



IMMW22

International Magnetic
Measurement Workshop

26 - 30 SEPTEMBER | VIRTUAL
CAMPINAS-SP, BRAZIL



**Overview of Magnetic
Measurement Activities at
Fermilab**

J. DiMarco
28 September 2022

Acknowledgements –

The programs presented here involve the efforts of many people in our Magnet and Test and Instrumentation departments, including, but not limited to (and in no particular order):

G. Velev,
D. Harding,
T. Strauss,
G. Chlachidze,
S. Stoynev,
S. Feher,
J. Nogiec,
K. Trombly-Freytag,
P. Akella,
D. Walbridge,
P. Thompson,
D. Assell,
M. Baldini,
V. Kashikhin,
V. Nikolic,
M. Kifarkis,
A. Makulski,
D. Orris,
M. Tartaglia,
K. Badgley,
O. Kiemschies

Apologies to those I've left off...

Magnetic Measurement Activities at Fermilab

Focus on the following:

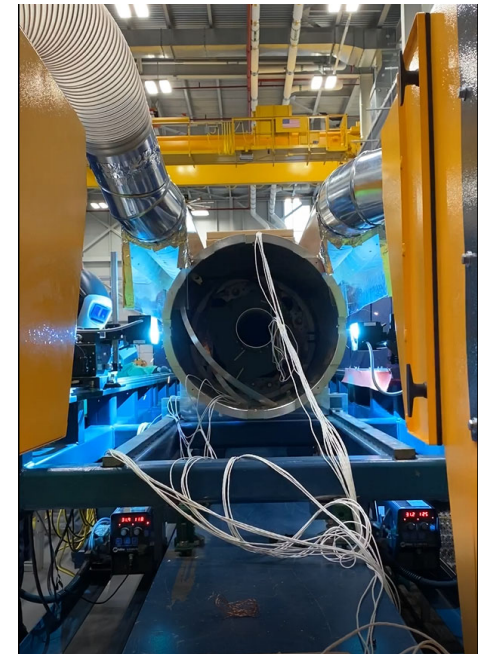
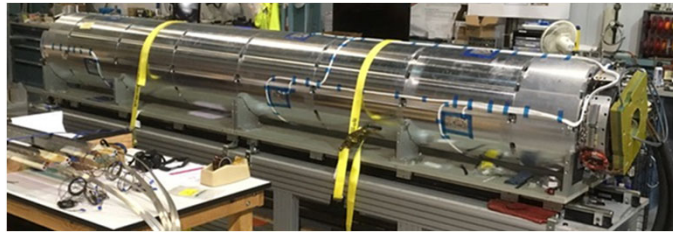
1. Triplet quadrupoles for the US Hi-Lumi-LHC Accelerator Upgrade Project (AUP)
 - i. Alignment measurements with Single Stretched Wire (SSW)
 - ii. Field quality - rotating coil
2. Proton Power Upgrade magnet measurements for ORNL
 - i. Hall probe – new facility for scanning
 - ii. Dipole SSW
 - iii. Curved single wire bundle flatcoil
3. Probe projects
 - i. 1m probe for Argonne
 - ii. 12mm DQS probes for NSLSIIu
4. Other upcoming projects
 - i. PIP-II Booster upgrade
 - i. Multi-channel curved PCB array 15Hz, 20Hz
 - ii. Pulsed magnet – field integral and homogeneity (20kA in 0.2ms, 0.5ms dwell)
 - ii. ITER Hall probe calibrations
 - iii. Mu2e Detector Solenoid field mapping ($1e-4$)
 - iv. New Vertical Test facility

US Hi-Lumi-LHC Accelerator Upgrade Project (AUP)

Interaction Region Quadrupoles

- 10 cryo-assemblies each having two 4.5m-long Nb₃Sn high-gradient quadrupole magnets each.
- 150mm bore, 132 T/m gradient at 16.2kA
- Magnets are being assembled at LBNL, vertically tested at 1.9K at BNL, then assembled in pairs and tested at 1.9K at Fermilab

- Alignment measurements with Single Stretched Wire (SSW)
- Field quality - rotating coil



2 magnets welded
into single
stainless steel skin

First cryo-assembly has magnets MQXFA03, MQXFA04 - alignment measurements with SSW during fabrication

11.023 m

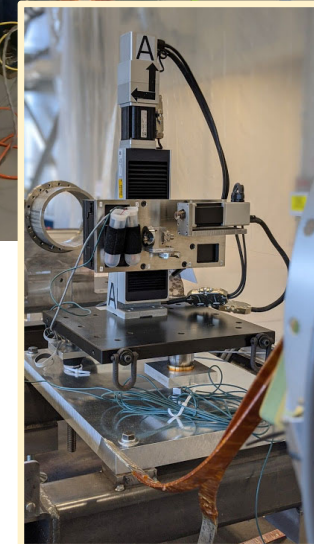
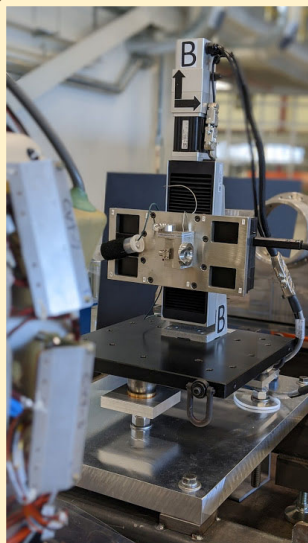
Z=0



EMMA – based data acquisition system (see talk by N. Nogiec on Monday)

SSW for alignment pre/post welding measures:

- Axis of each magnet to $100\ \mu\text{m}$ at ends ($25\ \mu\text{rad}$)
- Centers to $25\ \mu\text{m}$
- Roll to $100\ \mu\text{rad}$
- Z-center (axial) to 1mm

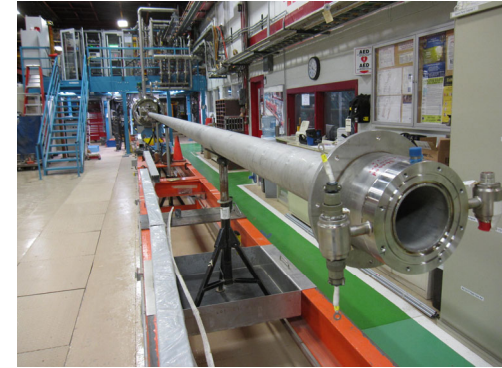


$1\ \mu\text{m}$ accuracy
Aerotech stages



First article is ready to be sent to cold test facility!

1.9K Magnet Test Facility (MTF)



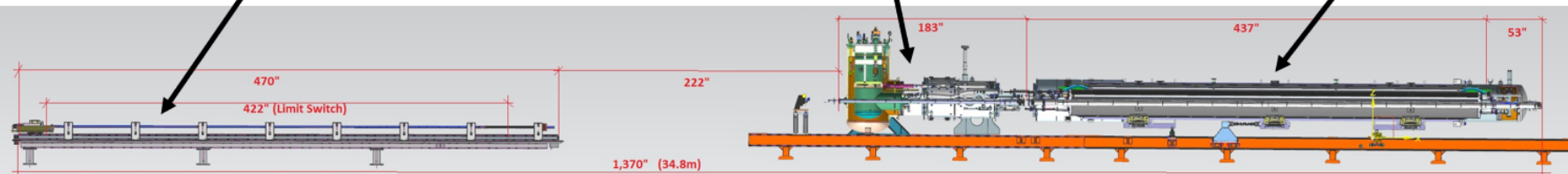
100mm
warm
bore tube
diameter

Rotating coil
motion system

Feedcan/adapter box
(bore diameter 45mm)

Precision motion rail

Magnet assembly
(magnet bore
diameter 100mm)

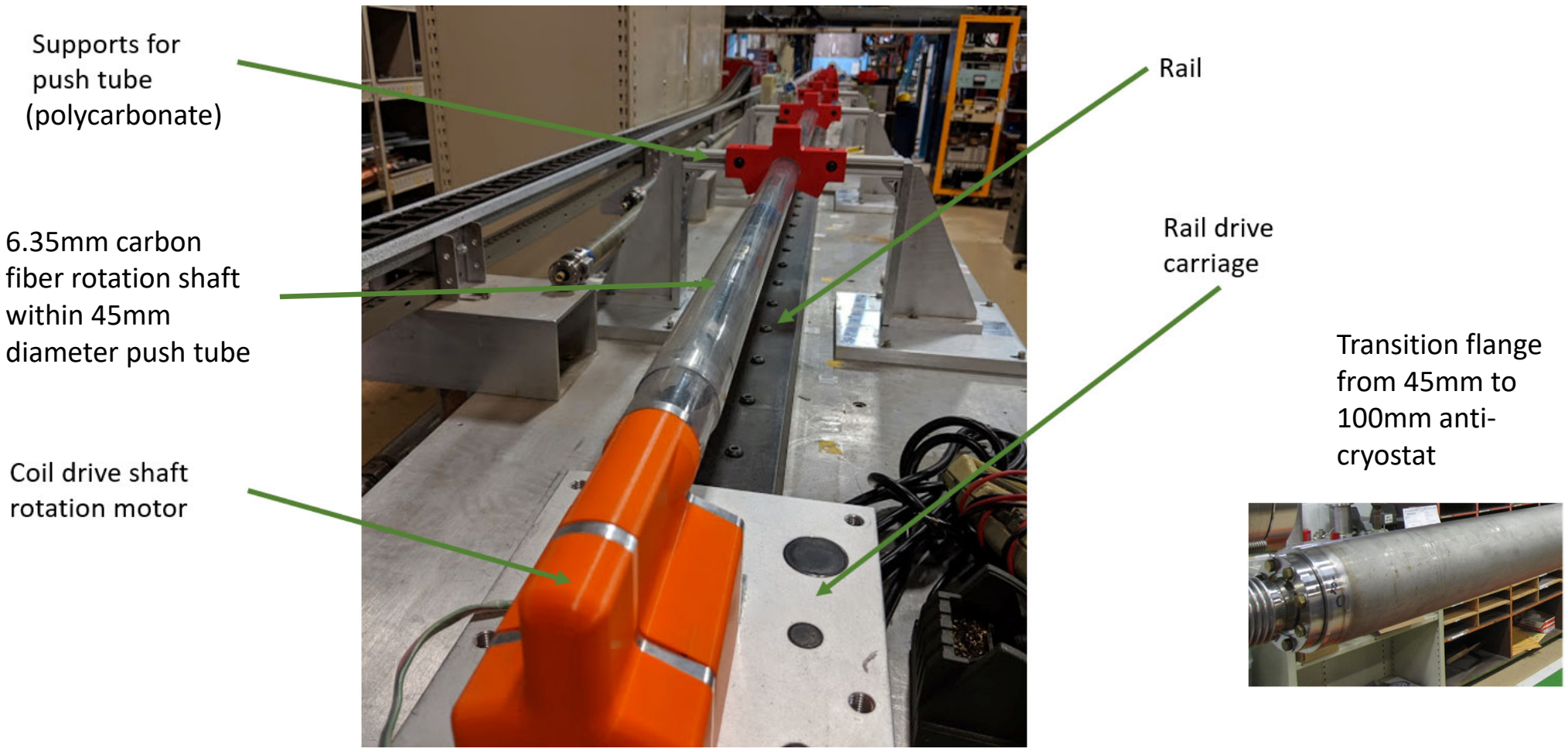


12m (10m stroke)

10m

11m

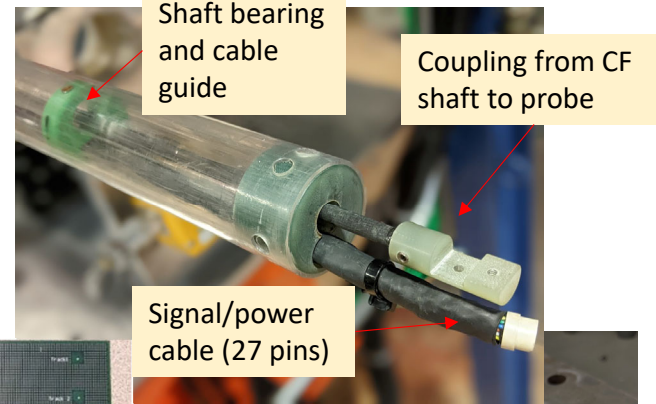
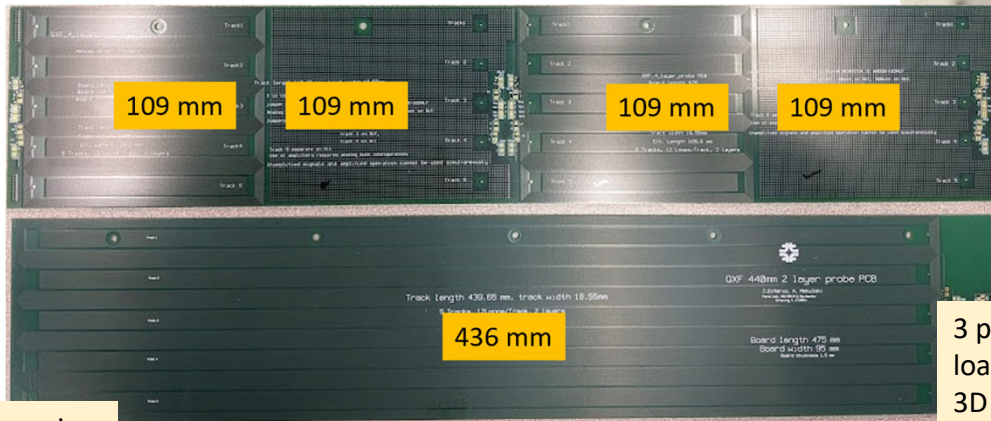
22m shaft needed to connect rotational motor to probe



Push tube and CF drive shaft are quasi-flexible and sag to bottom of WBT after about 1m past flange

Rotating Coil 'FERRET' probe

Probe has both 436mm length probe and 2x109mm probes encased in stiff CF plates— can obtain magnet integrals as well as local end fields

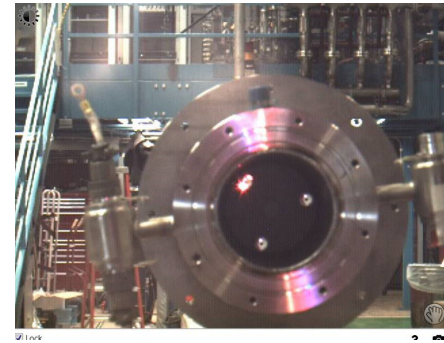
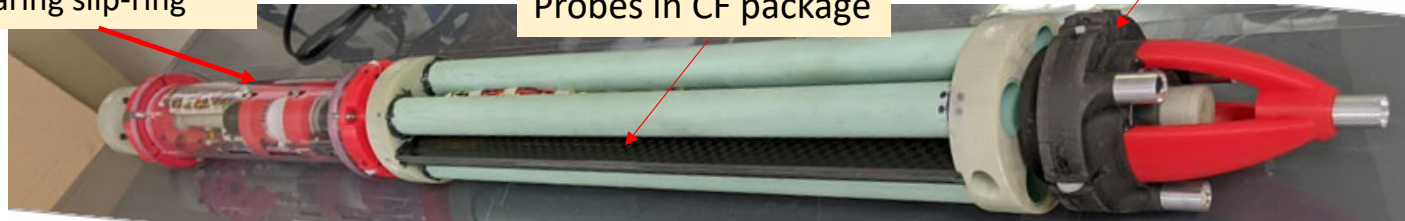


Leica AT960

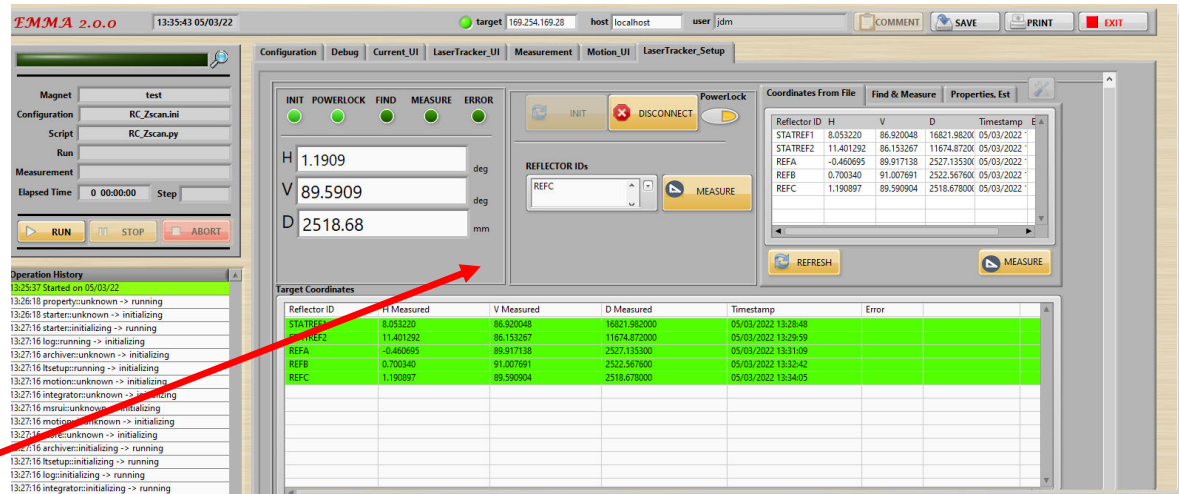
Laser Tracker targets on probe give distance as well as yaw and pitch angles of probe

Non-metal encoder and ceramic bearing slip-ring

Probes in CF package

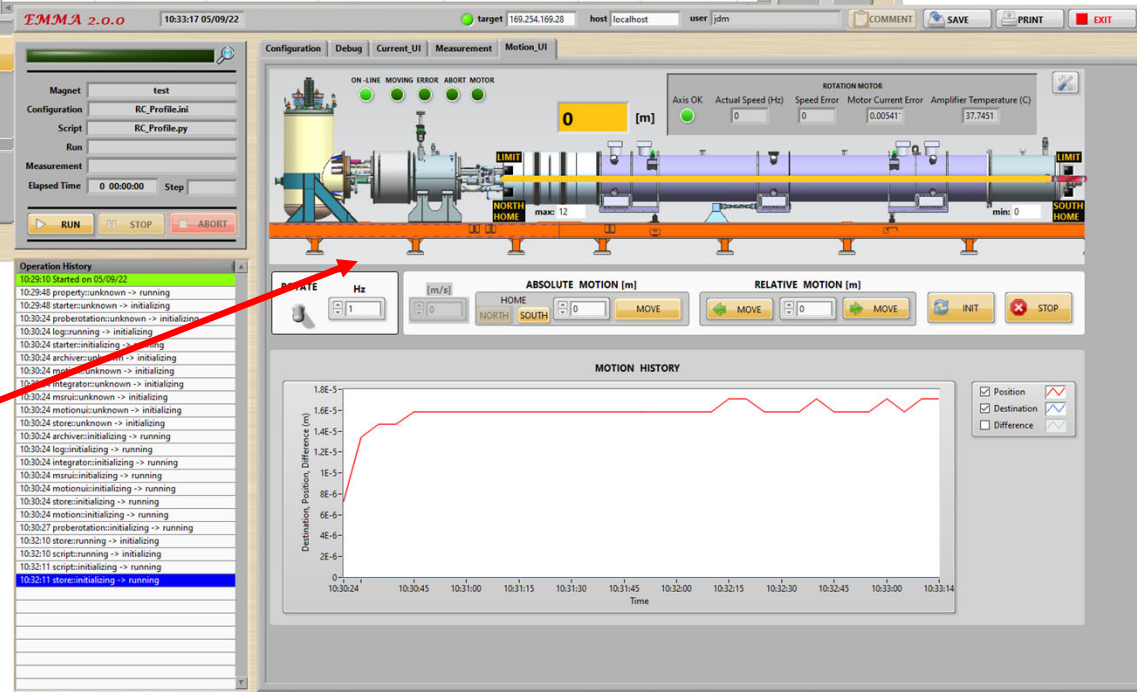


EMMA data acquisition/control for rotating coil



Laser Tracker set-up panel

Probe signals acquired with National Instruments 4464 24-bit ADC at 204.8kHz with FPGA integration; streaming 8 channels of 1024 angles/rev flux data with 4Hz rotation rate



Motion User Interface panel

Proton Power Upgrade magnet measurements for Oak Ridge National Lab (ORNL)

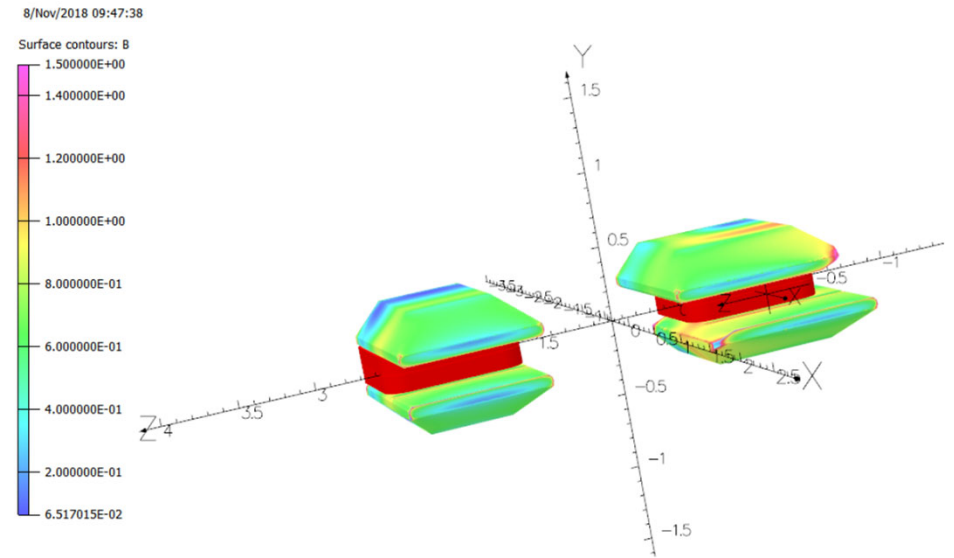
To double power for Spallation Neutron Source to 2.8MW. Fermilab designed, building and testing new chicane dipoles and beam dump septum magnets.

Chicane dipole (measure individually and for pair)

- Field mapping with Hall probes (mapping to $1e-3$ in special regions)
- Field integrals with SSW (strength to $1e-4$, homogeneity to $1e-4$)

Dump Septum

- Dipole and quad field integrals along curved beam path to $1e-4$



2.1m separation between chicane magnets. Effective lengths about 1.4m

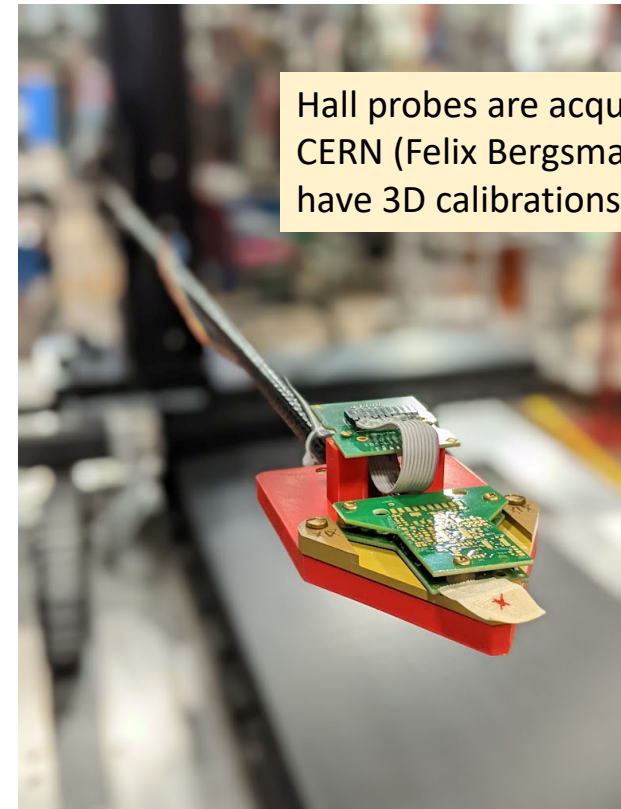
First chicane dipole magnet is ready for delivery to test facility



Test facility has new 3-axis mapper – 1m travel, 10um accuracy, Aerotech stages.



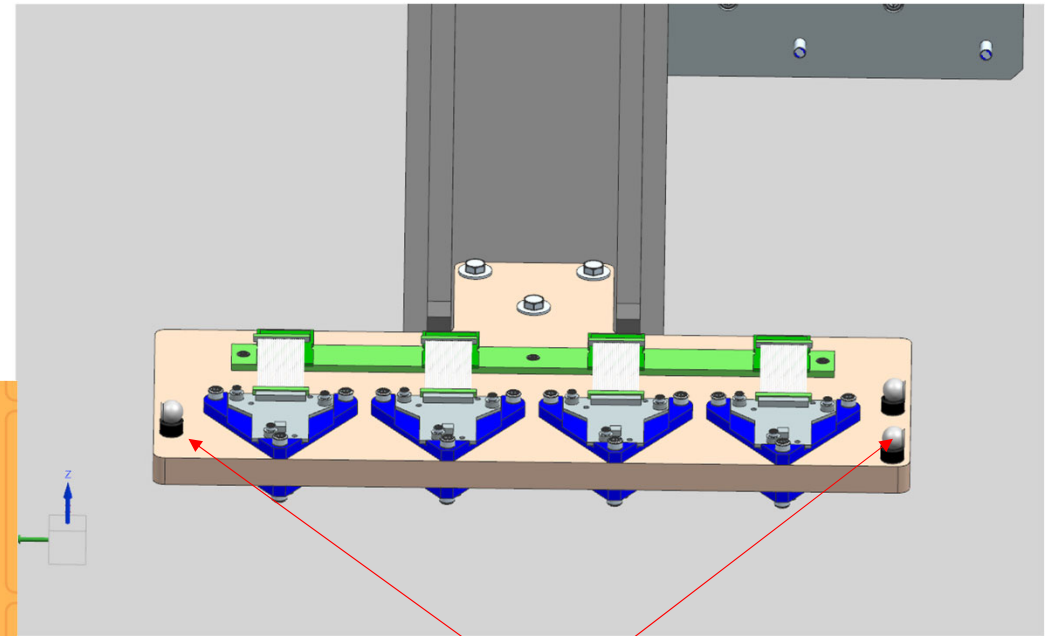
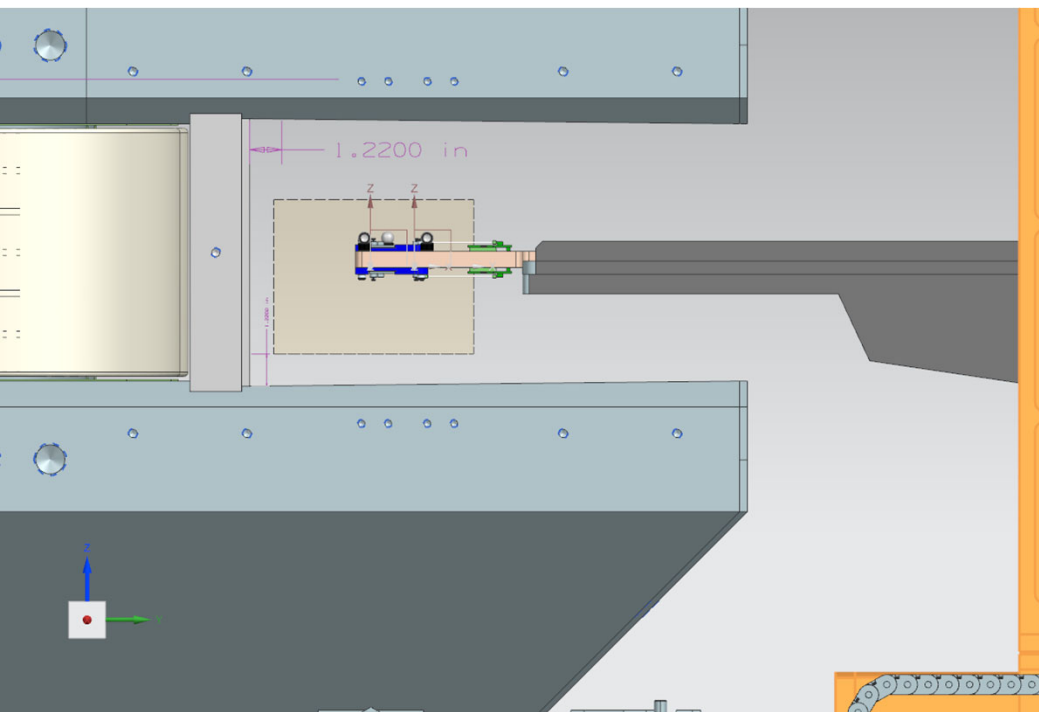
Single Hall probe on holder for evaluation in test magnet



Hall probes are acquired from CERN (Felix Bergsma) and have 3D calibrations to $1e-4$

These Hall probes will also be used for Mu2e detector solenoid mapping

After testing individual probes, 8 of them will be arrayed on a holder as shown



Laser tracker target fiducials

Probes can be made to overlap positions during motion as needed to establish intercalibration

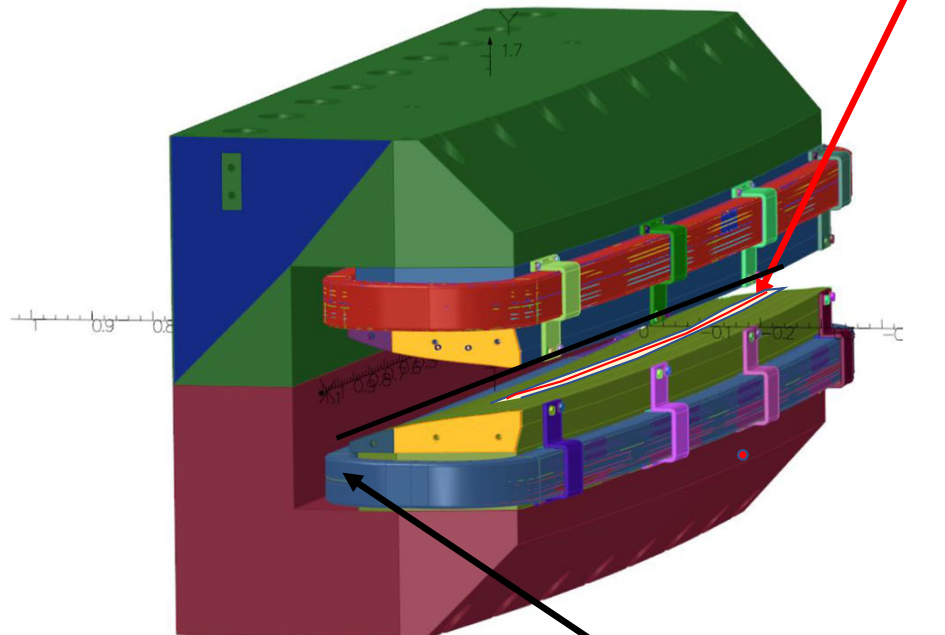
Septum magnet- Dipole and gradient field integrals in gap

Single Multi-turn Flatcoil (SMF) on stiff strongback.
Curved shape matching beam trajectories. (Next 6 months)

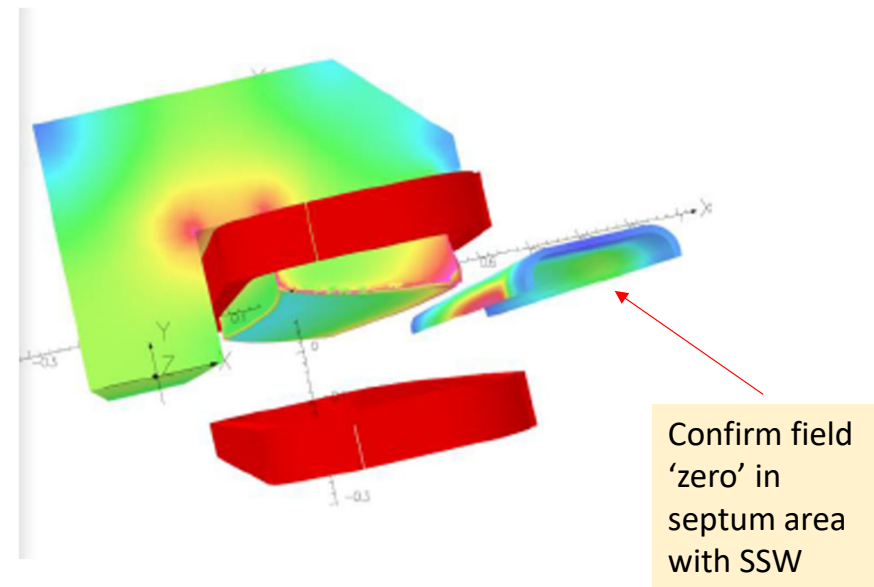
SMF slides on stationary surface within the magnet
at center of gap

Translated precisely at each end by the Aerotech stages on the test
stand to achieve high-accuracy dipole and gradient integral
measurements. Inside edge of magnet serves as reference surface.

Like a curved, multi-turn version of SSW



Stationary
multi-turn
return wire that
completes loop

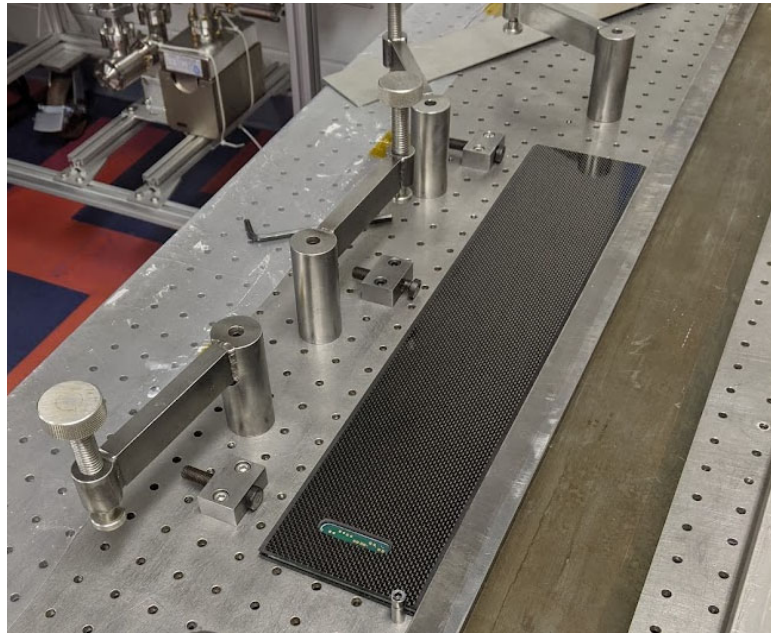


Confirm field
'zero' in
septum area
with SSW

Probe development

A standard fabrication process for PCB probes has been developed and applied to the latest probe projects

- APSU 1m probe
- AUP MQXF probes
- NSLSIIu probes



Optical table, straight edges are used together with tooling to sandwich PCB probes in high-stiffness carbon fiber (plates or pultruded strips).

The PCB/CF package is then inserted into slots machined into end plugs, aligned, and secured in place with additional supports that span the two end plugs

1m PCB probe for APSu

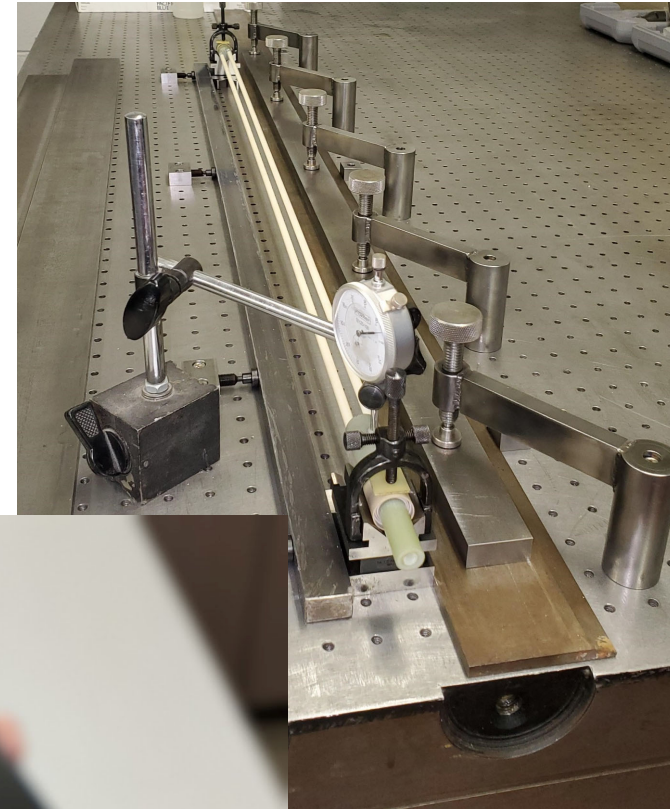
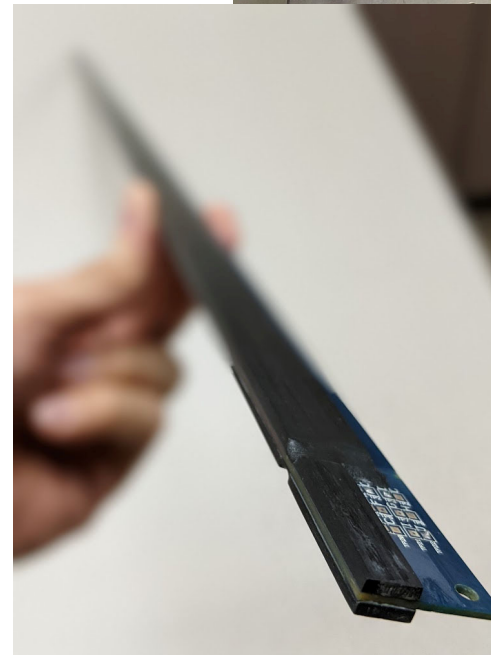
21mm wide, 1001mm long, 14-layer PCB.
4 tracks per layer with 4-turns per track .

Note ceramic support rods shown are switched to CF in final probe

Final assembly inserts this into a High Modulus Carbon Fiber outer sleeve with 22.2mm ID, 23.8mm OD

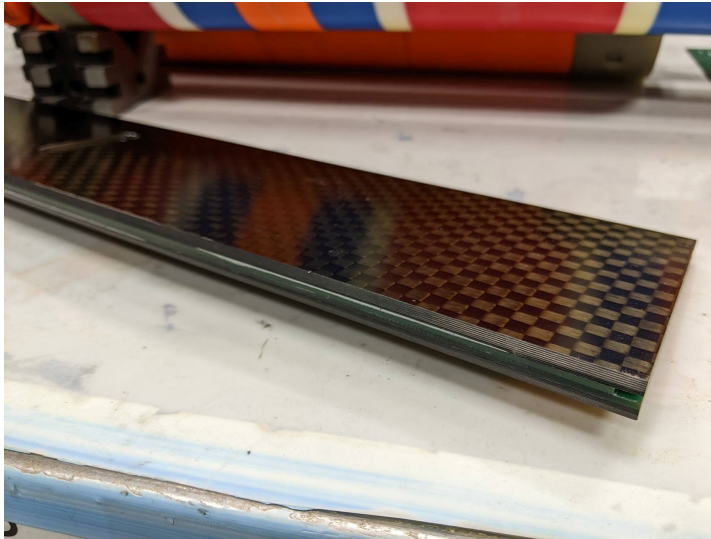
Aspect ratio > 45:1

Radial clearance to outer sleeve < 0.6mm



AUP MQXF probe

Similar technique applied
for MQXF AUP probes



NSLSII upgrade at BNL

Needed 12mm diameter probes

Combined purpose to measure quad magnets as well as sextupole

12mm diameter DQS-buck probe, 270mm active length (aspect ratio 22.5)

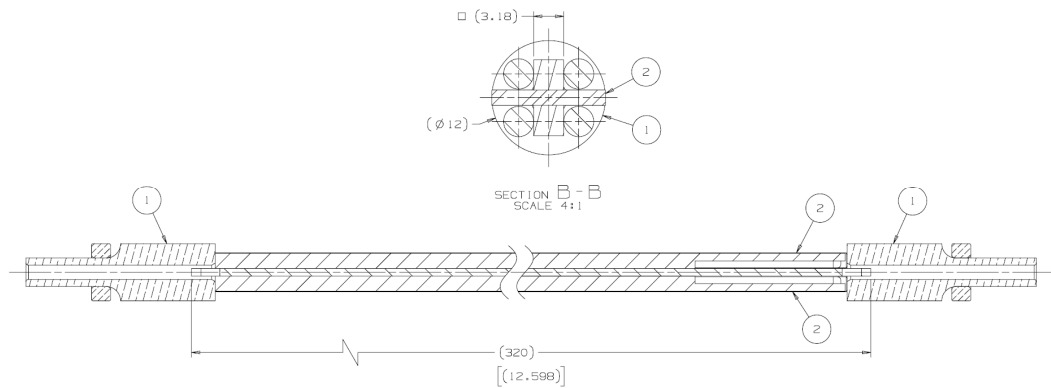
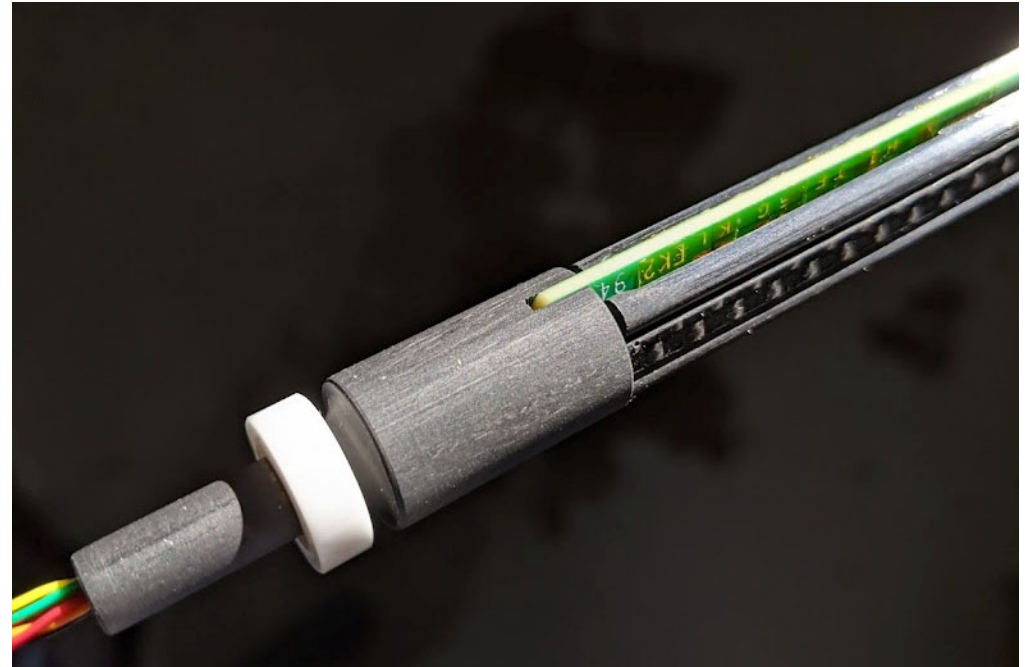
16-layer, 6 tracks/layer, 3-4 turns per track

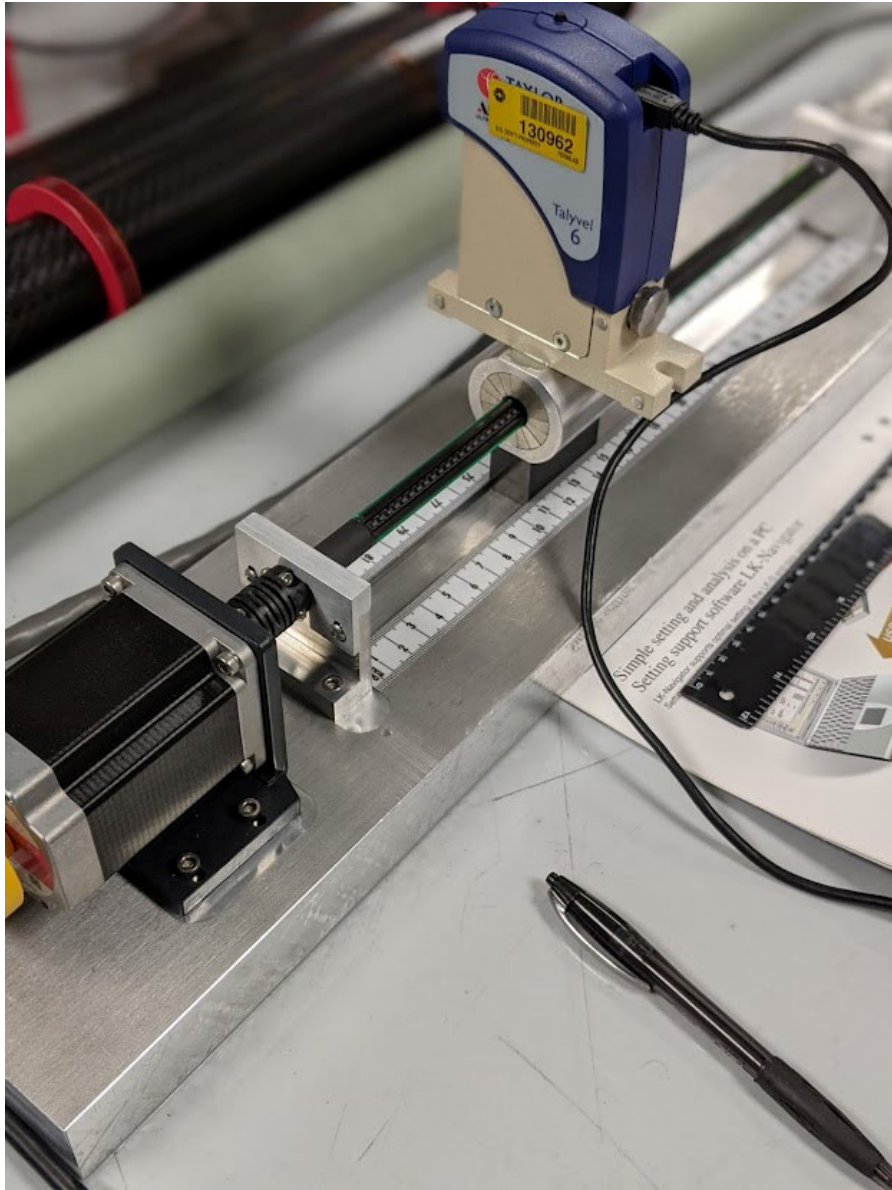
75um trace / 75um space on PCB



Probe fabrication:

- Carbon fiber end parts and CF support plate/rods.
- 3 complete probes were fabricated with the carbon fiber parts



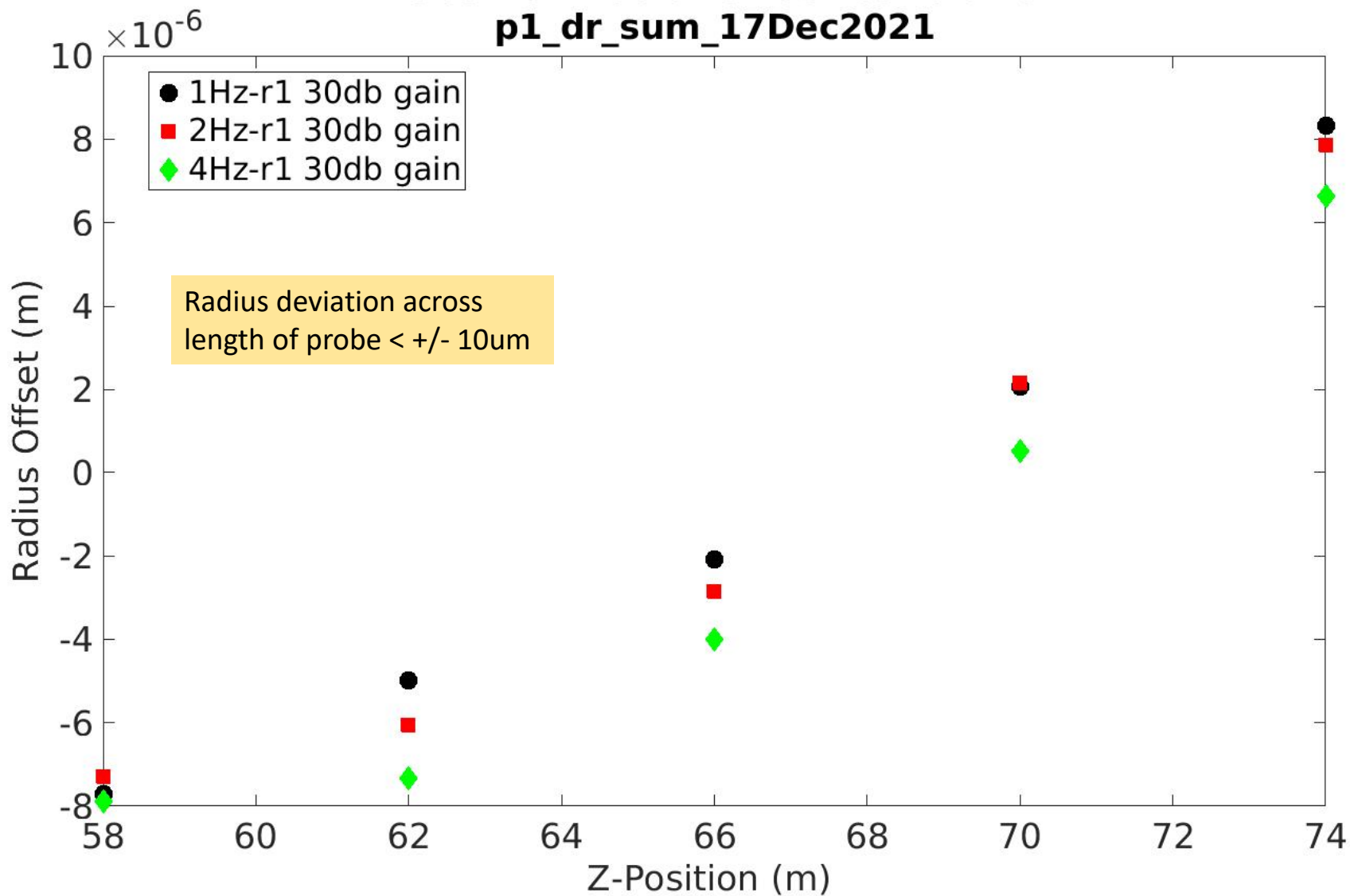


Test platform for evaluating probes

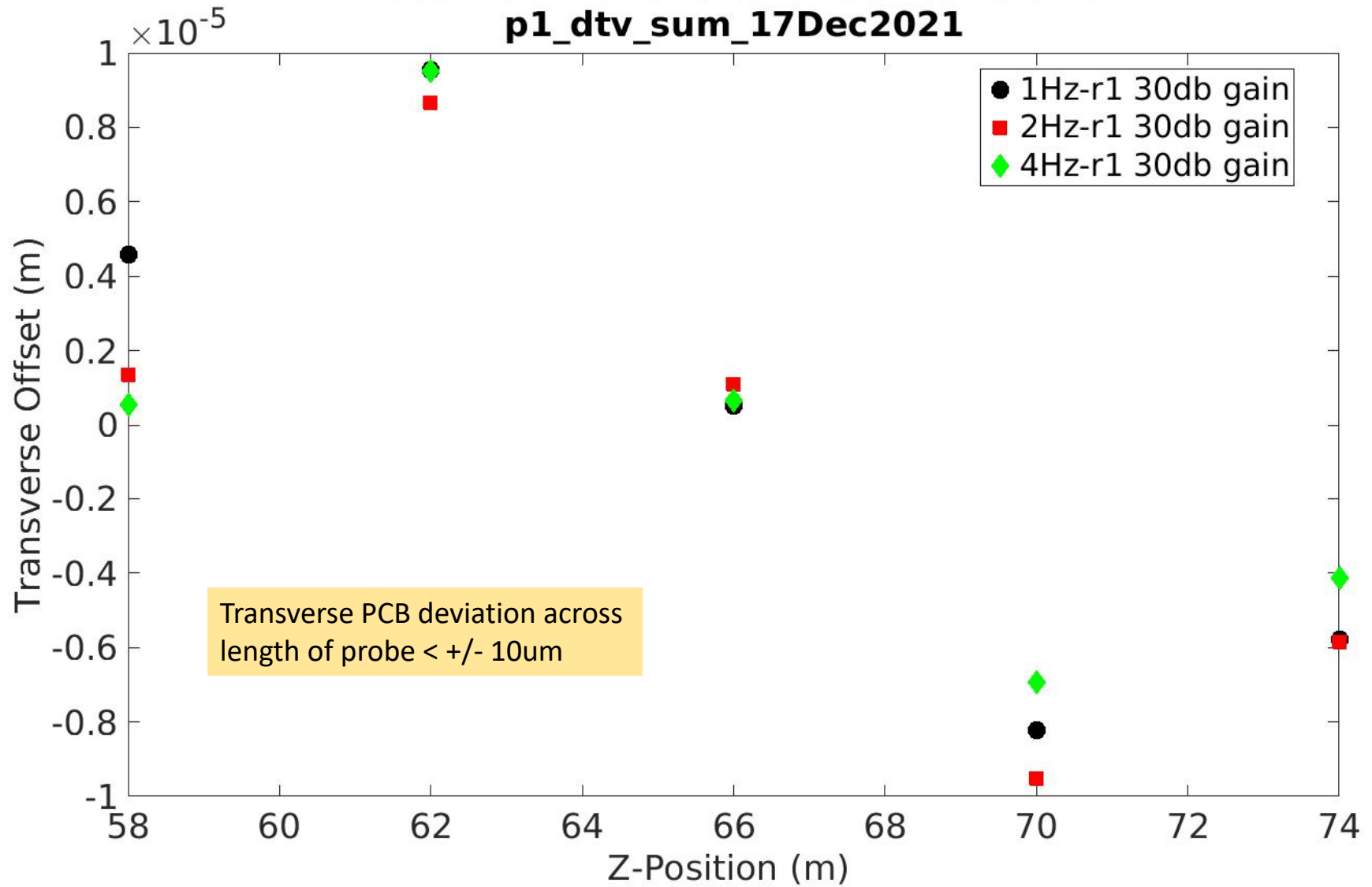
- Bearings clamped at each end
- Encoder, slipping, motor
- Magnet can slide in machined groove across length of probe
- Micro-level monitors angle of magnet at each position



Probe PCB Radial Offset Calibration p1_dr_sum_17Dec2021



Probe PCB Transverse Offset Calibration p1_dtv_sum_17Dec2021

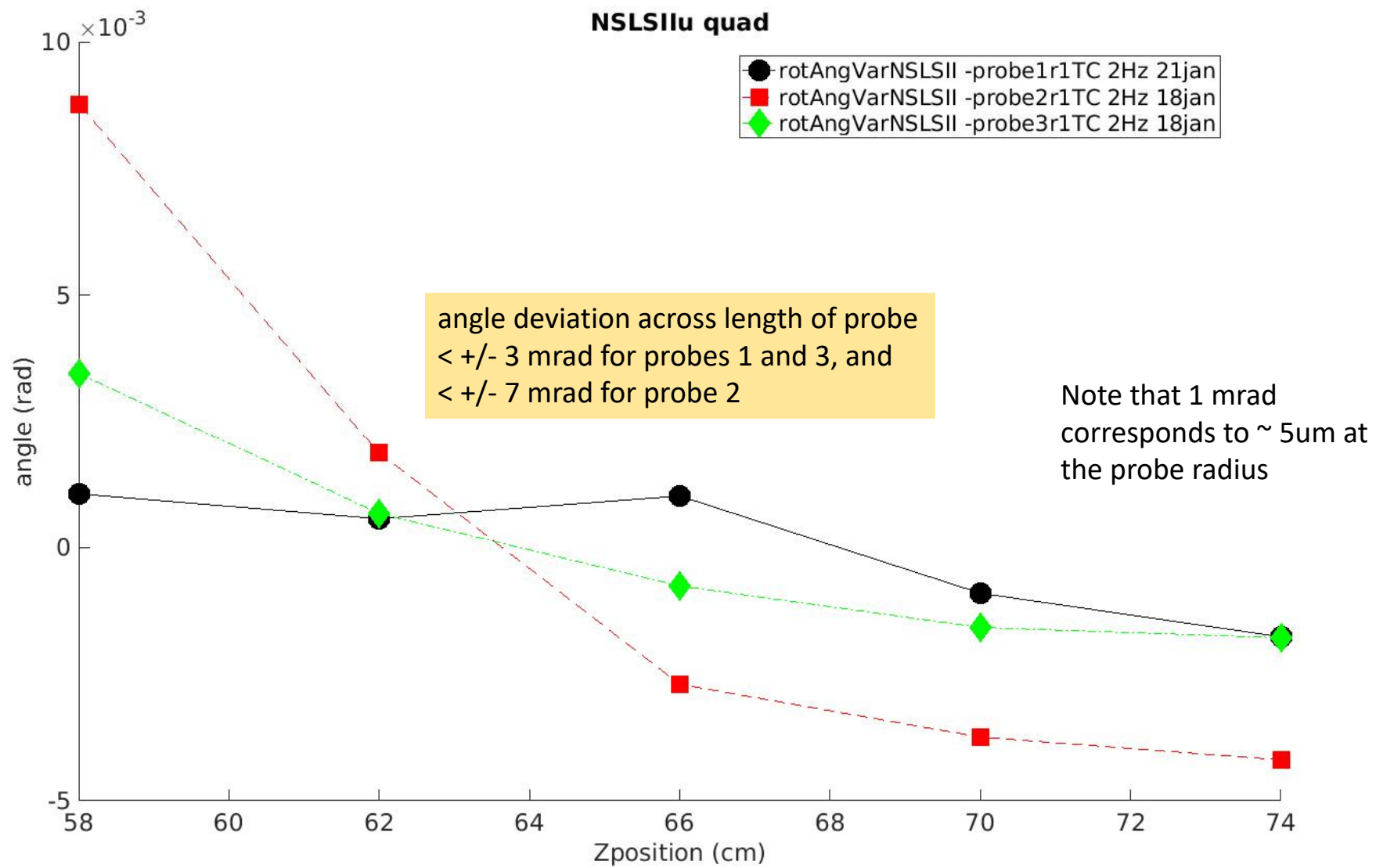


Buck ratio summary

	DB_ratio*	QB_DQB1	QB_DQB2	QB_DQSB	SB_DQSB*
P1	15	650	1100	1400	250
P2	150	195	650	195	130
P3	30	3000	3000	3000	150

Buck ratio = harmonic amplitude of particular order in the UB winding / harmonic in buck winding

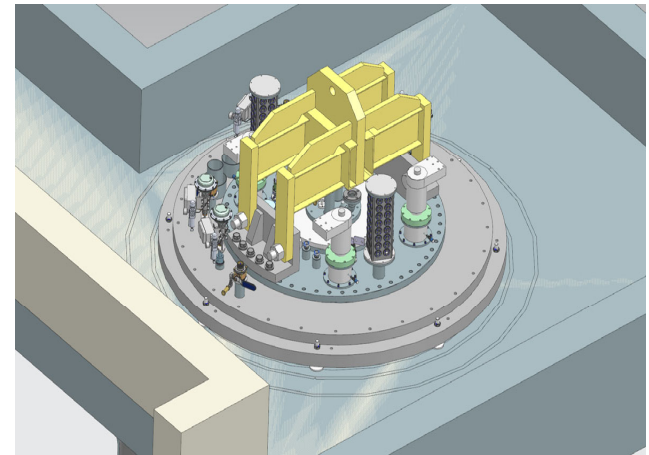
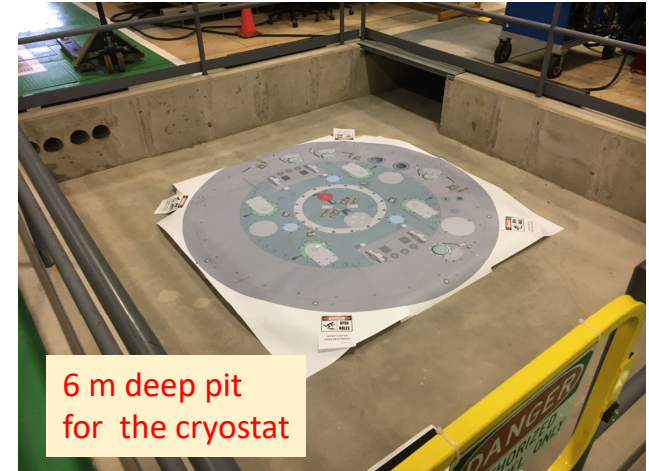
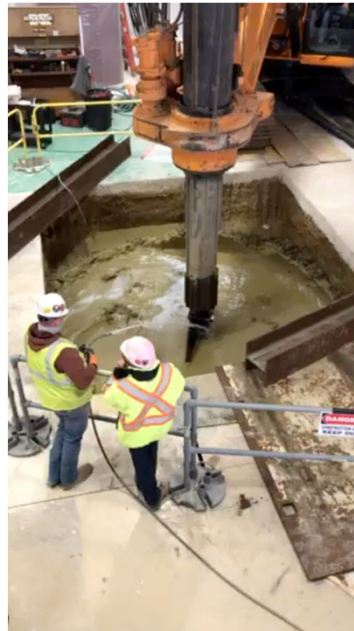
* These harmonics can be small to start with (unlike main fields), so with small numerator BR may not appear large in any case.



In closing, we mention a new facility that will be online shortly...

HighFieldVMTF

- Fusion mode (FES) - cable test
 - 15 T@1.9K (~15 kA) main dipole with diameter 1.3 m
 - Anti-cryostat with sample holder for cable test
- Magnet R&D mode
 - Large aperture/large diameter magnets LTS@1.9
 - Hybrid magnet tests (LTS + HTS) at 1.9 K powered with 24 kA and 16 kA PSs
 - Full diagnostics and protection
 - Dedicated top & lambda plate



Thanks for your attention!

Courtesy George Velev