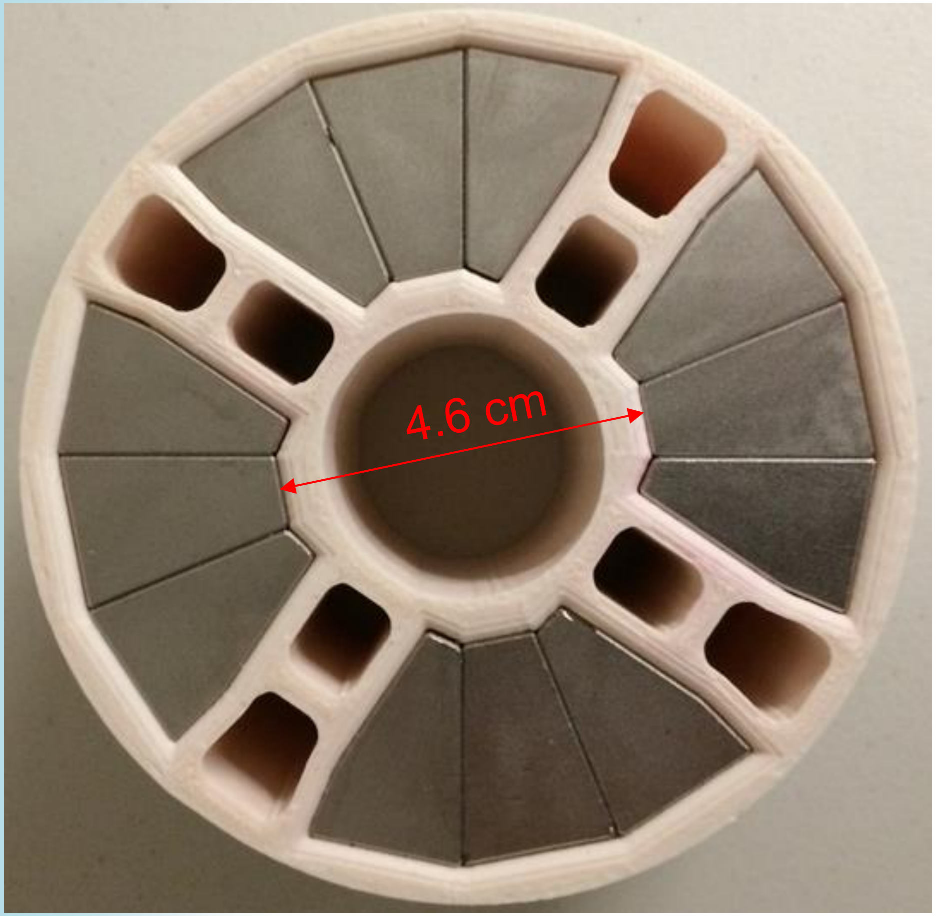
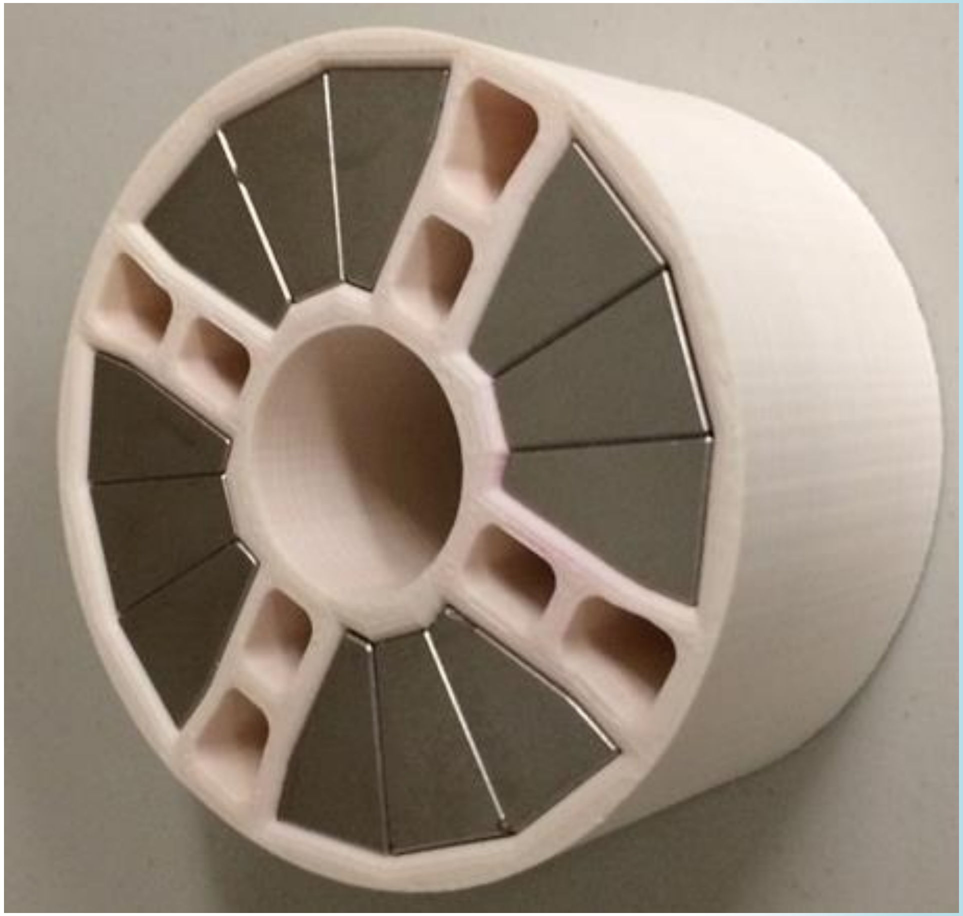
Correcting Permanent Magnets with Iron Wires

See my June 24, 2015 talk for background

First Magnet Prototype (x5 built)





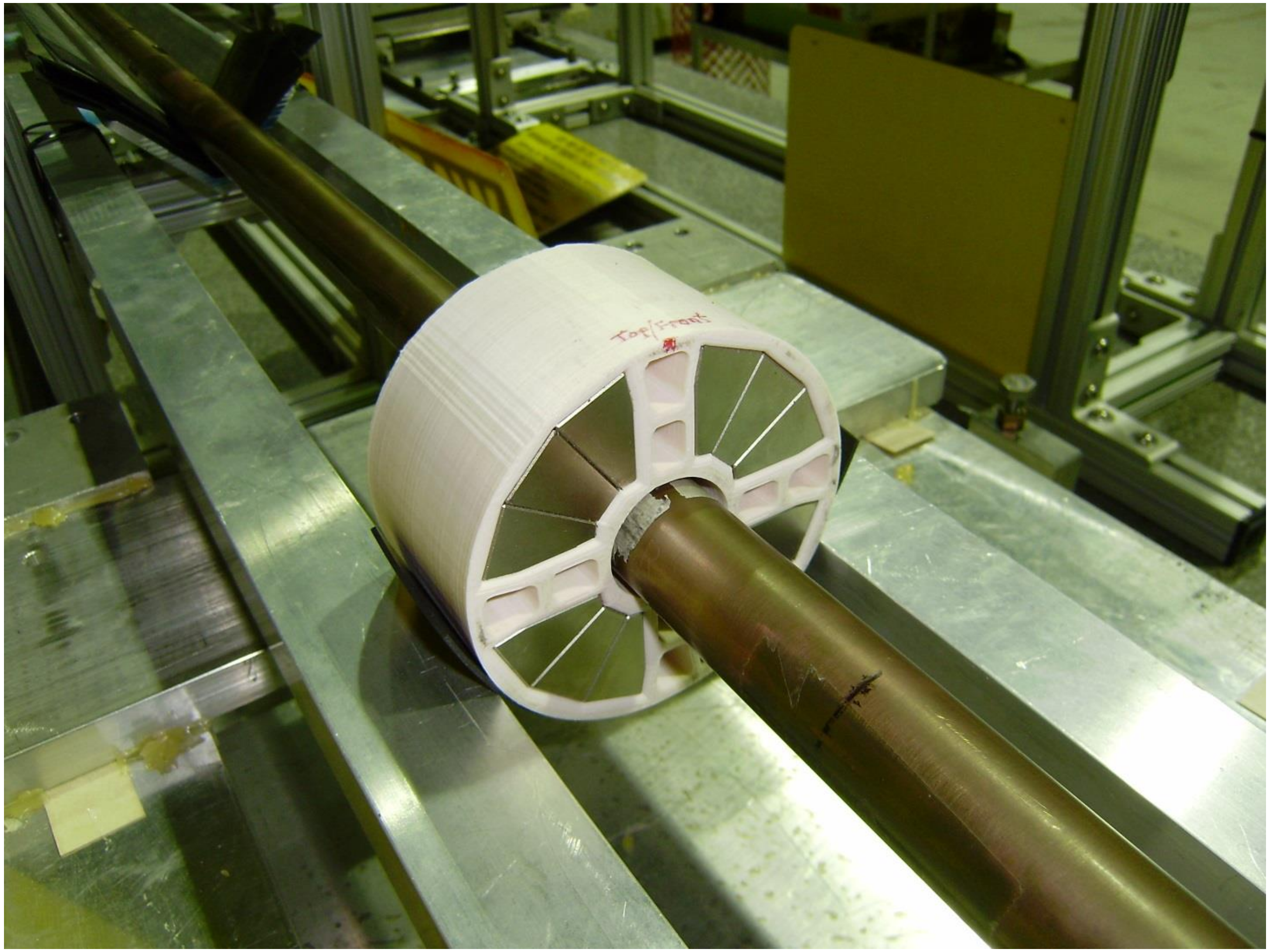
Recap…

First Magnet Prototype (x5 built)

- One of 3 options in the eRHIC magnet LDRD
  - Others were Wuzheng/iron poles and rectilinear
- Design by Nick Tsoupas, open midplane ±8mm
- Assembled by George Mahler with 3D printer
- Material SmCo N26HS provided by Shin-Etsu
  - Unfortunately blocks adjacent to the open midplanes had wrong magnetisation direction
    - But this was a known error so can be simulated
    - Produces primarily 12-pole

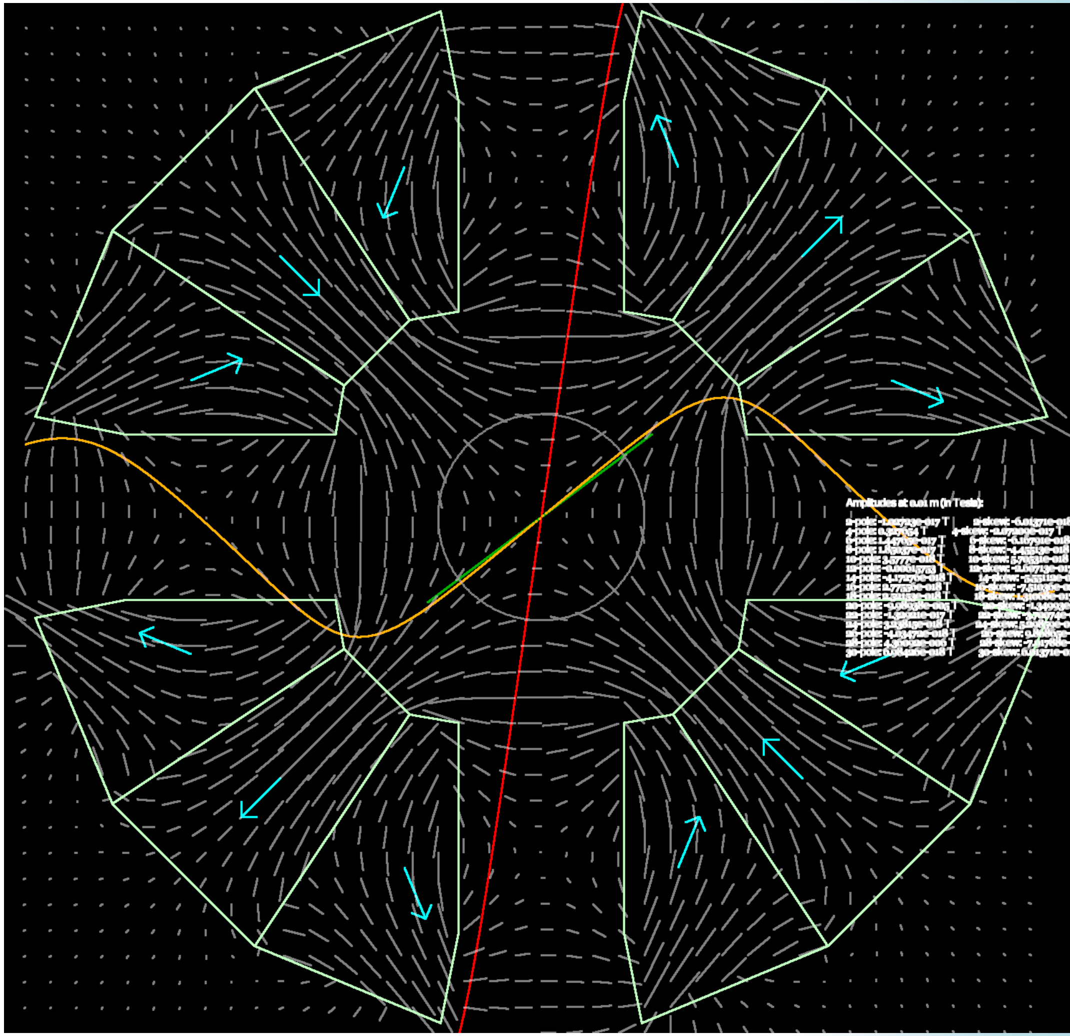
Recap…

Rotating Coil Measurement in Building 902 Annex by Animesh Jain



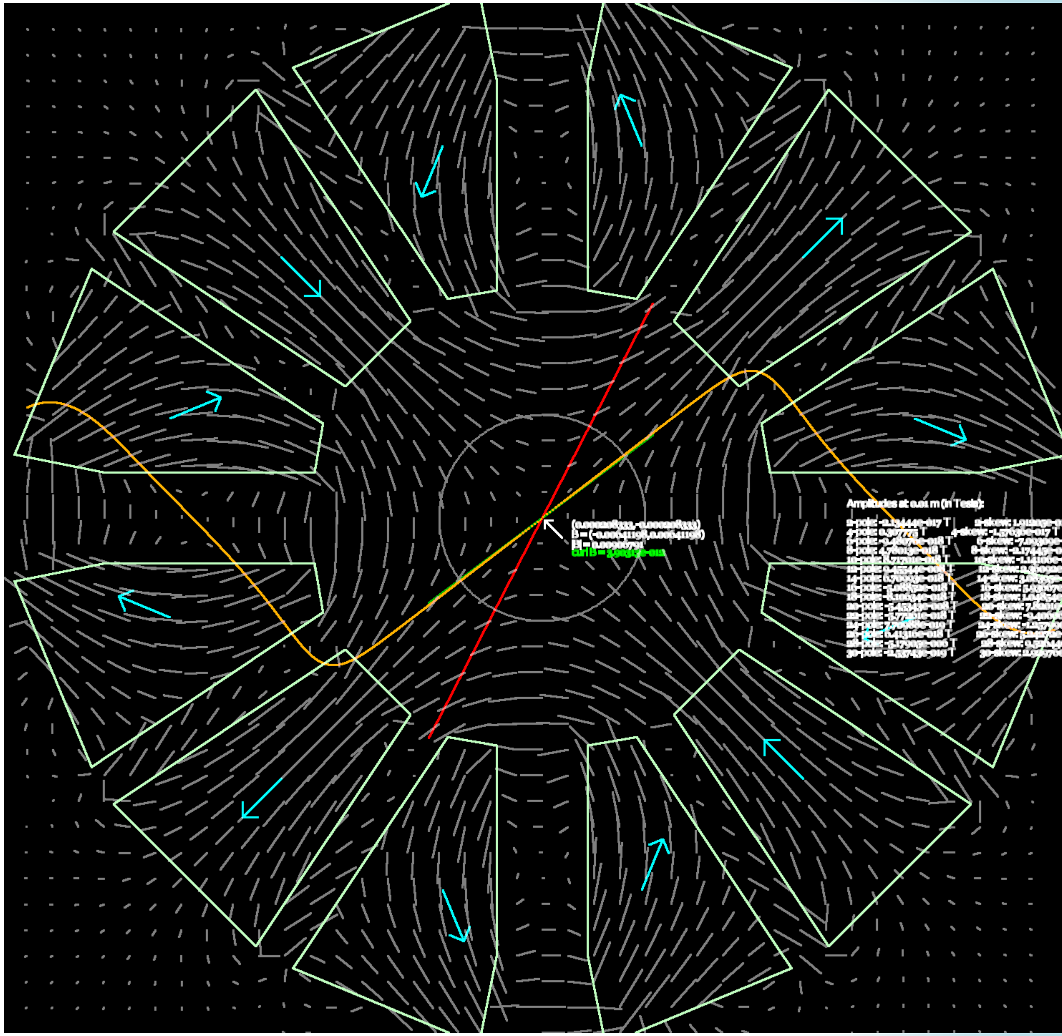
Stephen's PM2D Code

- Assumes fixed **M** vector in each block (1.07T here)
  - Equivalent surface currents
  - Biot-Savart law
- Assumes μ=1
  - Actually ~1.05



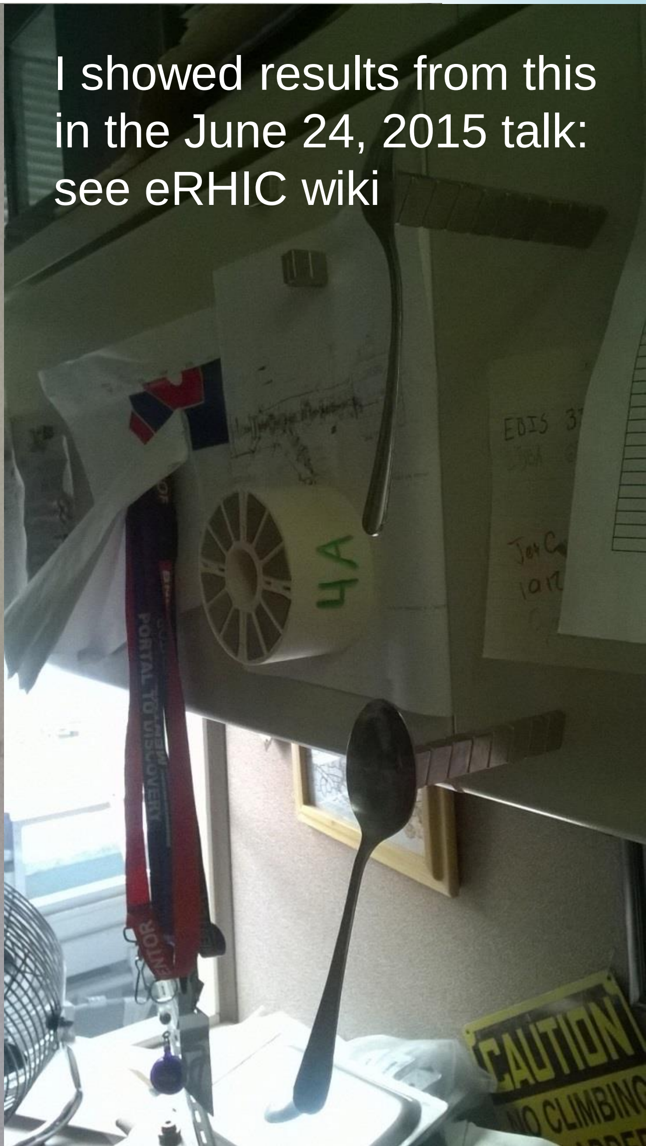
PM2D Suggests Displacements

- Nulls 12-pole and 20-pole in theory
- $\Delta x = -3.607$mm
- $\Delta y = 2.147$mm
- New magnet holders 3D printed
- Magnet 4, **5** blocks reused → “004A”, “**005A**” respectively



Recap…

Magnet PMQ_004A



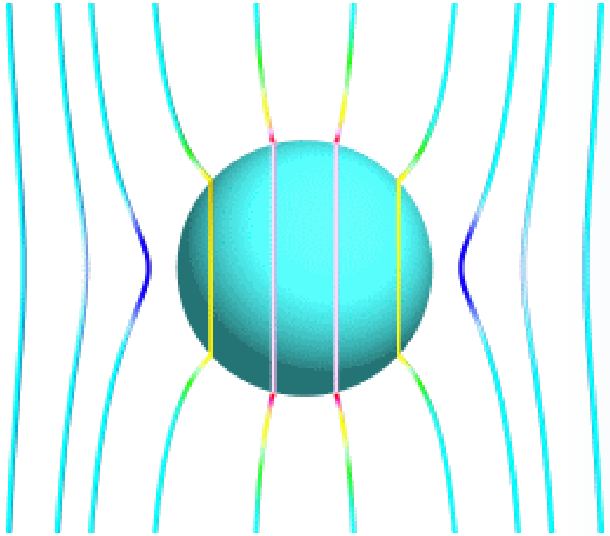
I showed results from this in the June 24, 2015 talk: see eRHIC wiki

Construction/Magnetisation Errors

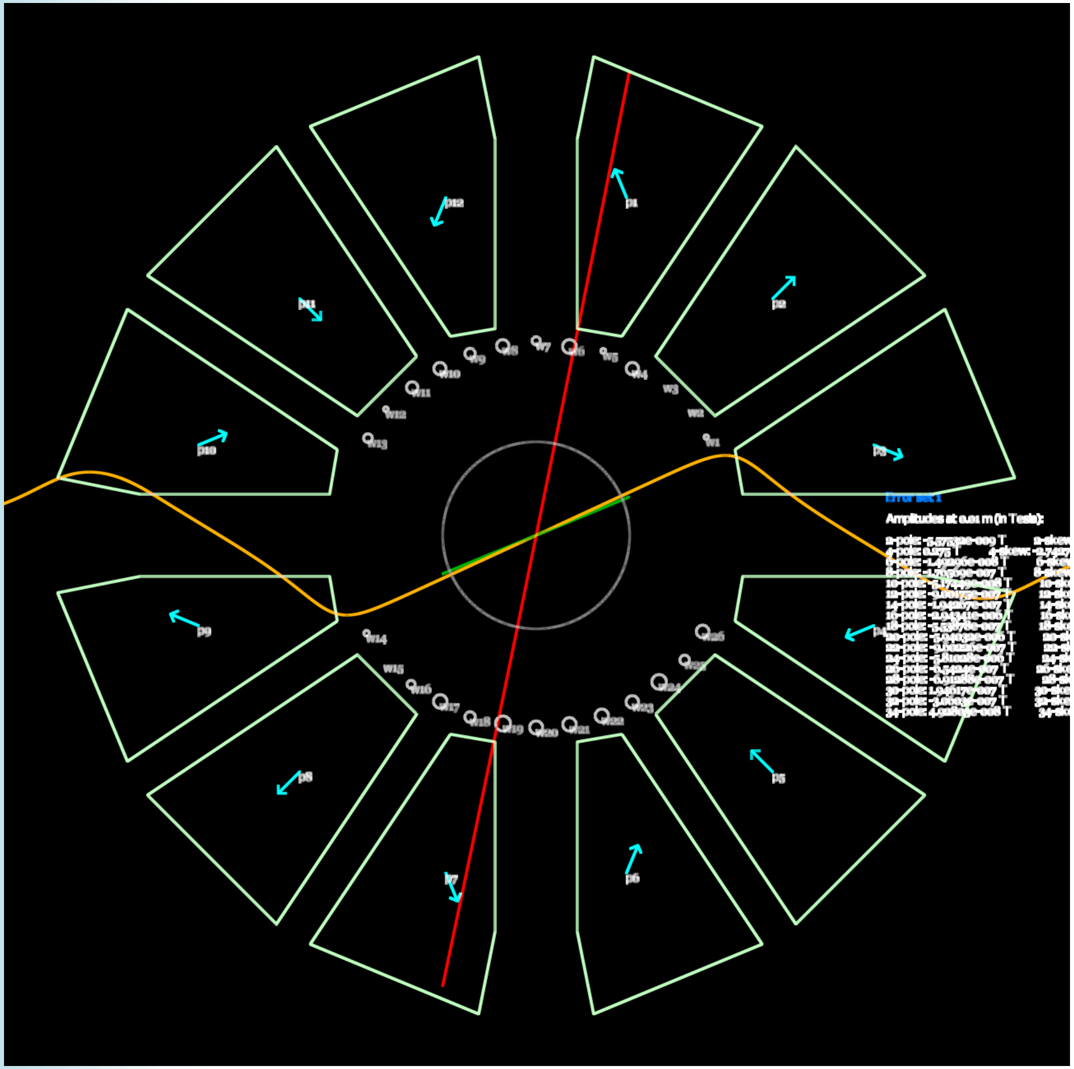
- As measured in the radiation test, magnetisation varies at 1e-2 level per block
- Also 3D printing construction errors
- Can feed the measured error poles back into PM2D and ask it to optimise a cancellation
  - This requires many (>20) variables
  - Typically requires only small adjustments because field error is only 1% of entire field

Iron Wire Field Model (2D)

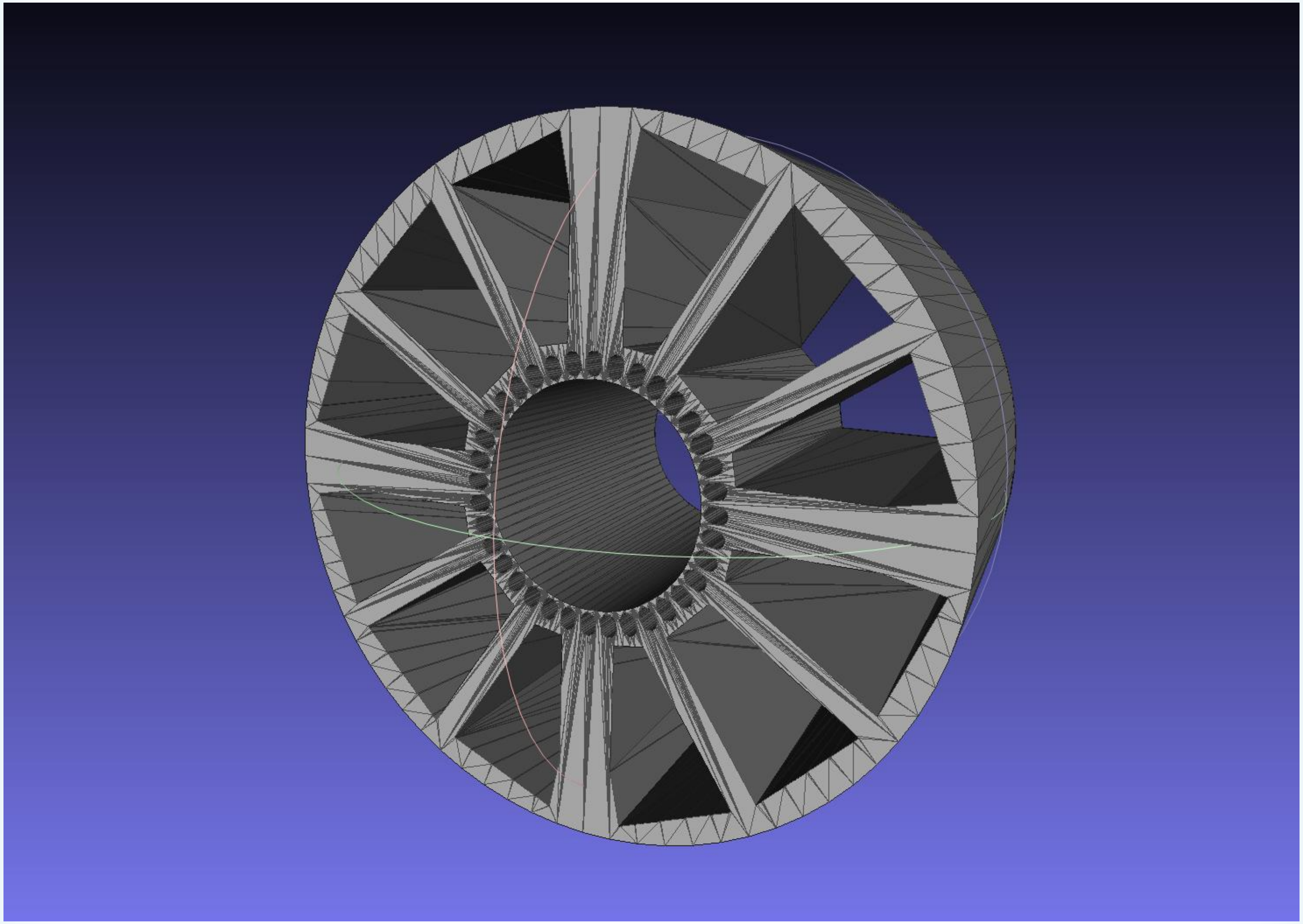
- $\mu=\infty$ iron cylinder in a uniform magnetic field
- Magnetisation equal to external field **M**=**B**
  - Uniform magnetisation, actually produces same internal and external field as a "cos θ" SC dipole
  - External field is a perfect dipole magnetic source added to background field
    - Strength ∝ Area*|B|



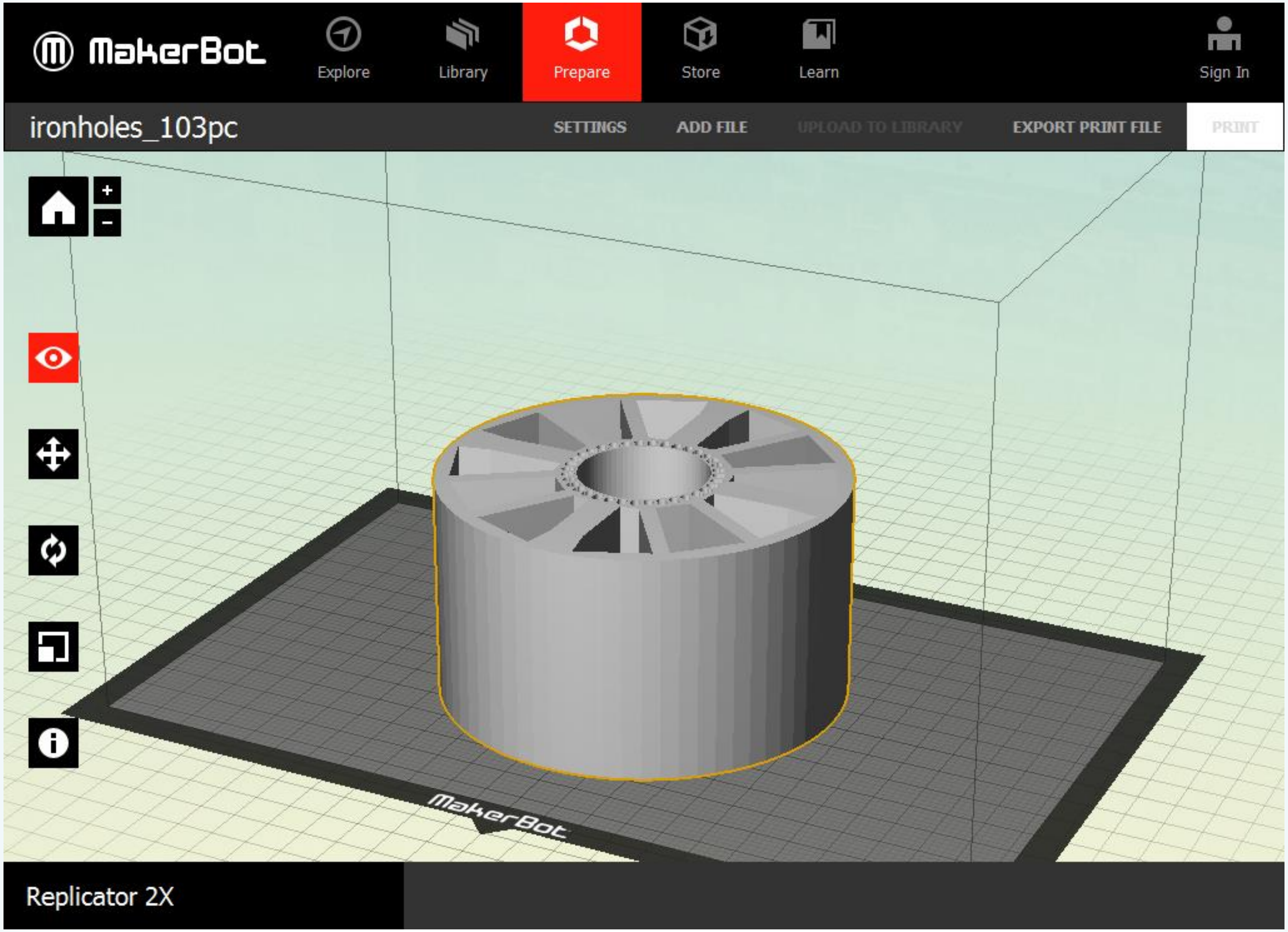
Iron Wires Correction in PM2D



.STL Mesh Generated by PM2D



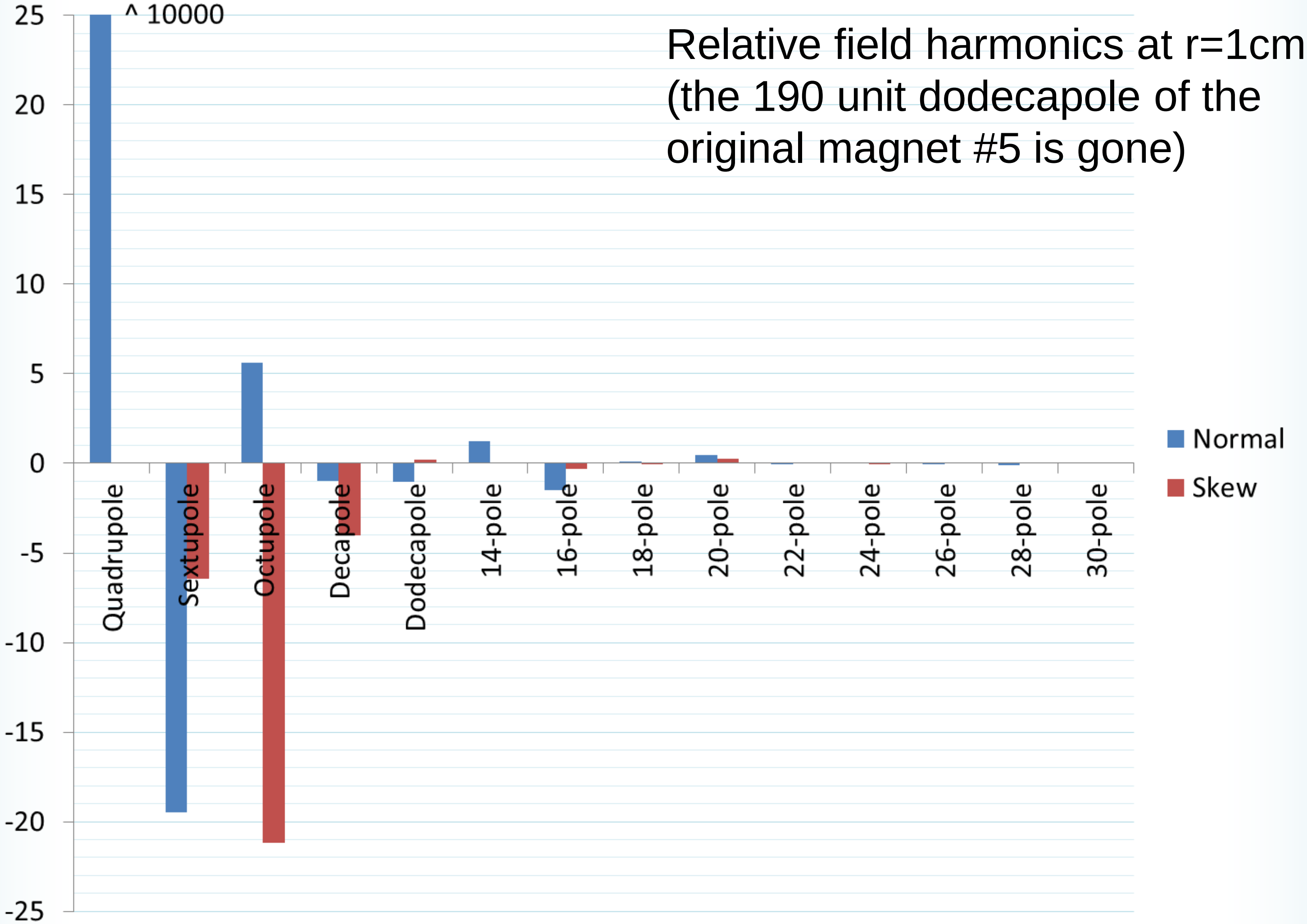
Loads into 3D Printer Software



Magnet PMQ_005A

Cross-sectional areas:
0.099 mm^2
0.268 mm^2
0.852 mm^2

Measurement of 5A Without Shims

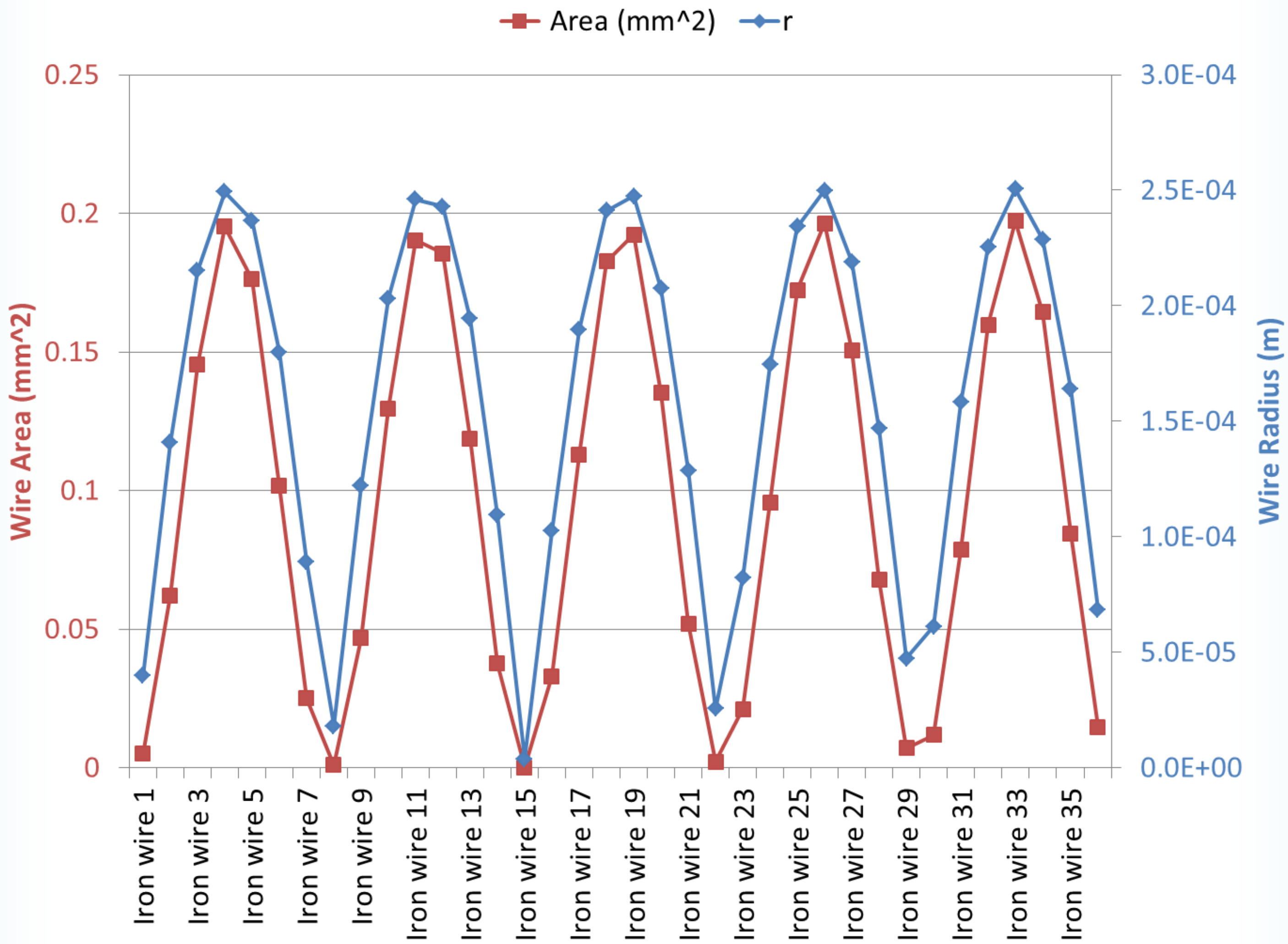


Relative field harmonics at r=1cm (the 190 unit dodecapole of the original magnet #5 is gone)

First Test: Sextupole Cancellation

- In an ambient quadrupole field, a sextupole can be produced by iron distributed as cos 5θ around the aperture (actually $1 + \cos(5\theta + \phi)$)
- In general, iron area ~ cos $(n+m)\theta$ where:
  - n = ambient field order, 2 for quadrupole
  - m = generated field order, 3 for sextupole
- cos 2θ, cos θ and 1 do nothing!
- cos 4θ can tune the quad strength up or down

Area of Iron Required



Wires Inserted

Block name	Area (mm^2)	Wires required
Iron wire 1	0.00496357	0.0499782x14mil (L=2.99869mm)
Iron wire 2	0.062105144	0.625337x14mil (L=37.5202mm)
Iron wire 3	0.145364964	1x14mil 0.463681x14mil (L=27.8208mm)
Iron wire 4	0.19526015	1x14mil 0.966076x14mil (L=57.9645mm)
Iron wire 5	0.176144346	1x14mil 0.773599x14mil (L=46.4159mm)
Iron wire 6	0.101674355	1x14mil 0.0237597x14mil (L=1.42558mm)
Iron wire 7	0.025053385	0.252263x14mil (L=15.1358mm)
Iron wire 8	0.001021355	0.010284x14mil (L=0.617042mm)
Iron wire 9	0.046747343	0.470699x14mil (L=28.242mm)
Iron wire 10	0.12956357	1x14mil 0.304576x14mil (L=18.2746mm)
Iron wire 11	0.190304071	1x14mil 0.916173x14mil (L=54.9704mm)
Iron wire 12	0.185574328	1x14mil 0.868549x14mil (L=52.1129mm)
Iron wire 13	0.118753385	1x14mil 0.195729x14mil (L=11.7437mm)
Iron wire 14	0.03757978	0.378391x14mil (L=22.7035mm)
Iron wire 15	4.59488E-05	0.000462659x14mil (L=0.0277595mm)
Iron wire 16	0.032966989	0.331945x14mil (L=19.9167mm)
Iron wire 17	0.112823295	1x14mil 0.136018x14mil (L=8.16111mm)
Iron wire 18	0.182563542	1x14mil 0.838233x14mil (L=50.294mm)
Iron wire 19	0.19236357	1x14mil 0.93691x14mil (L=56.2146mm)
Iron wire 20	0.135221996	1x14mil 0.361551x14mil (L=21.6931mm)
Iron wire 21	0.051962176	0.523207x14mil (L=31.3924mm)
Iron wire 22	0.002066989	0.0208125x14mil (L=1.24875mm)
Iron wire 23	0.021182794	0.21329x14mil (L=12.7974mm)
Iron wire 24	0.095652784	0.963128x14mil (L=57.7877mm)
Iron wire 25	0.172273755	1x14mil 0.734626x14mil (L=44.0775mm)
Iron wire 26	0.196305785	1x14mil 0.976604x14mil (L=58.5963mm)
Iron wire 27	0.150579797	1x14mil 0.516189x14mil (L=30.9713mm)
Iron wire 28	0.06776357	0.682312x14mil (L=40.9387mm)
Iron wire 29	0.007023068	0.0707153x14mil (L=4.24292mm)
Iron wire 30	0.011752812	0.118339x14mil (L=7.10035mm)
Iron wire 31	0.078573755	0.79116x14mil (L=47.4696mm)
Iron wire 32	0.159747359	1x14mil 0.608497x14mil (L=36.5098mm)
Iron wire 33	0.197281191	1x14mil 0.986426x14mil (L=59.1855mm)
Iron wire 34	0.16436015	1x14mil 0.654943x14mil (L=39.2966mm)
Iron wire 35	0.084503845	0.85087x14mil (L=51.0522mm)
Iron wire 36	0.014763598	0.148655x14mil (L=8.91929mm)

eRHIC Permanent Magnet Quadrupoles PMQ_0005 & PMQ_005A (10-Sep-2015)

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

Quantity	PMQ_0005 Run 2	PMQ_005A* Run 1_02(†)	PMQ_005A* Run 2(††)
Integrated Gradient (T)	1.9024	1.6501	1.6519
Normal Dipole	--	--	--
Normal Quadrupole	10000.00	10000.00	10000.00
Normal Sextupole	-11.95	**-19.46**	**-0.58**
Normal Octupole	3.61	5.61	5.21
Normal Decapole	3.86	-0.99	-0.84
Normal Dodecapole	**-190.26**	**-1.03**	-1.06
Normal 14-pole	1.03	1.25	1.04
Normal 16-pole	-1.31	-1.47	-1.52
Normal 18-pole	0.07	0.12	0.13
Normal 20-pole	**-2.91**	**0.44**	0.40
Normal 22-pole	-0.01	-0.03	-0.01
Normal 24-pole	0.04	0.05	0.03
Normal 26-pole	-0.02	-0.01	-0.01
Normal 28-pole	0.12	-0.12	-0.12
Normal 30-pole	0.00	0.00	0.00

Quantity	PMQ_0005 Run 2	PMQ_005A* Run 1_02(†)	PMQ_005A* Run 2(††)
Field Angle (mr)	--	--	--
Skew Dipole	--	--	--
Skew Quadrupole	--	--	--
Skew Sextupole	-5.28	**-6.42**	**-0.63**
Skew Octupole	-18.51	-21.20	-21.18
Skew Decapole	-8.52	-4.02	-4.23
Skew Dodecapole	**-4.96**	**0.22**	0.32
Skew 14-pole	0.85	0.07	-0.16
Skew 16-pole	-0.13	-0.31	-0.33
Skew 18-pole	0.10	-0.05	-0.06
Skew 20-pole	0.01	0.24	0.23
Skew 22-pole	0.00	0.00	0.01
Skew 24-pole	0.01	-0.01	-0.02
Skew 26-pole	0.01	0.00	0.01
Skew 28-pole	0.00	0.00	0.00
Skew 30-pole	0.00	0.00	0.00

*** PMQ_005A is magnet built from magnets taken from PMQ_0005 and installed in a modified holder to reduce 12-pole**

(†) ***Magnet was measured with the magnet rotated 90 deg. about its axis, and flipped end-for-end, as compared to PMQ_005 measurements. The data were transformed in post-processing to correspond to the old orientation.***

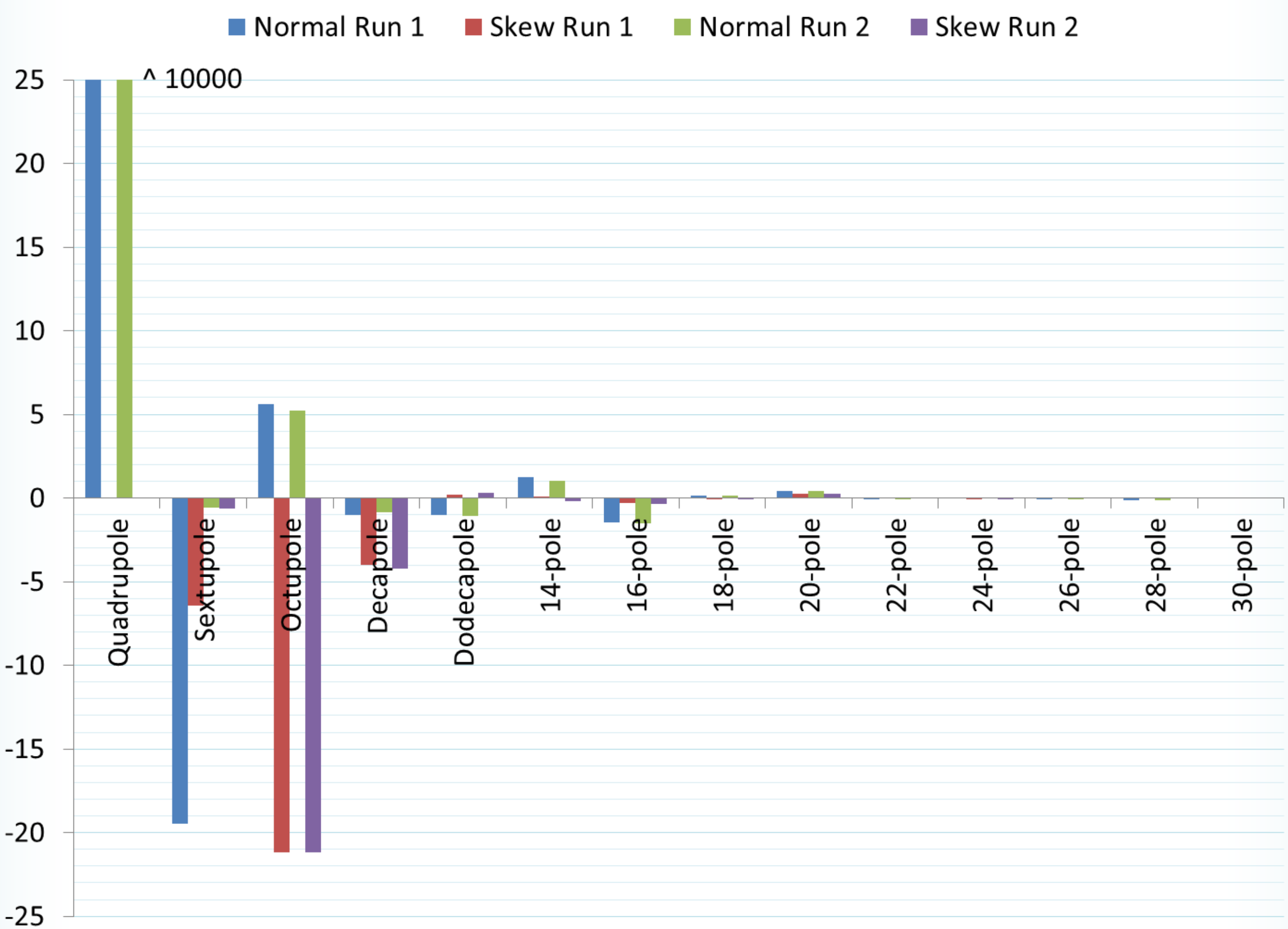
(††) **Run 2 is measurement in PMQ_005A with iron shims to reduce unallowed field harmonics.**

(Note: Magnet name used for tesing was ERHIC-PMQ_0105 to avoid non-numeric serial number).

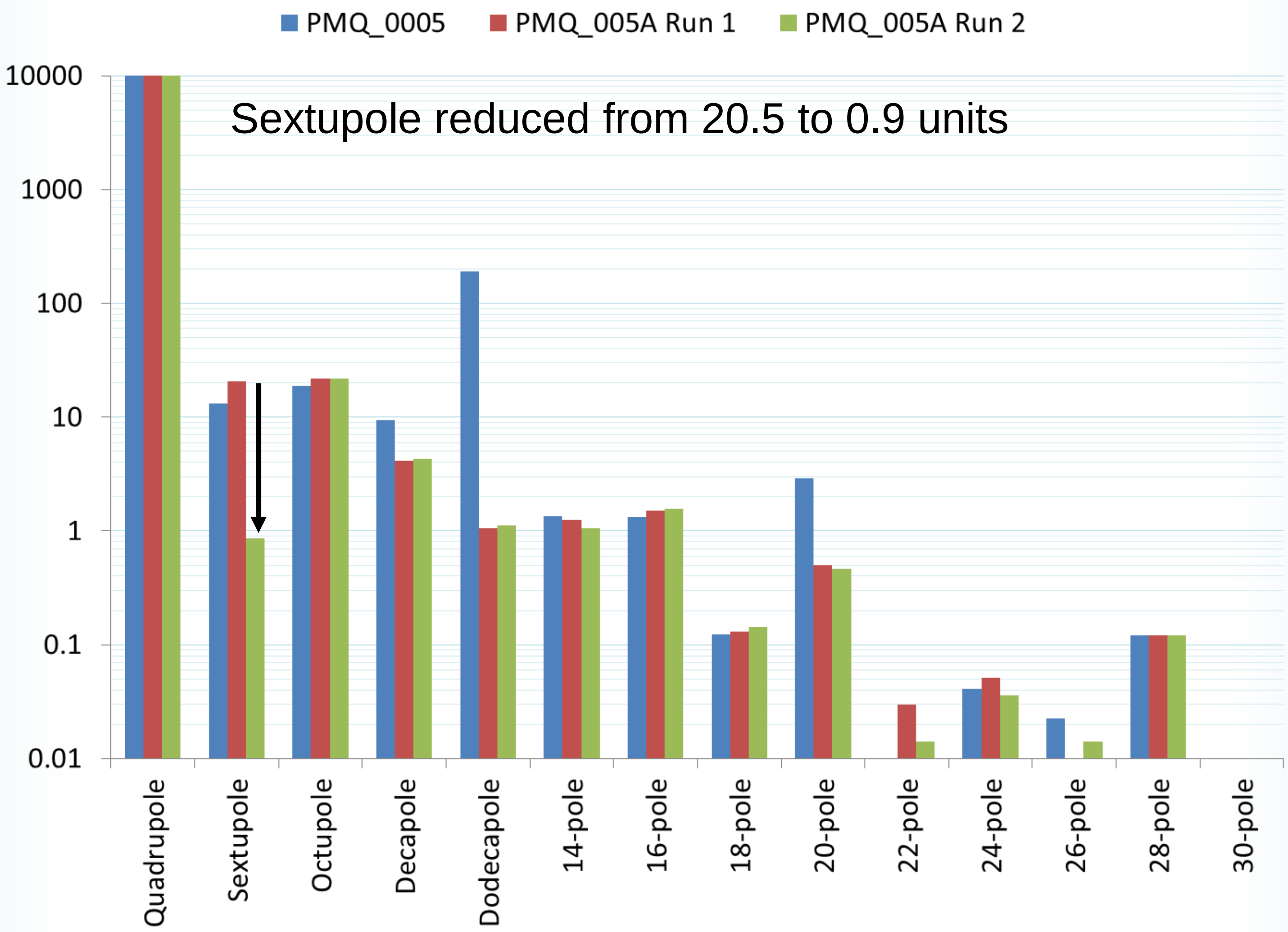
Results e-mail

- I didn't tell Animesh what pole I was trying to shim, so as not to bias his data processing that virtually realigns the magnet, removing dipole (translation) and skew quad (rotation)
  - Animesh: **"I am not sure which harmonics were targeted when working out the iron shims, but it is clear that the sextupole terms (both normal and skew) have been shimmed remarkably well. There is practically no change in any other harmonic although it would have been nice to see some reduction in the skew octupole term."**

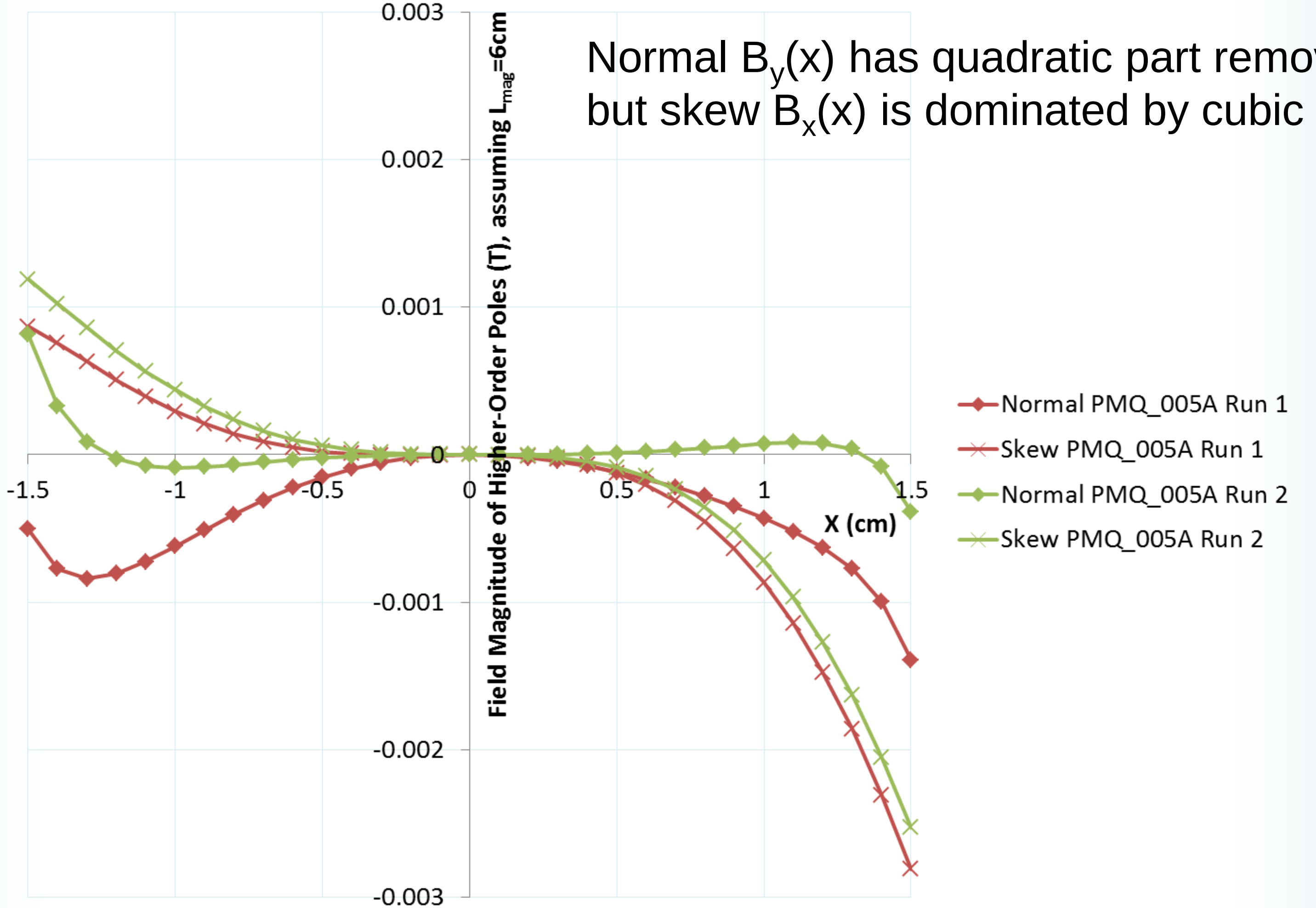
Relative Field Harmonics at r=1cm



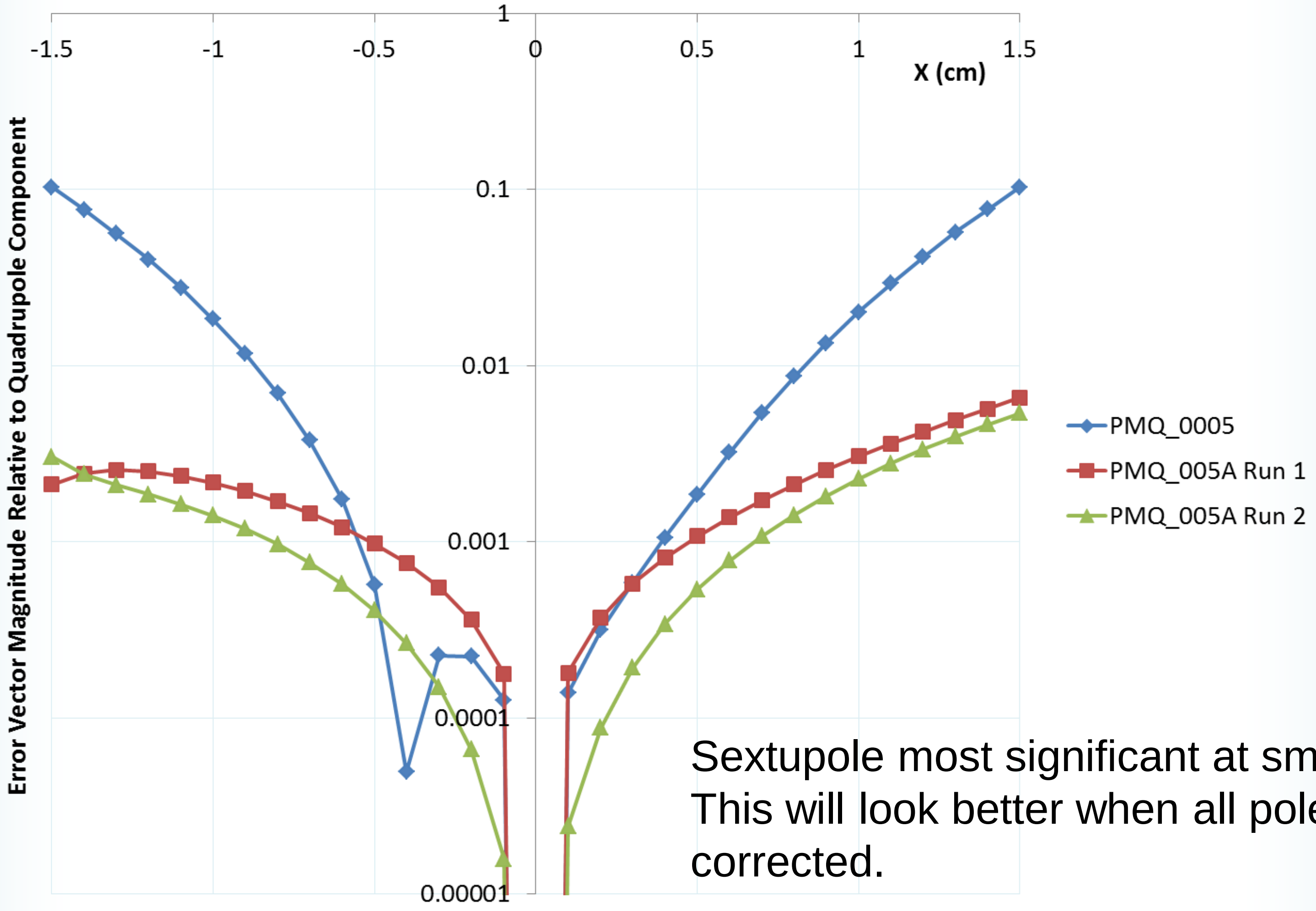
Pole Moduli at r=1cm



Field Profiles Along X Axis

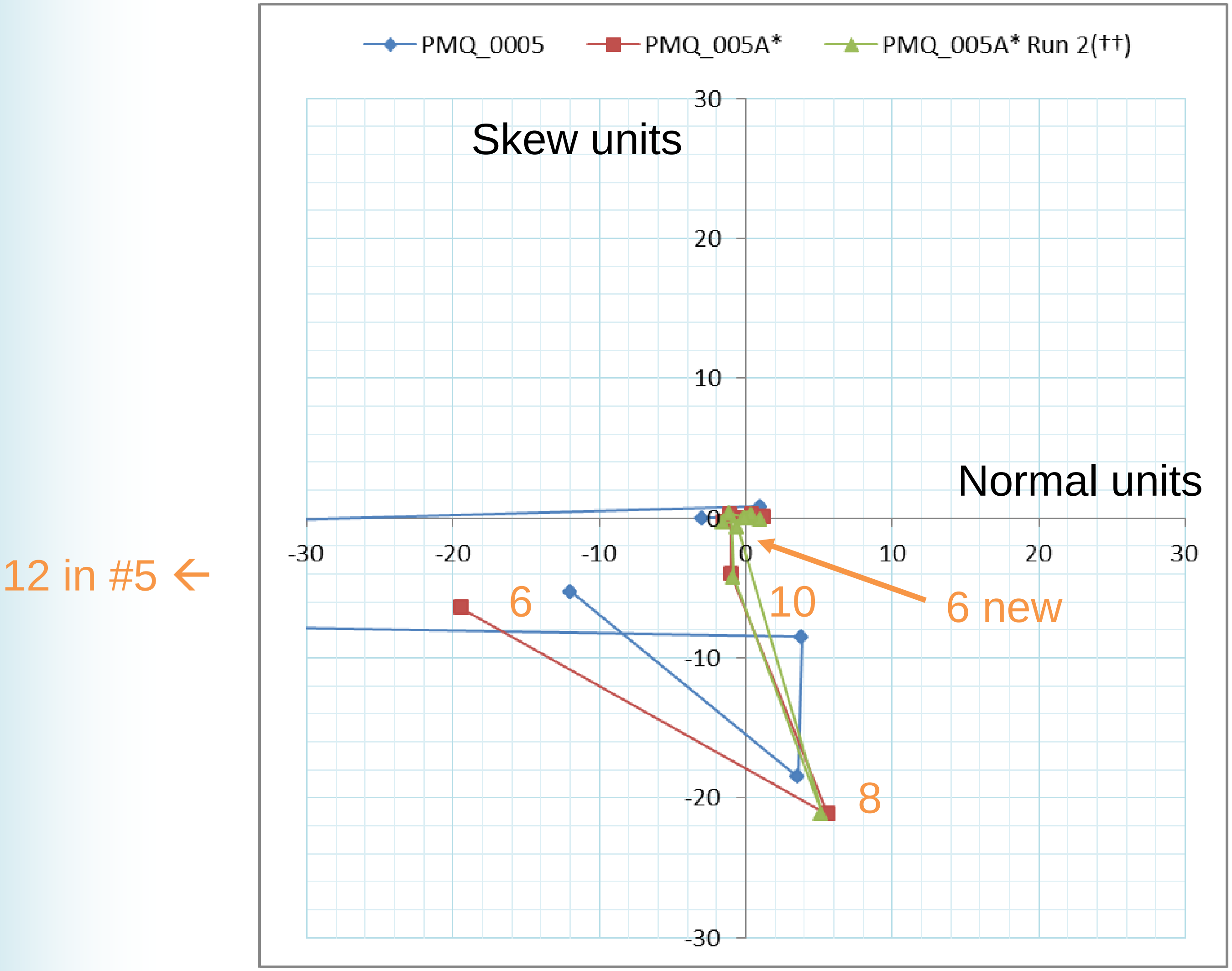


Relative Field Error on X Axis



Sextupole most significant at small x. This will look better when all poles are corrected.

Multipole Vectors



Future Work

- Next test will be cancelling all poles at once
  - Do not anticipate problems, but should do it
- Can also do second iteration to see if further improvement is possible
- Have found corrections with <u>open midplane</u> (not using the 5 wires to the left and right) although not quite as good according to PM2D
  - Should also test this
- Effect of iron shell around the outside

Conclusions for eRHIC

- If correction quality continues to be this good, "bare" PM designs are acceptable for eRHIC
- Construction and material costs are low
  - No tight tolerances or fussy material specs
  - Replace 3D print by extrusion for mass production
  - Steel wire costs virtually nothing
- Incurs 1 or 2 additional rotating coil measurements (we would do 1 anyway)
- Should be costed fully vs. iron poled magnet