# Cβ Halbach Magnet QF and BD Prototypes: Unshimmed Results

From the BNL rotating coil

Thanks to: John Cintorino, Animesh Jain, George Mahler

# Magnets BD#2 and BD#3

# Magnet QF#1

# Design Development

- 3D printed plastic put inside Al tube to prevent warpage (only use plastic for "difficult" shapes)
- Blocks are self-supporting once all 16 are jammed in place
  - Inner metal parts were made for safety but turns out are not needed
  - We will put shim holders there instead

# Unshimmed BD#2,3 Harmonics

## C-beta Halbach type BD magnet #2 PMQ_0302 (1-Jun-2016)

Field harmonics are in "units" of $10^{-4}$ of the *quadrupole field* at a reference radius of 10 mm.

| Quantity | PMQ_0302 Run 2 (1-Jun-2016) | PMQ_0303 Run 1 (1-Jun-2016) |
|---|---|---|
| Integrated Gradient (T) | -1.1825 | -1.1806 |
| Normal Dipole | 19704.4 | 19704.3 |
| Normal Quadrupole | -10000.0 | -10000.0 |
| Normal Sextupole | 14.8 | 17.5 |
| Normal Octupole | 11.2 | 5.6 |
| Normal Decapole | 0.5 | -0.6 |
| Normal Dodecapole | -1.6 | 0.0 |
| Normal 14-pole | 0.1 | -0.1 |
| Normal 16-pole | 0.0 | 0.0 |
| Normal 18-pole | 0.0 | 0.0 |
| Normal 20-pole | 0.0 | 0.0 |
| Normal 22-pole | 0.0 | 0.0 |
| Normal 24-pole | 0.0 | 0.0 |
| Normal 26-pole | 0.0 | 0.0 |
| Normal 28-pole | 0.0 | 0.0 |
| Normal 30-pole | 0.0 | 0.0 |

| Quantity | PMQ_0302 Run 2 (1-Jun-2016) | PMQ_0303 Run 1 (1-Jun-2016) |
|---|---|---|
| Integ. Dipole (T.m) | 0.023299 | 0.023264 |
| Skew Dipole | 0.00 | -0.04 |
| Skew Quadrupole | 0.00 | 0.04 |
| Skew Sextupole | 6.32 | 6.60 |
| Skew Octupole | -9.95 | -11.26 |
| Skew Decapole | 3.43 | 1.38 |
| Skew Dodecapole | -0.02 | 0.00 |
| Skew 14-pole | 0.16 | -0.23 |
| Skew 16-pole | 0.03 | 0.03 |
| Skew 18-pole | -0.02 | 0.02 |
| Skew 20-pole | 0.01 | 0.00 |
| Skew 22-pole | 0.00 | 0.00 |
| Skew 24-pole | 0.00 | 0.00 |
| Skew 26-pole | 0.00 | 0.00 |
| Skew 28-pole | 0.00 | 0.00 |
| Skew 30-pole | 0.00 | 0.00 |

# Unshimmed QF#1 Harmonics

**C-beta Halbach type QF magnet #1 PMQ_0501 (2-Jun-2016)**

Field harmonics are in "units" of $10^{-4}$ of the quadrupole field

***Reference radius used is 25 mm*** ←

| Quantity | 2-Jun-2016 PMQ_0501 Run 2 |
|---|---|
| Integrated Gradient (T) | 1.3579 |
| Normal Dipole | -- |
| Normal Quadrupole | 10000.0 |
| Normal Sextupole | -6.9 |
| Normal Octupole | 12.5 |
| Normal Decapole | -1.7 |
| Normal Dodecapole | -2.6 |
| Normal 14-pole | 2.1 |
| Normal 16-pole | -5.6 |
| Normal 18-pole | -3.5 |
| Normal 20-pole | 0.5 |
| Normal 22-pole | 1.0 |
| Normal 24-pole | 0.3 |
| Normal 26-pole | 0.2 |
| Normal 28-pole | 0.0 |
| Normal 30-pole | -0.1 |

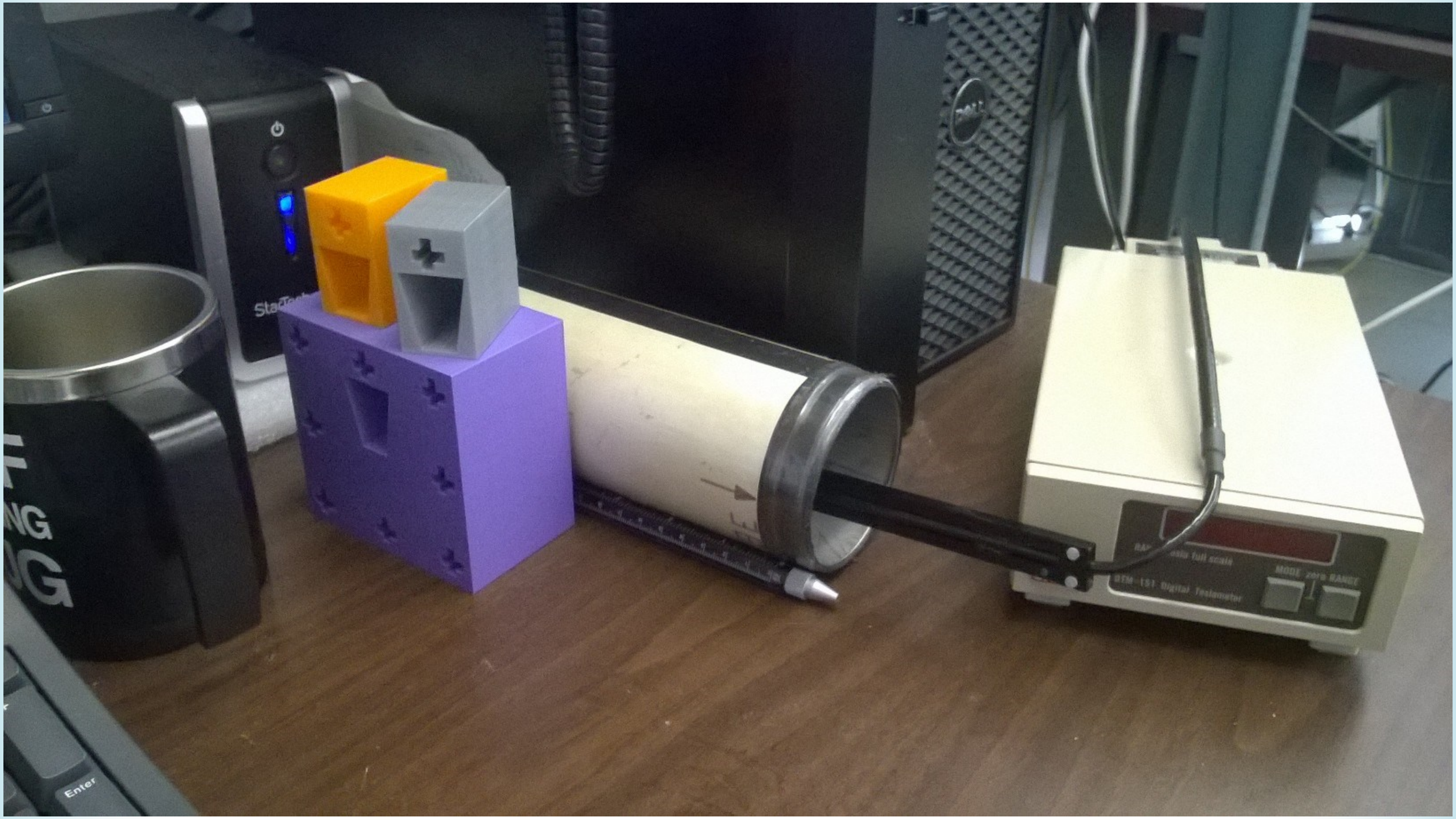
| Quantity | 2-Jun-2016 PMQ_0501 Run 2 |
|---|---|
| Field anlge (mr) | -- |
| Skew Dipole | -- |
| Skew Quadrupole | -- |
| Skew Sextupole | 12.66 |
| Skew Octupole | 21.22 |
| Skew Decapole | -15.00 |
| Skew Dodecapole | 19.33 |
| Skew 14-pole | 10.01 |
| Skew 16-pole | -2.51 |
| Skew 18-pole | 4.07 |
| Skew 20-pole | 1.12 |
| Skew 22-pole | 2.05 |
| Skew 24-pole | -0.95 |
| Skew 26-pole | 0.43 |
| Skew 28-pole | 0.29 |
| Skew 30-pole | -0.10 |

# Field Strength vs. Spec

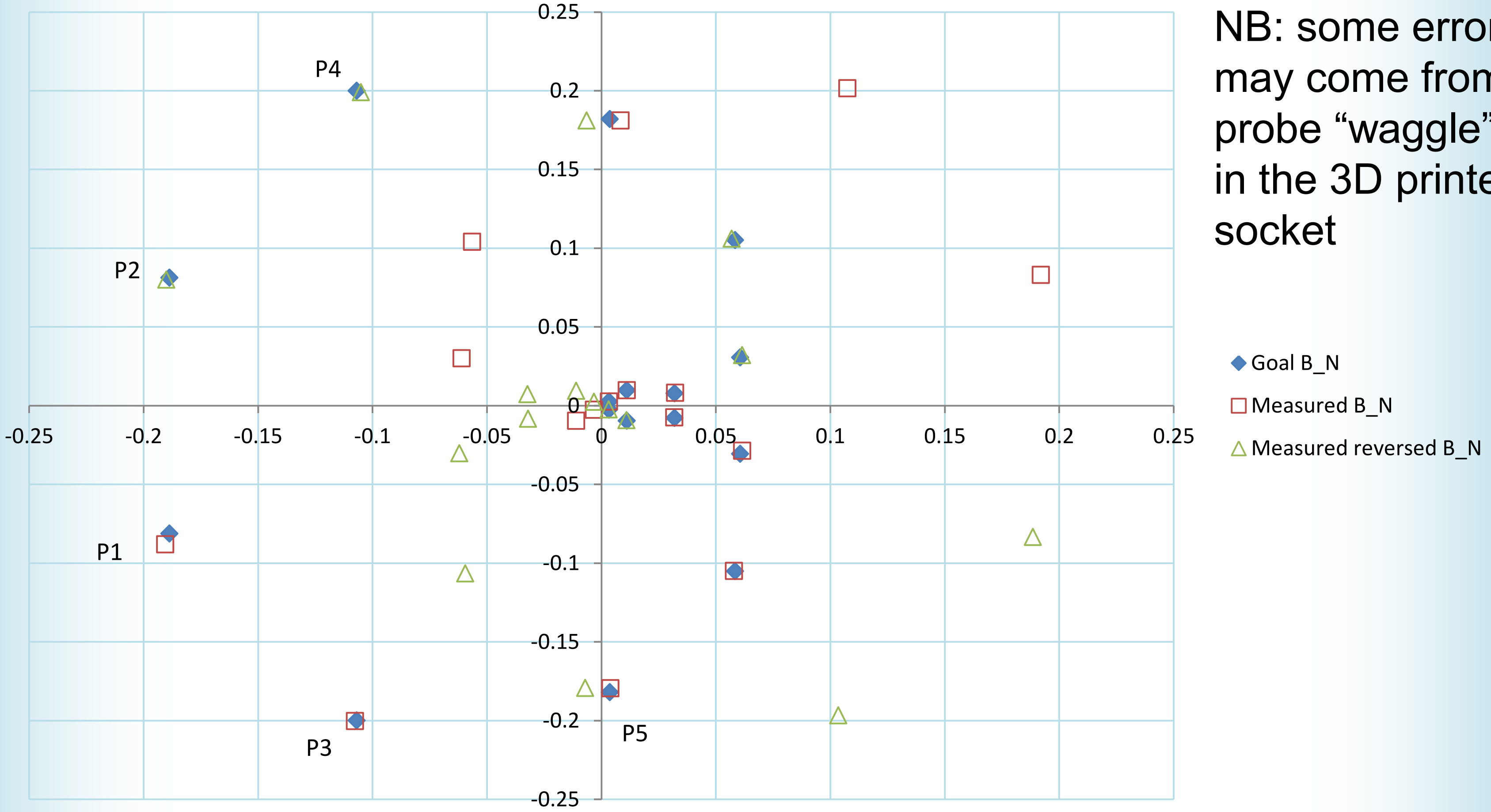
| Magnet | Length (nominal) | Integral Dipole | Integral Quad | Average Dipole | Average Quad | Spec. Dipole | Spec. Quad | Dipole error | Quad error |
|---|---|---|---|---|---|---|---|---|---|
| BD2 | 0.06186 | 0.023299 | -1.18245 | 0.37665 | -19.115 | -0.37679 | 19.11912 | -0.036% | -0.021% |
| BD3 | 0.06186 | 0.023264 | -1.18063 | 0.37607 | -19.0857 | -0.37679 | 19.11912 | -0.190% | -0.175% |
| QF1 | 0.057441 | | 1.357912 | | 23.64004 | | -23.6236 | | 0.069% |

- Note the sign error
  - Yes, I did put the Hall probe in the wrong way around when I tested the blocks
    - Some blocks were labelled at the wrong end, some labels were swapped, so had to test to get orientation
- Fortunately can flip magnets end-over-end

# XY Point Field Test Equipment

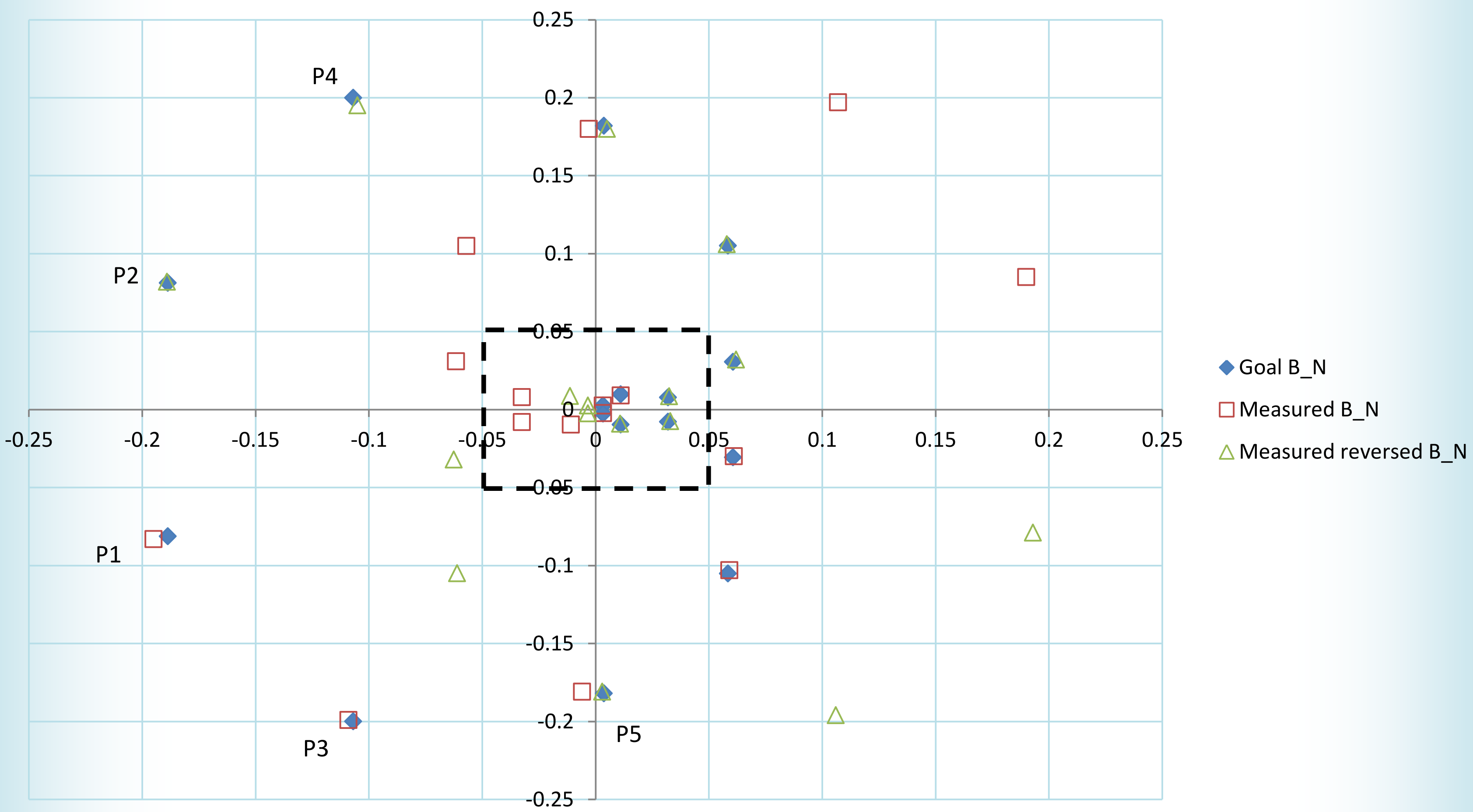


# BD#2 Point Fields vs. PM2D Model

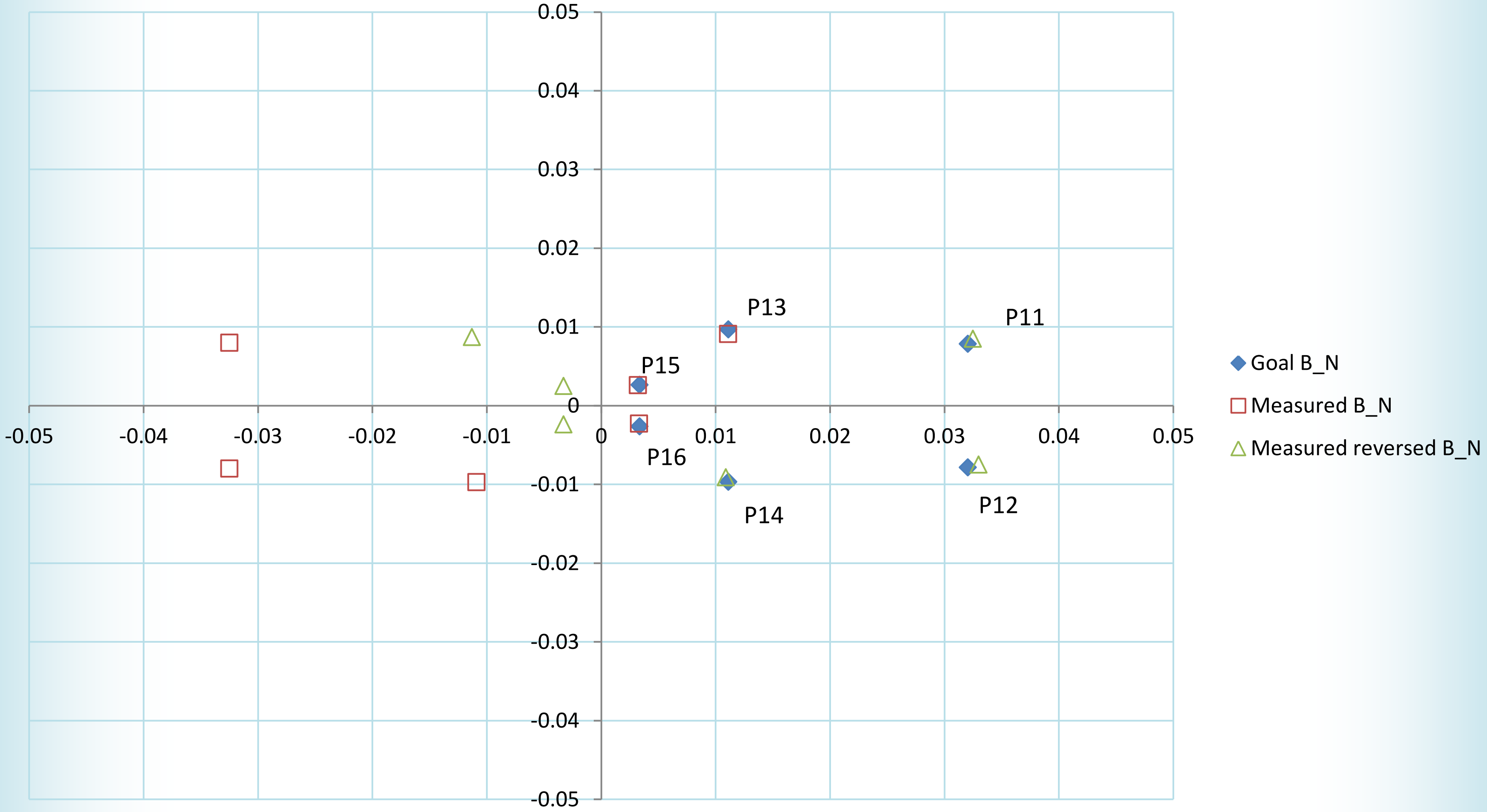



NB: some error may come from probe “waggle” in the 3D printed socket

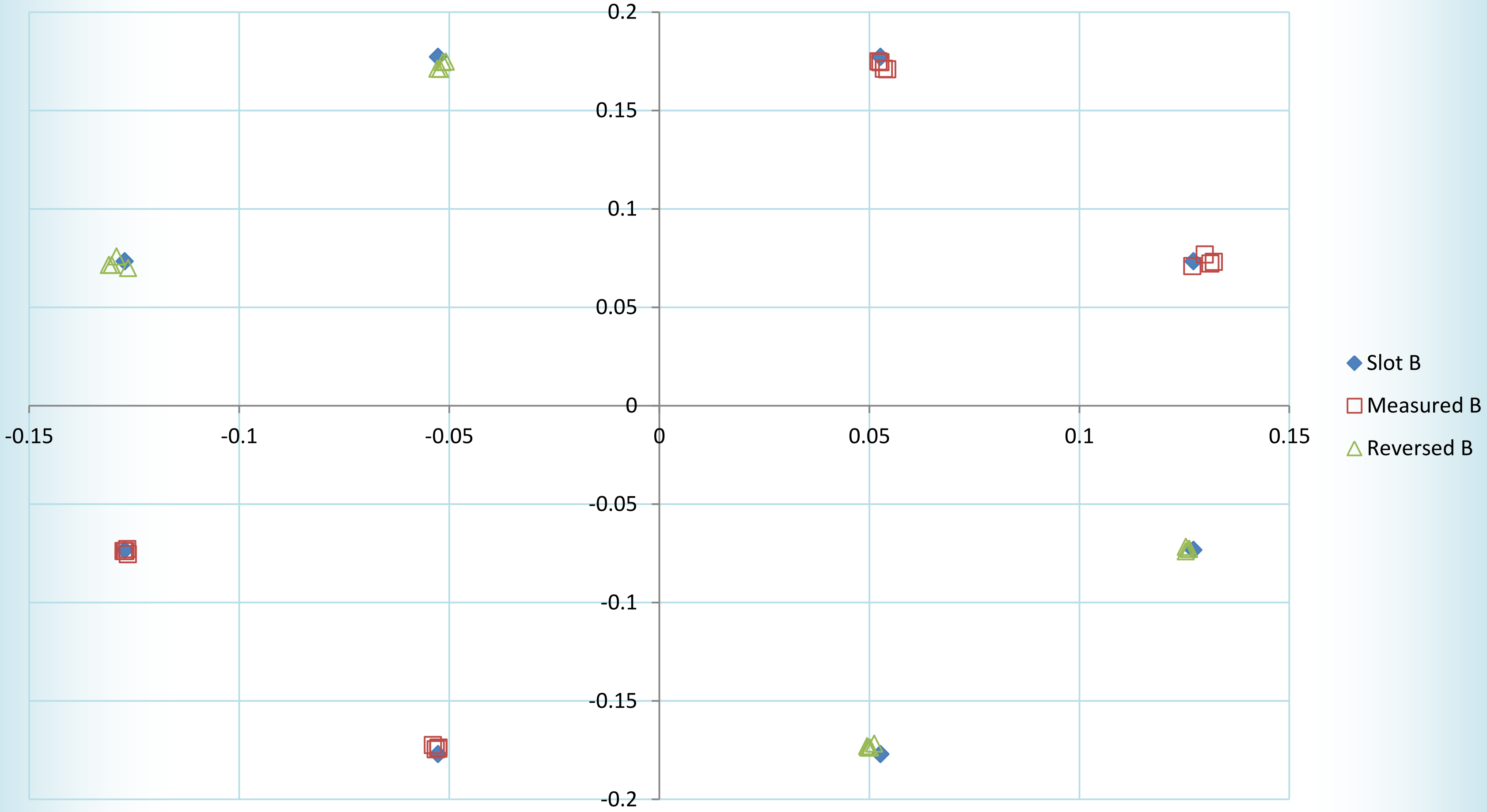
# BD#3 Point Fields vs. PM2D Model



# BD#3 Point Fields Zoom



# QF#1 Point Fields vs. PM2D Model



# Higher Harmonic Figure of Merit

- Quadrature sum of units (normal and skew) from sextupole up (10000 units = main quad)

$$\sqrt{\sum_{n=3}^{15} a_n^2 + b_n^2}$$

- Depends on reference radius
  - Small radius: sextupole is dominant
  - Large radius: higher order pole contributions increase rapidly

# All Unshimmed Figures of Merit

| Series | Magnet | Material | Bore radius | FOM with R = 10mm | 20mm | 25mm | FOM at R = 53% bore | 53% bore = |
|---|---|---|---|---|---|---|---|---|
| Cbeta Halbach prototypes | BD2 | NdFeB | 30.70mm | 22.29 | 78.56 | 203.39 | 51.00 | 16.27mm |
| | BD3 | NdFeB | 30.70mm | 22.60 | 65.14 | 170.63 | 45.69 | 16.27mm |
| | QF1 | NdFeB | 37.20mm | 7.08 | 22.82 | 40.04 | 22.12 | 19.72mm |
| eRHIC Halbach shim-test quad | 5A | SmCo | 22.52mm | 29.61* | 529.80(??) | N/A | 39.90* | 11.94mm |
| Cbeta iron-poled prototype | Qd | NdFeB+Fe | 23.00mm | 16.55 | 60.27 | N/A | 21.87 | 12.19mm |

Red = extrapolated beyond coil radius, less accurate

Blue = original coil measurement radius

* This magnet was successfully shimmed down to FOM 1.94 at R = 10mm, or 3.06 at R = 53% bore

# Conclusion

- The multipole content of Cbeta Halbach prototypes is similar to the shim test magnet
  - Can expect similar (good) shimming results
    - As described in previous talks, few e-4 level harmonics
  - BD is somewhat worse (2-3x) than QF
  - QF is roughly as good as Holger’s first iron Qd
    - Both being unshimmed first assemblies
- Strength errors are all <0.2%, well within corrector range