Recent Magnetic Measurement Activities at Fermilab

09Oct2024

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***Abstract*— Magnetic measurements are performed at Fermilab for both projects internal to the lab and as well as work for other laboratories. This talk briefly overviews the current projects and types of measurements we're currently involved in, focusing on the more interesting or challenging.**

Recent projects:

- **US-LHC Hi-Lumi Accelerator Upgrade Project (AUP)**
- **Magnets built for Oak Ridge National Lab (ORNL) Proton Power Upgrade (PPU)**
- **Fermilab's Proton Improvement Plan (PIP-II)**

Measurements include

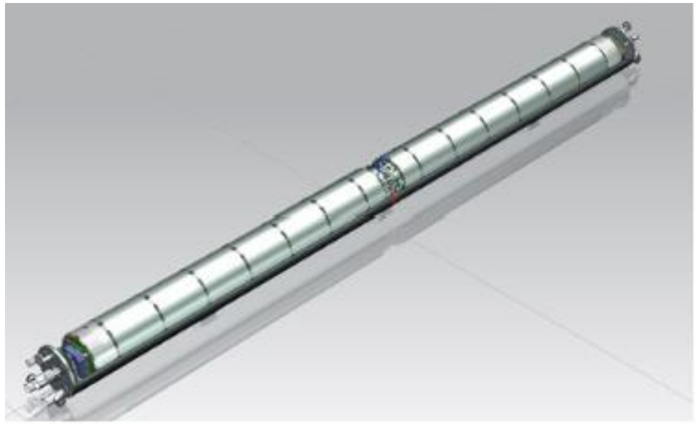
- **Large magnet lengths and apertures**
- **Curved magnet trajectories**
- **Measurements during AC magnet excitation.**

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

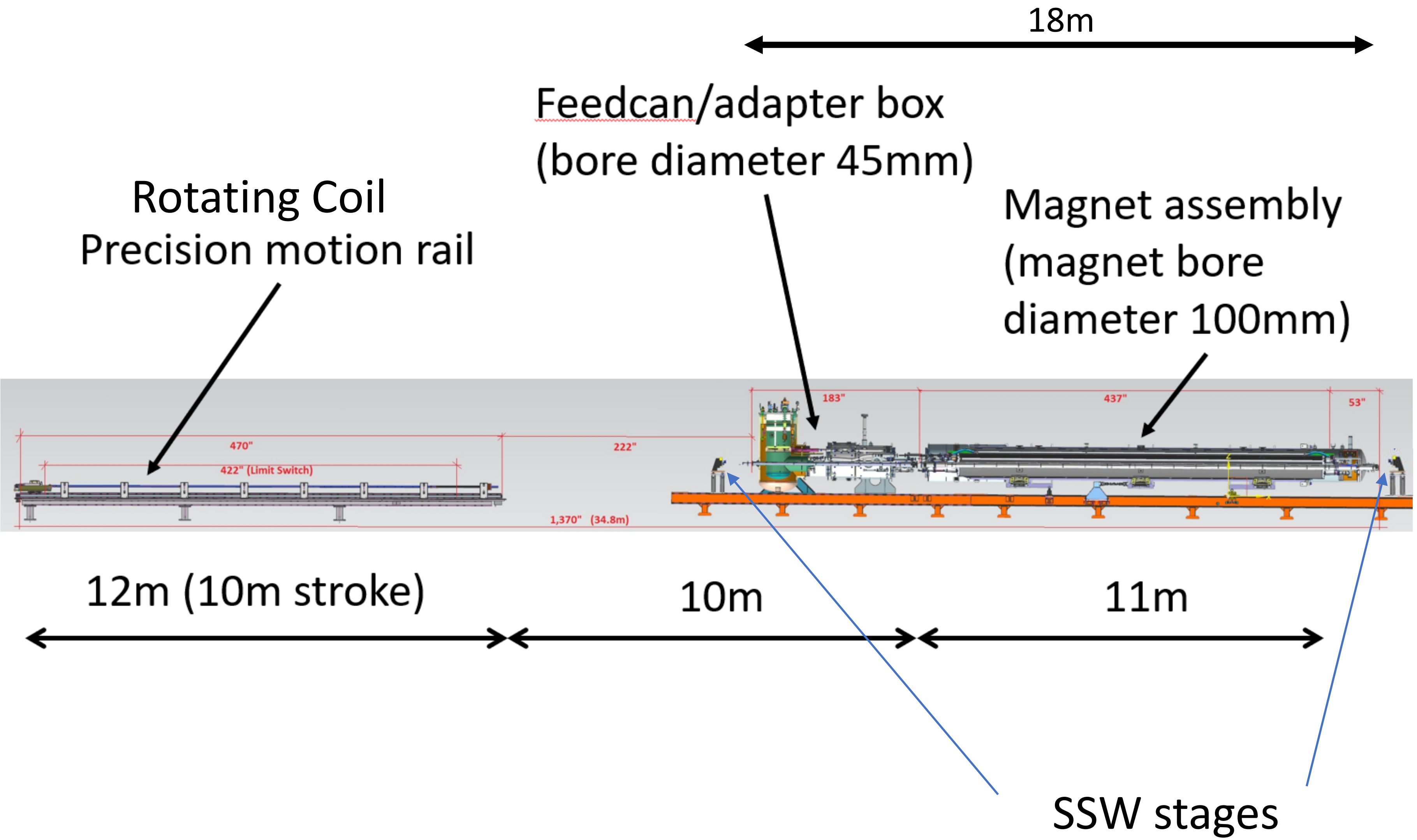
The HL-LHC AUP Project is tasked with the delivery of 10 MQXFA Cryomodules (CM) in the next few years.

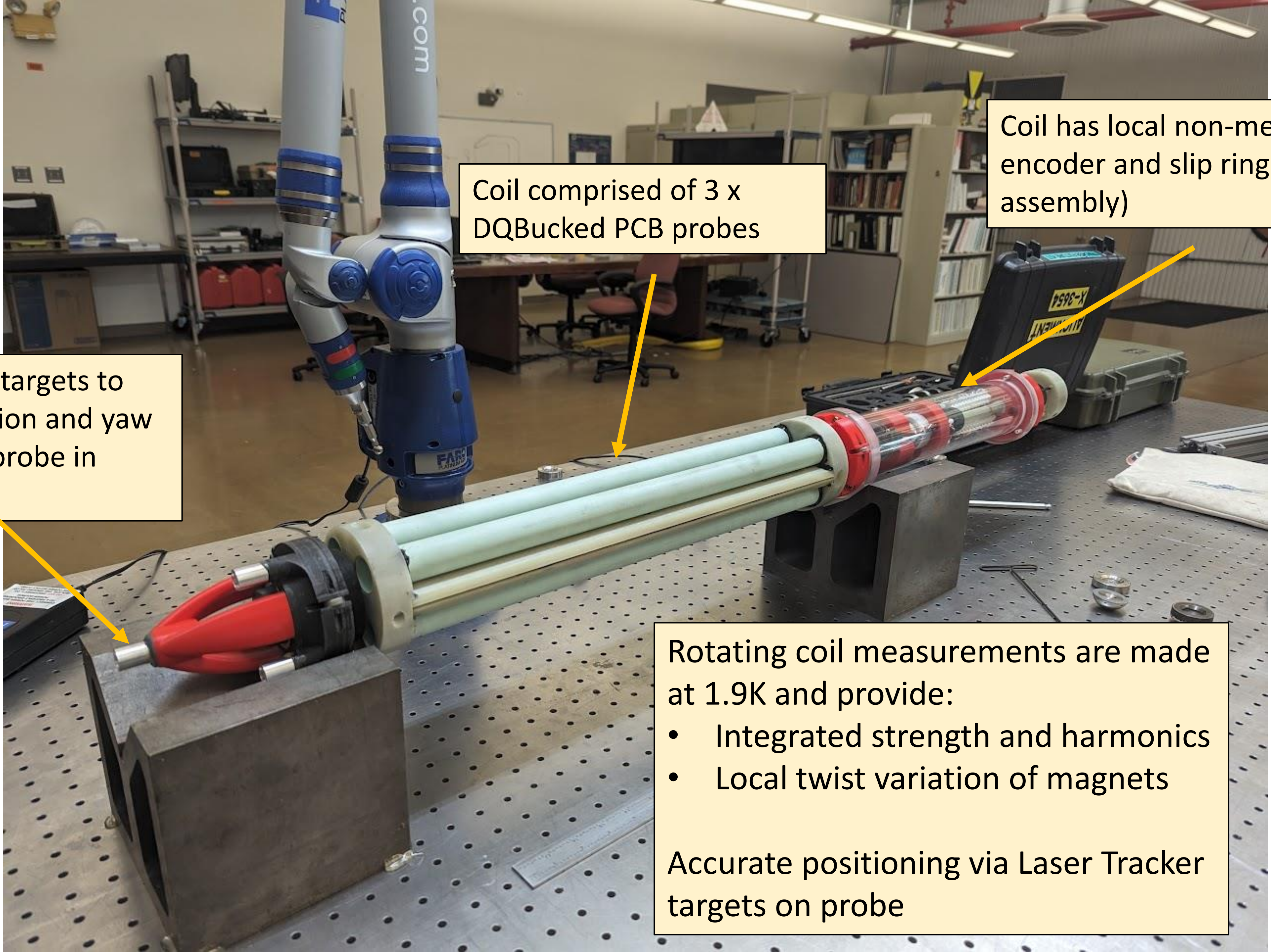
These are large-aperture (150 mm) low-β focusing Nb3Sn quadrupoles operating at 1.9K, and bring Nb3Sn technology into use for accelerator applications.

Fermilab is in charge of the final assembly of 10 CM (2 x 4.2 m magnets in each) and final magnetic measurements at 1.9K operating temperature.



Magnetic measurements at horizontal test bench





Laser tracker targets to provide position and yaw and pitch of probe in magnet

Coil comprised of 3 x DQBucked PCB probes

Coil has local non-metallic encoder and slip rings (FERRET assembly)

Rotating coil measurements are made at 1.9K and provide:

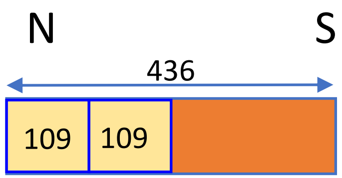
- Integrated strength and harmonics
- Local twist variation of magnets

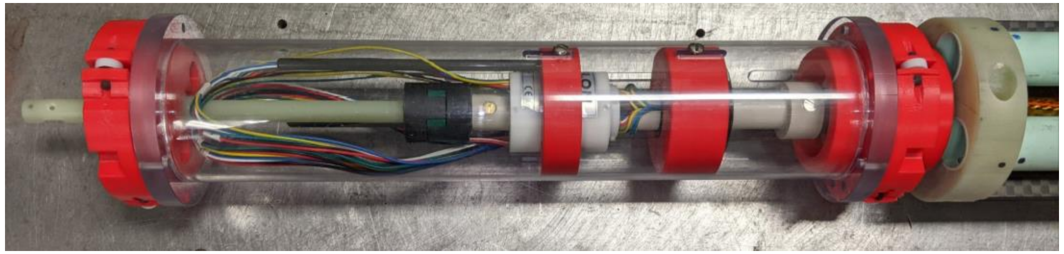
Accurate positioning via Laser Tracker targets on probe

Rotating coil ‘FERRET’ probe

Probe has 436mm-long winding and two ‘back-to-back’ 109mm-long windings.

Cryo Feed





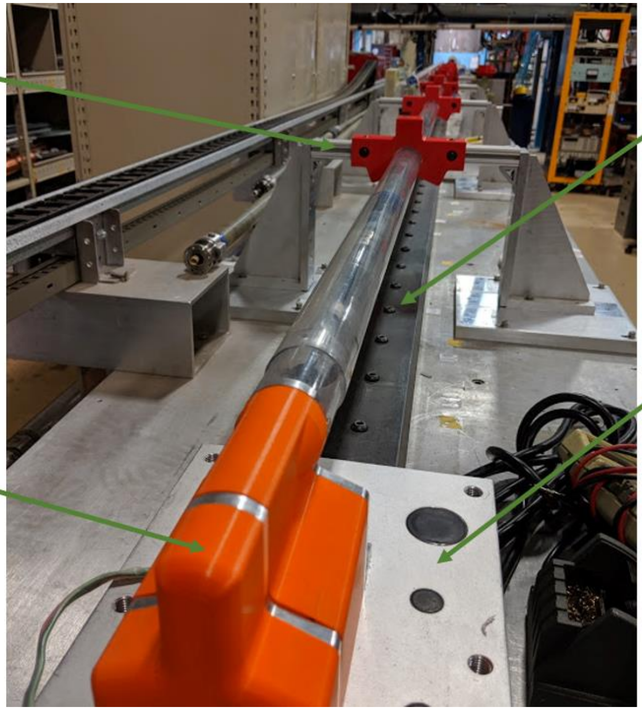
Local encoder and slipring

Supports for push tube

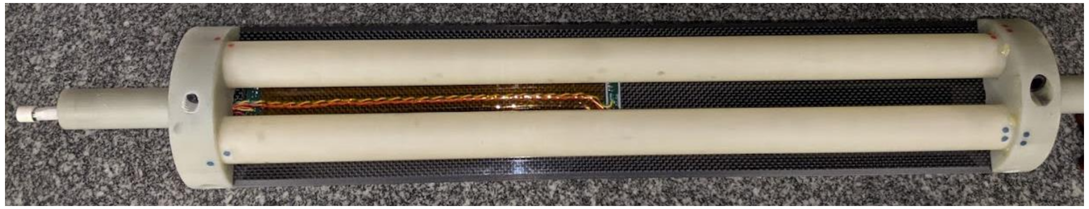
Rail

Rail drive carriage

Coil drive shaft rotation motor

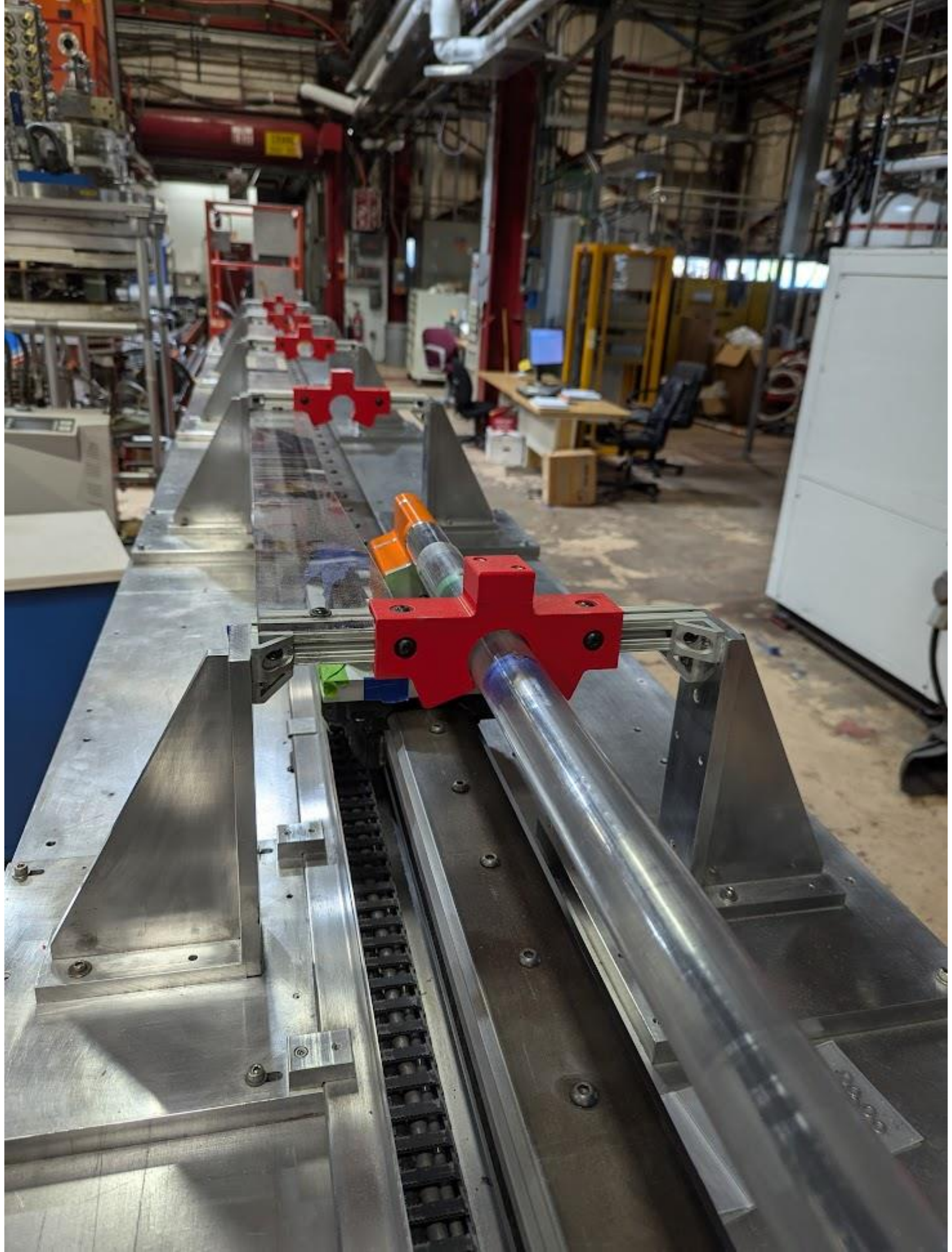


<u>22m-long</u>, 6mm diameter carbon fiber rotating drive shaft and polycarbonate push-tube



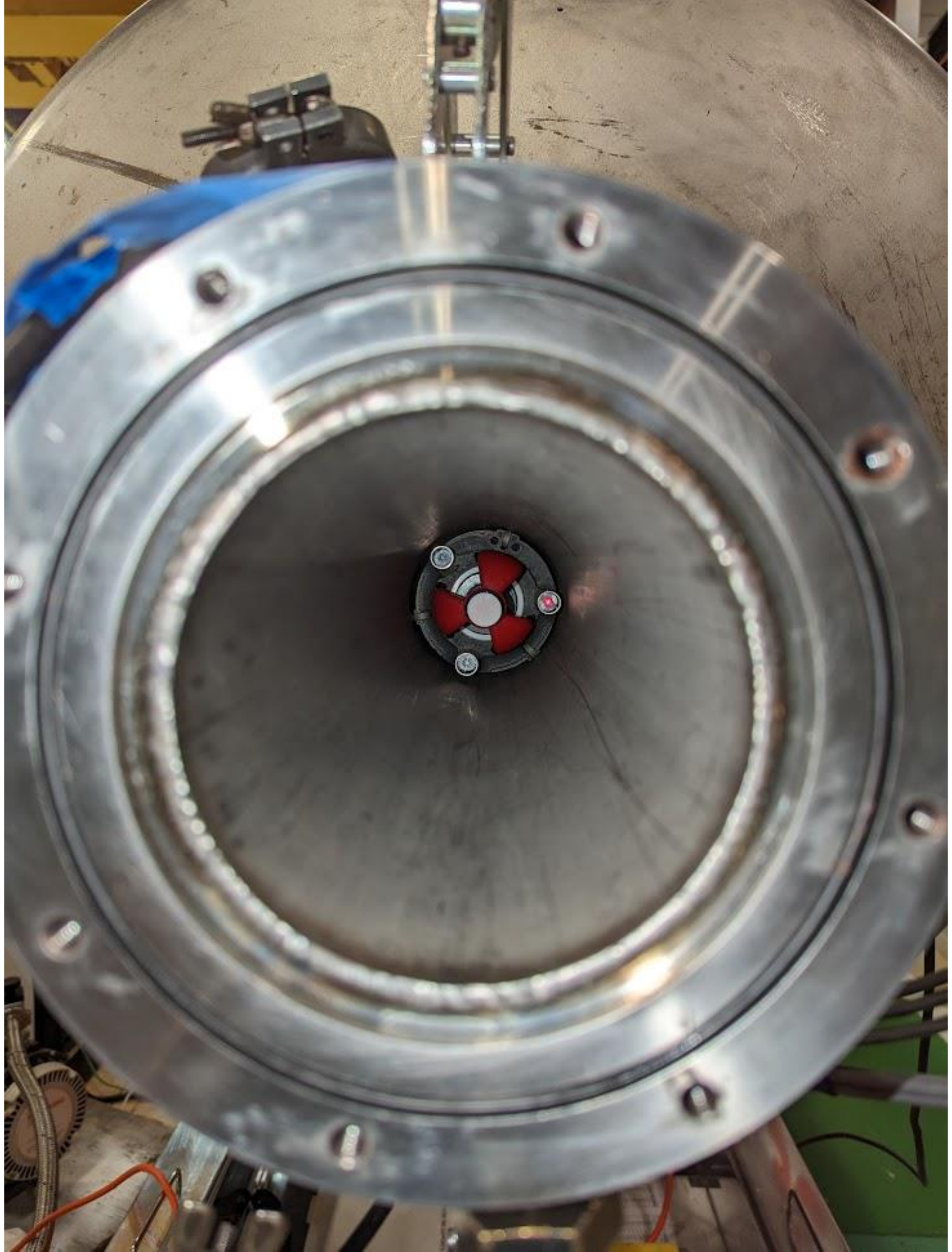
PCB probes stiffened with carbon fiber or G10

Laser tracker targets visible from non-drive end

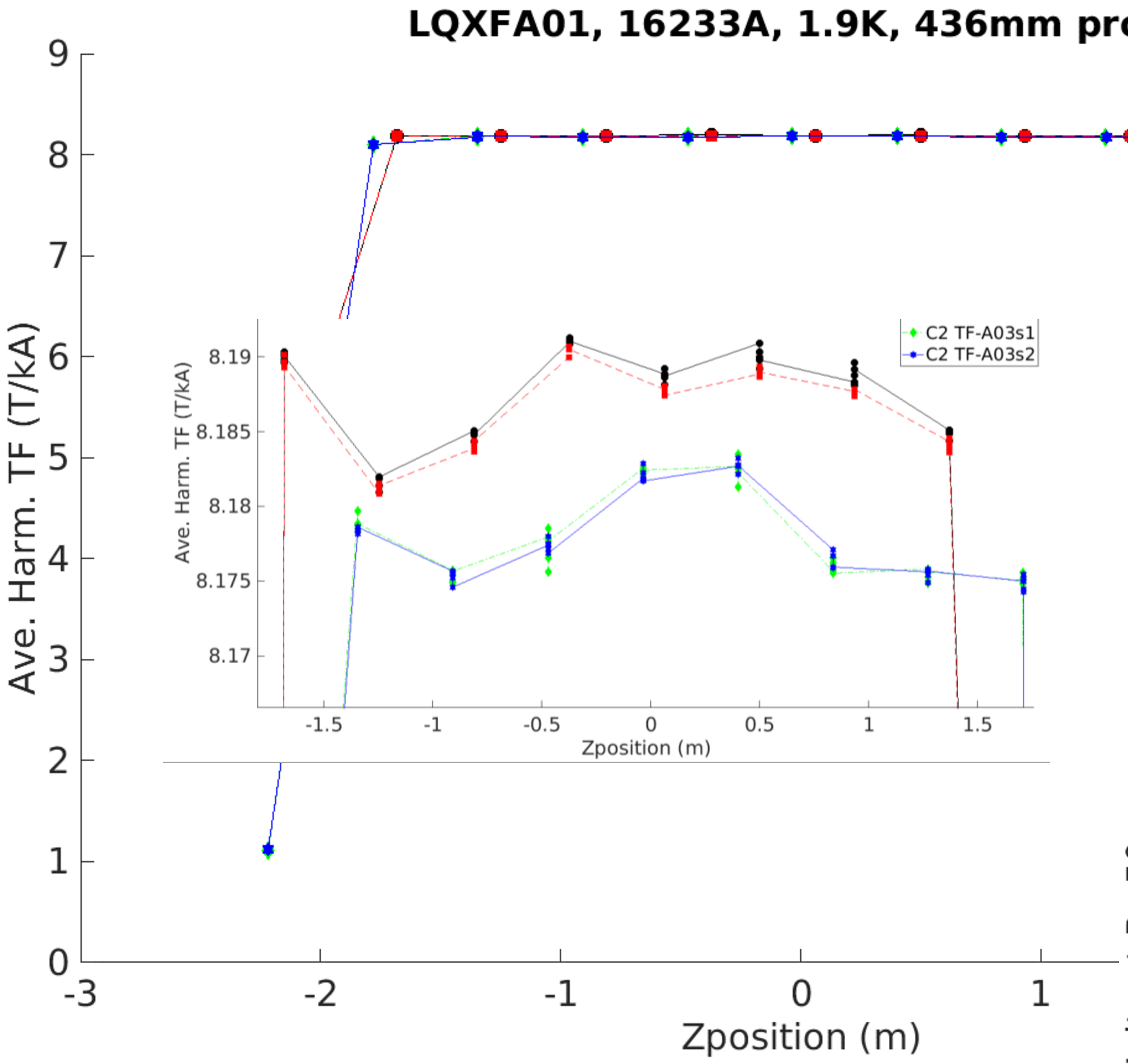


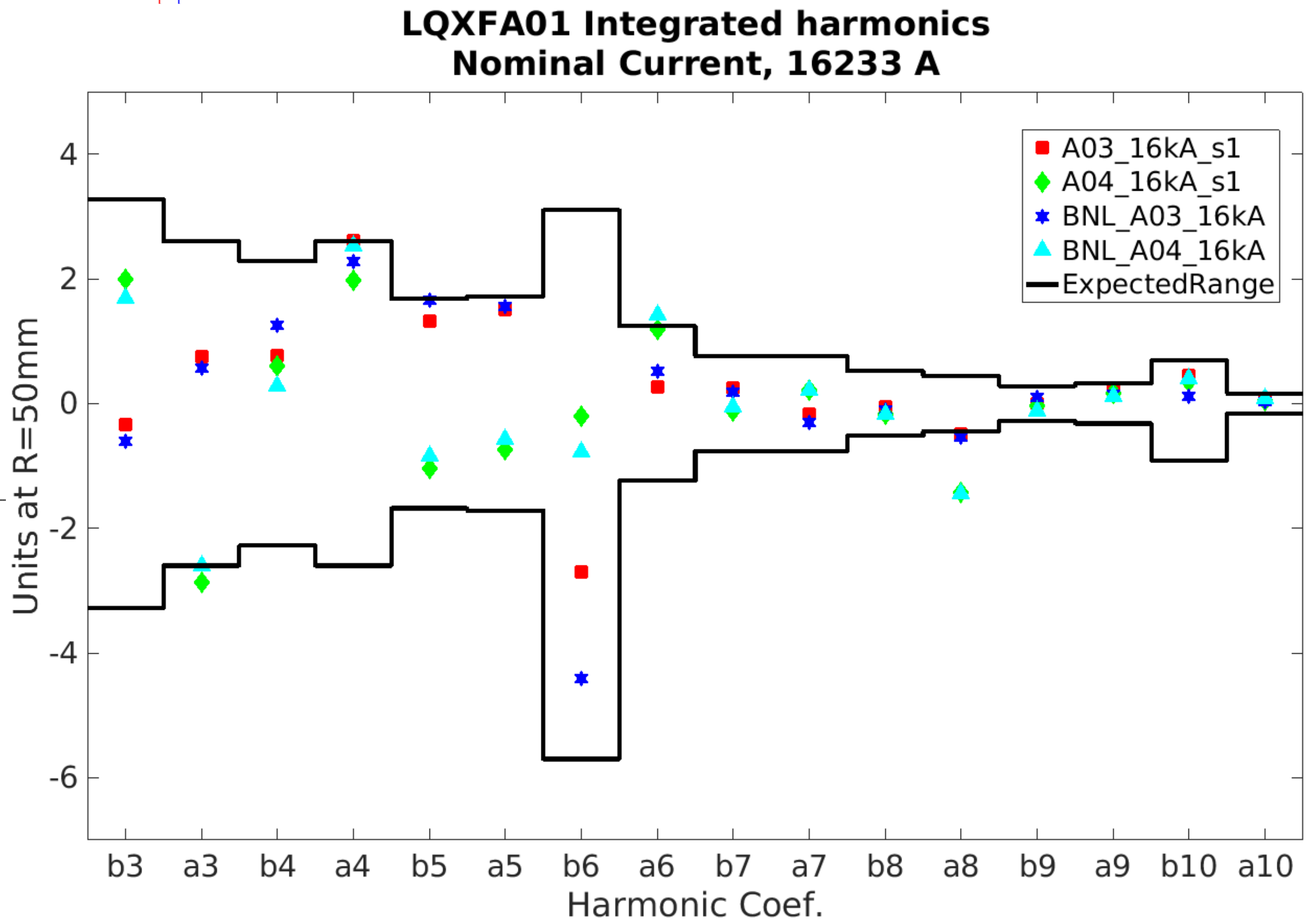
Axial positioning using the 22m-long polycarbonate ‘push-tube’ having a 6.35 mm carbon fiber rotating shaft

Note that the push tube is supported and motor assembly constructed so that there are no need for moving ‘gates’ during translation.

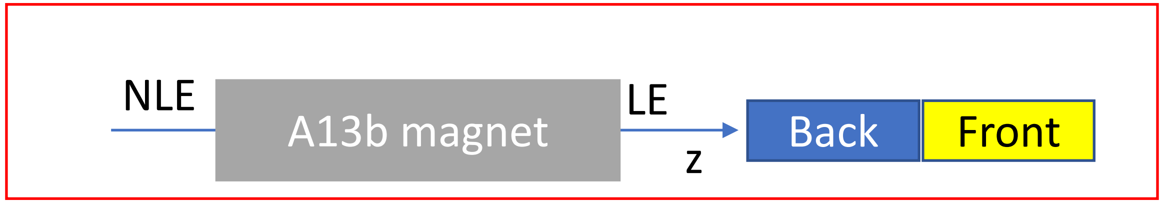


Strength and harmonics (compared to measurements at BNL) for the 1st CM

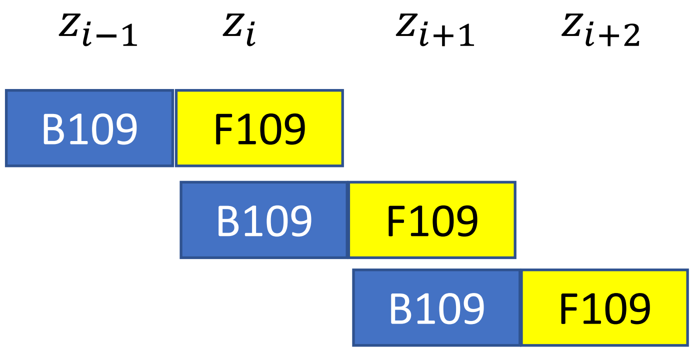




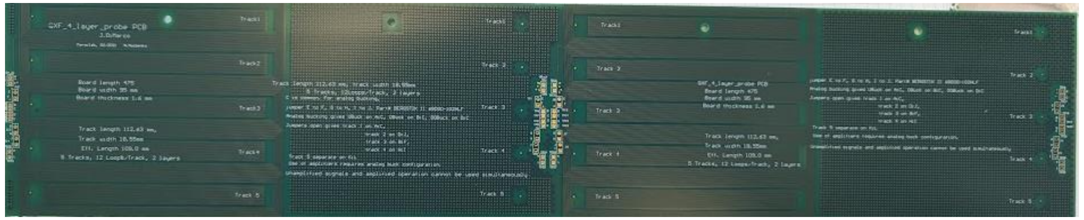
Dual-probe technique of measuring local magnet twist



Scan is made starting at NLE so that "back" probe trails "front" probe

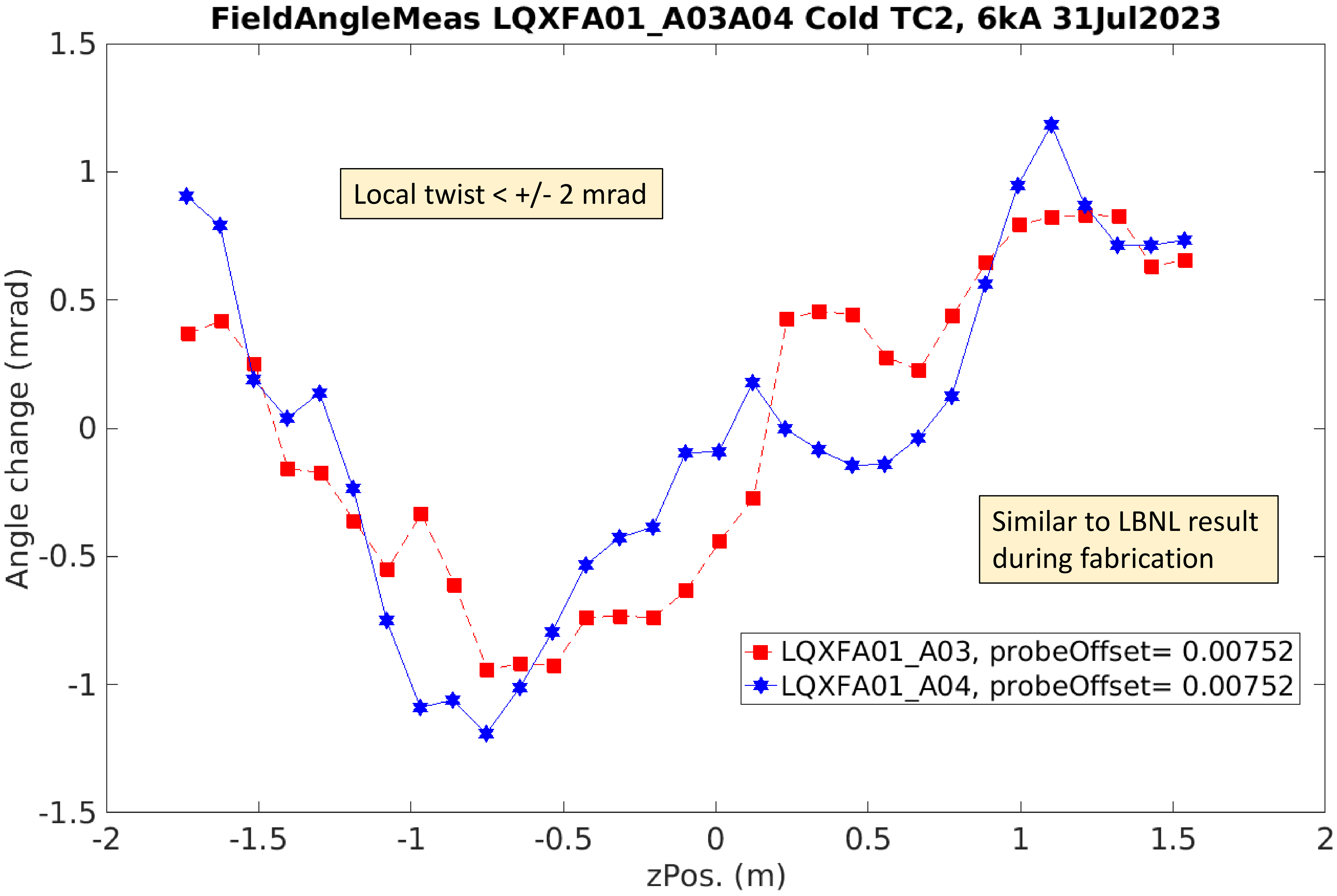


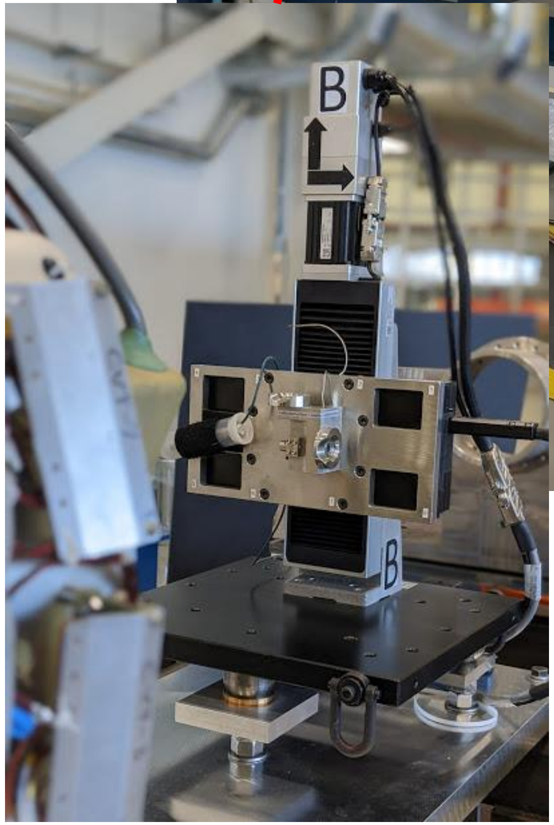
Two probes of same length –
Z-scan is performed such that every step overlaps the previous front probe position with the current back probe position

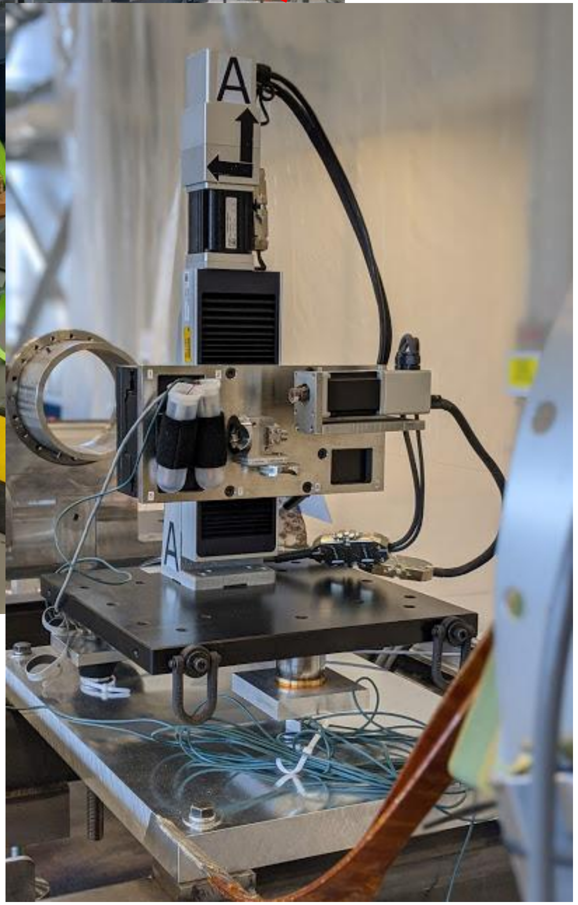


The cumulative sum of the difference between probes yields the magnet variation (the **calibrated probe offset is subtracted** when determining the differences)

$$\theta_r(i) = \sum_{n=1}^{i} (\theta_{Fn} - \theta_{Bn}) - \theta_{FB\_offset}$$

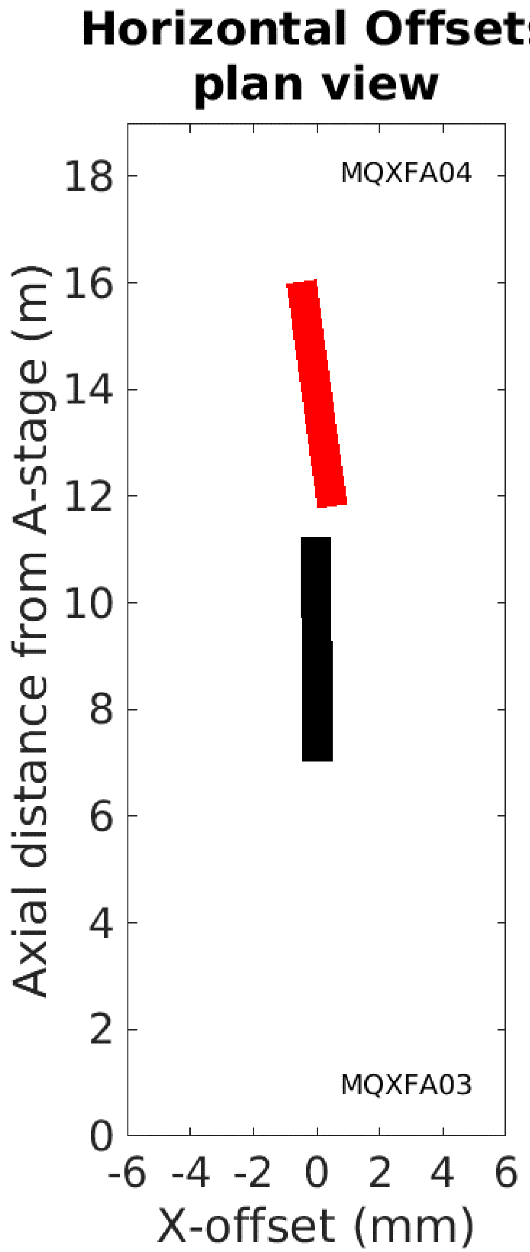

FieldAngleMeas LQXFA01_A03A04 Cold TC2, 6kA 31Jul2023
Local twist < +/- 2 mrad
Similar to LBNL result during fabrication
LQXFA01_A03, probeOffset= 0.00752
LQXFA01_A04, probeOffset= 0.00752
Angle change (mrad)
zPos. (m)
1.5
1
0.5
0
-0.5
-1
-1.5
-2
-1.5
-1
-0.5
0
0.5
1
1.5
2





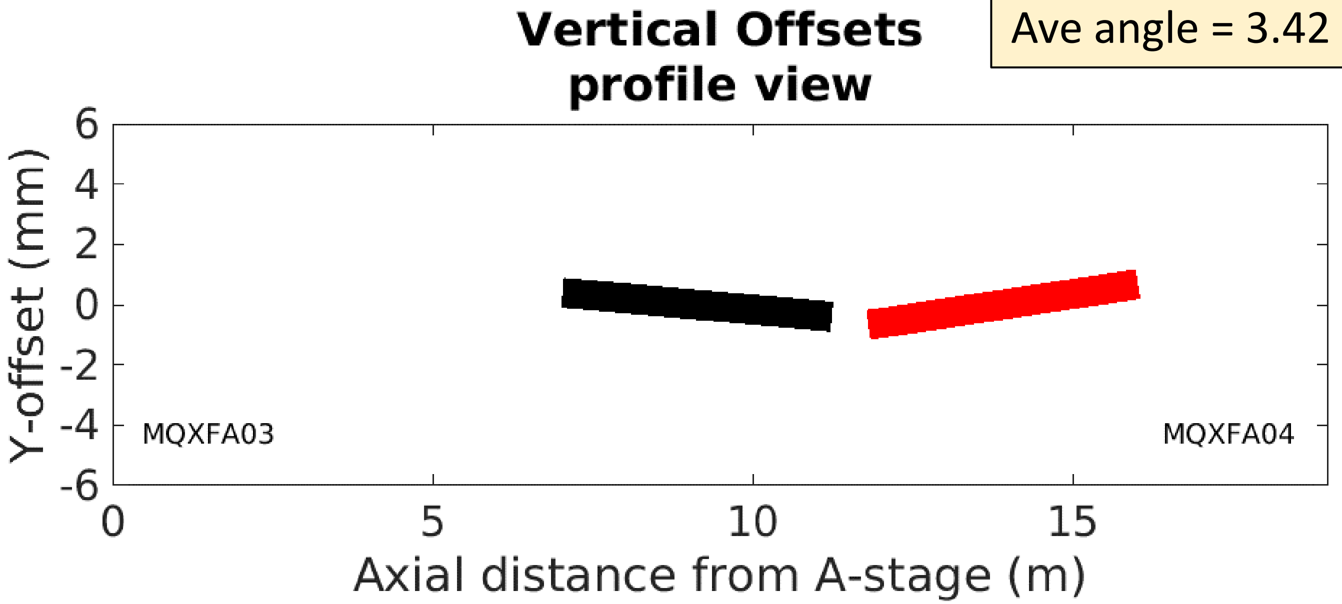
SSW system in use during fabrication

MQXFA03/MQXFA04 Alignment
After move to average axis
23Aug2023 - cold TC2, 2K

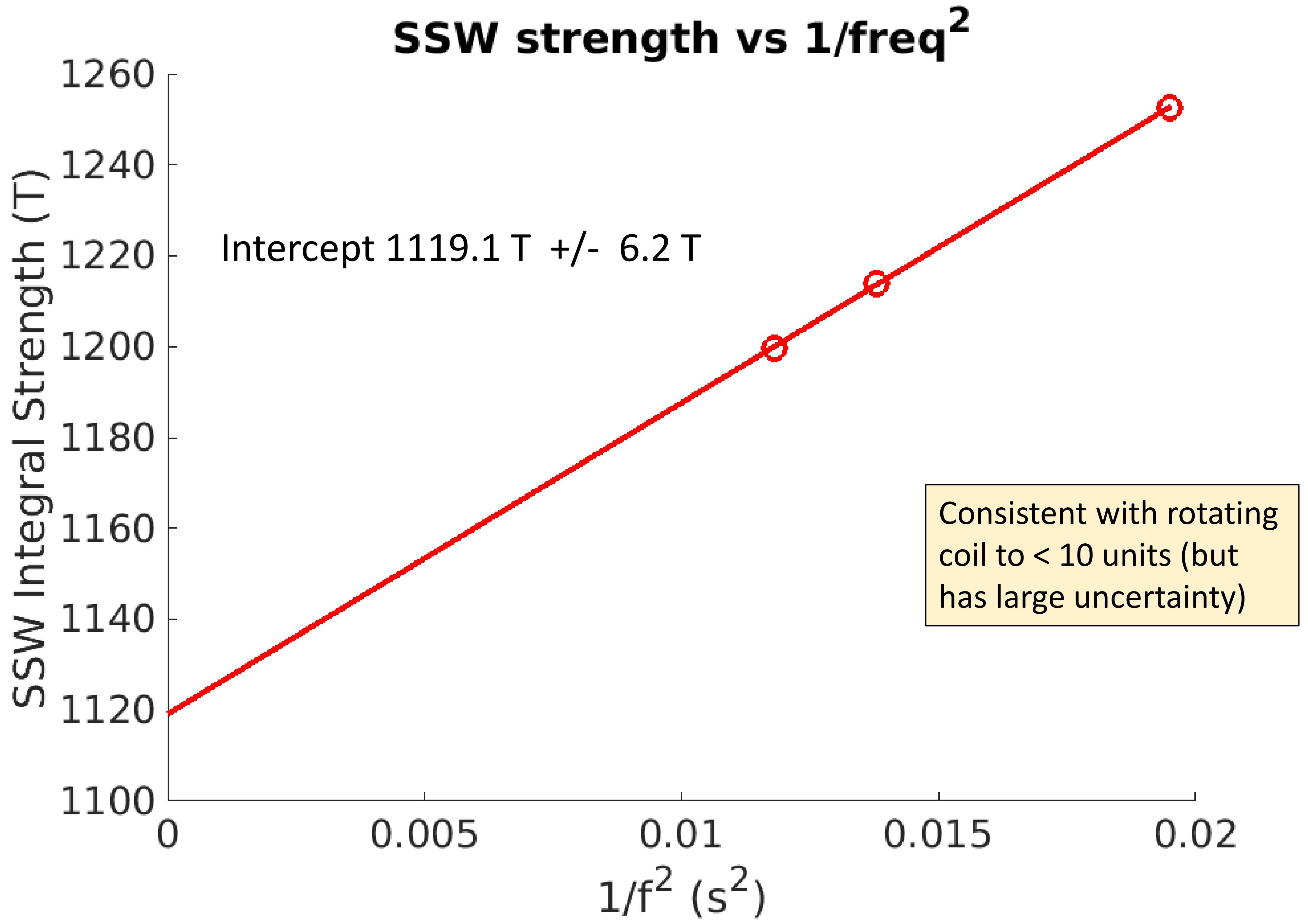


MQXFA03 Lead End: X= 0.042, Y= 0.394 mm
MQXFA03 Interface End: X= -0.030, Y= -0.402 mm
MQXFA04 Interface End: X= 0.498, Y= -0.676 mm
MQXFA04 Lead End: X= -0.482, Y= 0.681 mm

MQXFA03 roll angle = 4.59 mrad
MQXFA04 roll angle = 2.26 mrad
Delta angle = 2.32 mrad
Ave angle = 3.42 mrad



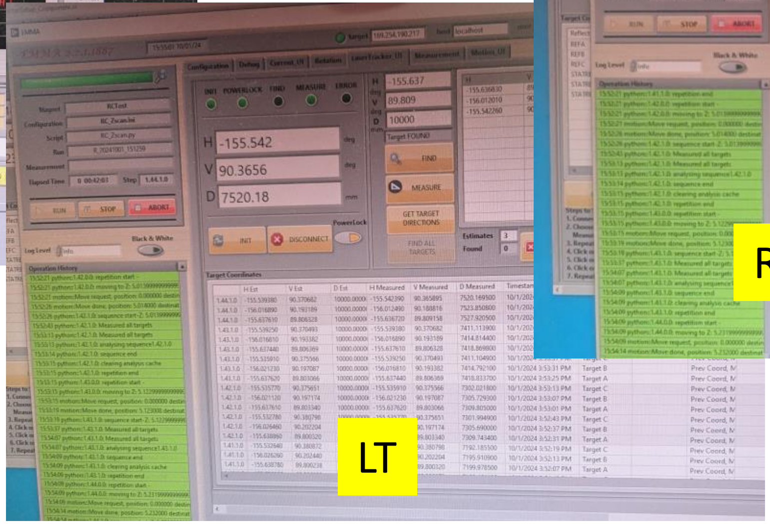
SSW_R_20230823_181305_AC_PitchYaw, SSW_R_20230823_180625_AC_PitchYaw

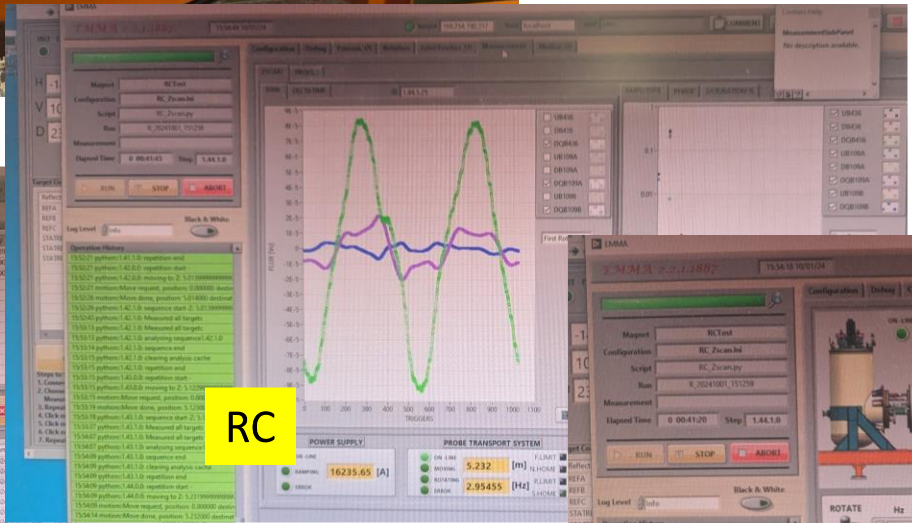


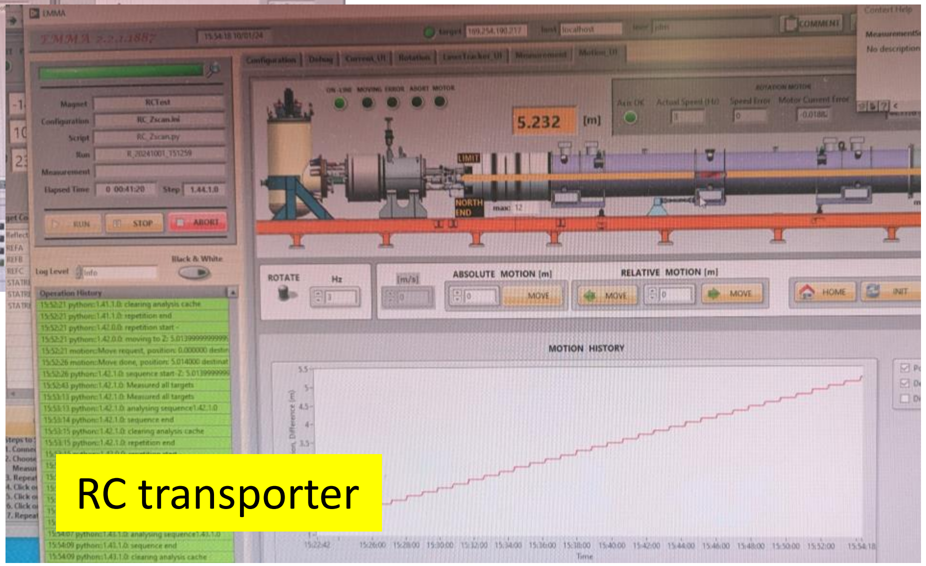
SSW strength vs 1/freq^2
SSW Integral Strength (T)
1/f^2 (s^2)
1260
1240
1220
1200
1180
1160
1140
1120
1100
0
0.005
0.01
0.015
0.02
Intercept 1119.1 T +/- 6.2 T
Consistent with rotating coil to < 10 units (but has large uncertainty)

Extensible Magnetic Measurements Software Framework fully implemented for all measurements (SSW, RC, Hall probes, etc.)

- Common UI
- Interface with power supply, LT, motion systems, data acq., etc.
- Scripting of measurement sequences







Magnets for Oak Ridge National Laboratory Proton Power Upgrade (PPU)

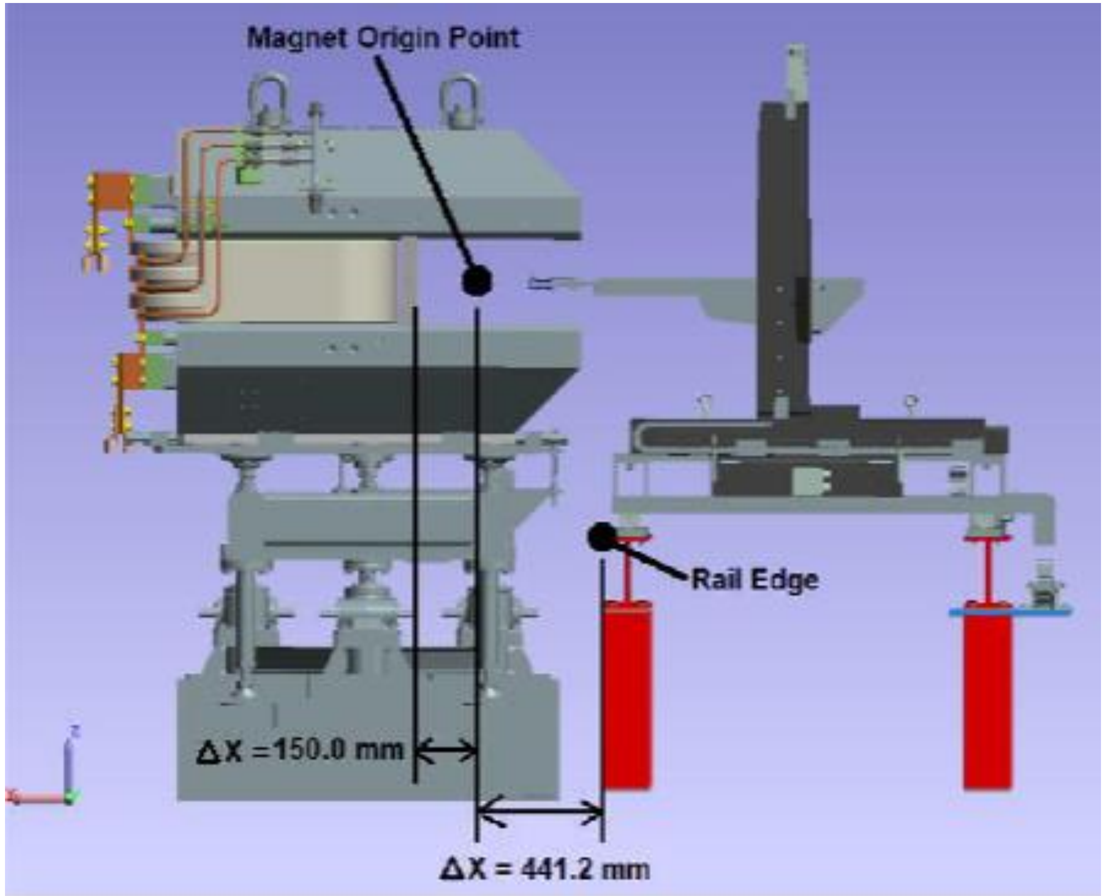
Two Proton Power Upgrade (PPU) Chicane Dipole magnets, OCA001 (“D2”) and OCB001 (“D3”), and a spare were designed, built and tested by Fermilab for the Oak Ridge National Laboratory. A combined function ‘dump septum’ magnet was similarly also part of the effort.

Detailed studies were made of the field strength and field:

- Hall probe field maps show very good agreement with model predictions throughout the large magnetic volume, with some small deviations that may be related to actual, versus assumed, magnet steel properties, or possibly due to the steel support structure. These are also used for proper placement of the D2 stripping foil.

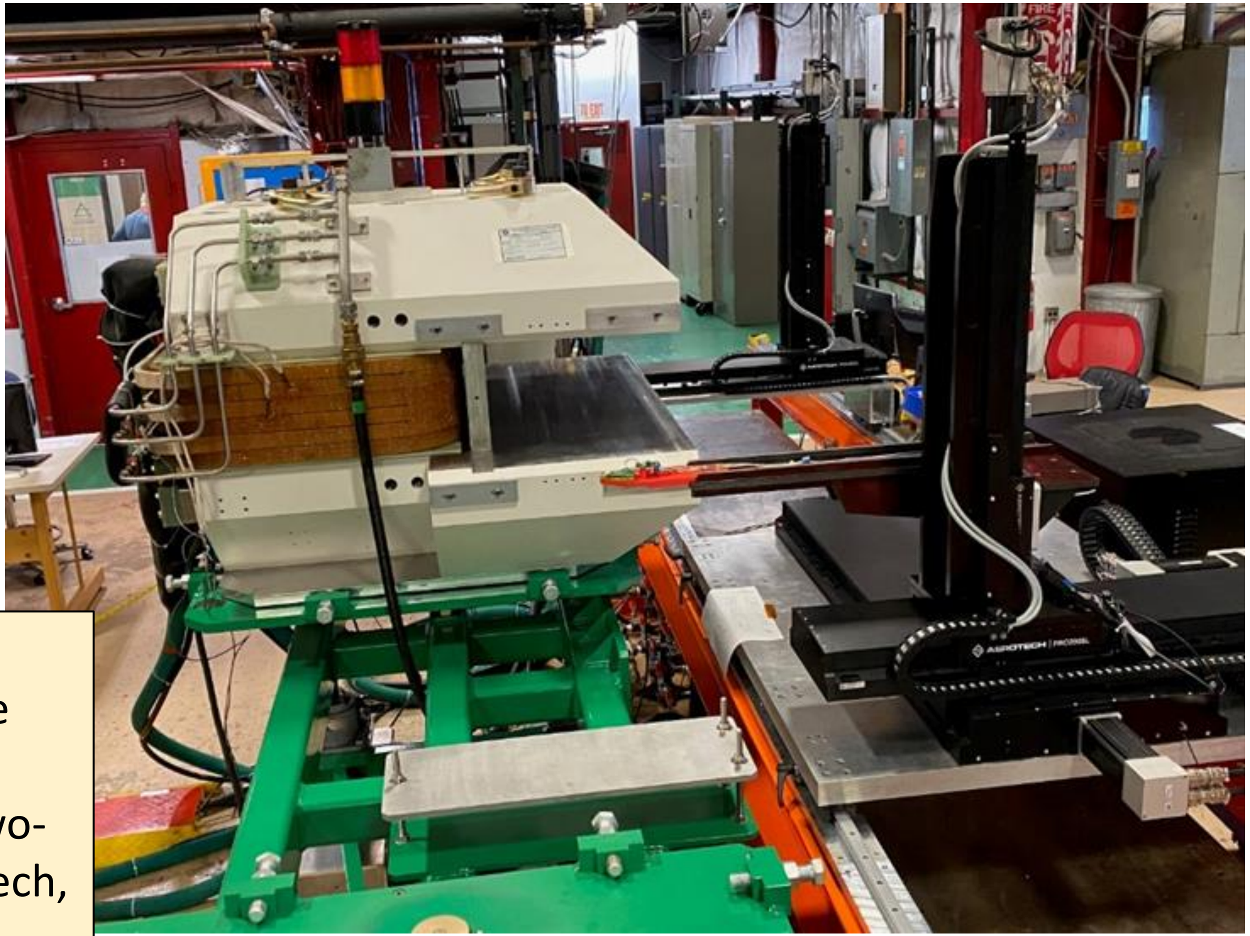
- The integrated field strength and field quality were measured with a SSW for and meet requirements at both the 1.3 and 1.0 GeV settings.

- The septum magnet had additional measurements with a curved single-wire bundle flatcoil



Very large magnets – had to mounted on the floor next to our test stand (!)

Good field region ~200 mm (reference radius 100 mm)



Mechanical improvements to our test stand

- New precision rails purchased an adjusted to be true at 0.05 mm level
- Two new motion stages for probes, one with two-axis and one with three-axis capabilities (Aerotech, 10 micron precision full range, load capacity of 50kg. The horizontal and vertical stages have 600 mm range, axial 1000 mm range.)
- Renishaw absolute position encoder along the entire length

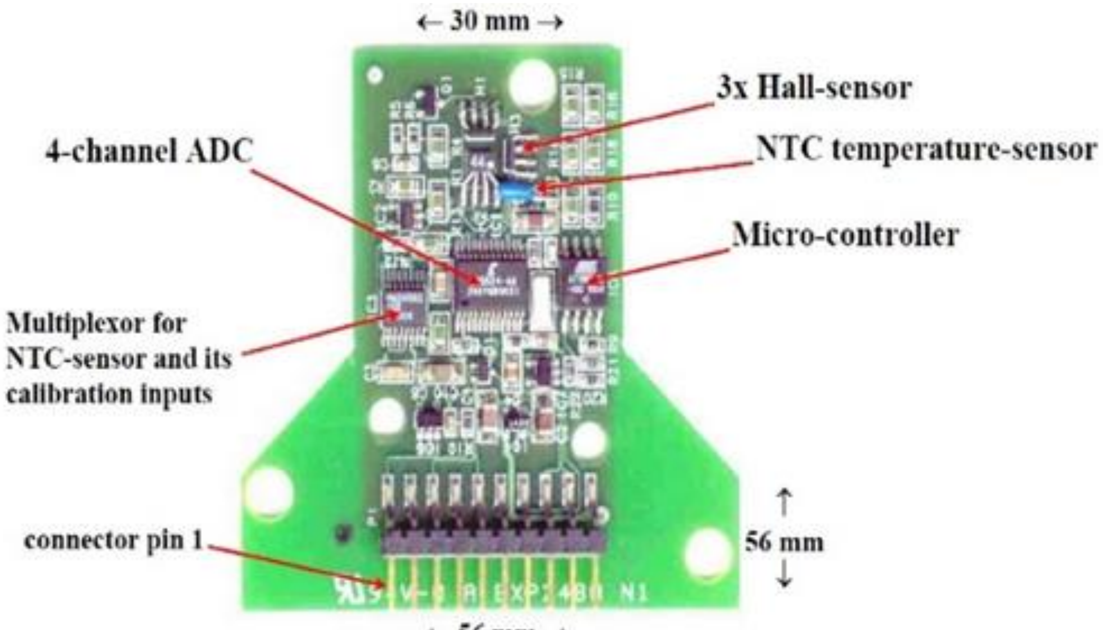


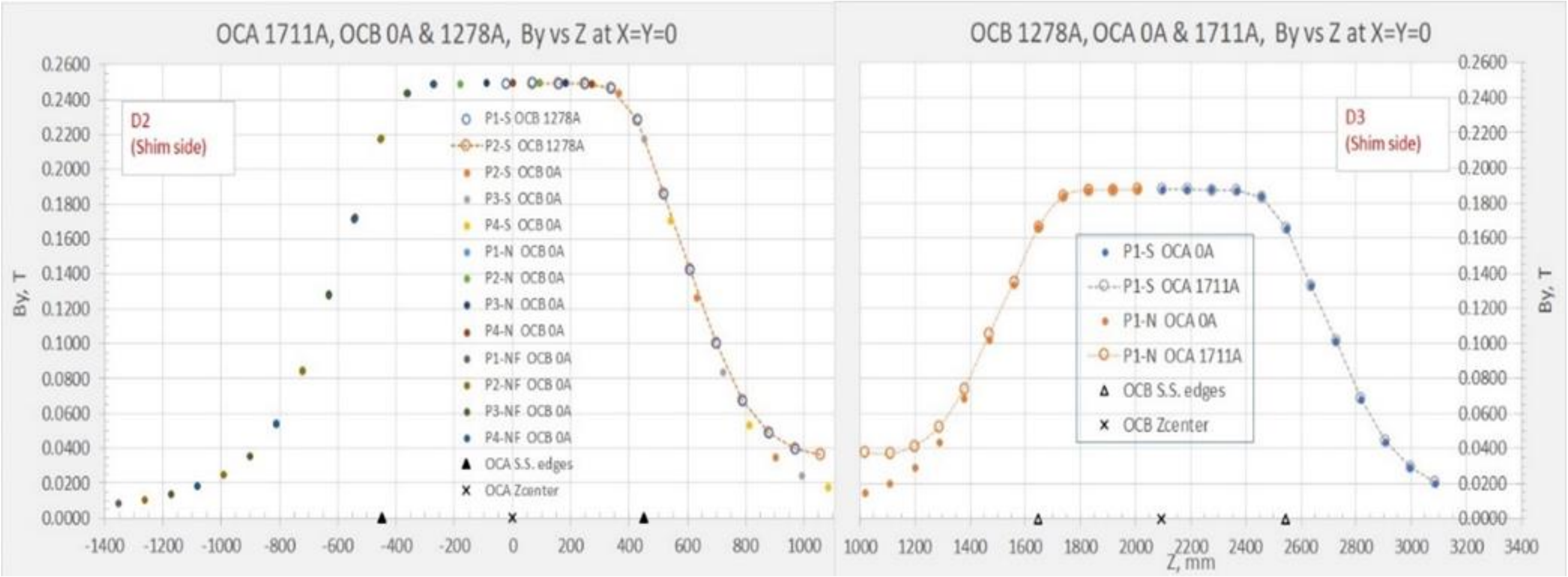
Figure 1. The B-sensor module.

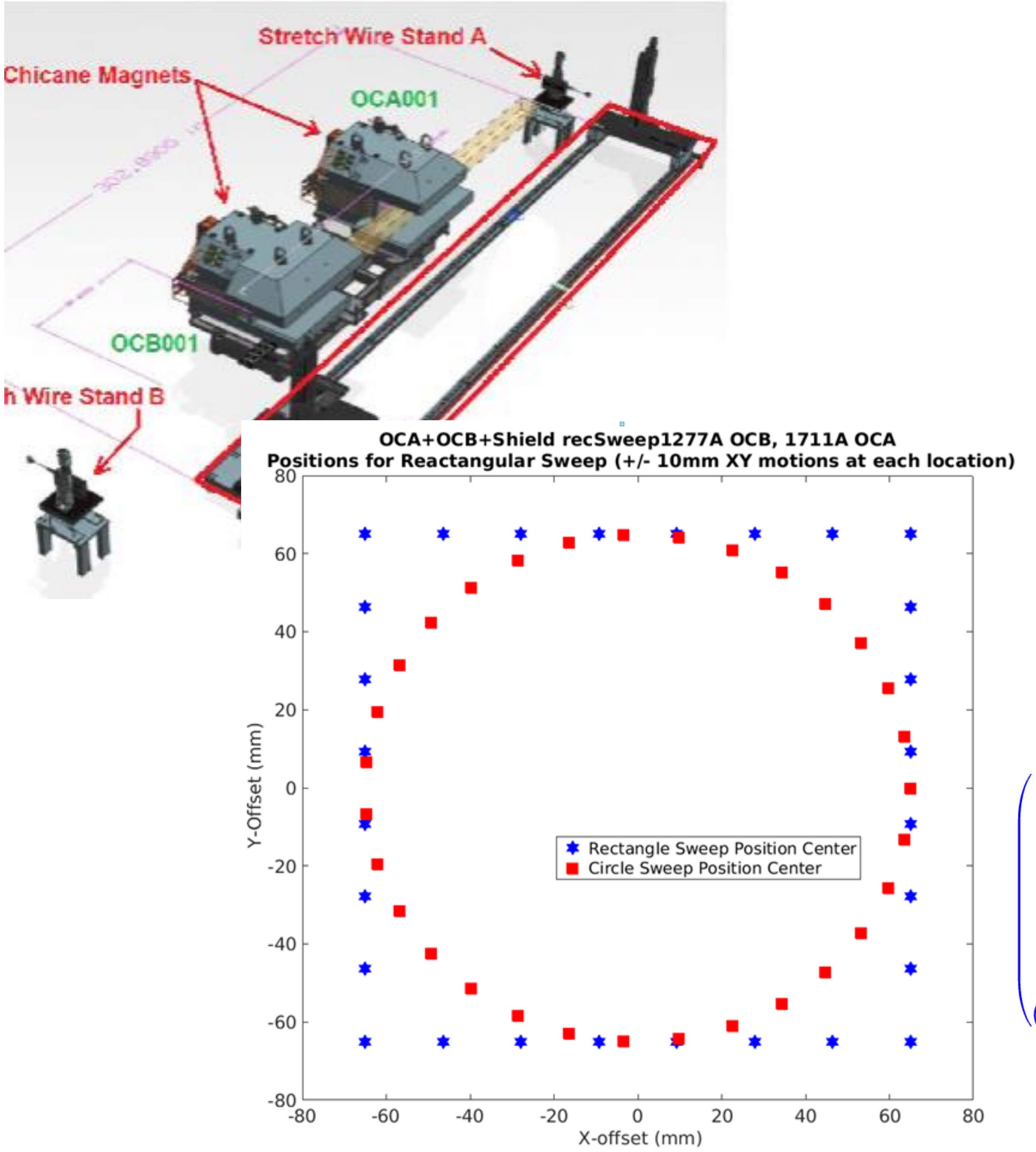
A set of CERN/NIKHEF Hall probes and electronic readout system was used for the bulk of “point scan” magnetic field measurements. These have three Hall elements mounted on the face of a small glass cube (~5mm on a side) to provide a 3-D field measurement within a small volume;

The PC Board is housed in a G-10 support which has 3 metal spheres (glued into wells with epoxy) for mounting to a support structure.

Field measurements are digitized by an on-board 24-bit ADC, and the probes are calibrated by CERN to a precision 1e-4
of one part in 10,000 with spherical harmonic coefficients that correct for small non-orthogonality of the Hall elements (ref. F. Bergsma, previous IMMWs).

Array of 8 Hall probes for mapping the aperture


OCA 1711A, OCB 0A & 1278A, By vs Z at X=Y=0
D2
(Shim side)
P1-S OCB 1278A
P2-S OCB 1278A
P2-S OCB 0A
P3-S OCB 0A
P4-S OCB 0A
P1-N OCB 0A
P2-N OCB 0A
P3-N OCB 0A
P4-N OCB 0A
P1-NF OCB 0A
P2-NF OCB 0A
P3-NF OCB 0A
P4-NF OCB 0A
OCA S.S. edges
OCA Zcenter
By, T
OCB 1278A, OCA 0A & 1711A, By vs Z at X=Y=0
D3
(Shim side)
P1-S OCA 0A
P1-S OCA 1711A
P1-N OCA 0A
P1-N OCA 1711A
OCB S.S. edges
OCB Zcenter
Z, mm
By, T



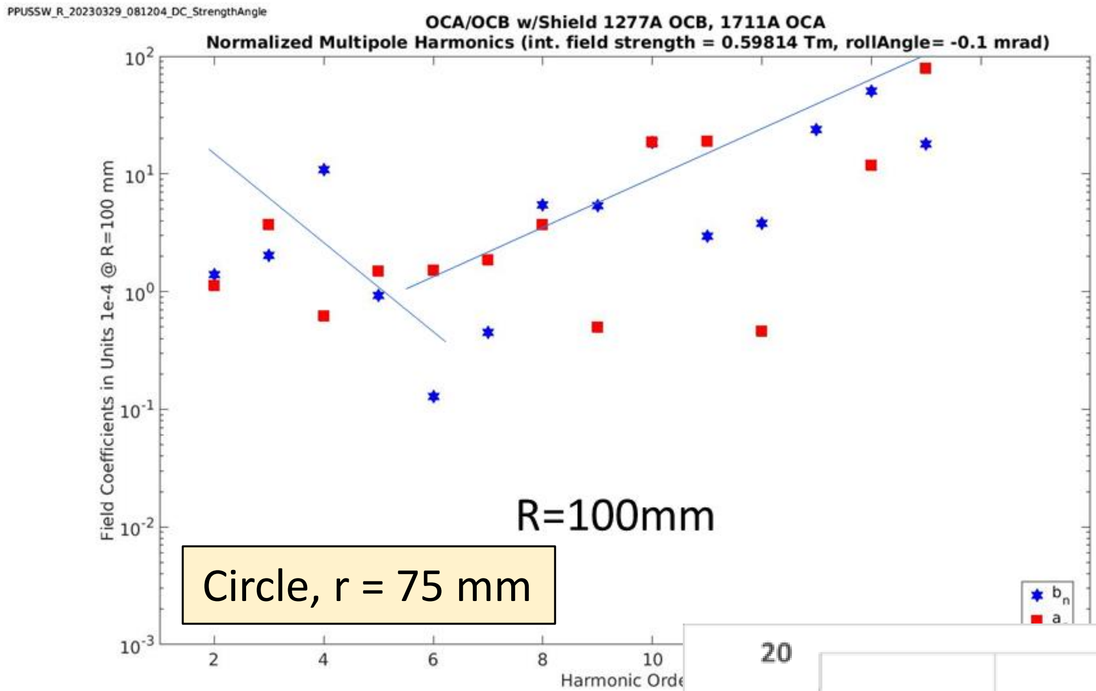
SSW stages only have ~150 mm range, but 'good field' region has reference radius of 100 mm.

To make better measurements of the harmonics reported at that radius, used a square wire pattern rather than circular (radius in the corner is about 100 mm)

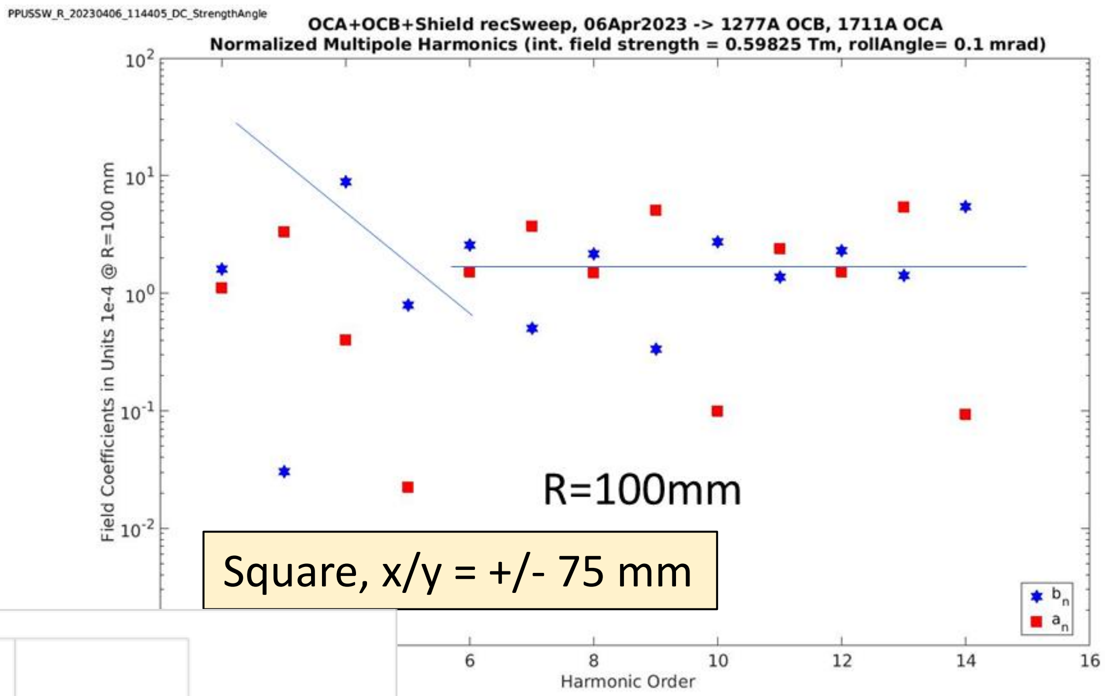
Use matrix solution finding sensitivity at each position without approximations

$$\begin{pmatrix} (K_1(\theta_1)e^{i*1*\theta_1}) & (K_2(\theta_1)e^{i*2*\theta_1}) & (K_3(\theta_1)e^{i*3*\theta_1}) & & (K_{15}(\theta_1)e^{i*15*\theta_1}) \\ (K_1(\theta_2)e^{i*1*\theta_2}) & (K_2(\theta_2)e^{i*2*\theta_2}) & (K_3(\theta_2)e^{i*3*\theta_2}) & \cdots & (K_{15}(\theta_2)e^{i*15*\theta_2}) \\ (K_1(\theta_3)e^{i*1*\theta_3}) & (K_2(\theta_3)e^{i*2*\theta_3}) & (K_3(\theta_3)e^{i*3*\theta_3}) & & (K_{15}(\theta_3)e^{i*15*\theta_3}) \\ & \vdots & & \ddots & \vdots \\ & \vdots & & \vdots & \vdots \\ (K_1(\theta_{128})e^{i*1*\theta_{128}}) & (K_2(\theta_{128})e^{i*2*\theta_{128}}) & (K_3(\theta_{128})e^{i*3*\theta_{128}}) & & (K_{15}(\theta_{128})e^{i*15*\theta_{128}}) \end{pmatrix} \begin{pmatrix} C_1 \\ C_2 \\ C_3 \\ \vdots \\ \vdots \\ C_{15} \end{pmatrix} = \begin{pmatrix} \varphi_1 \\ \varphi_2 \\ \varphi_3 \\ \vdots \\ \vdots \\ \varphi_{128} \end{pmatrix}$$

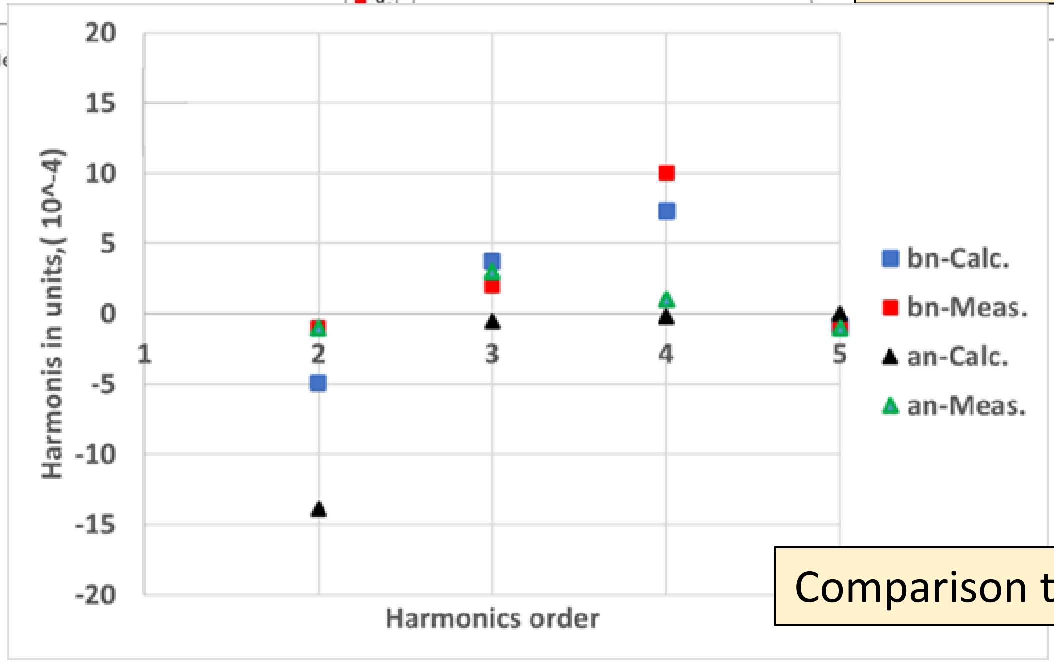
SSW Measurements around perimeter (reported at reference radius R=100 mm)



Circle, r = 75 mm

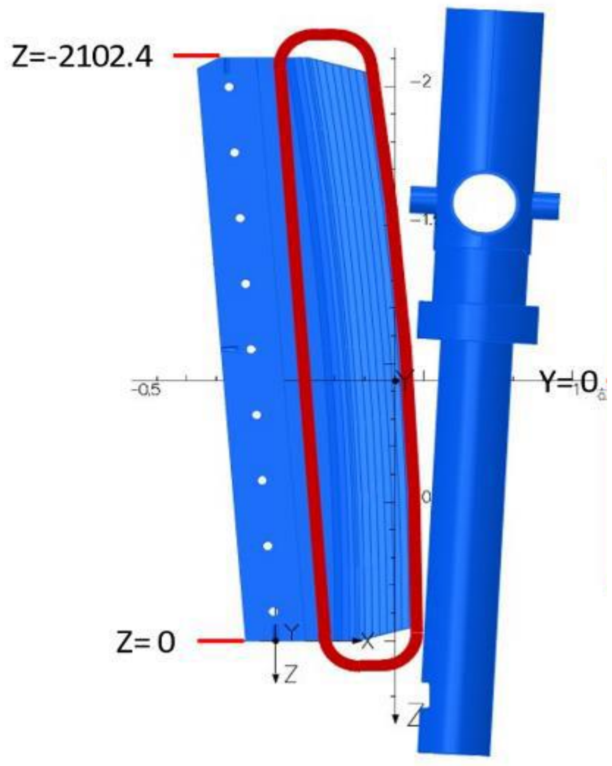


Square, x/y = +/- 75 mm



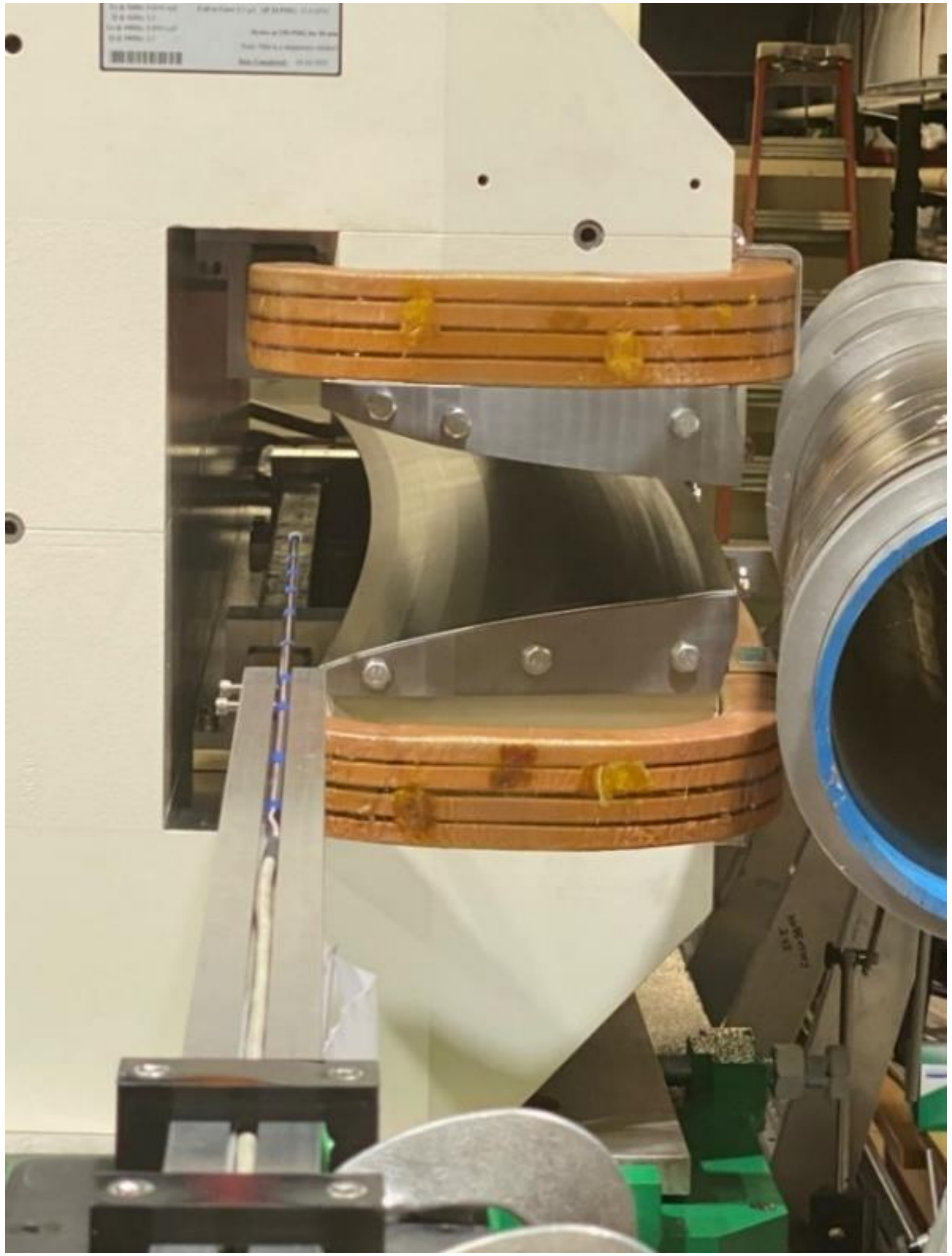
Comparison to calculation

PPU Dump Septum



Two beams enter the magnet (or go into the ‘zero field’ septum) on different trajectories, but are bent so they are ‘dumped’ to the same the same downstream target.

Need to accurately measure the integrated field along the two different curved paths.

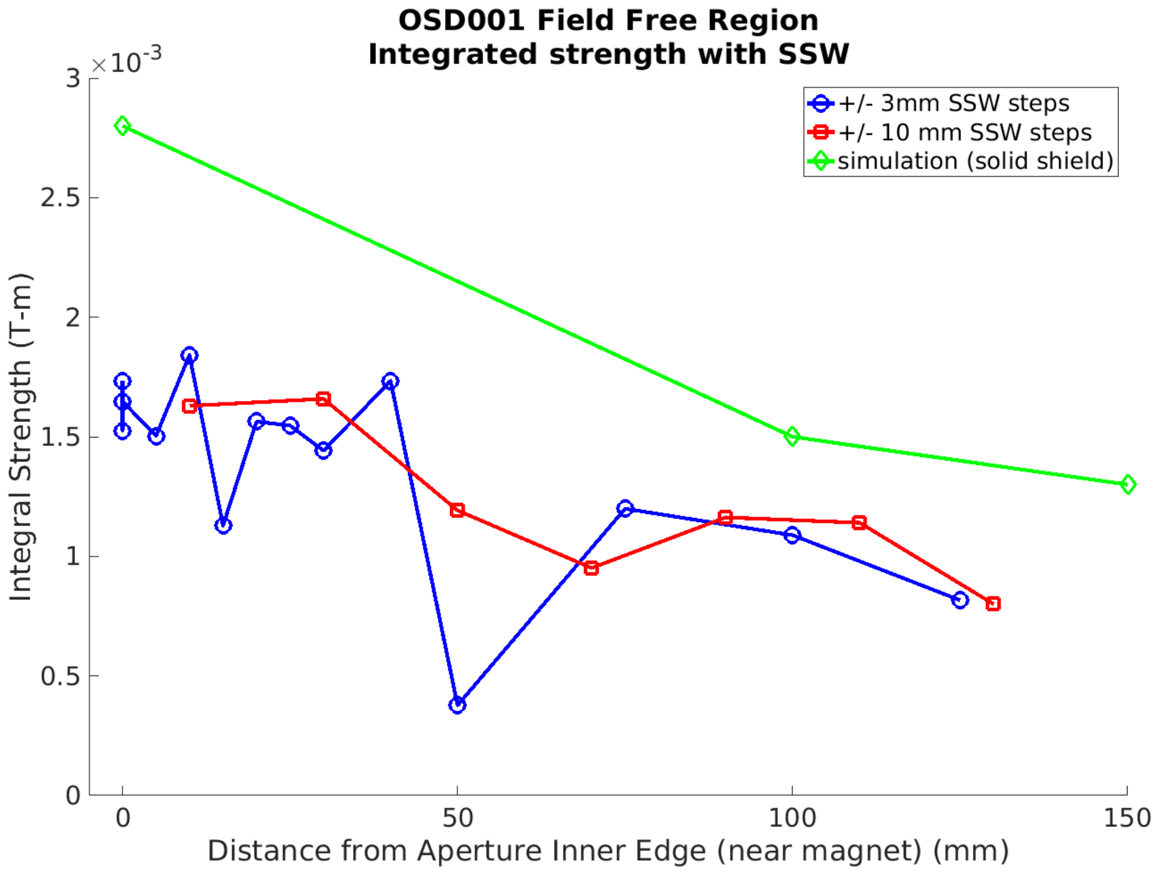


View of curved poles and shielded septum (during Hall probe end field measurements)

SSW measurements were made and compared to calculation of straight line integrals

SSW Measurements vs Simulation			Simulated	Measured	
Trajectory chord	Enter [x,z] (m)	Exit [x,z] (m)	Integral By, (T-m)	Integral By, (T-m)	% diff
H^0	[0.475, 0.655]	[0.179, -2.724]	1.0992	1.0980	-0.11
H^-	[0.355, 0.655]	[0.079, -2.724]	0.8030	0.8021	-0.11

Measurements in 'field free' septum region



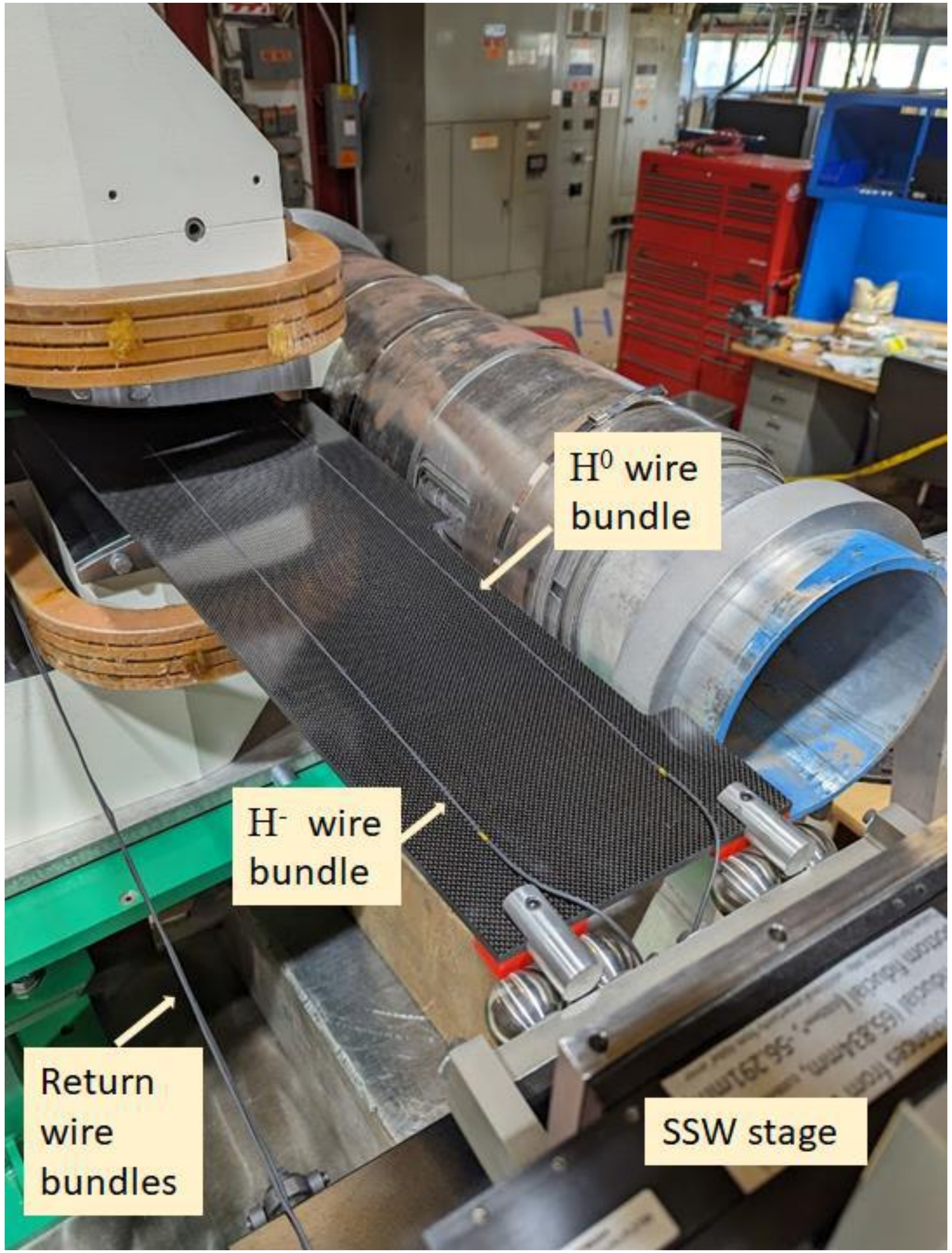
Measurements on the beam trajectories

A single wire bundle flatcoil was fabricated to measure along the two nominal trajectories.

The wire bundle consists of 12 insulated wires twisted together, but connected in series (so as to multiply the signal), within a jacket of 2.4mm outer diameter (the return loop of each wire bundle lying stationary along the back-leg of the magnet).

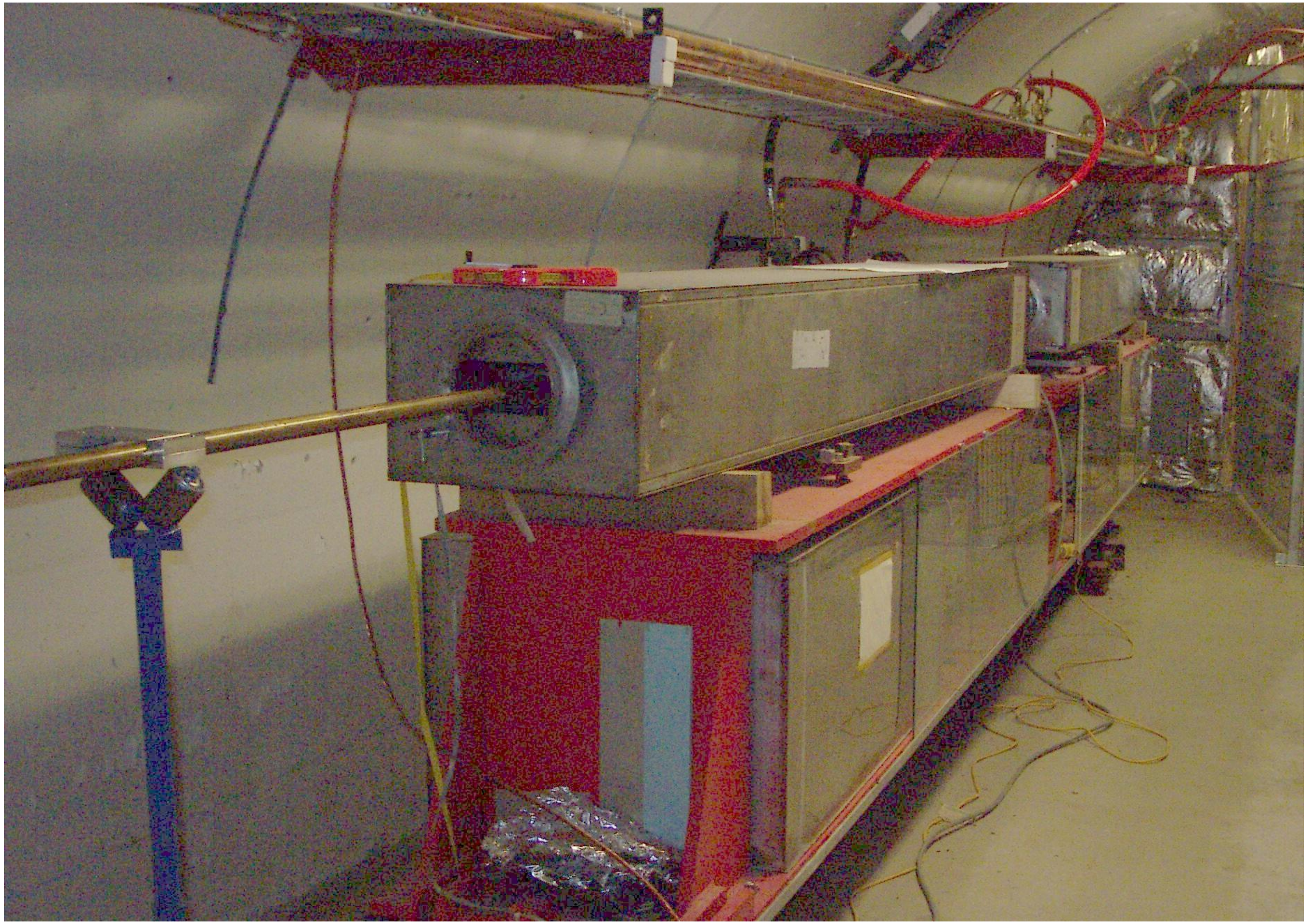
The grooves are machined into a 3.35 m-long (132"-long) carbon fiber plate, which is supported by the stages at its ends, and by roller assemblies within the magnet.

The change in flux induced in each wire bundle loop stems from the precise translation of the flatcoil in the magnetic field. Since this motion is controlled using the SSW stages, which have 1 micron motion accuracy, a measurement of the integrated voltage during movement yields a high-accuracy measurement of the dipole and gradient field integrals.


H^0 wire bundle
H^- wire bundle
Return wire bundles
SSW stage

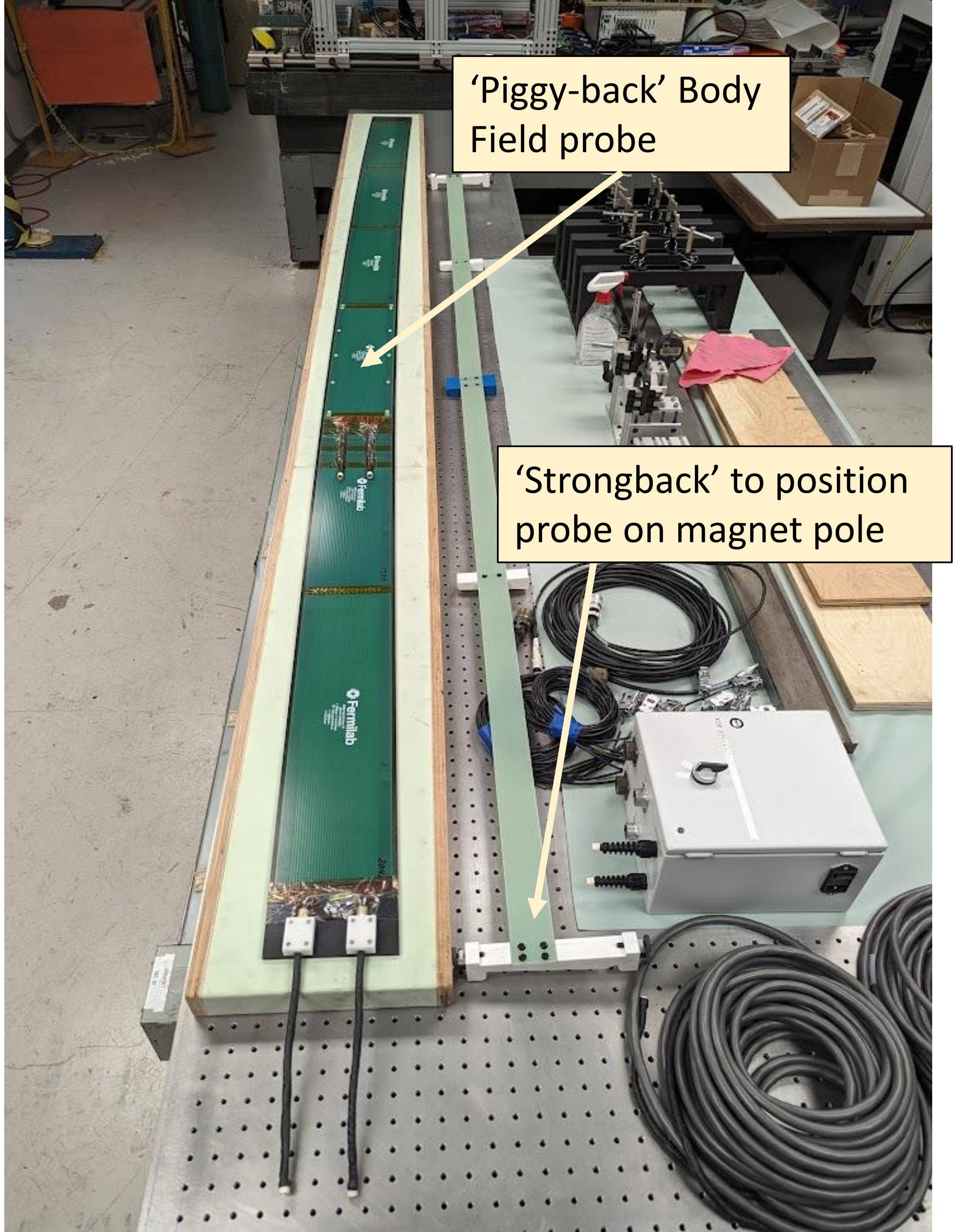

Flatcoil Trajectories	Simulated Integral By, (T-m)	Measured Integral By, (T-m)	s.d. (T-m)	Meas-Siml % diff
H^0	1.2390	1.2371	0.0003	-0.15
H^-	0.8528	0.8527	0.0003	-0.01

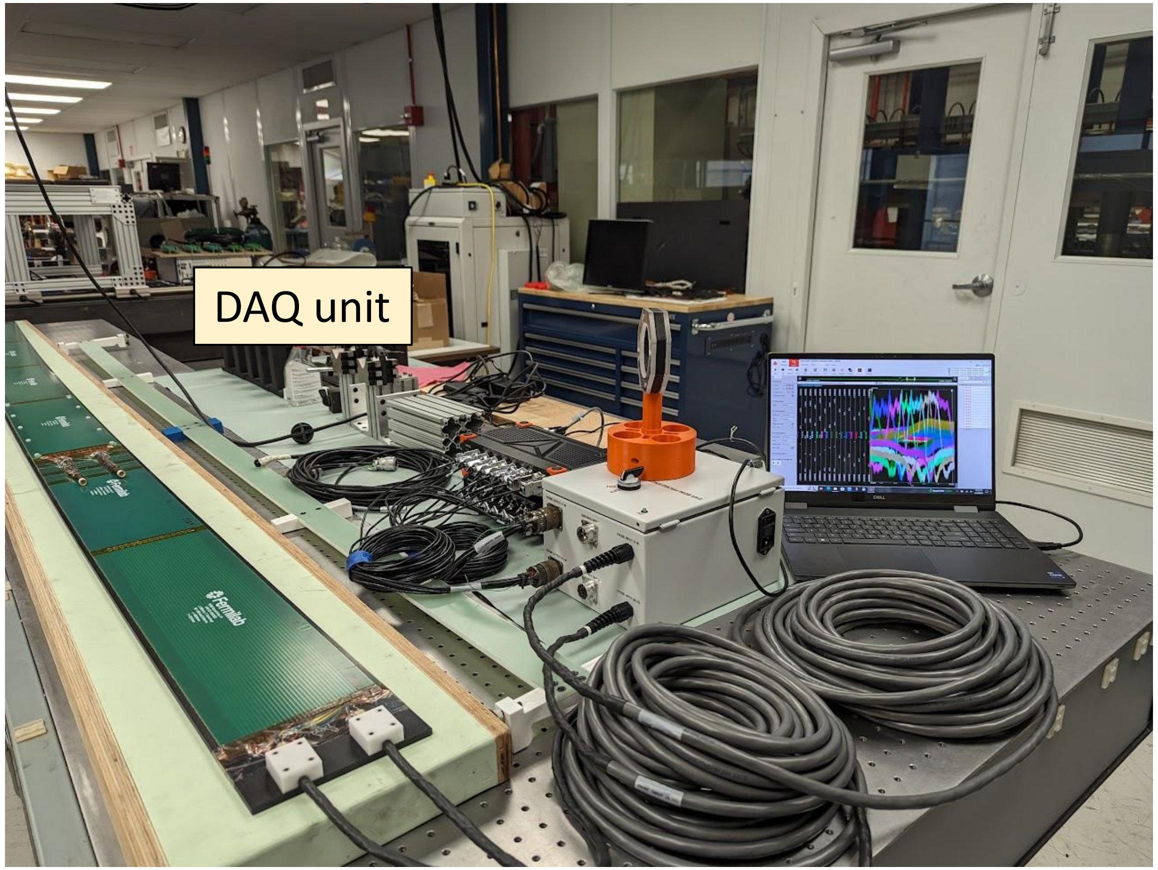
Combined Function Magnets for Fermilab’s Proton Improvement Plan (PIP-II)

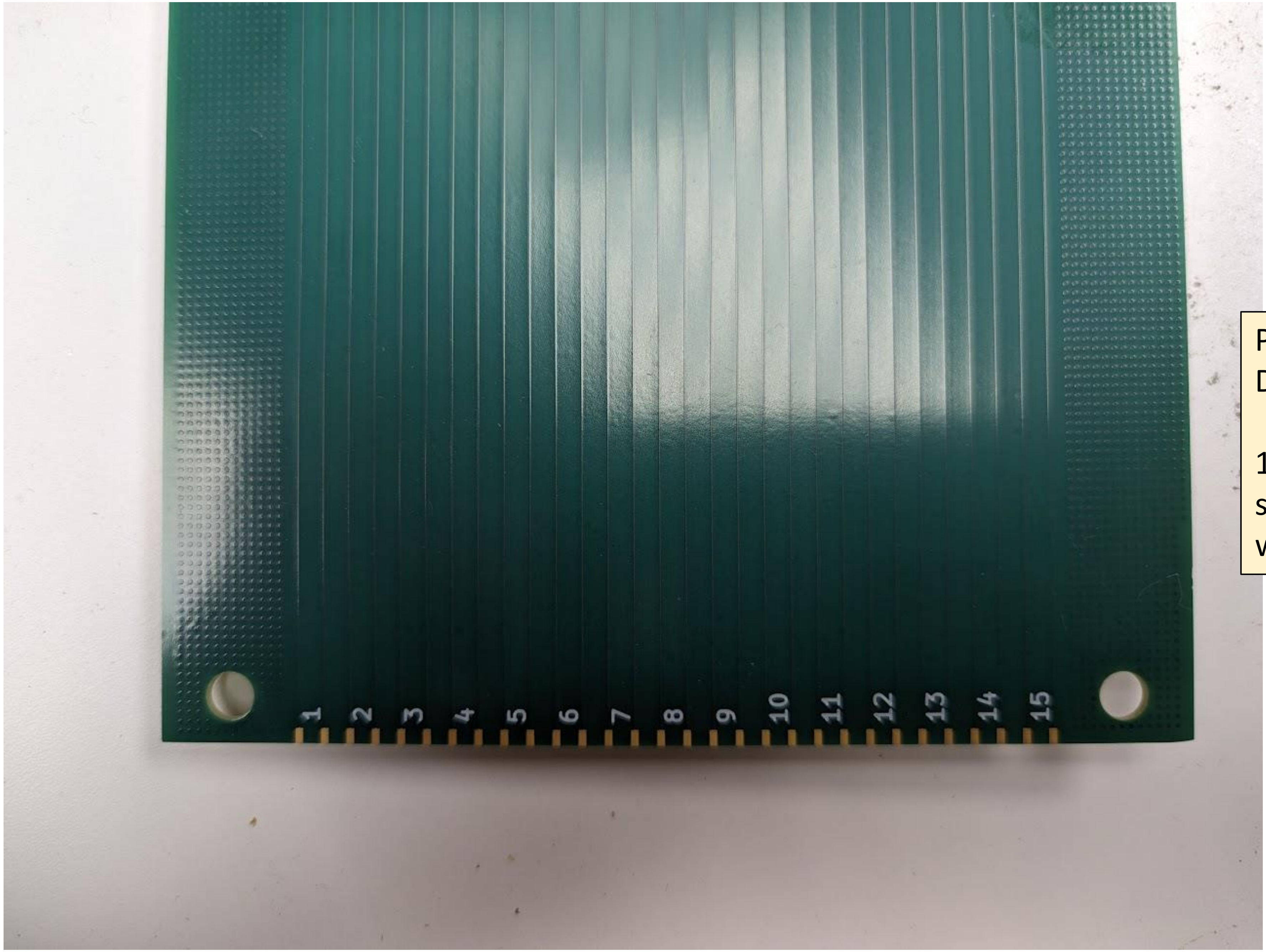


15 Hz Booster magnet (combine function dipole/quad) will be upgraded to 20Hz and additional magnets fabricated

Probe to measure integral AC fields



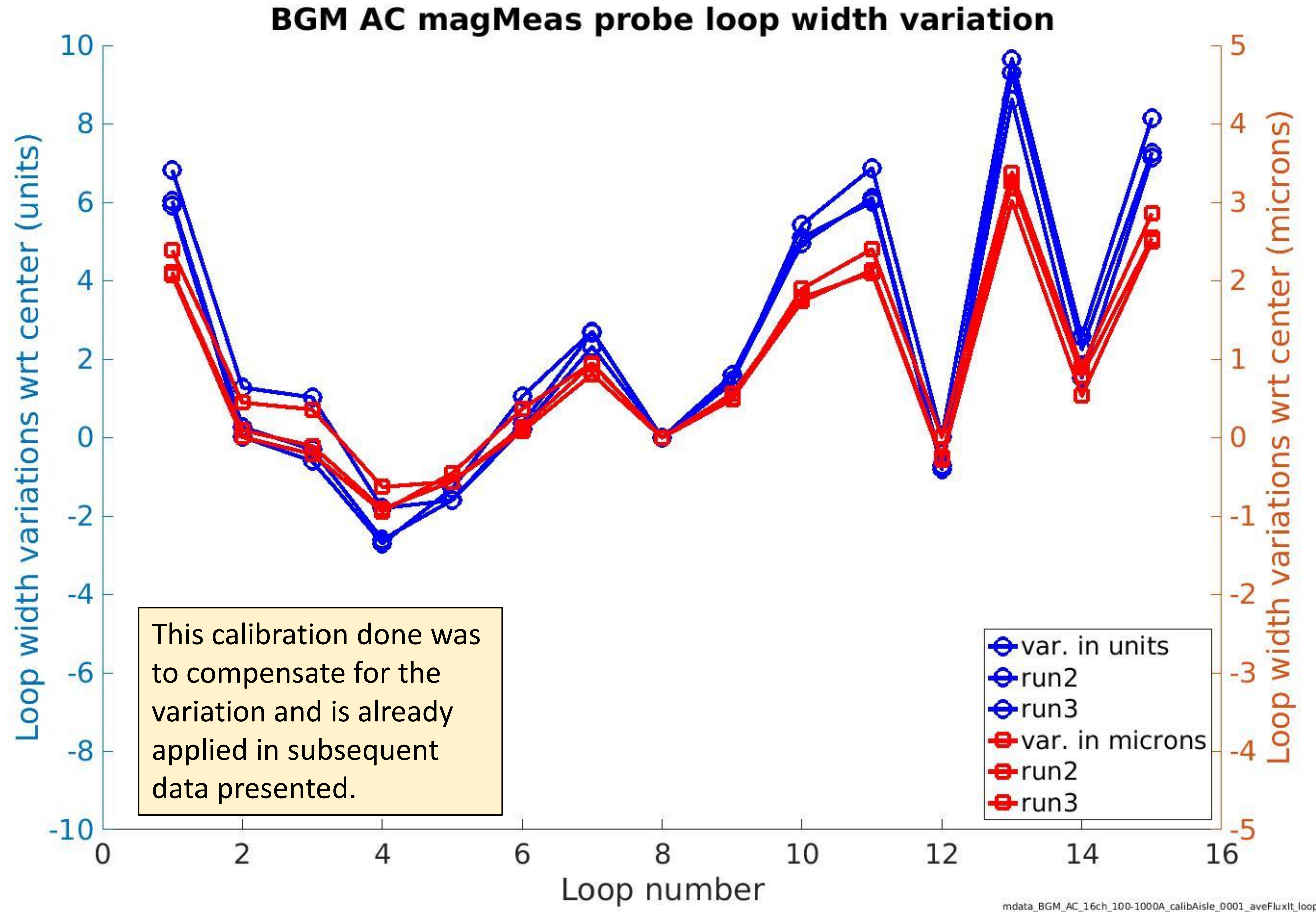




Probe is curved to match the D magnet radius.

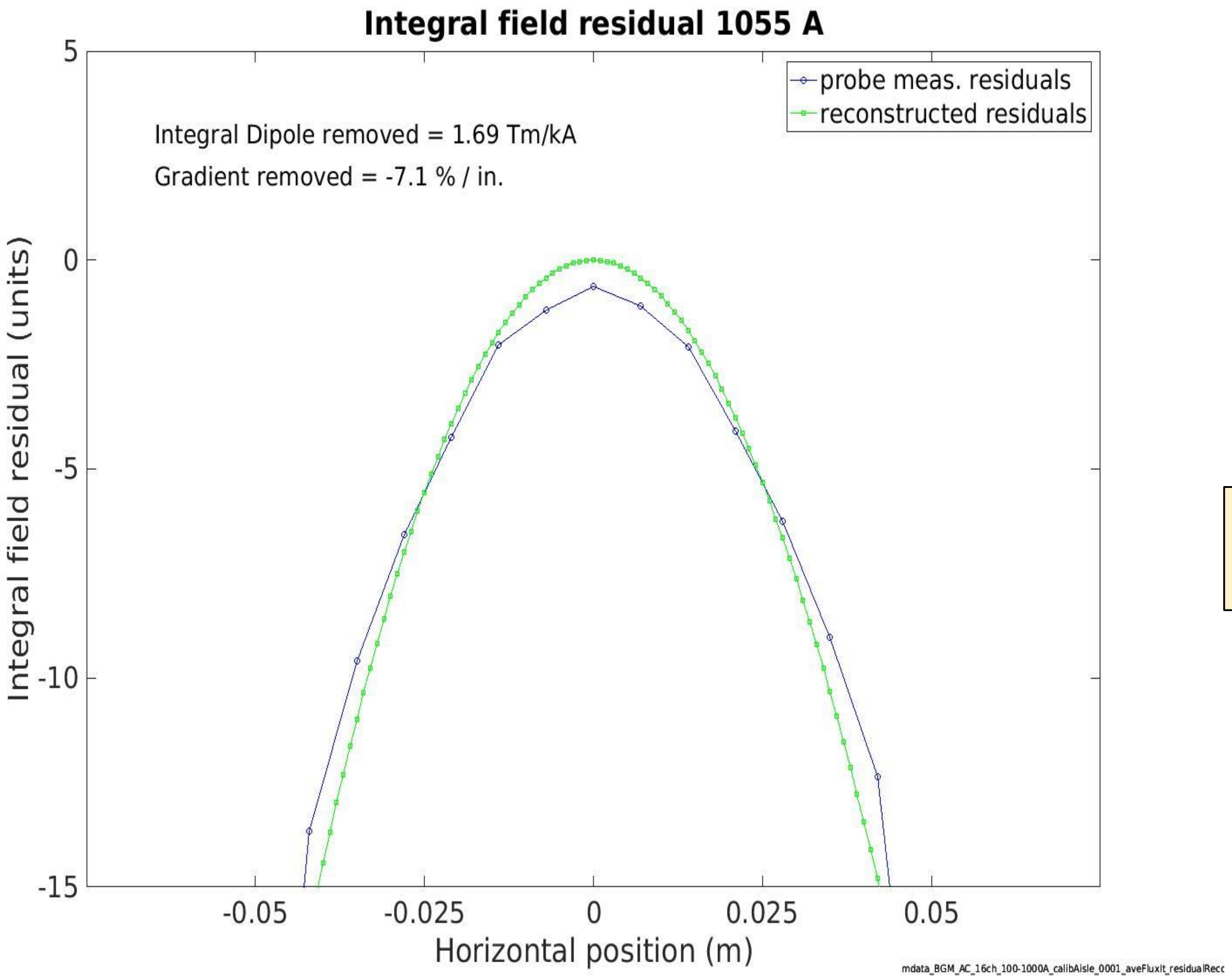
15 loops, 3.5mm wide each, separated by 7mm, total width = 101.5 mm

Probe situated within magnet. Note that probe can slide +/- 3.5mm to stops on strongback so that loops can be cross-calibrated at same horizontal position in magnet.



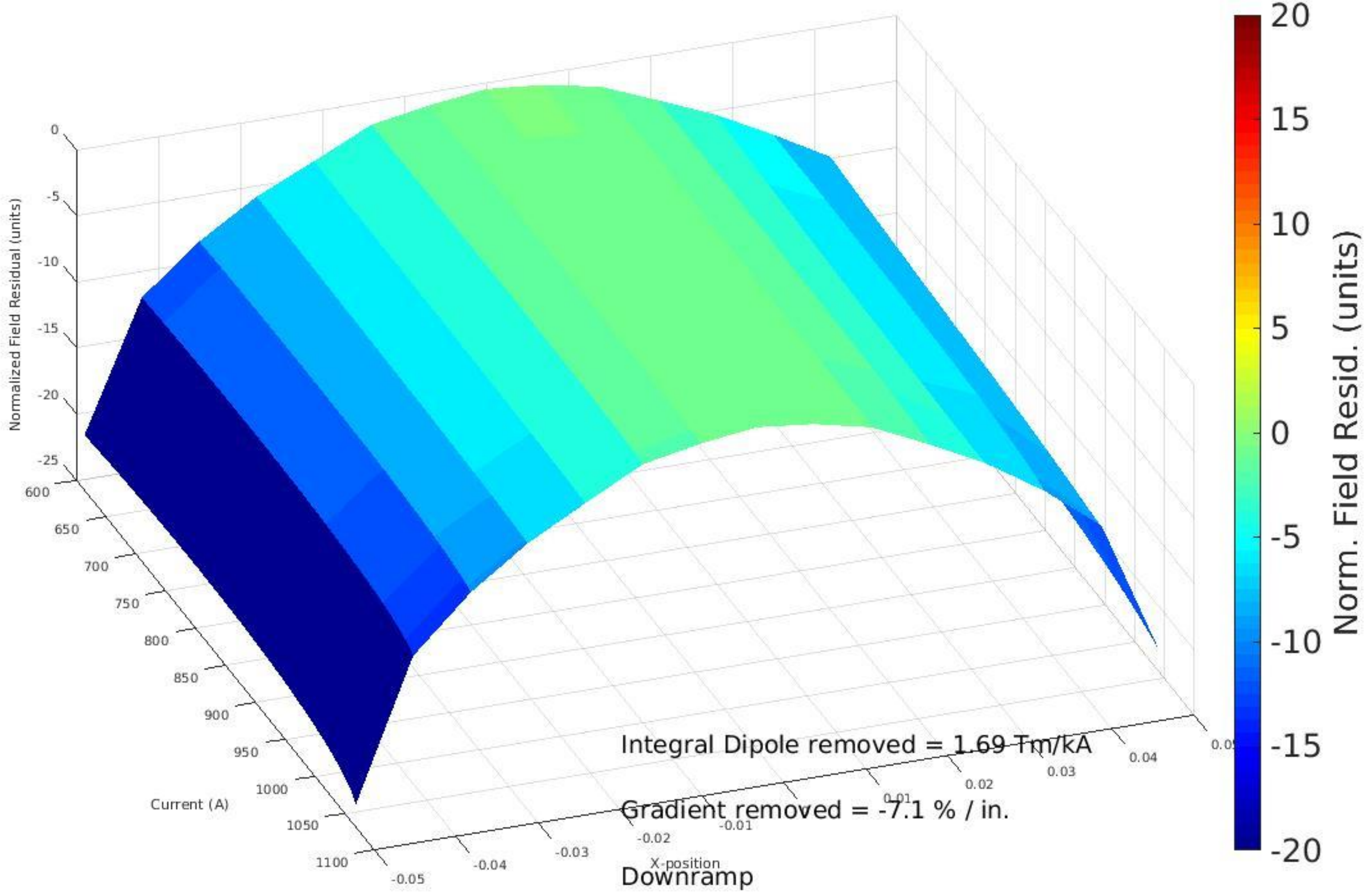
This calibration done was to compensate for the variation and is already applied in subsequent data presented.

mdata_BGM_AC_16ch_100-1000A_calibAisle_0001_aveFluxIt_loopWidthVa

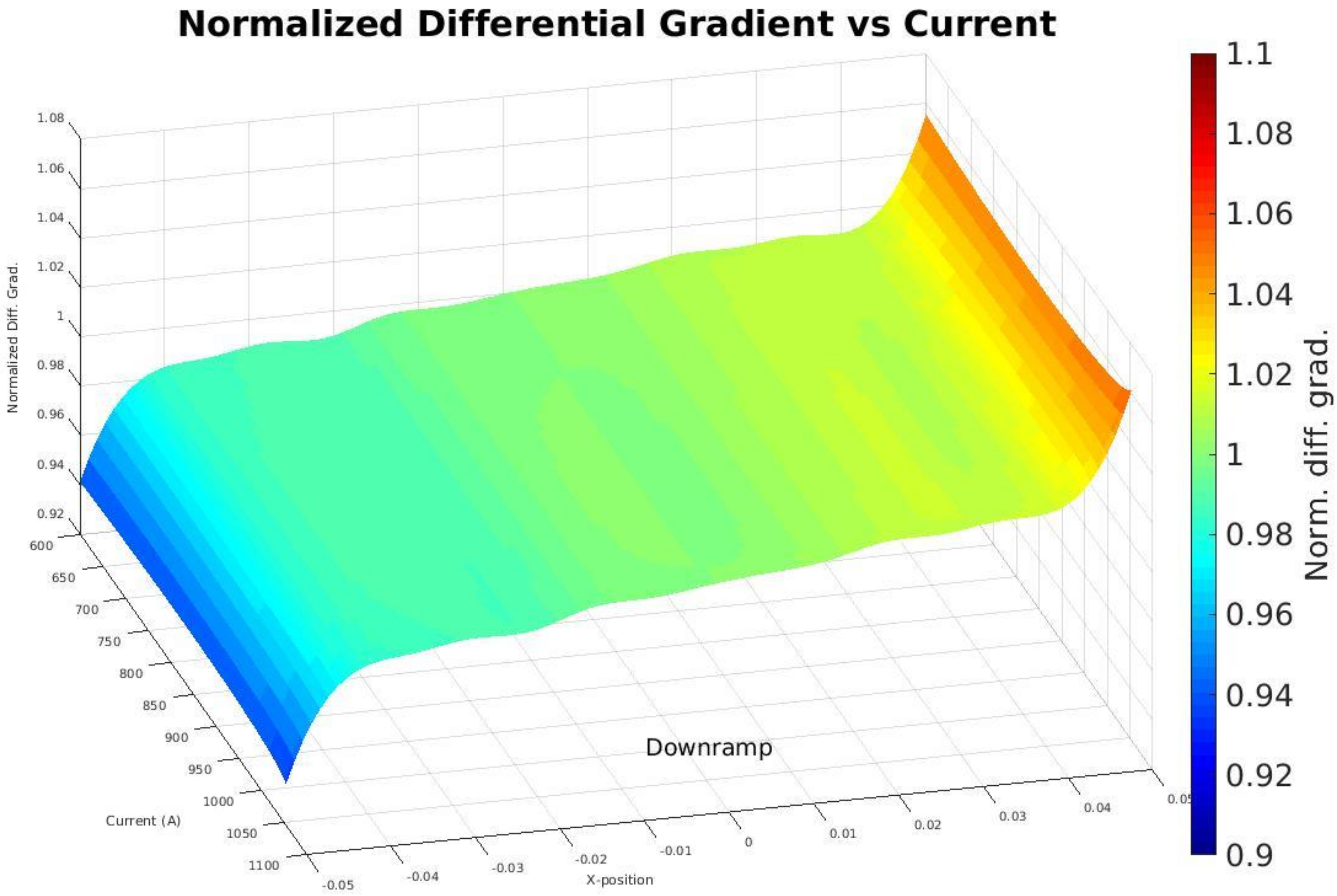


Note that current cycles from ~110 A to ~1055 A

Normalized Field residual vs Current



mdata_BGM_AC_16ch_100-1000A_calibAisle_0001_aveFlux



mdata_BGM_AC_16ch_100-1000A_calibAisle_0001_aveFlux

Thanks for your attention