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

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Measuring the Magnetic Field in Terms of the Free Proton

Measure the magnetic field using nuclear magnetic resonance (NMR). The field at the location of a proton in an NMR water sample differs from the applied field:

$$B_{\text{meas}} = (1-\delta_t)B$$
$$= \left[1-\sigma(\text{H}_2\text{O},T)-\delta_b-\delta_p-\delta_s\right]B$$

Paramagnetic ion cont. (δ_p); Diamagnetic shielding (σ); Bulk diamagnetic shape $(\varepsilon-4\pi/3)\,\chi$ (δ_b); Probe structure (δ_s)

$$\sigma(\text{H}_20, 25^\circ\text{C}) = (25680.0 \pm 2.5)\times 10^{-9}$$ [Metrologia **51**, 54 (2014)]

$$\chi(\text{H}_20) = -0.72\times 10^{-6}(\text{CGS})$$ [Nucl. Instrum. Meth. A, **394**, 349 (1997)]

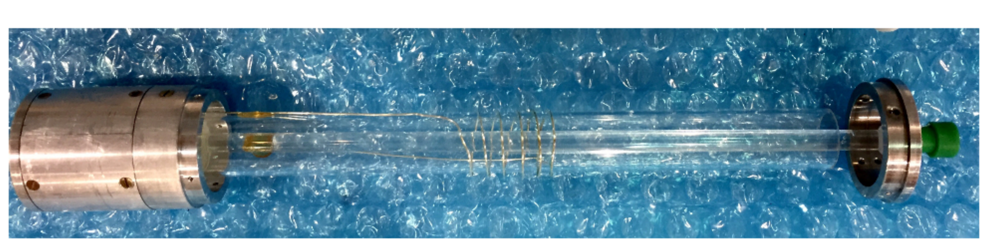
New Plunging Probe Design

The plunging probe is an NMR probe whose calibration factors (above) are well known, and is used to calibrate the NMR trolley probe measurements in terms of the free proton precession frequencies

Goals:
- Minimize magnetic footprint of the probe; reduce the amount of materials used
- Need to account for calibration factors not only in the analysis of the data, but also in the design process
- Strive for good RF field homogeneity
- Control other systematics (position, temperature, field drift over time):

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

At ANL test facility:
- Uncertainties (x ~ 10 ppb/mm, y ~ 26 ppb/mm, z ~ 5 ppb/mm)
- Temperature dependence (~ 10 ppb/deg C)
- Field drift (~ 9 ppb/hr)
- Expect factor of 2 larger field inhomogeneity at FNAL



Basis for new plunging probe design: an absolute calibration probe used in the previous experiment, BNL E821 (aluminum housing removed)

Design considerations:
- RF coil: trade off between smaller effect on field (large diameter) and large S/N (small diameter)
- Higher quality materials: low magnetic susceptibility materials, high purity water
- Careful consideration of environment (temperature and field monitoring)

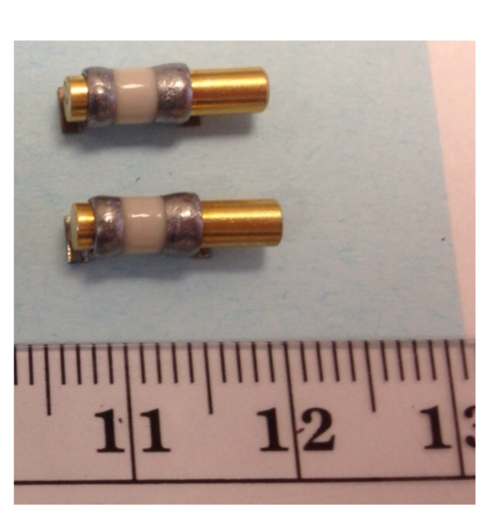
Material Studies

Need to quantify how much the components of the probe perturb the field

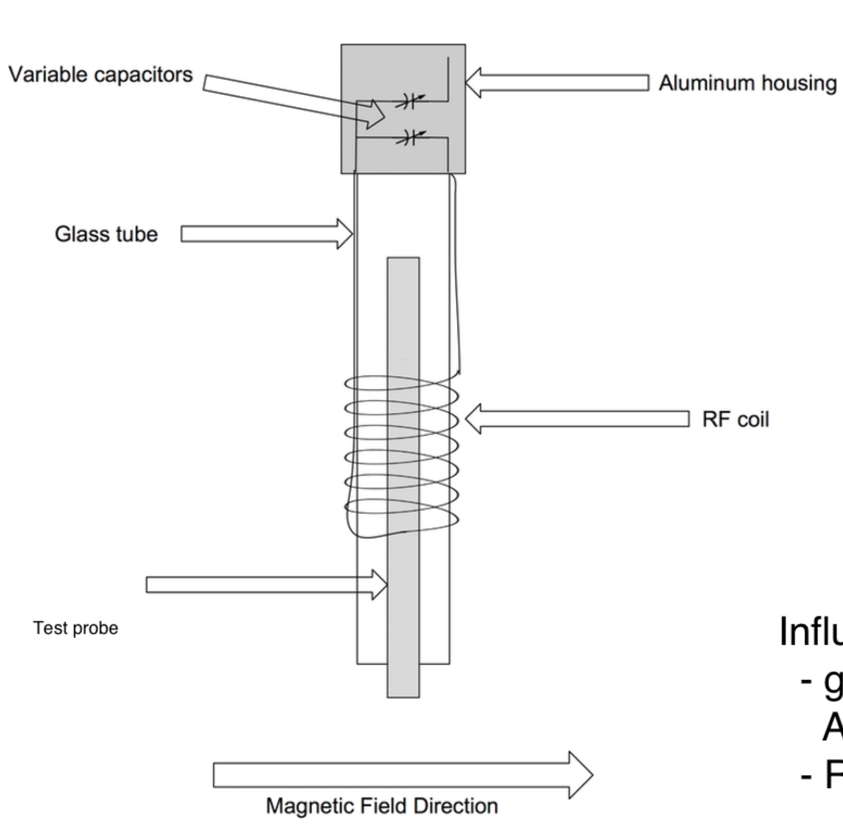
RF coil: near-zero magnetic susceptibility wire (Al-Cu combination; Al inside thin Cu tube): 0.24 Hz (4 ppb)

Zero-susceptibility wire

Variable capacitors < 0.18 Hz (3 ppb)



Variable capacitors



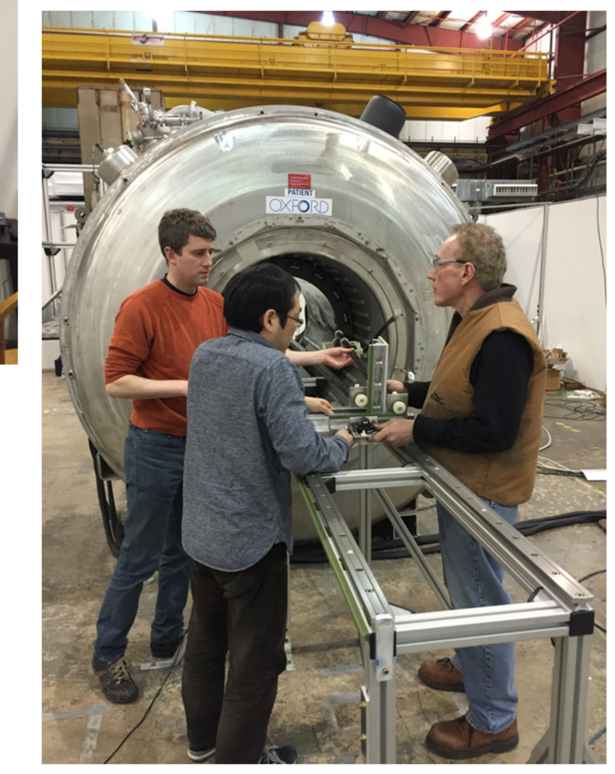
Example setup for testing the BNL E821 probe

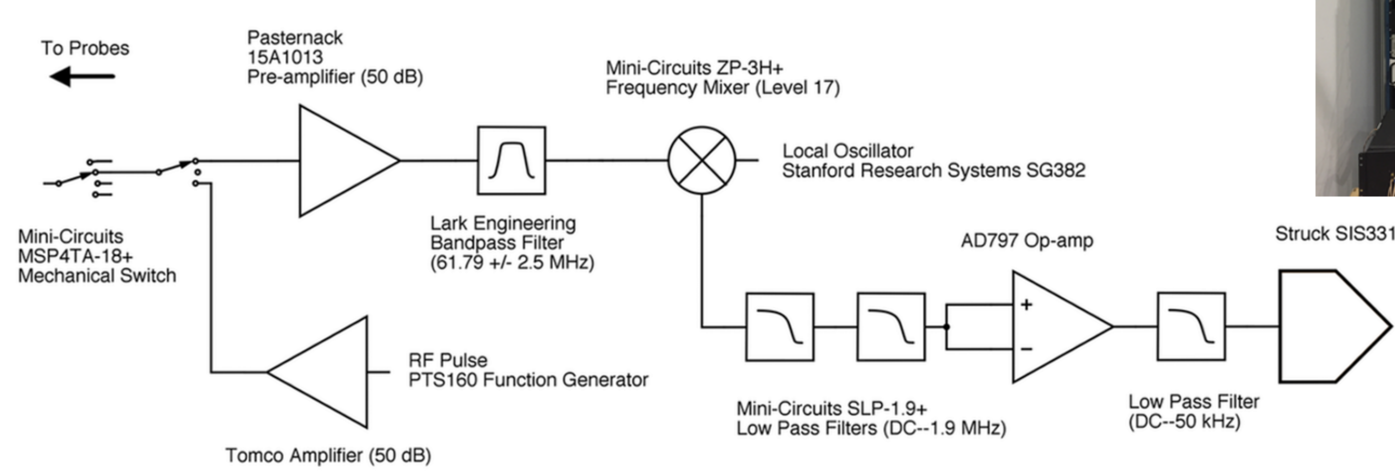
Influence of probe:
- glass tube + RF coil + capacitors + Al housing: 2.7 Hz (45 ppb)
- Rotational effect: 1.2 Hz (20 ppb)

NMR Electronics and Data Acquisition

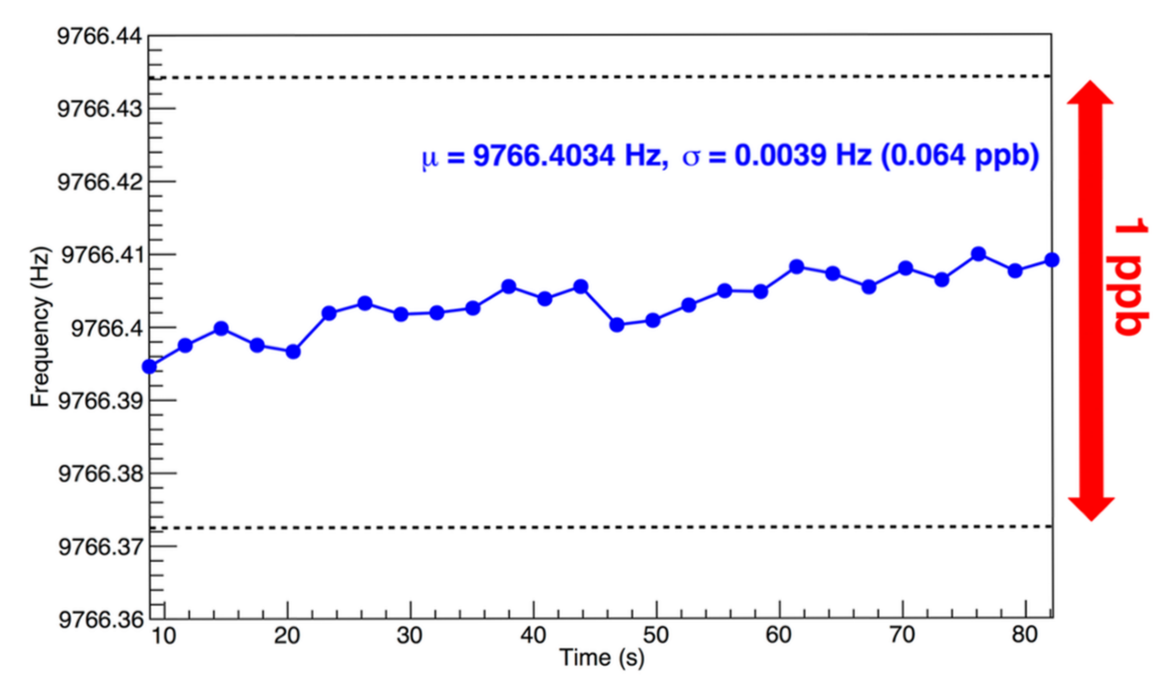
Bandwidth: 61.79 MHz +/- 50 kHz (833 ppm)
Amplitude: ~ 1 V at t ~ 0
RMS Noise: ~ 1 mV
S/N: ~1000 at t ~ 0
Resolution: < 1 ppb

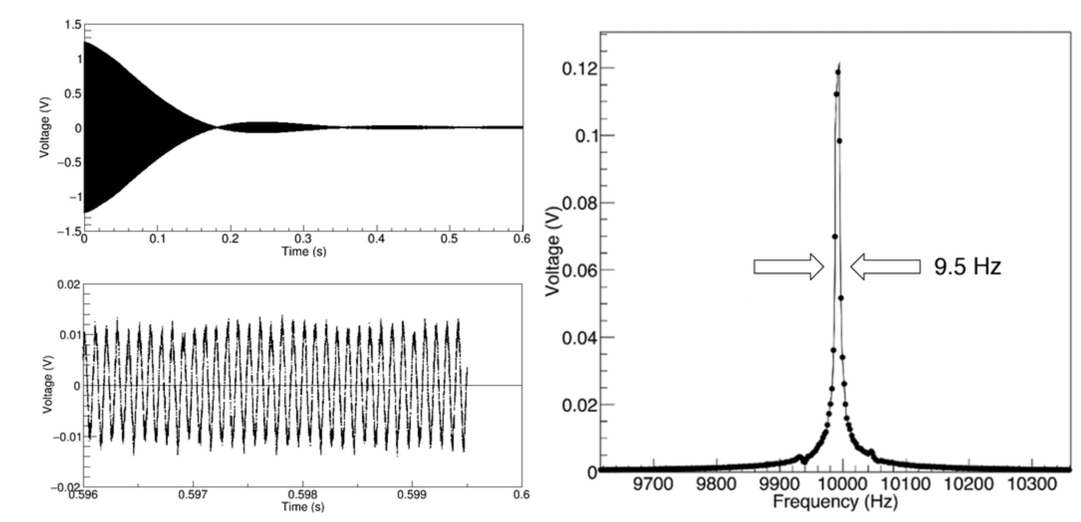
Setup at Argonne National Lab





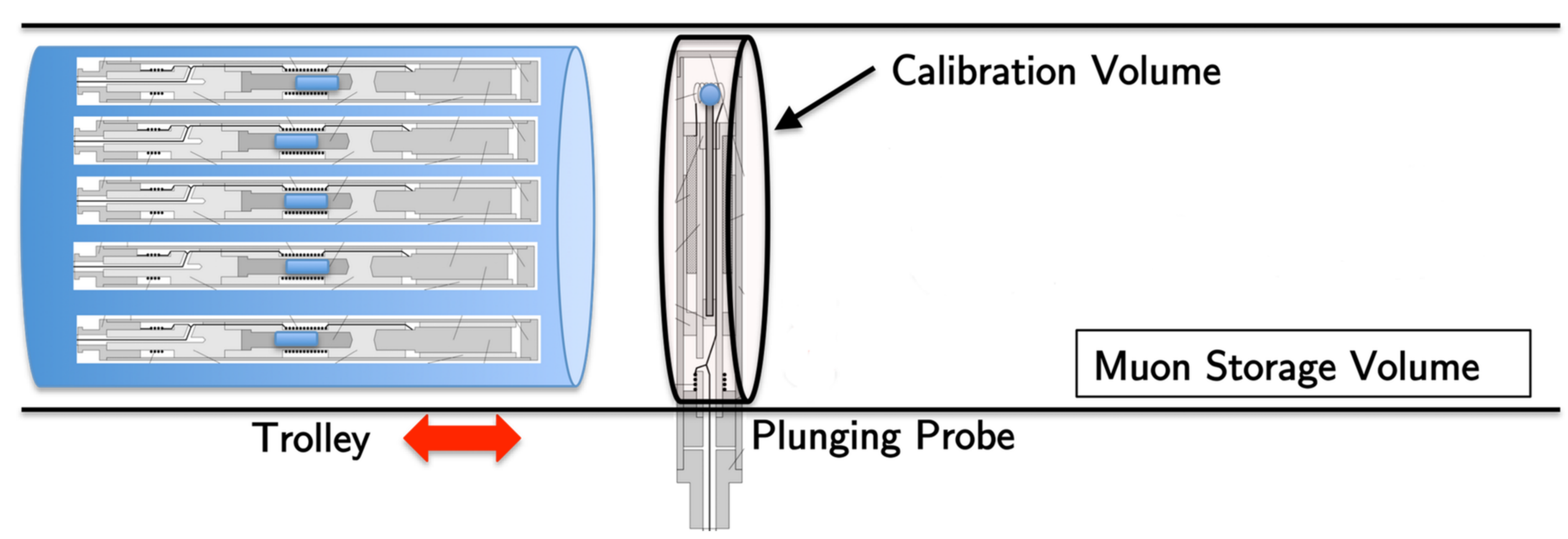
Schematic diagram of NMR electronics





Sample water NMR data

Procedure to Calibrate NMR Trolley Using Plunging Probe



1. Move plunging probe into the desired position in the field and take a measurement
   - Use linear encoders and a camera to determine position of plunging probe and trolley to < ~1 mm
2. Pull plunging probe out of the area and move the NMR trolley into the same position; take a measurement
3. Repeat for confirmation of the difference in measurements
4. Combining this difference with the corrections due to diamagnetic shielding and material effects, magnetic images in muon storage ring's pole pieces gives the calibration

Outlook and Next Steps

Plunging probe design is finalized; build and test probe in MRI solenoid magnet

Testing of materials is ongoing

Construction of calibration stage for use at ANL (for calibration against spherical water NMR probe) is underway

Reduce remaining gradients in MRI solenoid magnet

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