Developments Towards a High-Speed/Accuracy Multi-vertex PCB Probe

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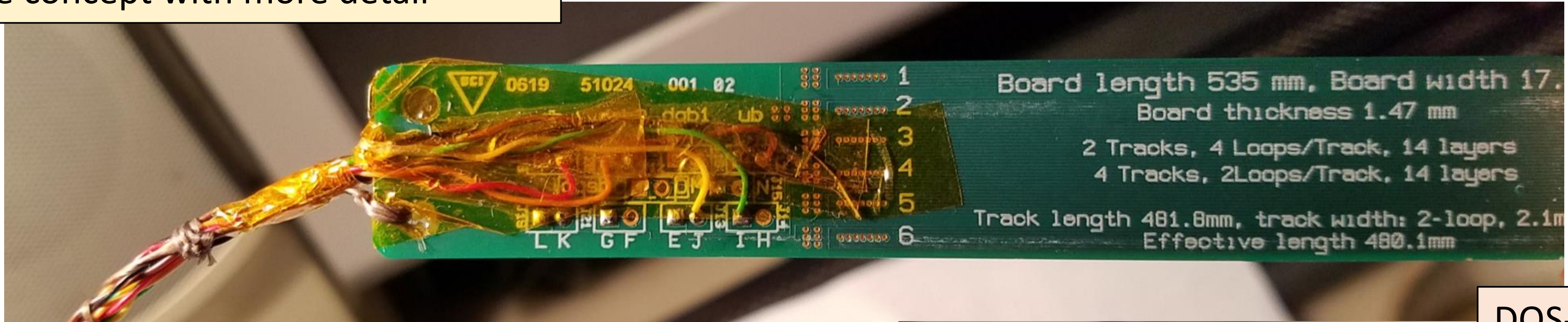
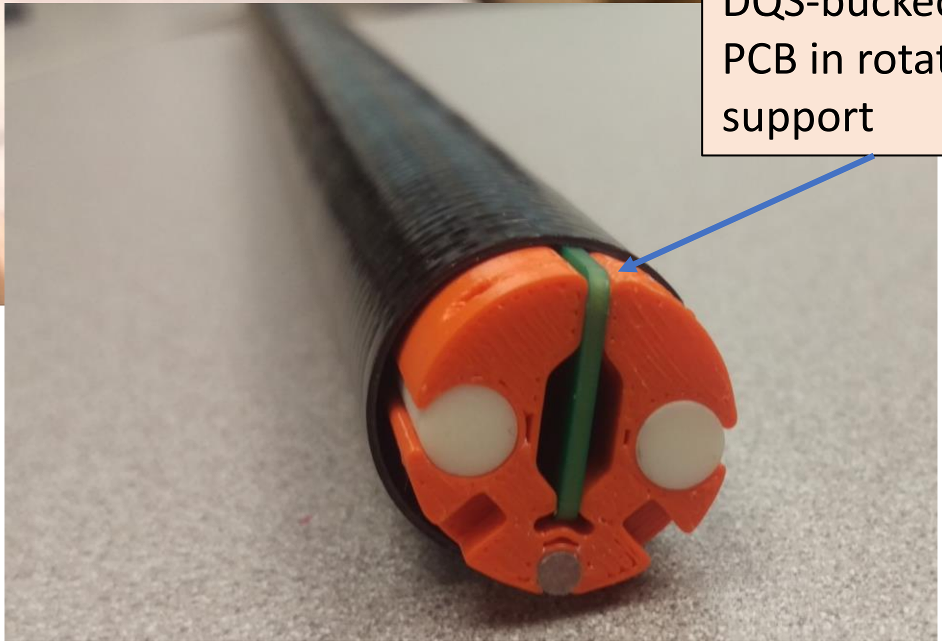
Reviewing a few slides from IMMW21 (2019) which also presented the concept with more detail

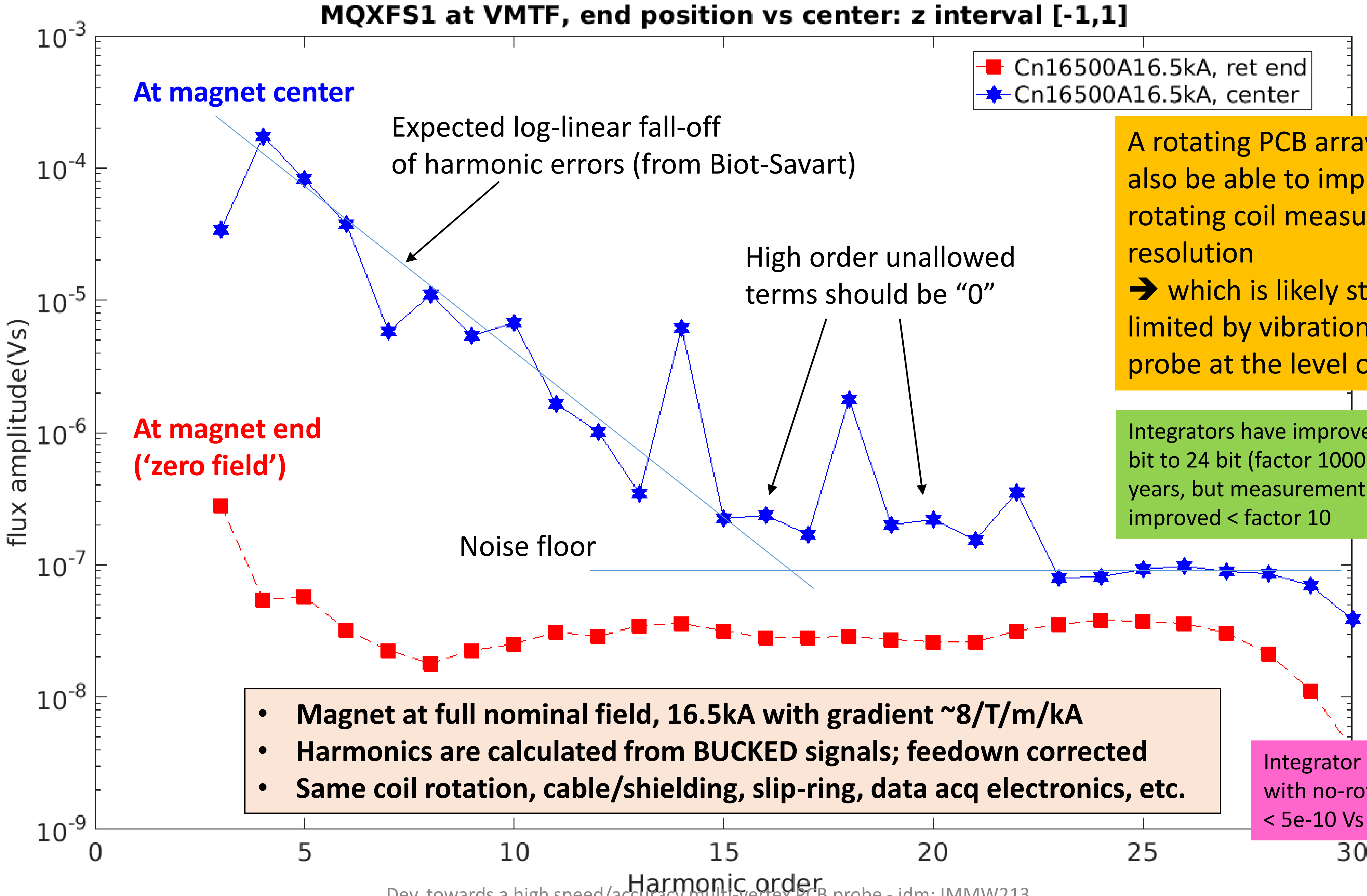




DQS-bucked PCB in rotating support

Printed Circuit Boards have become routinely used for <u>rotating</u> coil probes, featuring

- micron level placement of wires
- multi-layer designs with high sensitivity
- geometries which allow high levels of suppression of effects from main fields (“bucking”)



At magnet center

Expected log-linear fall-off of harmonic errors (from Biot-Savart)

High order unallowed terms should be "0"

At magnet end ('zero field')

Noise floor

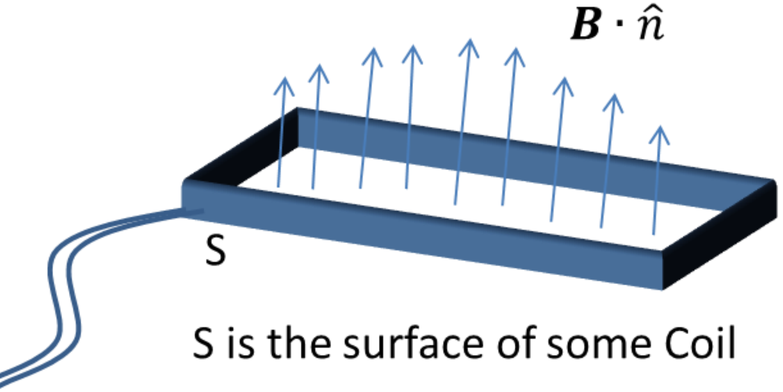
A rotating PCB array might also be able to improve rotating coil measurement resolution
➔ which is likely still limited by vibrations of the probe at the level of ppm

Integrators have improved from 14 bit to 24 bit (factor 1000) over 25 years, but measurement resolution improved < factor 10

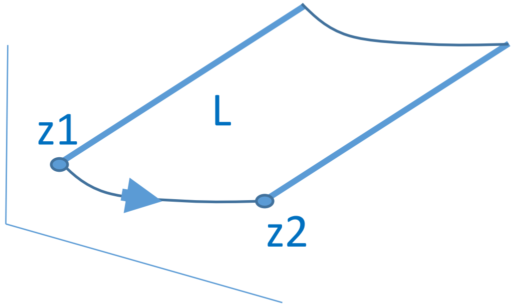
- **Magnet at full nominal field, 16.5kA with gradient ~8/T/m/kA**
- **Harmonics are calculated from BUCKED signals; feedown corrected**
- **Same coil rotation, cable/shielding, slip-ring, data acq electronics, etc.**

Integrator noise with no-rotation is < 5e-10 Vs at n=30

Magnetic Field Determination



S is the surface of some Coil



Flux

Field

'Arbitrary motion'

end pos.

start pos.

$$\Delta\boldsymbol{\Phi} = \mathbf{Re}\left[\frac{\boldsymbol{LR}}{\boldsymbol{n}}\sum_{\boldsymbol{n}=1}^{\infty}(\boldsymbol{B_n} + \boldsymbol{iA_n})\left(\left(\frac{\boldsymbol{z_2}}{\boldsymbol{R}}\right)^{\boldsymbol{n}} - \left(\frac{\boldsymbol{z_1}}{\boldsymbol{R}}\right)^{\boldsymbol{n}}\right)\right]$$

Measure flux *change* from integrated coil voltage during motion (or field change) ➔ **does not depend on path**, only start and stop of measurement.

From MEASURED ***ΔΦ***, along with **coil** & **motion information**, ➔ **B**

① Integrator or ADC/voltmeter

② Have to know the geometric parameters of the coil itself

③ path independent, but have to get the probe to move to correct, or at least known, motion positions

① Flux Measurement

Integrator or ADC/voltmeter

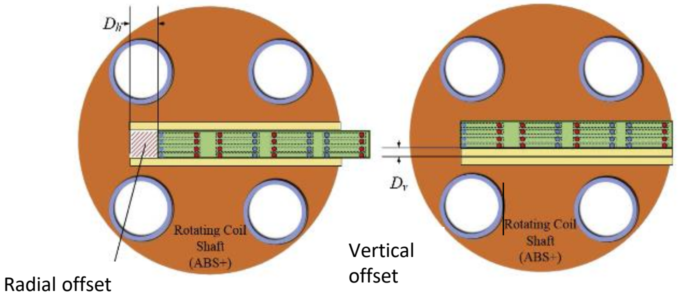
Use 24-bit integrator based on sigma-delta ADC

16 channels simultaneous acquisition

② Probe Calibration

Know the geometric parameters

PCB-probes allow for a straightforward, micron–level in-situ calibration in any quadrupole or higher field.



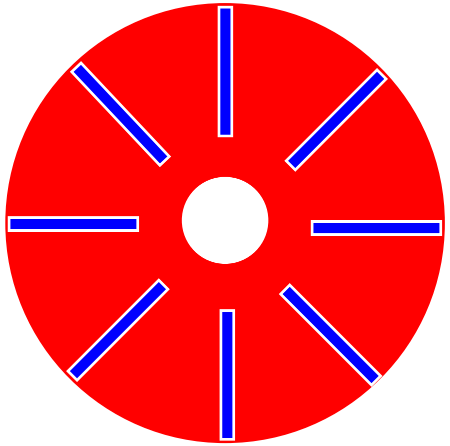
③ Motion/vibration mitigation

Correct, or at least known, motion positions

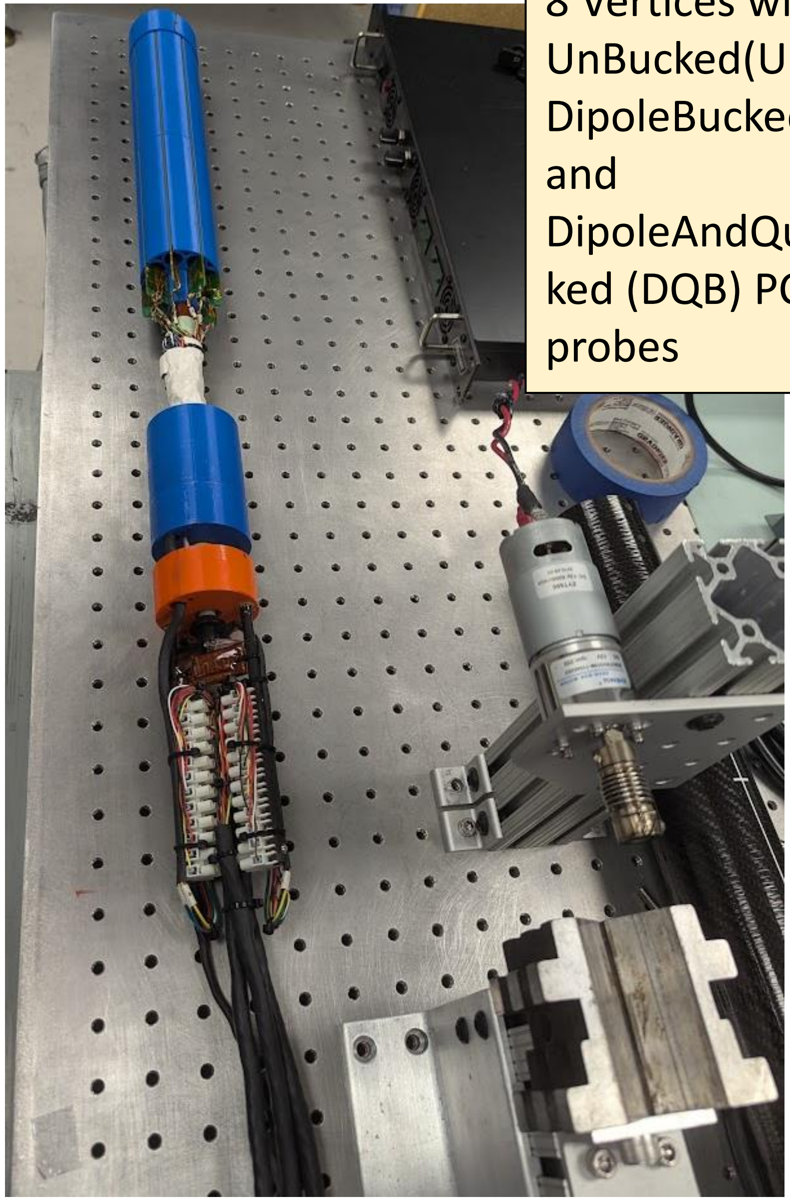
If probe rotates perfectly with no vibrations, this is just an encoder.
Bucking dominant magnetic fields also mitigates against vibration effects.
With MV probe, possibly can further mitigate vibrations

Investigate the possibility of achieving the following with a Multi-Vertex (MV) PCB array:

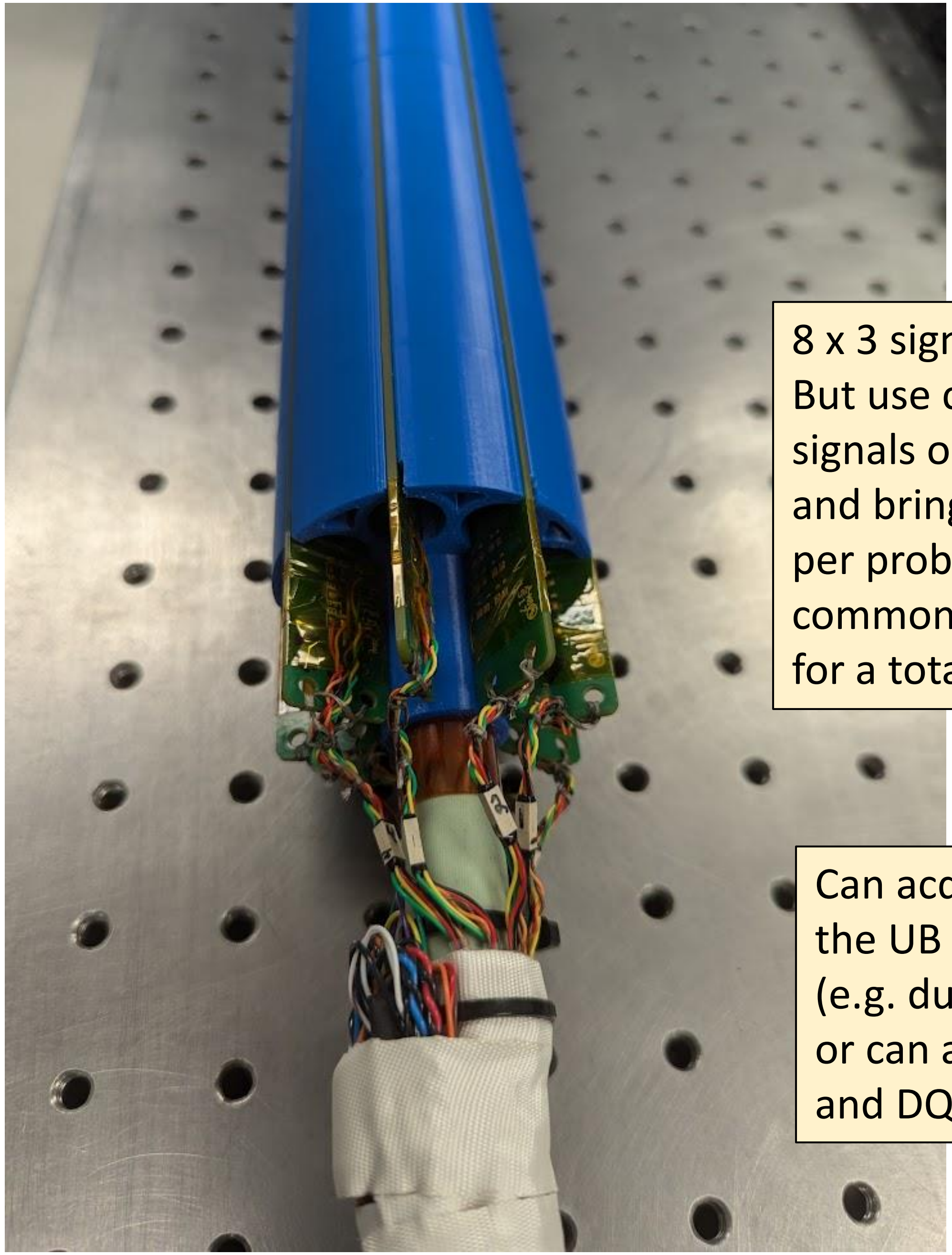
- high-speed measurements
- higher accuracy/resolution measurements
  (mitigate vibrations for all harmonic orders,
  reduce 1/f noise effects by measurements at faster speed)



8-vertex probe will be used as an example with 128 angular encoder positions. Scaling to a higher number of probe vertices and encoder angles is straightforward in the analysis.

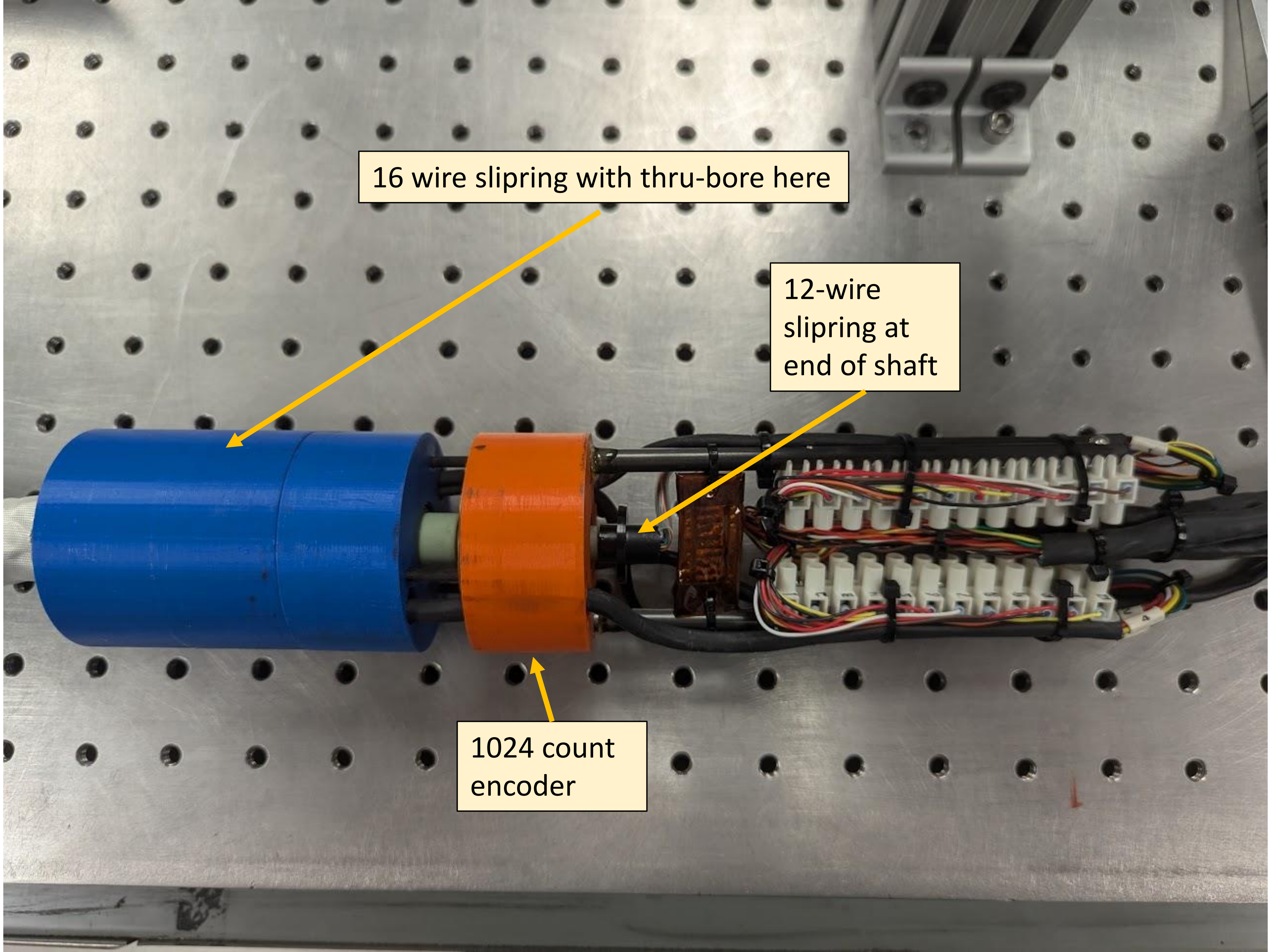


8 Vertices with UnBucked(UB), DipoleBucked (DB) and DipoleAndQuadBucked (DQB) PCB probes



8 x 3 signals (48 wires) But use common to signals on a given probe and bring out 3 wires per probe and 1 common for all 8 probes for a total of 25 wires.

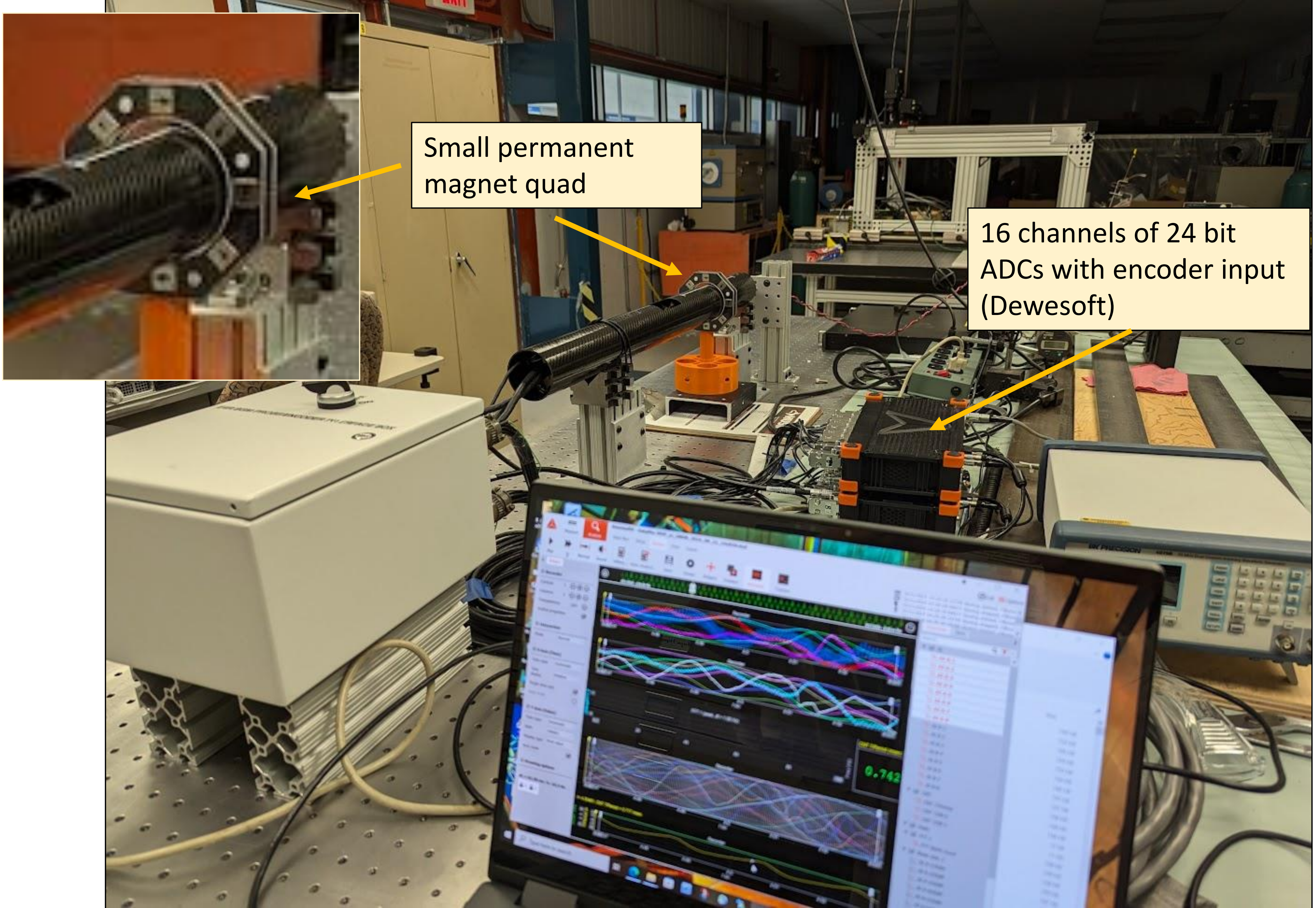
Can acquire data with all the UB and DB signals (e.g. during calibration), or can acquire all the UB and DQB signals



16 wire slipring with thru-bore here

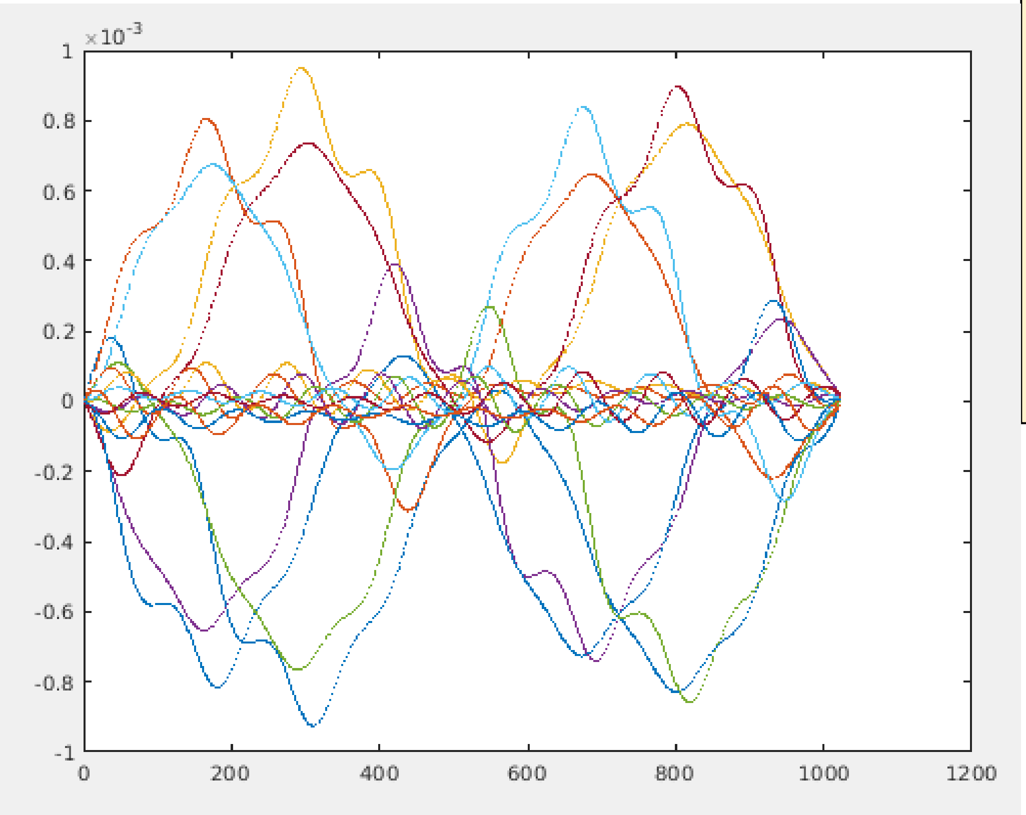
12-wire slipring at end of shaft

1024 count encoder



Small permanent magnet quad

16 channels of 24 bit ADCs with encoder input (Dewesoft)



Calibration run UBDB

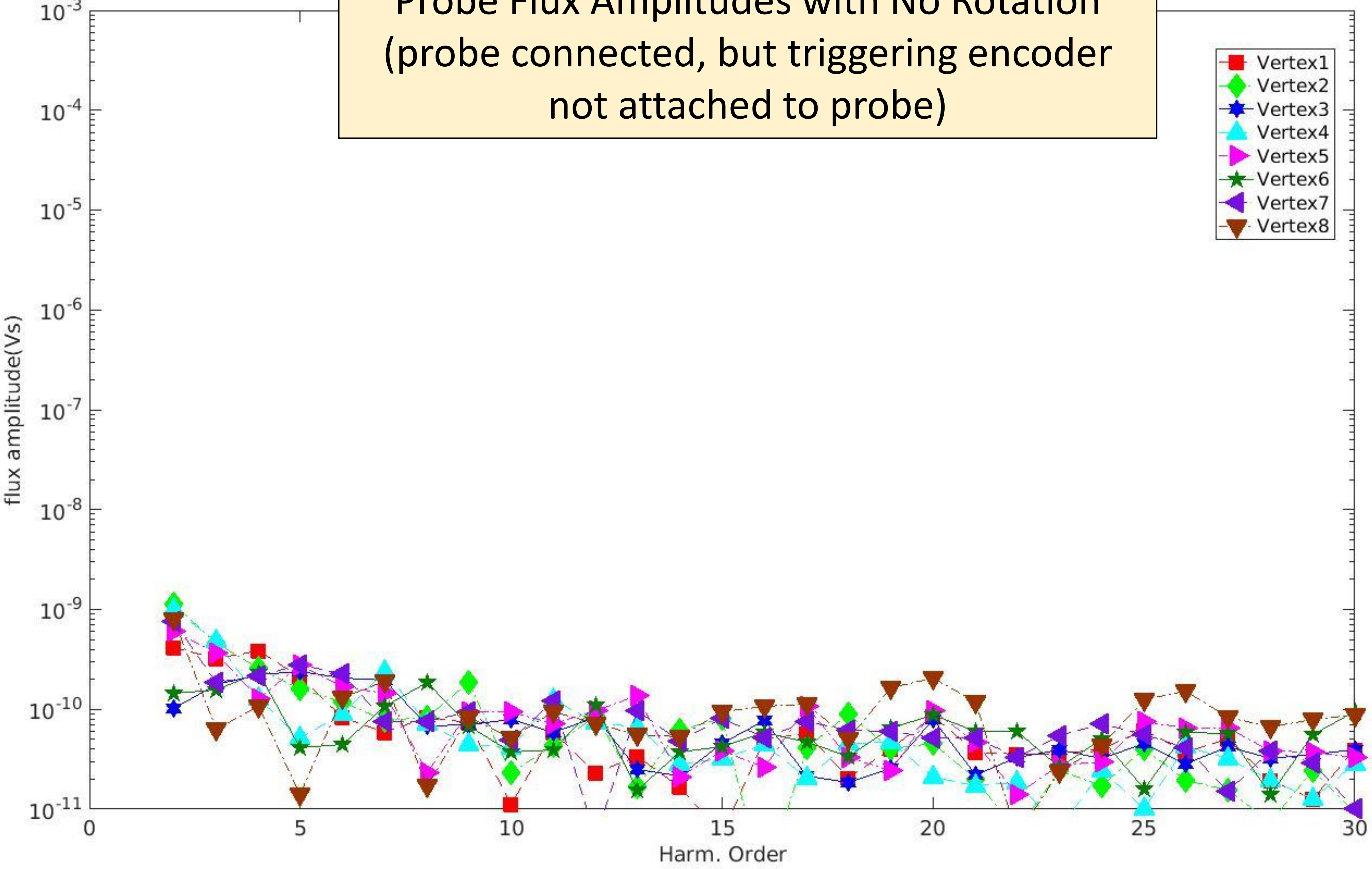
Determined the probe offsets with respect to ideal orientation and wrt each other

The standard deviation in radial offset position was 0.16 mm

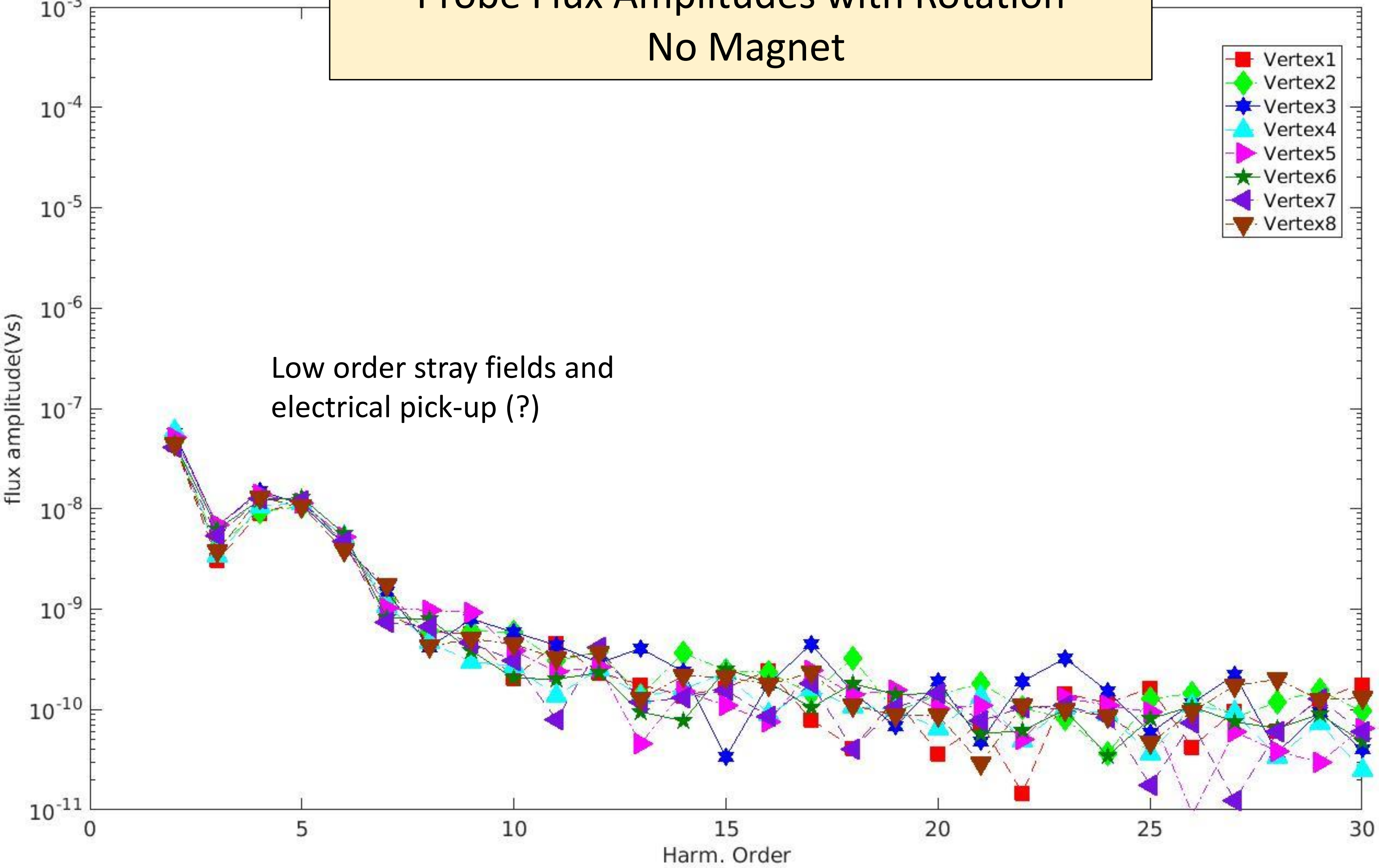
The mean transverse offset was -0.30 mm with s.d. 0.25 mm

→ This should lead to full knowledge of probe positions in MV array at level of microns.

Probe Flux Amplitudes with No Rotation (probe connected, but triggering encoder not attached to probe)

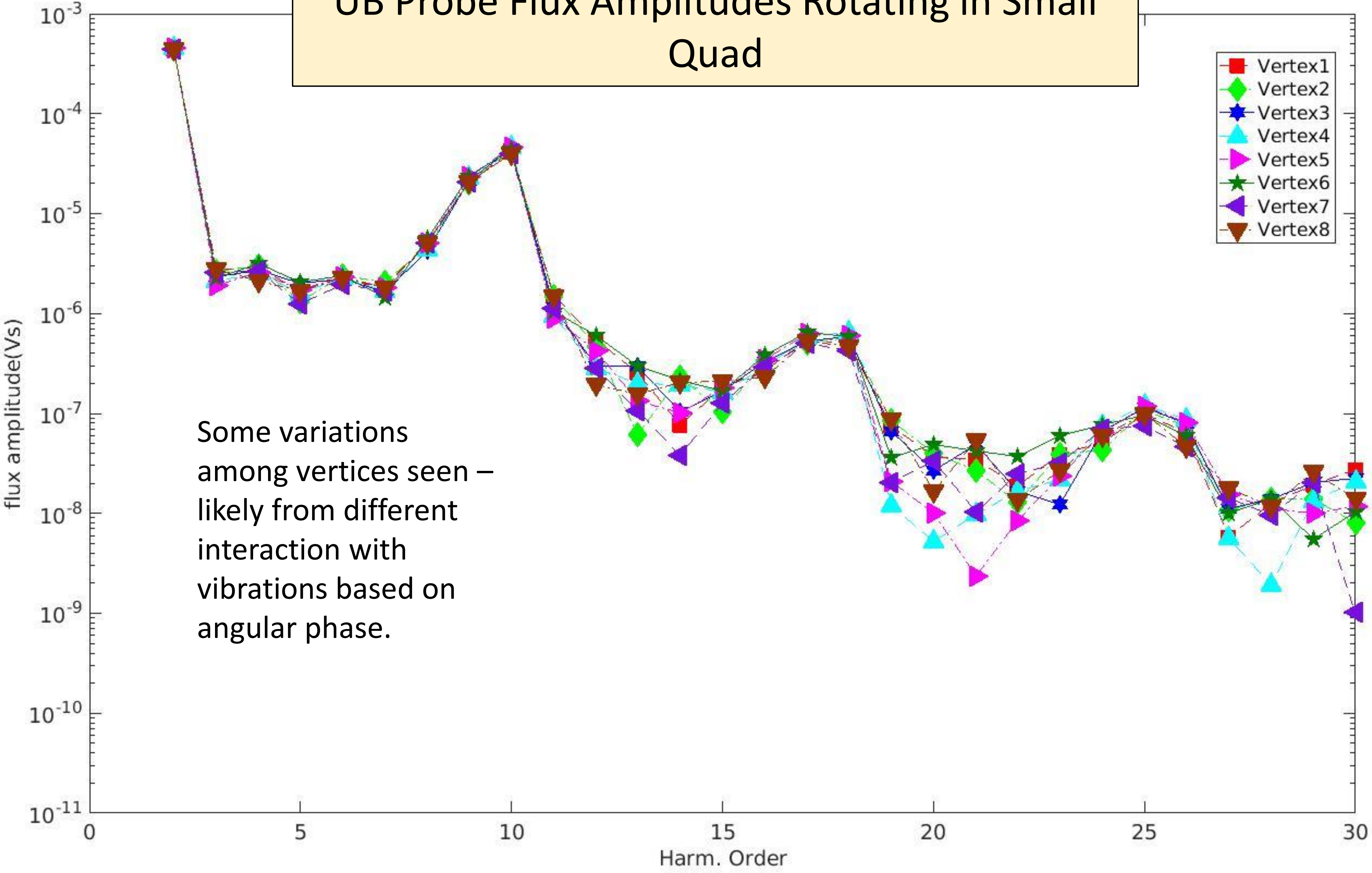


Probe Flux Amplitudes with Rotation
No Magnet



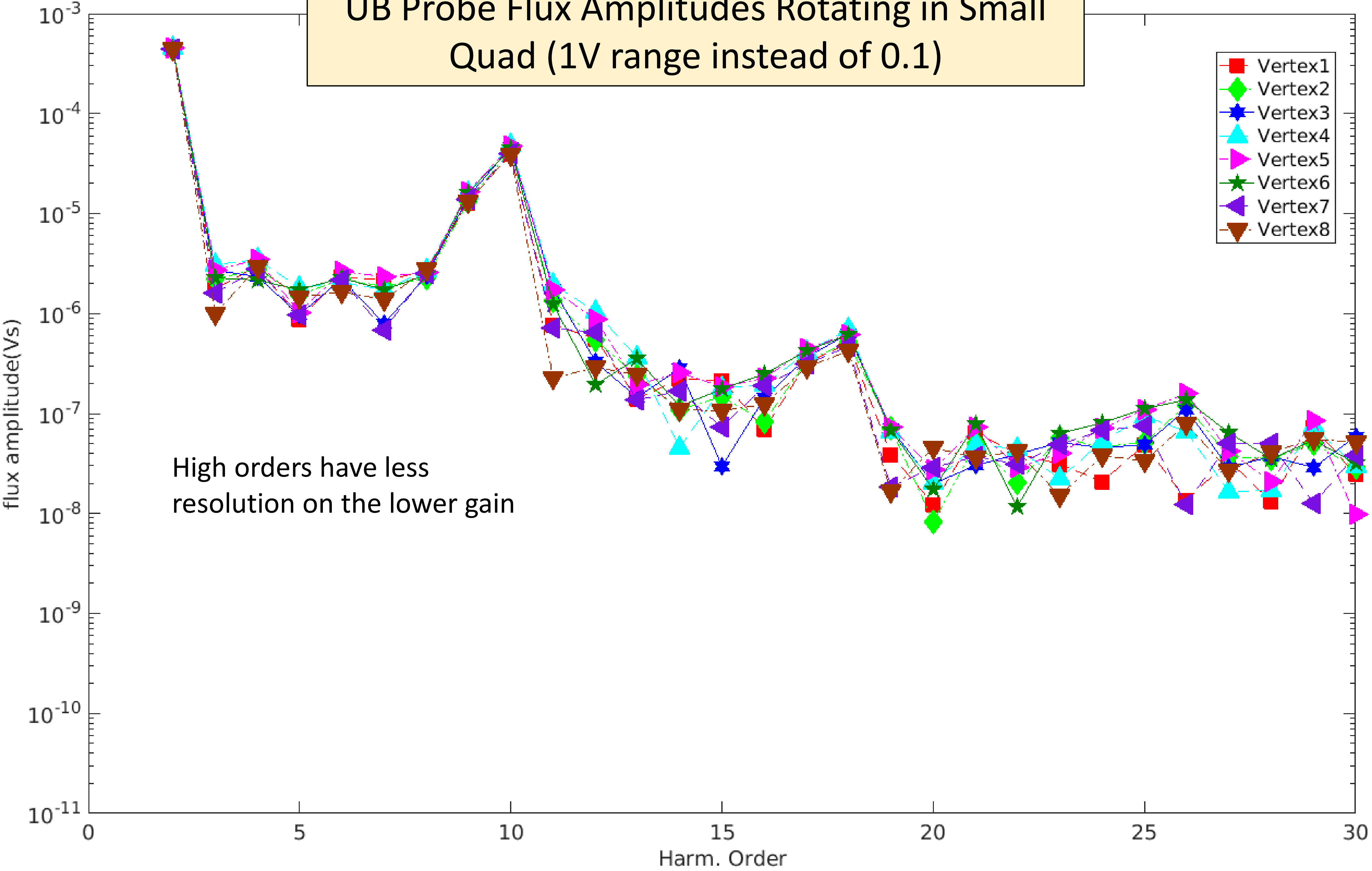
Low order stray fields and electrical pick-up (?)

UB Probe Flux Amplitudes Rotating in Small Quad



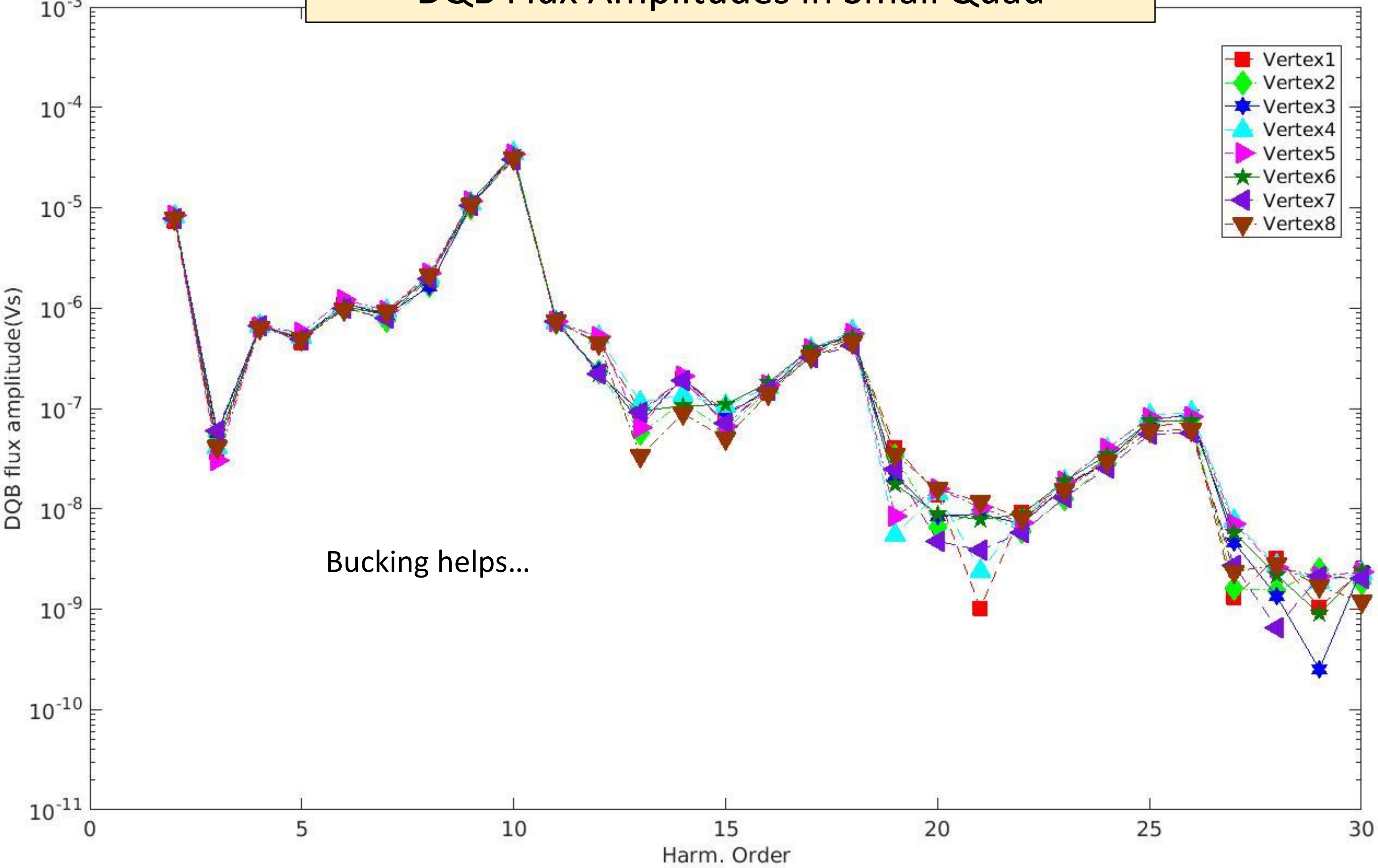
Some variations among vertices seen – likely from different interaction with vibrations based on angular phase.

UB Probe Flux Amplitudes Rotating in Small Quad (1V range instead of 0.1)



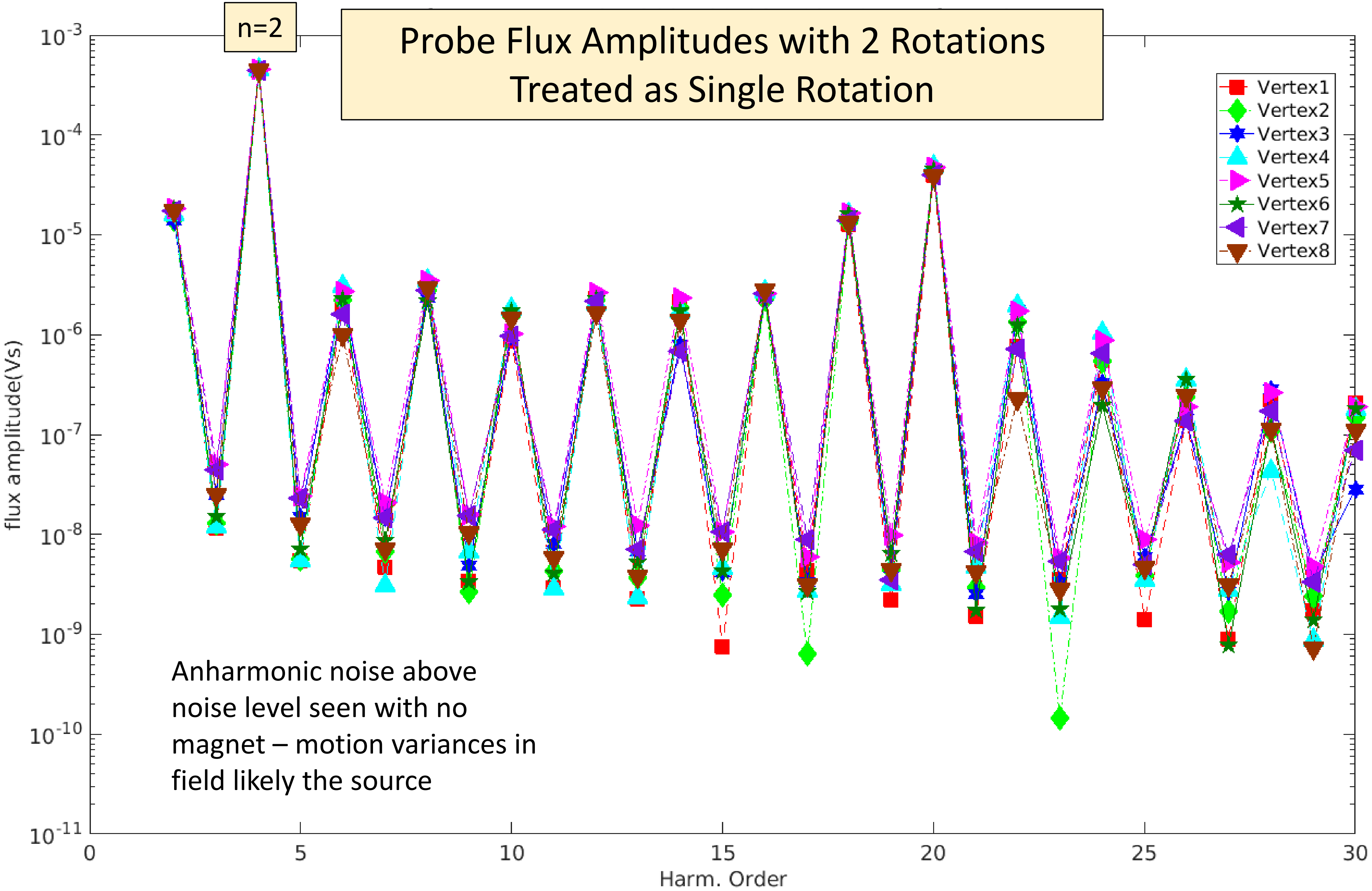
High orders have less resolution on the lower gain

DQB Flux Amplitudes in Small Quad



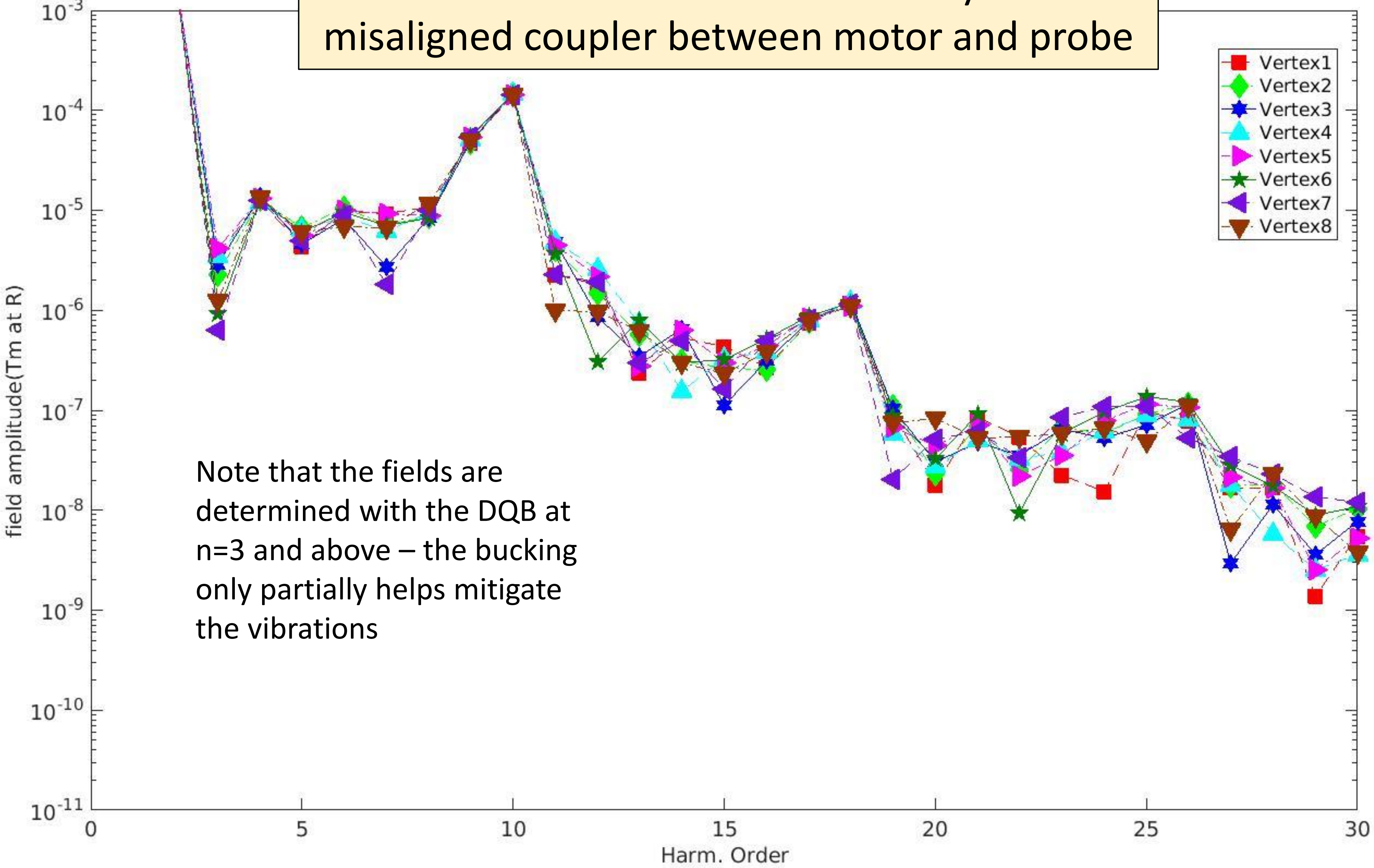
Bucking helps…

Probe Flux Amplitudes with 2 Rotations Treated as Single Rotation

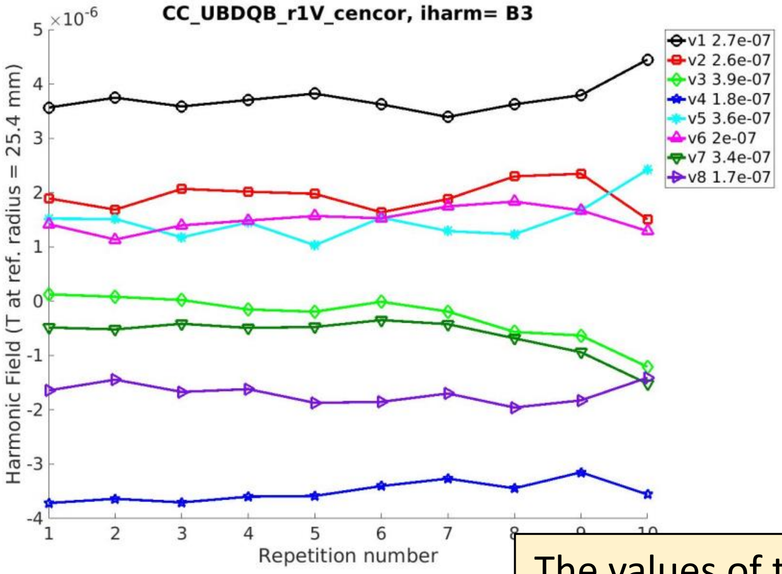


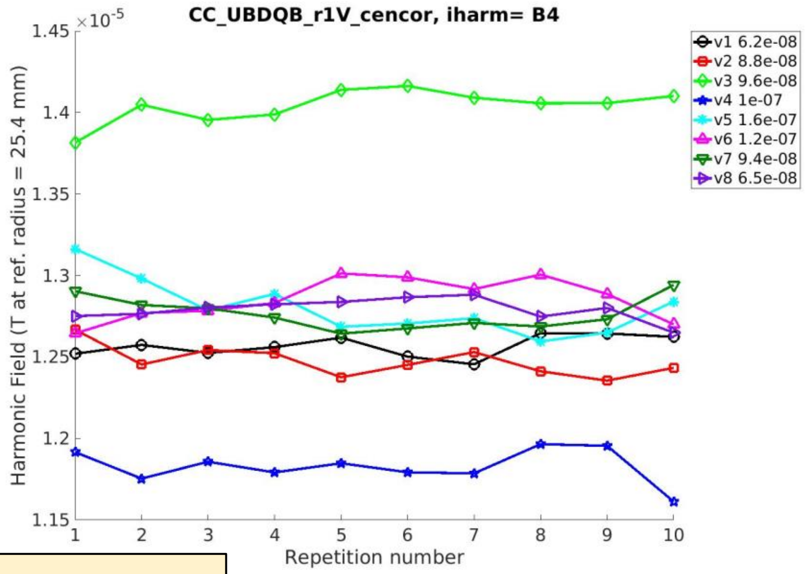
Anharmonic noise above noise level seen with no magnet – motion variances in field likely the source

Fields with vibrations induced by stiff misaligned coupler between motor and probe

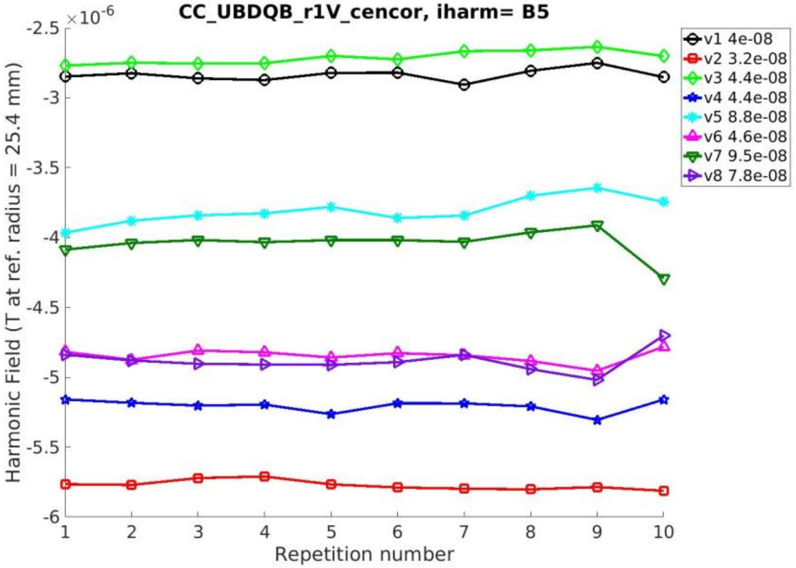


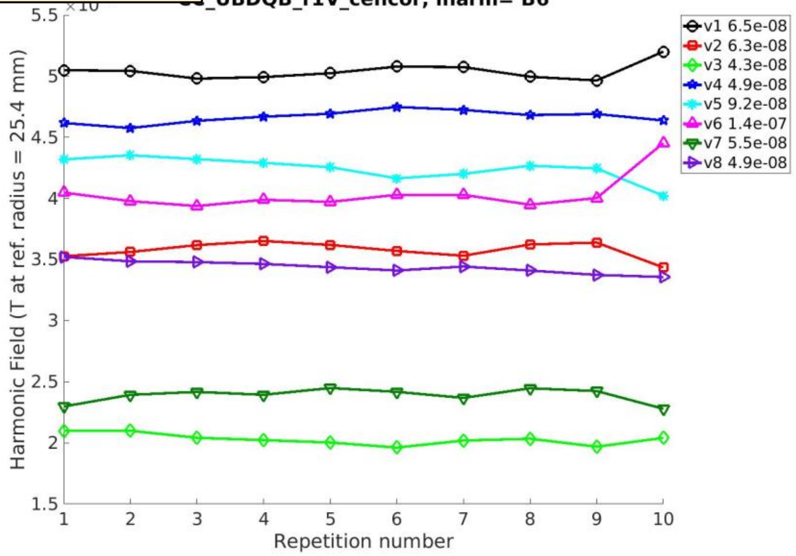
Note that the fields are determined with the DQB at n=3 and above – the bucking only partially helps mitigate the vibrations



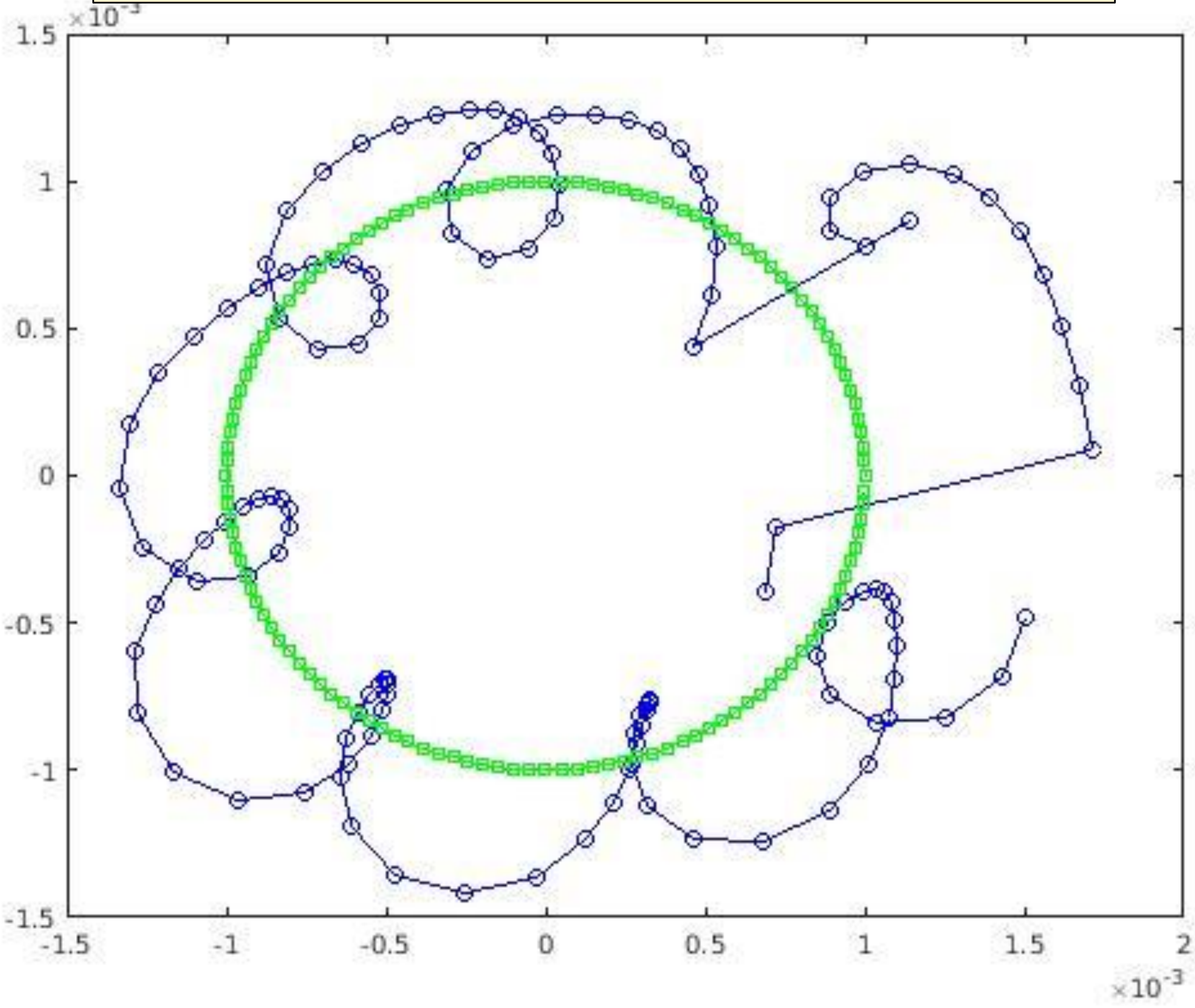


The values of the harmonics with the stiff coupler tend to repeat well even though they differ from each other – not random but induced from the repeated vibrations

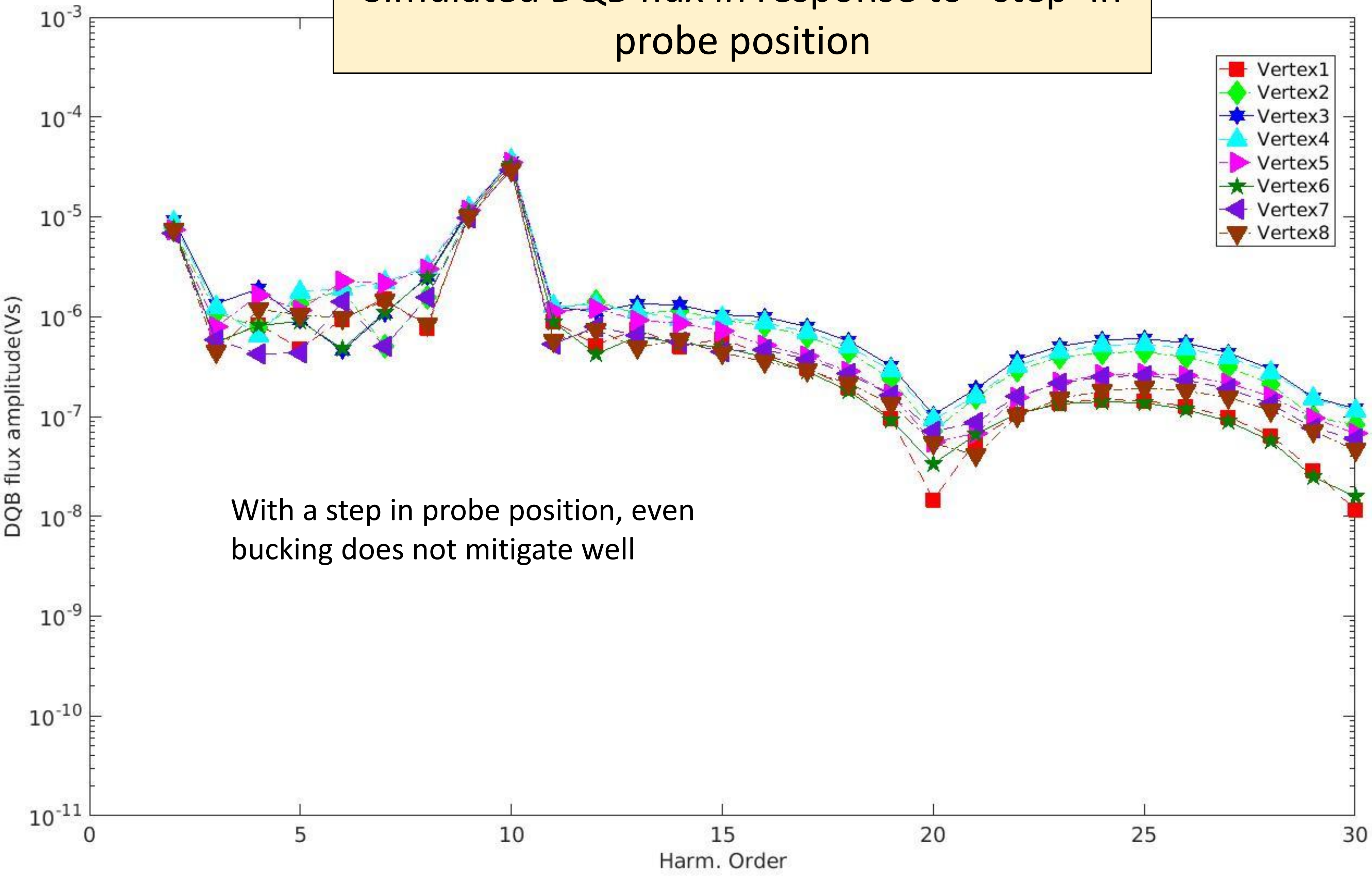




Simulate ‘step’ in probe position by 1mm for 13 out of 128 angular positions



Simulated DQB flux in response to 'step' in probe position



With a step in probe position, even bucking does not mitigate well

Determining actual probe motion

For each angle, determining the 3 error terms with 8 points

For each angle, $\theta_1, \theta_2, \ldots, \theta_{128}$, express the measured flux (e.g. for θ_1) as

Flux contribution terms ➔

⬇ Vertices

Unknown errors at θ_1

Flux at each vertex at θ_1

$$\begin{pmatrix} K_n^{V_1 nom}(\theta_1)\cdot C_n & \frac{\partial K_n^{V_1 nom}(\theta_1)}{\partial x}\cdot C_n & \frac{\partial K_n^{V_1 nom}(\theta_1)}{\partial y}\cdot C_n & \frac{\partial K_n^{V_1 nom}(\theta_1)}{\partial \theta}\cdot C_n \\ K_n^{V_2 nom}(\theta_1)\cdot C_n & \frac{\partial K_n^{V_2 nom}(\theta_1)}{\partial x}\cdot C_n & \frac{\partial K_n^{V_2 nom}(\theta_1)}{\partial y}\cdot C_n & \frac{\partial K_n^{V_2 nom}(\theta_1)}{\partial \theta}\cdot C_n \\ \vdots & & \ddots & \vdots \\ \vdots & & & \vdots \\ K_n^{V_8 nom}(\theta_1)\cdot C_n & \frac{\partial K_n^{V_8 nom}(\theta_1)}{\partial x}\cdot C_n & \frac{\partial K_n^{V_8 nom}(\theta_1)}{\partial y}\cdot C_n & \frac{\partial K_n^{V_8 nom}(\theta_1)}{\partial \theta}\cdot C_n \end{pmatrix} \begin{pmatrix} 1 \\ dx(\theta_1) \\ dy(\theta_1) \\ d\theta(\theta_1) \end{pmatrix} = \begin{pmatrix} \varphi^{V_1}(\theta_1) \\ \varphi^{V_2}(\theta_1) \\ \vdots \\ \vdots \\ \varphi^{V_8}(\theta_1) \end{pmatrix}$$

Contributions from sensitivity derivatives

Solve for these

Where the $\frac{\partial K_n^{V_1 nom}(\theta_1)}{\partial x}$ e.g. are the sensitivity derivatives for a particular vertex at a particular angle and are calculated from the difference of $K_n^{V_1 nom}(\theta_1)$ found at nominal coordinate positions and with all x-coordinates shifted by a small amount

The C_n are averages determined from the nominal vertices analysis – when the analysis is repeated including the vibrations, these can be iterated if necessary

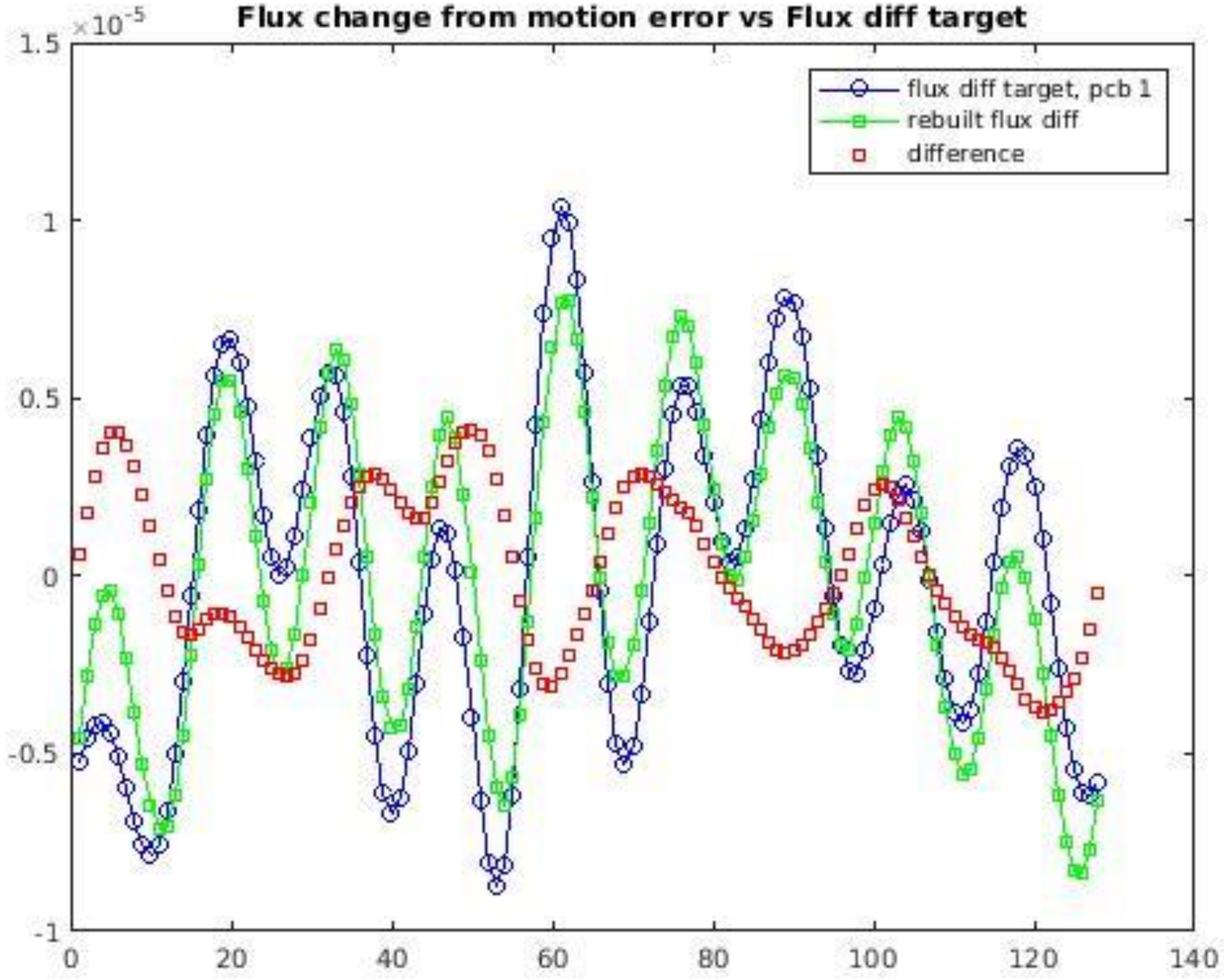
Calculate derivatives with small steps that are linear wrt +/- errors

Find the motion offsets at each of the 128 angles. Then can generate for each vertex, 128 coil sensitivities with the offsets imbedded so have the ACTUAL sensitivity of the probe at every angle.

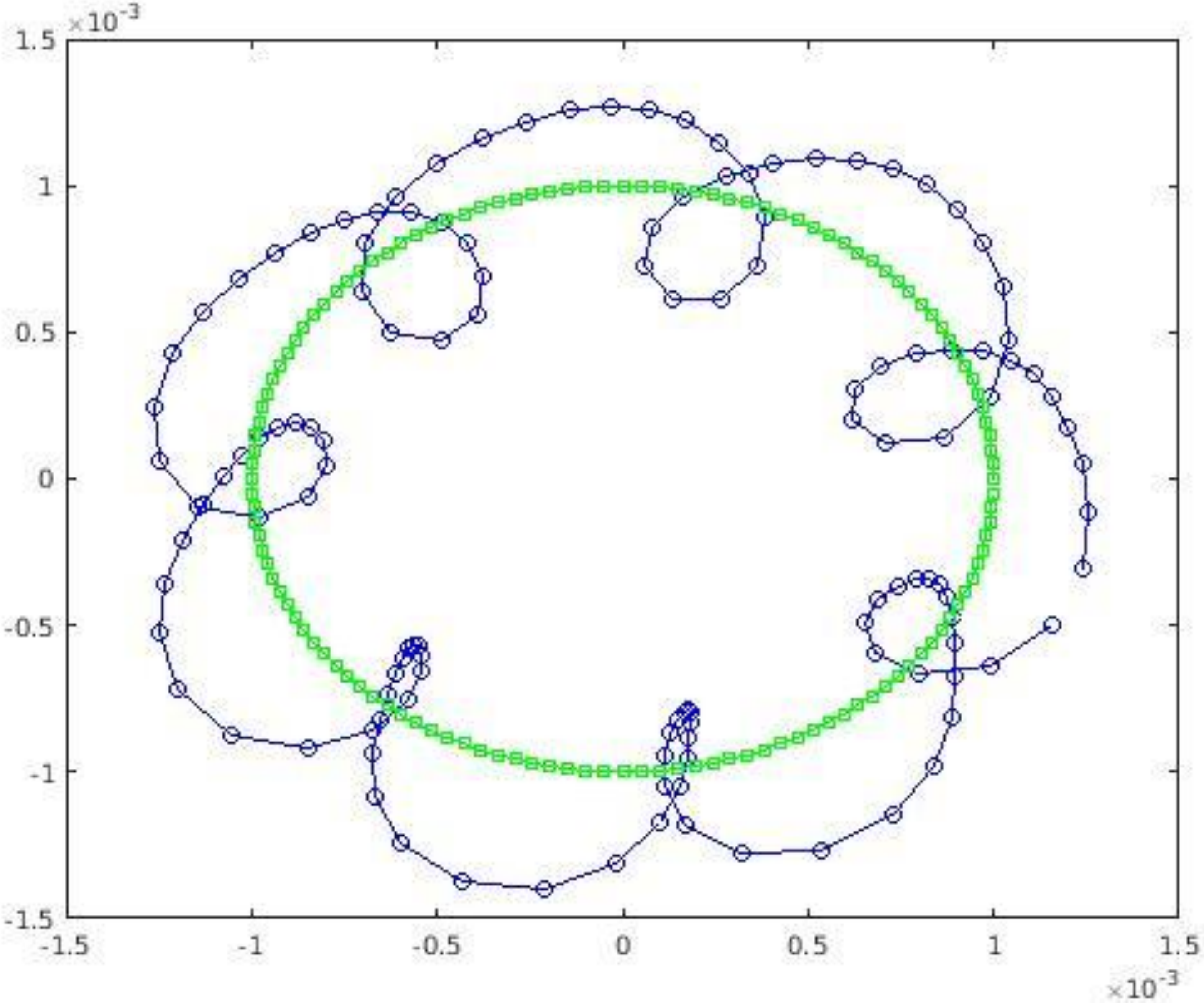
Generate Kn(theta) based matrix for each vertex and solve – each vertex SHOULD yield the same harmonics (having seen the appropriate vibration offsets) – but at least can see if the variation among results of the different probes has decreased for each harmonic.

Can then also just use a fraction (1/8th) of each rotation from the probes and combine them with their Kn(theta) sensitivities in a matrix and find the harmonics at 8 times faster speed.

$$\widetilde{\boldsymbol{K}_n}(\boldsymbol{\theta}) = \sum_{j=1}^{N_{wires}} \frac{\boldsymbol{L_j R}}{\boldsymbol{n}} \left(\frac{\boldsymbol{z_j(\theta)} + \boldsymbol{z_j^{vib}(\theta)}}{\boldsymbol{R}} \right)^{\boldsymbol{n}} * (-\boldsymbol{1})^{\boldsymbol{j}}$$

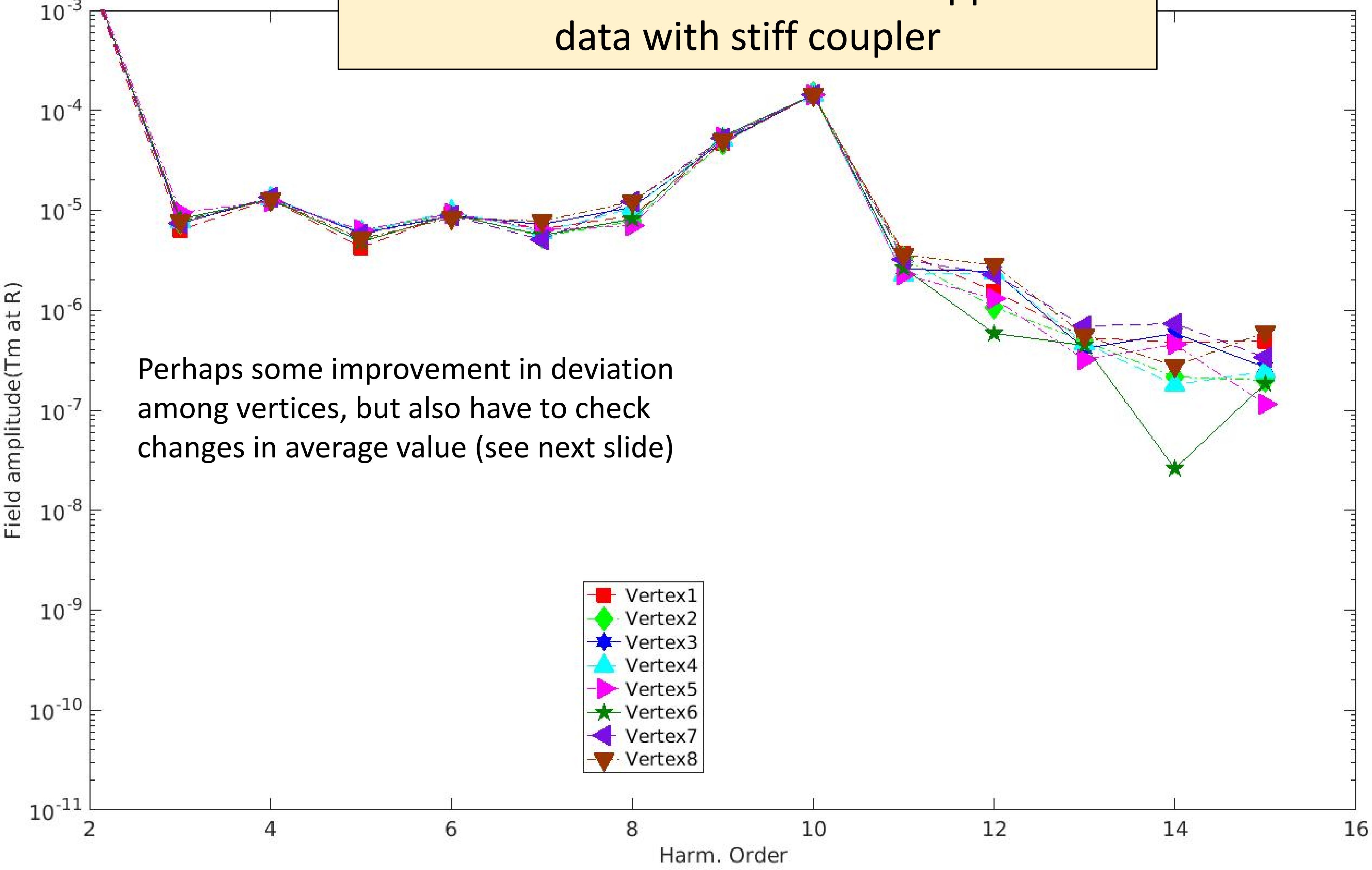

Flux change from motion error vs Flux diff target
×10^-5
1.5
1
0.5
0
-0.5
-1
0
20
40
60
80
100
120
140
flux diff target, pcb 1
rebuilt flux diff
difference

Motion Correction determined compared to ideal rotation trajectory



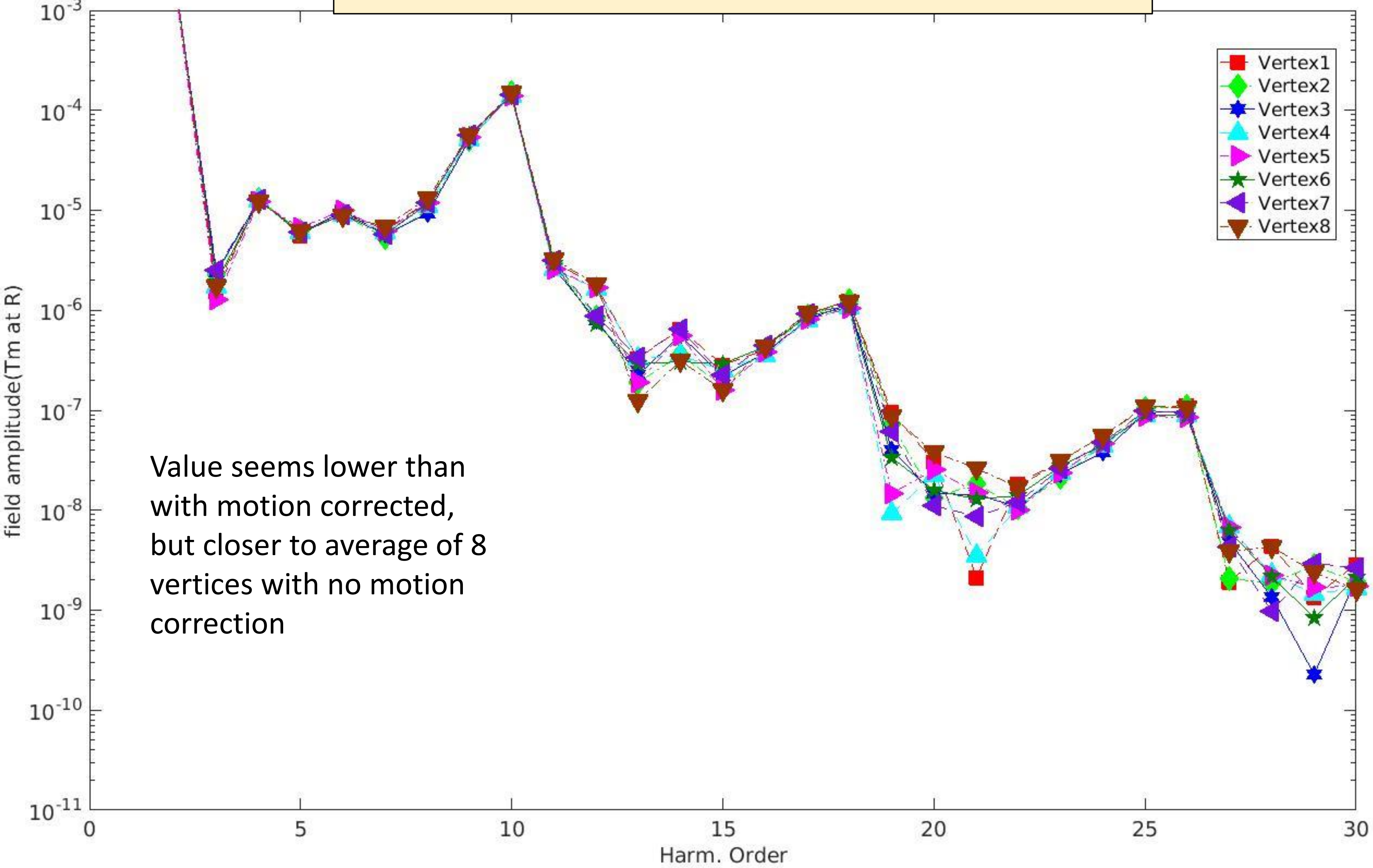
The loops seem to be an artefact of the very large 20 pole (?) – perhaps the motion correction with 8 points is not sufficient to handle the ~500 unit term

Fields after motion correction applied to data with stiff coupler

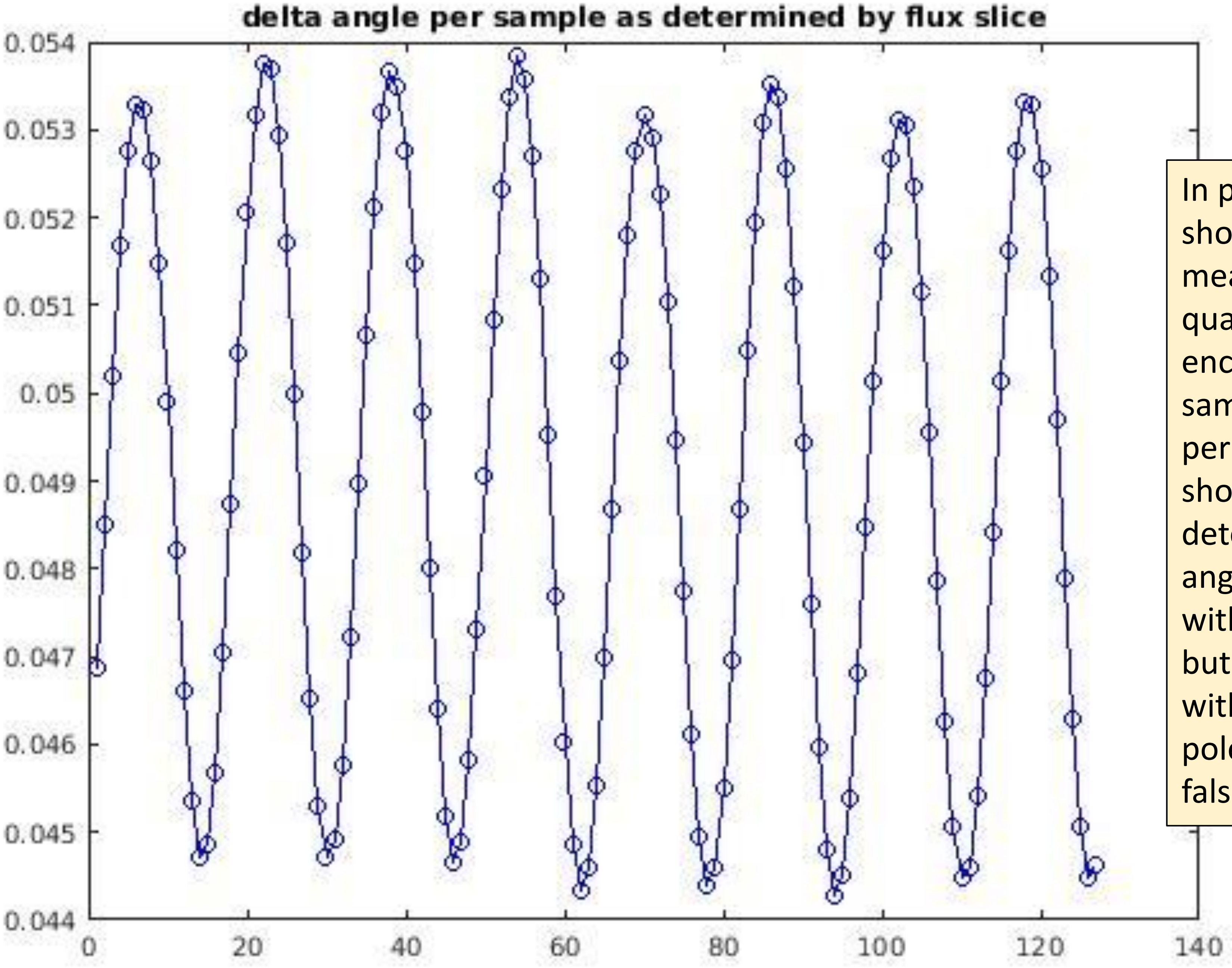


Perhaps some improvement in deviation among vertices, but also have to check changes in average value (see next slide)

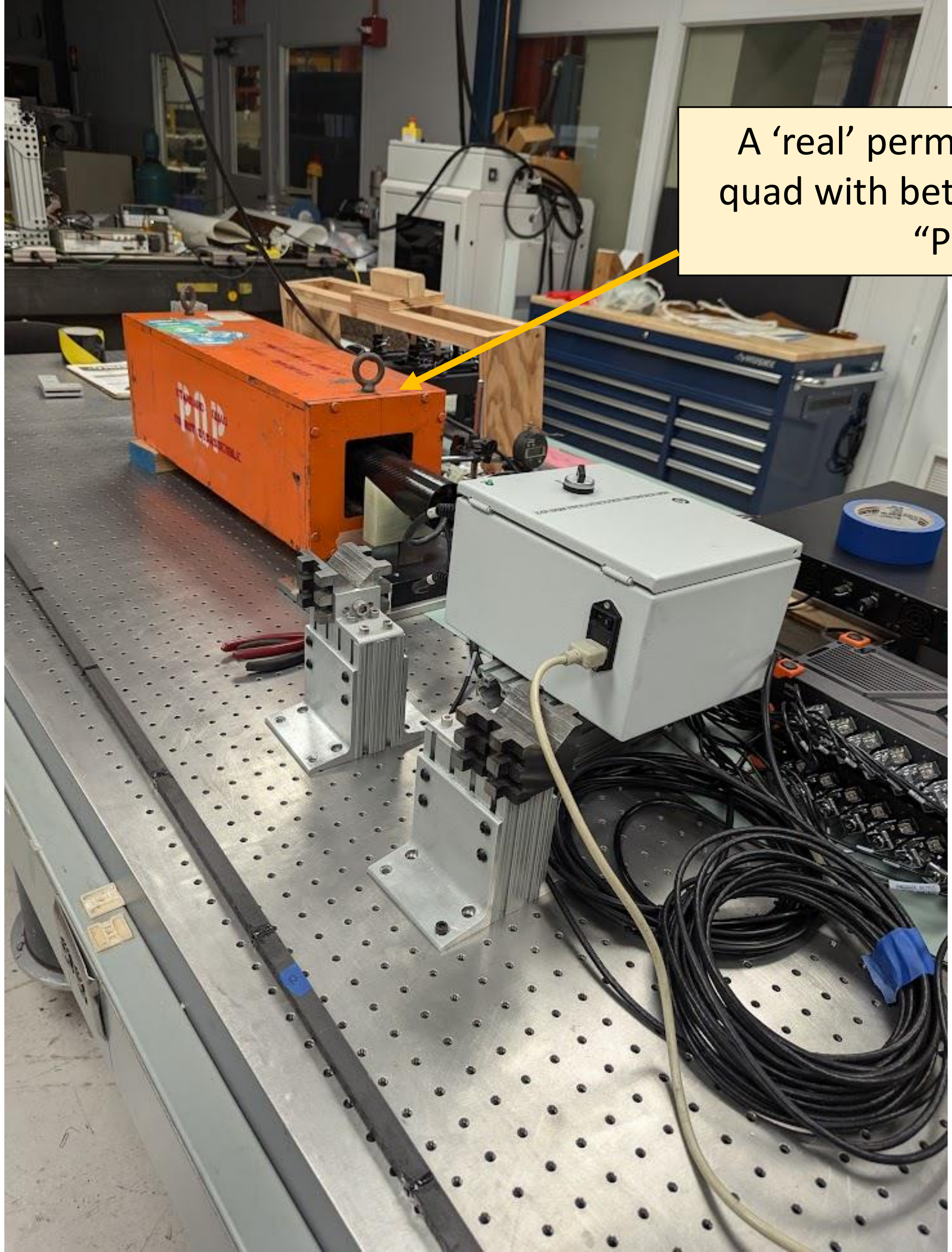
Fields with low induced vibrations



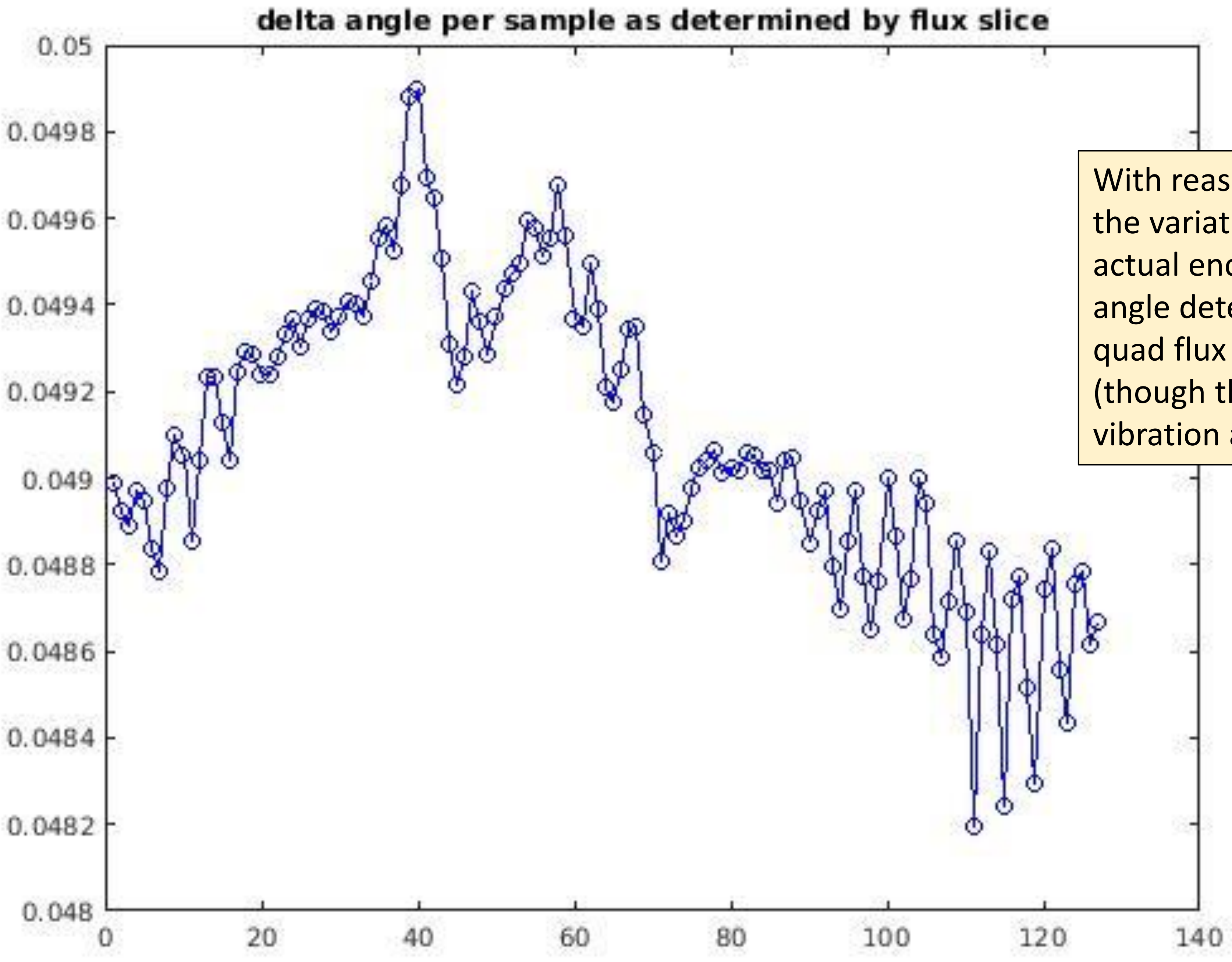
Value seems lower than with motion corrected, but closer to average of 8 vertices with no motion correction



In principle, should get a measurement of quad for each encoder trigger (8 samples around perimeter) – should be able to determine probe angle even without encoder – but in this case with very large 20-pole, there is a false variation

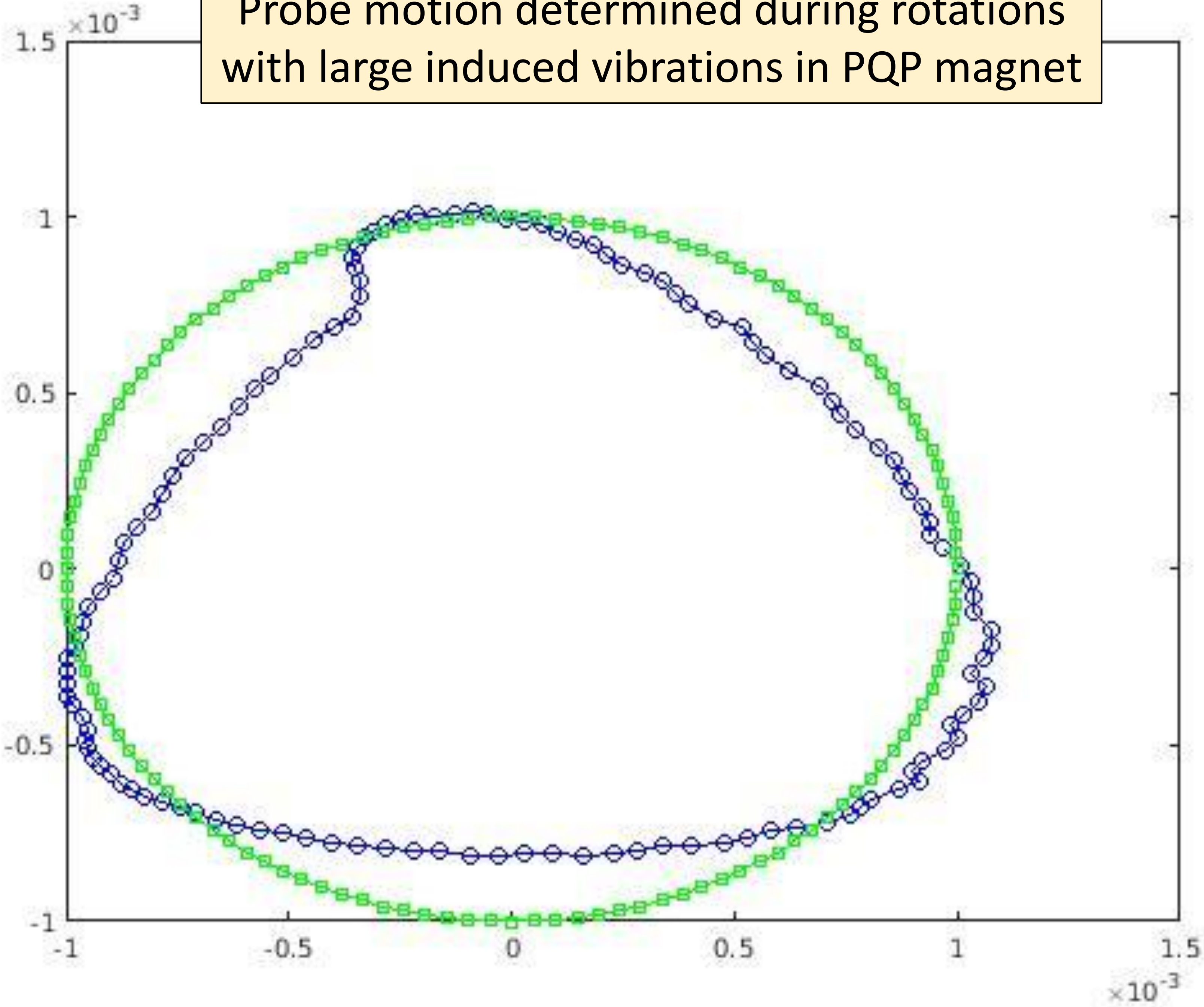


A ‘real’ permanent magnet quad with better field quality “PQP”

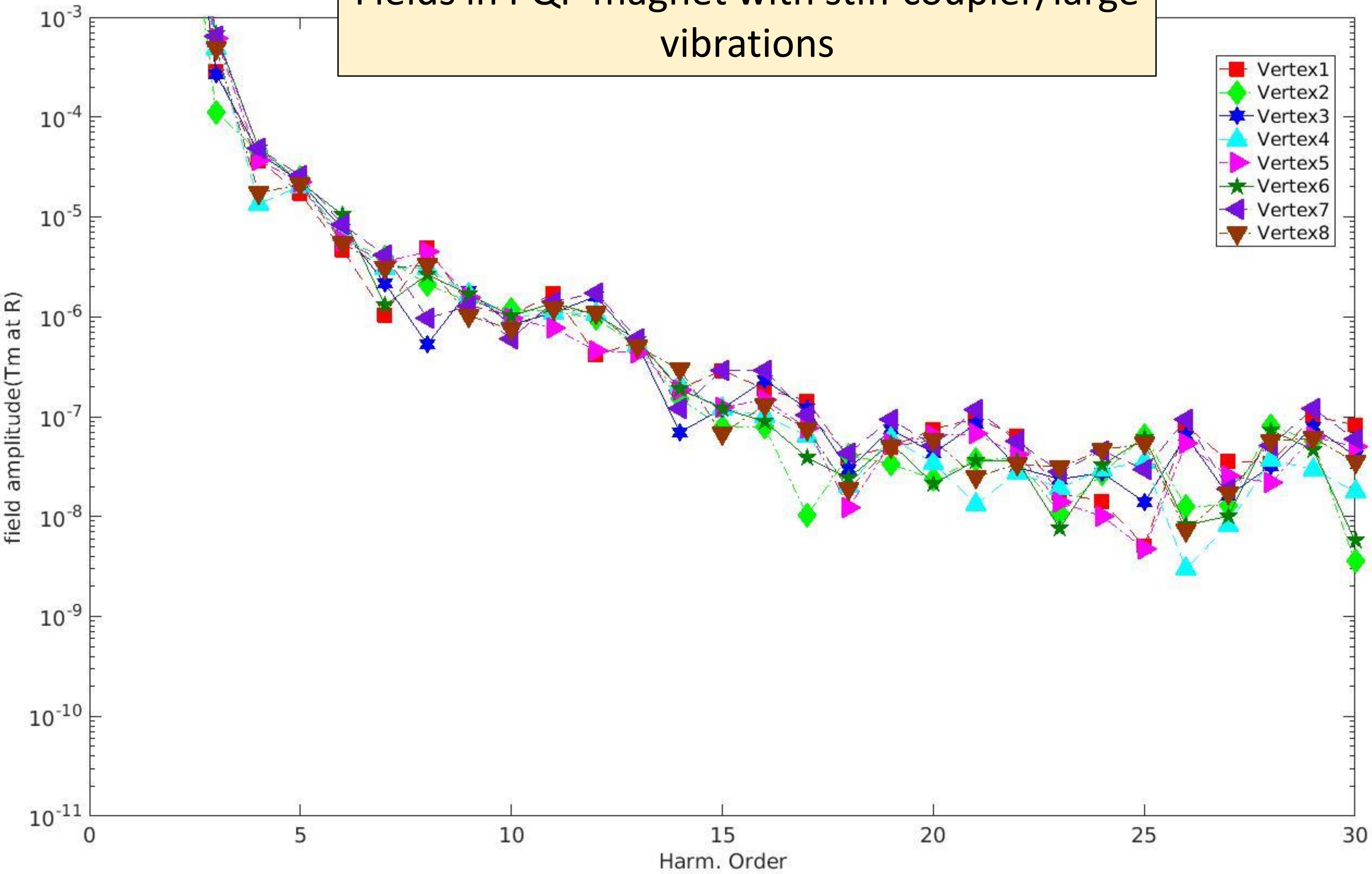


With reasonable field quality, the variation between the actual encoder and the delta angle determined by the quad flux slice is ~0.5 mrad (though this is with large vibration as well).

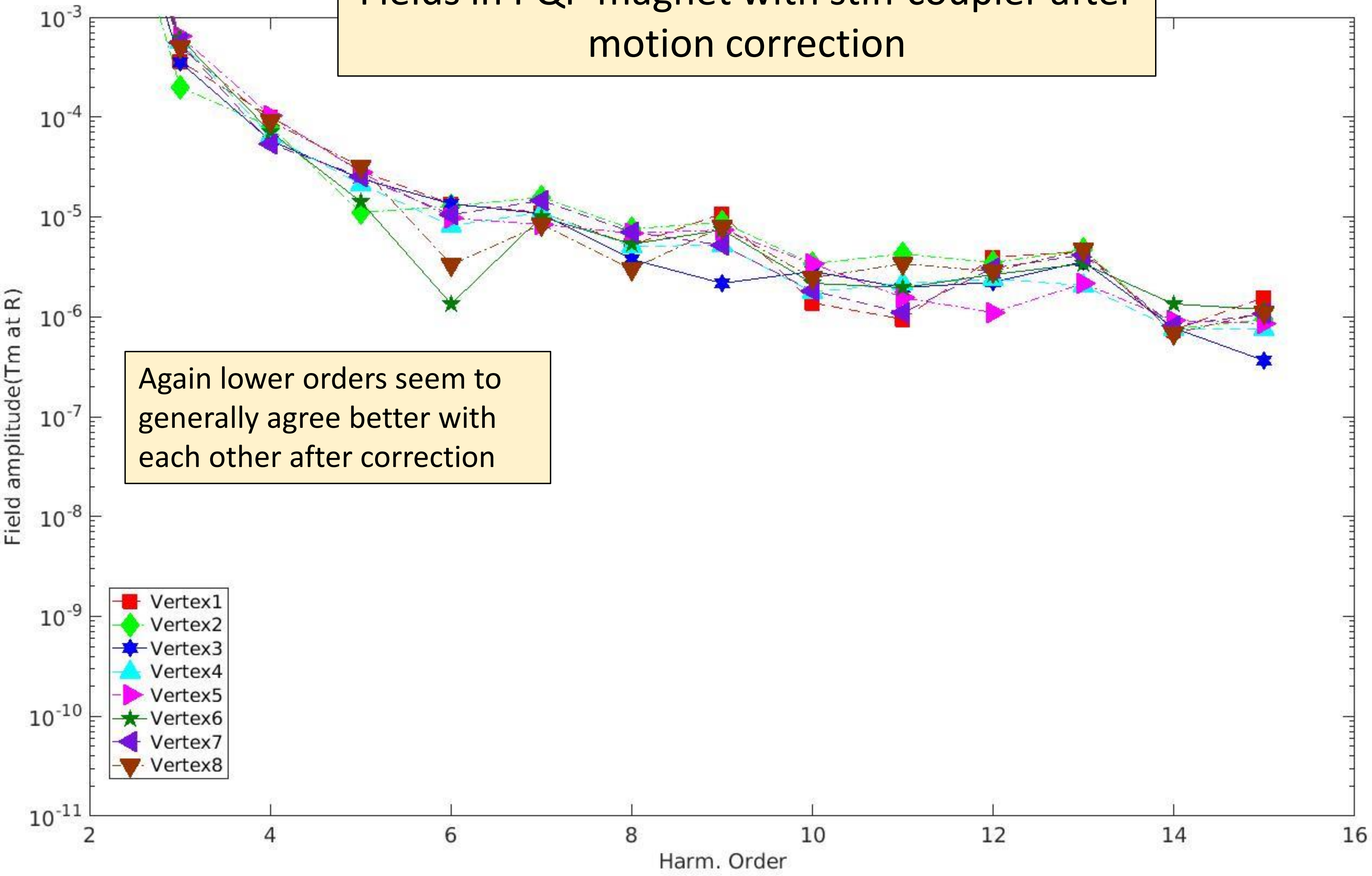
Probe motion determined during rotations with large induced vibrations in PQP magnet



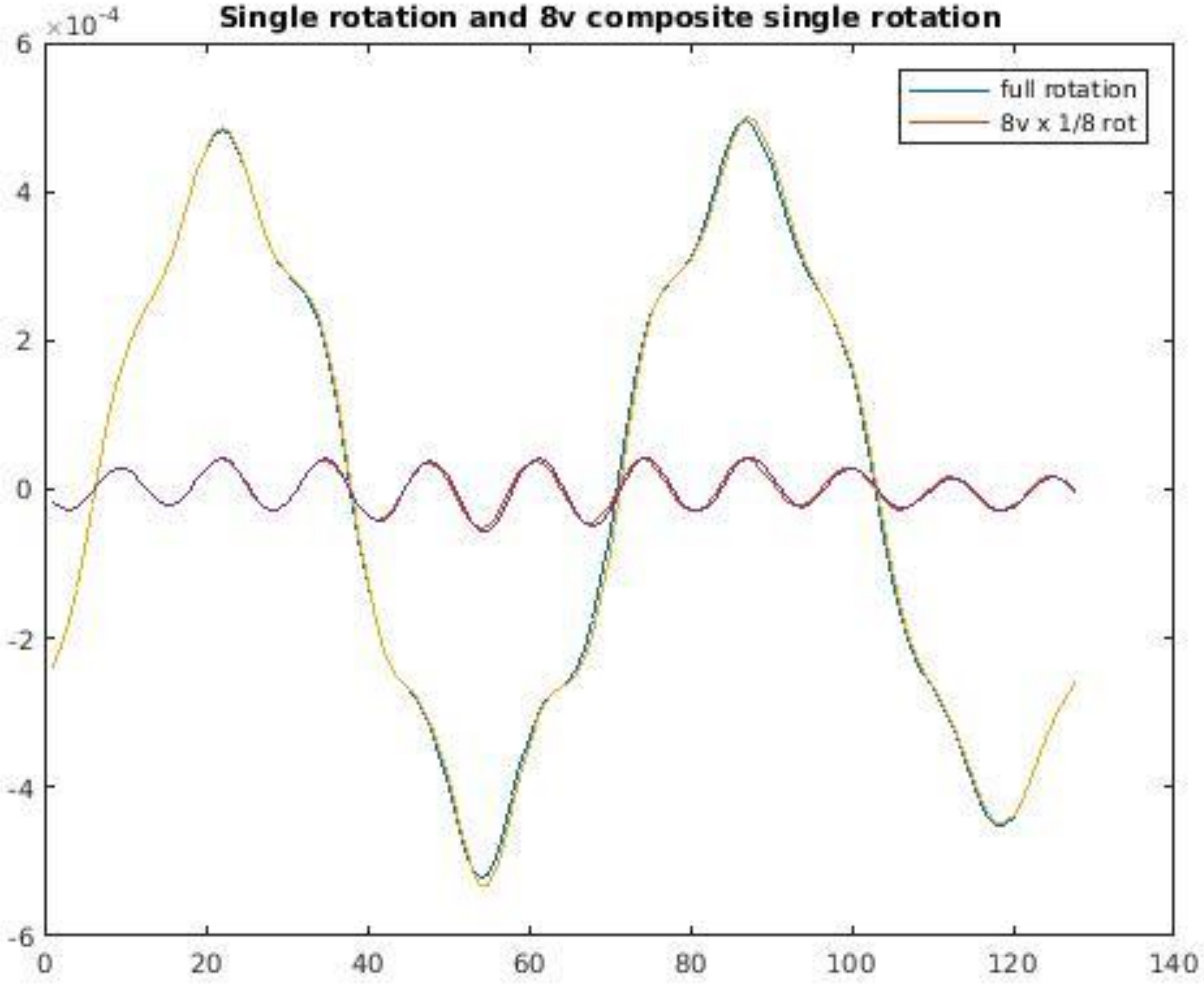
Fields in PQP magnet with stiff coupler/large vibrations



Fields in PQP magnet with stiff coupler after motion correction



Again lower orders seem to generally agree better with each other after correction



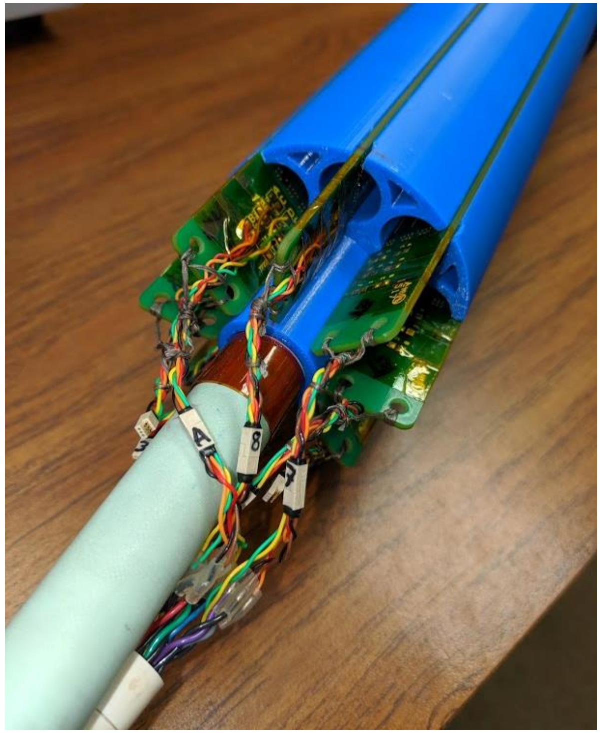
The composite rotation from the 8 vertices seems reasonably good, but haven't had time to explore this much further…

Summary and status

First measurements have been made with a 8 vertex PCB probe.

The effects of vibrations are quite clear and not always mitigated by bucking. The motion correction afforded by the 8v probe seems to reduce the spread among individual vertices, but further tests have to make sure systematic error is not added. A simple averaging of the multiple vertices also seems to give results close to low-vibration measurements.

Further testing in various magnets and vibration conditions will continue, as well as analysis of the high-speed composite rotations…



Thanks for your attention!