Field Mapping System

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Mu2e Collaboration Meeting, Frascati
13 June 2025

Intro to Field Mapping

- Field mapping charge: measure field in DS bore to precision of 10^{-4} for |B|, 0.1 mrad for $\hat{\mathrm{B}}$
  - In tracker region, this is field accuracy of 1G
  - Informal goal: e- momentum uncertainty from magnetic field <40 keV
- Plan: step Hall probe array through DS volume to obtain grid of field measurements
  - 10^{-4} precision for Hall probe measurements
  - 100 um position, 0.1 mrad orientation accuracy from laser tracker
  - Convert grid of measurements to magnetic field model for offline use

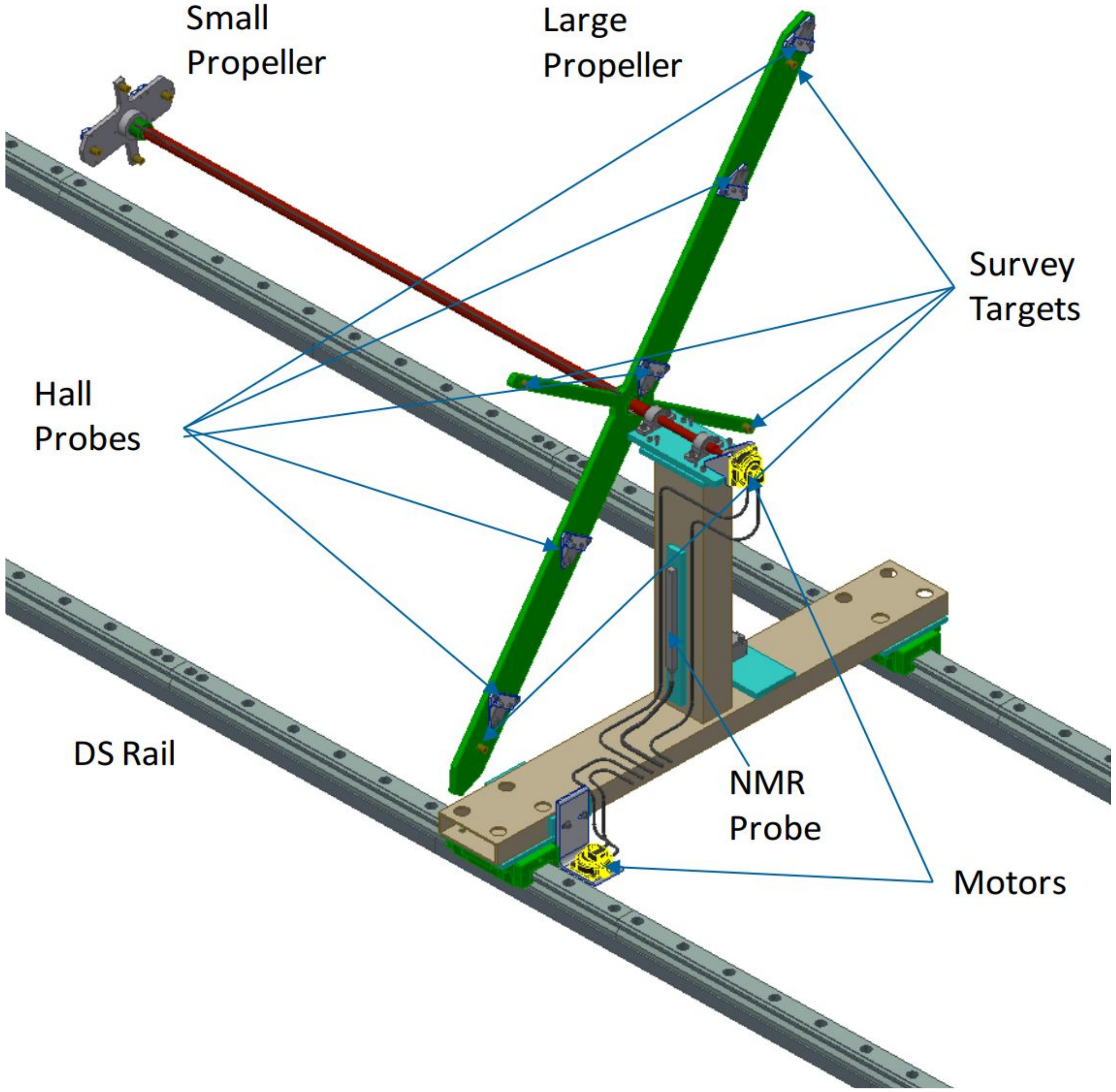
Detector Solenoid Field Mapper

Temperature / humidity sensors

Thermal Enclosure

Motion Control (EMMA)

DAQ / DQM



Laser Tracker (Leica AT40X)

+ mounting fixture
+ monuments

FMS Workshop at Collaboration Meeting

Start	Title	Author(s)	Topic(s)	File(s)	Length
09:30	Hall Probe Calibration Results (First Probe)	Cole Kampa	Solenoids FMS	PDF of Slides	00:30
10:00	FMS laser tracker integration update	Susan Dittmer	B-Field Solenoids	LT_status_JuneCM.pdf	00:15
10:15	Update on NMR Field Monitoring System	Matthew J. Bressler *et al.*	Solenoids	FMS_Workshop_J...pdf	00:15
10:30	Roundtable / AOB	None	None	None	00:30

Invited talk from NMR Field Monitoring group: David Kawall, Matt Bressler (U Mass)

Recent / Ongoing Work

- Lots of progress since last update [docdb 50551] at September CM
  - Completed transition from Project to Operations
  - Restarted Hall probe calibration + first results
  - Integration tests at Argonne
    - Motion controller tests
    - Integration of laser tracker
  - Gear rack / bracket redesign

Hall Probe Calibration

- Achieving 10^{-4} precision from Hall probe measurements requires calibration in known magnetic field
  - Calibration provided by CERN/ NIKHEF insufficient
  - Hall voltage may drift with time, requiring recalibration
- Calibrate Hall probes in test magnet at IB2
  - Long effort with many twists and turns (see right)
  - Effort led by Cole, with invaluable aid from Thomas Strauss (FNAL)

Hall Probe Calibration History

- This list is not exhaustive.
  e.g. I recall we had to replace a component in the temperature enclosure but I can't find the details; missing several CMM campaigns, etc.
- Nearly all points of progress should have Thomas' name on it – I ran out of space.

- 2015:
  - Formation of FMS (FNAL, ANL, NU)
- 2016:
  - Summer students worked on simulation and measurement of calibration magnet uniformity [Daniele Marchetti, Francesco Restuccia]
- 2017:
  - 20 Hall probes procured for FMS (CERN / NIKHEF "BsCAN" sensors, originally developed for ATLAS)
- 2018:
  - Cole joins Hall probe calibration as lead analyst (Fall 2018)
- 2019:
  - SmarAct motors malfunctioning and sent for repairs (3 month repair)
    - Not long before this the motors were on loan to J-PARC group calibrating LakeShore Hall probes at ANL (COMET TS measurement)
  - Temperature enclosure installed (January)
  - Fuse / transformer blown in line used for calibration magnet power supply and replaced (January-March)
  - Hall probe CMM (dates? Or remove)
  - Calibration DAQ computer replaced (April)
  - 3D maps of calibration magnet using Zaber gantry and NMR probe (May)
  - Magnet characterization measurements (June-November)
  - Hall probe long-term stability measurements (August-December)
- 2020:
  - Hall voltage vs. |B| initial measurements started and interrupted by COVID (March)
  - Hall probe base plate (magnet mount to SmarAct/Hall probe) fabricated at FNAL (July)
  - Calibration DAQ computer died and replaced (July-September)
  - NMR sent for calibration (September-January 2021)
  - First data of Hall probe rotating in magnet using SmarAct motors (September)
  - SmarAct motors malfunctioning and sent for repairs (October - February 2021)

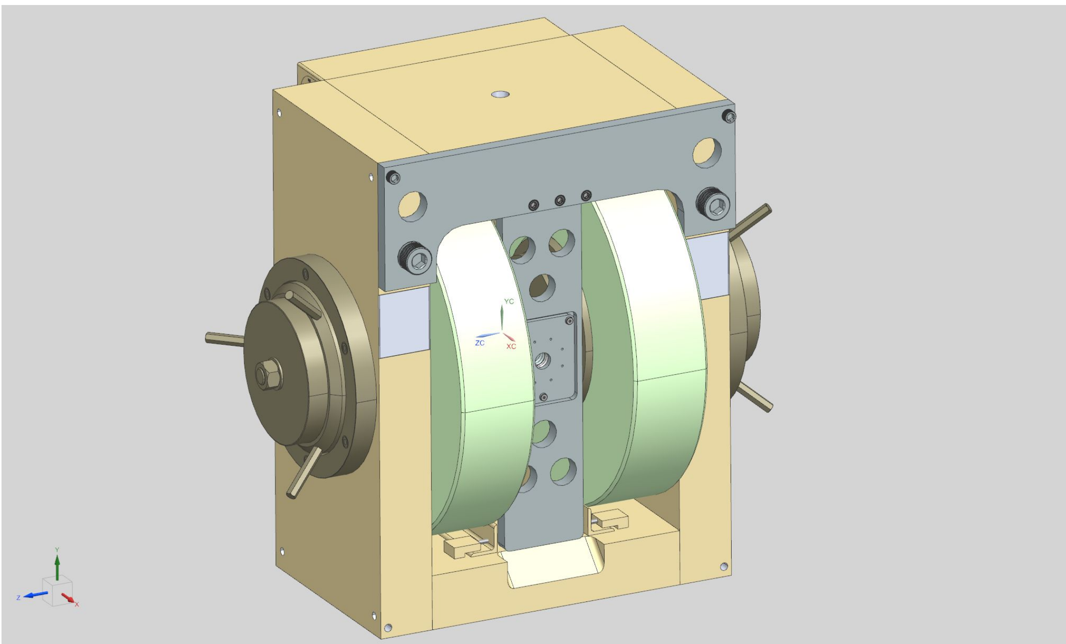
Hall Probe Calibration History (2)

- 2021:
  - Power Supply wiring fixes (fried wire; loose termination on interlock) (July)
  - |B| vs. Magnet Current measurements with NMR and modeling (February - March)
  - |B| vs. distance from pole tip, a.k.a. "pole-to-pole measurements) (June)
  - Hall voltage vs. |B|, temperature extended measurements (July)
  - Glycol chiller (purchased by NU) installed for cooling calibration magnet coils (September-March 2022)
    - Fixed long-standing problem with running magnet >1.0 T with heat exchanger using pond water
    - Earlier temporary fix repurposed a smaller chiller from FNAL graveyard, but capacity was low and the chiller ultimately died.
- 2022
  - New set of pole-to-pole measurements (May - June)
  - First set of rotational data with upgraded system (intermittently, July - January 2023)
    - Rotations with several temperatures but only a single |B| completed before SmarAct malfunction
  - Metrology group performed laser tracker measurements of the calibration system and found O(10 mrad) errors in reproducibility of installing the Hall probe fixture. This led to efforts to redesign the Hall probe fixture. (December)
- 2023
  - **SmarAct malfunction and sent for repairs (January) – still not returned**
    - Rest of Hall probe fixture sent along with the motors, including the kinematic plate (originally, SmarAct provided this fixture)
  - Calibration analysis code initial development, demonstrated to be sufficient, at least for angular + temperature dependence (January) [docdb-44397]
  - 8 Hall probes loaned for ORNL chicane magnet mapping in IB1 (January - June)
    - 1 probe was broken during this campaign
    - A new set of 10 Hall probes procured for this project and for Mu2e if needed as part of this arrangement [Thomas Strauss]
  - New mounting fixture (magnet to Hall fixture) designed by Tom Nicol to address repeatability issues (February - March)
    - Fixture fabricated at NU machine shop (November - January 2024)
  - Calibration LabView software update to use newer MCS2 motor controller. This allowed us to use the spare SmarAct motors we have on hand. (November)

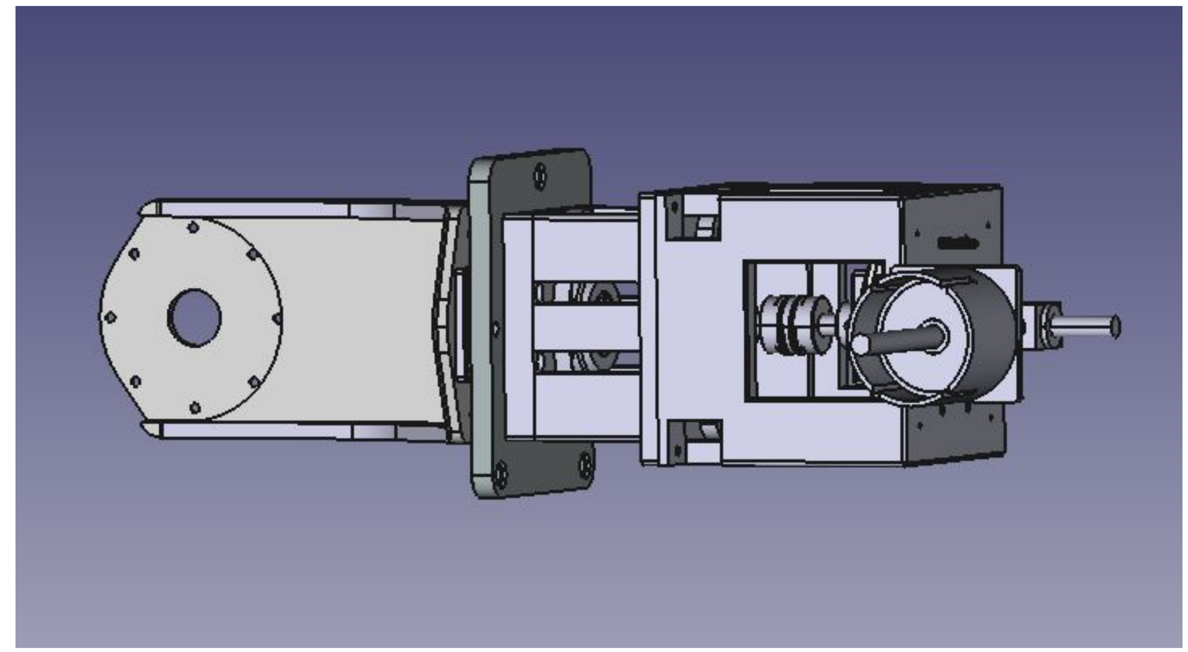
Hall Probe Calibration History (3)

- 2024:
  - FMS reorganized and revived (May)
  - Alternative to SmarAct motor vendor search in progress (July – ongoing)
    - A few vendors with reasonable options have backed out at during procurement
    - Will require design modifications
  - Calibration equipment turned back on and exercised (August)
    - Power supply had a loose interconnect wire again
  - Adjust Hall probe fixture design to accommodate Tom Nicol's magnet fixture design (October - April 2025)
    - Required several prototype iterations (PLA). Final version 3D printed in carbon fiber at NU.
  - Modification of Tom Nicol design due to unexpected requirement to offset horizontally from center (October)
    - Horizontal adjustment added. New part machined by Cole. (January 2025)
- 2025:
  - **Successful commissioning of the new Hall probe fixture, production version (April 16)**
  - **Full calibration dataset collected for the first probe (April 16 - May 21)**
    - PLA kinematic plate is temporary – we probably can not use this dataset in the long run
  - SmarAct acting up, maybe. (May 21 – ongoing)
    - Motor stuck at the very end of the first probe measurement campaign. The motor had to be physically unbound after powering down
    - After unbinding, the binding/sticking behavior observed was observed more regularly
    - Binding soothed by decreasing motor speed and acceleration during the scan (minimal impact on total scan time)
    - As it stands today, we occasionally see "sticking" behavior, but it is short lived and self-corrects.
  - **Data collection for the second probe is underway [Susan and Jinglu]**
    - Swapped to spare PAI kinematic plate we used in the past for the metrology efforts

Hall Probe Calibration: Fixture Redesign



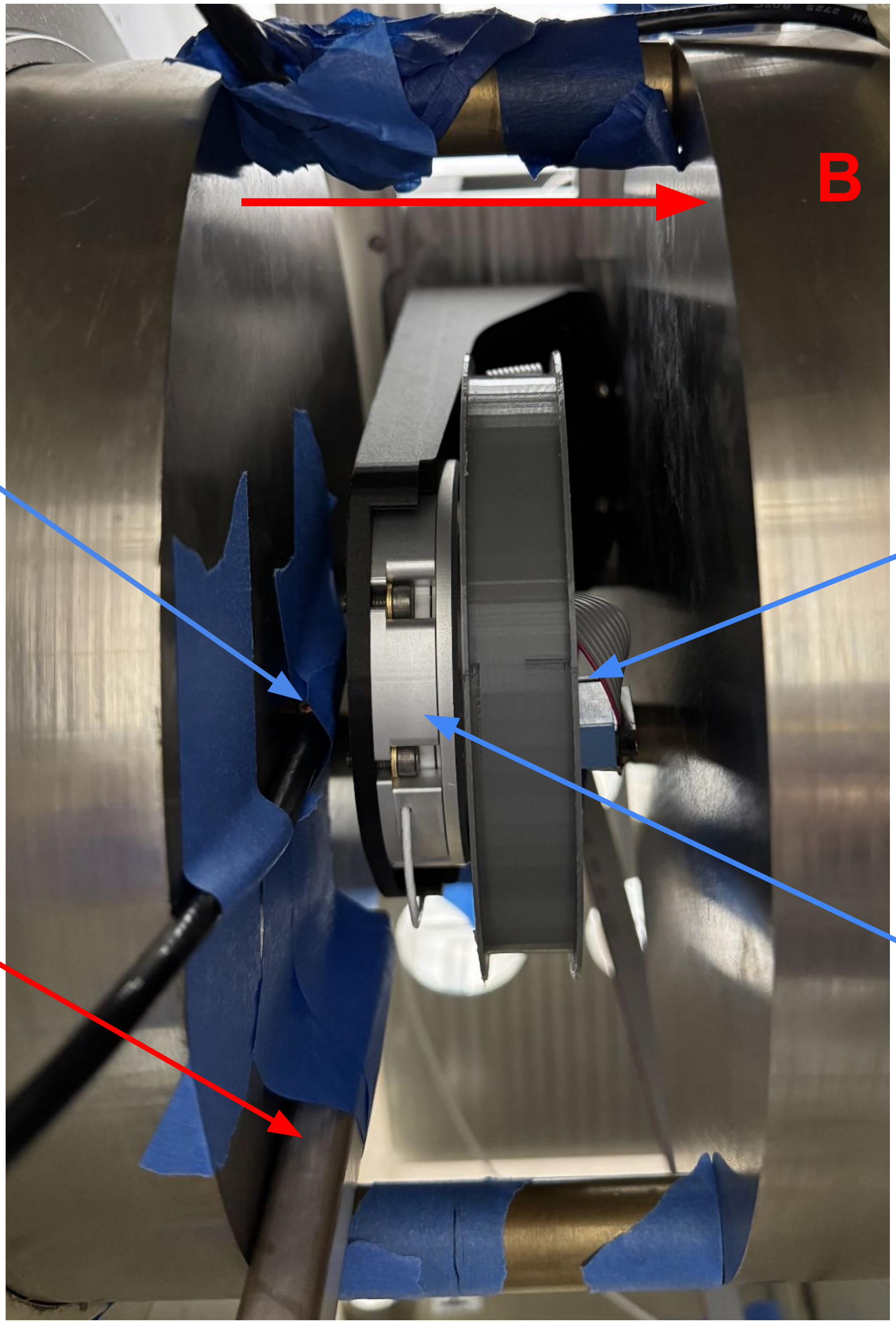
- Side-load the probe to cleanly attach directly to the magnet – everything above the base plate is unchanged (motor, fixture, Hall probe, …)
- 2 taper pins for positioning
- 3 shoulder bolts hold base plate in “T” bracket.



- Side-loading required unexpected modifications due to additional torque from gravity and cantilever load
- Also separated motor (Axis 0, i.e. θ) from the Hall fixture:
  1. Carbon fiber shaft through coaxial bearing remove load from the motor
  2. Counterweight balances torque

Hall Probe Calibration: Setup

Inside the magnet



(+1 polarity,
i.e. big propeller)

(current < 0)

NMR Probe
(0.70 T - 2.1 T)

Hall probe

Axis 1 (ϕ)

NMR Probe
(0.26 T - 0.78 T)

could not physically fit it in uniform region
→no in-situ measurement of |B| < 0.7 T

Hall Probe Calibration: Data and Analysis

- Scan over |B|, temperature, angle
  - |B| = [0.75,1.3] (9 points) x (+,- polarity)
  - Temperature = [15C, 35C] (5 points)
  - Angle 1 = [-1°, 14°] (16 points)
  - Angle 2 = [0°, 360°] (25 points)
- Data analysis
  - Goal: determine $V_i^{Hall}(|B|,\theta,\phi,T)$; invert to get $B_i(V_{x,y,z}^{Hall}, T)$
    - Assume $V(|B|, \mathrm{temp}, \theta, \phi) = \sum_k \sum_n \sum_l \sum_{m \leq l} c_{knlm} T_n(|B|) T_k(\mathrm{temp}) Y_l^m(\theta, \phi)$
  - Initial fits to orient $\vec{\mathrm{B}}$, Hall element axes vs rotation axes
  - Final fit to extract coefficients c_{knlm}

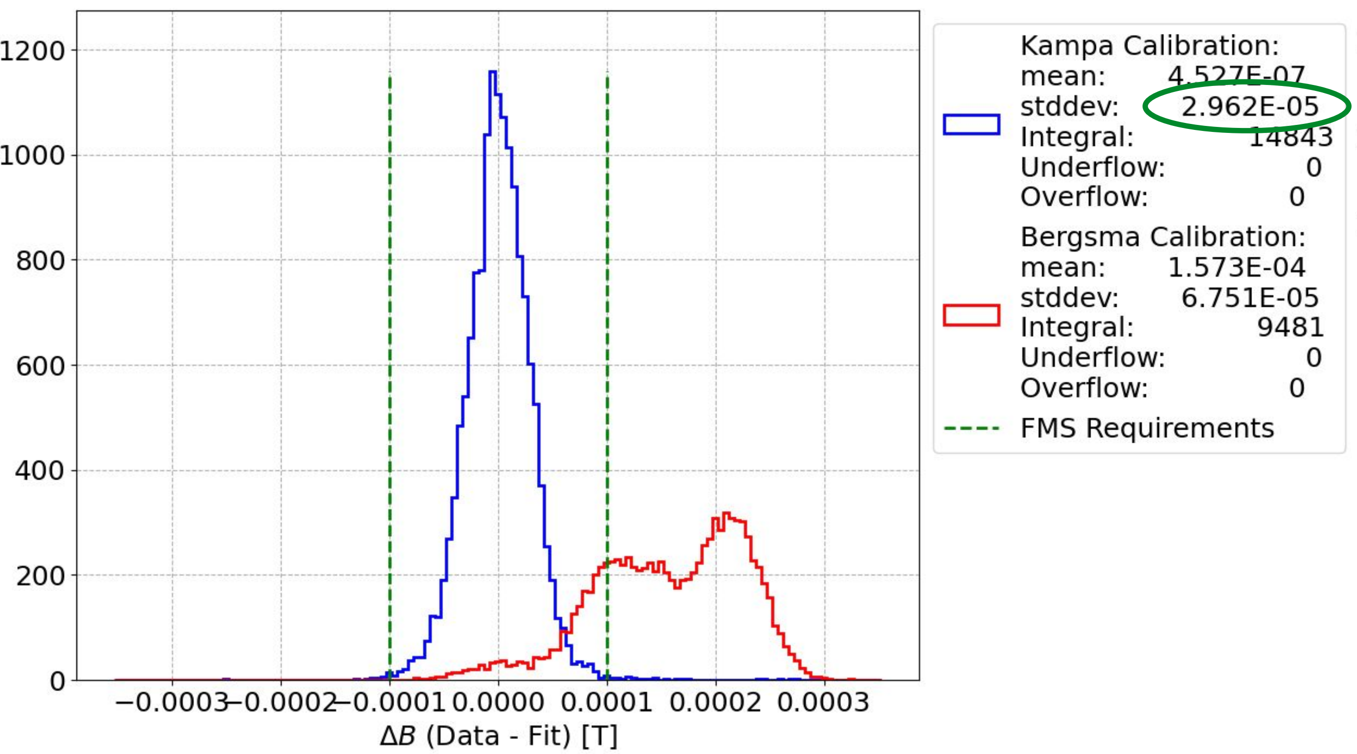
Many subtleties I am skipping here — see Cole's slides [docdb 53005] for details

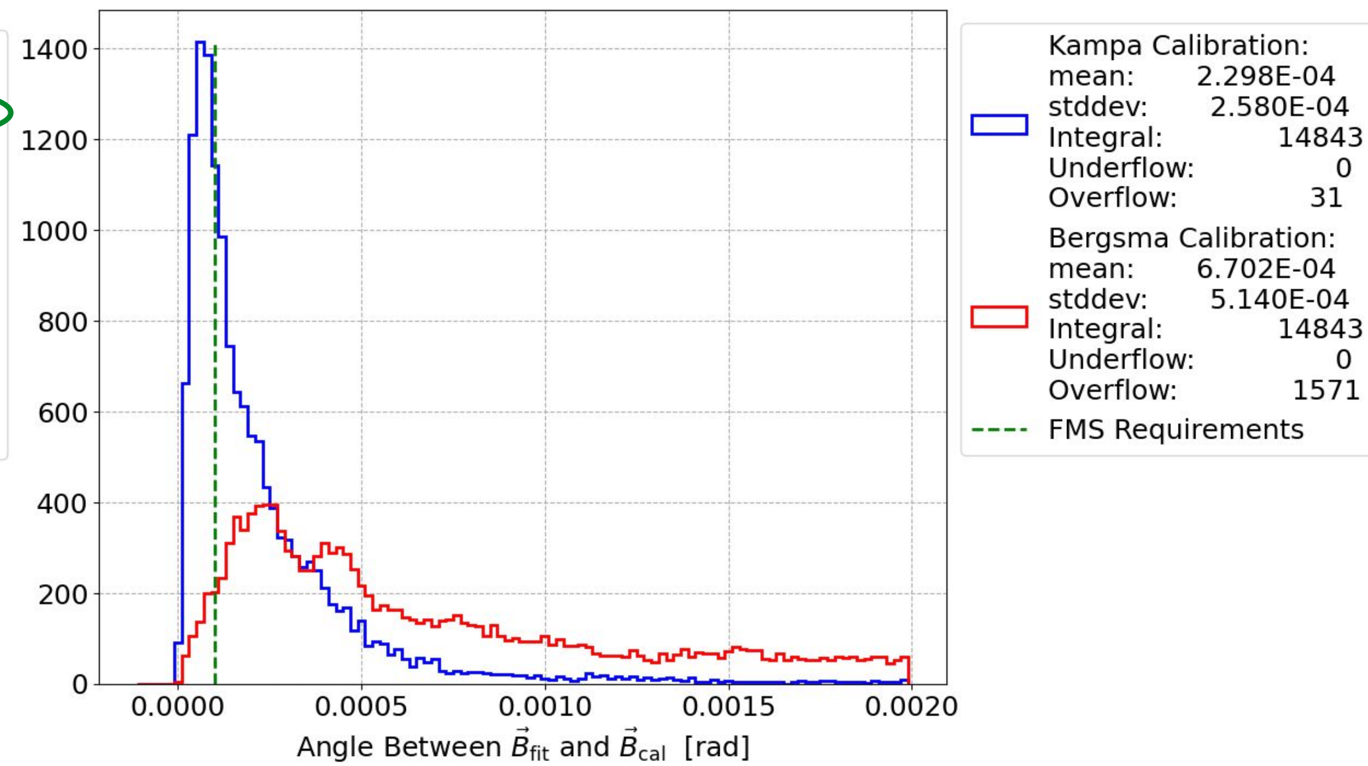
Hall Probe Calibration: Results

|B| Residual

Thermal noise is 0.3G — at limit!

B Angular Error





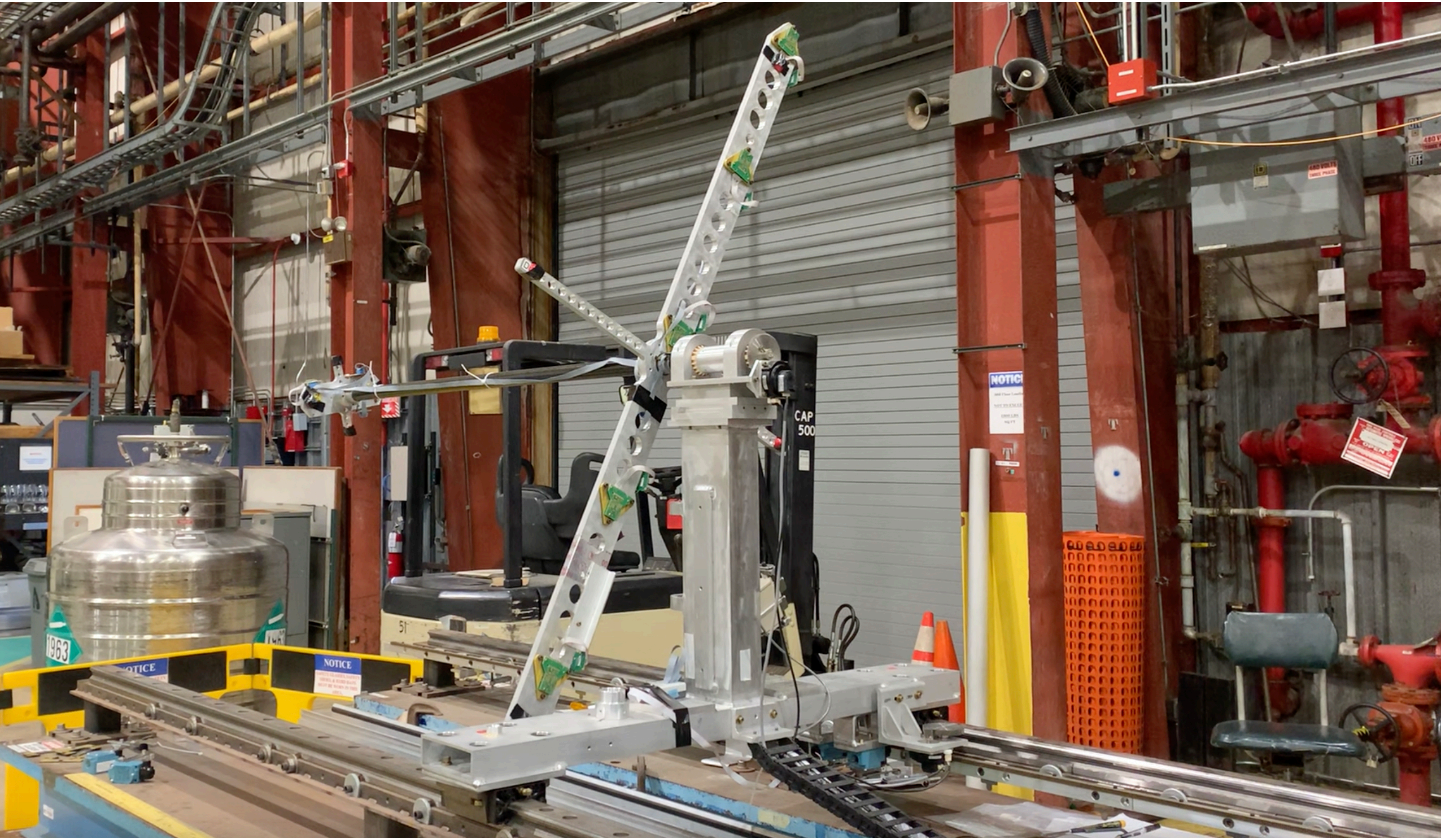
06/10/2025 Cole Kampa (Northwestern University) FMS (CM) | Hall Probe Calibration 9

- Results shown for 25C
- Performing calibration with temperature decomposition leads to modes in angular error
    - Likely temperature dependence of angular orientation (thermal expansion?)
- New effect with current fixture —> under investigation

Hall Probe Calibration: Next Steps

- Continuing to calibrate probes in test magnet
    - 14 probes total, scans for probe #2 in progress
- Troubleshoot angular dependence on temperature
- Investigating alternatives to SmarAct motors
    - Currently running with pair of SR-7021 —> no spares in hand
        - Motor 2 bound after calibration of 1st probe, and after unbinding began sticking. After adjusting rotation speed / acceleration, this is infrequent and self-correcting, but still present
    - Pair of SR-9219C arriving soon (?) (numerous delays)
    - Several alternate vendors have fallen through in procurement
    - Considering redesign with Motor 2 located outside magnet bore, coupled to optical encoder at rotation axis
        - Need <0.1 mrad precision for measurement, but only ~0.1 degree for actual position
        - Allows us to consider moderately magnetic / non-piezoelectric motors (cheaper, more robust)

ANL Test Stand : Overview



ANL Test Stand : Overview

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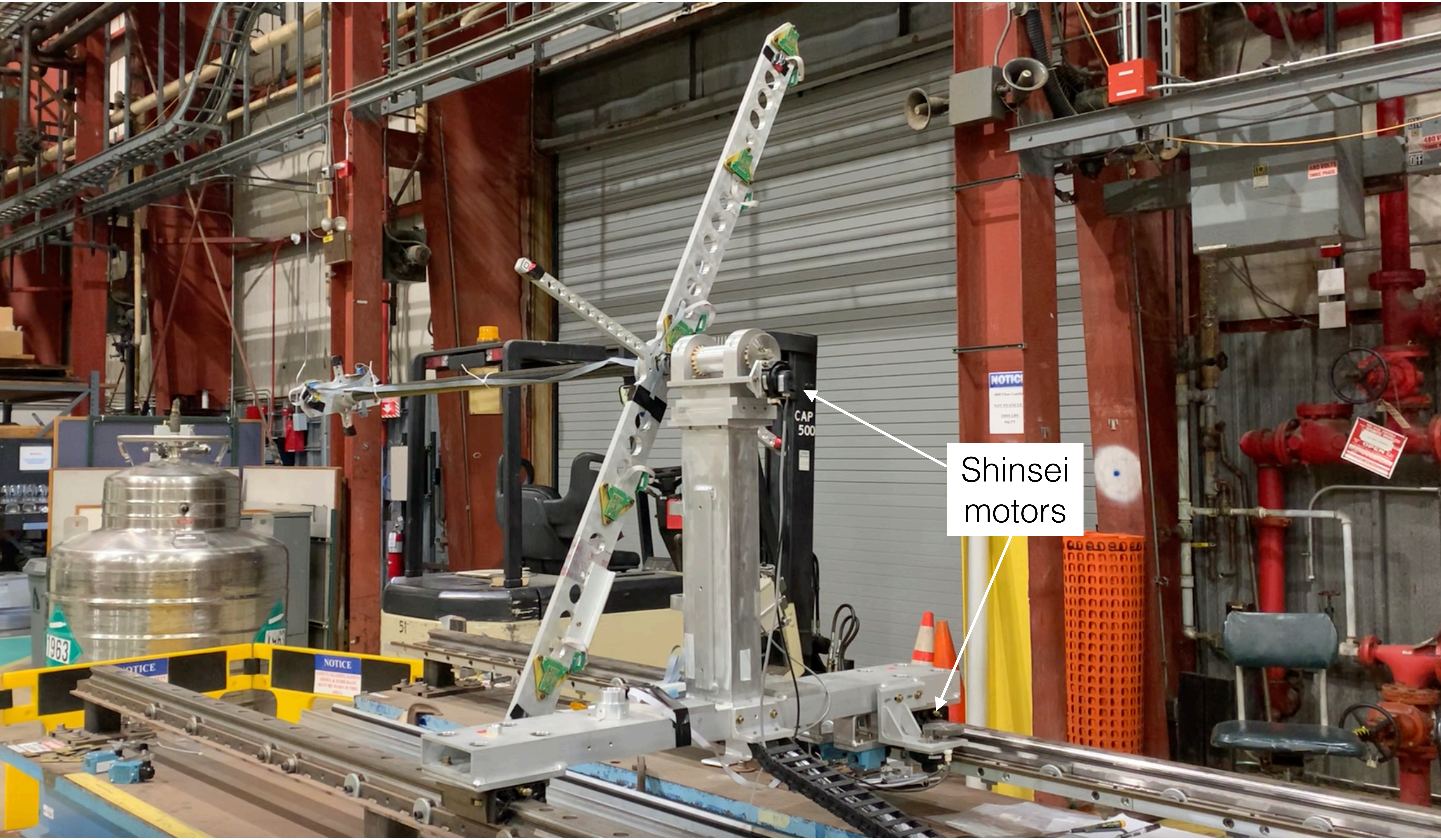


ANL Test Stand : Overview

Not shown:

- NMR probe in MRI magnet
- AT401 laser tracker
- Galil control board + motion control laptop
- DAQ laptop with LabVIEW, EMMA

ANL Test Stand: Motion Controller Tests

- Propeller motion driven by pair of Shinsei motors with Galil controller
  - Laptop w/ LabVIEW interface provides communication with top-level EMMA control
- Lots of ongoing work by Lei to characterize performance
- Issues solved
  - Difficulty enabling motors at startup —> fix to Galil code
  - Different Z scales between Galil / EMMA / physical reality —> fixes to Galil and EMMA, still investigating (see below)
  - Jerky motion —> tested different drivers, tuned motor speed
  - Abrupt homing —> fixed Galil bug setting deceleration rate to maximum
- Next steps
  - EMMA commands occasionally not received by Galil controller —> possible issue with intermediate LabVIEW layer, investigating whether this can be removed
  - Delay updating status / position after movement causes EMMA timeout —> partially fixed, occasional errors remain
  - Variability in Z motion —> does not seem to be physical issue with motor, investigating

ANL Test Stand: Laser Tracker Integration

- DSFM uses laser tracker to locate propeller in DS volume, using 8 reflectors mounted on propeller arms
  - Fixed reflectors in Mu2e hall, DS determine lab frame
- Purchased refurbished AT401 from Asset Exchange ($30k) for tests at Argonne
  - Previously, needed to schedule time with FNAL metrology to use AT403
  - Thanks to Myron Campbell (U Michigan) for funding!
- Thanks to Chuck Wilson (FNAL) for training!
- AT401 vs AT403:
  - Same operating conditions, measurement precision, software interface
  - Not tested in magnetic field —> will use AT403 for final mapping

ANL Test Stand: Laser Tracker Integration

- Only have 4/6 fixed reflectors —> manually move reflectors between fixed mounts
- To locate DSFM, need to measure >=3 reflectors per propeller (enough for plane fit)
  - By design, 3/4 reflectors should be visible at all points (4th sometimes blocked by propeller support)
  - EMMA logic predicts future reflector positions (including those not currently visible) based on current measurements
- Laser tracker successfully integrated; can now perform short scans
  - 8 theta steps from 0 to 360; Z = 20, 70 mm
  - >=3 reflectors visible on big propeller at all steps; locations within ~2 cm of expectation
  - Laser tracker still 'loses' reflectors on small propeller —> expected locations being slightly off causes laser to be blocked by support
- Next steps:
  - Optimize EMMA code to improve predicted position; test performance over longer scans
  - Use laser tracker to accurately measure Z motion / variability

Gear Rack / Bracket Redesign

- Motion along z driven by motor and gear at propeller foot, moving along gear rack mounted to 2nd tier bar

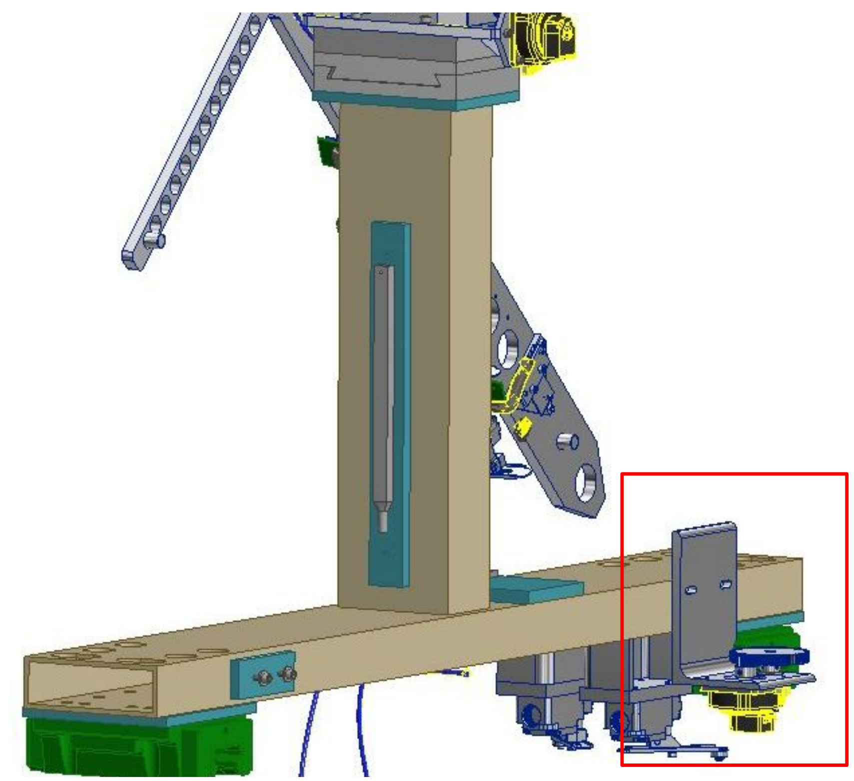
- Gear rack needs redesign for smaller footprint, to allow permanent installation in DS without interfering with detector train

    - Mounting interface to 2nd tier bar already fixed / communicated

- Gear bracket needs redesign to maintain coupling between gear, gear rack

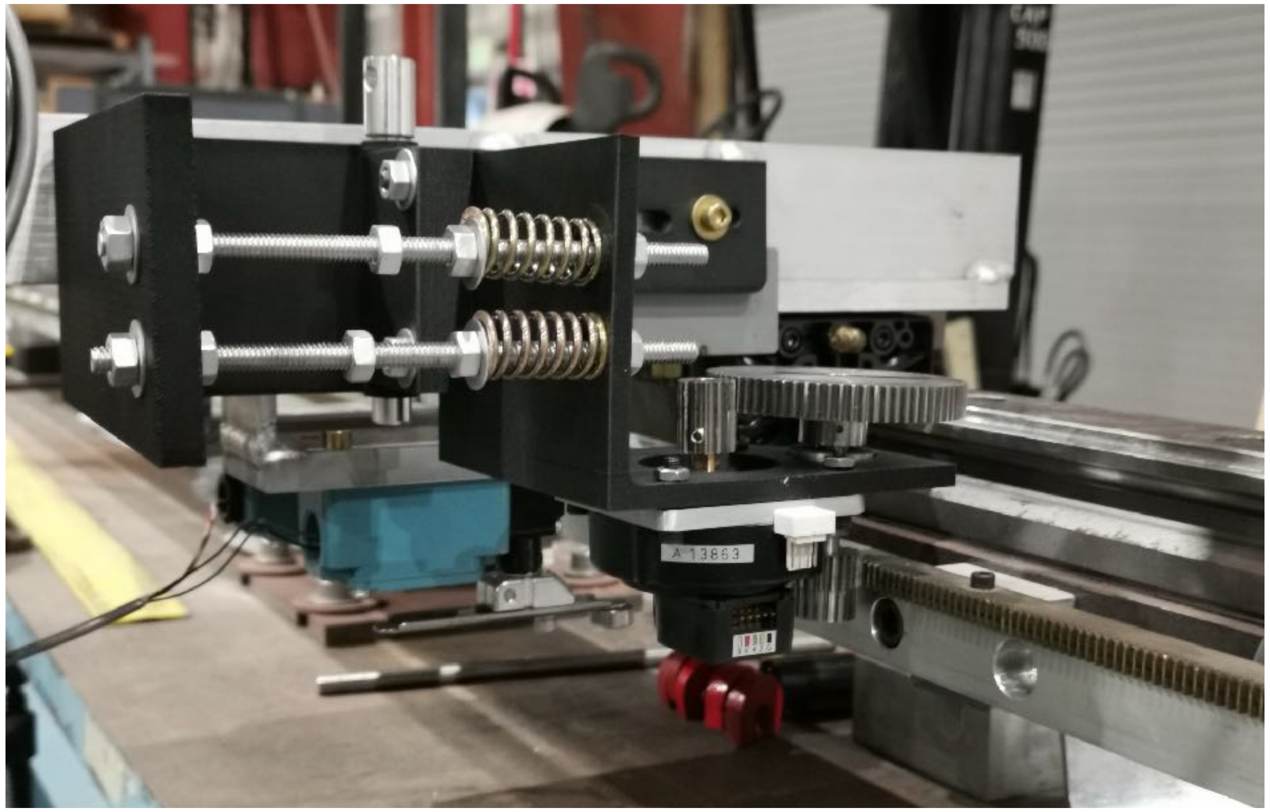
    - Adding spring-mount to prevent decoupling if gear rack not perfectly straight

    - Working with Jeff White (ANL), Izaiah Butler (NIU), Robert Fernandez (NIU), and Aidan Marshall (NIU) on design



Gear Bracket Redesign

- Bracket prototype 3D printed for quick testing, but encountered issues with print
  - Insufficiently rigid
    - Sag disengages driving gear from gear rack
    - Spring tension pushes printed piece out, rather than gear in
  - Too small spacing between drive gear and motor gear
    - Widened mounting hole to fix, but now slight misalignment between drive shaft, motor shaft
- Could be fixed with a different material / machined part —> continuing to iterate



NMR Field Monitoring

Proposed Scheme

(VPSP Port at Z= 14.561 m)

- 6 probes along 2nd tier bar. Probes 1-4 designed for 100% field only.
  1. Z = 8.546 m (start of tracker, DS-8)
  2. Z = 9.496 m (DS-8 to DS-9 transition, under bearing block)
  3. Z = 10.546 m (middle of DS-9)
  4. Z = 11.496 m (DS-9 to DS-10 transition)
  5. Z = 12.896 m (Downstream Calo. Most sensitive to the rebar effects. 70%-100% field)
  6. Z = 12.896 m (50% field)
- #3 is the originally proposed location in a homogenous region
- #2, 4, and 5 can detect "squeeze" along Z, as well as generally being sensitive to shifts in Z.
- #2 is directly underneath a Tracker bearing block.
- #5 detects 100% & 70% field. #6 in the same location (within a few cm) to detect 50% field.
  - Run to upstream VPSP port is only ~1.7 m.

- To measure ϕ dependence, add a few more probes at Z=12.896 m, but at different ϕ locations. Plan to run cabling to the same feedthrough port as the other probes.
  7. ϕ = 180 deg, Z = 12.896 m
  8. ϕ = 90 deg, Z = 12.896 m

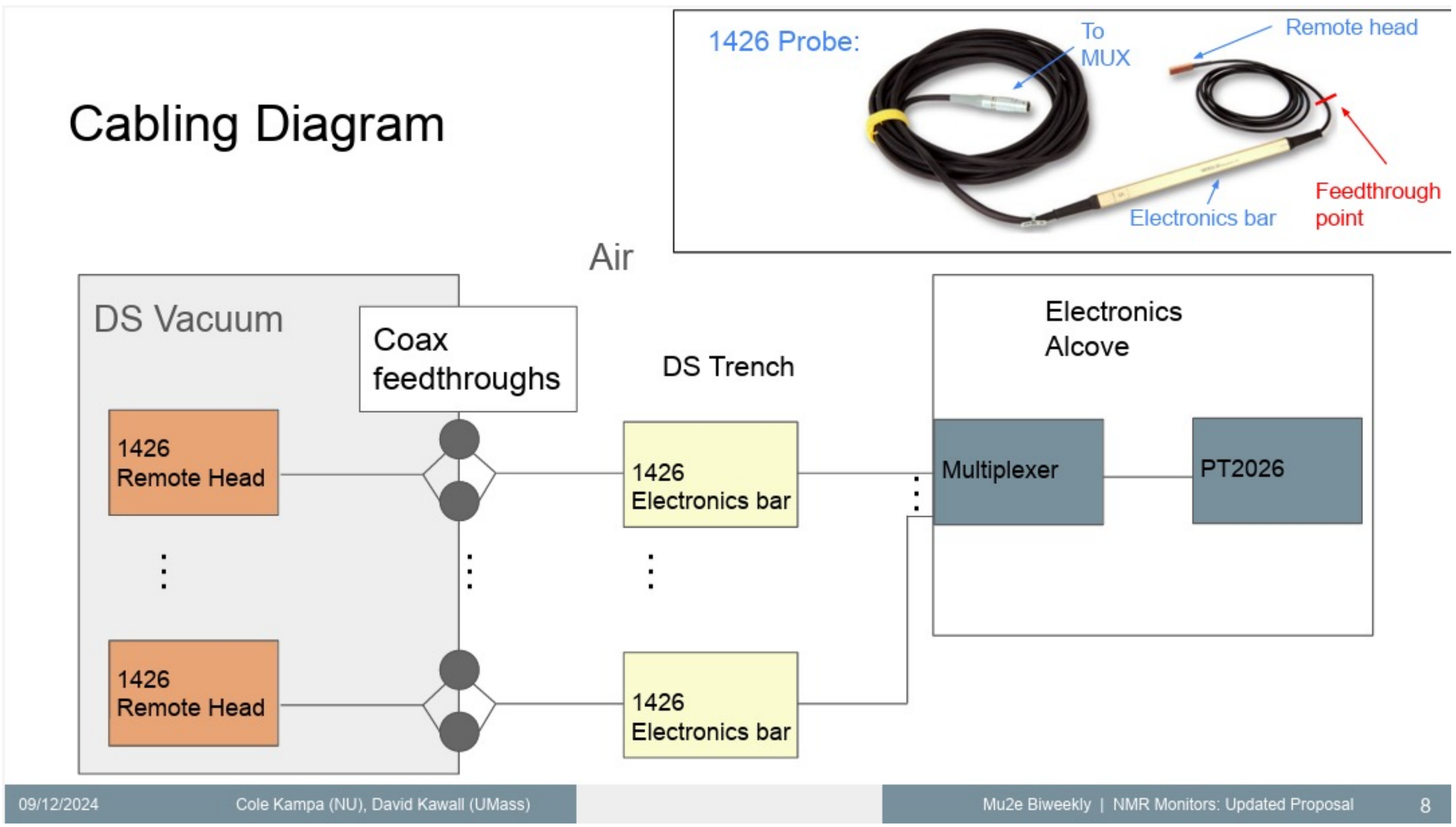
09/12/2024 Cole Kampa (NU), David Kawall (UMass) Mu2e Biweekly | NMR Monitors: Updated Proposal 13

Matt Bressler, Dave Kawall, UMass Amherst FMS Workshop June 10, 2025 2

Field monitoring is independent effort from FMS, led by Dave Kawall and Matt Bressler (UMass Amherst)
Close collaboration —> invited talk in FMS parallel

NMR Field Monitoring : Cabling

NMR B Field Monitoring System



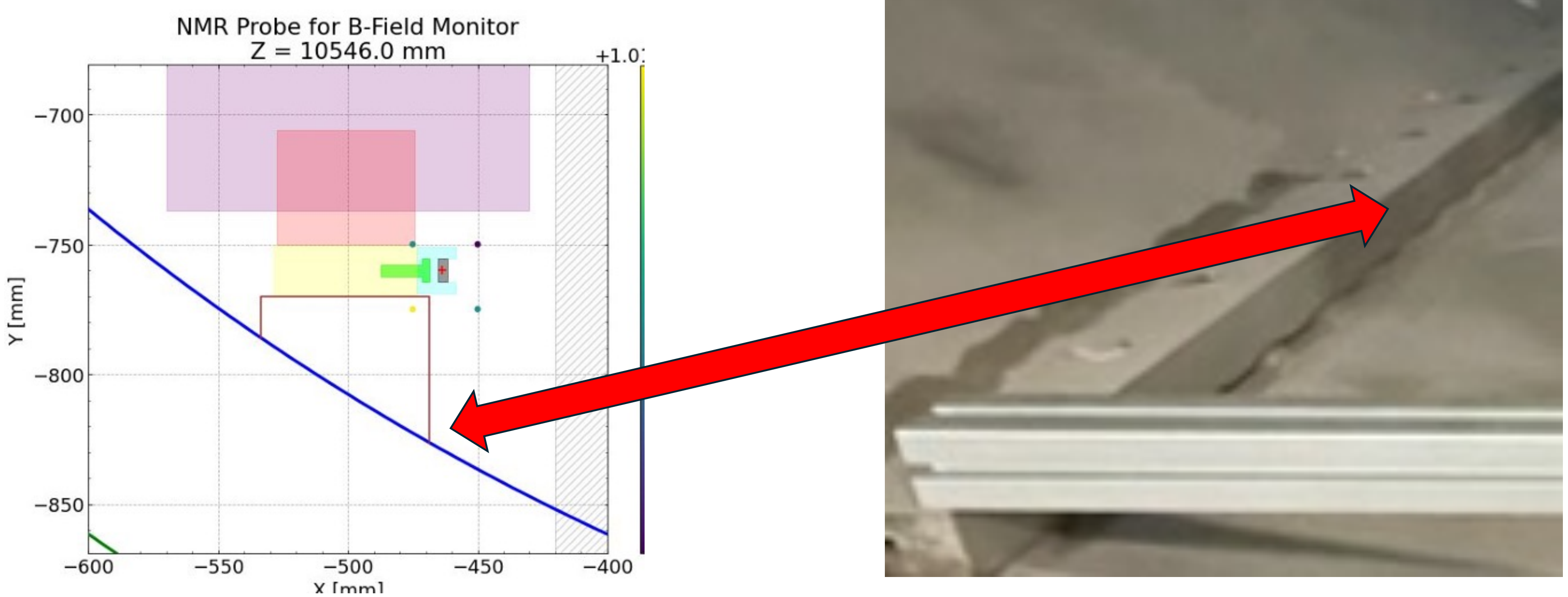
Matt Bressler, Dave Kawall, UMass Amherst

FMS Workshop June 10, 2025

- Dave and Matt iterating with Metrolab on coax cable / feedthrough
- Cable requirements: non-magnetic, vacuum-compatible, low-attenuation, **well-shielded**, small-radius
  - Can reduce noise with careful placement
- Feedthroughs must be vacuum-tight, compatible with VPSP flange —> investigating options
  - Need feedthroughs for coax, 8-connector cables

NMR Field Monitoring : Other Work

2nd Tier Bar Mount



- Investigating magnetic susceptibility of welds along 2nd tier bar
  - Weld bead with permeability 1.6, diameter 0.5 cm causes 10^{-4} relative field perturbation at 6 cm
  - Plan for Andy to measure magnetic susceptibility at next GA visit
- Considering different options for magnetic probe heads
  - Fully custom —> can adjust sample size, material

Summary

- Lots of FMS work in past 8 months
  - Calibration of 1st Hall probe in FNAL test magnet, program continuing for remaining probes
  - Active testing at Argonne setup, including motion controller improvements and laser tracker integration
  - Mechanical design improvements for gear rack, mounting bracket
- FMS next steps:
  - Continue Hall probe calibration and incorporate full temperature dependence
  - Use tests at Argonne setup to optimize EMMA, motion control
  - Finalize mechanical designs for gear rack, bracket
- NMR field monitoring investigating hardware requirements, magnetic environment
  - Active communication with Metrolab

BACKUP