Generalised Halbach Magnets for a Non-Scaling FFAG Arc

Thanks to:

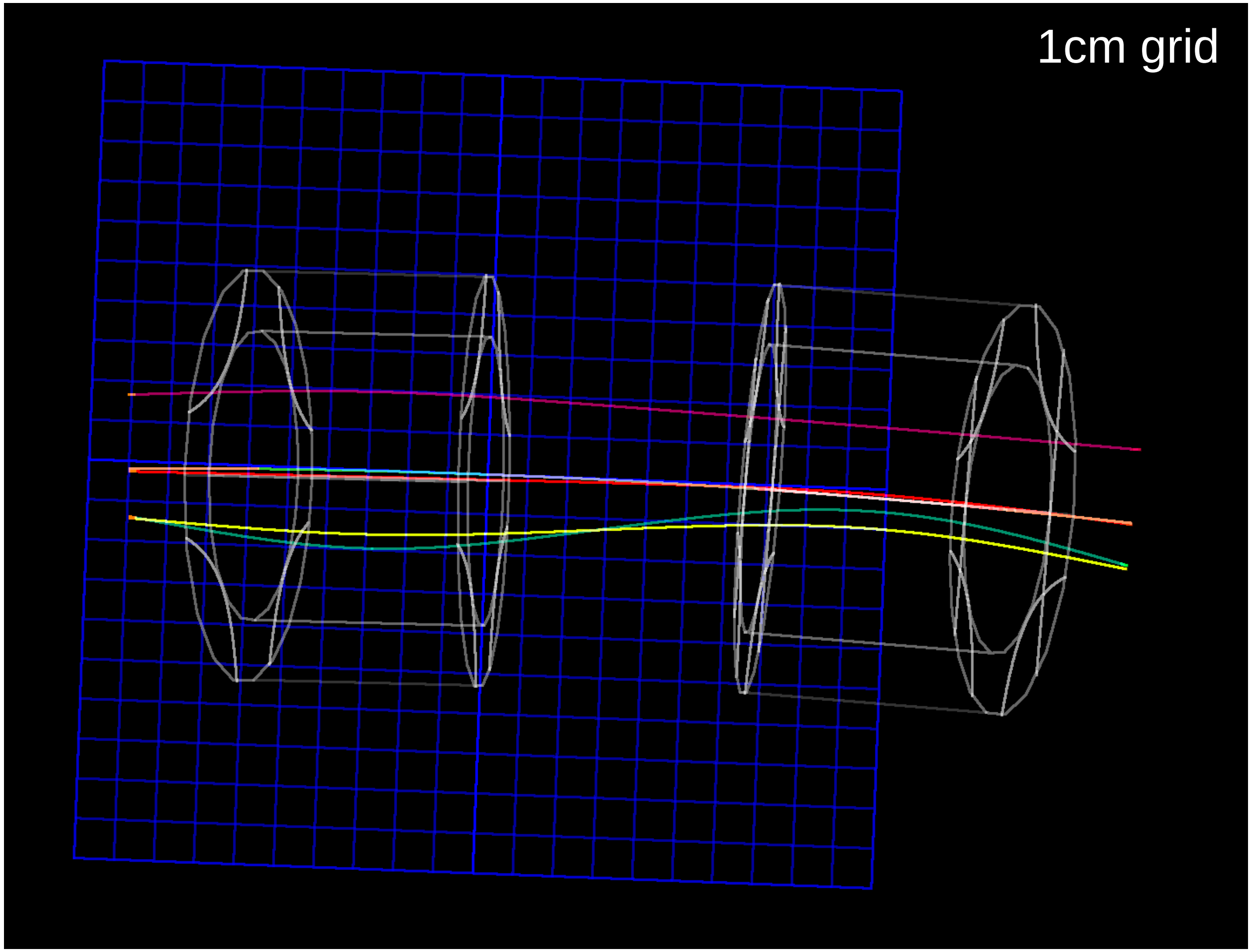
George Mahler – engineering

John Cintorino, Animesh Jain – magnet measurement

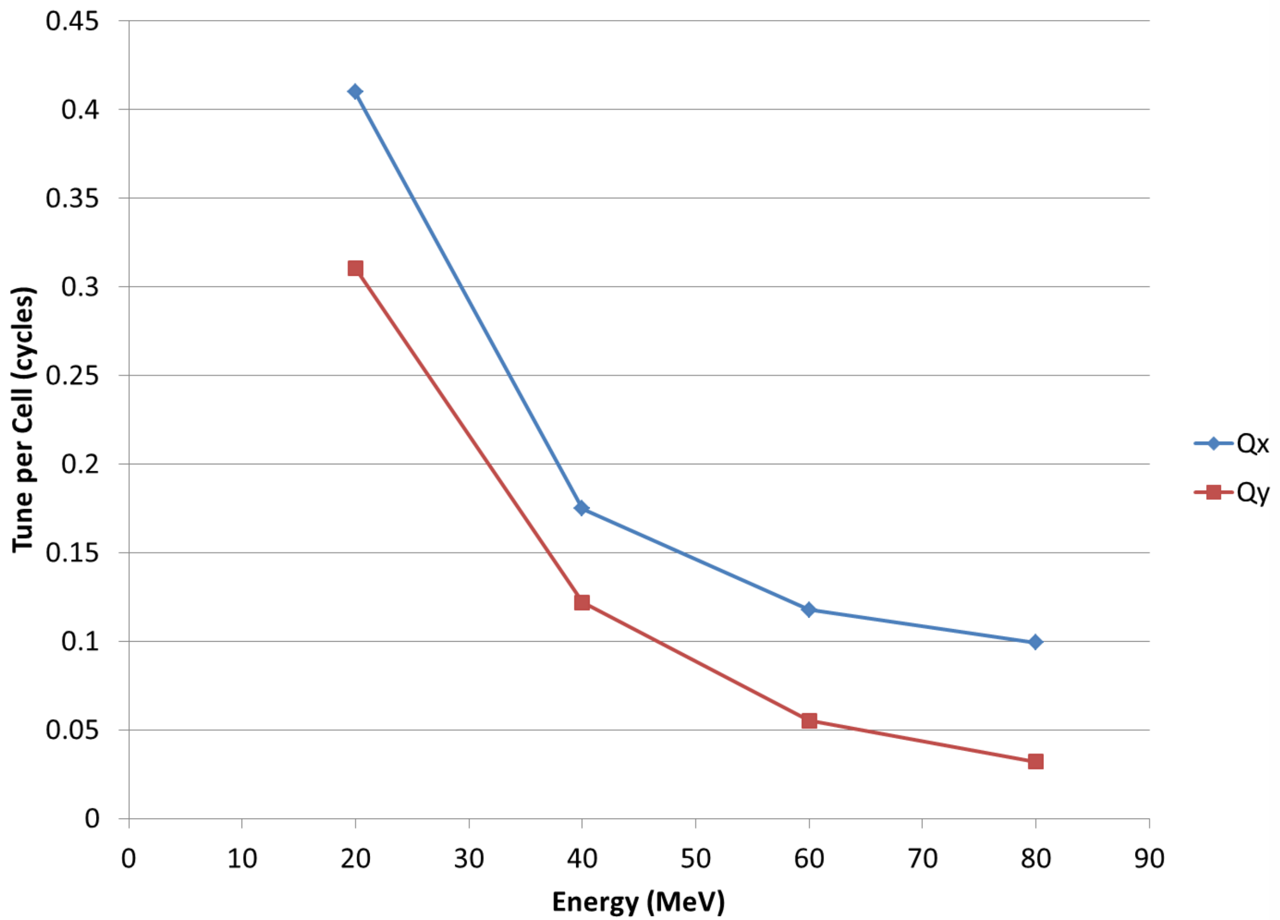
20-80MeV NS-FFAG Beamline

Parameter	Value	Units
Particle species	Electron	
Energy range	20-80	MeV
Cell Length	0.251751	m
Cell Angle	6.666…	degrees (54 per turn)
R = avg. radius of curvature	2.16364	m
Max orbit excursion	19.83	mm (from circle radius R)
Tune range per cell	$Q_{y,80}$ = 0.032, $Q_{x,20}$ = 0.410	cycles
Cell lattice	halfD2, QF, D1, BD, halfD2	
Drift lengths	D1 = 67.55, D2 = 64.90	mm
Number of cells	6	
Total length	1.51051	m
Total angle	40	degrees

20, 40, 60, 80MeV in NS-FFAG Cell

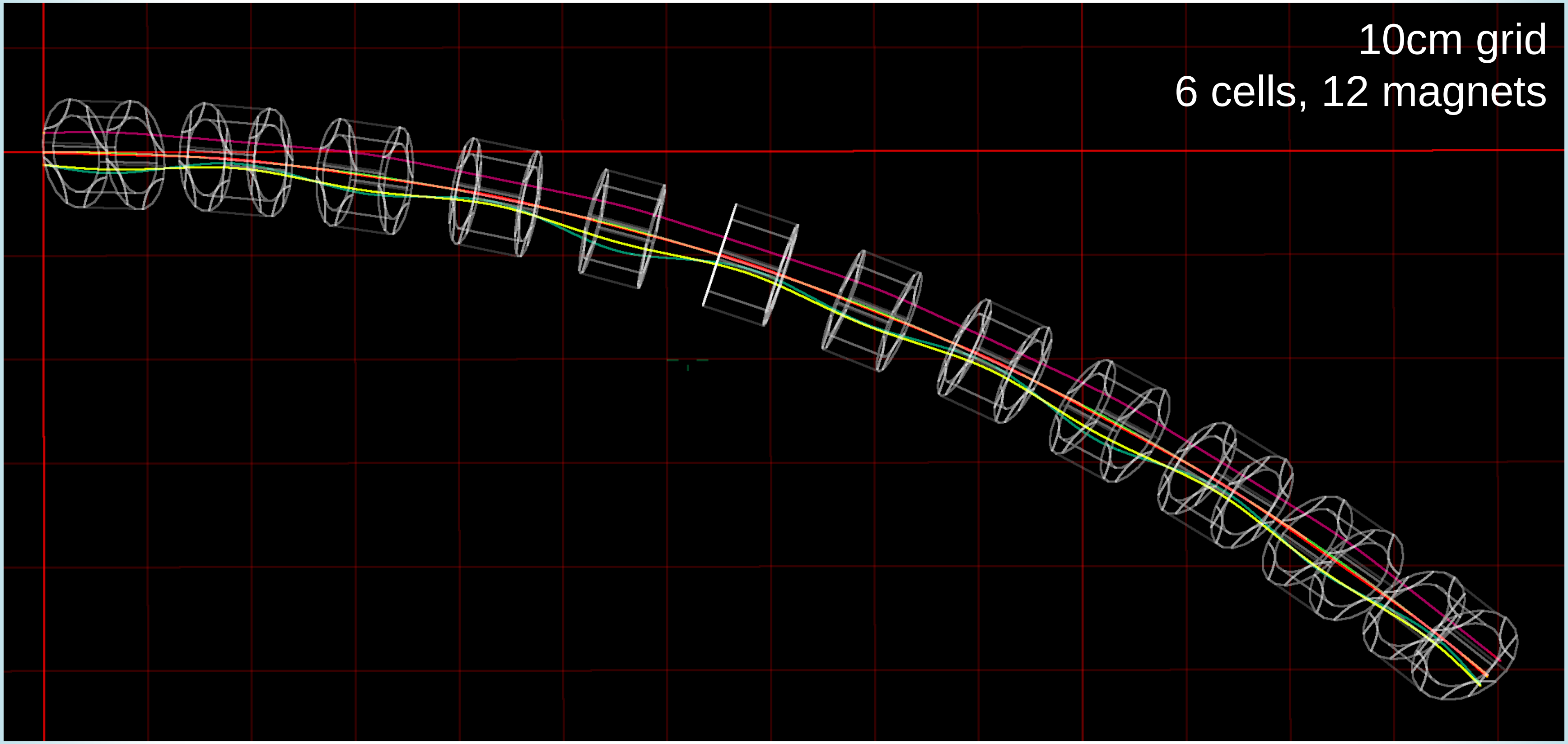


Tunes



0.45
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
Tune per Cell (cycles)
0
10
20
30
40
50
60
70
80
90
Energy (MeV)
Qx
Qy

40 degree NS-FFAG Beamline



Why am I making this odd thing?

- I had some spare Halbach magnets from CBETA prototyping that they're not using
- The 20-80MeV BNL ATF energy range matches the energy range of CBETA magnet halves
  - This is by luck, also George Mahler's idea
- It demonstrates 4x energy range in a non-scaling FFAG for the first time (I think)
  - Very useful for risk-reduction in the eRHIC design, which uses exactly such FFAGs as transfer lines

Two Magnet Ideas

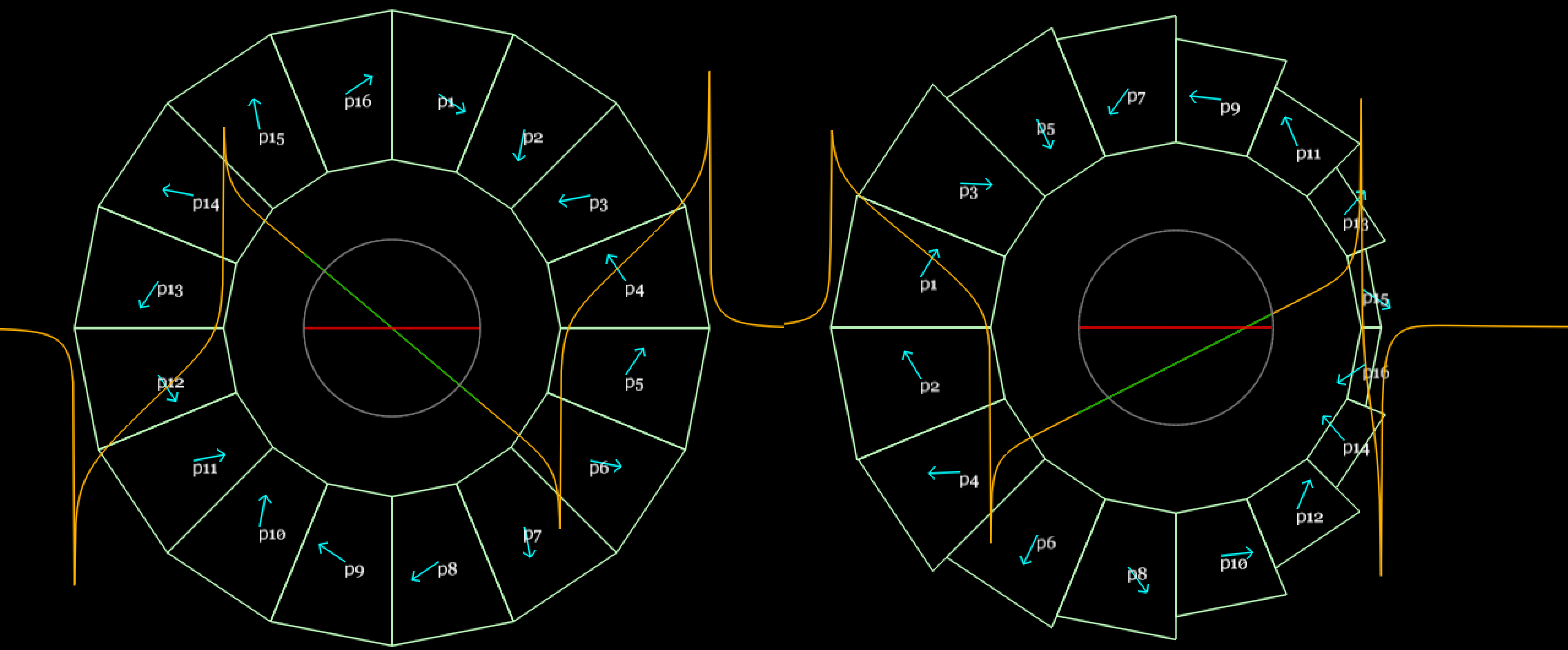
- Generalised Halbach arrangement
  - Vary the size and magnetisation direction of the magnet wedges
  - Can produce “any” field configuration
  - Or an existing field configuration shifted to better reflect the aperture required by the beams
- Permanent magnet shimming with iron wires
  - Reduces field errors from “factory” ~1e-2 level to ~1e-4 level for accelerator magnets, cheaply

Magnet Parameters

Parameter	"QF" magnet	"BD" magnet	Units
Length	57.44	61.86	mm
Dipole $B_y(x=0)$	0	-0.37679	T
Quadrupole dB_y/dx	-23.624	19.119	T/m
Inner radius (magnet pieces)	37.20	30.70	mm
(shim holder)	34.70	27.60	mm
"Pole-tip" field (magnet pieces)	0.879	(-)0.964	T
Max field at r=1cm	0.236	(-)0.568	T
Outer radius (magnet pieces)	62.45	59.43	mm
(tubular support)	76.2	76.2	mm

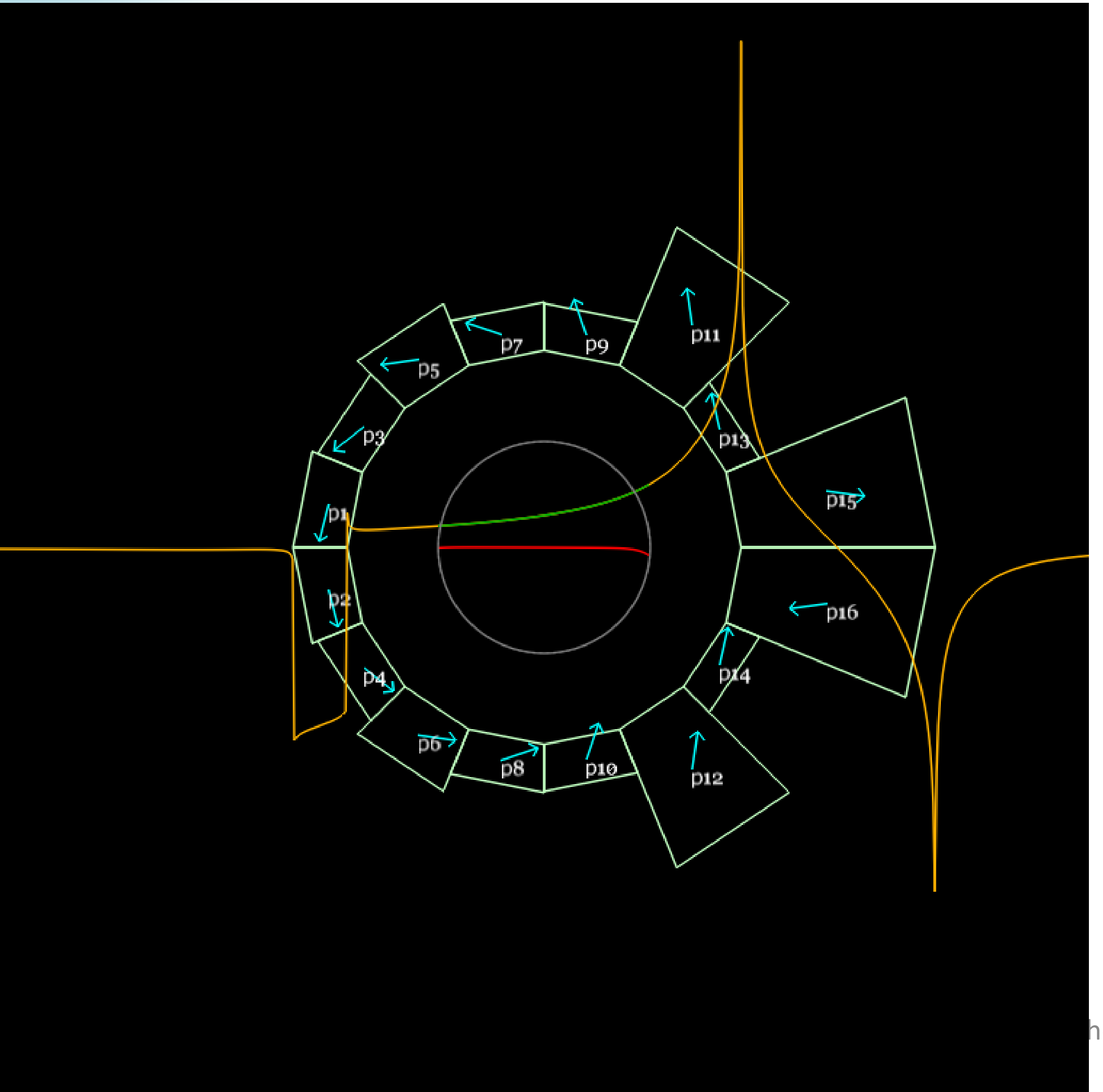
Generalised Halbach design

My current sheet approximation code (PM2D) is good enough



Material grade: N35SH from AllStar Magnetics, B_r(eff.)=1.194T

Scaling FFAG example



$B_0 = 0.2T$
$R_0 = 5m$
$k = 125$

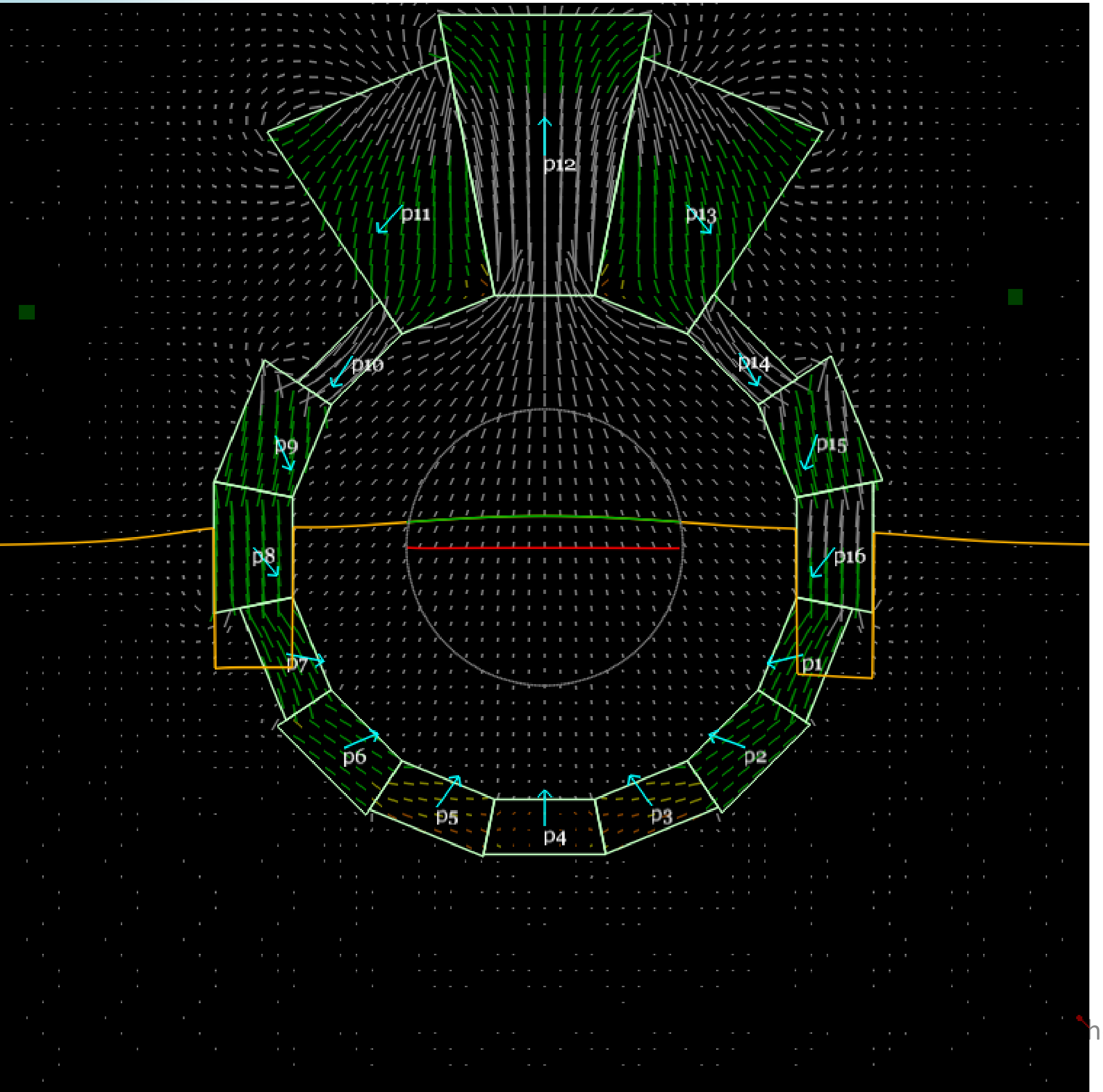
"e-fold length" = R_0/k = 40mm
Target GFR = 20mm
Aperture radius = 36.5mm

x (mm)	**B_y (T)**
-36.5	0.0800
-20	0.1212
0	0.2000
20	0.3294
36.5	0.4965

Max field error = 5.4 Gauss
RMS field error = 0.9 Gauss

Cross-section area = 45.0cm^2

VFFAG example



$B_0 = 0.2T$
$k = 25m^{-1}$

"e-fold length" = 1/k = 40mm
Target GFR = 20mm
Aperture radius = 36.5mm

y (mm)	**B_y (T)**
-36.5	0.0803
-20	0.1213
0	0.2000
20	0.3297
36.5	0.4981

Max field error = 3.0 Gauss
RMS field error = 1.0 Gauss

Cross-section area = 43.1cm^2

Photos of magnets (unshimmed)

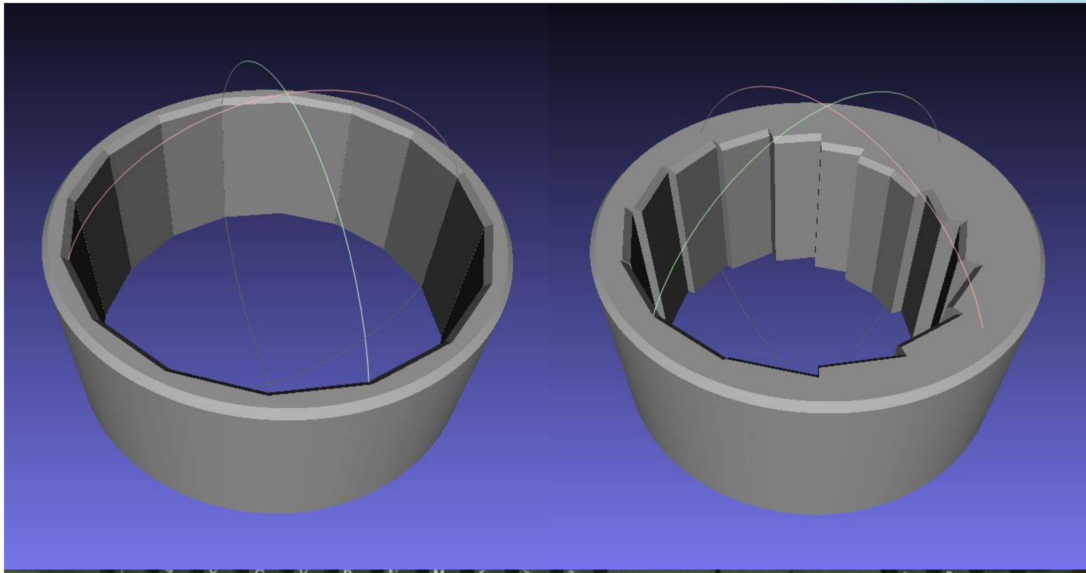
3D Printed Magnet Holder

- Field optimiser

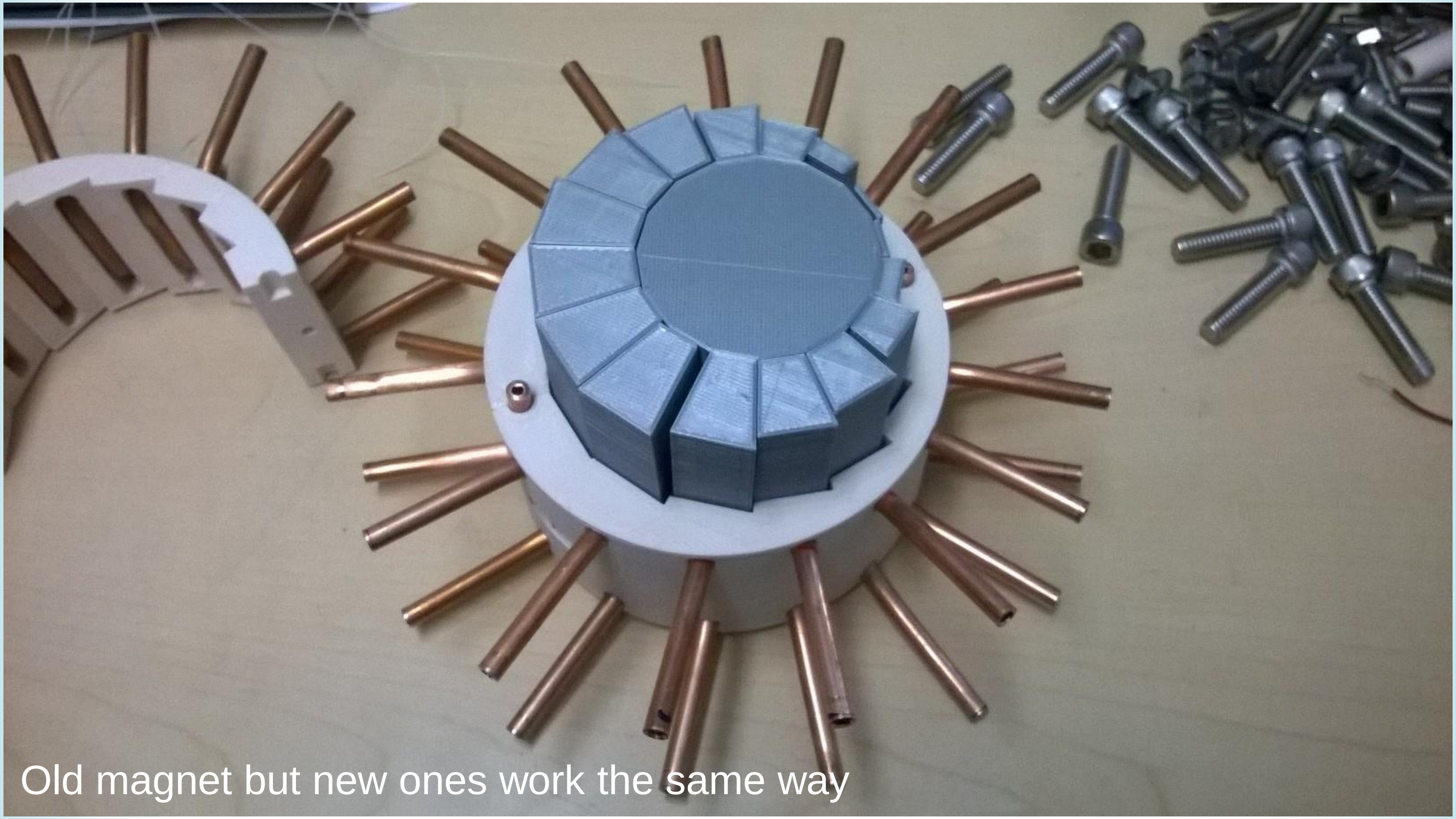
→ Magnet wedge dimensions

→ 3D print file (.stl mesh)

and block spec. for manufacturer

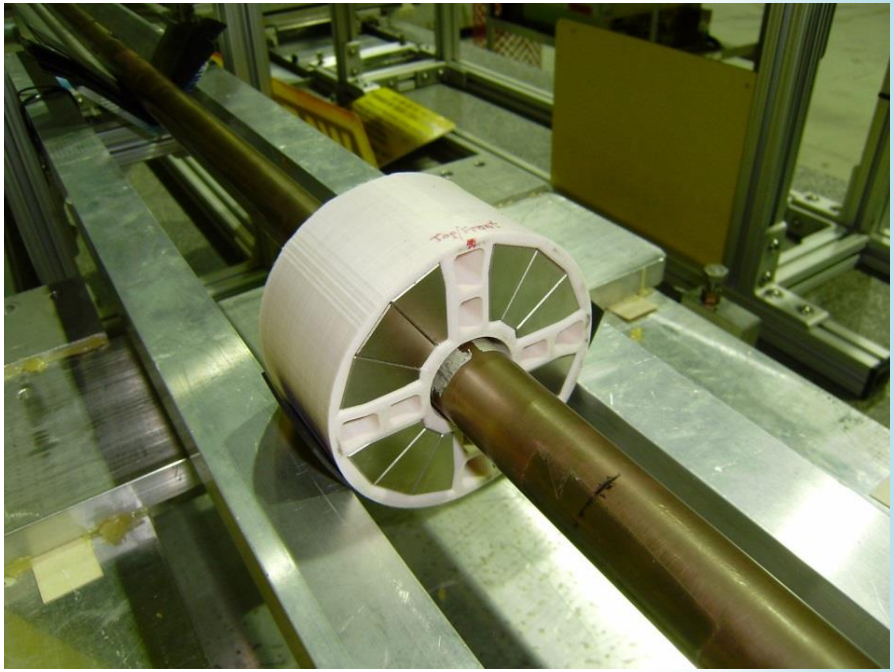


Assembly with Dummy Blocks



Rotating Coil

- Gives multipole field amplitudes at a given radius (R=10mm here)
- Stated as fraction of main multipole (quad here) times 10000 to give “units”
- <0.5 unit accuracy



Even older magnet shown here but brass tube is a rotating coil at BNL

Unshimmed Rotating Coil Results

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	PMQ_0501 Run 2 (2-Jun-2016)
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	PMQ_0501 Run 2 (2-Jun-2016)
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

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

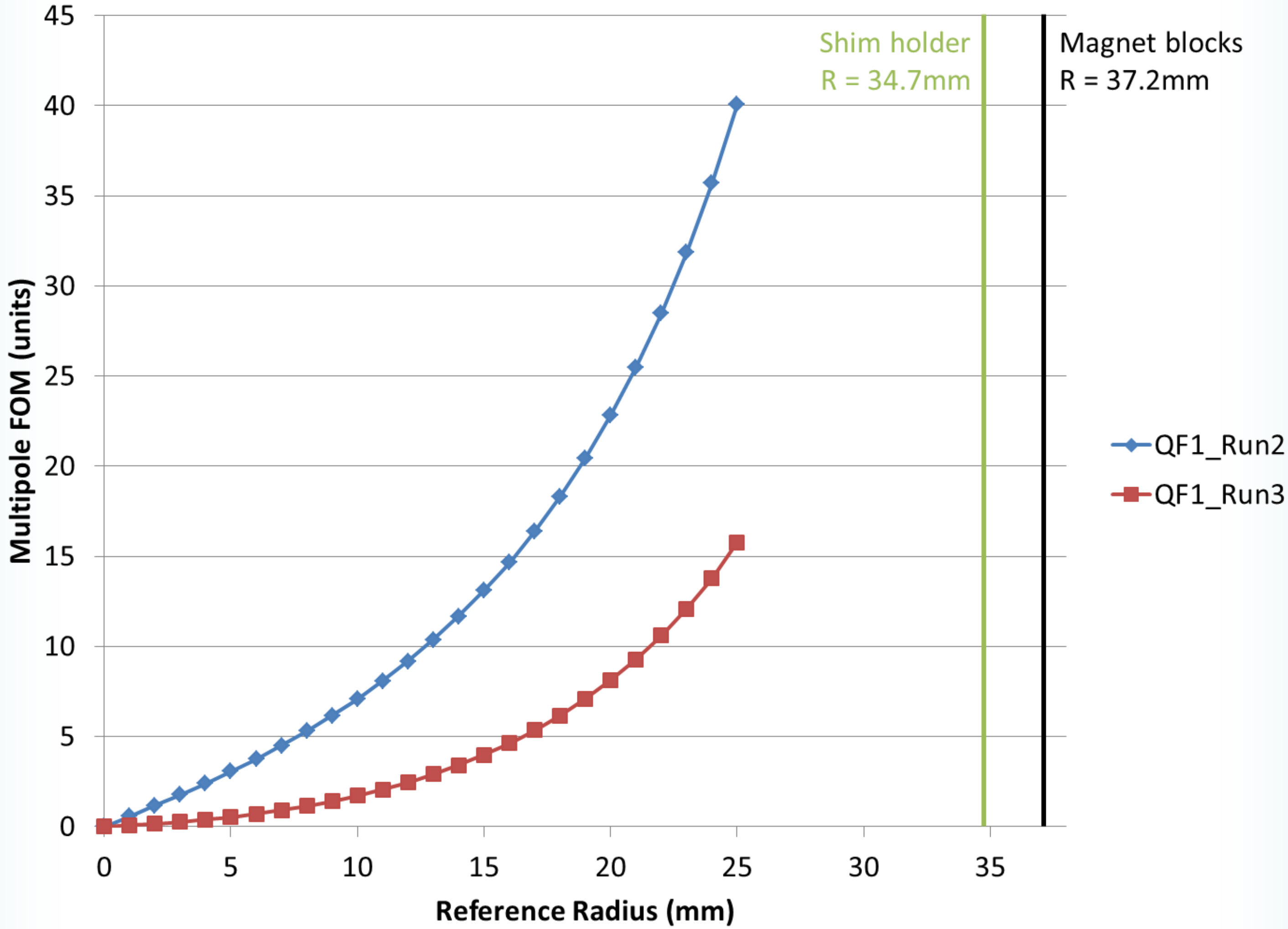
Higher Harmonic Figure of Merit

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

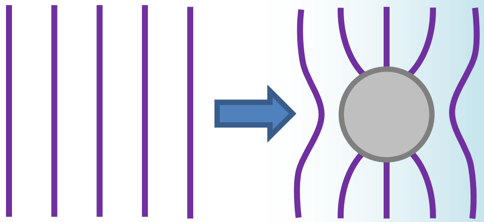
$$\sqrt{\sum_{n=3}^{15} a_n^2 + b_n^2}$$

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

Figure of Merit vs. Radius

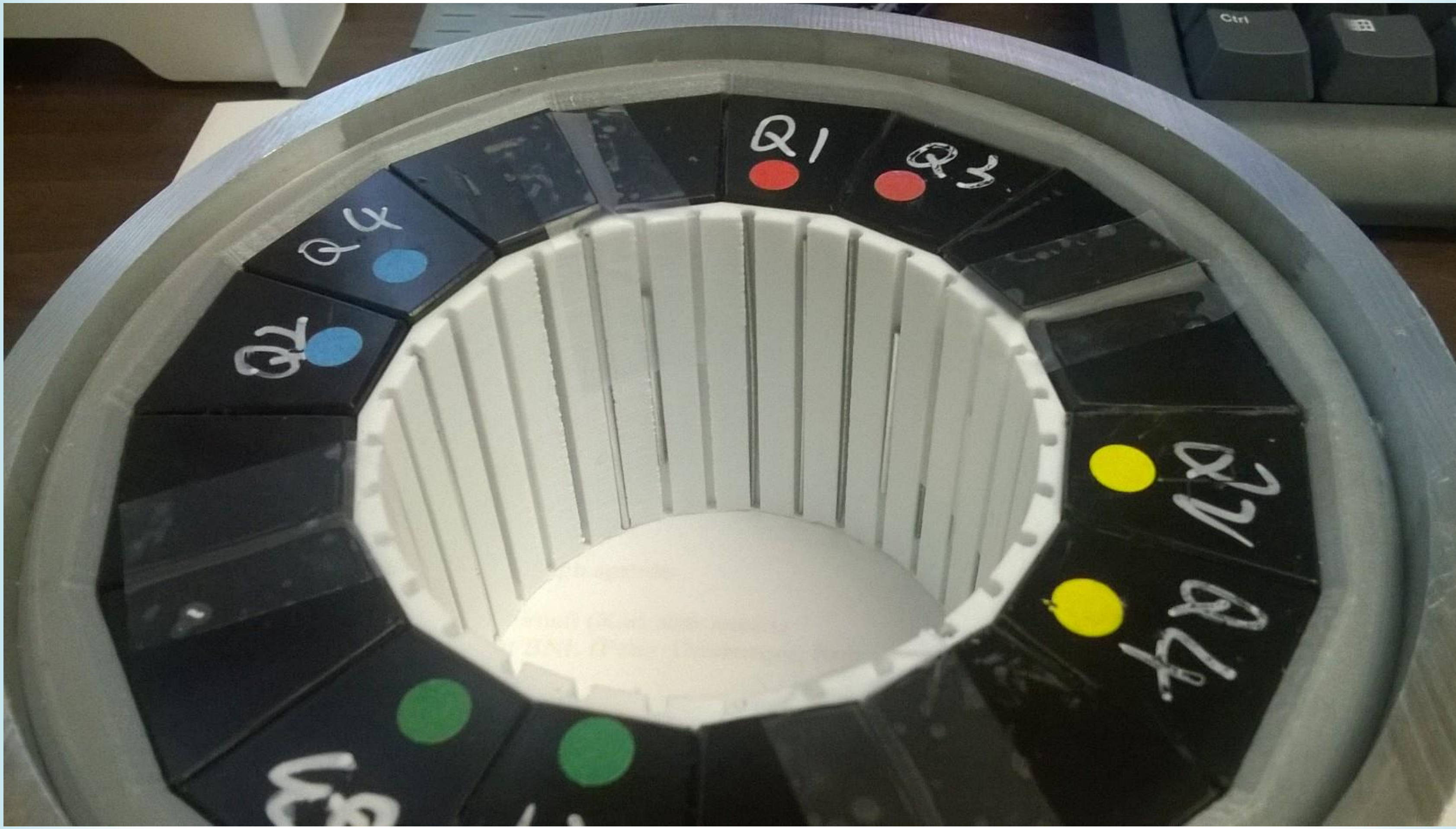


Iron Wire Shimming Theory

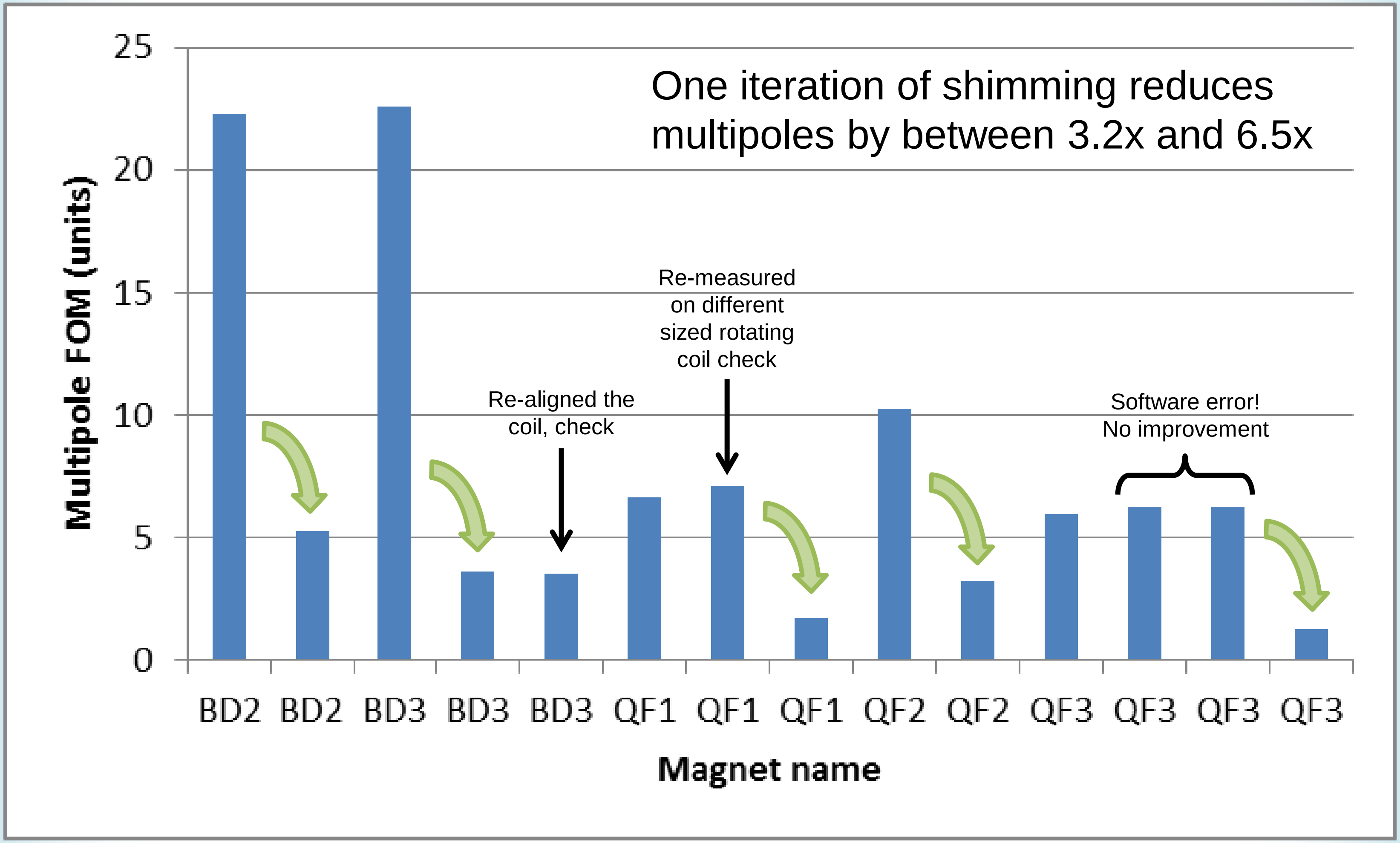


- Placing a $\mu=\infty$ iron cylinder into a uniform **B** field distorts the field lines so they are perpendicular to the surface
- Cylinder acquires the surface currents of a $\cos(\theta)$ dipole, giving uniform **B** and **M** inside and an external dipole outside
- Optimise masses/radii of 32 iron wires placed inside magnet bore to cancel measured errors

3D Printed Shim Holder



Shimming Results (one iteration)



Best so far: QF3

Table 1: Field harmonics from ERHIC-PMQ_0503_0004_001 at R=10mm. The nominal magnet length is 57.4412mm and the average field corresponds to 23.6386 T/m.

Field harmonic	Normal units	Skew units
Dipole	0.00	-0.00
Quadrupole	10000.00	0.00
Sextupole	-0.18	-0.94
Octupole	0.34	0.17
Decapole	-0.65	0.09
Dodecapole	-0.05	0.02
14-pole	-0.02	-0.01
16-pole	-0.00	0.00
18-pole	0.00	0.00
20-pole	-0.00	-0.00
22-pole	-0.00	-0.00
24-pole	-0.00	0.00
26-pole	0.00	-0.00
28-pole	0.00	-0.00
30-pole	-0.00	-0.00

2nd shimming iteration

eRHIC Permanent Magnet Quadrupole PMQ_005A (26-Apr-2016)

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

	15-Dec-2015	18-Apr-2016	26-Apr-2016
Quantity	PMQ_005A* Run 6(†)	PMQ_005A* Run 10(††)	PMQ_005A* Run 11(†††)
Integrated Gradient (T)	1.6483	1.6513	1.6509
Normal Dipole	--	--	--
Normal Quadrupole	10000.00	10000.00	10000.00
Normal Sextupole	-18.67	-4.37	0.26
Normal Octupole	5.34	-1.19	-1.53
Normal Decapole	-0.88	0.35	-0.72
Normal Dodecapole	-1.04	-0.80	0.09
Normal 14-pole	1.16	0.18	0.03
Normal 16-pole	-1.46	-0.25	0.03
Normal 18-pole	0.12	0.04	0.00
Normal 20-pole	0.45	0.20	0.03
Normal 22-pole	-0.01	0.02	0.06
Normal 24-pole	0.03	0.01	0.01
Normal 26-pole	0.00	-0.01	-0.03
Normal 28-pole	-0.12	-0.10	-0.10
Normal 30-pole	0.00	0.00	0.01
Field quality figure of merit	29.62	6.69	1.94

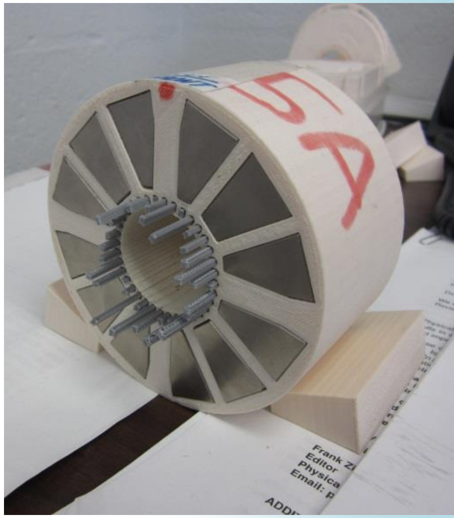
	15-Dec-2015	18-Apr-2016	26-Apr-2016
Quantity	PMQ_005A* Run 6(†)	PMQ_005A* Run 10(††)	PMQ_005A* Run 11(†††)
Field Angle (mr)	--	--	--
Skew Dipole	--	--	--
Skew Quadrupole	--	--	--
Skew Sextupole	-5.69	-0.50	0.51
Skew Octupole	-21.09	-4.69	0.47
Skew Decapole	-4.11	-1.01	-0.38
Skew Dodecapole	0.29	0.03	0.41
Skew 14-pole	-0.09	0.05	-0.12
Skew 16-pole	-0.31	0.04	0.03
Skew 18-pole	-0.03	-0.07	0.05
Skew 20-pole	0.23	0.04	0.04
Skew 22-pole	0.00	0.03	0.01
Skew 24-pole	-0.01	-0.02	0.02
Skew 26-pole	0.00	0.00	0.00
Skew 28-pole	0.00	-0.01	-0.02
Skew 30-pole	0.00	0.00	0.01

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

(†) Run 6 is measurement repeated with no iron shims, after several iterations of measurements with iron shims.

(††) Run 10 is iteration #1 with all wires pushed radially outward using thin wedges.

(†††) Run 11 is iteration #2 with all wires pushed radially outward using thin wedges.

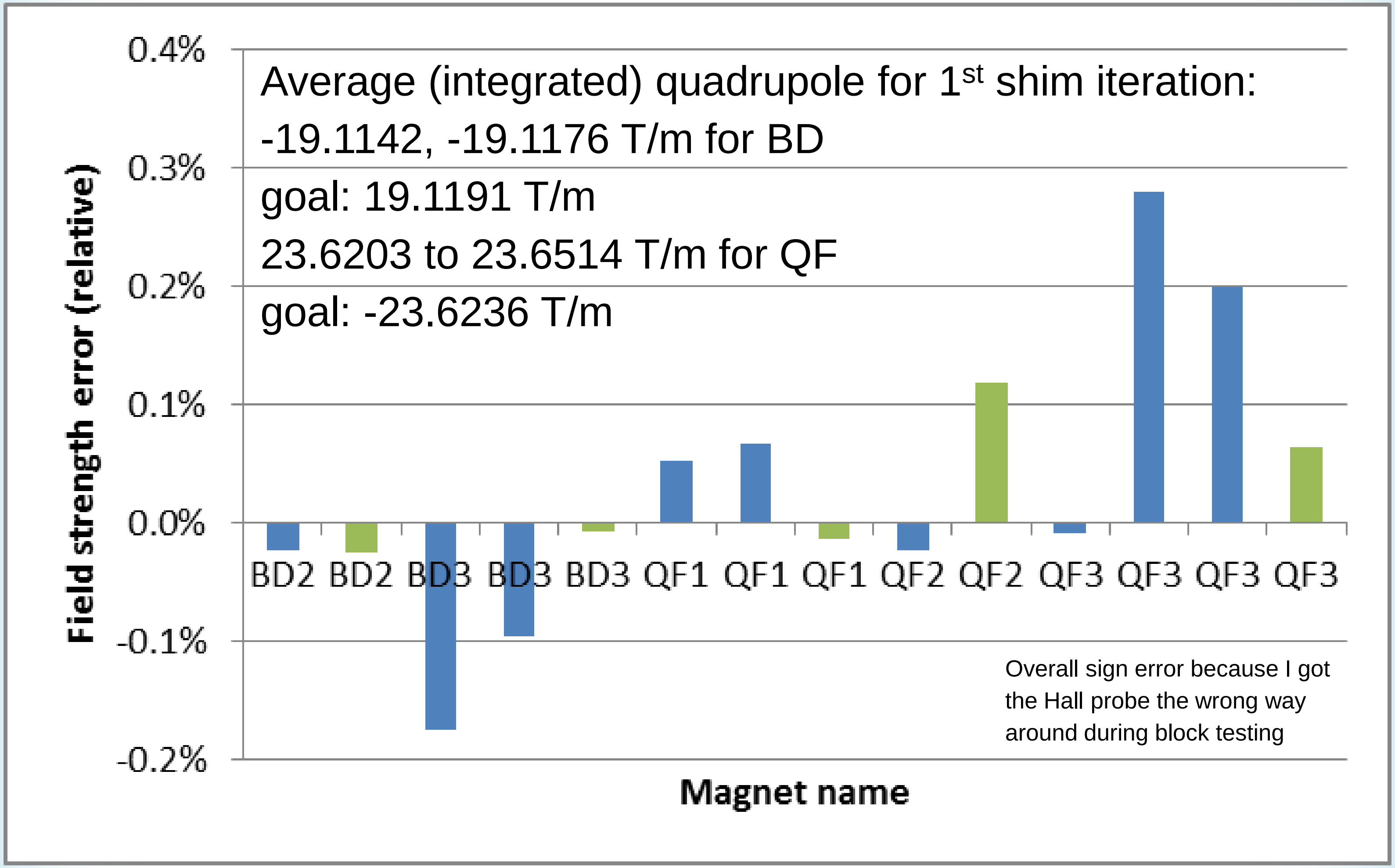


Of a previous test quadrupole magnet "5A"

3D printer was worse so had to use clamps for position accuracy!

1 iter → 4.4x, 2 iters → 15.3x

Field Strength vs. Spec



Cost and Labour per Magnet

- Permanent magnet wedges (AllStar N35SH)
  - $1052.67 per QF magnet (16 wedges)
  - $758.00 per BD magnet (16 wedges)
- Labour ~8h per magnet: 3h measurement, 2h shimming, 2h assembly, 1h 3D printer setup
- Required infrastructure
  - 3D printer ($2-3k), used Ultimaker 2 Extended+
  - Rotating coil (~$50k)

Limitations

- Strength
  - Upper limit to quad*aperture (pole tip field)
  - Watch out for demagnetisation from reverse fluxes (OK so far up to ~1T pole tip)
    - Choosing a high H_{cj} grade increases resistance to this
- Can't have rapidly varying field w.r.t. aperture
- Temperature coefficient of NdFeB ~-0.12%/K
- Choose high H_{cj} grade for radiation resistance

Benefits

- No power consumption
  - No power supply, no copper wires or windings
- Any field shape you like within strength limits
- No "cross-talk" between iron surfaces in compact lattices
- Can be assembled with mallet
- 1e-4 accuracy is possible after shimming
- Seems cheap, at least for short magnet length

THE END