# Rotating Printed-Circuit-Board Probe Measurements

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20Sep2011

IMMW17

# Acknowledgements:

John Tompkins, Clark Reid, Tom Wokas, Will Smith,
Andrzej Makulski, George Velev, Guram Chlacidze, Mike Tartaglia,
Cosmore Sylvester, Darryl Orris

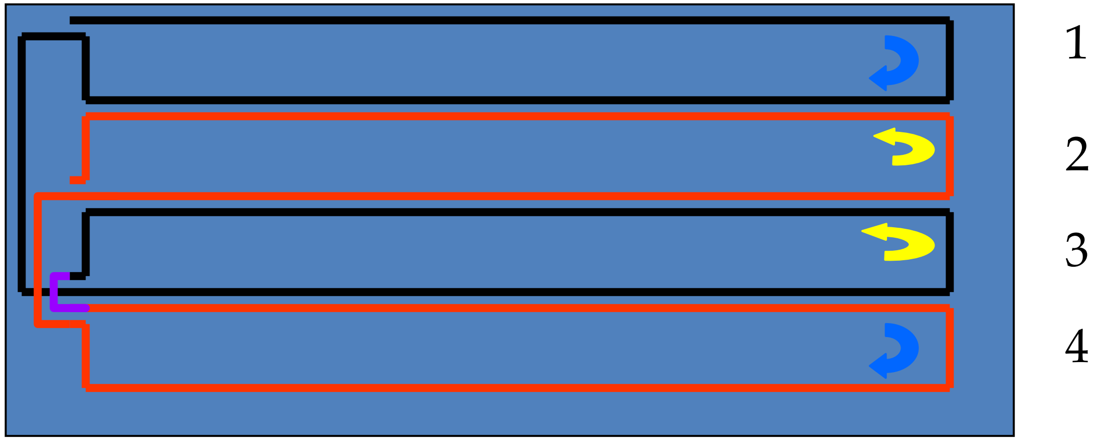
# Outline

- DQ bucked pcb probe
  - standard implementation at FNAL
  - brief review of design and how it works
- Implementations in the last couple of years
  - Ferret
  - 'vFerret'
  - 2-in1 design
  - On-board amplifiers
  - LBNL probe
- Test results
  - LQS02 results vs TAN
  - LBNL results
  - Calibration measurements with coffee can magnet
- Calibration
  - Radius
  - Phase
- Remarks
  - Shorts
  - Procurement
- Conclusions

# 'Standard' pcb configuration at Fermilab

(*brief review from IMMW15*)

- If start with 4 identical loops with even spacing between them, but wire them with opposite polarities as shown:




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

**Voltage across just loop 1 ➔ UnBucked (UB) signal**

**Voltage across 1+3 ➔ Dipole Buck (DB)**

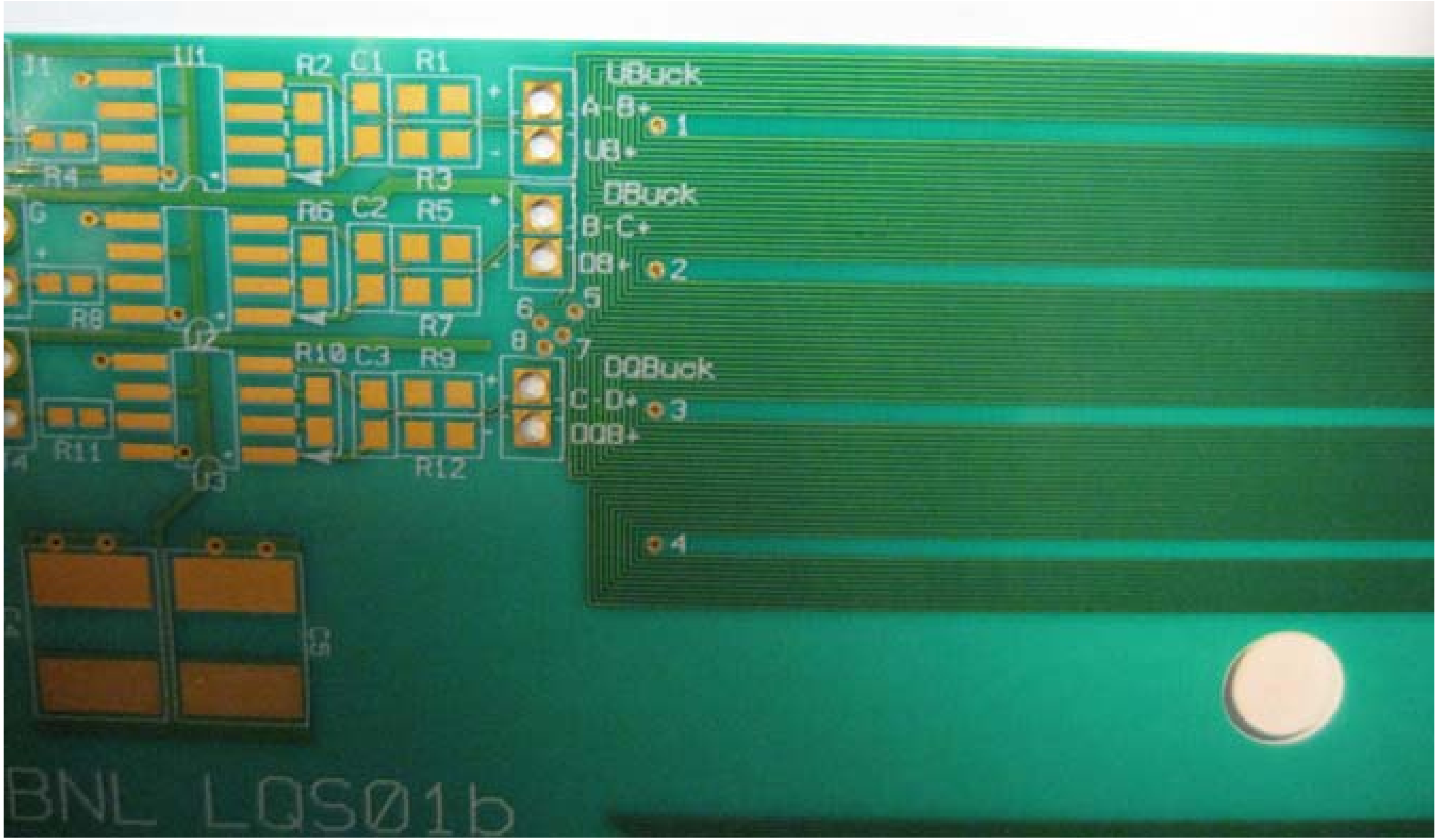
**Since 1+3 measures gradient and 2+4 also does, bucking these two pairs will buck both dipole and quadrupole.**

**Voltage across combined (1+3)+(2+4) ➔ Dipole and Quad Buck (DQB)**

# 'Standard' pcb configuration at Fermilab
(*continued*)

- Typically:
  - **2-layer** (front/back)
    - Can inspect position of conductors
    - Can check for shorts and even repair them (ok for one or two but tedious)
    - Avoids expenses of multi-layer boards
  - **Thin** (0.25mm)
    - To minimize any loops formed across thickness of board
    - Can contact and mold wire trace positions with external surfaces (i.e. can sandwich the pcb on flat surfaces to force wires to be truly planar)
  - Have **traces positioned with ~2μm accuracy**
  - **'Sandwiched'** between two stiffener panels for **overall thickness about 3.5mm**

- Basically use the **pcb technology + assembly to be able to inspect and control wire geometry** to high accuracy…

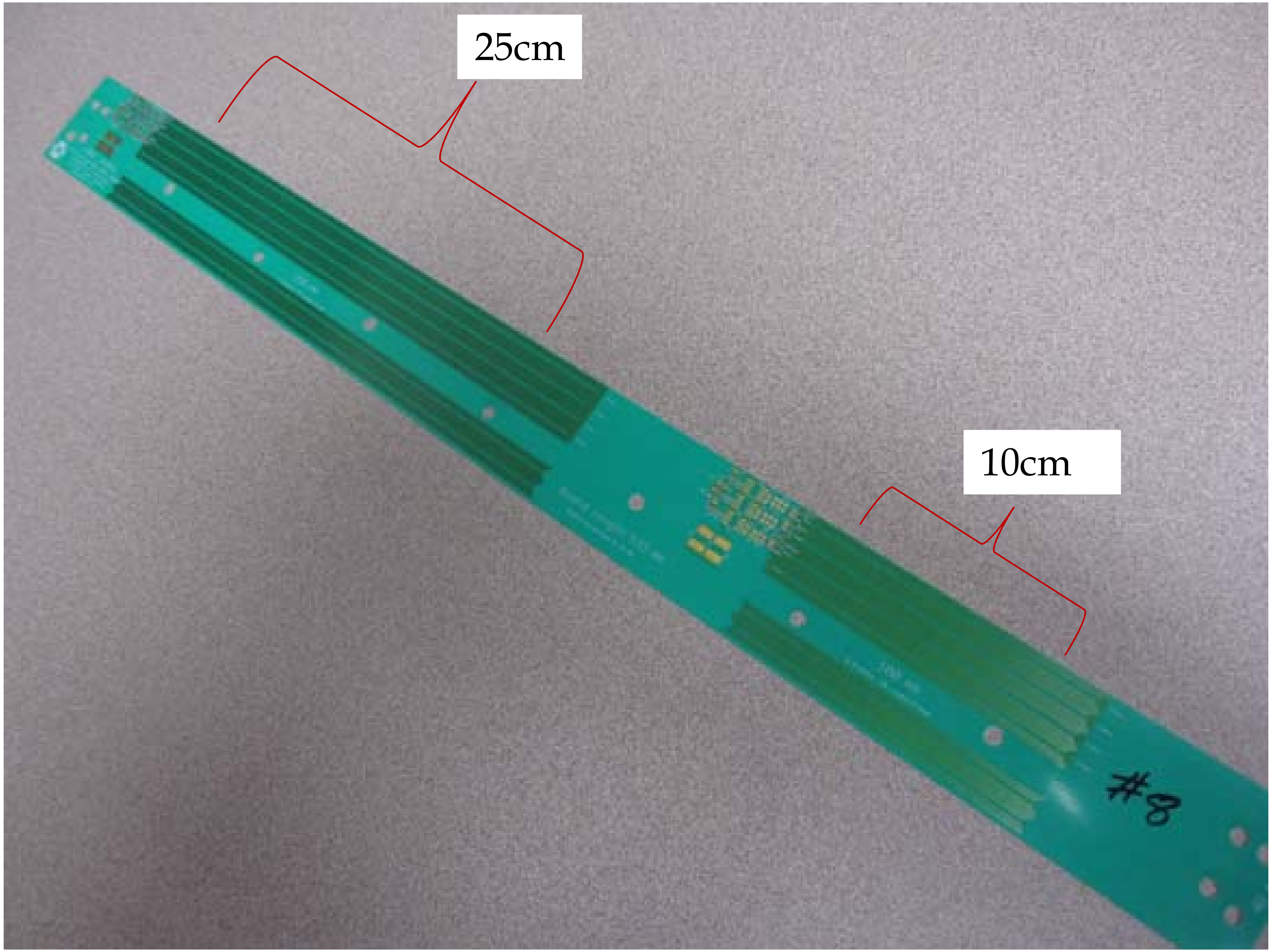

J1
U1
R2
C1
R1
UBuck
A-B+
1
UB+
R4
R3
DBuck
G
R6
C2
R5
B-C+
DB+
2
R8
R7
U2
6
5
8
7
R10
C3
R9
DDBuck
C-D+
3
DDB+
R11
R12
U3
4
BNL LQS01b

# Recent Implementations ➔ Ferret

- Ferret system (previous presentation)

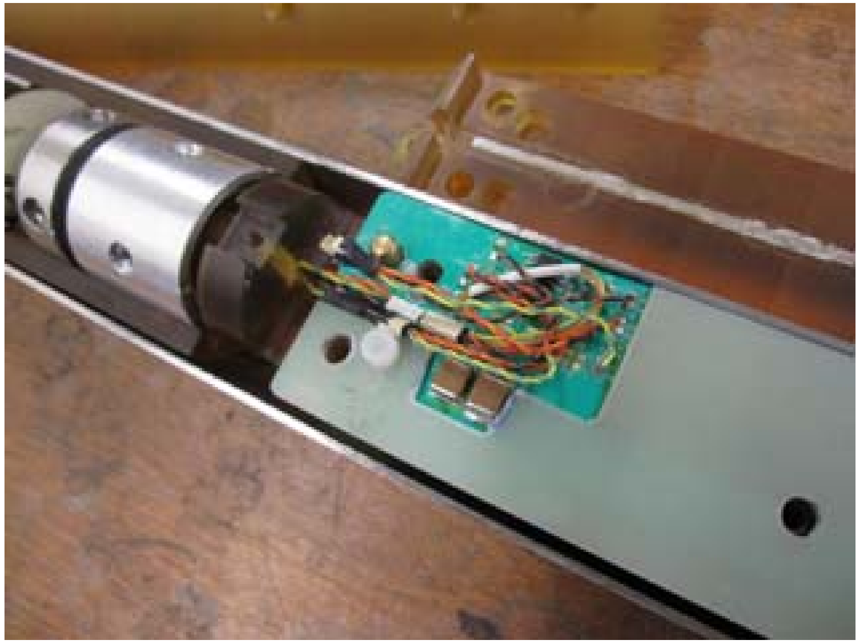
# Recent Implementations ➔ 2-in-1 probes (*continued*)

- 2-in-1 pcb probes
  - Place 2 separate DQBuck circuits with varying parameters on the same board.
- Easier to tailor probes for particular uses (e.g. measuring over integer number of magnet cable twist-pitch)
- Avoids duplicate work for mechanics of multiple probes
- Operational convenience in switching probes


25cm
10cm
#8

# Recent Implementations ➔ on-board amplifiers (*continued*)

- Compact, low-noise pre-amplifier circuit built on to pcb probes
  - Surface mount components
  - Gain up to 1000
  - Upstream of slip-rings, electronics
  - Easier way to compensate for low signals than e.g. doubling number of layers, etc. (of course, there are noise limits where amps cannot help, and then have to add layers …)



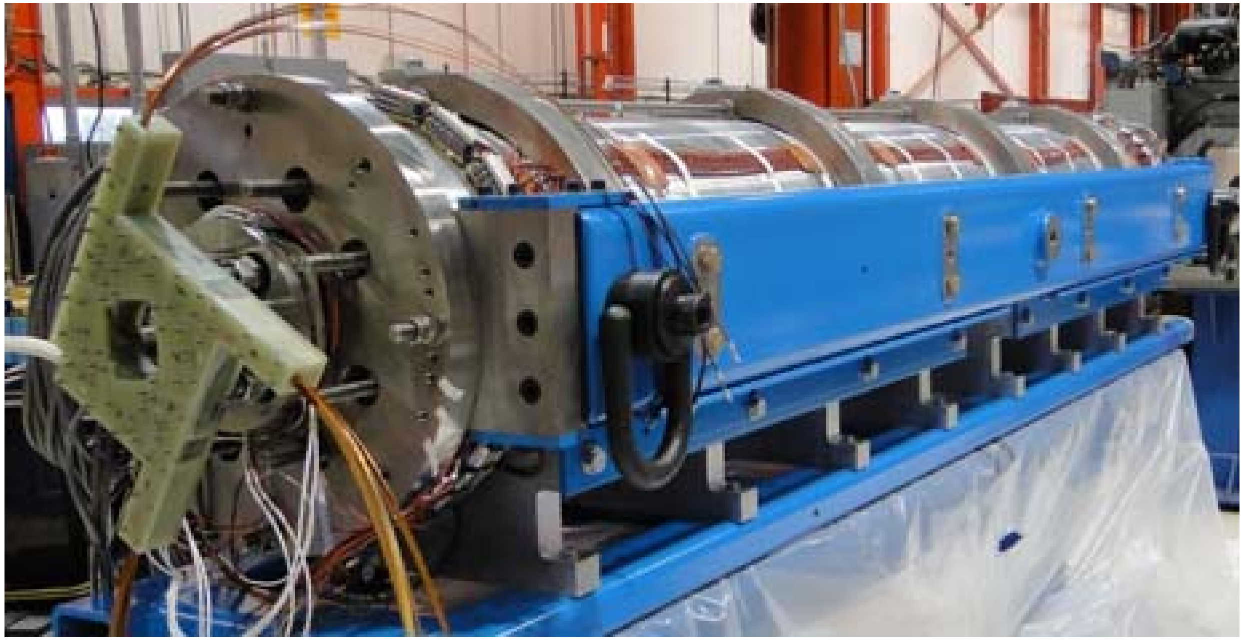
# Recent Implementations ➔ 'vFerret' (*continued*)

- 'vFerret'
  - Uses strongback from ferret in Vertical Magnet Test Facility
  - Modified bearings to contact beam pipe (or warm bore tube)
  - External drive, encoder, slip-ring, etc. (so not really a 'ferret' probe !)

- Circuit board extends beyond the strongback
  - Can optimize to whatever aperture is available
  - Adaptable to fit various aperture sizes (requires bearing block adaptors and new circuit board) (e.g. building new warm bore for LARP quads to be able to measure field at larger radius – new probe becomes trivial)

# Test Results ➔ LQS02

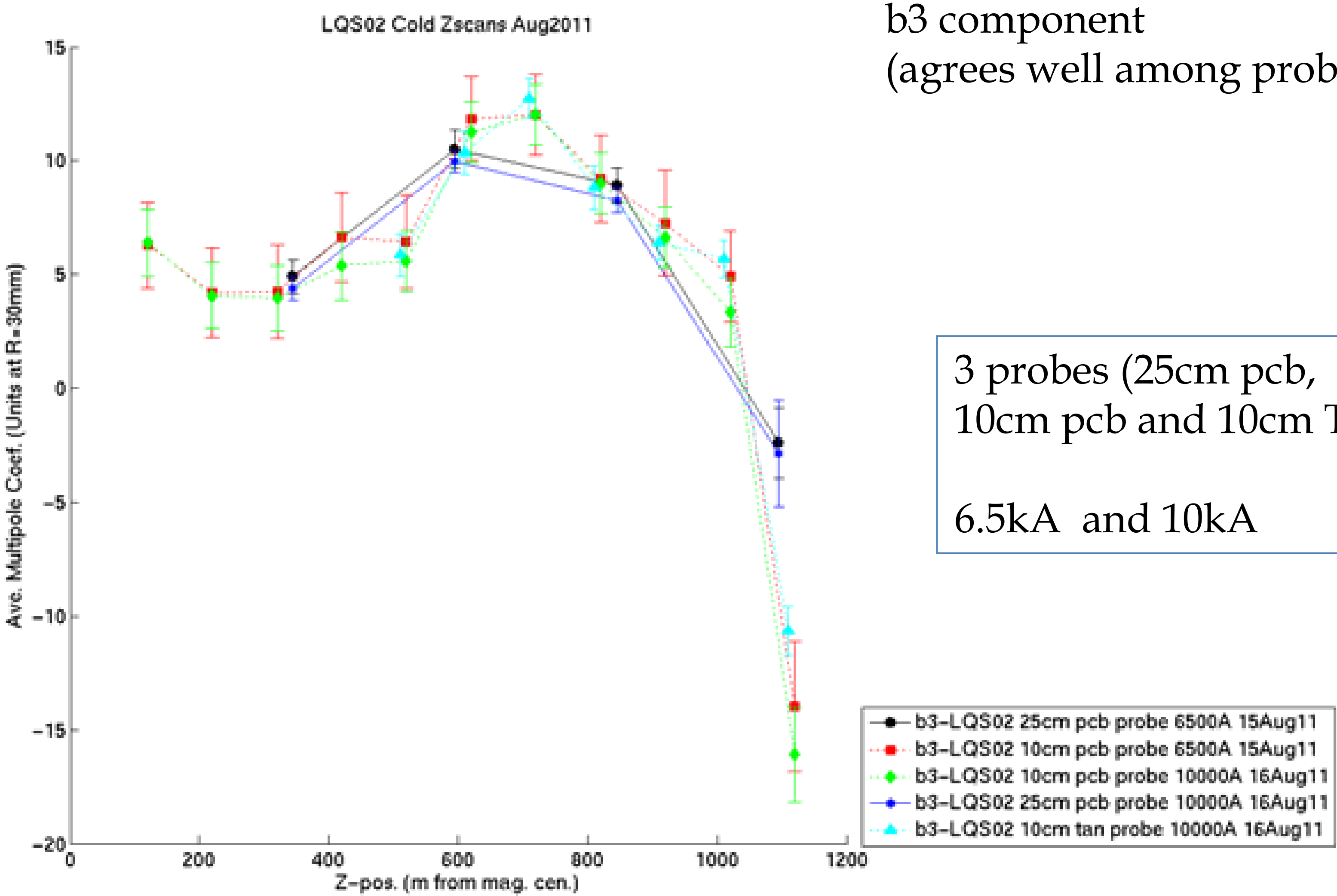
- **2nd Nb3Sn Long Quadrupole by LARP (US LHC Accelerator Research Program)**
  - **Aperture: 90 mm**
  - **Magnet length: 3.7 m**
  - **Gradient: 200+ T/m**
- **➔ Cold - tested in Vertical Magnet Test Facility(VMTF)**



# Test Results ➔ LQS02 (*continued*)

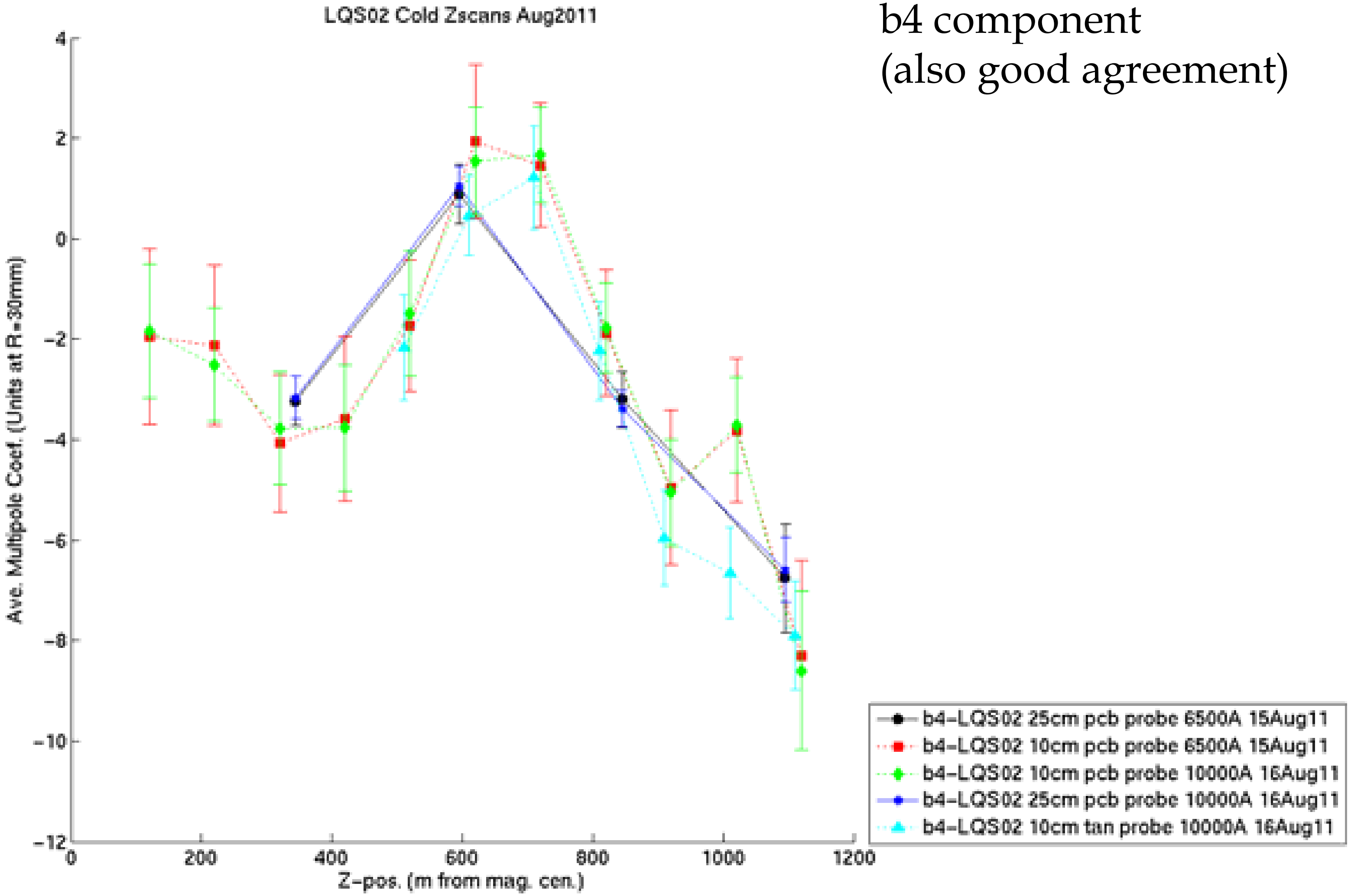
- LQS02 cold zscans at 6500A, 10kA
- Used (un-amplified) vFerret 25cm and 10cm probes
- Also measured with 10cm Tangential probe (use digital bucking)
- All pre-amp gains were set to 1 – error bars are a bit large (average is based on 64 rotations of data)
- (note probe positions do not line up exactly)

# b3 component
(agrees well among probes)



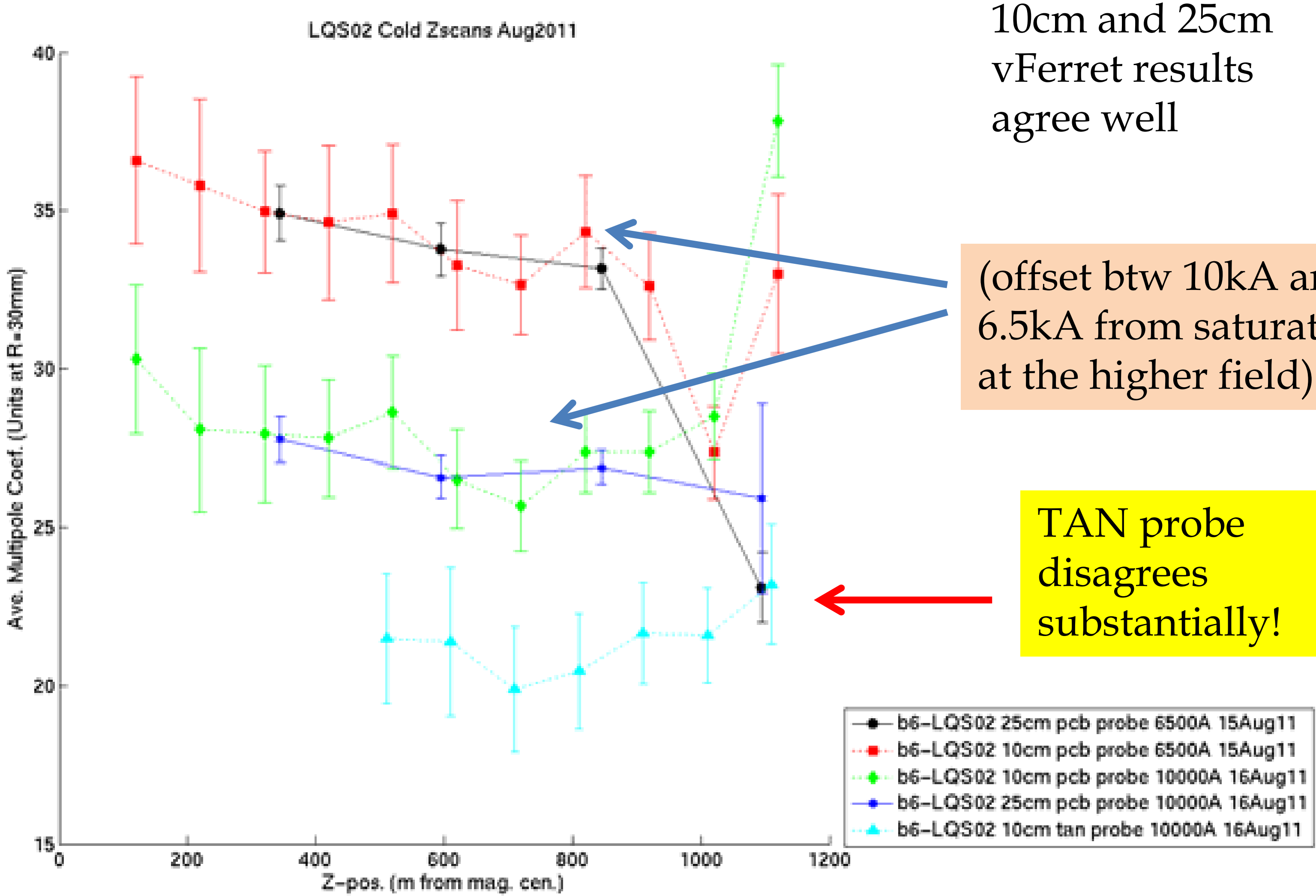

3 probes (25cm pcb, 10cm pcb and 10cm Tan)

6.5kA and 10kA




b4 component
(also good agreement)

# b6




10cm and 25cm vFerret results agree well

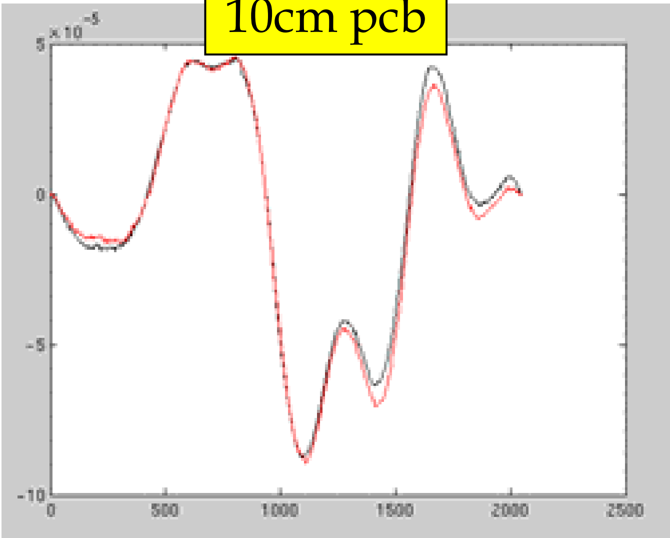
(offset btw 10kA and 6.5kA from saturation at the higher field)

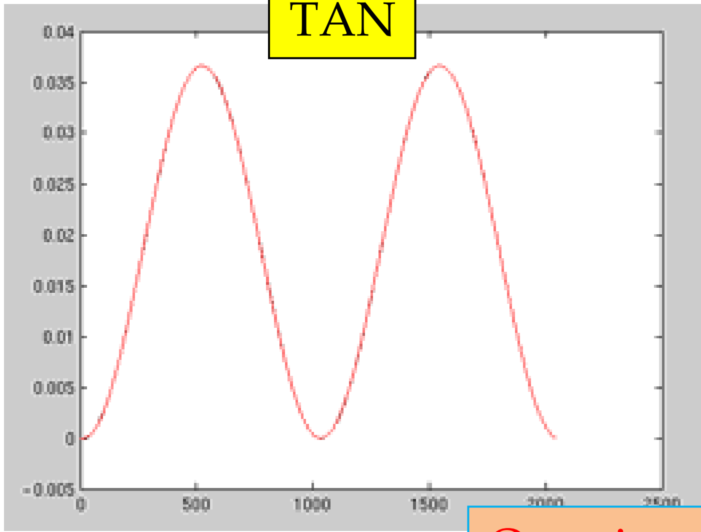
TAN probe disagrees substantially!

**Still looking into this discrepancy**…

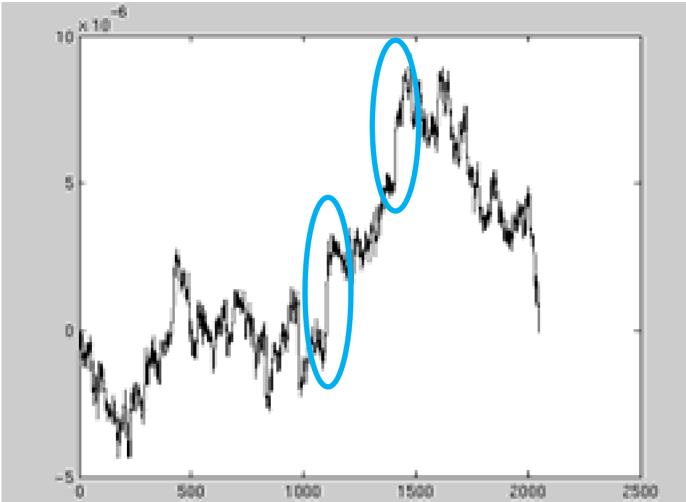
Seems that there may be some problem in the integration from the ADC.

2 rotations




2 rotations difference



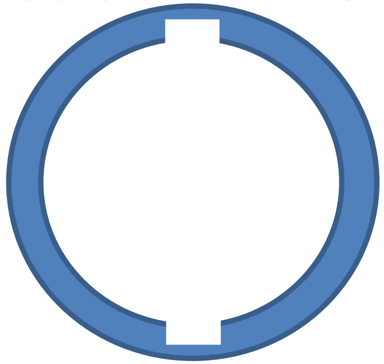

Seems that effect scales with signal – pcb DQB signal sees relatively small effect in harmonics because fundamental field is removed.
For TAN, the digital bucking does not help because effect is in the datacq.

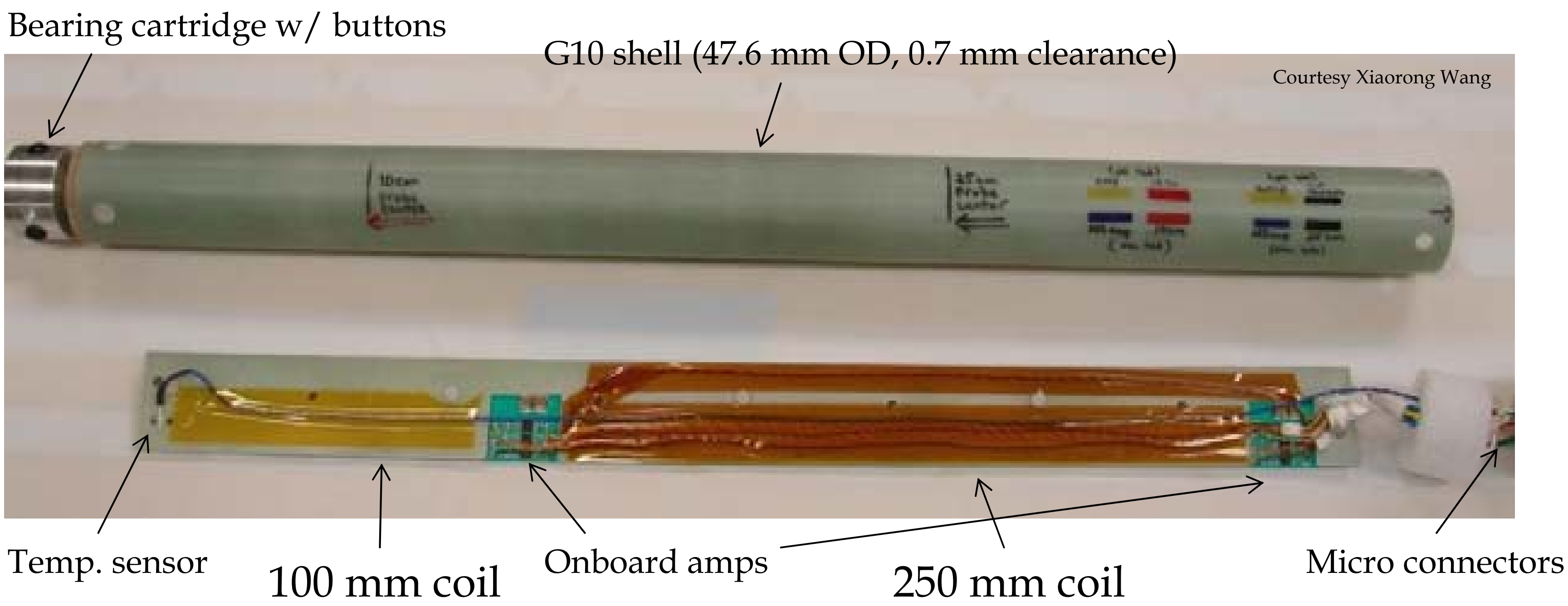
# Recent Implementations → pcb in cylinder

- Built for LBNL
  - Measurement of 'HQ' $Nb_3Sn$ magnets for LARP development program
    - 120mm aperture
    - 1m length model
    - 195 T/m gradient
  - LBNL only had 85cm probe with 45mm radius or 10cm probe with 25mm radius → needed short probe with large radius to validate field model with measurements.
  - Probe was fabricated quickly
    - Pcb's delivered in a couple weeks
    - 2-3 weeks additional time to get cylinder through machine shop (mostly waiting)

# Rotating probe for LBNL HQ Measurements

- **PCB within G10 support cylinder**
  - Groove is 'broached' into inner diameter of cylinder
  - Pcb in G10 stiffener 'sandwich' slides in to cylinder
  - Reliable (technique has been successfully used for several years)
  - Converts pcb to a 'standard' mechanical package
    - similar to other probes on outside
- .



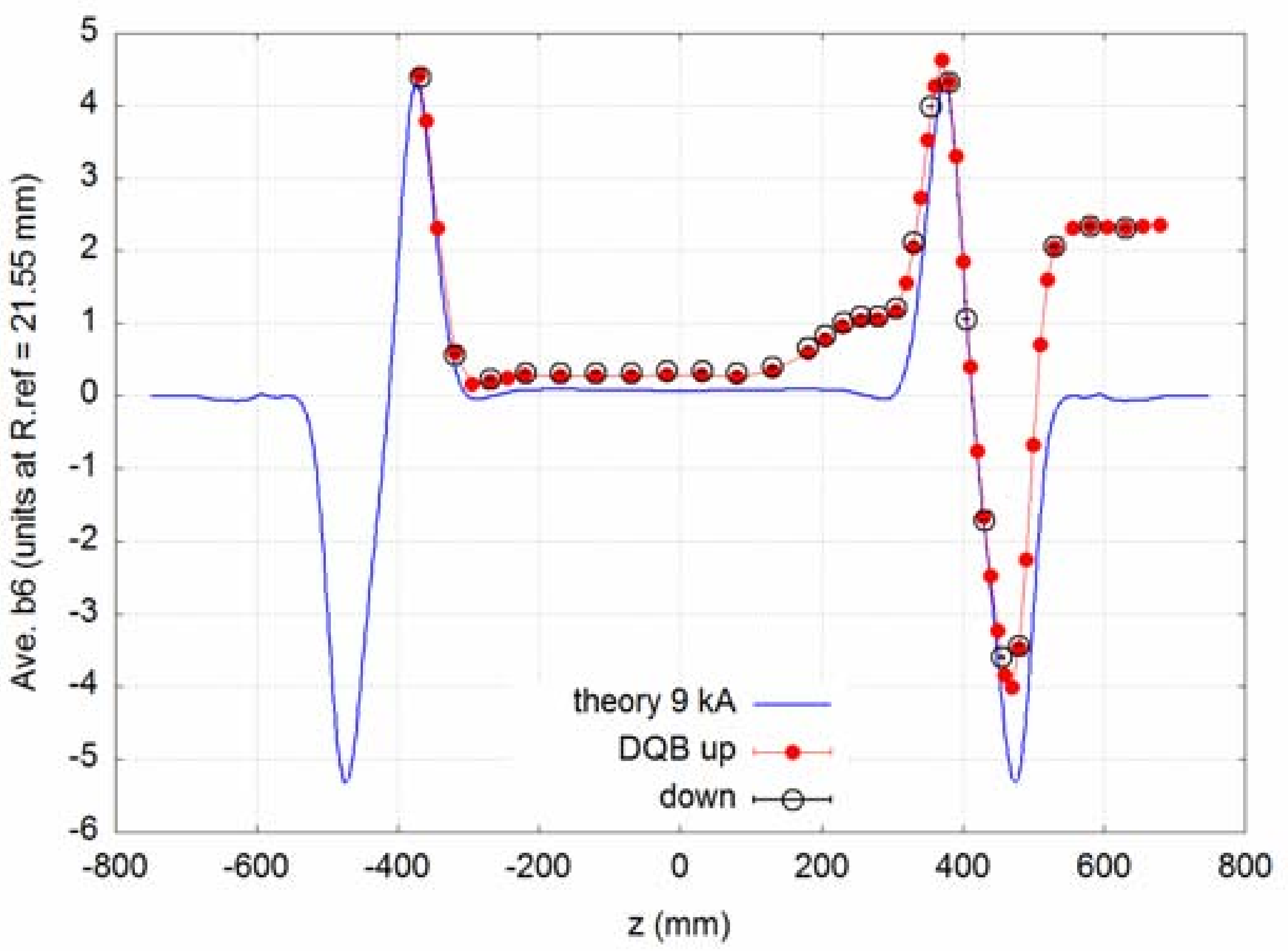



Featured 2-in-1 probes (10cm and 25cm) and pre-amplifier circuits

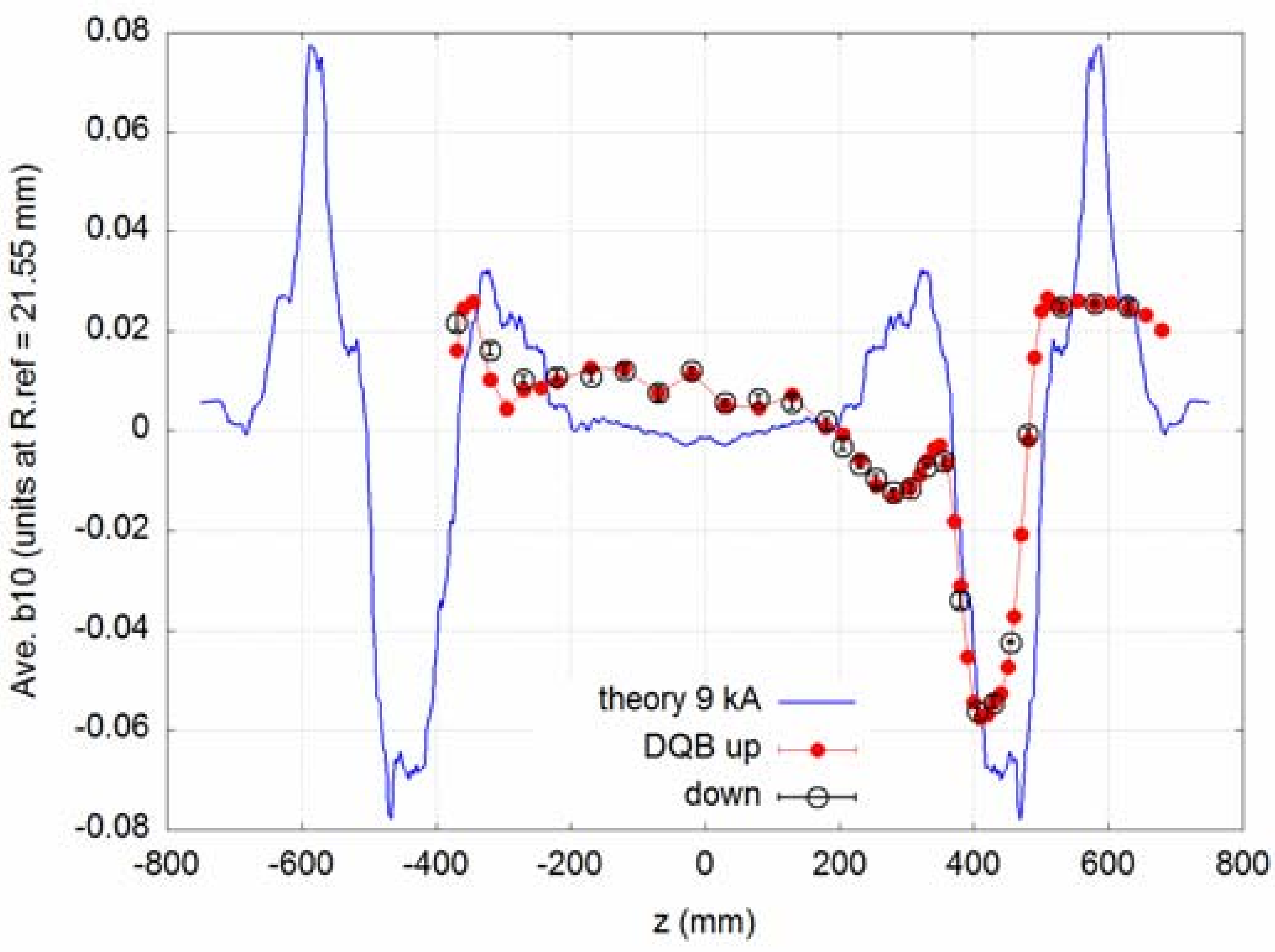
Can be connected to give **amplified/unamplified 10cm/25cm** probe signals

# Test Results ➔ HQ01D

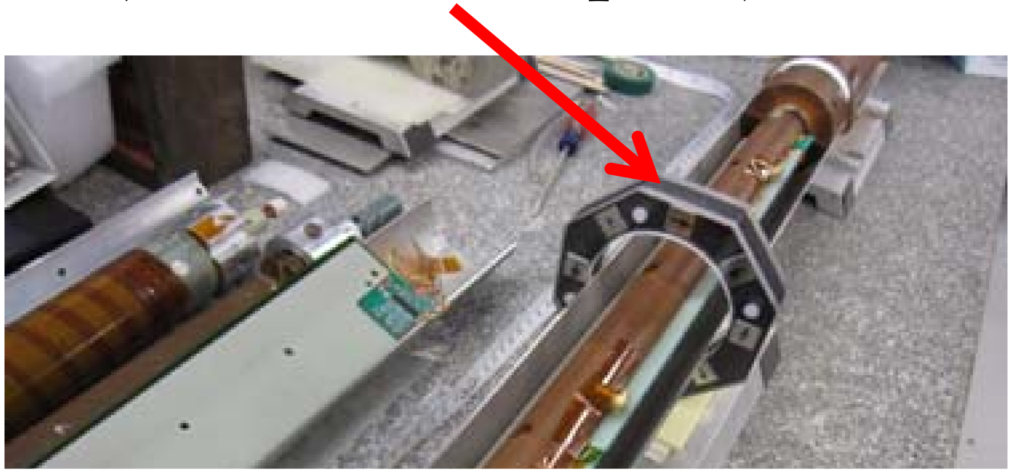
b6, Rref = 21.55 mm
100 mm pcb, 9 kA



# HQ01D, b10, Rref = 21.55 mm
# 100 mm pcb, 9 kA



# Test Results ➔ TCCQ ("coffee can" quad)

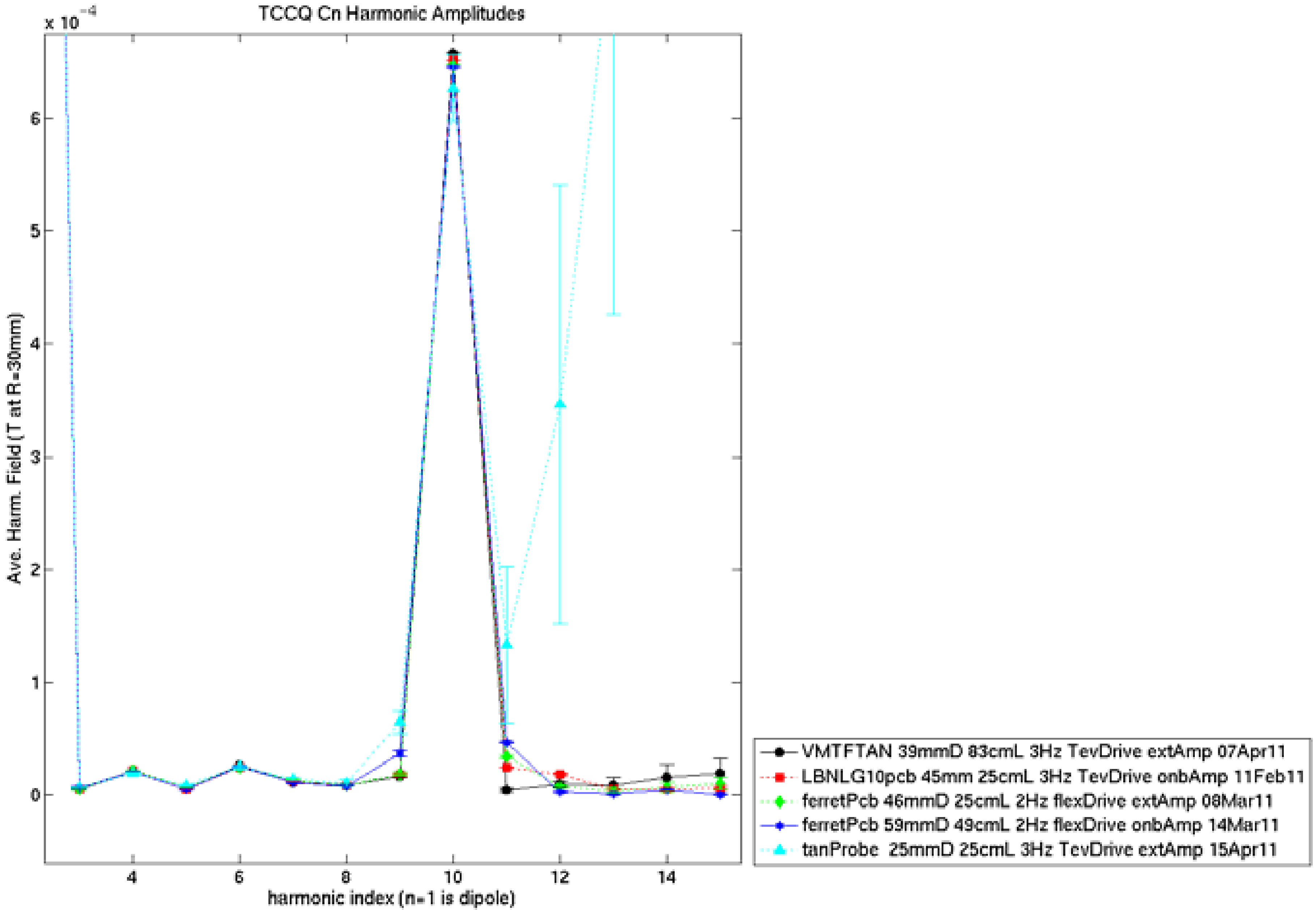


Nickel plated NdFeB magnets constrained in plastic holder

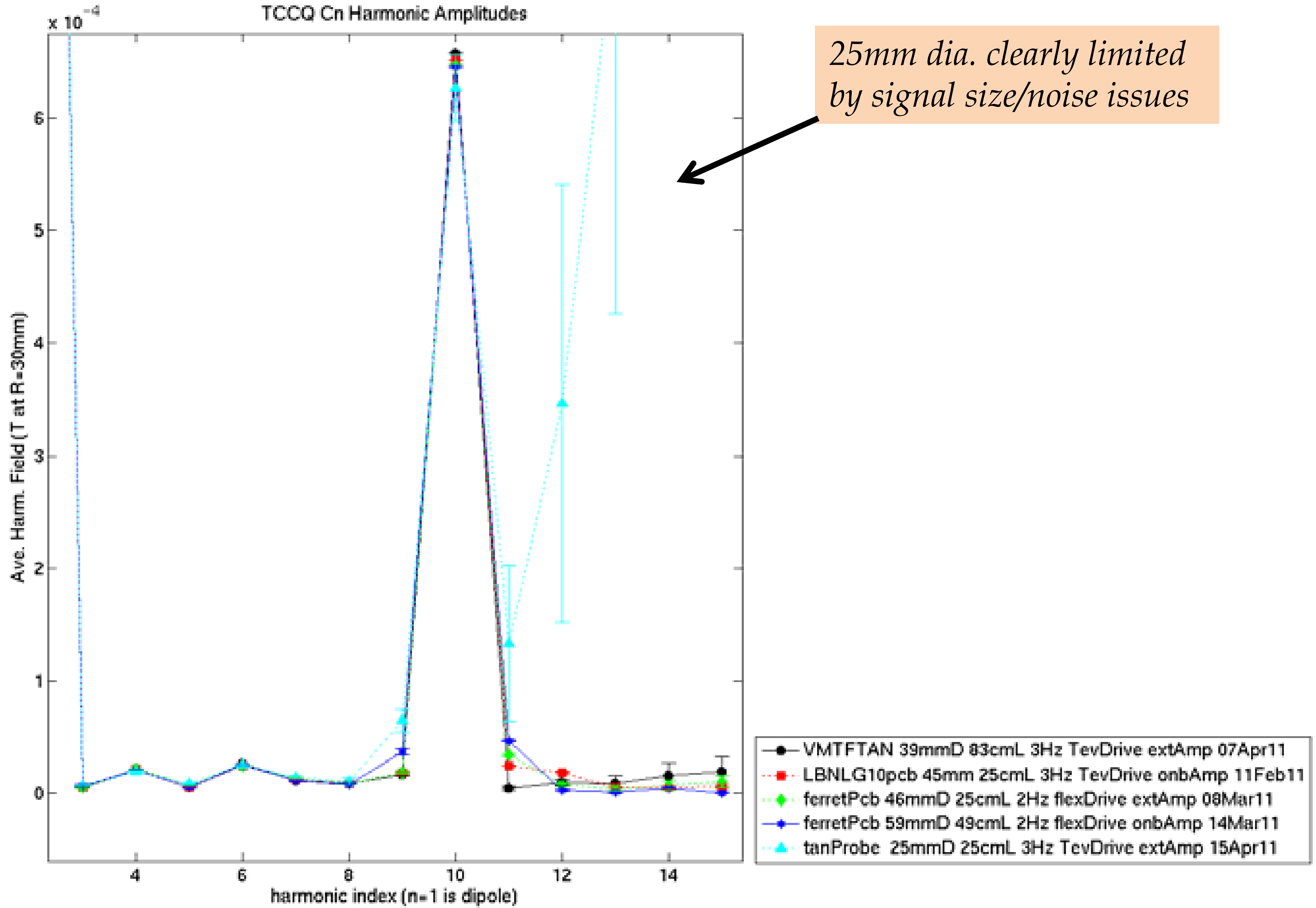
Wanted a 'dirty' field so that could measure non-zero high-order harmonics

Measured with the following probes/configurations (note that all probes long enough so that have integral field):

| Probe | Speed | Dia. | Drive | Amplifiers |
|---|---|---|---|---|
| VMTF_TAN | 3Hz | 39mm | Tev | External |
| LBNL_G10pcb | 3Hz | 43mm | Tev | onBoard |
| Ferret | 2Hz | 46mm | Flex | External |
| Ferret | 2Hz | 59mm | Flex | onBoard |
| TAN_25 | 3Hz | 25mm | Tev | External |



TCCQ Cn Harmonic Amplitudes
x 10^-4
Ave. Harm. Field (T at R=30mm)
harmonic index (n=1 is dipole)
VMTFTAN 39mmD 83cmL 3Hz TevDrive extAmp 07Apr11
LBNLG10pcb 45mm 25cmL 3Hz TevDrive onbAmp 11Feb11
ferretPcb 46mmD 25cmL 2Hz flexDrive extAmp 08Mar11
ferretPcb 59mmD 49cmL 2Hz flexDrive onbAmp 14Mar11
tanProbe 25mmD 25cmL 3Hz TevDrive extAmp 15Apr11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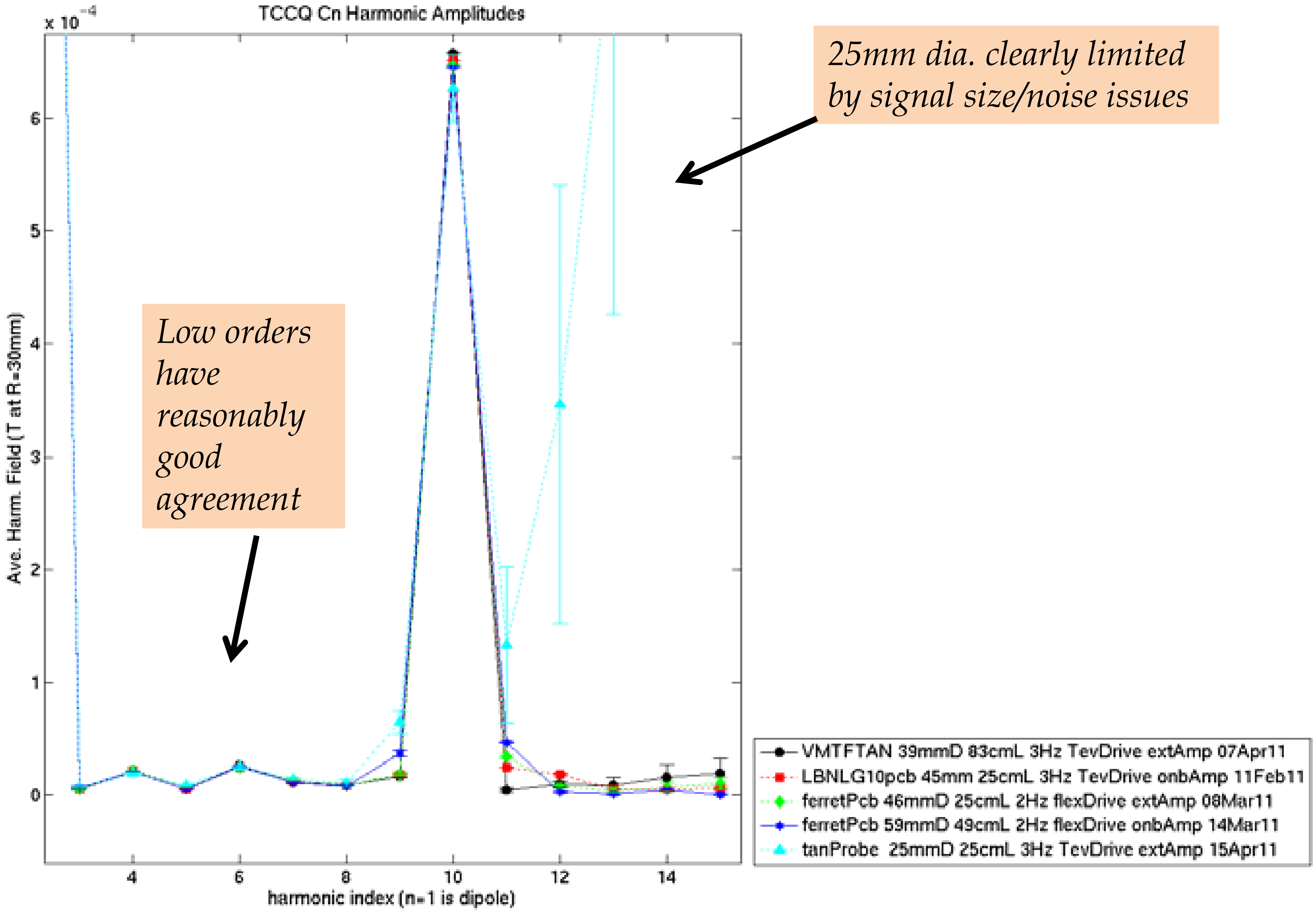
25mm dia. clearly limited
by signal size/noise issues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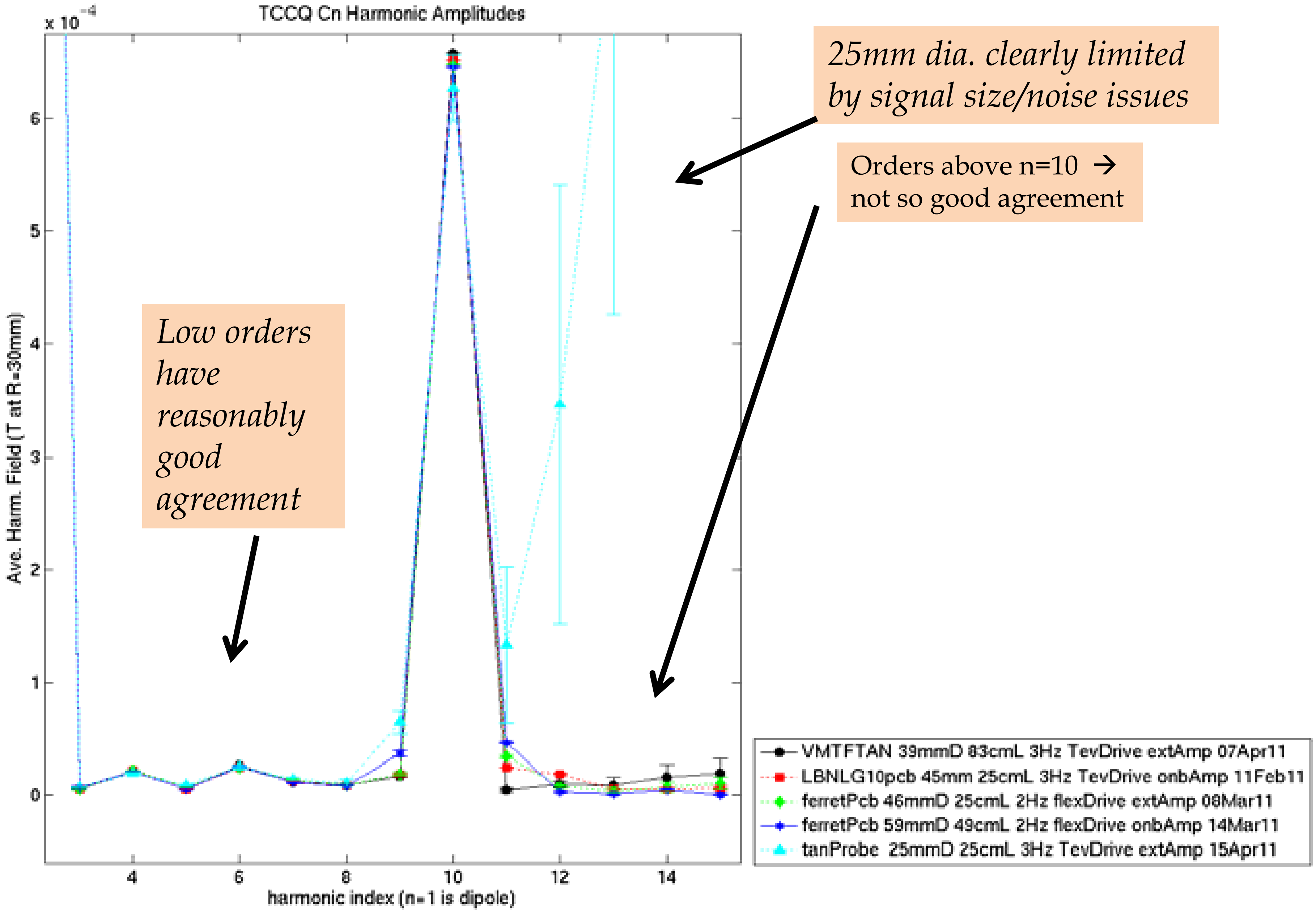
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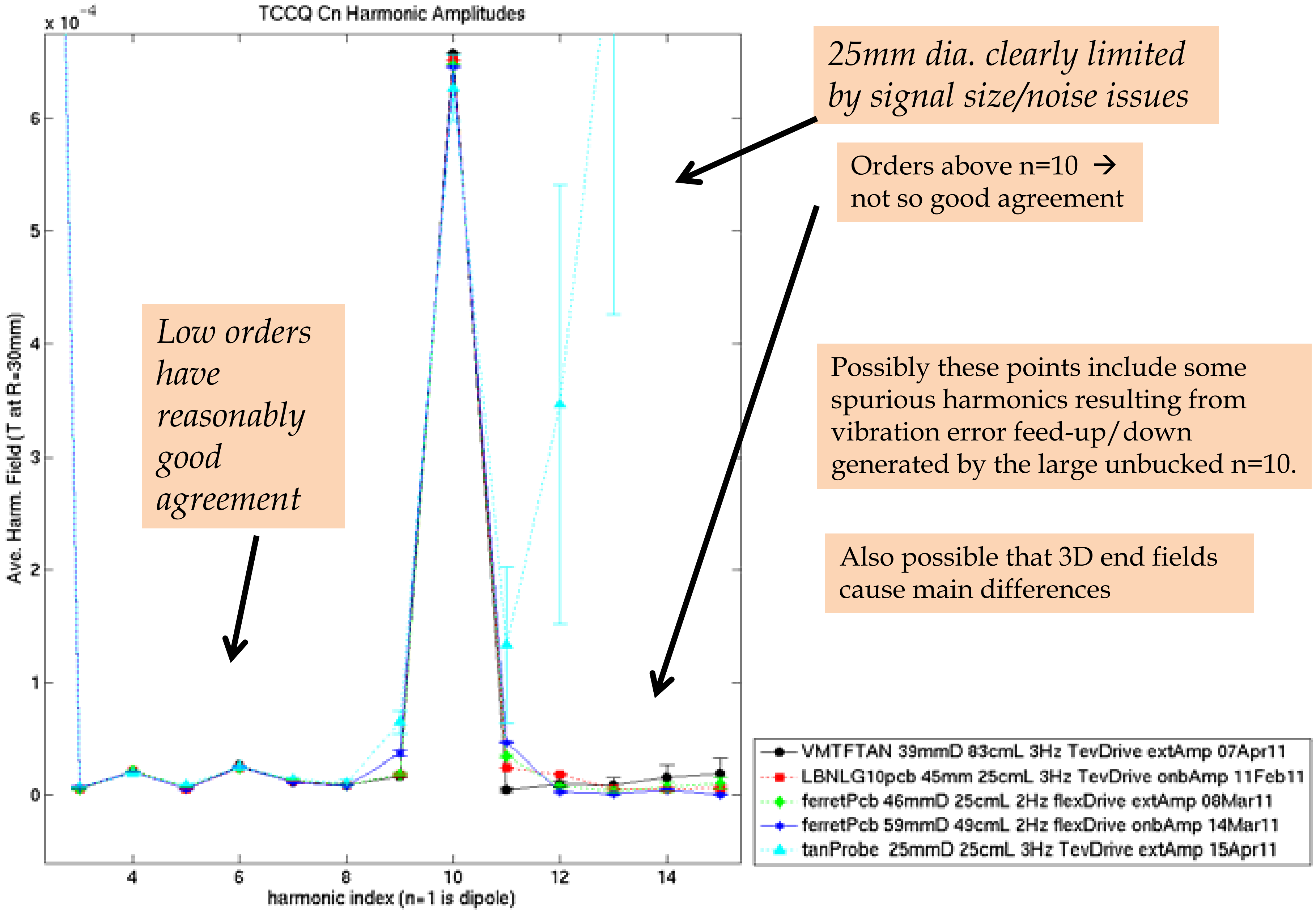
*25mm dia. clearly limited by signal size/noise issues*
Orders above n=10 → not so good agreement
*Low orders have reasonably good agreement*



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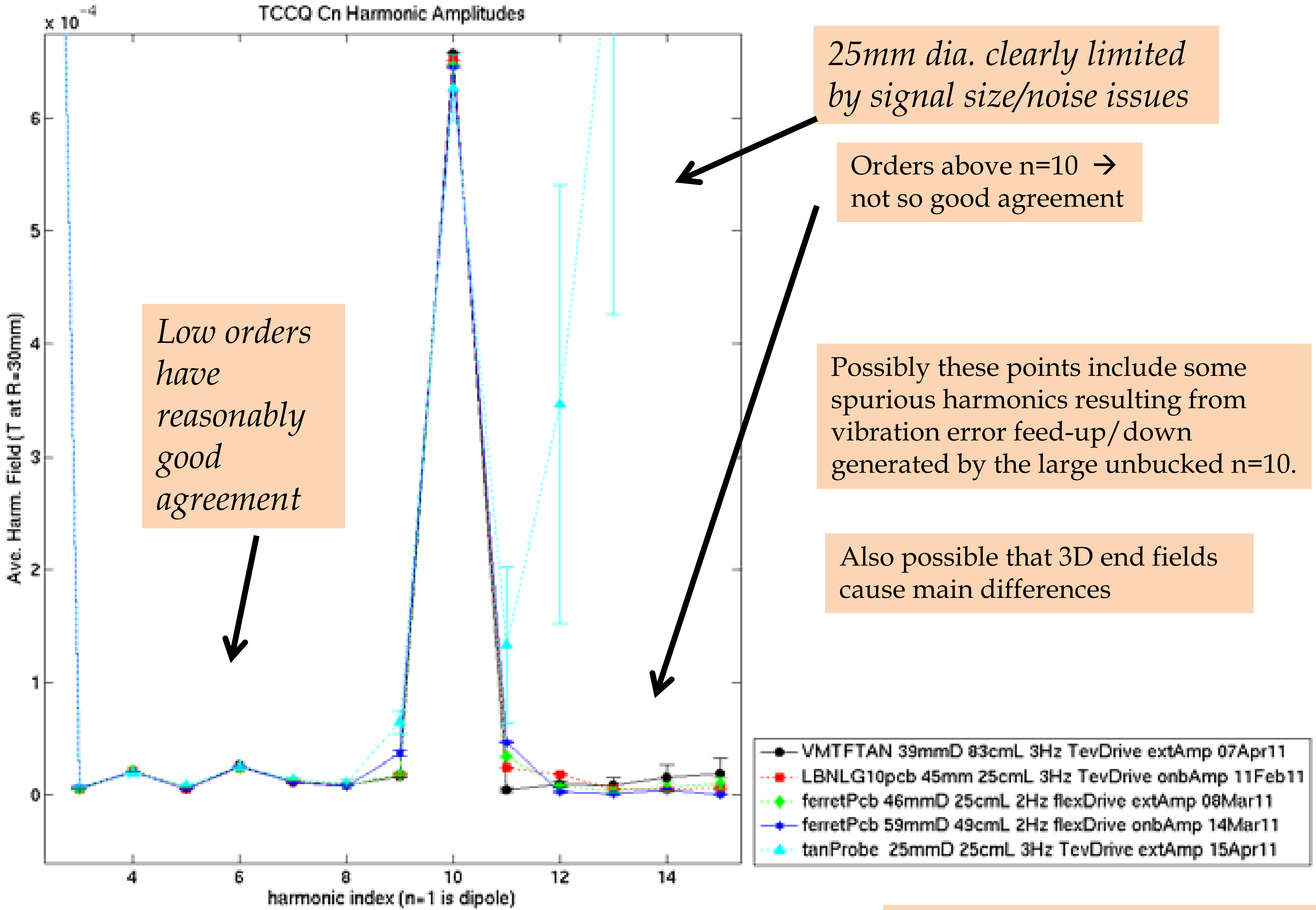
Orders above n=10 → not so good agreement
Possibly these points include some spurious harmonics resulting from vibration error feed-up/down generated by the large unbucked n=10.
Also possible that 3D end fields cause main differences

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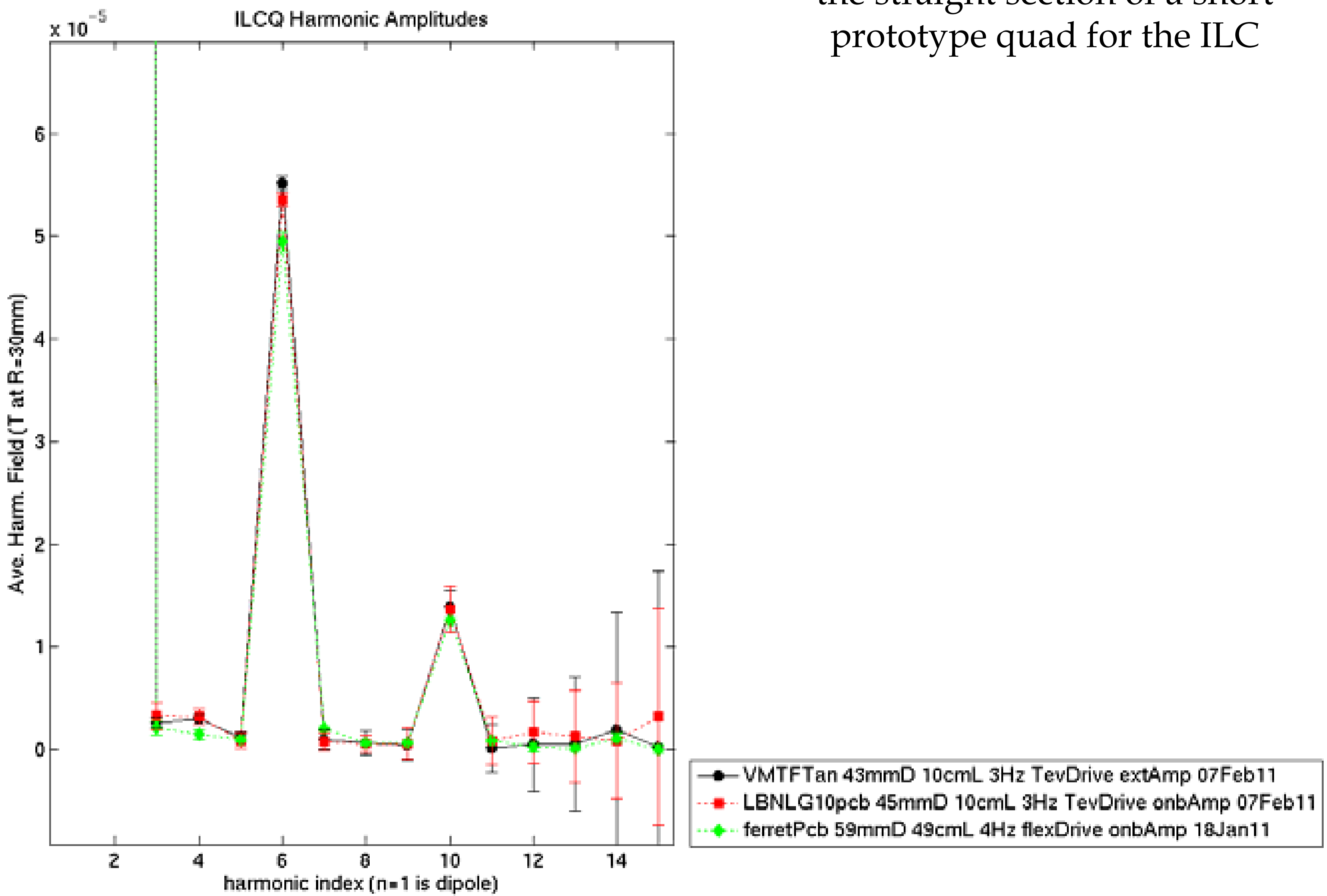
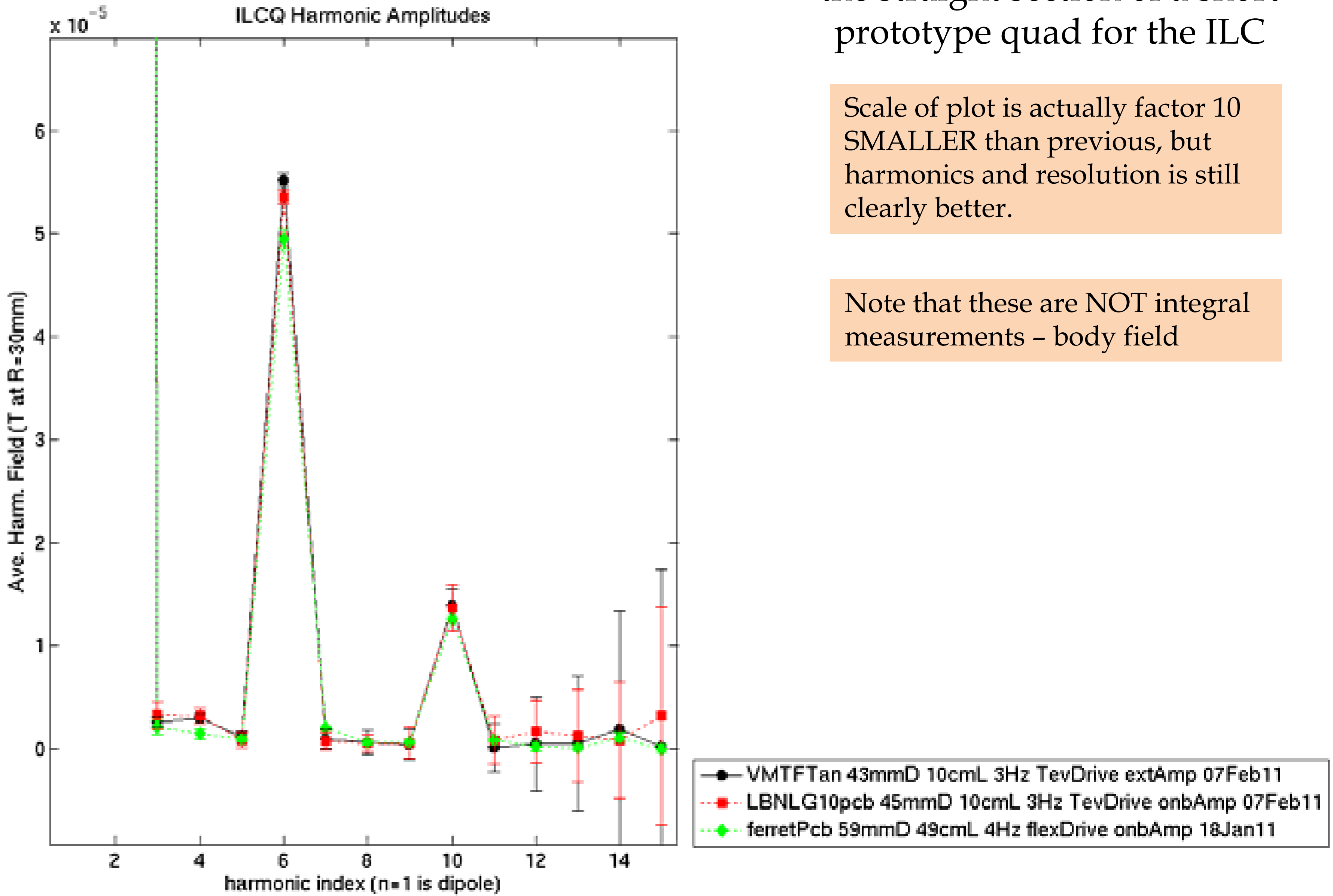
Not really understood … comments?




These are warm measurements in the straight section of a short prototype quad for the ILC

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Scale of plot is actually factor 10 SMALLER than previous, but harmonics and resolution is still clearly better.

Note that these are NOT integral measurements – body field

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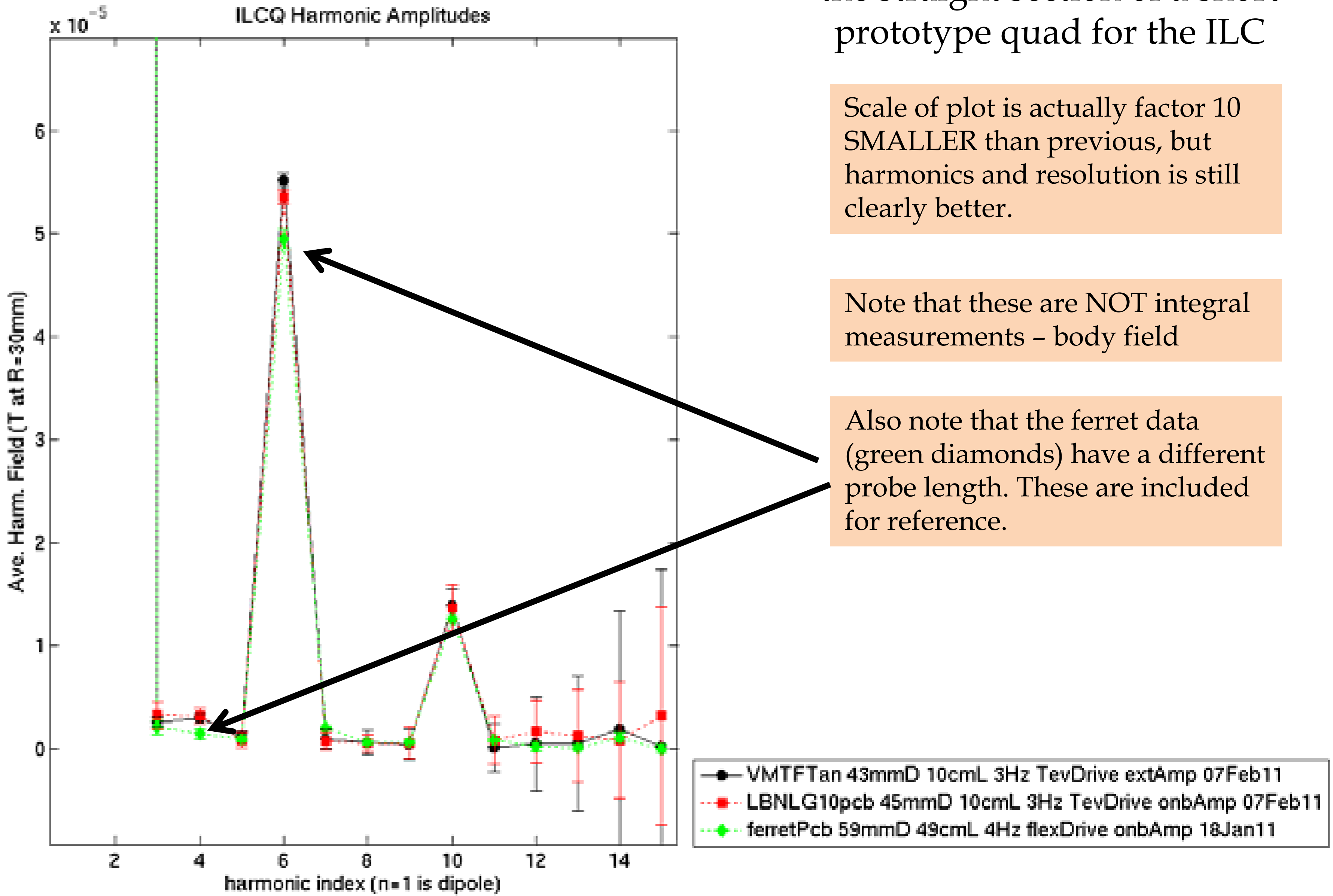


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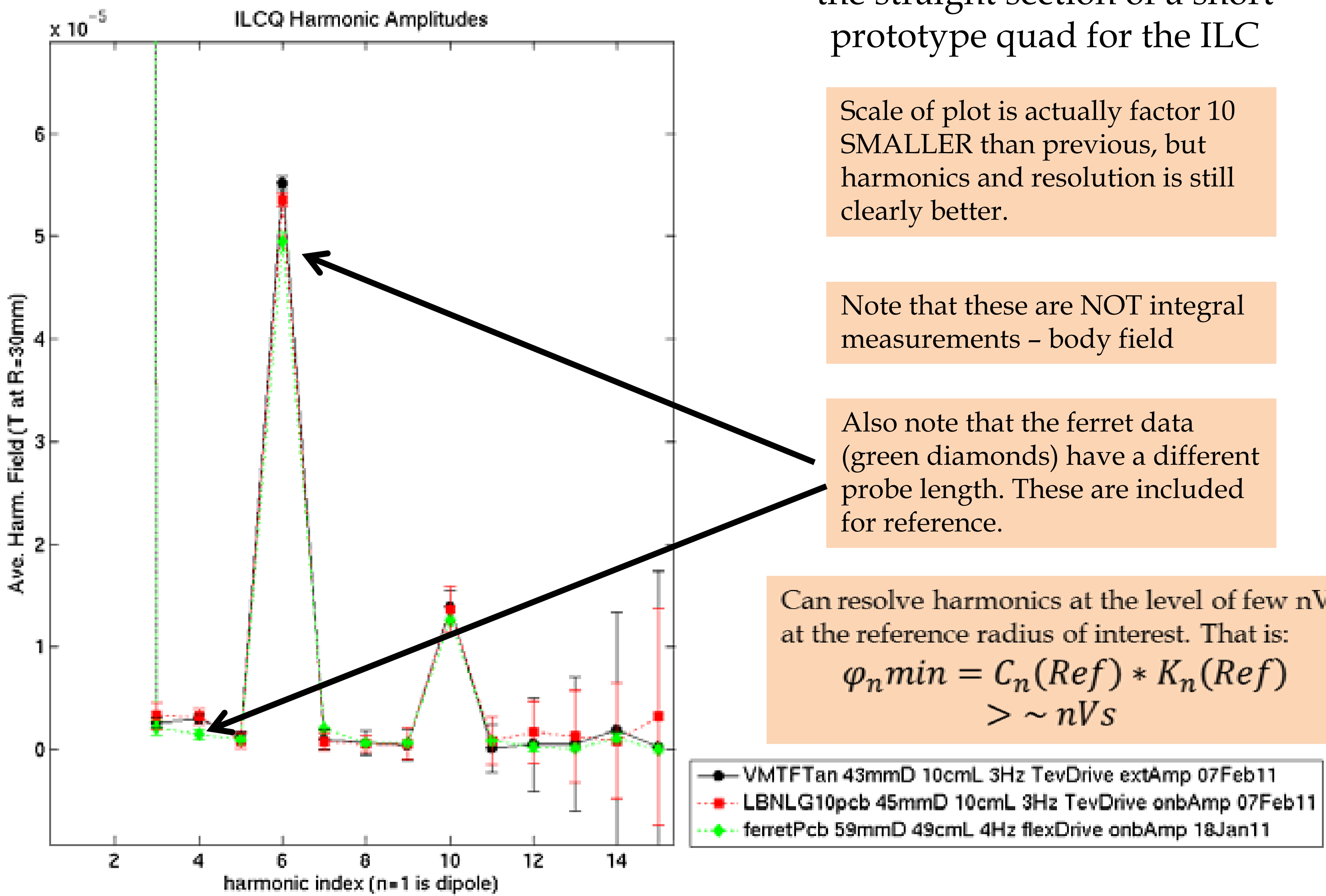
Also note that the ferret data (green diamonds) have a different probe length. These are included for reference.

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Can resolve harmonics at the level of few nVs at the reference radius of interest. That is:

$$\varphi_n min = C_n(Ref) * K_n(Ref) > \sim nVs$$

# Calibrating PCB Position

- Discussed in previous IMMWs how to calibrate **radial position** of the pcb in a probe
  - Any quadrupole magnet measurement
  - DBuck signal is 'radius independent' because of high buck ratio (typically ~1000)
  - UBuck signal depends on radius
  - The correct radial position of board to use in the parameter file is found when the **same quadrupole strength is obtained** for both UB and DB analyzed signals.

- Board can also be **displaced 'vertically'** off the plane of the rotation axis. The calibration of this offset is also straightforward.
  - Again can be applied to any measurement in quadrupole field
  - Vertical offset causes some small change in magnitude of quadrupole sensitivity (this is at the level of a couple units in the UB signal for a 0.5mm displacement). This however is indistinguishable from a radial error.
  - Vertical offset also causes a clear **difference in phase between UB and DB signals** ➔ this is typically > 20mrad for 0.5mm displacement
  - The correct vertical offset for the pcb parameter file is found when the UB and DB phases are the same in the reduced data.

# Check for shorts

- Circuit board companies often will not check closely for shorts on the board – it is one circuit ‘net’ and it connects start and end points, and that’s enough for their usual customer.
- They have automated optical inspection as usual check for shorts – but it is not 100% effective
- Best is to take resistance measurements at points across the board – some companies are willing to offer this service.
- Require that variations in resistance be less than about ½ turn worth of resistance (there are some natural variations from plating thickness etc.)
- With company resistance inspection, we were able to procure 45 pcb’s of 1m length, each having 22 layers …and NO SHORTS (well ok, we procured 48 and there were a couple or three that were bad)

# A sample resistance check

| octant | track | side | 25cm probe board resistance 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 1 | 1 front | 38.5 | 40.3 | 32.6 | 36.8 | 32.4 | 38.9 | 40.3 | 33.2 | 39.4 | 40.6 |
| | 2 | 1 back | 39.3 | 39.8 | 34.5 | 42.1 | 36.8 | 38.9 | 39.5 | 36.0 | 42.3 | 40.2 |
| | 3 | 3 back | 40.8 | 40.2 | 34.8 | 41.0 | 36.4 | 37.9 | 41.2 | 37.3 | 42.6 | 41.5 |
| | 4 | 3 front | 38.6 | 39.7 | 33.9 | 39.4 | 34.1 | 40.0 | 40.6 | 33.5 | 40.4 | 41.1 |
| | 5 | 4 front | 39.0 | 38.5 | 33.6 | 38.9 | 33.8 | 38.3 | 39.9 | 33.9 | 39.8 | 40.5 |
| | 6 | 4 back | 39.7 | 41.1 | 34.9 | 41.7 | 36.9 | 39.3 | 39.9 | 36.9 | 42.9 | 41.0 |
| | 7 | 2 front | 39.3 | 39.9 | 33.6 | 38.2 | 33.1 | 39.4 | 41.2 | 33.3 | 40.1 | 40.6 |
| | 8 | 2 back | 40.0 | 39.4 | 34.6 | 41.1 | 36.5 | 38.1 | 39.6 | 36.4 | 42.2 | 40.5 |
| | | | 40.8 | 41.1 | 34.9 | 42.1 | 36.9 | 40.0 | 41.2 | 37.3 | 42.9 | 41.5 |
| | | | | | | | | | | | | |
| | 1 | 1 front | 0.94 | 0.98 | 0.93 | 0.87 | 0.88 | 0.97 | 0.98 | 0.89 | 0.92 | 0.98 |
| | 2 | 1 back | 0.96 | 0.97 | 0.99 | 1.00 | 1.00 | 0.97 | 0.96 | 0.97 | 0.99 | 0.97 |
| | 3 | 3 back | 1.00 | 0.98 | 1.00 | 0.97 | 0.99 | 0.95 | 1.00 | 1.00 | 0.99 | 1.00 |
| | 4 | 3 front | 0.95 | 0.97 | 0.97 | 0.94 | 0.92 | 1.00 | 0.99 | 0.90 | 0.94 | 0.99 |
| | 5 | 4 front | 0.96 | 0.94 | 0.96 | 0.92 | 0.92 | 0.96 | 0.97 | 0.91 | 0.93 | 0.98 |
| | 6 | 4 back | 0.97 | 1.00 | 1.00 | 0.99 | 1.00 | 0.98 | 0.97 | 0.99 | 1.00 | 0.99 |
| | 7 | 2 front | 0.96 | 0.97 | 0.96 | 0.91 | 0.90 | 0.99 | 1.00 | 0.89 | 0.93 | 0.98 |
| | 8 | 2 back | 0.98 | 0.96 | 0.99 | 0.98 | 0.99 | 0.95 | 0.96 | 0.98 | 0.98 | 0.98 |

Doing better than 50% is not bad for a ‘high-throughput’ company.
A manufacturer which guarantees no shorts may charge $300/board instead of $60

# Conclusions

- We’ve employed pcb probes in a number of applications
- The pcb based probes seem to work well → cross-checks with other probes have strong consistency
- Some nice properties
  - Put together probes quickly
  - High accuracy at low cost
  - calibrate
- Some downside - signal size can be smaller (though can compensate with amplifiers usually, or multiple layers if needed). Limitation in length to ~1m or so.