Rotating Circuit Board Probes for Magnetic Measurements

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IMMW15

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Introduction

Cicuit Board Probes – an appealing concept –

- Acccurate trace locations
- Manufacture probes reproducibly, cheaply, quickly.

Development at FNAL

- Circuit board trace configurations with bucking of fundamental fields (to ease dynamic range requirements and reduce feed-up from vibration effects)
- Designs which have comparable sensitivity with standard rotating coil probes.
- Analysis which can deal with it

Generalized Rotating Probe Harmonics Analysis

Dealing with complex or non-ideal rotating harmonics probes is straightforward

Measure $$\phi(\theta) = \Re \sum_{n=1} C_n K_n e^{(in\theta)}$$

Field $$C_n = B_n + iA_n$$

Any number of wires

Any positions

Wire polarity sign

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

Complex conjugate of $\phi(\theta)$ FFT

$$C_n = \frac{F_n^*}{K_n}$$

Use FFT of rotating probe signal and calculated sensitivities to find Fields

Applicable to all rotating coil data systems

T. Ogitsu, J. DiMarco, 1999

Probe Parameter Files for Wire Locations

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Length(m)	NTURNS	Radius(m)	Phi(rad)
WINDING TAN1			
0.81788	15	0.019539	0.541068
0.81788	15	0.019539	0.768448
WINDING 2P1			
0.830275	1	0.019617	4.81057
0.830275	1	0.019617	1.66898
WINDING 2P2			
0.827126	1	0.019603	-0.359452
0.827126	1	0.019603	2.78215
WINDING 4P1			
0.820725	1	0.019628	-0.414082
0.820725	1	0.019628	1.15672
0.820725	1	0.019628	2.72752
0.820725	1	0.019628	4.29832
WINDING 4P2			
0.823925	1	0.019595	0.152808
0.823925	1	0.019595	1.72361
0.823925	1	0.019595	3.2944
0.823925	1	0.019595	4.8652

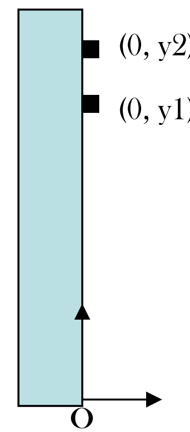
Sample parameter file for tangential probe.

File is read-in and Kn calculated for n=1-15 for each winding

Rows alternate '+' and '-' vertices.

A Simple Circuit Board Probe

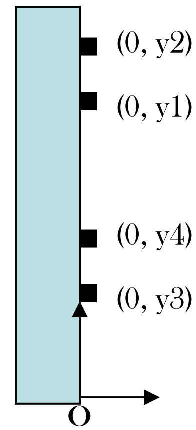
- Radial coil in a plane



$$K_n = \frac{R}{n}\left(L_1(iy_1)^n - L_2(iy_2)^n\right)$$

Dipole Bucked Probe

- Combine 2 simple coils with opposite handedness – n=1 term bucks



$$K_n = \frac{R}{n}\left(L_1(iy_1)^n - L_2(iy_2)^n\right) - \frac{R}{n}\left(L_3(iy_3)^n - L_4(iy_4)^n\right)$$

Still sensitive to other orders - other terms don't buck because of radial dependence on powers of ***n***

Dipole Quad Bucking

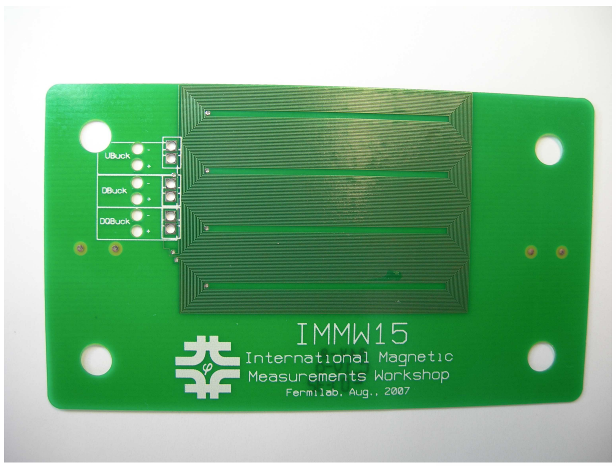
- Combine 2 dipole buck pairs with opposite handedness – n=1,2 terms bucks

Loops 1,3 buck dipole, as do loops 2,4

Since 1,3 measures gradient and so does 2,4, bucking these two pairs bucks both dipole and quadrupole.

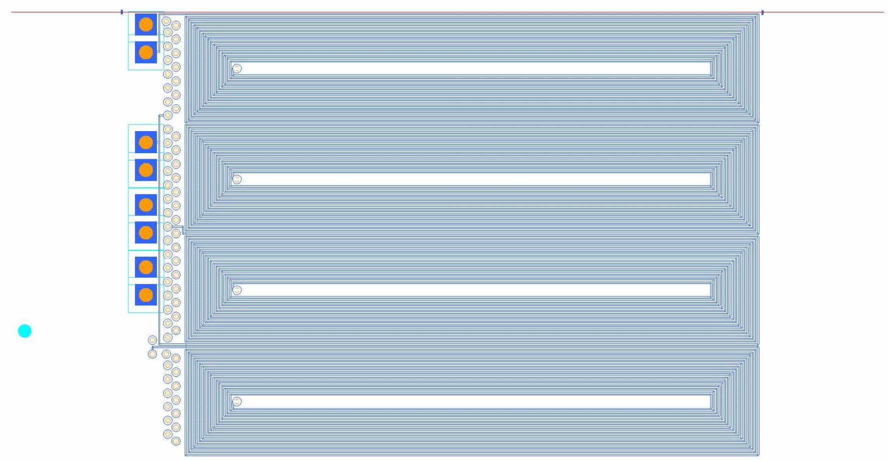
39mm DQ Bucking HFQ Probe

2-layer "IMMW" version



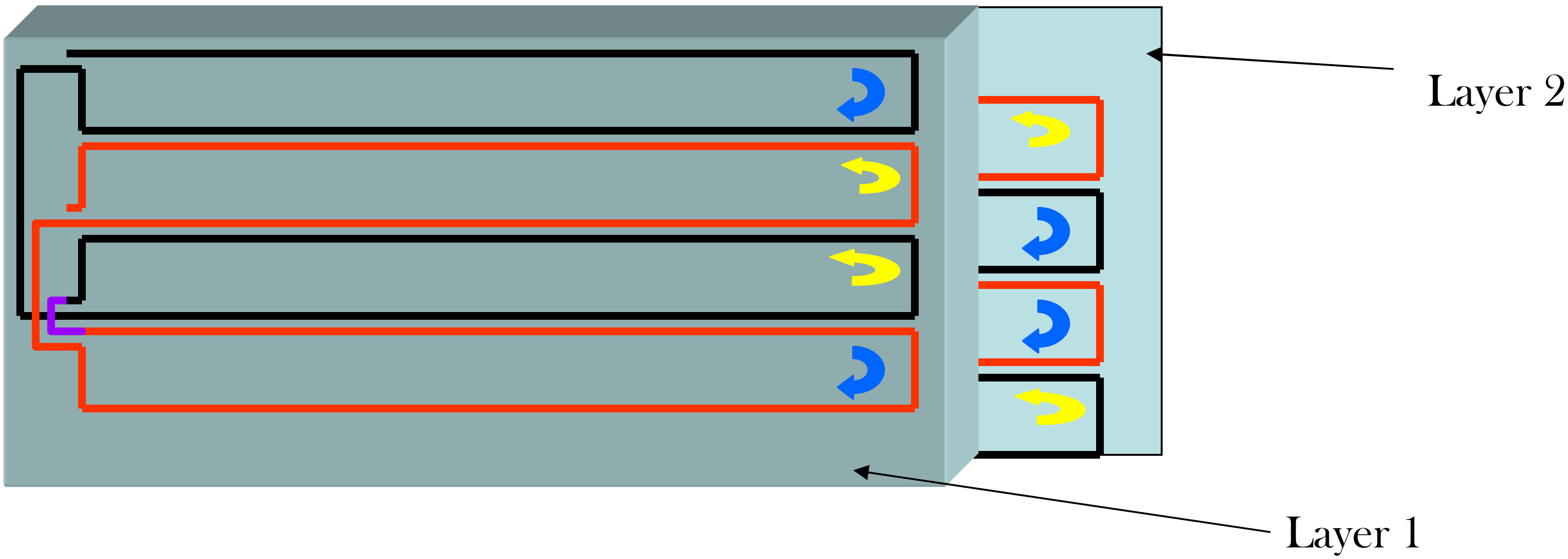
18 turns per loop
0.1mm space/trace
39mm effective length

30-layer version
(note extra via holes for interlayer connections)



Dipole Quad Sextupole Bucking

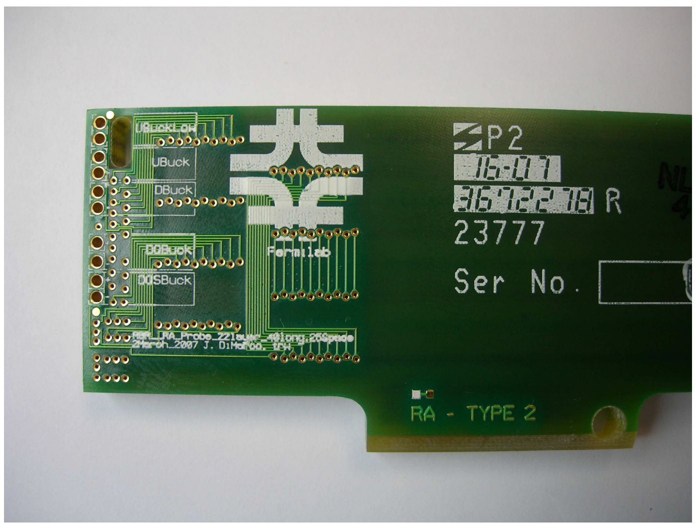
- Combine 2 DQ buck layers with opposite handedness (and offset from each other) → n=1,2,3 terms buck



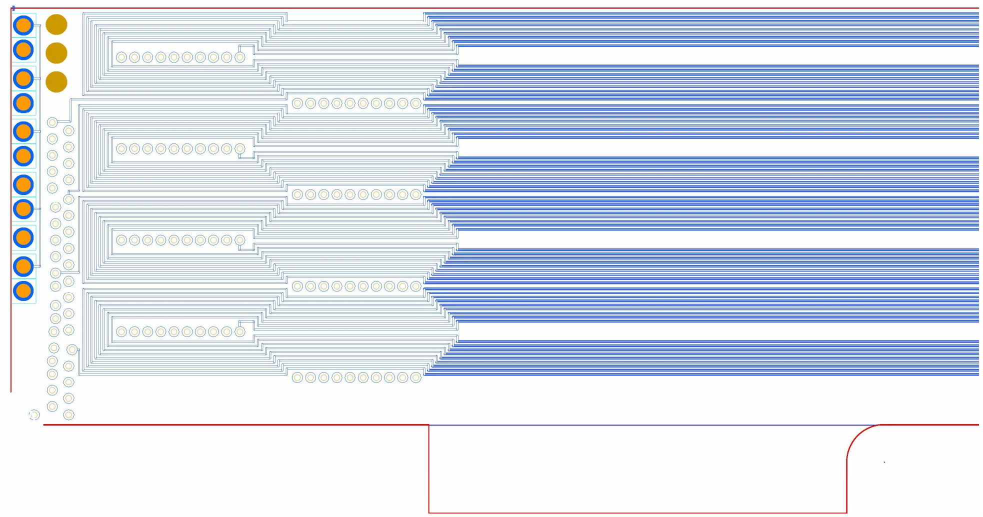
Combined layer 1 loops buck dipole-quad, as do layer 2 loops.

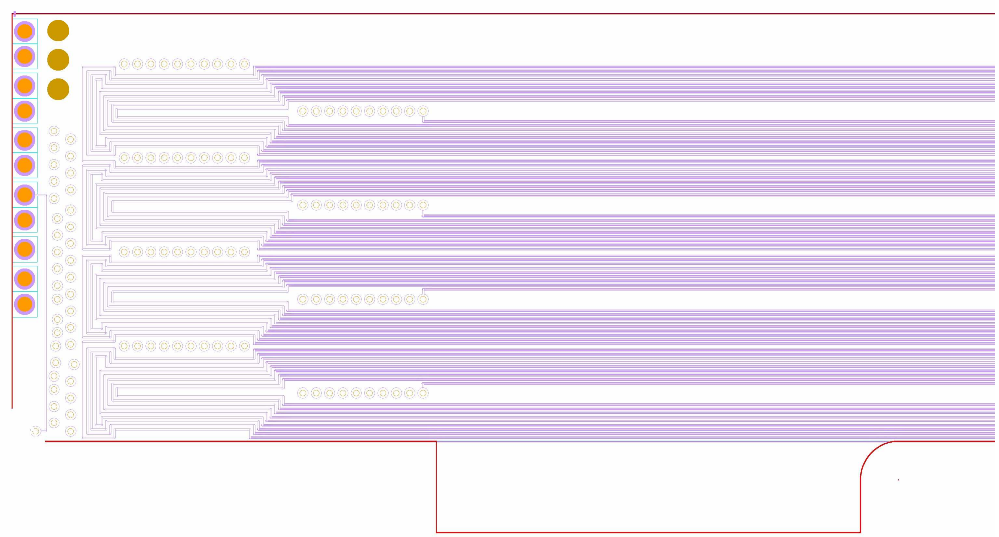
Since layers 1, 2 measure gradient difference (sextupole),
bucking these two layers bucks sextupole in addition to dipole and quadrupole.

DQS Bucking Probe for BMA Fixed Coil Measurements



9 turns per loop
0.15mm/0.1mm space/trace
1m (40”) length

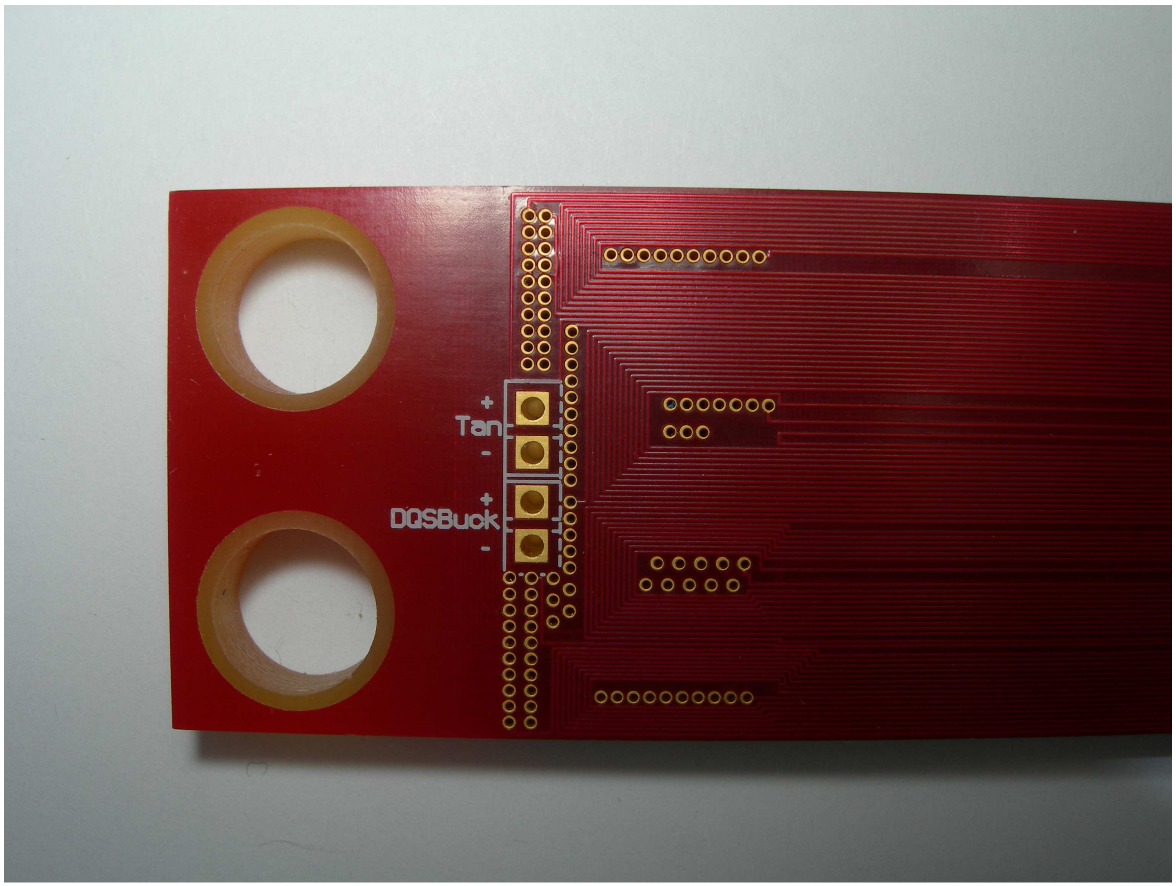


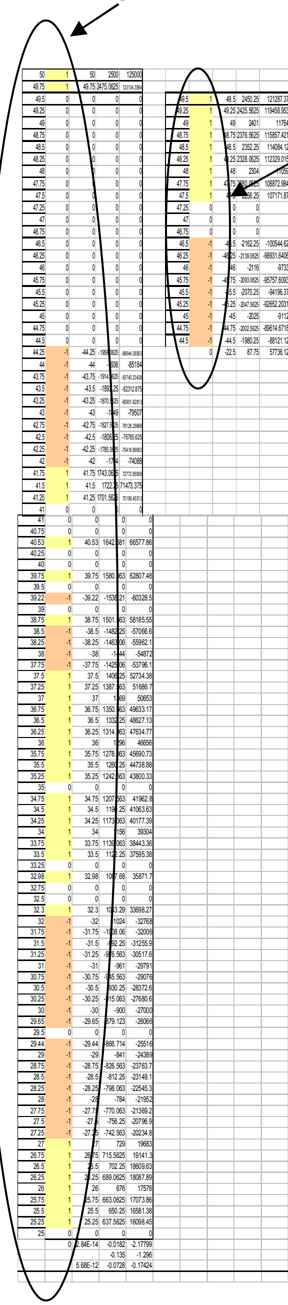


C:\PPD_JOBS\RBR_RA_Probe_22layer_22long.25Space\PCB\RBR_RA_Probe_22layer_22long.25Space.pcb - Page 1 of 1 pages.

Trace design comments

The previous style probes (continuous loops) seem to have some level of optimization (e.g. short end regions). However, there are other ways to make bucked circuit board probes. Depending on application, other geometries may be preferred/better (e.g. if probe extends out the magnet, may not care as much about trace patterns in probe ends)



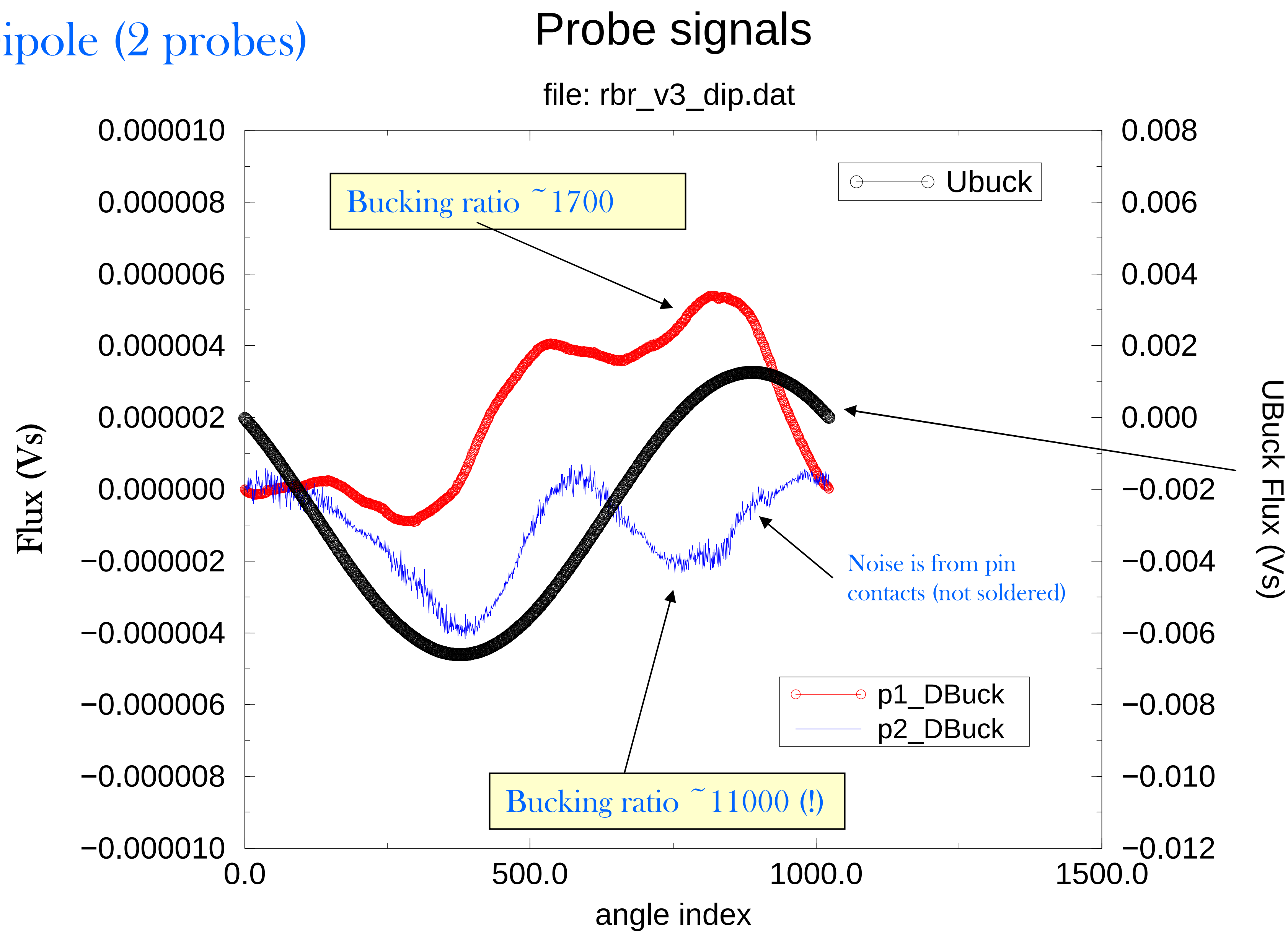


Trace layout for earlier revision of DQS bucking probe (yellow wire positions indicate '+' wires, while orange indicate '-' wires)

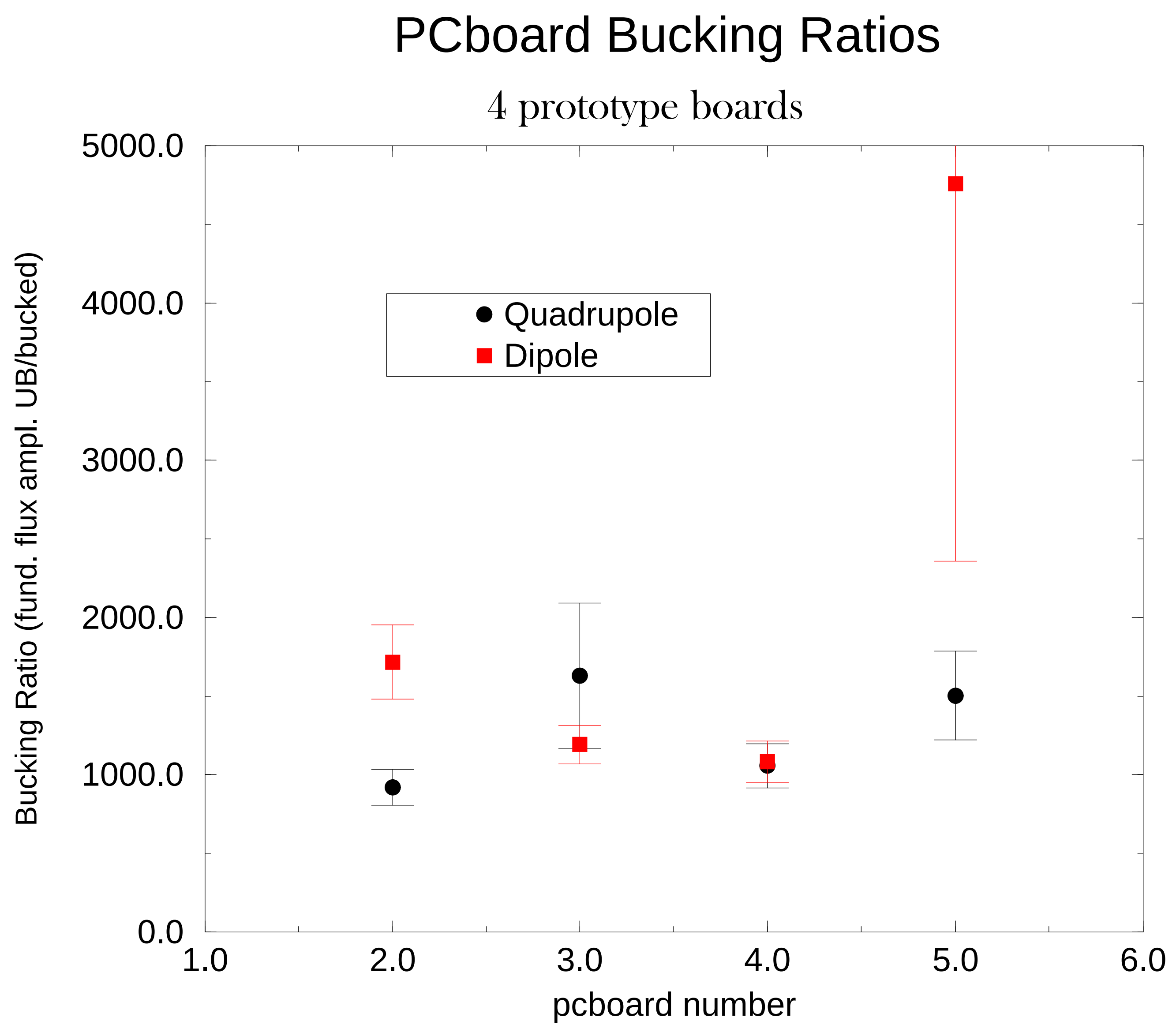
mechanics

- Using probes themselves as support
- Using cylinder diameter
- Using cylinder radius
- Having probe sticking through slot to maximize radius

Buck ratio in Dipole (2 probes)



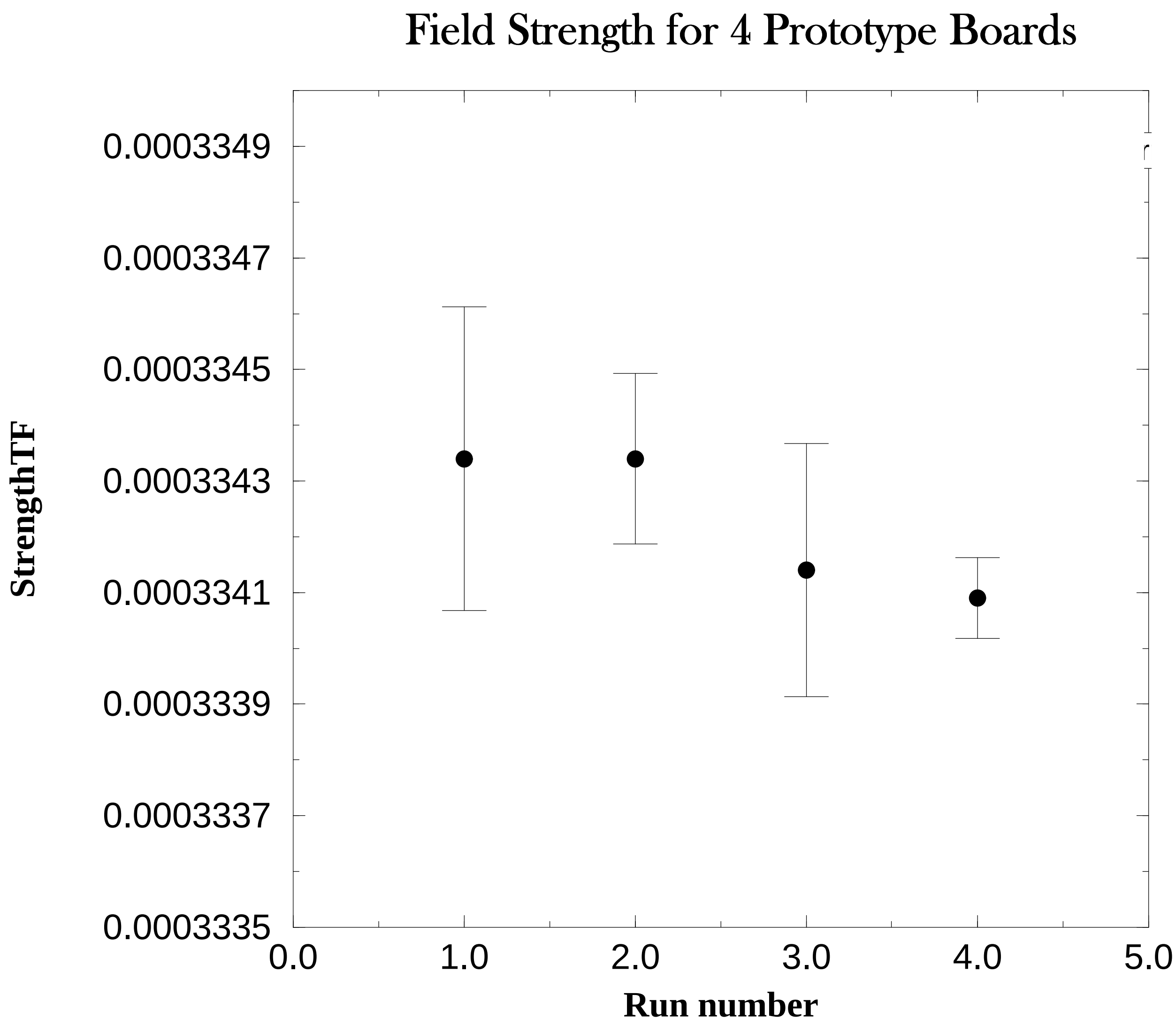
Dipole and Quad buck ratios



Dipole Field Strength

4 different boards

s.d. is about 4 units.



Quad Field Strength

Can measure quadrupole field strength with Unbucked Winding or with Dipole-Buck Winding.

With **DB** winding, if the bucking is nearly perfect, then the probe radius of rotation doesn't matter much – get an absolute measurement of quadrupole field at the level of 0.1-0.4 % without calibration or knowledge of rotation radius. (Can then go back and use the fact that DB quad strength = Unbucked quad strength to determine radius of rotation of unbucked winding for harmonics).

(likewise true for sextupole measurement with DQ buck winding)

Distance shift between loops

~ 5-10 units

Average radial position of UBuck loop

$$g_{meas} \approx g\left[1+\frac{\bar{\varepsilon}'-\bar{\varepsilon}}{D}+\frac{1}{buckRatio}*\left(\frac{\bar{x}'}{D}+\frac{\Delta\varepsilon}{\Delta\varepsilon-\Delta\varepsilon'}\right)\right]$$

Δg ~ 5units for 5μm shift

~ 2 for this RBR

Bucking ratio dependent term: ~0 for very high buck ratio

Difference in width error of the two loops. This term is an implicit function of BR

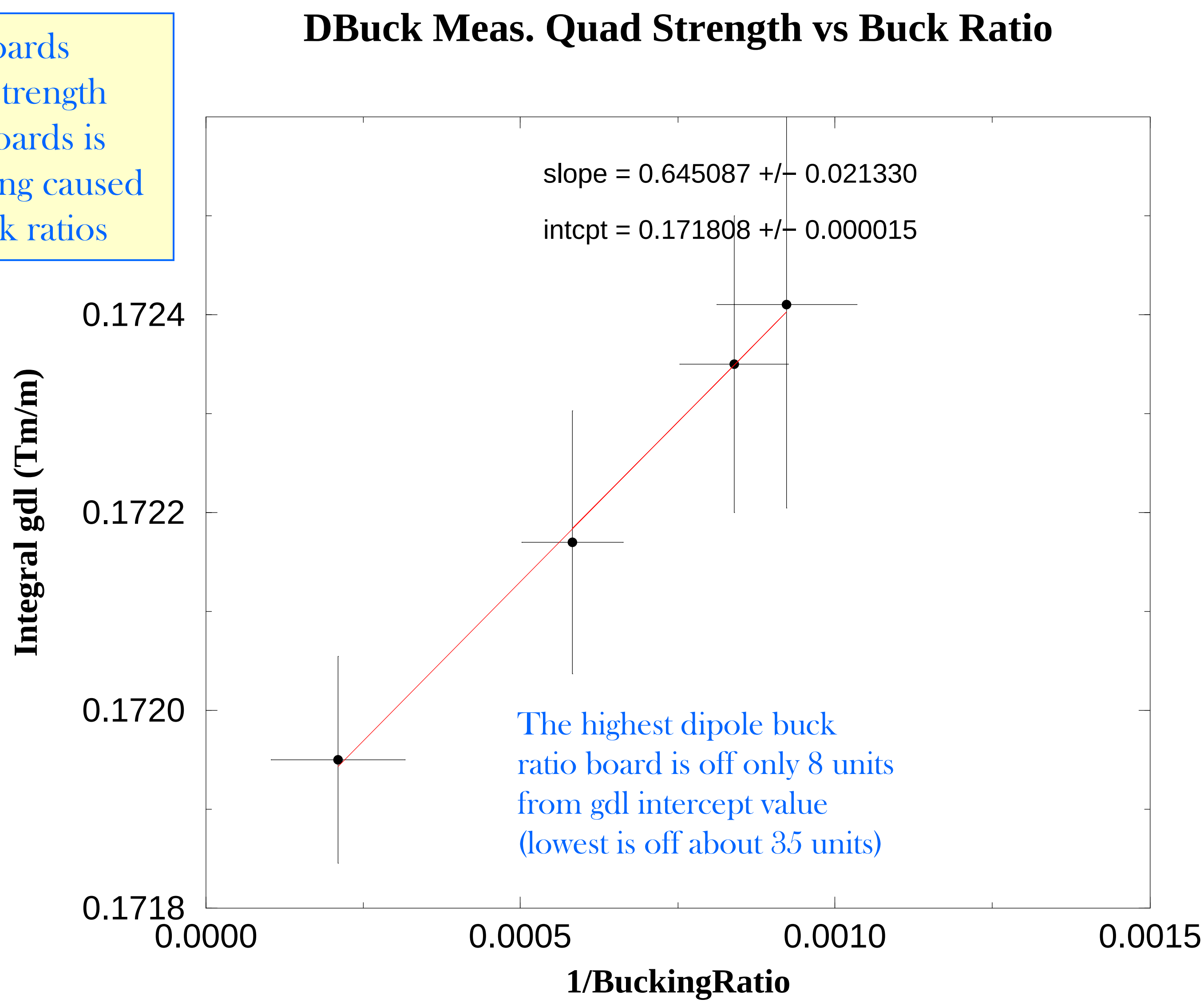
$$buckRatio*\left(\Delta\varepsilon-\Delta\varepsilon'\right)=w$$

$$\Delta\varepsilon/w \approx 10\ units\ \ for\ 5\,\mu m\ err$$

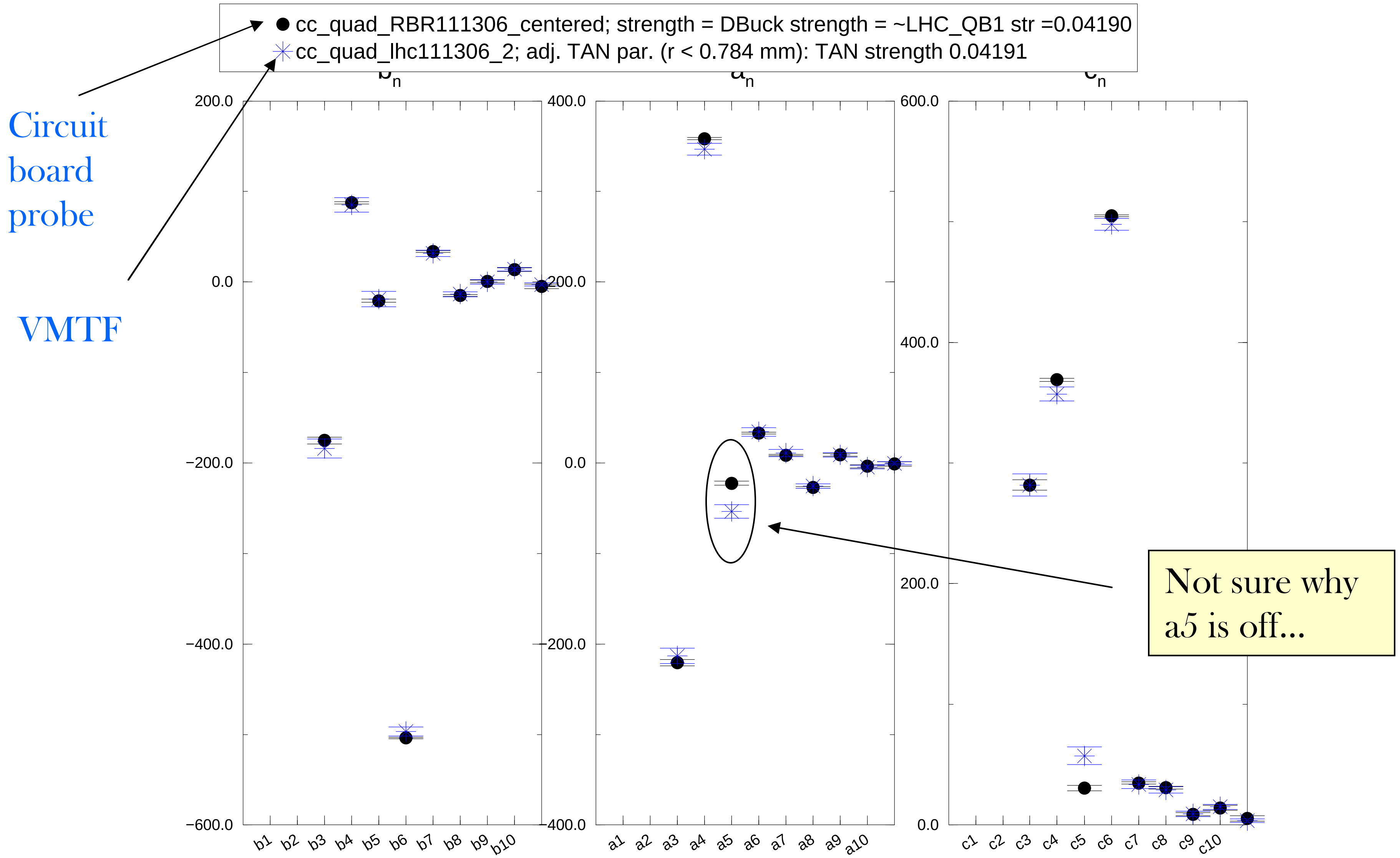
If all error is in DBuck loop, this term is always 1; if all error is in Ubuck loop, this term is 0. In general depends on err distribution.

DBuck quad strength vs buck ratio

For 4 prototype boards tested, Measured strength variation among boards is consistent with being caused by different in buck ratios



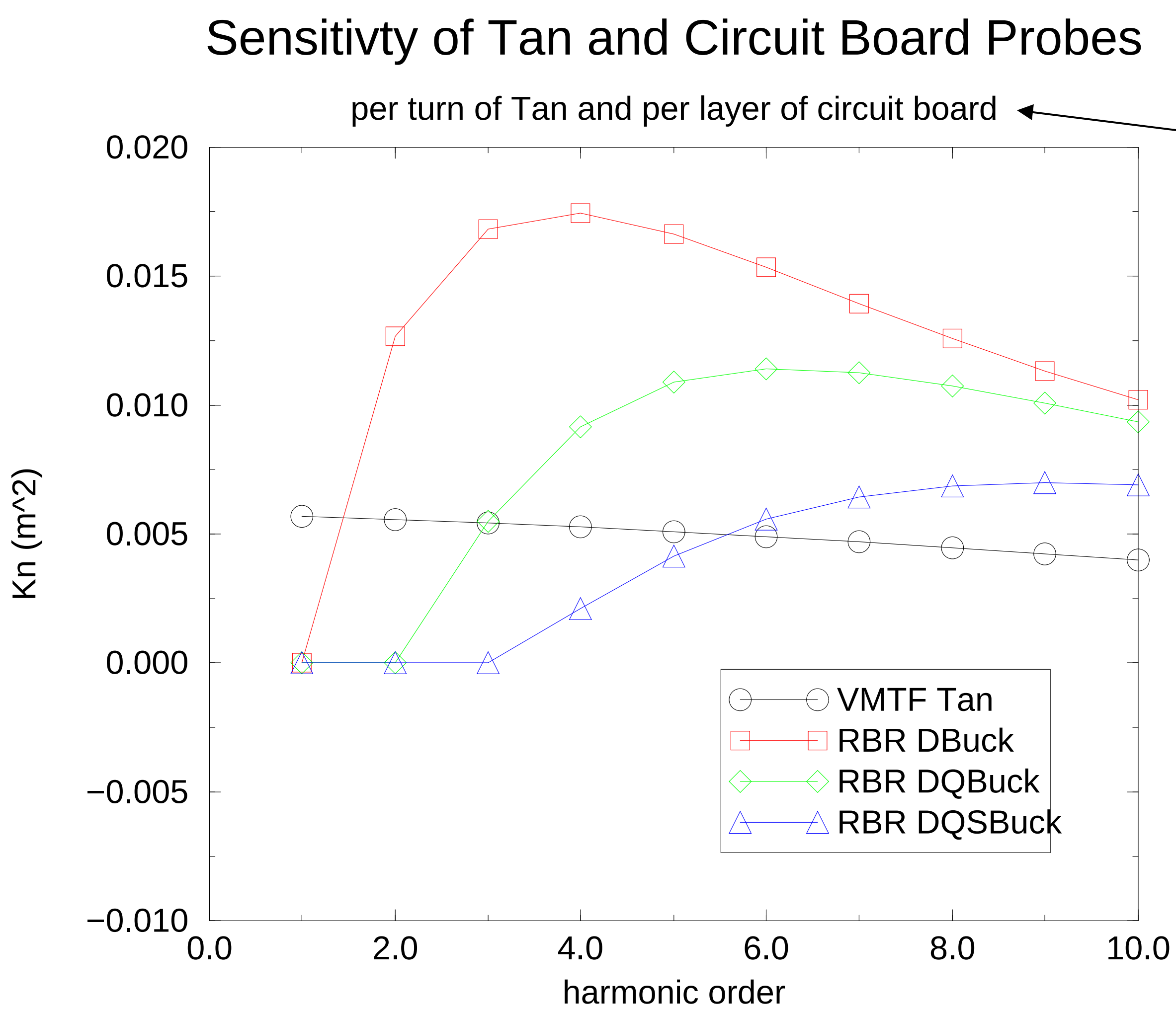
Harmonics of short "coffee can" magnet measured with circuit probe and VMTF tangential probe.



How does Circuit probe sensitivity compare to Tangential coil for a given aperture?

- Assumptions for a generalized comparison
  - Tan has 15 deg. opening angle. Use unbucked **K**n (best case)
  - Use circuit board with 4 loops, assume trace spacing is 0.25mm (0.15mm/0.1mm space/trace)
  - Fill circuit board with traces allowing 1mm in center of loops for connection vias (similar to existing probe designs)

Tangential vs. circuit board Kn comparison



Comparison made normalized to number of TAN turns and number of circuit board layers (e.g. 20 turn TAN winding compared to 20 layer circuit board

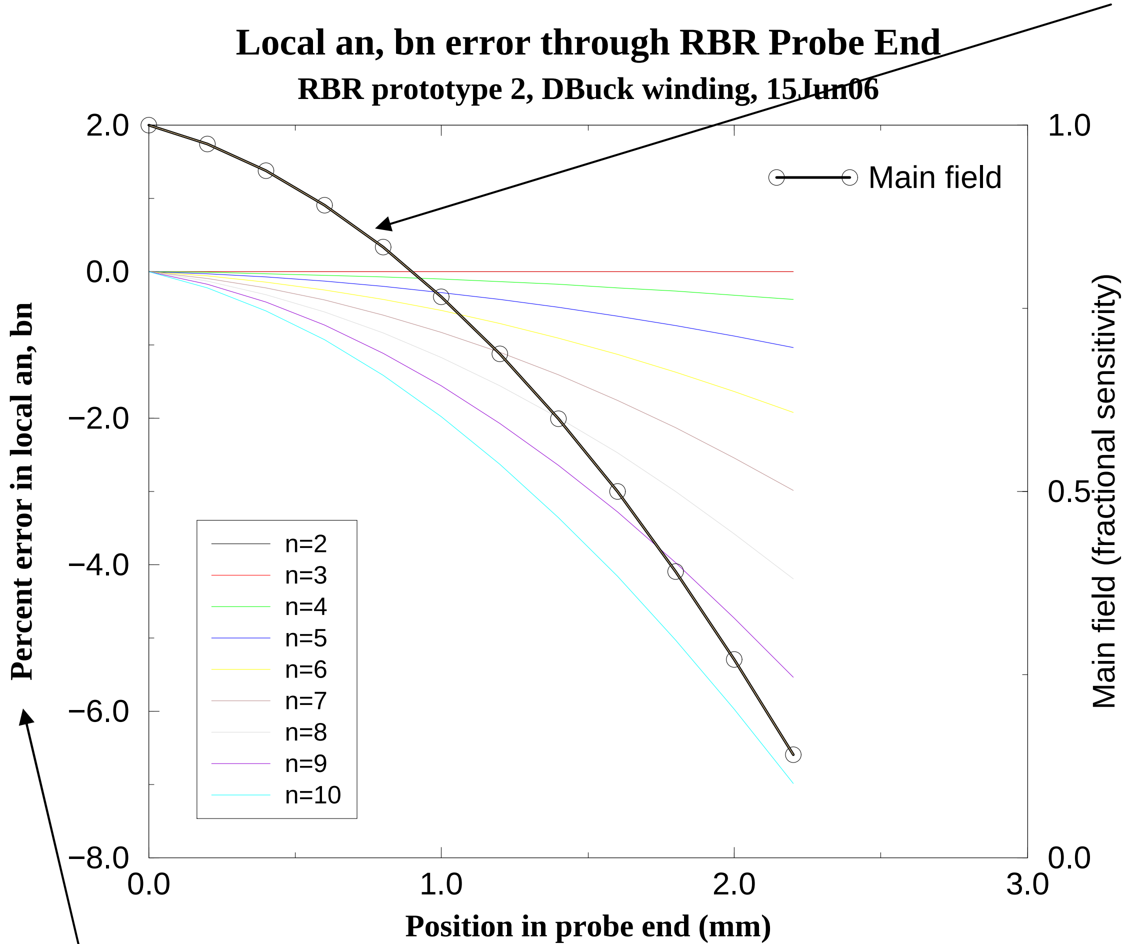
➔Conclusion: Generally, circuit board probes will have comparable or a bit higher sensitivity for a probe of a given radius.

Probe End Effects - strength

- Ends winding areas can be fairly short even compared to traditional probes (2-3mm end for probe with 10-15 turns per loop)

- Strength → accounted for if use exact lengths of traces when calculating sensitivity (or can use "effective length") (effective length of end of circuit board loop is ~0.63% of physical length of end).

Harmonics end effects



Strength drops through end region – can precisely calculate Kn or use effective length of probe (length it would be if it dropped as step function). (About 63% of physical length (for this prototype)).

End effects on measured harmonics are small - few percent error locally (i.e. in the 2-3mm end itself!). Though this is already small, gets further diluted since main field is decreasing through end.

Few percent of harmonic (which is at level of units to start with).

Most probes are much longer than the end regions, so end effects on total harmonic integral is negligible.

costs

- 2 layer, 39mm: $10
- 30 layer, 39mm (with buried vias): $1500
- 22 layer, 1m: $400
- 22 layer, 1.2m: $4000
- Buried vias, layers, increase costs: to some extent also tight spacing of space/trace
- Some ‘setup’ fees – can be significant depending on job and company.

notes

- Resistances can be high – (kOhms) – have to have high impedance inputs to electronics.
- Shorts can occur during production – testing/inspection needed (optical, resistance).

conclusions

- Circuit boards can be incorporated as a tool for precision magnetic measurements.
- Can provide accurate strength of fundamental fields and higher multipoles.
- Some care needed in design and in fabrication (experienced circuit board designer and a company that you can work with help a lot).
- Compare well with tangential probes; analysis straightforward.
- Hard to push much past 1m in length.