Rotating Coil Probe Activities at Fermilab

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Thanks to colleagues involved with the probe work presented here:

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* CERN/PACMAN program/Univ. Sannio
(March – May and October – Nov 2016)

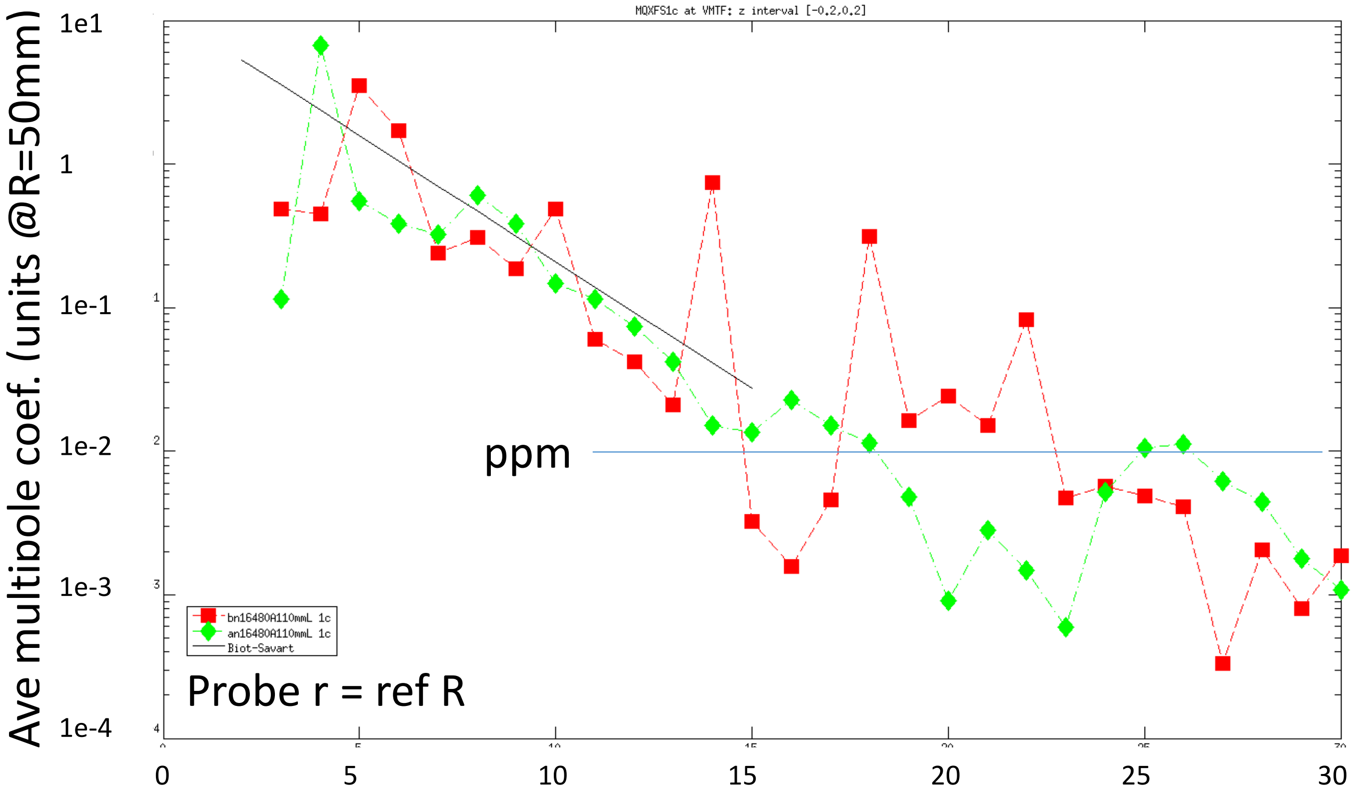
1. Recent probes
2. Getting the probe length right
3. Testing PCB probe self-calibration
4. Long probe

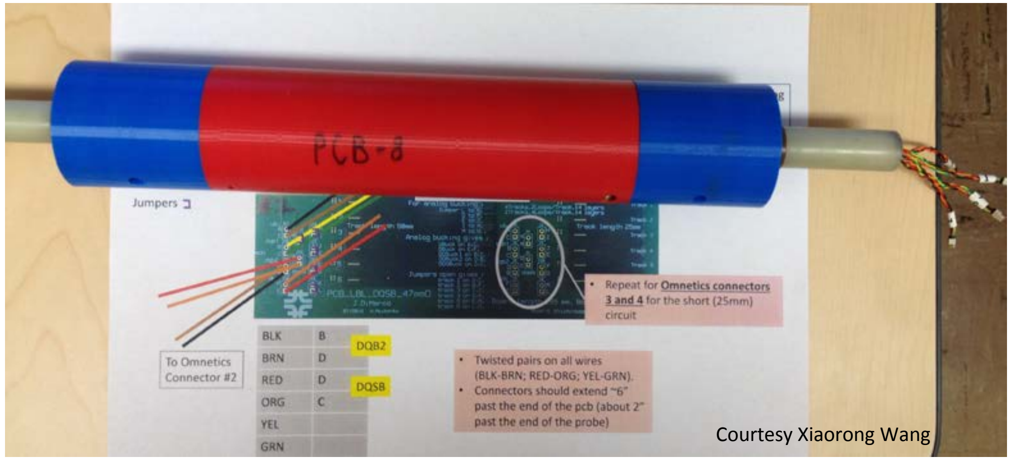
1) Recent probes built with PCBs

	Name	Active Length	Rot. Diameter	nLoops/track	nLayers	Project
a	LBL- DQS-Buck	25mm, 50mm	47mm	2	14	FRIB, CCT measurements, etc.
b	ANL – M4 (DQBuck)	250mm	20.7mm	5	14	Curved trajectory for M4 magnet
c	FNAL/BNL MQXF (DQBuck)	110mm, 220mm	100mm	12	2	MQXF 1.2m model and 5m production magnets
d	ANL – Q8 (DQBuck)	825mm	22.4mm	4	14	APS upgrade Q8 integral meas

MQXF probe (Hi-Lumi magnets for CERN)
(similar probe also to be delivered to BNL)

Bucking ratio 2700/4000 for 220mm/110mm lengths





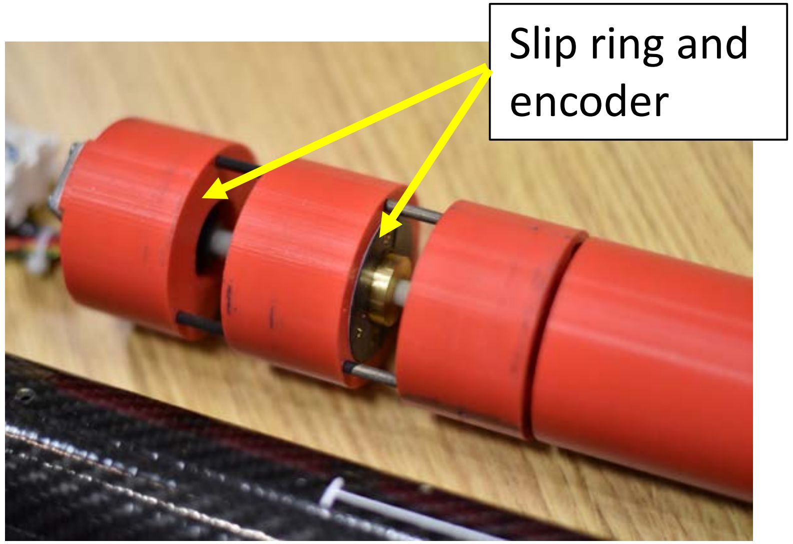
25mm-long/50mm-long Dipole-Quad-Sextupole-Buck probe for LBNL

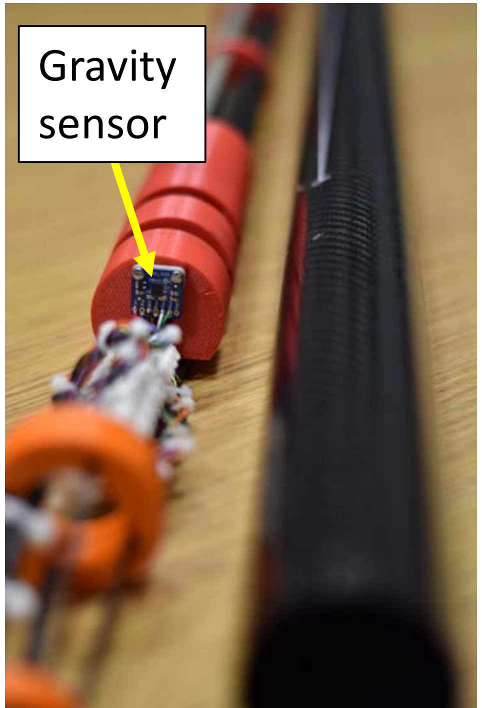
(Duplicate probe but wired for Dipole-Buck also sent to LBL)

250mm-long, DQBuck probe for measurements of M4 magnet at ANL for APS-upgrade

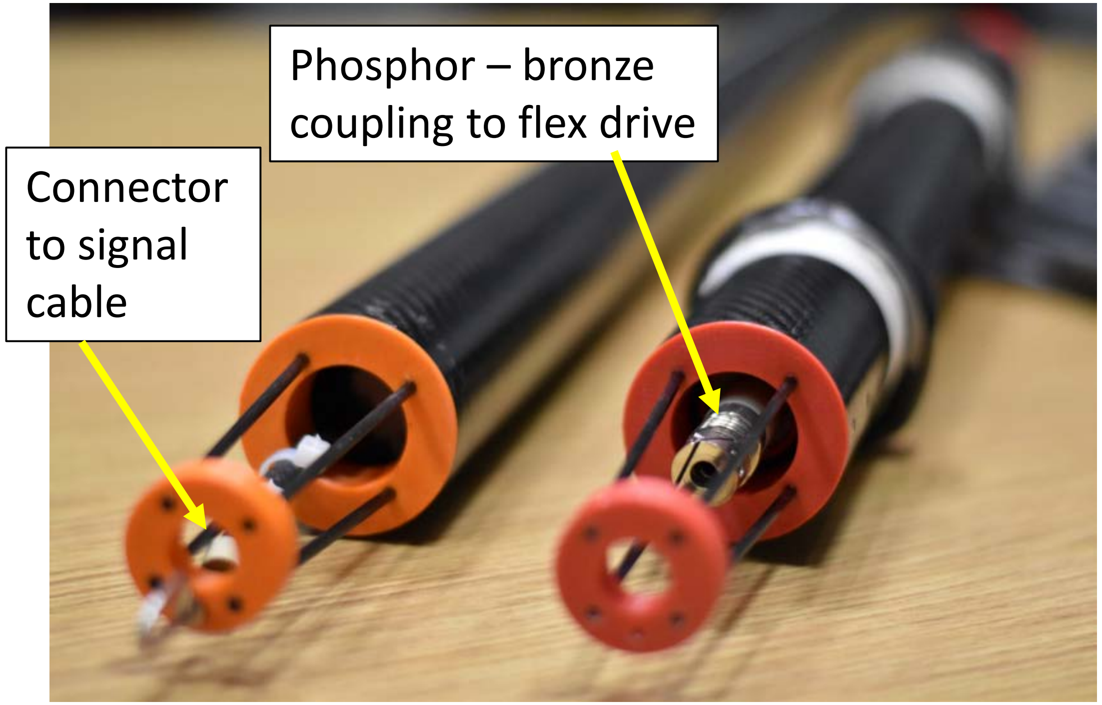
Probe rotates at center of 2.5m long, 23.8mm OD tube (ID=22.5mm, trace radius 10.35mm**).** Tube is translated within magnet (ends are on stages which move in Z) so that probe measures effective harmonics of a curved trajectory.

Also a couple of new ferret probes were made (50mm diameter, 100 and 1000mm active lengths)

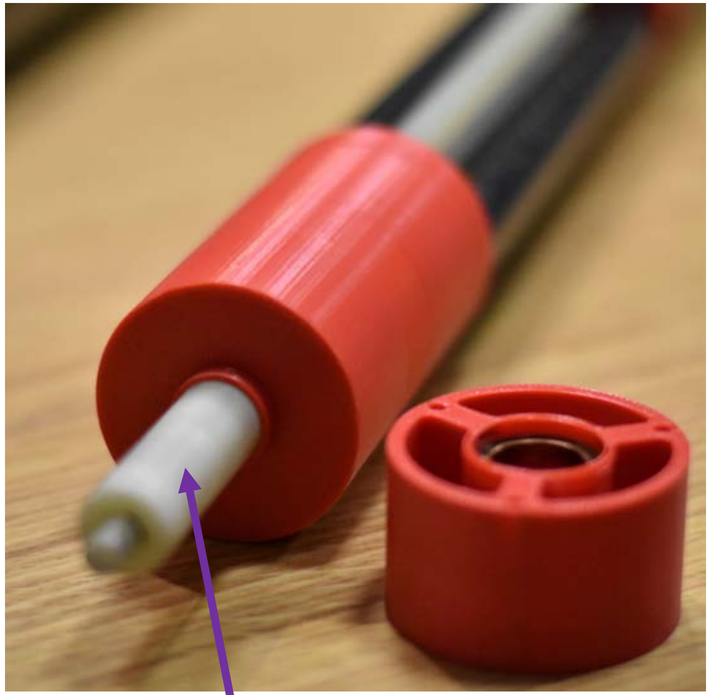




Intended for general purpose measurements and to test components/design. Scaled version of probe may be used for Hi-Lumi IR quad production measurements

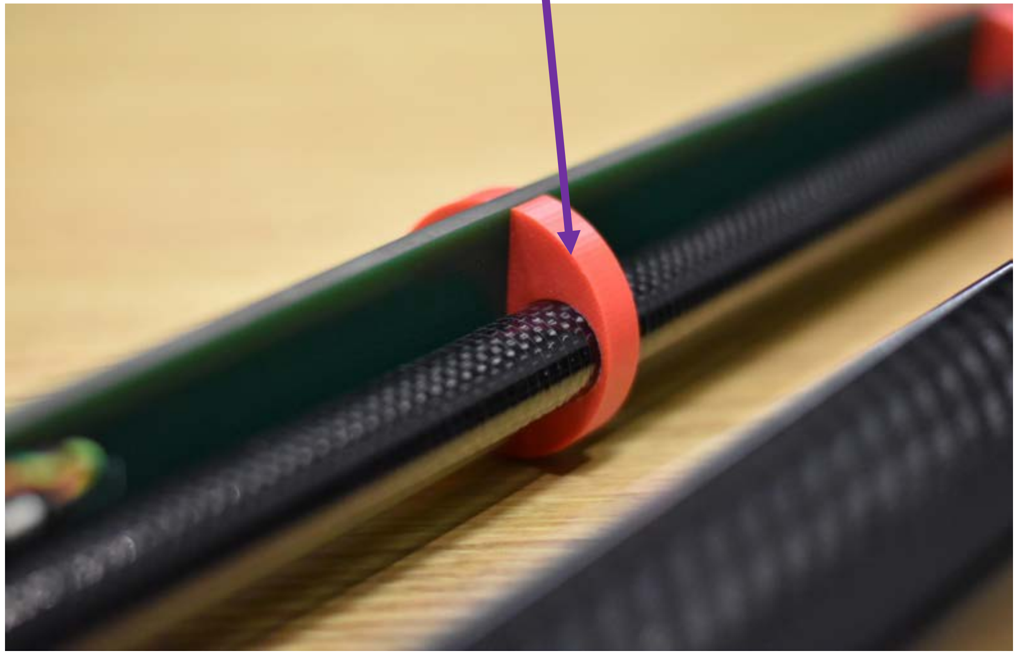


Some new PCB probe mechanics features

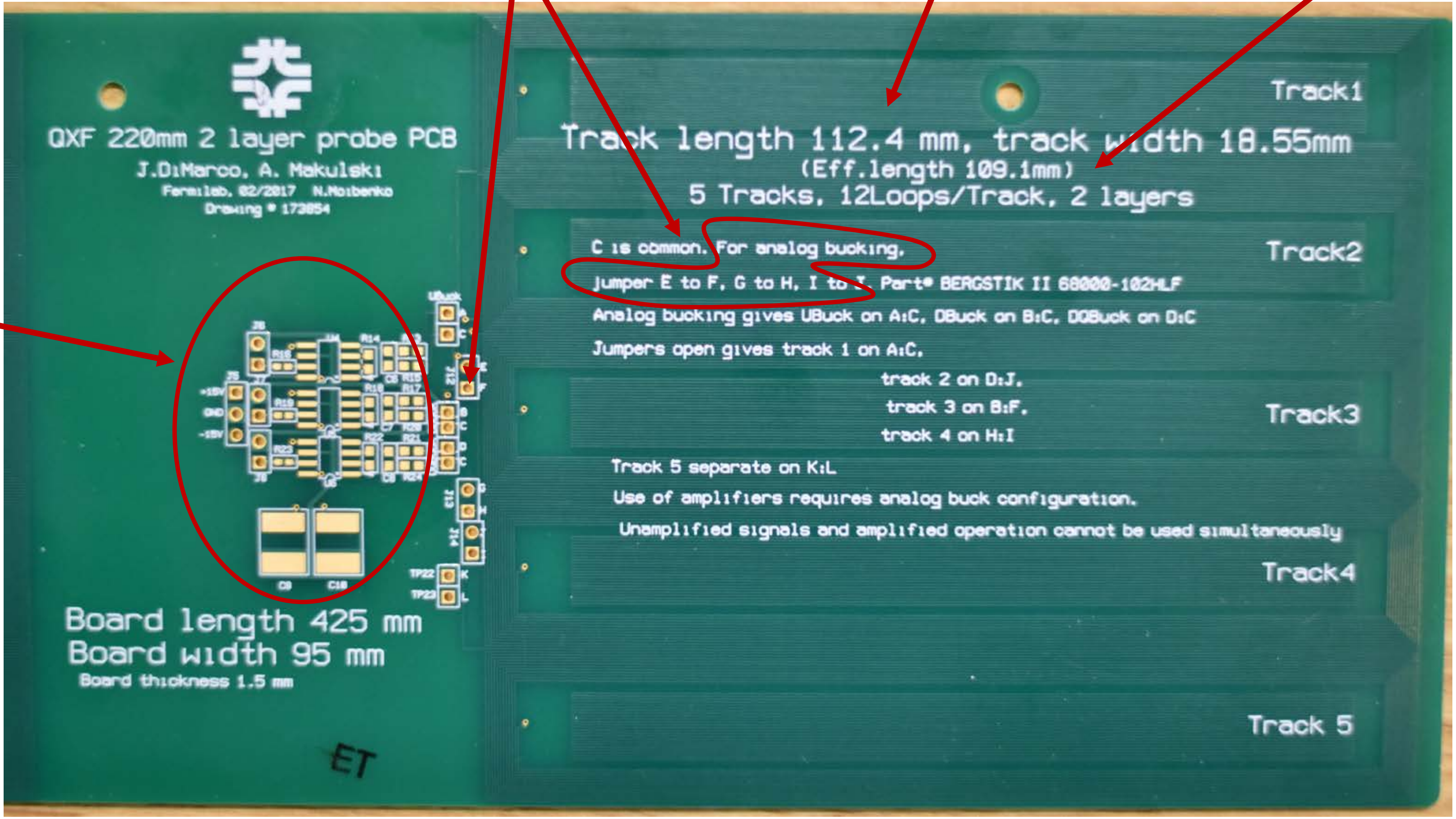


Rather than 3D print the shaft on which the bearing sits – which tends to be too weak mechanically with ABS material – instead print end support with appropriate hole to receive G10 rod

'Disk' supports are used to support the PCB and rigidly couple the support rods to it. This saves weight and plastic and makes assembly easier.



A counter-balance can be eaily calculated and incorporated when the pcb is not

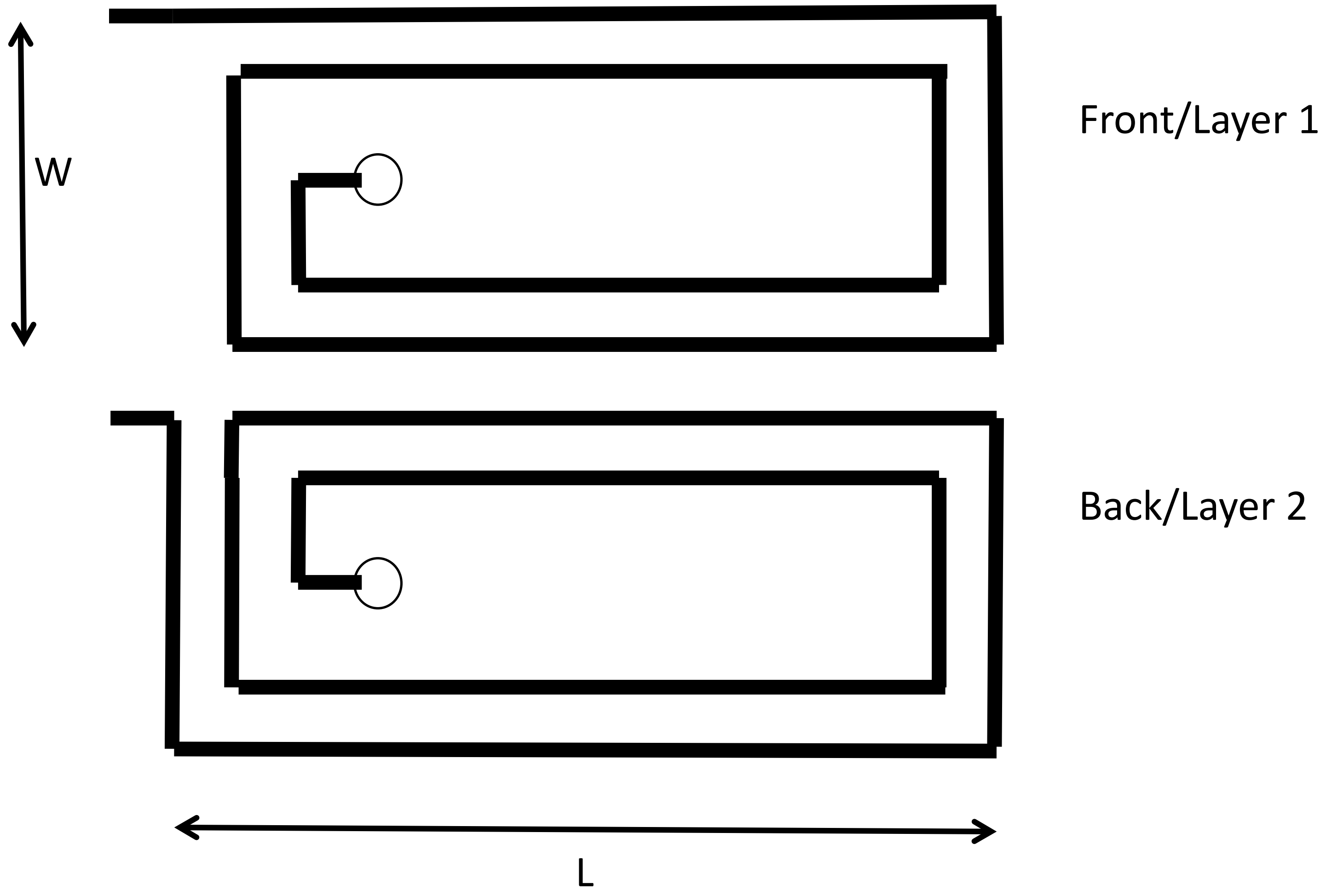

Optional analog bucking connection via jumpers
Documentation on PCB
Physical and effective length given
Surface mount, on-board amplifier circuit (not always used)
QXF 220mm 2 layer probe PCB
J.DiMarco, A. Makulski
Fermilab, 02/2017 N.Moibenko
Track1
Track length 112.4 mm, track width 18.55mm
(Eff.length 109.1mm)
5 Tracks, 12Loops/Track, 2 layers
C is common. For analog bucking,
Track2
jumper E to F, G to H, I to J. Part# BERGSTIK II 68000-102HLF
Analog bucking gives UBuck on A:C, DBuck on B:C, DDBuck on D:C
Jumpers open gives track 1 on A:C,
track 2 on D:J,
track 3 on B:F,
track 4 on H:I
Track3
Track 5 separate on K:L
Use of amplifiers requires analog buck configuration.
Unamplified signals and amplified operation cannot be used simultaneously
Track4
Board length 425 mm
Board width 95 mm
Board thickness 1.5 mm
Track 5
ET

2) PCB probe Loop Length

$$K_n = \sum_{j=1}^{N_{wires}} \frac{L_j R}{n} \left(\frac{(x_j + iy_j)}{R} \right)^n (-1)^j$$

For integral probe can set to 1; otherwise need to get length right for PCB loops which are entirely within the field

Have 2 turns per layer – what is the length of each turn?

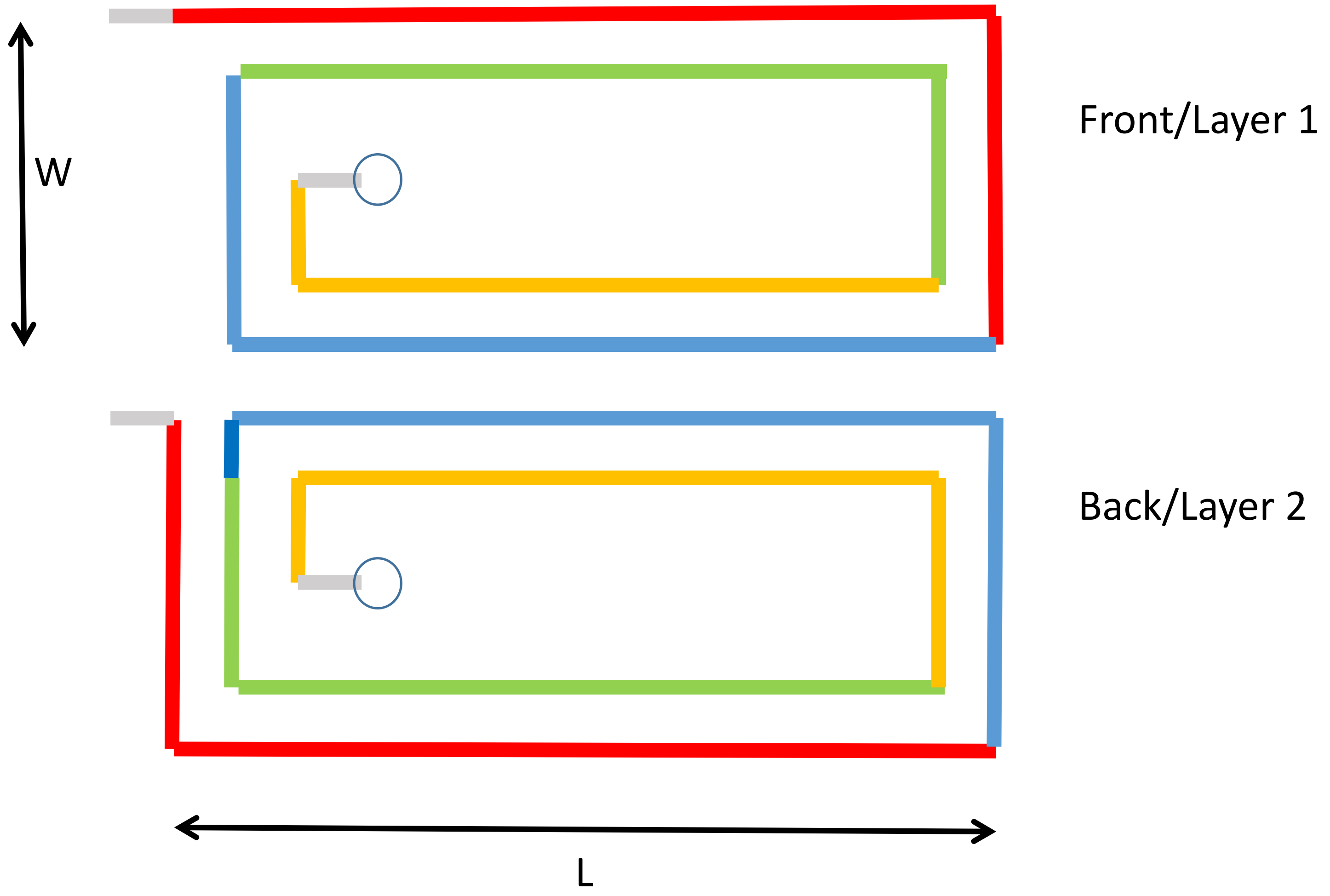


2) PCB probe Loop Length

$$K_n = \sum_{j=1}^{N_{wires}} \frac{L_j R}{n} \left(\frac{(x_j + i y_j)}{R} \right)^n (-1)^j$$

Becomes clear when realize that have to consider layer pair to get loops

- L * W
- (L - Δ) * W
- (L – 2 Δ) * (W - 2Δ)
- (L – 3 Δ) * (W - 2Δ)



Gives 2 turns with width W and average length L- Δ/2

Gives 2 turns with width W- 2Δ and average length L- 5Δ/2

Best to just calculate Kn using each individual trace length on the probe when possible

After have the Kn with the actual wire lengths, can recalculate the Kn’ with all the wire lengths the same (i.e. =L’: this is the case where there are no ‘ends’ in the probe).

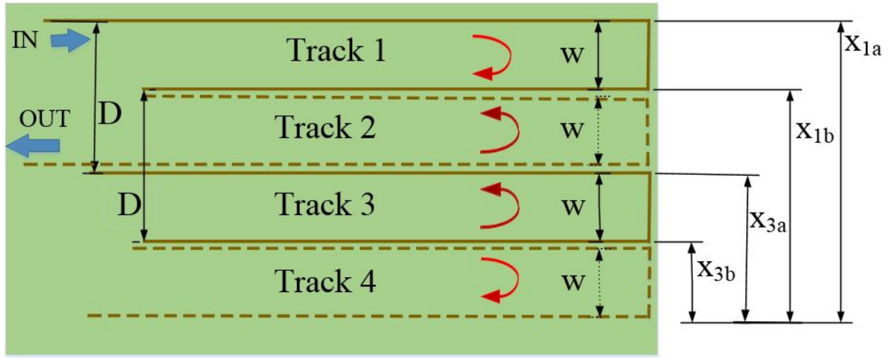
When Kn’=Kn, then L’ is the equivalent length of the PCB ➔ **need to do this when trying to achieve a probe of an exact length** (e.g. to match twist pitch or have a precise step in axial scanning).

Note that this is a (weak) **function of harmonic order**
Typically care in trying to get the integral strength of the fundamental field so want to move the probe according to that ➔ use fundamental harmonic for setting length (e.g. find $K_2=K_2'$ for quad)

3) Experimental check of 'auto-calibration' with standard radially bucked PCB probes

(mentioned in previous IMMWs (e.g. IMMW18))

Tried to make a probe that could be used to verify technique.
Summary of technique follows:



Probe sensitivity Kn is sum over the individual wires of the probe

$$K_n = \sum_{j=1}^{N_{wires}} \frac{L_j R}{n} \left(\frac{(x_j + iy_j)}{R} \right)^n (-1)^j$$

For Dipole Bucked winding (Track 1 – Track3), winding position errors (N turns = 1 and length L=1):

$$B_2 = \frac{\phi_1 - \phi_3}{k_1^1 - k_2^3} = \frac{\phi_1 - \phi_3}{\frac{1}{2R}(x_{1a}^2 - x_{1b}^2 - (x_{3a}^2 - x_{3b}^2))}$$

Setting $\frac{B_2}{R} = g$ and allowing errors, ϵ, in wire position

$$g_{calc} = g * \left(1 - \frac{x_{1a}}{D}\frac{1}{DBR} + \frac{1}{D}(\epsilon_{1b} - \epsilon_{3b}) + \frac{1}{w}(\epsilon_{3a} - \epsilon_{3b})\right)$$

Where Dipole Bucking Ratio (DBR) is:

$$DBR = \frac{w}{(\epsilon_{1a} - \epsilon_{1b}) - (\epsilon_{3a} - \epsilon_{3b})}$$

Note that error terms represent strength error from:
a) Different width btw track 1 and 3,
b) radial separation error, or
c) absolute loop width error
respectively.

From this, find dipole bucked (DB) measurement of quadrupole gradient:

- will be accurate at the level of 0.1%-0.2% without any calibration (for typical PCB mfg. errors)
- is **insensitive to radial positioning error** (only first term depends on x1a – e.g. if that is off by 10%, then the error term changes by 10% (which is just 1-2 units)).
- is **insensitive to PCB offset error**

$$K_2^1 - K_2^3 = \frac{1}{2}\{[(x_{1a}^2 + i2 * x_{1a} * y) - (x_{1b}^2 + i2 * x_{1b} * y)] - [(x_{3a}^2 + i2 * x_{3a} * y) - (x_{3b}^2 + i2 * x_{3b} * y)]\}$$

and the terms in y cancel because x1a-x1b=x3a-x3b=D

The unbucked (UB) measured amplitude and phase are sensitive to both radial and offset errors.

Since UB amplitude and phase should be the same as DB if the errors dR and dV are zero,

➔ Comparing the UB amplitude and phase to DB should allow for solving for the offsets dR and dV

Quadrupole strength measured by the DB winding of the coil is

$$B_2^{DB} = \frac{F_2^{Track1} - F_2^{Track3}}{K_2^{Track1} - K_2^{Track3}} = \frac{\left(F_2^{Track1} - F_2^{Track3}\right) * R}{D * w}$$

Where the F are the Fourier coefficients from the measurement. Quadrupole strength measured by the UB winding (track1), is simply

$$B_2^{UB} = \frac{F_2^{Track1}}{K_2^{Track1}}$$

where the sensitivity is

$$K_2^{Track1} = \frac{w}{R}(\bar{r} + i * 2y)$$

and where y is the offset of the PCB plane from the radius and $\frac{(x_{1a}+x_{1b})}{2} = \bar{r}$ is the average radius of the UB winding. Since the field measured by both windings is the same $B_2^{UB} = B_2^{DB}$, and the unknown quantities $\bar{r}$ and y could be determined from evaluation of the modulus and phase of

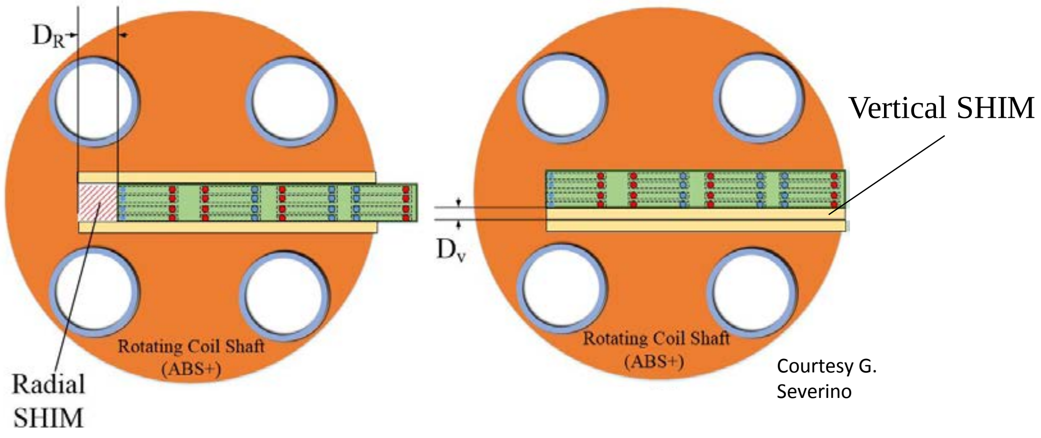
$$\bar{r} + i * 2y = \frac{F_2^{Track1}}{\left(F_2^{Track1} - F_2^{Track3}\right)}$$

This calibration can be performed for any measurement in a quadrupole field and gives an ‘auto-calibration’

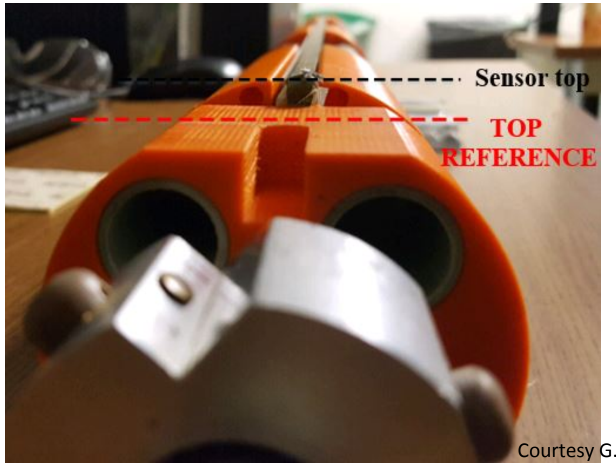
Wanted to confirm that the auto-calibration works so we made measurements with pcb displaced by either vertical (~2mm) or radial (~5mm) shims.

Compare:

- CMM measurements of mechanical offset of PCB
- Probe measurements with 'auto-calibration' determination of radial and vertical PCB offsets



Courtesy G. Severino



Courtesy G. Severino

Probe determined shift (mm) Vertical	CMM shift (mm) Vertical
1.679	1.679

Probe determined shift (mm) Radial	CMM shift (mm) Radial
6.271	6.304

Repeatability is on the order of ~10um

Results are in very good agreement (<30um, within meas error) even with the large shims that were used.

Probe mechanics may not be stable

1.593mm- -4.704mm = 6.297 (immediately after CMM meas)
1.593mm - 4.653mm = 6.246 (few days before CMM meas)

CMM determined 6.304

Calibration can also be used ‘dynamically’ (rotation by rotation) so that variations in probe mechanics that change over time or probe position are compensated for.

4) Long Probe

Length limits on 'PCB-coils' ?

- Have seen that pcbs are great for small coils – even very small coils like the CERN one for CLIC magnets
- How about limitations at the other extreme – 1m or so ok - but beyond that?

At Fermilab have several vintage 'Morgan coils' (multi-pole wound probes) that are 2.5-3m in length. How would we develop something similar if had to replace them (or make one with larger radius) ?

Multipole coil at Fermilab with 2p, 4p, 6p, 8p, 10p, 14p windings

Length limits on ‘PCB-coils’ ? (continued)

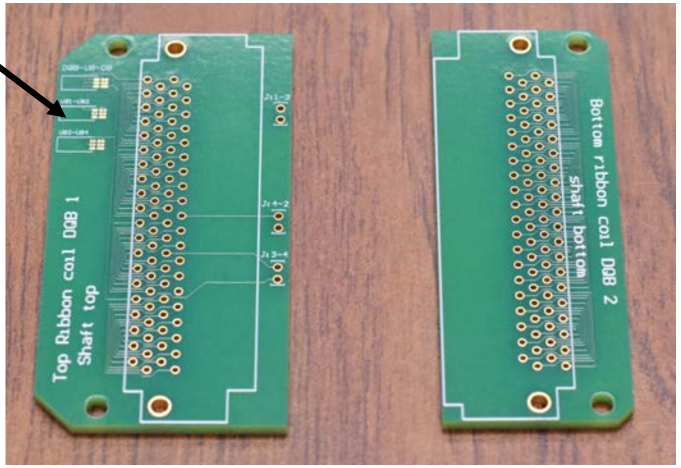
- The thought was to use a “Ribbon cable” fashioned as a radial probe at the ends with 4 sets of loops (for quadrupole) to have the usual radial bucking.

- Ends would form loops through ribbon-cable connector interfaced to ribbon and then onto a PCB
- Ends might be ‘messy’ as the cable transitions through connector - not neatly controlled etchings on PCB – but this would be used as an integral probe and so would not matter (outside magnet field)

➔ Could be easily extensible – length limited only by mechanical structure.

- Project for student (Giordana) to design PCBs to serve as ends which configure conductors of ribbon cable wires into loops (both for DQ buck and DQS buck versions)
- Low-cost **proof-of-principle test** ➔ use standard ribbon cable (instead could have etched traces on long flex circuit- see e.g. Tor Pedersen’s talk in IMMW19)
- Standard cable, **‘insulation-displacement contact’** (**IDC**) connectors (no soldering!)

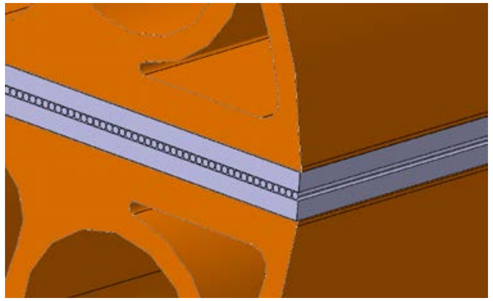
Lead end (with surface mount pads for signal connections) and return end PCB pieces (by G. Severino)



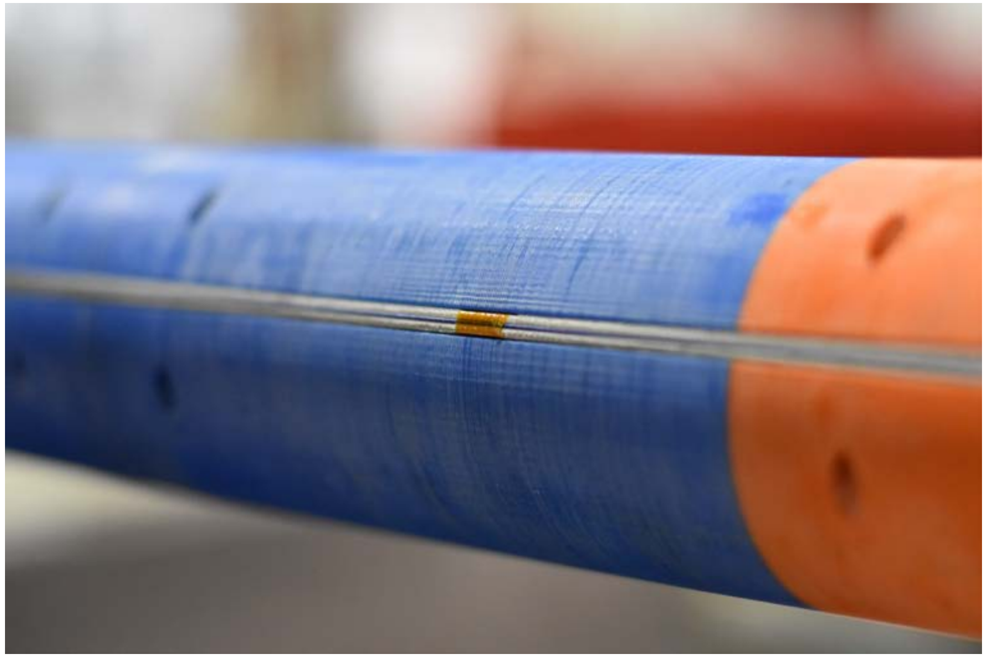
80 conductor ribbon cable with 0.635mm spacing (mfg. claims 40um position tolerance on wires)

Connector interface is PCB mount connector

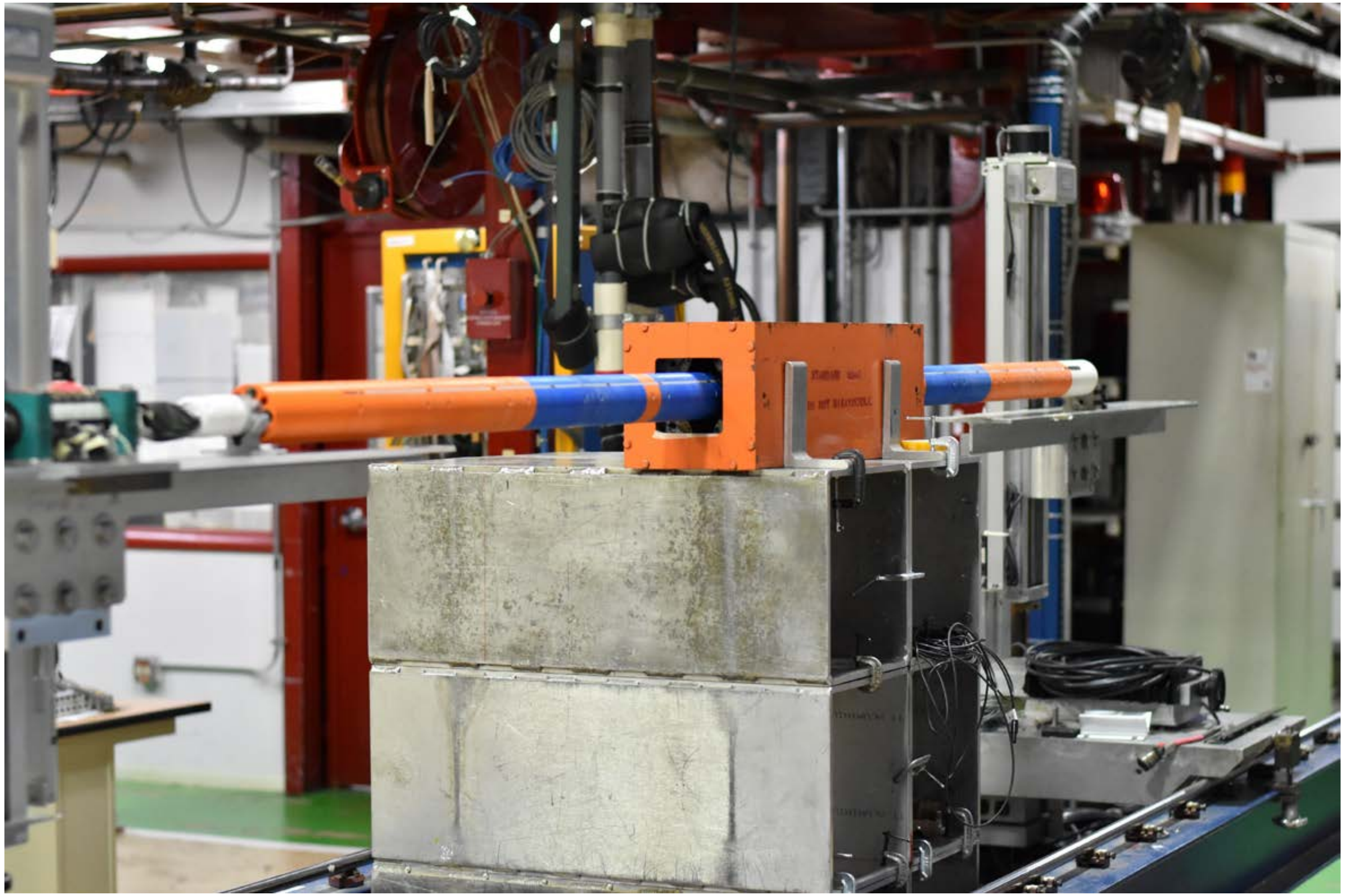
IDC connector snaps over cable to contact the 80 wires – no soldering.



Ribbon cable is sandwiched between 2 G-10 shims. These shims have shallow grooves milled every ~30cm so that kapton tape can secure them before insertion.

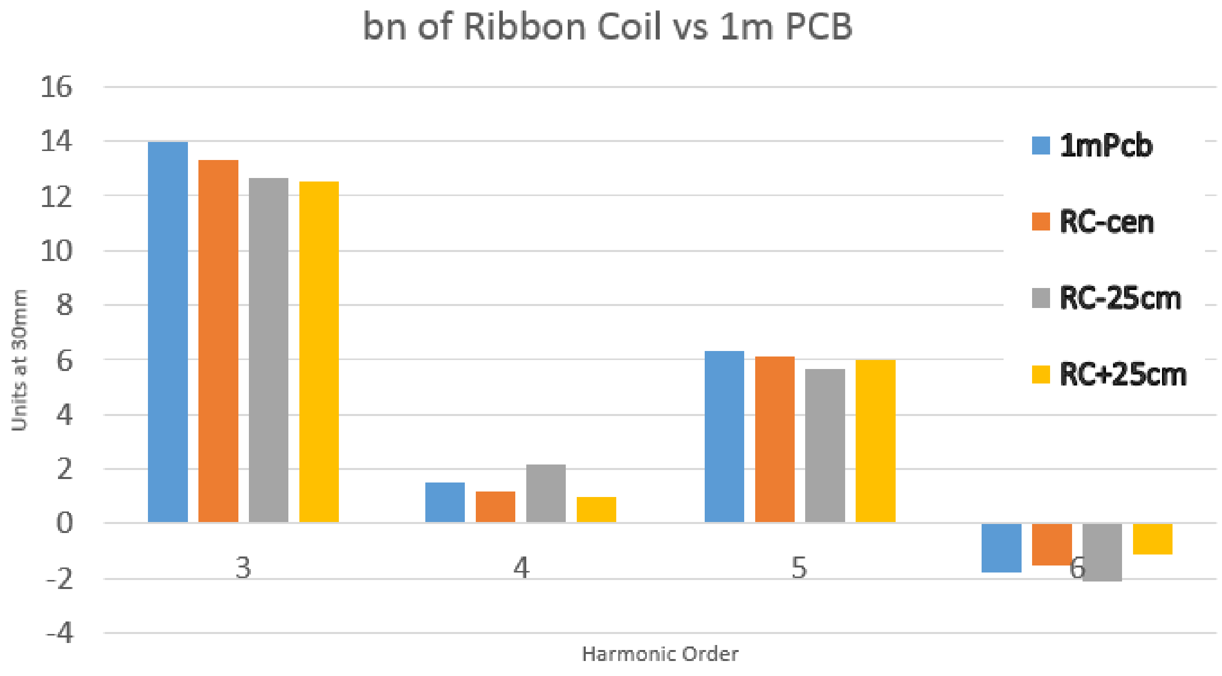


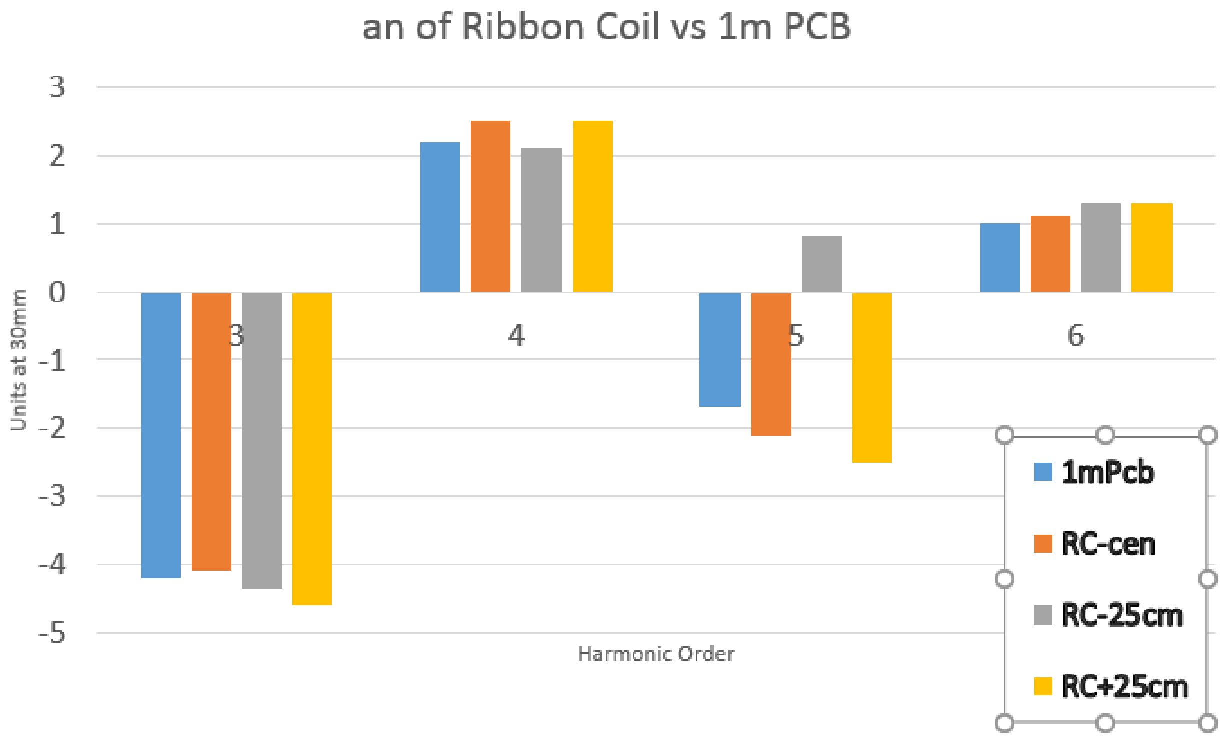
- Mechanical design was not rigid enough – sag is several millimeters. Placed bearing in the middle for support within magnet.



Measurements were made with probe centered (shown above) and with probe shifted by +/- 25cm longitudinally

Ribbon Cable probe: Centered in magnet and shifted by z=+/-25cm





TF:	BuckRatio:	
1.5784	750	1mPcb
1.5744	440	RC-cen
1.5743	400	RC-25mm
1.5763	480	RC+25mm

From auto-calibration:	dR(mm):	dV(mm):	
	0.295	0.091	RC-cen
	0.382	-0.007	RC-25mm
	0.118	0.153	RC+25mm

- Ribbon coil compares to 1m PCB only at the level of ~2 units
- Variation in coil position is on the order of 250um (corrected for (on average) by auto-calibration procedure)

- Not great … but possibilities for long and/or large aperture coils seem to be there
- Next round aim for improved mechanics and perhaps improved ribbon (e.g. long flex circuit)

Summary:

- Several PCB probes have been built by Fermilab for use in our own magnet measurements and for other labs.

- Some improvements in the boards and mechanics supporting them have been implemented.

- The experimental verification of the PCB 'auto-calibration' scheme was successful – the method worked well, even for large displacements, within the errors of measurement/stability of the mechanics (~30um).

- An exploration into making long coils by using ribbon cable to make a 'PCB-like' radial coil was undertaken. The results were reasonably encouraging, showing good bucking ratio and comparison with a rigid PCB to within about 2 units.