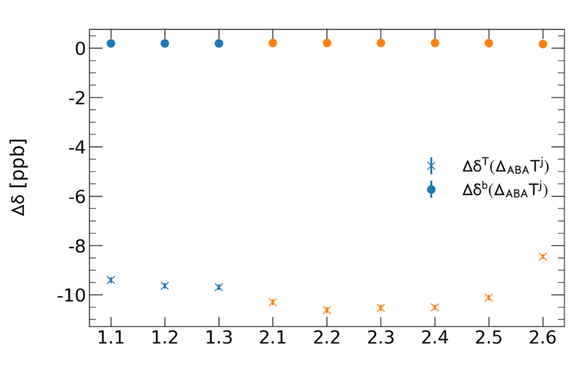
- 4-Tesla magnet facility at Argonne National Laboratory (Oxford OR66)
- Very stable and highlight uniform field due to passive and active shimming, local gradients below 2 ppb/mm
- Passive shimming based on single-value decomposition from field maps on a 50-cm diameter sphere obtained with Metrolab cameras



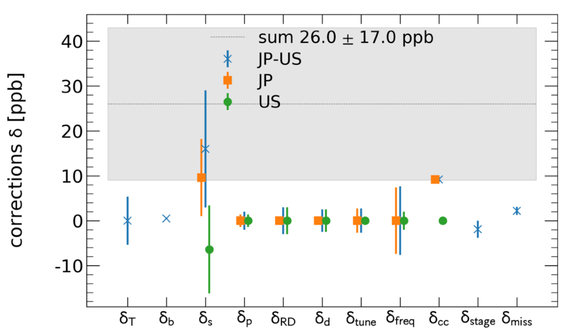
Measurement (1.45T)



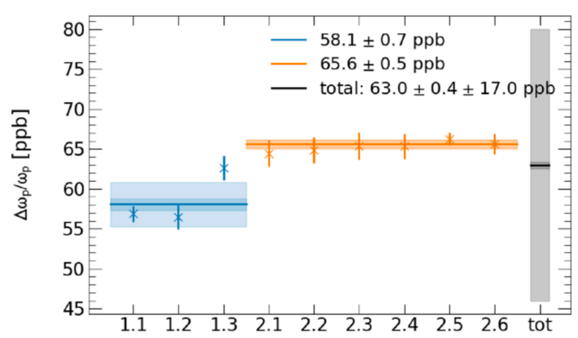
Raw difference measured at the same position from swapping the probes back and forth inside the magnet at 1.45T.



Temperature dependent corrections from diamagnetic shielding δ^T and bulk magnetic susceptibility δ^b



Correction terms from material effects (δ_s, δ_{cc}, δ_{stage}), water sample (δ_p), radiation damping (δ_{RD}), probe tune and frequency extraction (δ_{tune}, δ_{freq}), and misalignment (δ_{miss}).



Difference of the shielded proton precession frequency $\omega_{p'}$ between the FNAL and the J-PARC calibration probes at 1.45T.

Status

- Cross-calibration at 1.45T and 1.7T with uncertainties of ~17ppb
- The 3T calibration was delayed because of COVID
- The cross-calibration campaigns at 1.45T and at 1.7T yield a ~60ppb difference between the two probes (after unblinding)
- Thorough investigations and correction reevaluations have not led to any indication of the source of the discrepancy yet
- Next Step: Cross-calibration at 3T in October 2022

Additional Measurements

- The cross-calibration at 1.7T is motivated by the J-PARC Muonium Spectroscopy Experiment Using Microwave (MuSEUM). It yield a consistent difference of ~60ppb.
- The same facility is used to cross-calibrate the FNAL calibration probe with ^{3}He NMR probe developed by the University of Michigan

References

- H. Yamaguchi *et al*., "Development of a CW-NMR Probe for Precise Measurement of Absolute Magnetic Field" in *IEEE Transactions on Applied Superconductivity*, vol. 29, no. 5, pp. 1-4, Aug. 2019, Art no. 9000904, doi: 10.1109/TASC.2019.2895360.
- D. Flay *et al., "*High-accuracy absolute magnetometry with application to the Fermilab Muon g-2 experiment”, *JINST* **16** P12041, 2021.
- M. Farooq *et al.,* “Absolute Magnetometry with ^{3}He”, Phys. Rev. Lett. **124**, 223001, 2020.

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