Modified Halbach Magnets for Emerging Accelerator Applications

Permanent Magnets (PMs) in Accelerator Beamlines

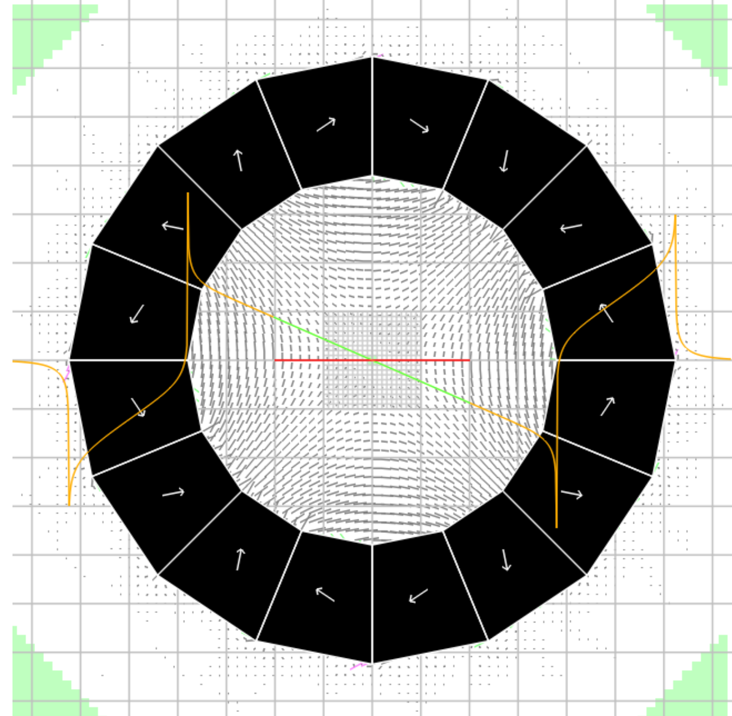
- Established uses:
  - Wigglers, undulators
  - Halbach quads in drift tube linacs
  - Halbach quads in interaction region of Cornell CESR collider
  - Hybrid magnets (PM+iron) for main bending field of FNAL recycler
- CBETA ERL (operating at Cornell 2019-20):
  - New uses:
    - Halbach magnet is main bending field (compact size, short drifts)
    - Combined-function dipole+quad Halbach (fewer lattice elements)
  - Done before but not at scale:
    - Tuning of Halbach magnets with iron rods for higher field quality
      - 200+ magnets tuned at BNL
- This talk explores from CBETA to future applications

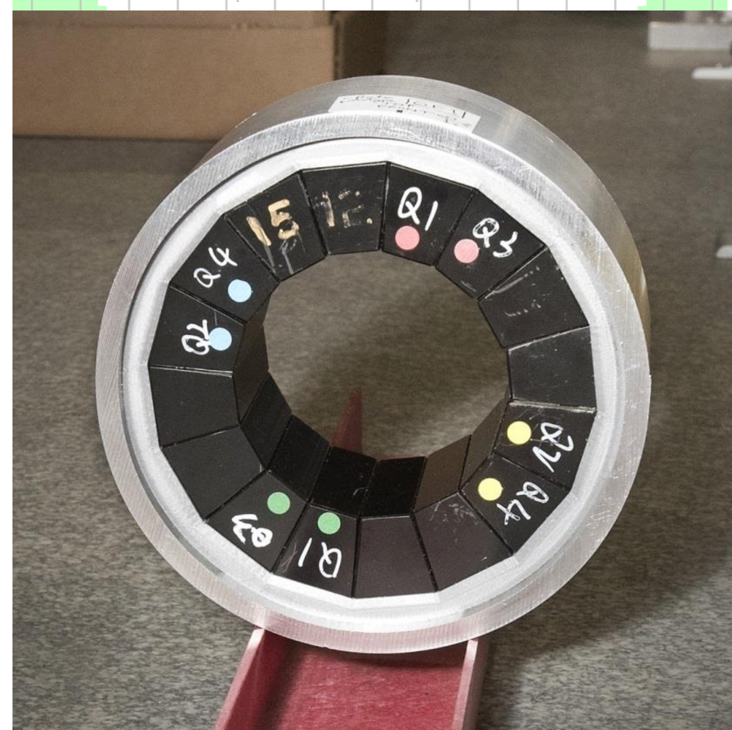
PM Domain of Applicability

- Field strength comparable to electromagnets
  - But not adjustable without EM corrector or motors
- Generally cheaper for small apertures
- There is a limit to radiation resistance
  - How much? "It depends"
    - On PM material, material grade, magnet geometry, field strength
    - On accelerator radiation environment near beam pipe
      - You must characterise this before getting any useful answers
  - Examples (mostly NdFeB material)
    - CBETA 1kGy lifetime dose limit (predicted $<2\times10^{-4}$ field change)
    - RHIC beam dump 700Gy, some grades near-unchanged, some bad
    - BLIP target area >>MGy, ~90% flux loss, SmCo some flux loss
    - CESR 65cm from interaction region(!) **SmCo** seems to work

Halbach-style Permanent Magnets

- Consist purely of PM material (no iron)
  - Generally smaller than PM+iron hybrid magnets: no iron loop
  - No cross-talk if placed close together (short drifts)
- Orientation of magnetisation in (usually) wedge-shaped PM pieces is used to produce desired harmonics in magnet aperture

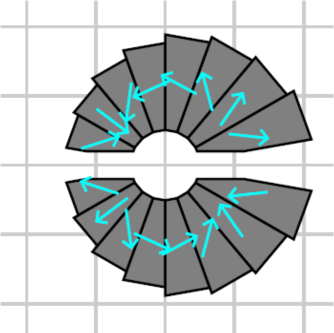




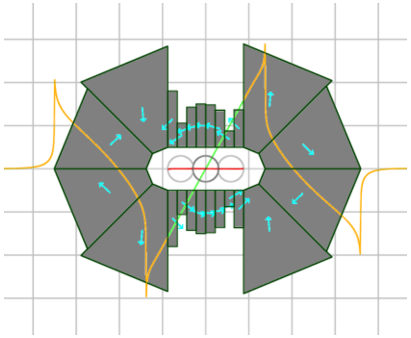
Halbach Magnet Variations

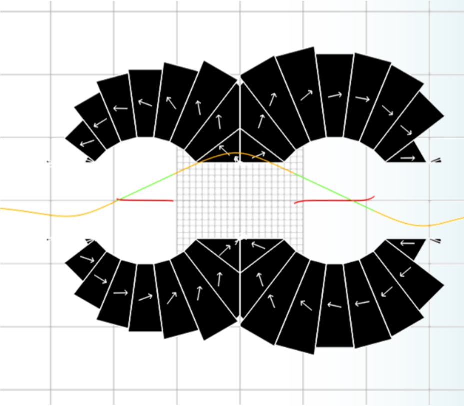
- Demonstrated (in accelerator)
  - Field tuning with iron rods
  - Combined-function magnets

- In development
  - Open midplane magnets



- Future research
  - Oval apertures
  - Multiple apertures





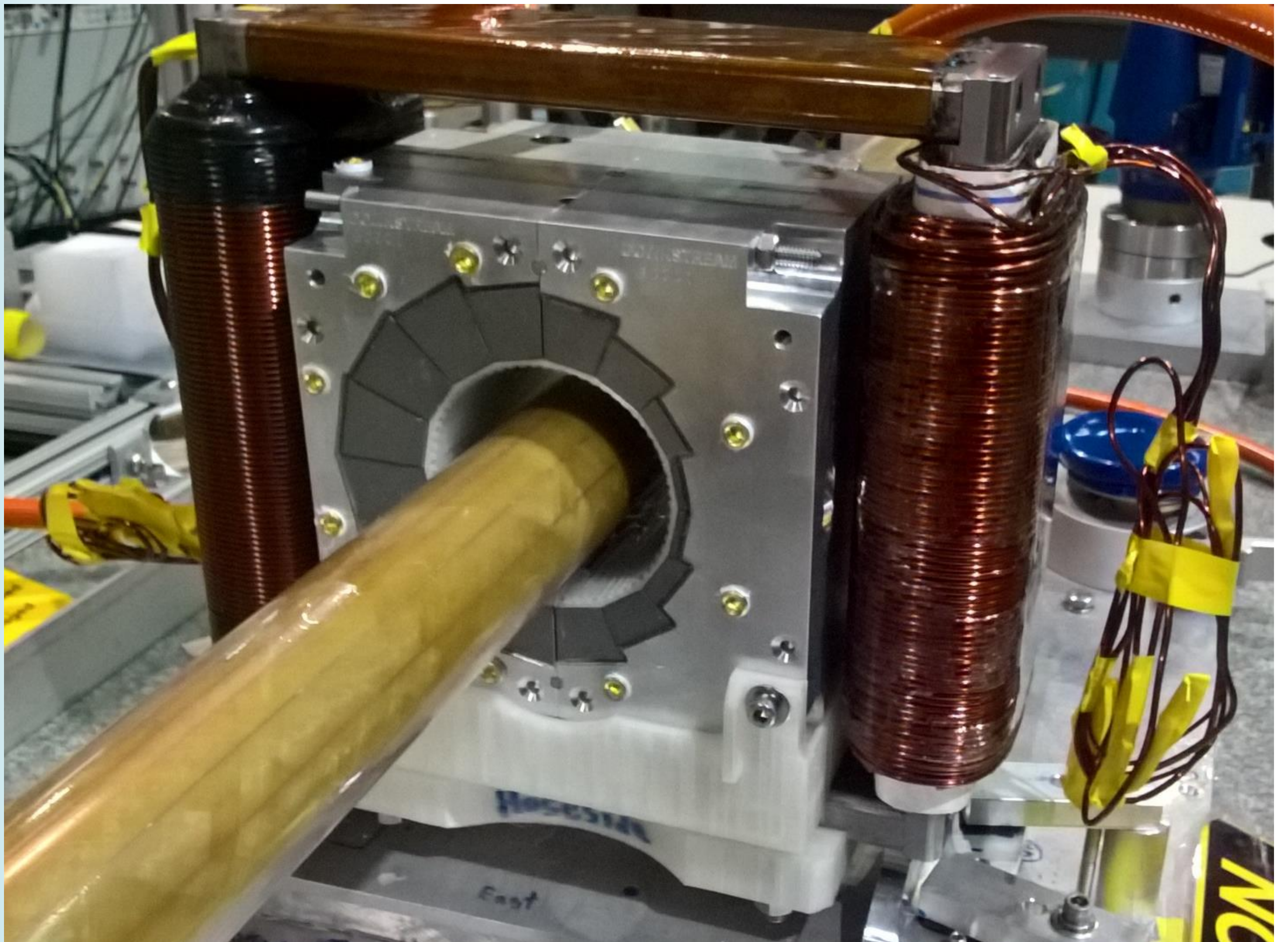
Halbach Magnet Proposals

Type	Project	Magnet	Dipole at x=0 (T) [Max beam field]	Gradient (T/m)	Needs open midplane?
ERL	CBETA	QF	0 [0.2891]	-11.5624	No
	(built already)	BD	-0.3081 [0.5868]	11.1475	No
Hadron therapy gantry		QF	0 [1.364]	155	No but oval
(Trbojevic design)		BD	1.8 [2.527]	-97	No but oval
Light sources	NSLS-II	CBII-F	0.26	250	Yes
	upgrade	CBII-D	0.49	-250	Yes
	PETRA-IV (o)	quads	0	50 to 95	Yes
		comb.-fn.	0.1976, 0.2861	25.83, 38.94	Yes
RLA	CEBAF 20GeV	F	0.8827 [1.910]	321.05	Yes
	upgrade	D	0.8827 [1.483]	-187.47	Yes
ILC damping ring (o)		quads	0	15	Yes
Plasma accelerator		quads	0	100 to 500	No

(o) = option, not baseline

Table is not exhaustive

CBETA Permanent Magnet Design



Stephen Brooks *et al.*, "Permanent magnets for the return loop of the Cornell-Brookhaven energy recovery linac test accelerator", Phys. Rev. Accel. Beams **23**, 112401 (2020); doi:10.1103/PhysRevAccelBeams.23.112401

Halbach design made of NdFeB material

This is a combined dipole+quad

Being measured on rotating coil at BNL

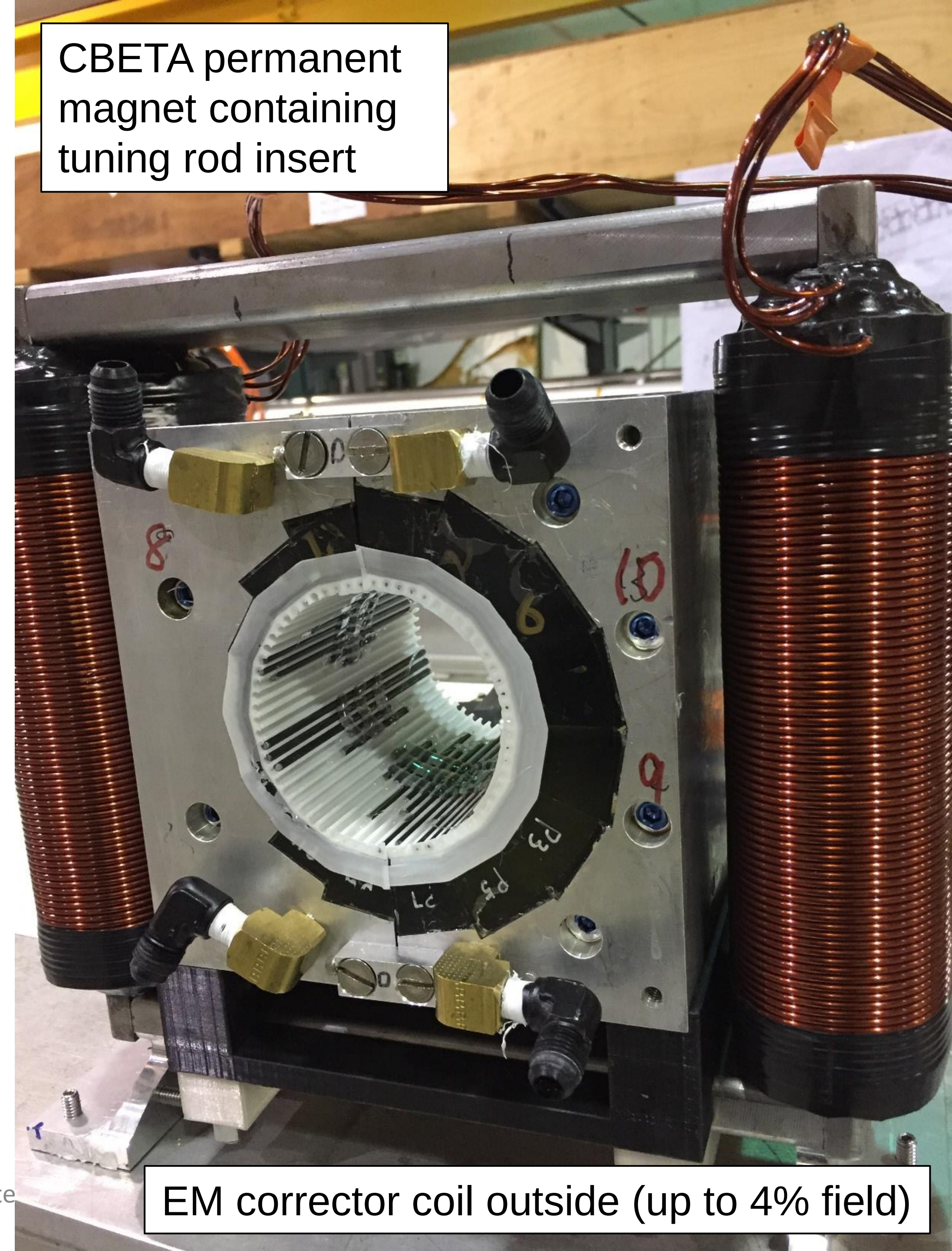
3D printed multipole corrector pack inside

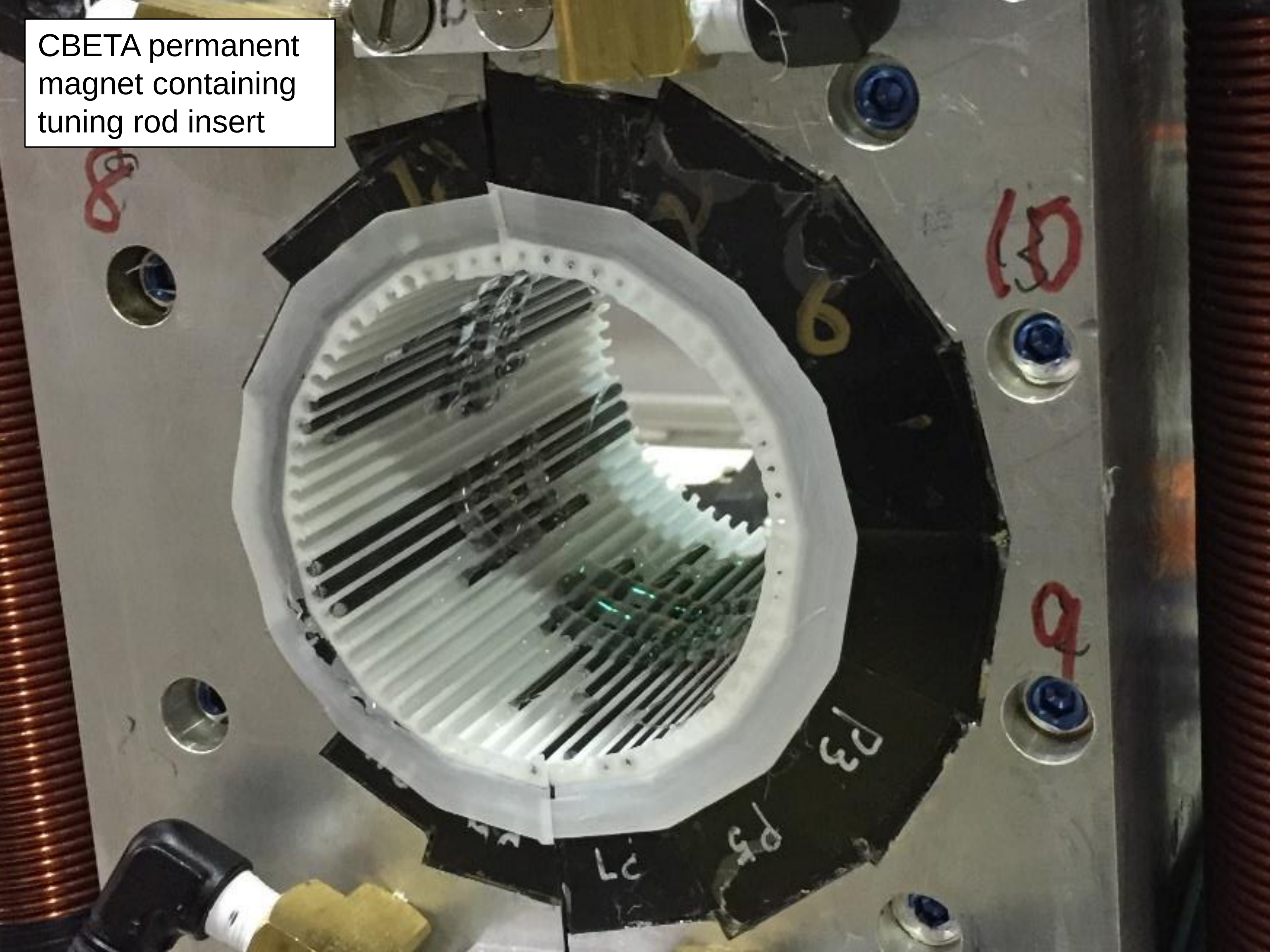
EM window-frame corrector coil outside

Temperature stabilised by water (orange hoses)

Iron Rod Correction Method

- Measure bare magnet harmonics
- Then calculate lengths of iron rods to be inserted around the aperture
- 3D printed insert with 64 slots




CBETA permanent magnet containing tuning rod insert

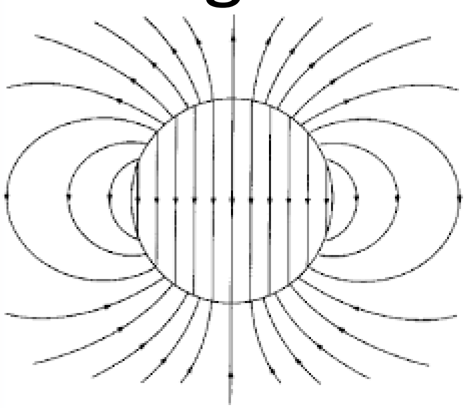
Field Calculation of Iron Rods

- Field of 2D perfect $\mu=\infty$ iron rod of circular cross-section, centre (0,0), in ambient field $\mathbf{B}_0$:

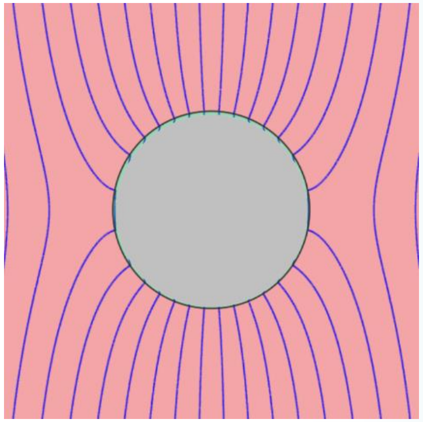
$$\mathbf{B}_{\mathrm{rod}}(x,y) = \frac{r_{\mathrm{rod}}^2}{(x^2+y^2)^2}\begin{bmatrix} B_{0x}(x^2-y^2)+B_{0y}2xy \\ B_{0x}2xy+B_{0y}(y^2-x^2) \end{bmatrix}$$

- Rod is magnetised with $\mathbf{M}=2\mathbf{B}_0$

$\mathbf{B}_{\mathrm{rod}}$



$\mathbf{B}_0+\mathbf{B}_{\mathrm{rod}}$



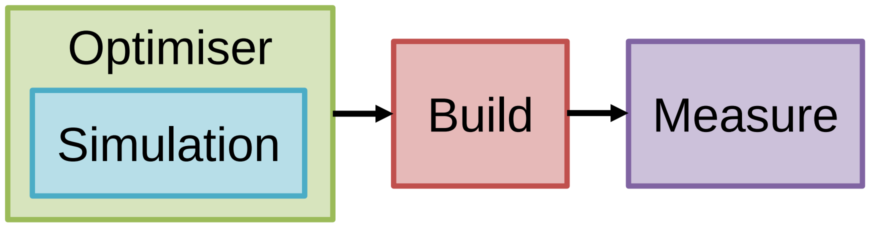
Error Sources (~10^{-2} level)

- Wedge magnetisation vector
  - 1-2° angle variation
  - ~1% strength variation
  - Comes from wedge manufacturing process
- Wedge position
  - 0.1-0.2mm XY displacement
  - Angle errors (fraction of a degree)
  - Comes from magnet assembly

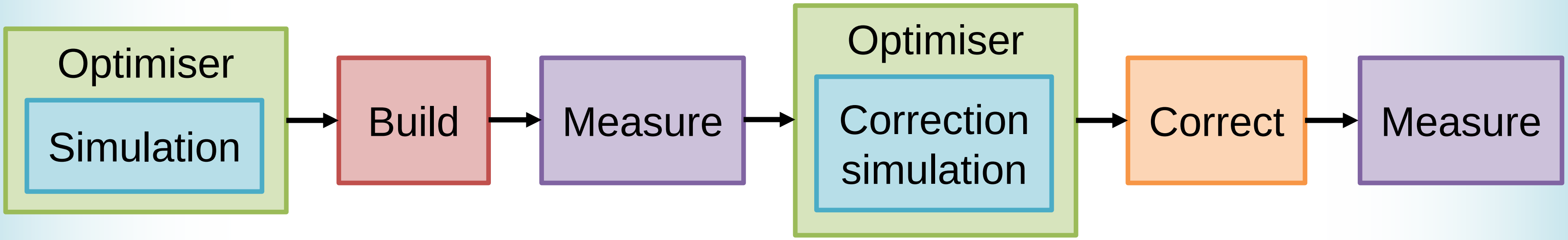
Can't be fixed with block sorting

Overall Philosophy

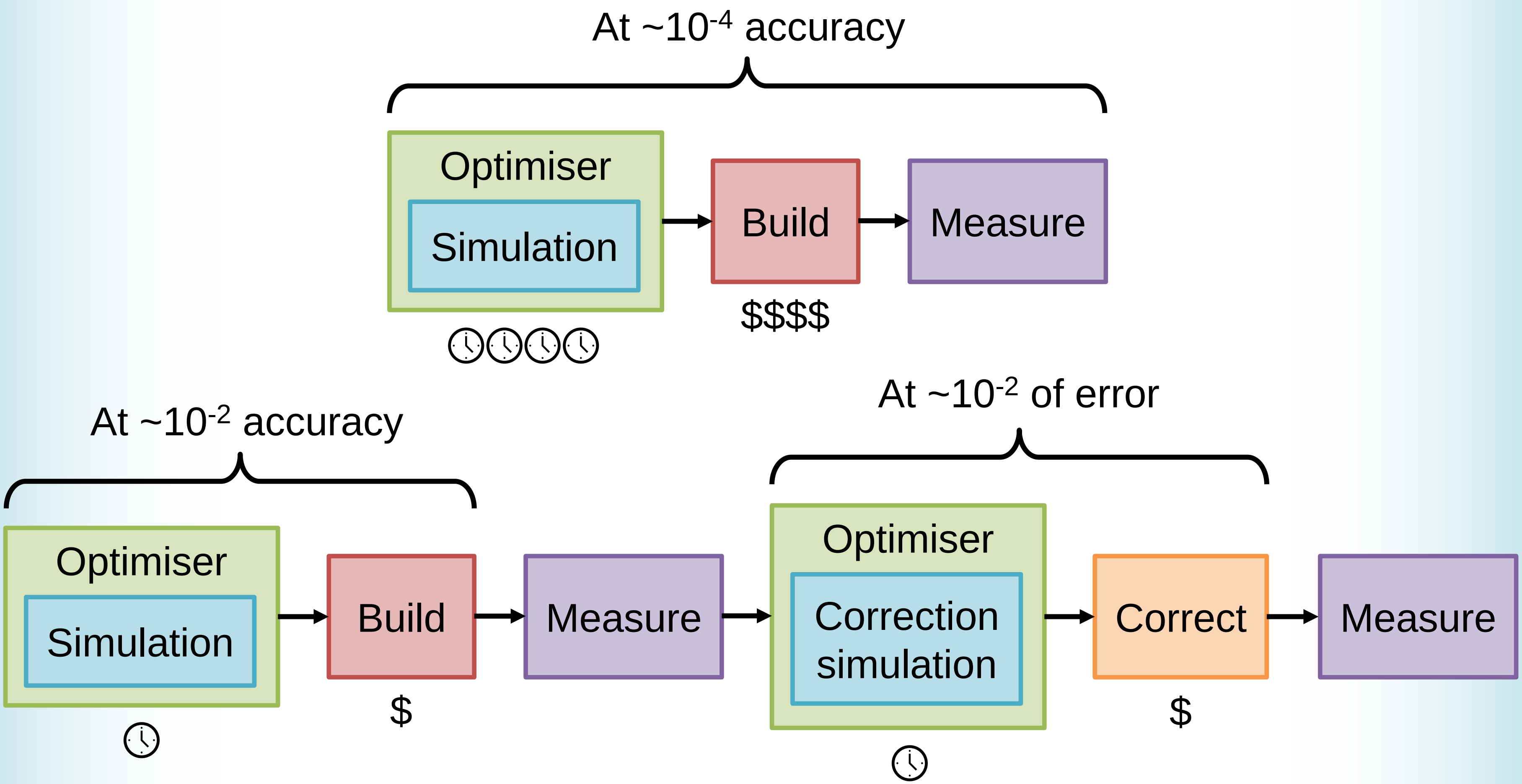
- Direct approach:



- Incorporating correction:



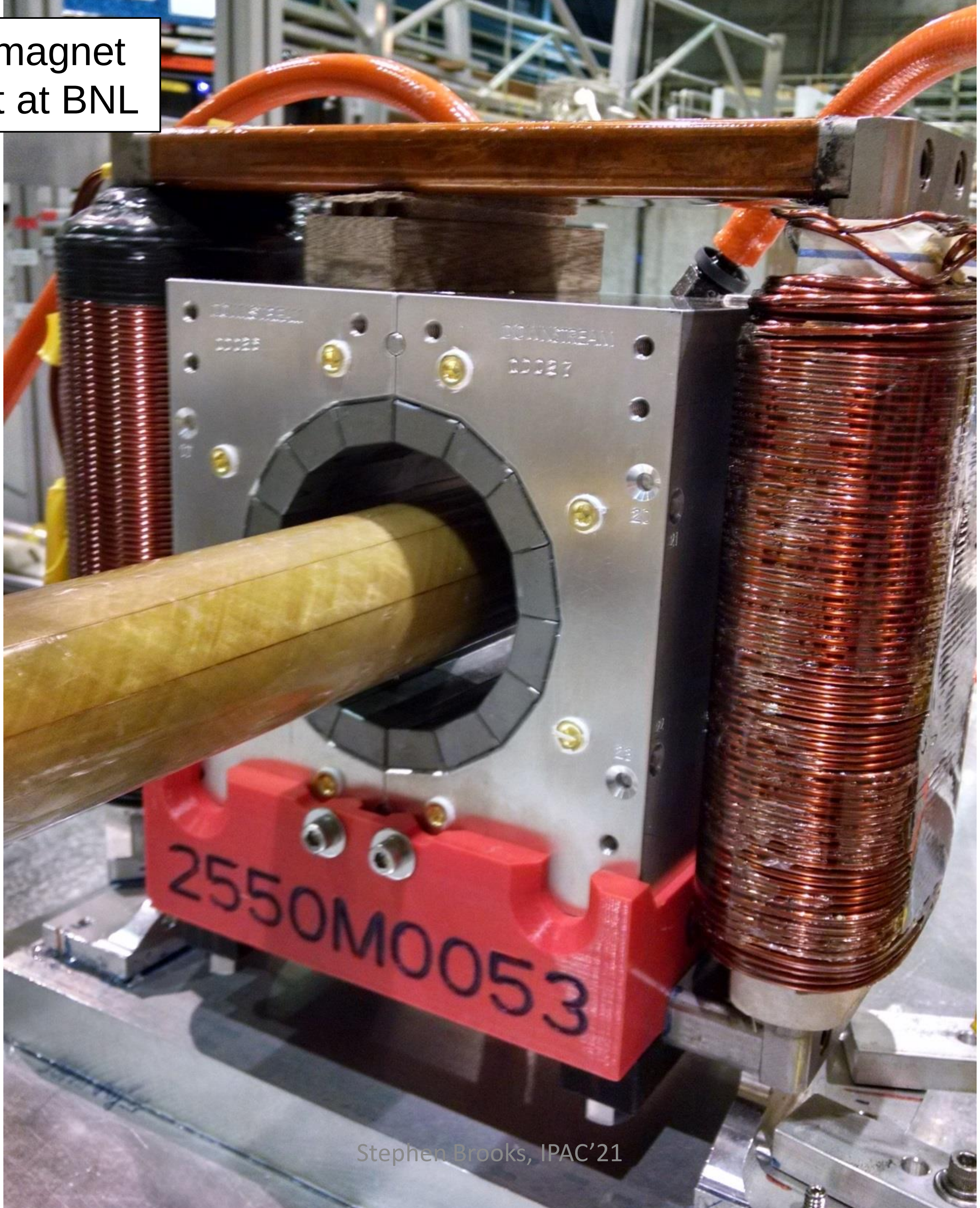
Correction Makes Precision Easier



Measurement steps still have to be $\leq 10^{-4}$

Permanent magnets shipped from KYMA

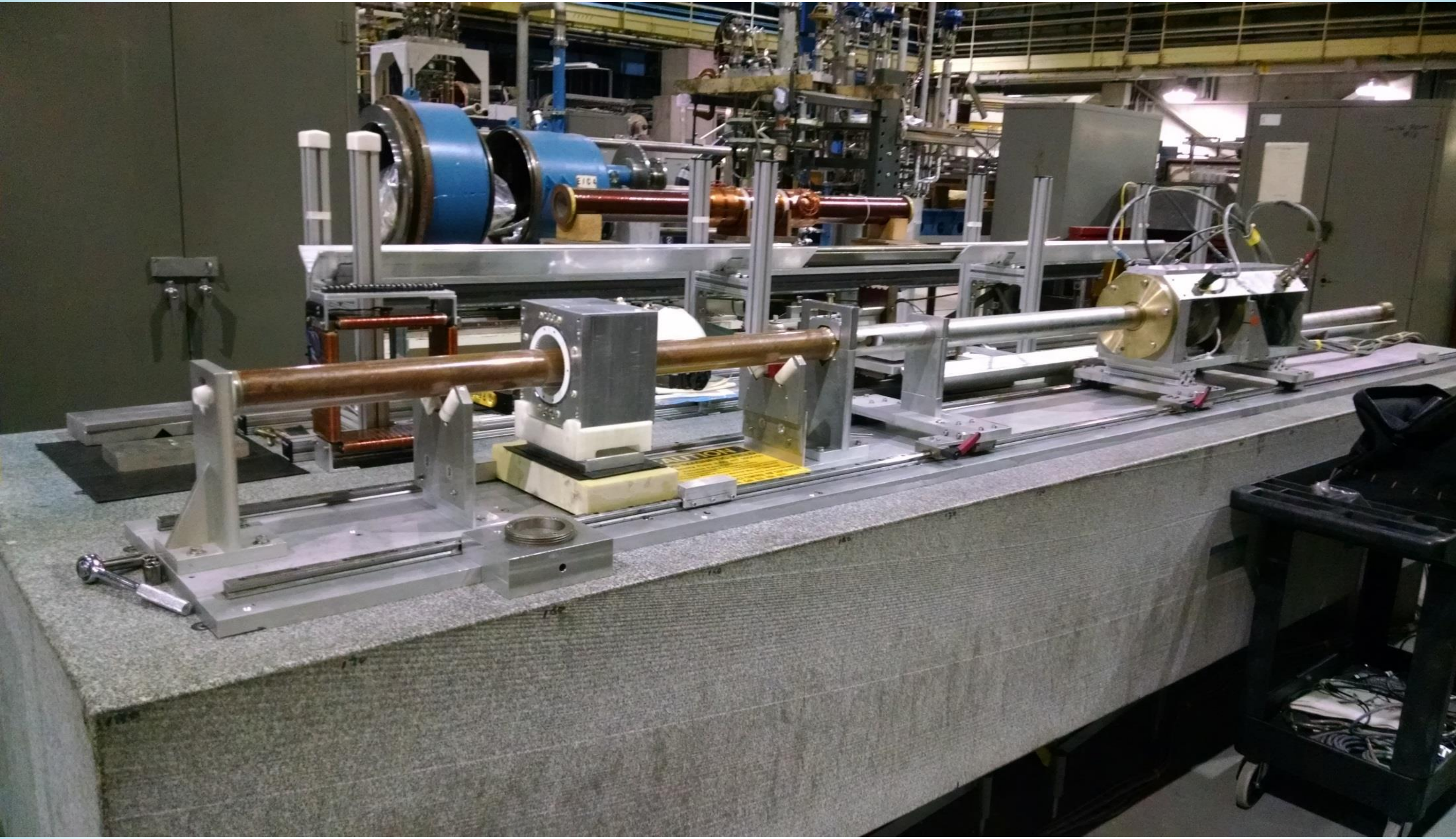
Rotating coil magnet measurement at BNL



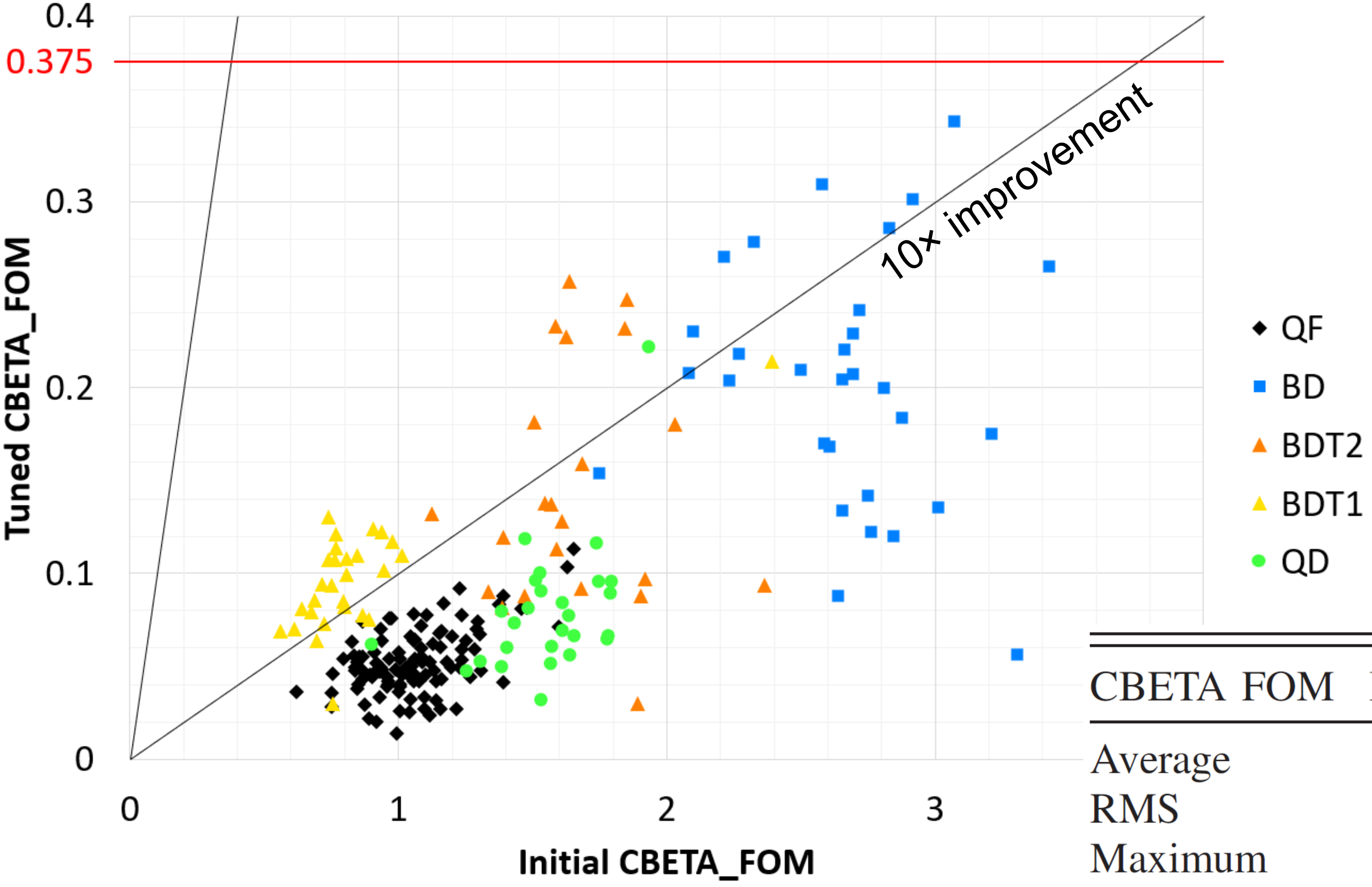
Rod tuning packs for CBETA magnets

Iron rod optimisation program was packaged so that technicians could run it: rotating coil data → rod lengths

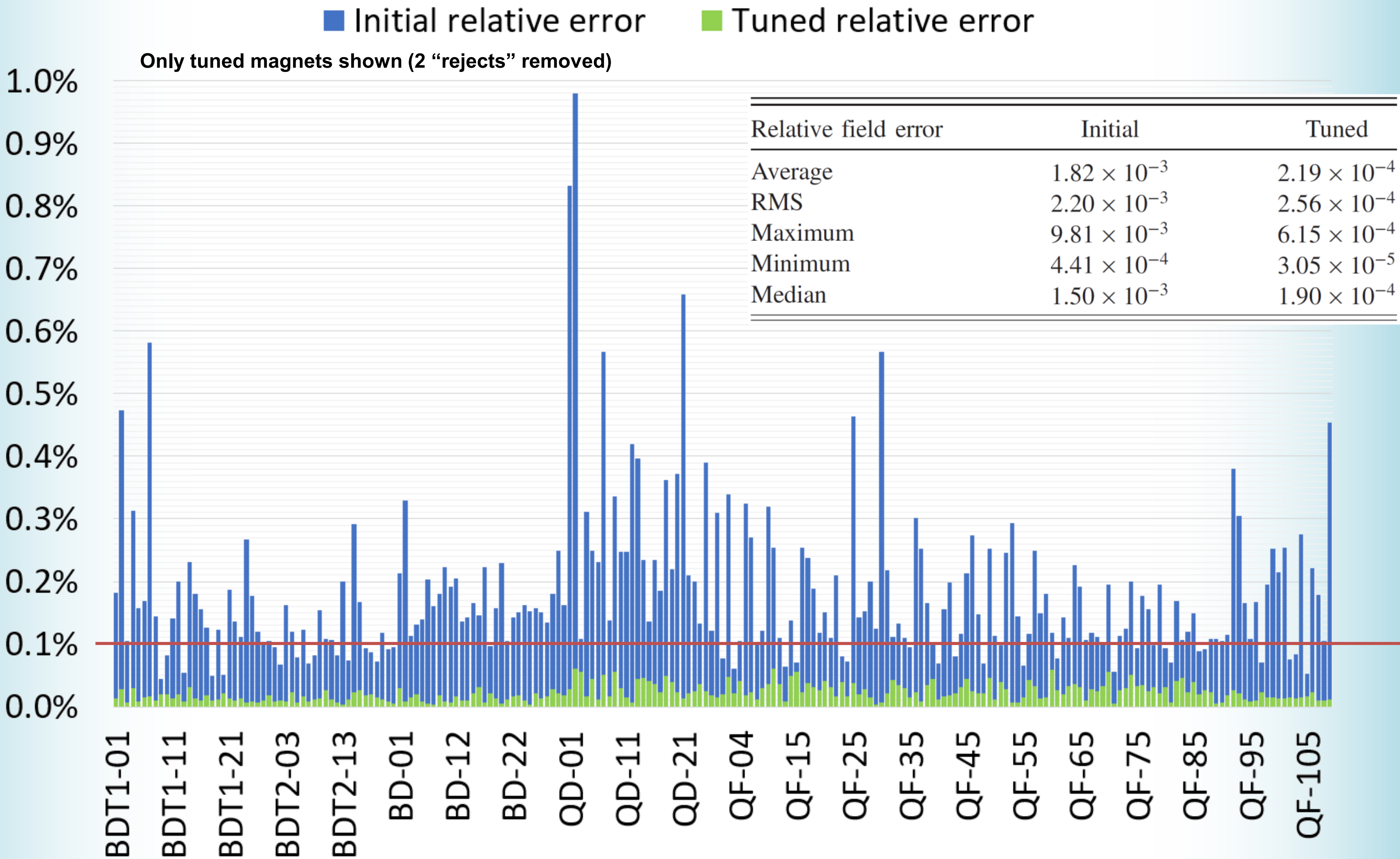
Rotating coil magnet measurement at BNL



Effect of Tuning (CBETA FOM)



CBETA FOM	Initial	Tuned
Average	1.380	0.092
RMS	1.515	0.113
Maximum	3.422	0.343
Minimum	0.562	0.014
Median	1.157	0.070

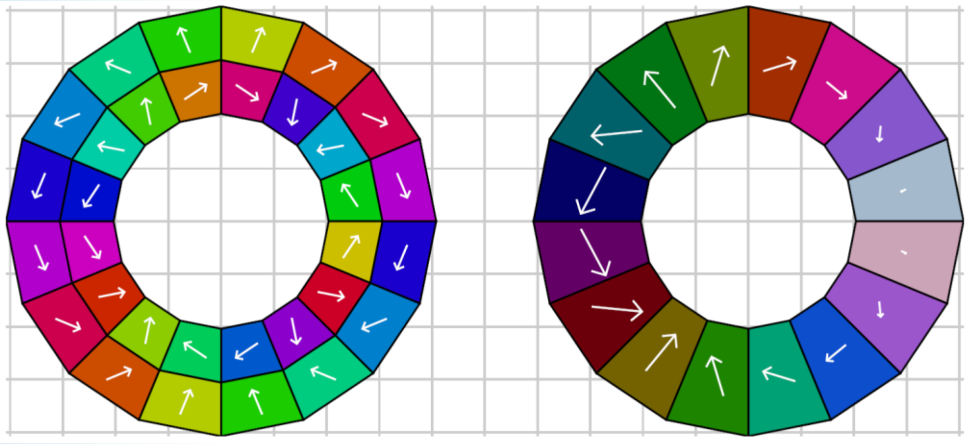


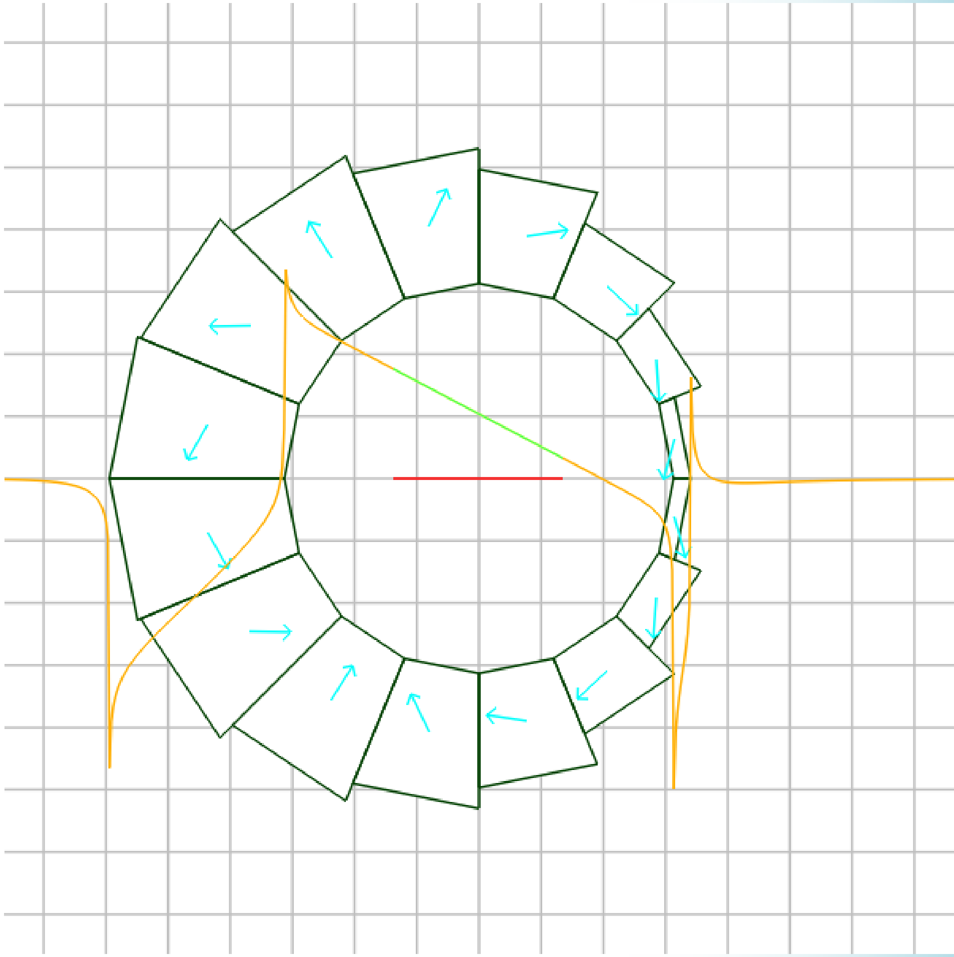
Relative field error	Initial	Tuned
Average	1.82×10^{-3}	2.19×10^{-4}
RMS	2.20×10^{-3}	2.56×10^{-4}
Maximum	9.81×10^{-3}	6.15×10^{-4}
Minimum	4.41×10^{-4}	3.05×10^{-5}
Median	1.50×10^{-3}	1.90×10^{-4}

CBETA Fixed-Field Return Arc

Combined-Function Magnet

Improvement over nested Halbach dipole and quadrupole (shown below) can be made by taking vector sum* of the two layers and implementing as a layer with constant magnetisation magnitude but variable wedge thickness.

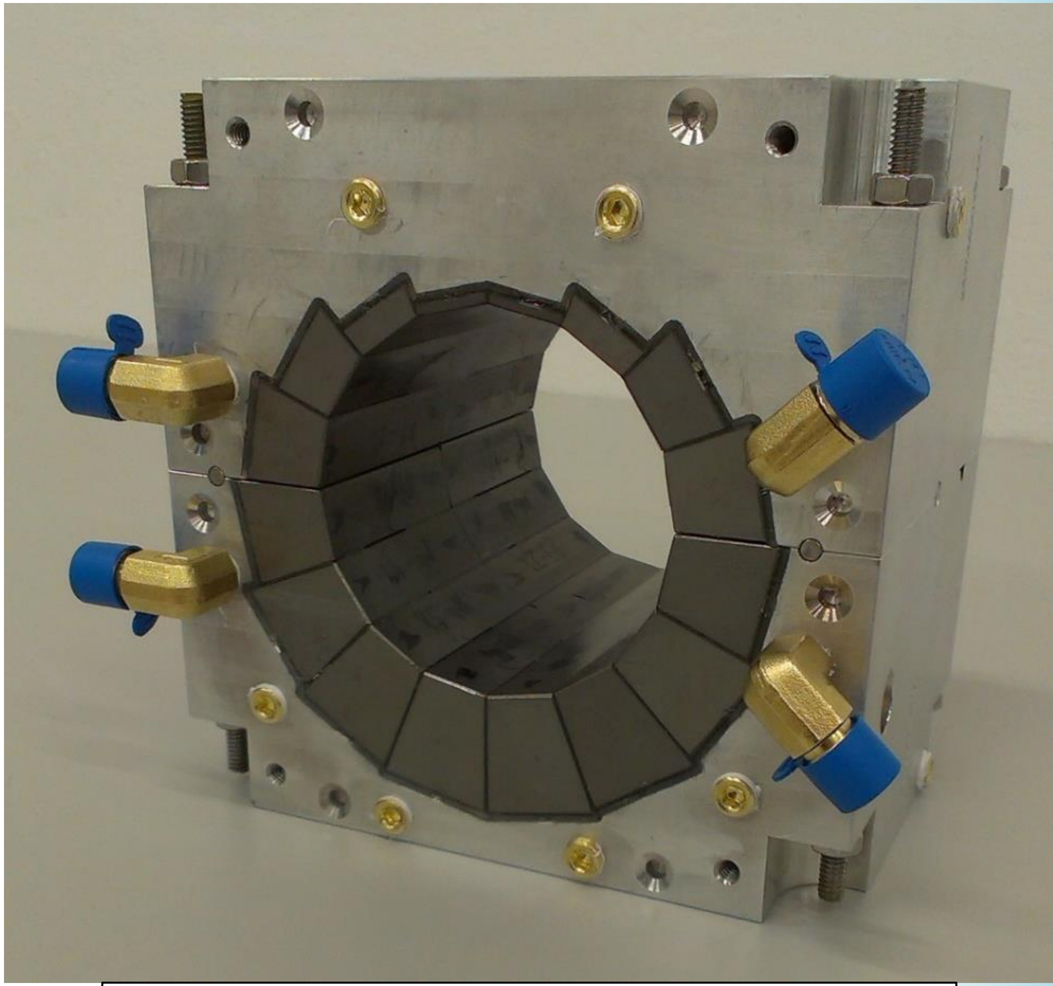




* Not exactly a vector sum, needs numerical optimiser for accurate design

CBETA Combined-Function Magnets

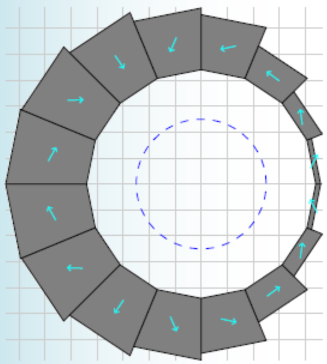
- 8 different wedge sizes
- Machined aluminium holder
- Successfully used with 42-150MeV electrons at CBETA
- 80 such magnets corrected to less than 10^{-3} error on a R=25mm aperture using iron rods



122mm length
-0.3081 T dipole
11.1475 T/m gradient
0.5868 T max field in good field region

Combined-Function Comparison

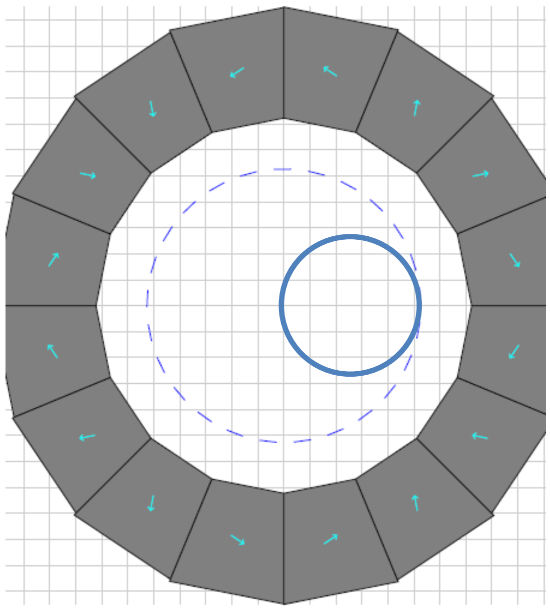
Combined-function (CBETA BD)



67.5cm^2

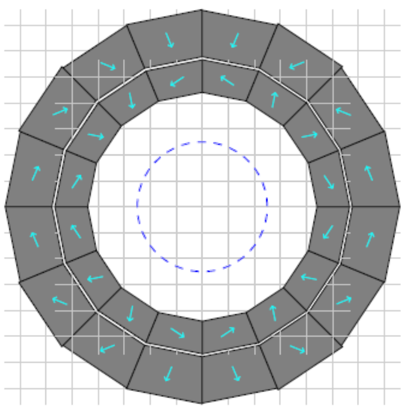
Aperture centered where it is needed for beam

Displaced quad



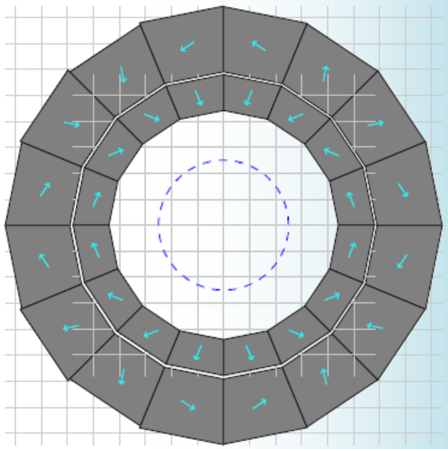
234.9cm^2

Quad in dipole



112.9cm^2

Dipole in quad



152.7cm^2

Quad scales less well with aperture than dipole

All designs 10^{-3} or better field quality

Combined-Function Uses

- Focussing and bending in one magnet
  - Fewer lattice elements, dispersion control
  - Possibly better dipole packing factor as result
- As well as CBETA ERL, found in:
  - Low-emittance synchrotron light source lattices
  - High energy aperture lines and storage rings
    - Permanent magnet hadron therapy gantry
    - Fixed-field accelerators e.g. CEBAF 20GeV upgrade
  - Some synchrotron accelerators

Magnets for modern and future light sources

- Modern lattices rely on quadrupole gradients ~>100 T/m
- Gaps reduced to 1-2 cm
- Trend towards complex combined magnets with field profiles tailored to the lattice requirements

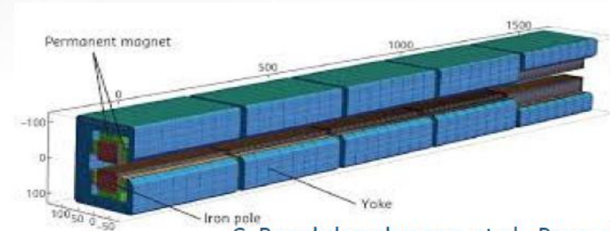
- MAX-4: single yoke with dipole and quadrupole magnets
- Advances in precise machining and integration
- Longitudinal gradient bends with multipole coils (Streun, SLS)
- Use of PM (ESRF-EBS)

- Transition to PM bending / focusing elements to save space
- Enabling lower power consumption

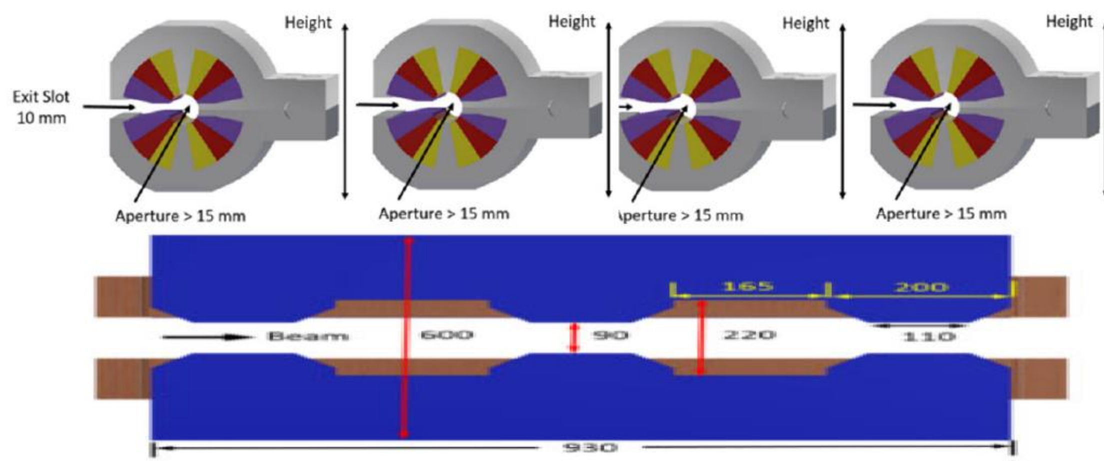
Sectioned magnets of MAX-4

M. Johansson, et al., J Synchrotron Radiat. 2014 21: 884–903

Longitudinal gradient dipole (ESRF)



C. Benabderrahmane, et al., Proc. of IPAC2016, Busan, TUPMB001

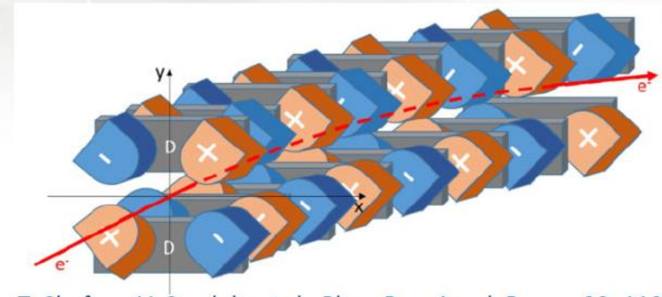


Constituents of Complex Bend magnets, PMQ and shell dipole (NSLS-II, BNL)

S. Sharma, et al., Proc.of IPAC2019, Melbourne, THPTS094

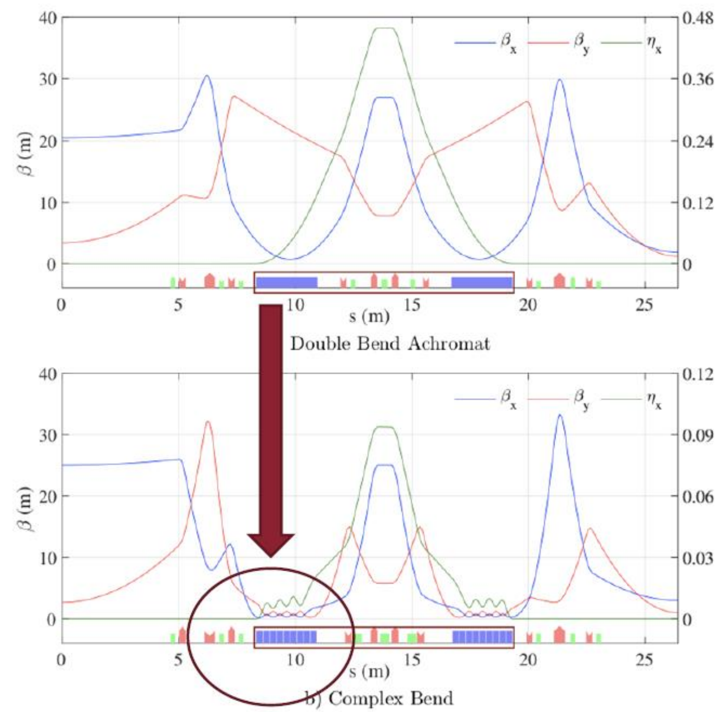
Sectioned magnets for low-emittance lattice design

- NSLS-II Complex Bend: a single element consisting of multiple B-Q poles
    - Quadrupole gradient < 200 T/m
      ⇒ use of permanent magnets
    - ✓ bending by the wide-gap long dipole magnet and strong focusing by short quadrupoles installed
      in the dipole's gap
    - ✓ combined B-Q Permanent Magnet elements



[G. Wang, T. Shaftan, V. Smaluk, et al., Phys. Rev. Accel. Beams 22, 110703 (2019)](#)

Proof-of-principle: 30x reduction in emittance vs DBA



[V. Smaluk, T. Shaftan, J. Phys.: Conf. Ser. 1350 012044 (2019)](#)

NSLS-II DBA
E=3 GeV
C=792 m
ε_x= 2000 pm

NSLS-IIU DCBA
E=3 GeV
C=792 m
ε_x= 65 pm

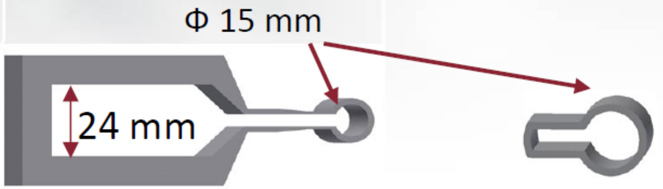
Benefits from replacing regular dipoles with Complex Bends:

- Possible design of lattices with record-low beam emittance
    - NSLS-II upgrade designs: 23 pm rad at 3 GeV with DA>+/-3 mm and MA with +/-4%
- Compact layout of Complex Bends
  ⇒ extra space for Insertion Devices and vacuum components

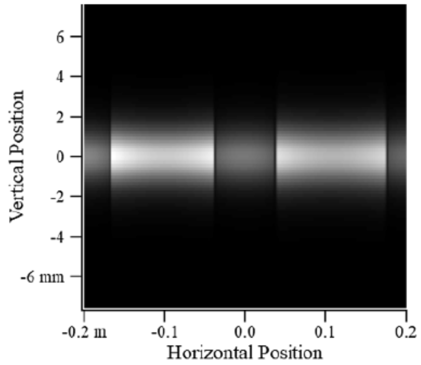
Challenges in Complex Bend development and R&D

- High gradients
  - Low field harmonics
  - Tuning for design field integrals
- Small gaps and tight geometry of magnets
  - Low space for pumping: ante-chamber where possible
  - Relying on NEG technology
- Design capable of handling high SR power loads
  - Extraction of SR from inside magnets
- Demagnetization of PMs by stray electrons and SR
- Minimizing chamber impedance and reducing heating due to wakefields
- NSLS-II has designed and built PMQs for a prototype of the CB
  - Magnetic measurements with rotating coil
  - Testing with 200 MeV beam
  - Demagnetization testing on the NSLS-II ring

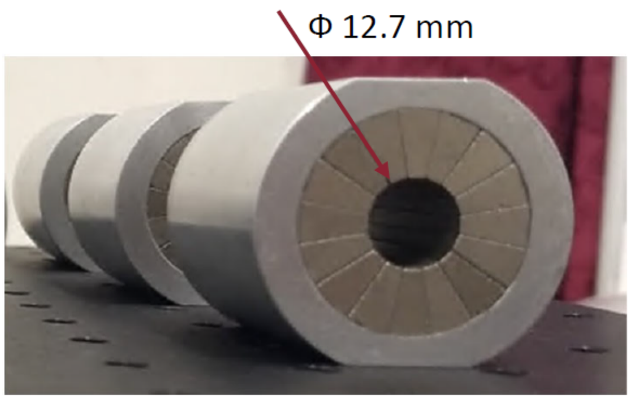
https://journals.aps.org/prab/abstract/10.1103/PhysRevAccelBeams.22.110703



VC with ante-chamber Neg-coated VC



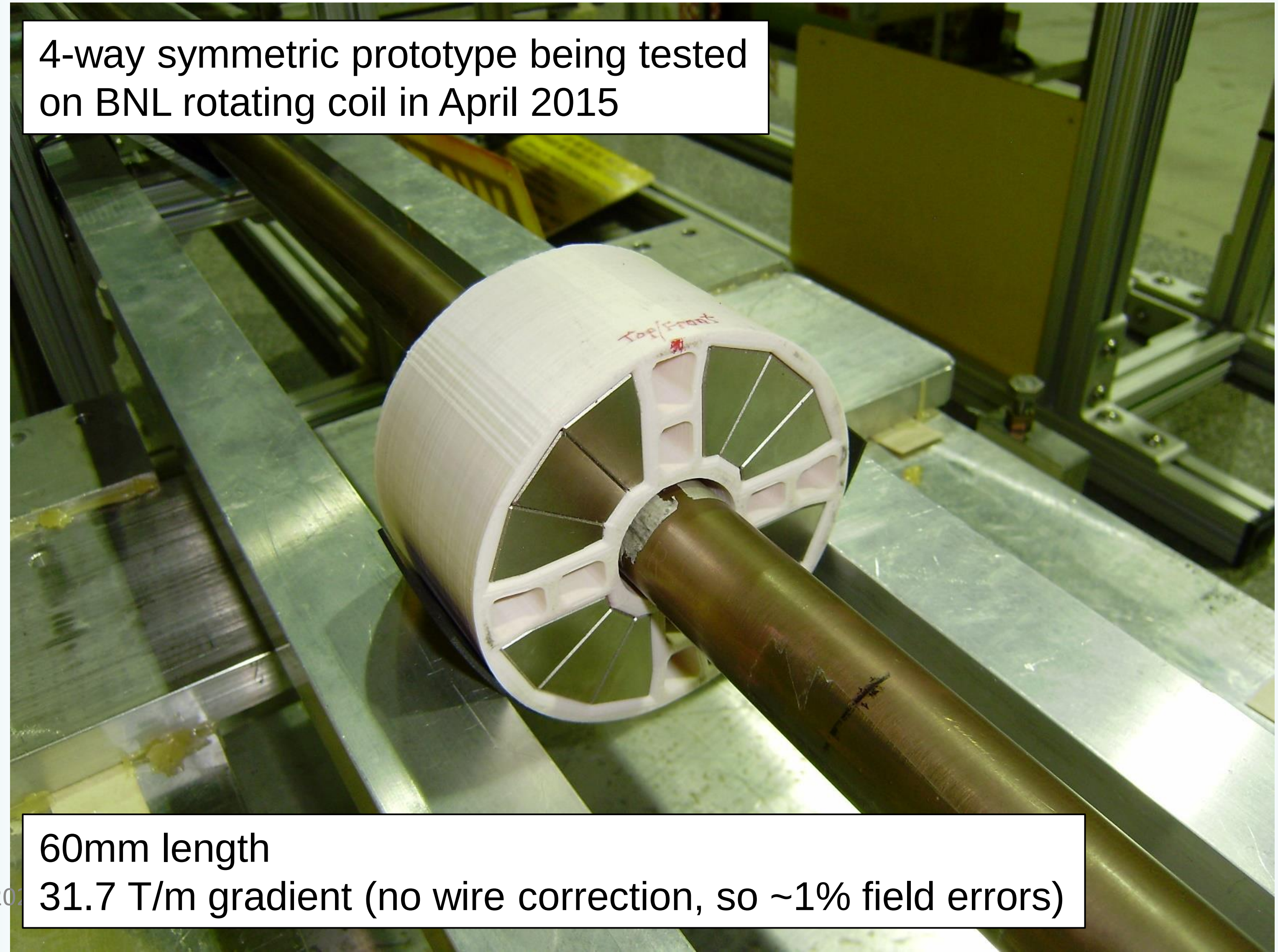
Synchrotron radiation pattern from Complex Bend



PMQs for a Prototype Complex Bend

Nick Tsoupas Open Midplane Quad

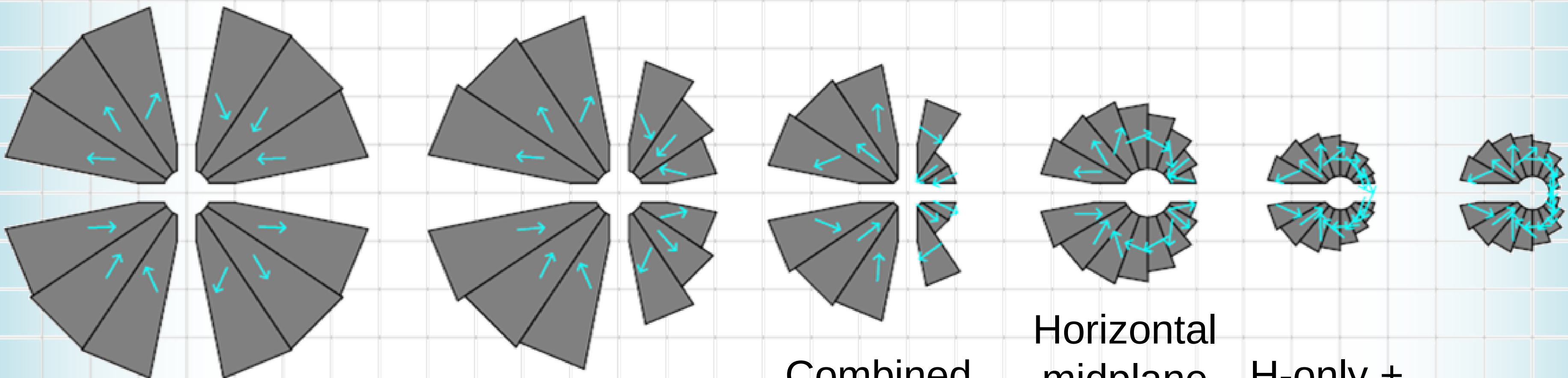
4-way symmetric prototype being tested
on BNL rotating coil in April 2015



60mm length
31.7 T/m gradient (no wire correction, so ~1% field errors)

Open Midplane Geometry Study

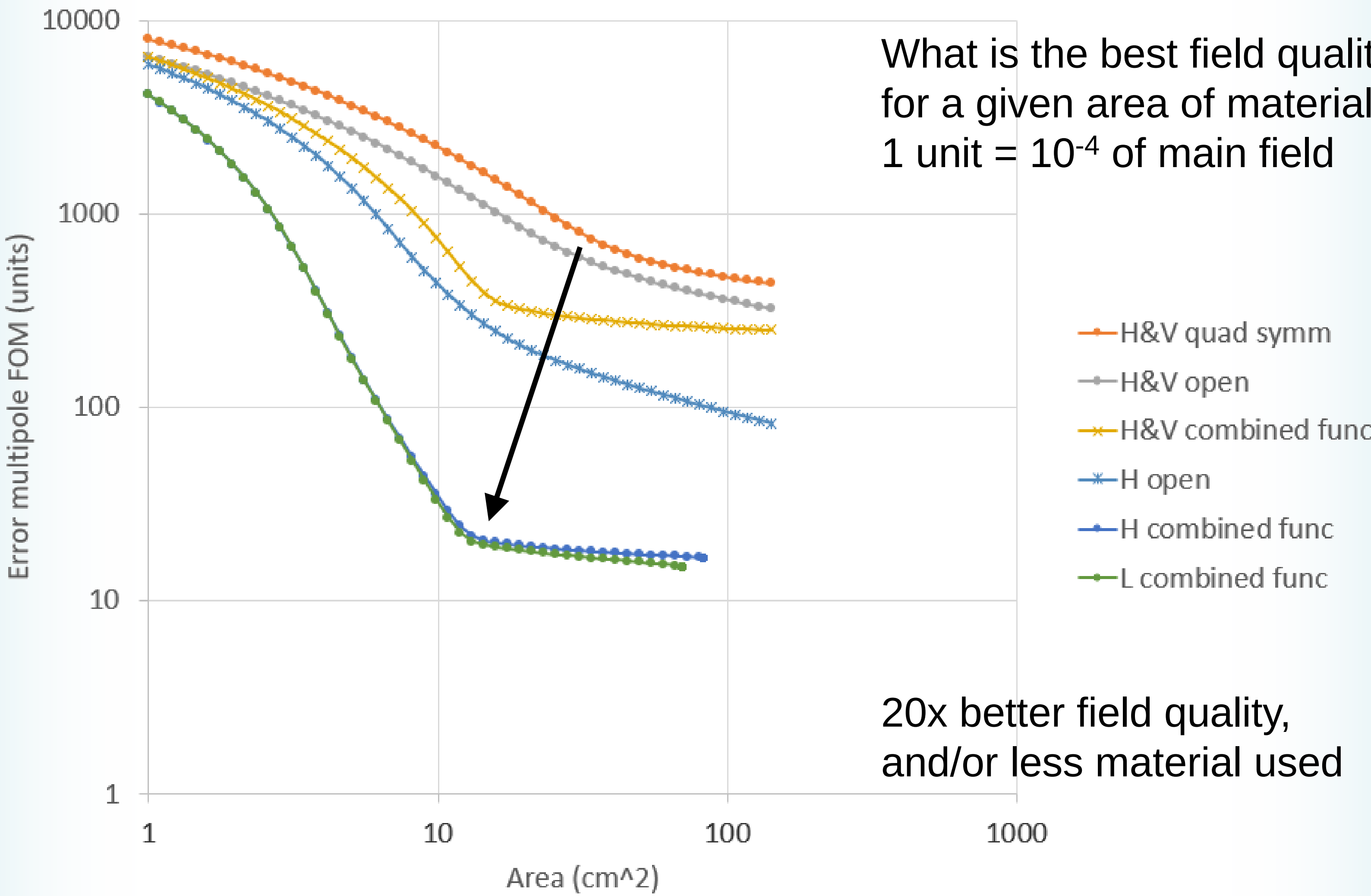
- -250T/m quadrupole combined with 0.49T dipole
  5mm Ø aperture, 2mm Ø good field region
  - 4mm gap open midplane slot
- B_r = 1.12T material



Offset quad symmetric | Offset quad non-symmetric | Combined function | Horizontal midplane only offset quad | H-only + combined function | Left-only midplane

Same aperture, same field, same field quality, improvement only by design modifications

Open Midplane Quality vs. Area

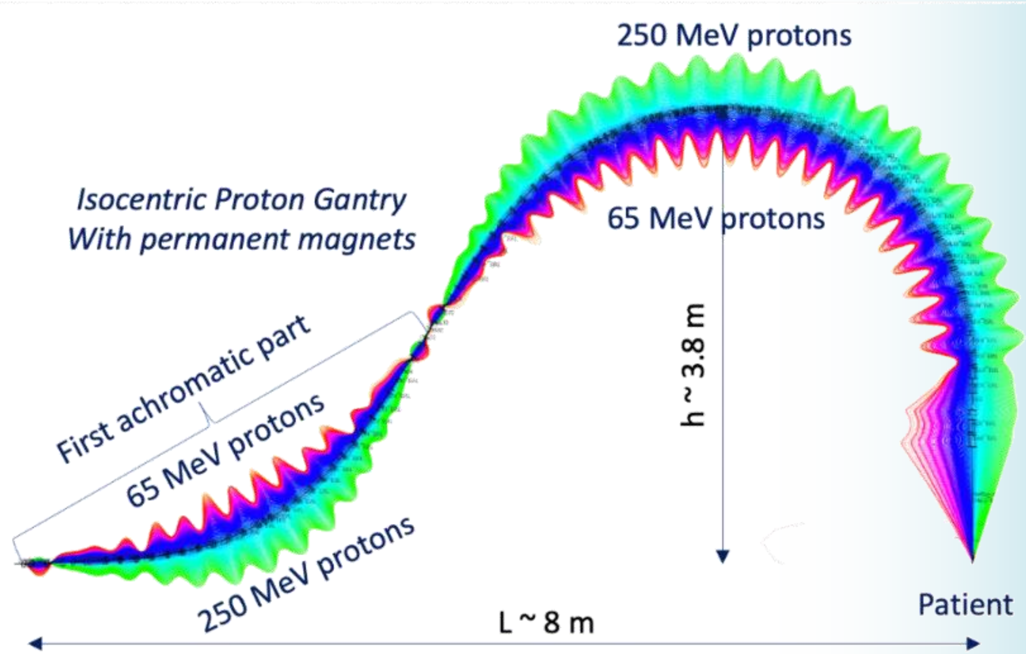


What is the best field quality for a given area of material?
1 unit = 10^{-4} of main field

20x better field quality, and/or less material used

PM Hadron Therapy Gantry

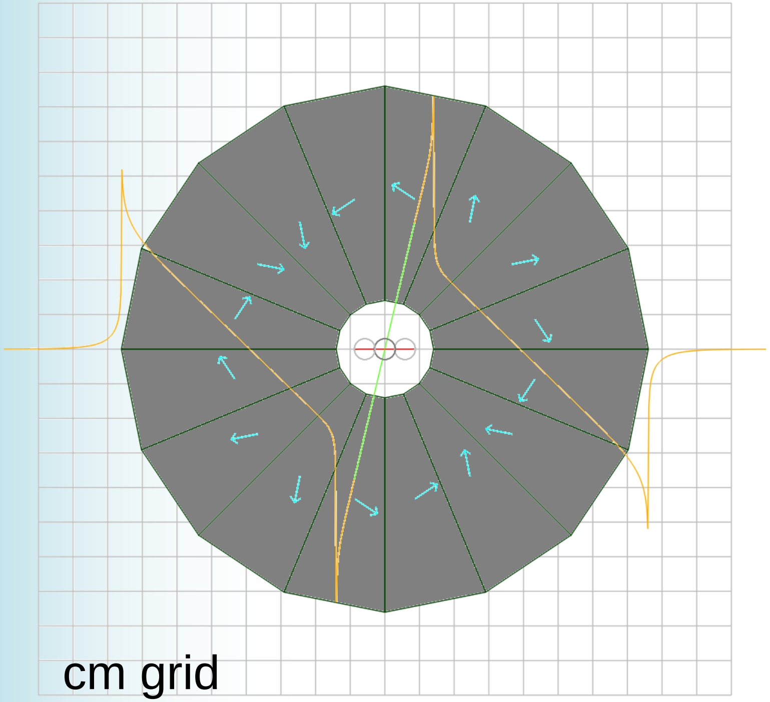
- Trbojevic design: a fixed-field gantry transports protons over the wide energy range 65-250MeV to the patient
  - Faster depth (energy) scanning because no magnet ramp
  - Lighter-weight and less power used than electromagnets
- Requires a horizontal beam excursion
  - Magnified trajectories shown on right
- Higher fields give a smaller rotating gantry
  - Want highest possible field gradient magnets!

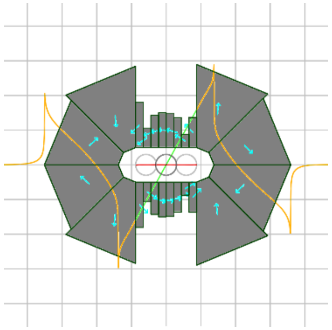


Dejan Trbojevic *et al.*, Proc. IPAC2017
This conference TUPAB030

Oval Aperture Comparison

- Therapy gantry QF magnet





Same scale!

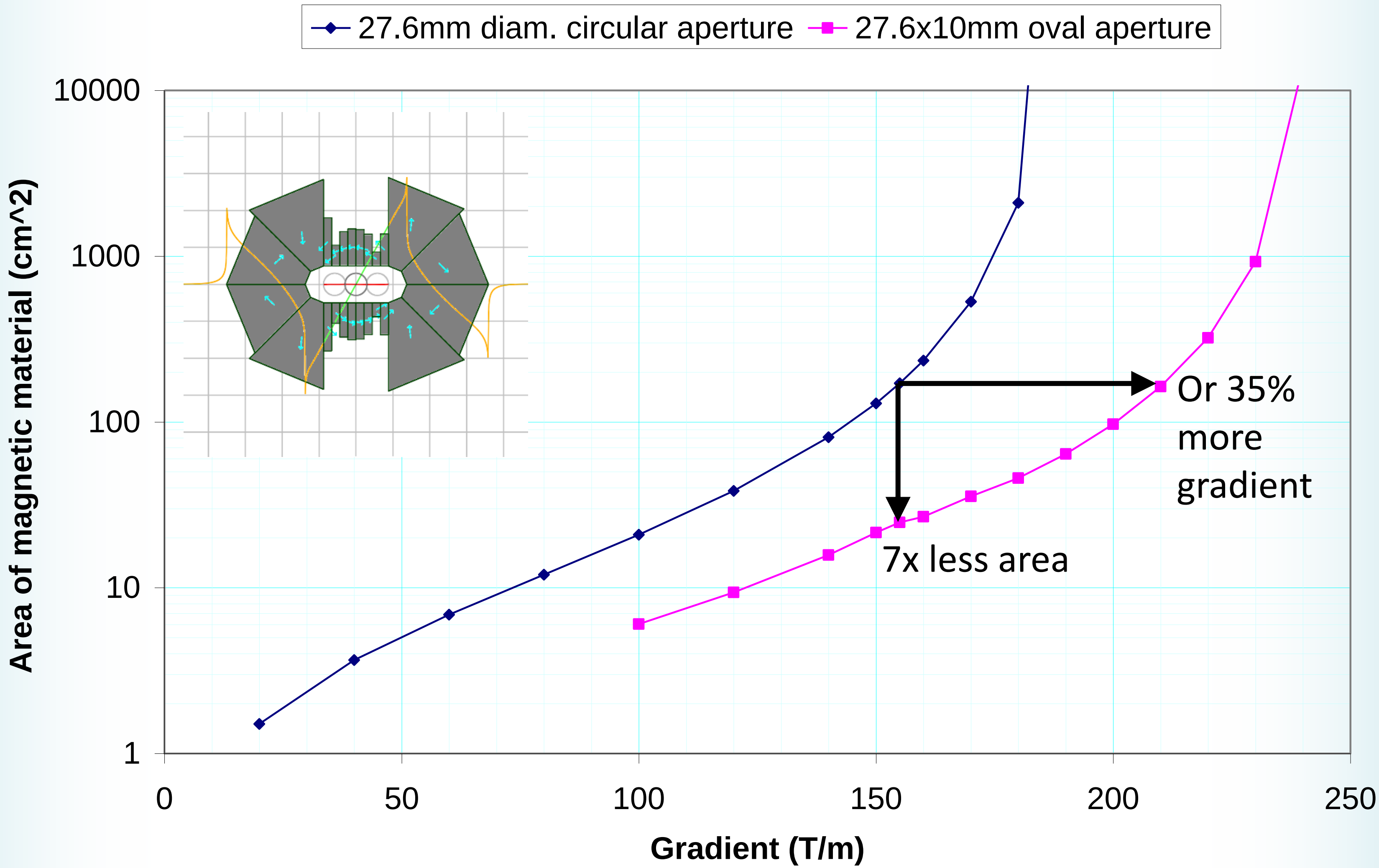
155T/m quadrupole
27.6mm horizontal aperture
B_r = 1.4T material
$<10^{-4}$ field midplane accuracy

Left: circular aperture
170.9cm^2 of material

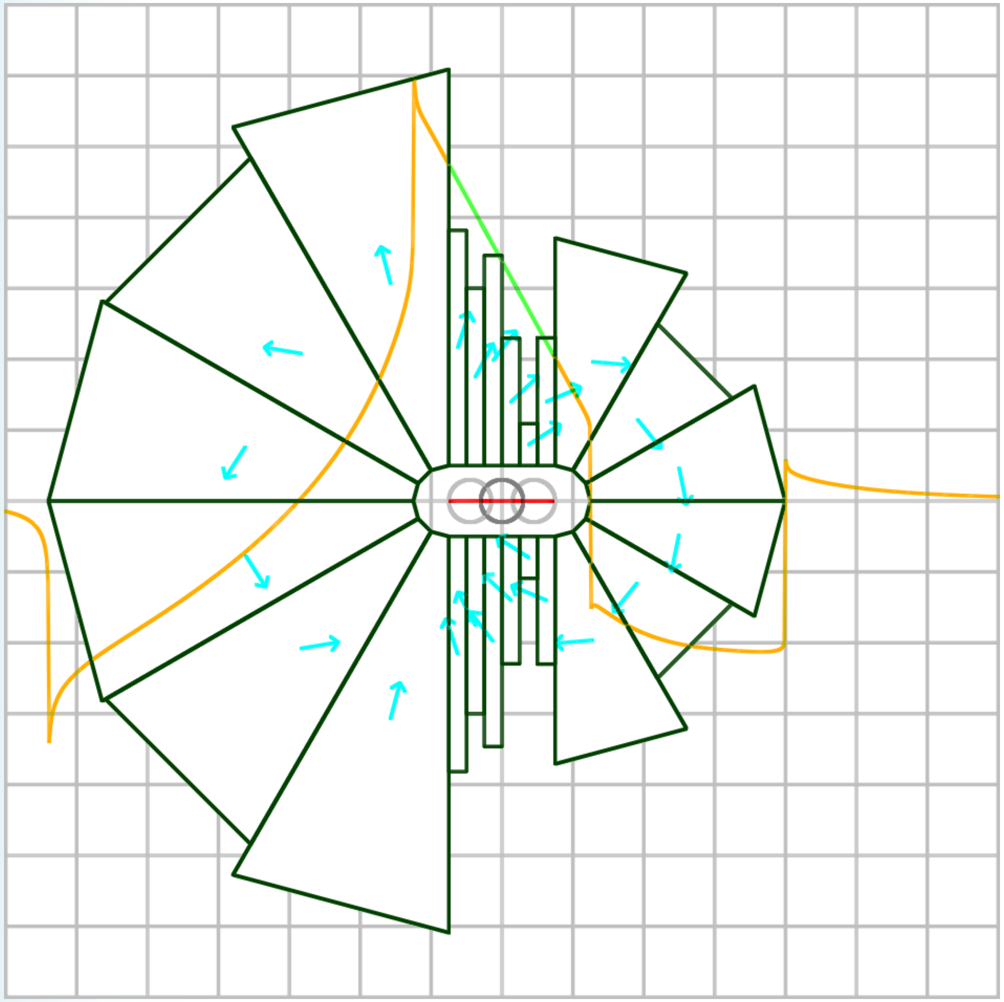
Right: oval aperture
10mm vertical height
24.0cm^2 of material

Sevenfold reduction in material use by only having aperture in the axis where it is needed

Oval Aperture Area vs. Strength



Oval Aperture Combined-Function

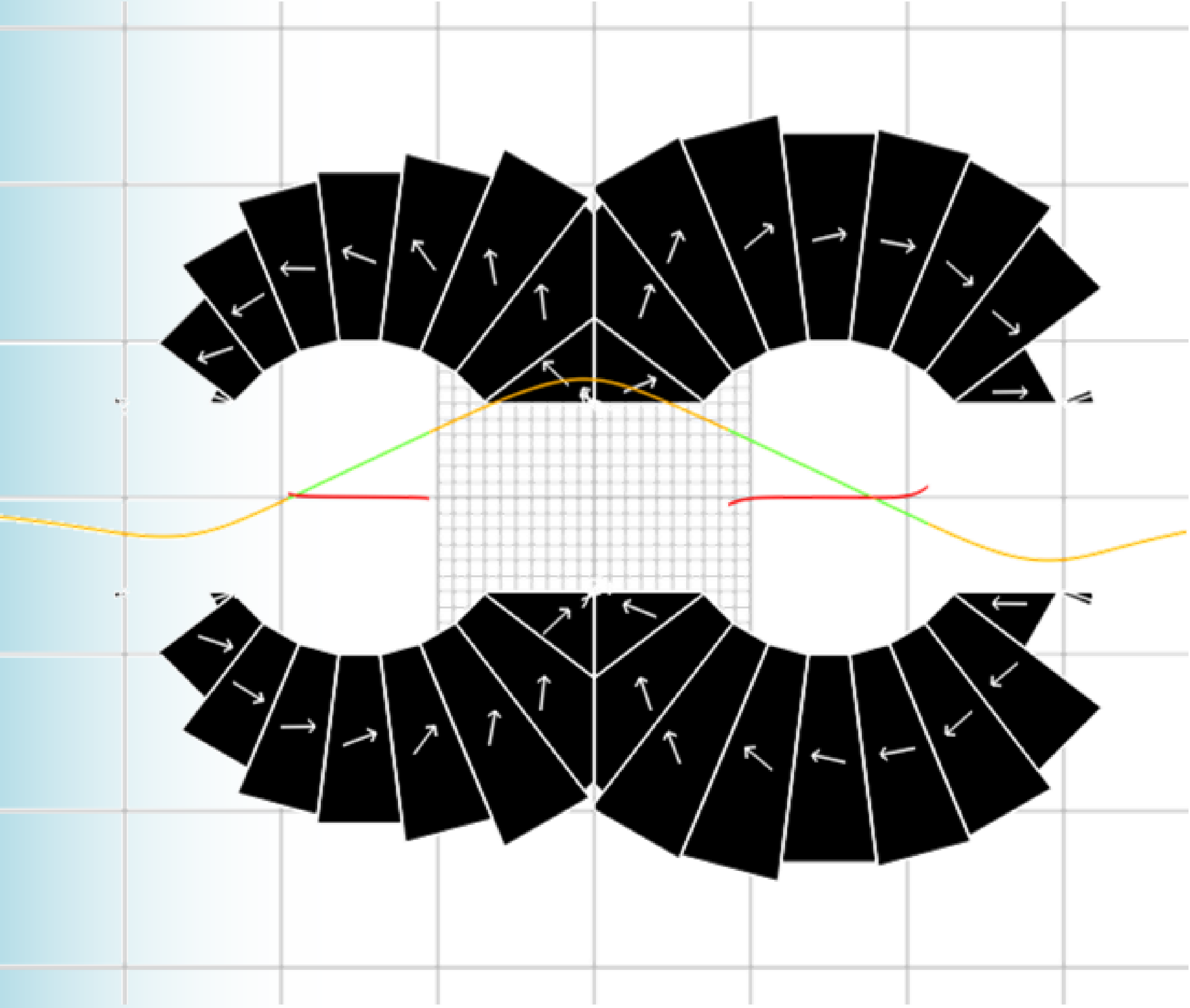


1.8 T dipole
-97 T/m gradient
2.527 T max field in good field region(!)

25.0mm horizontal aperture
B_r = 1.4T material
$<2\times10^{-4}$ field midplane accuracy

High fields put material into regime with high opposing flux (negative H field). This means demagnetisation is more likely, depending on grade, especially in presence of radiation. Future R&D will build and test such magnets.

Multiple Aperture Designs



Design produces a different combined function field in each aperture

3cm aperture separation
R10mm circular apertures
±6mm open midplane

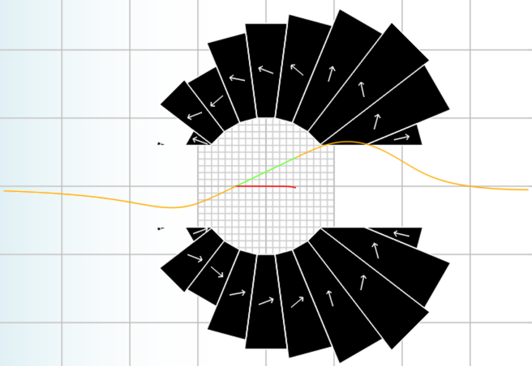
0.2190 T +49.515 T/m left
0.1382 T -49.515 T/m right

Good field radii
4.5mm left, 6.4mm right

Units (10^{-4}) field error
4.7 left, 18.0 right

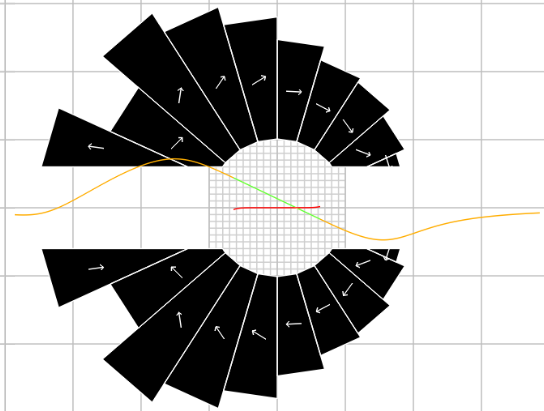
Comparison to Separate Magnets

Just BD (left)



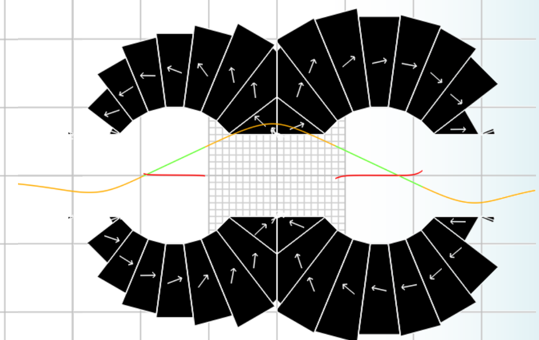
11.3cm^2

Just BF (right)



15.4cm^2

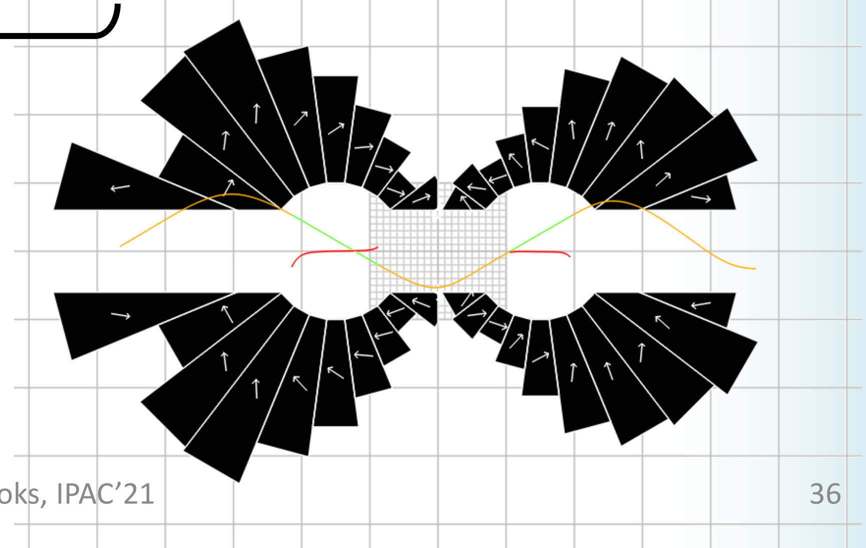
Two-hole



15.2cm^2

Total = 26.6cm^2

28.9cm^2 if you try to combine them in the “backwards” way →



Multiple Aperture Uses

- Cost savings
  - Some PM material volume savings
  - Build as a single component
    - Only one vacuum chamber, girder etc.
- Operational flexibility
  - Modern colliders require rings for many functions
    - Acceleration, accumulation, cooling, collision
  - Building multiple tracks cheaply allows one beam to be cooled while another is collided for example

Upcoming R&D

- Build and test prototypes of Halbach magnet variants discussed here
  - Parameter scan, several prototypes
  - Field test, field tuning, perhaps radiation test
  - $400k approved in total Oct 2021 to Sep 2023
- Build engineering prototype of NSLS-II upgrade magnet
  - Full field, full gradient, full length
  - Proposal underway (at NSLS-II), would be >$1M

Adaptations for Small Aperture

- Tuning rod cartridges use too much aperture
  - Iron rods could be adhered to tape rather than in grooves of 3D printed cartridge
  - Or placed in integrated vacuum chamber grooves
- BNL rotating coils too large for many cases
  - NSLS-II have a rotating wire measurement system
    - Designed for smaller apertures
  - Horizontal scans with Hall probe or vibrating wire are possible but positional accuracy may be worse

Conclusions

- 200+ accelerator quality Halbach permanent magnets produced and tested at CBETA
  - Iron rod shimming is a widely applicable method
- Many new applications of Halbach magnets proposed in accelerators around the world
  - Fixed field magnets in milder radiation areas
  - Power and cost saving (no power supply)
- Broad R&D activities at BNL
  - Exploratory tech development and project-specific