FCC-ee Design Project

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FUTURE CIRCULAR COLLIDER

John Adams Institute for Accelerator Science

UNIVERSITY OF OXFORD

ROYAL HOLLOWAY UNIVERSITY OF LONDON

Imperial College London

Meet the team

Beam Optics

Magnet Design

RF Cavity Design

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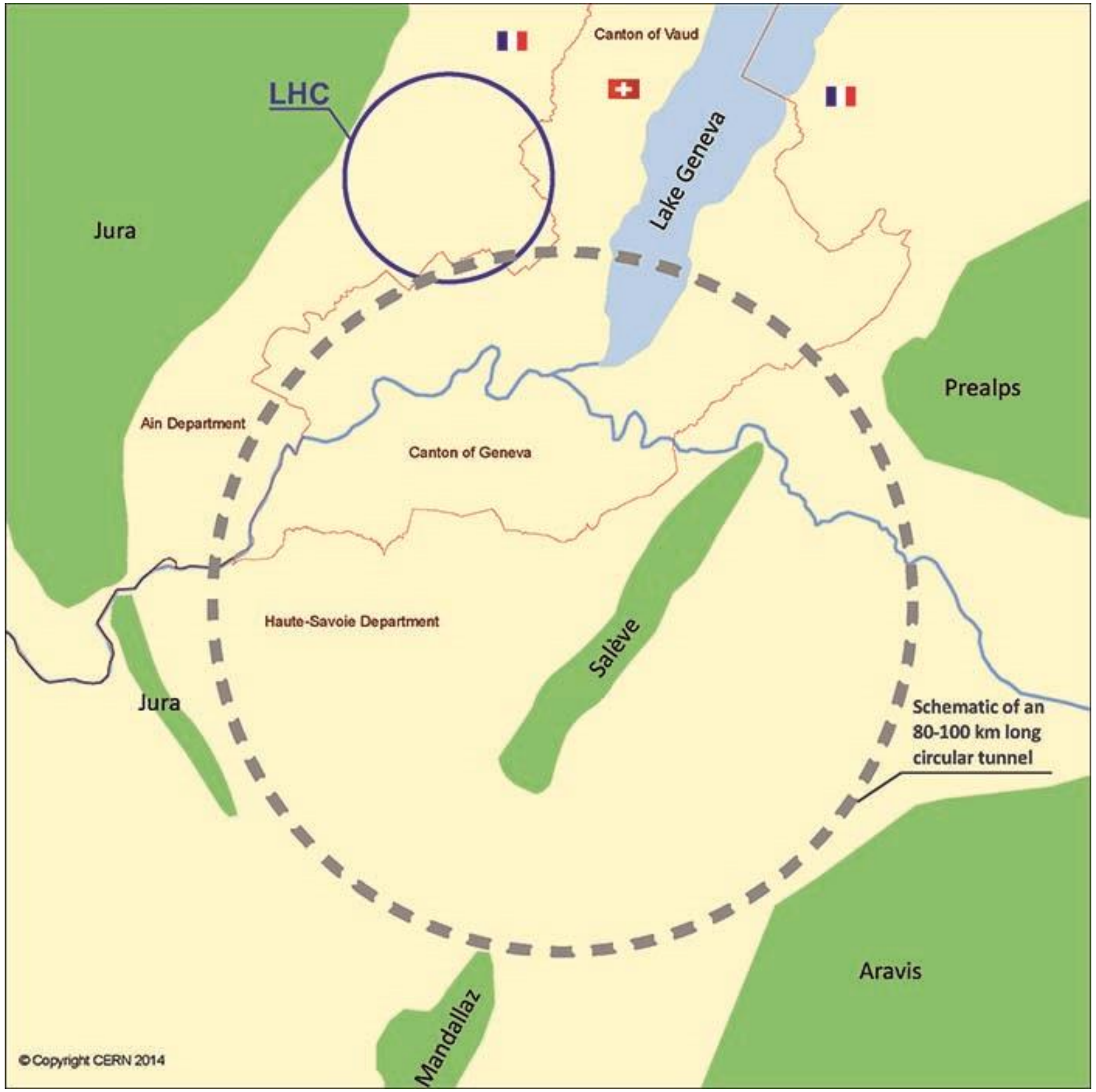
Introduction

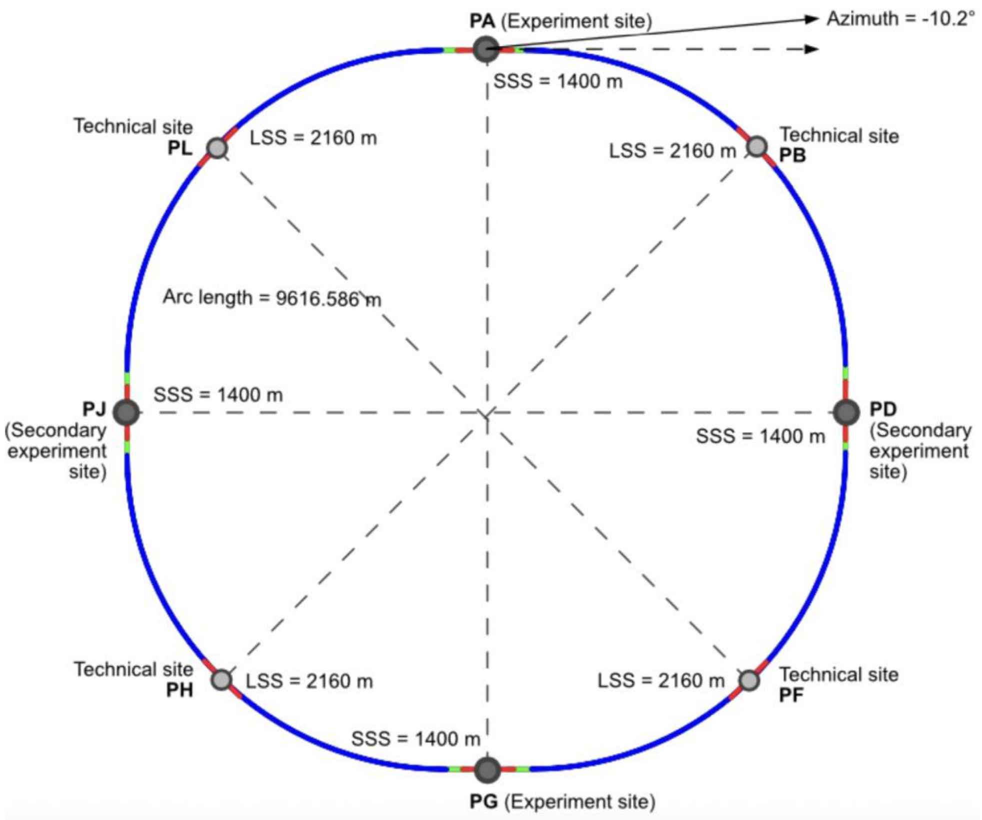
- Geneva region
- >~90 km circumference
- 4 collision points
- Double-ring configuration
- Collision energies between 90 and 365 GeV

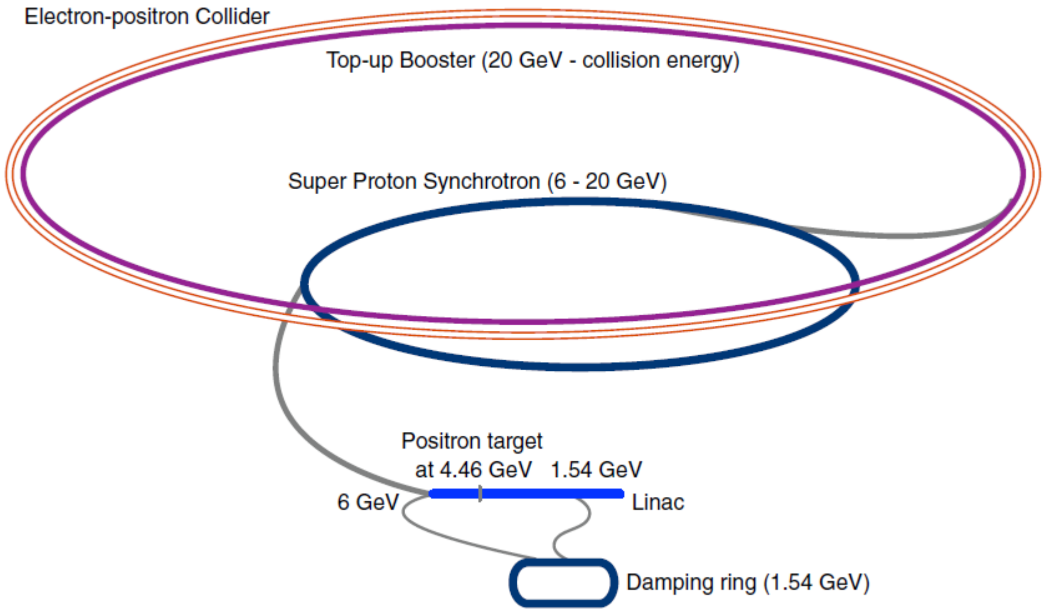
Goals to extend current research at LHC:

- Precision measurements of the properties of the Higgs boson
- Z and W bosons
- Top quark
- Higgs coupling to Z

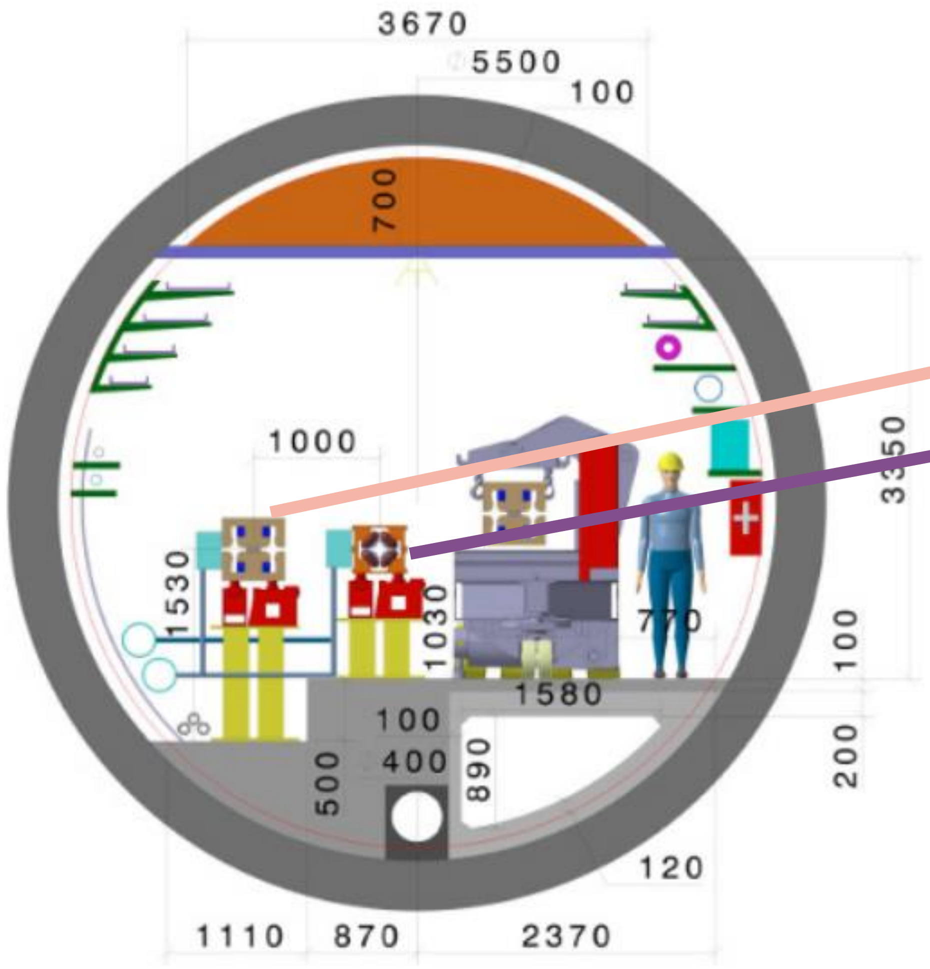


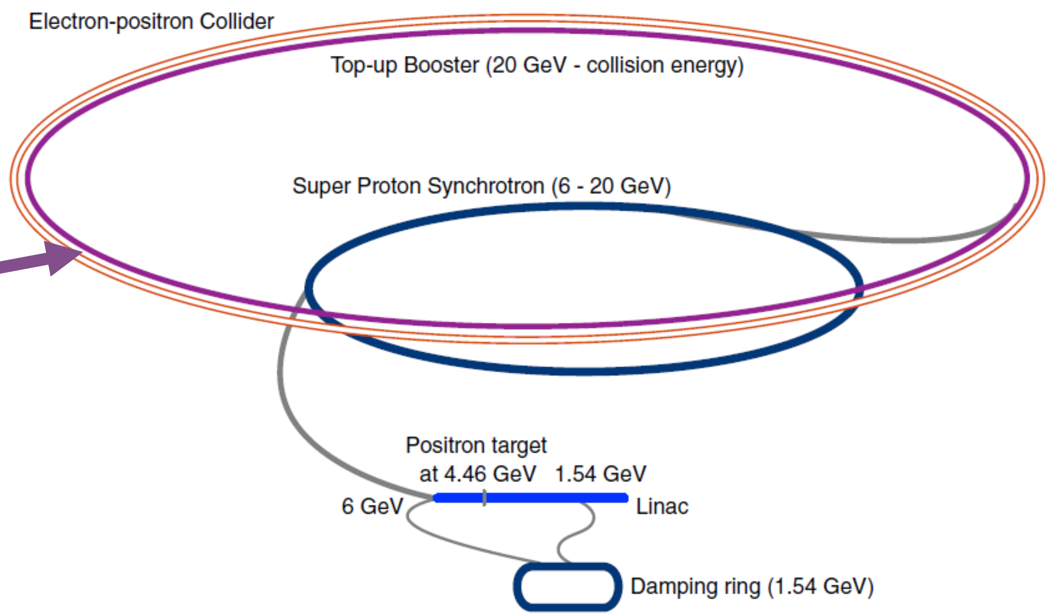
FCC-ee layout





FCC-ee layout





FCC-ee Design Parameters

Table 6.1. FCC-ee injector parameters.

Parameter (unit)	Z		W		H		$t\bar{t}$	
Beam energy (GeV)	45.6		80		120		182.5	
Type of filling	Initial	Top-up	Initial	Top-up	Initial	Top-up	Initial	Top-up
Linac bunches/pulse	2				1			
Linac repetition rate (Hz)	200		100					
Linac RF frequency (GHz)	2.8							
Bunch population (10^{10})	2.13	1.06	1.88	0.56	1.88	0.56	1.38	0.83
No. of linac injections	1040		1000		328		48	
PBR minimum bunch spacing (ns)	10		10		70		477.5	
No. of PBR cycles	8		1					
No. of PBR bunches	2080		2000		328		48	
PBR cycle time (s)	6.3		11.1		3.7		0.9	
PBR duty factor	0.84		0.56		0.30		0.08	
No. of BR/collider bunches	16640		2000		328		48	
No. of BR cycles	10	1	10	1	10	1	20	1
Filling time (both species) (s)	1034.8	103.5	266	26.6	137.6	13.8	223.2	11.2

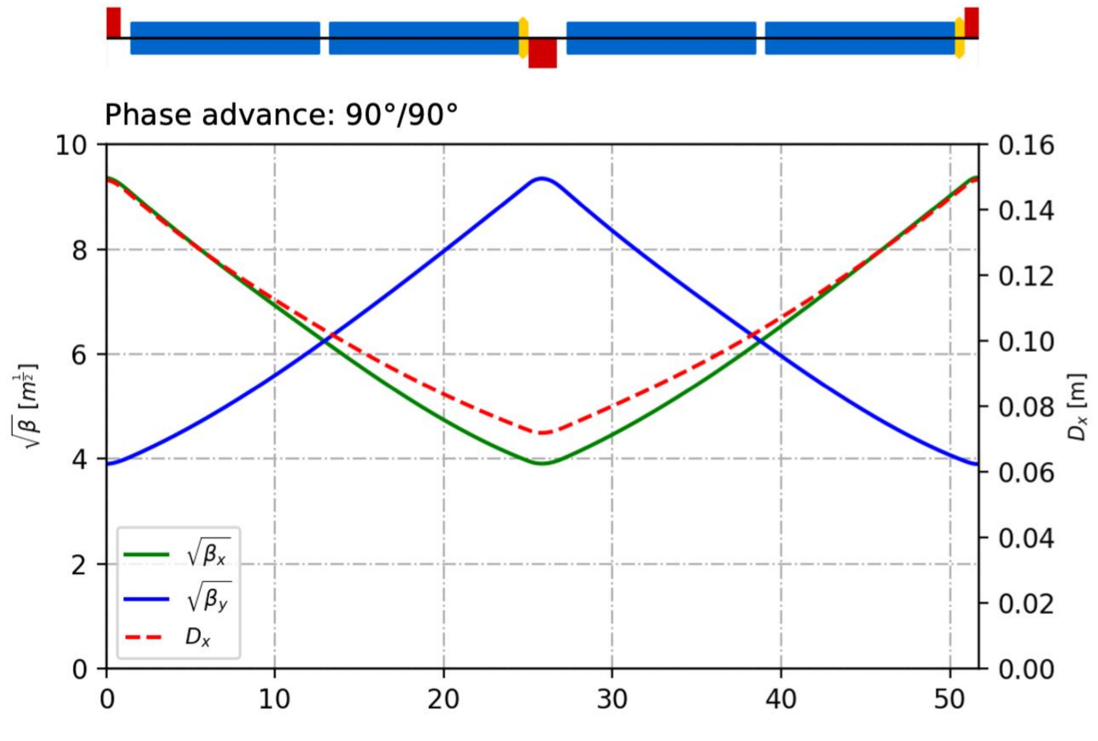
Table 1. Machine parameters of the FCC-ee for different beam energies.

	Z	WW	ZH	$t\bar{t}$	
Circumference (km)	97.756				
Bending radius (km)	10.760				
Free length to IP l^* (m)	2.2				
Solenoid field at IP (T)	2.0				
Full crossing angle at IP θ (mrad)	30				
SR power/beam (MW)	50				
Beam energy (GeV)	45.6	80	120	175	182.5
Beam current (mA)	1390	147	29	6.4	5.4
Bunches/beam	16 640	2000	328	59	48
Average bunch spacing (ns)	19.6	163	994	2763	3396
Bunch population (10^{11})	1.7	1.5	1.8	2.2	2.3
Horizontal emittance ε_x (nm)	0.27	0.84	0.63	1.34	1.46
Vertical emittance ε_y (pm)	1.0	1.7	1.3	2.7	2.9
Horizontal β^*_x (m)	0.15	0.2	0.3	1.0	
Vertical β^*_y (mm)	0.8	1.0	1.0	1.6	
Energy spread (SR/BS) σ_δ (%)	0.038/0.132	0.066/0.131	0.099/0.165	0.144/0.186	0.150/0.192
Bunch length (SR/BS) σ_z (mm)	3.5/12.1	3.0/6.0	3.15/5.3	2.01/2.62	1.97/2.54
Piwinski angle (SR/BS) ϕ	8.2/28.5	3.5/7.0	3.4/5.8	0.8/1.1	0.8/1.0
Energy loss/turn (GeV)	0.036	0.34	1.72	7.8	9.2
RF frequency (MHz)	400			400/800	
RF voltage (GV)	0.1	0.75	2.0	4.0/5.4	4.0/6.9
Longitudinal damping time (turns)	1273	236	70.3	23.1	20.4
Energy acceptance (DA) (%)	±1.3	±1.3	±1.7	-2.8 +2.4	
Polarisation time t_p (min)	15000	900	120	18.0	14.6
Luminosity/IP (10^{34}/cm^{2}s)	230	28	8.5	1.8	1.55
Beam-beam ξ_x/ξ_y	0.004/0.133	0.010/0.113	0.016/0.118	0.097/0.128	0.099/0.126
Beam lifetime by rad. Bhabha scattering (min)	68	59	38	40	39
Actual lifetime incl. beam-strahlung (min)	>200	>200	18	24	18

Notes. For $t\bar{t}$ operation a common RF system is used.

FCC-ee Booster Beam Optics

FCC-ee Booster - ARC FODO cell



Lengths:

L_{dipole} = 11.1 m

$L_{quadrupole}$ = 1.5 m

$L_{sextupole}$ = 0.5 m

- Phase advance: 90°/90°
- Sum of ARC lengths: 76 932.686 m
  - Fixed by FCC-hh design
- Number of dipoles: 5888

→ ARC FODO length of about 52 m

- Number of quadrupoles and sextupoles: 2944
- Max. quadrupole fields for E = 182.5 GeV:

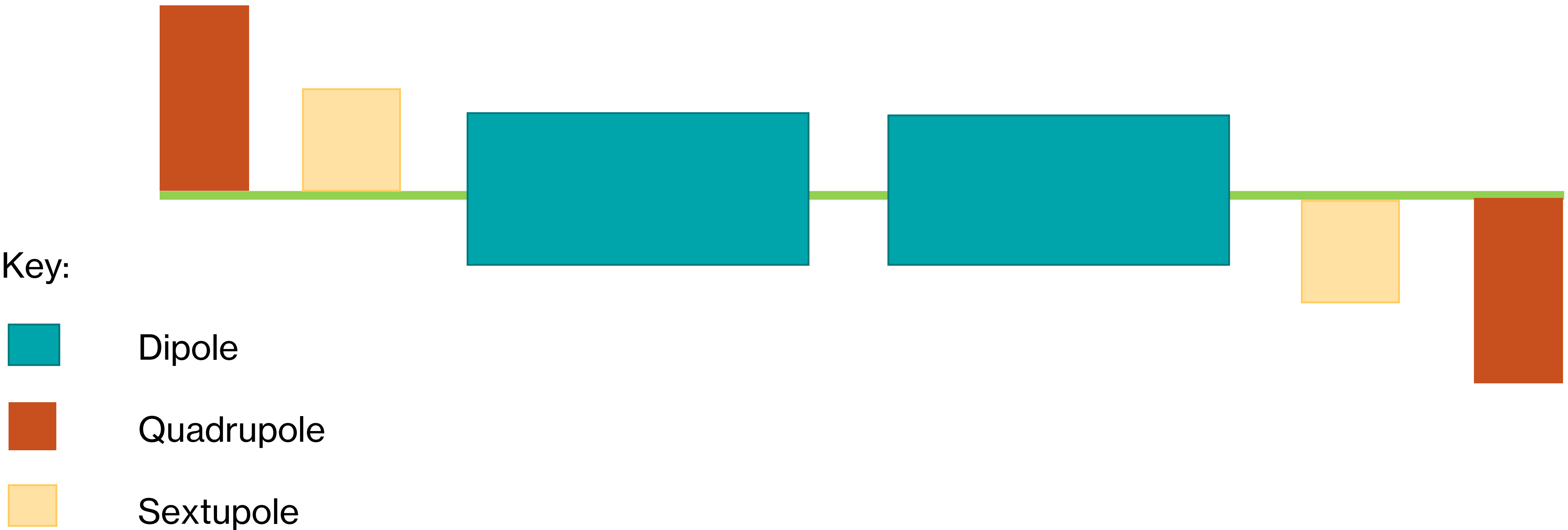
  $B_{1,max}$ = 22.63 T/m (from matching)

https://indico.cern.ch/event/1101643/contributions/4635249/attachments/2380938/4068188/Booster%20Design.pdf

FODO design: space for diagnostics

Total length: 52.264m

- "Your accelerator is only as good as its diagnostics" – *Emmanuel Tsesmelis*



FODO design: space for diagnostics

- Ideally BPMs are situated next to dipole corrector (kicker) magnets
  - Why?

$$\Delta \mathbf{u}_m = \mathcal{M} \boldsymbol{\theta}_n$$

- BPMs ~ 10cm long
- Dipole Kickers 20-30c

$$\mathcal{M}_{ik} = \frac{\sqrt{\beta_i \beta_k}}{2 \sin \pi \nu} \cos\left[\nu\left(\varphi_i - \varphi_k + \pi\right)\right]$$

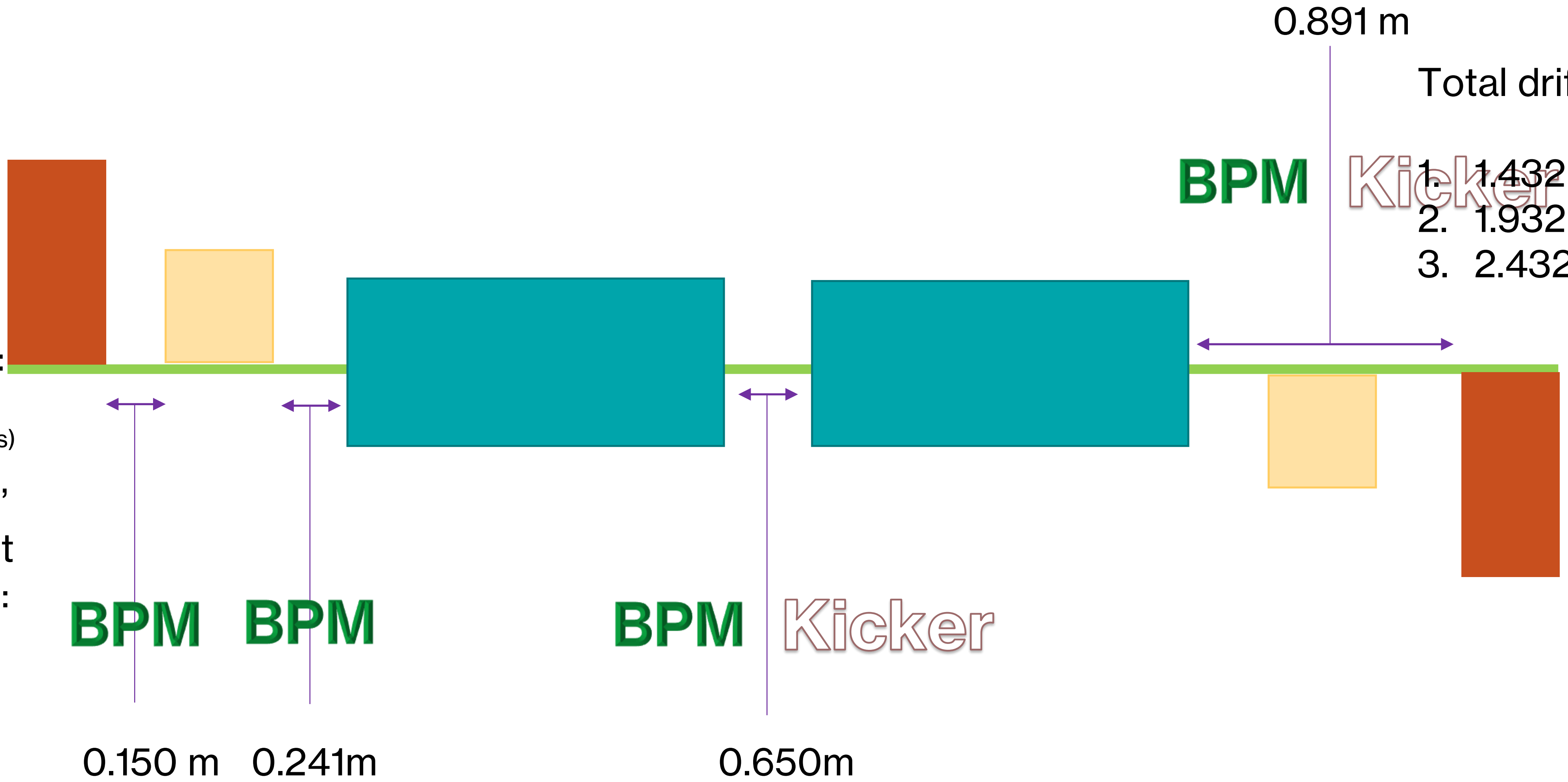
- ➔ estimate 35-45cm

FODO design: space for diagnostics

Total length:
52.264m

➔ ‘Minimum’:
51.832m
(for given dipoles)

➔ ‘Maximum’
Length left
to remove:
~1270m



Total drift space:

1. 1.432m (SD,SF)
2. 1.932m (SD,D)
3. 2.432m (D,D)

Comparison of Sextupole Schemes

Interleaved

2 FODO periodicity

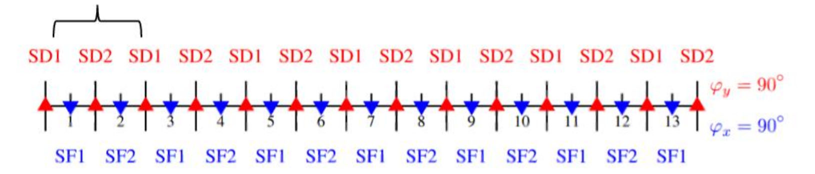


Fig. 6: Schematic of an interleaved sextupole scheme for a FODO cell lattice with $\varphi = 90^\circ$ phase advance in both planes. After every quadrupole a sextupole magnet is installed leading to a maximum number of sextupoles. The sextupoles that are separated by a phase advance of π form a family. In this case there are two families per planes.

Max. field for E = 182.5 GeV:

$k_{2,max}$ = 2.058

$B_{2,max}$ = 1251.7 T/m^2

Non-Interleaved A

6 FODO periodicity

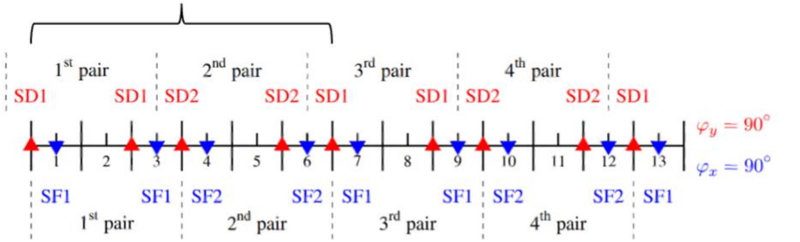
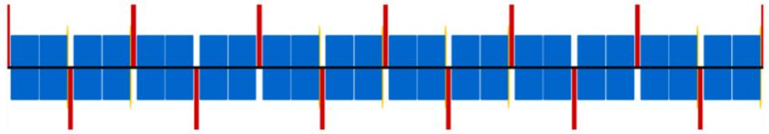


Fig. 7: Schematic of a non-interleaved sextupole scheme for a FODO cell lattice with $\varphi = 90^\circ$ phase advance in both planes. In each plane sextupole pairs are installed with a distance of π phase advance. The sextupoles are considered to only act in one plane and are interlaced with the ones of the other plane.



Max. field for E = 182.5 GeV:

$k_{2,max}$ = 3.125

$B_{2,max}$ = 1900.7 T/m^2

Non-Interleaved B

10 FODO periodicity

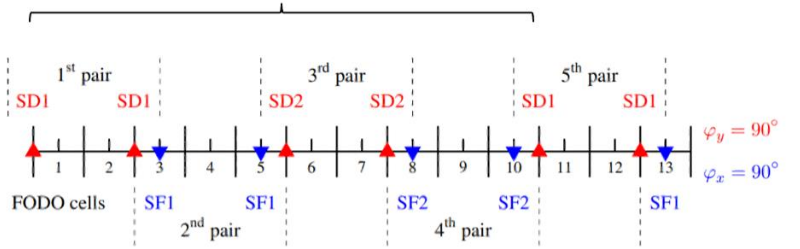
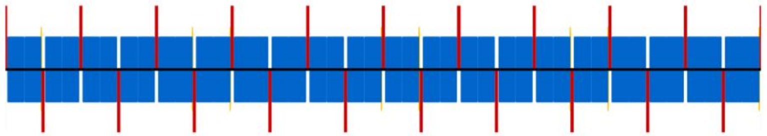


Fig. 8: Completely non-interleaved sextupole scheme for a FODO cell lattice with $\varphi = 90^\circ$ phase advance in both planes. In order to optimise the cancellation of the sextupole's geometric effect, only linear elements are installed between two sextupoles forming a pair.



Max. field for E = 182.5 GeV:

$k_{2,max}$ = 5.273

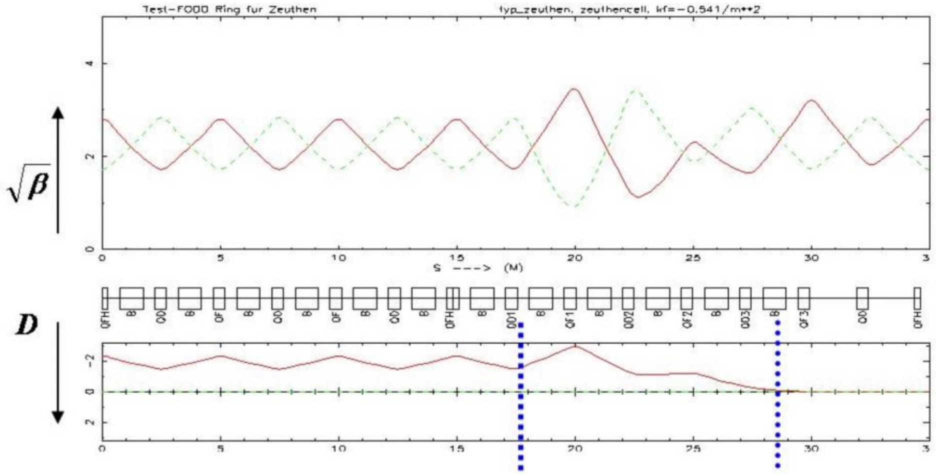
$B_{2,max}$ = 3207.5 T/m^2

https://arxiv.org/pdf/2111.14462.pdf

Comparison of Dispersion Suppressor Schemes

Quadrupole scheme

Introduce 6 flexible quadrupole magnets that correct for the six boundary conditions at the end:
-> DX=DDX=0 (no dispersion)
-> $\beta_{x/y}$- & $\alpha_{x/y}$-functions must be continuous



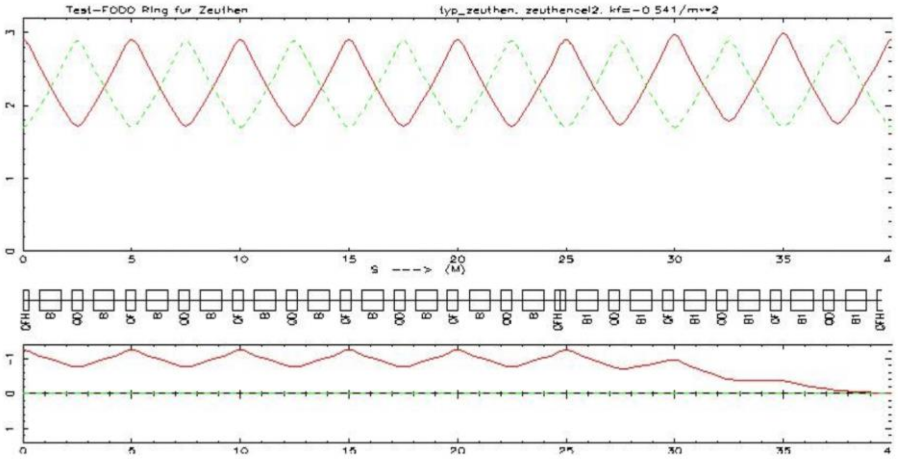
periodic FoDo structure

matching section including 6 additional quadrupoles

dispersion free section, regular FoDo without dipoles

Half Bend Scheme

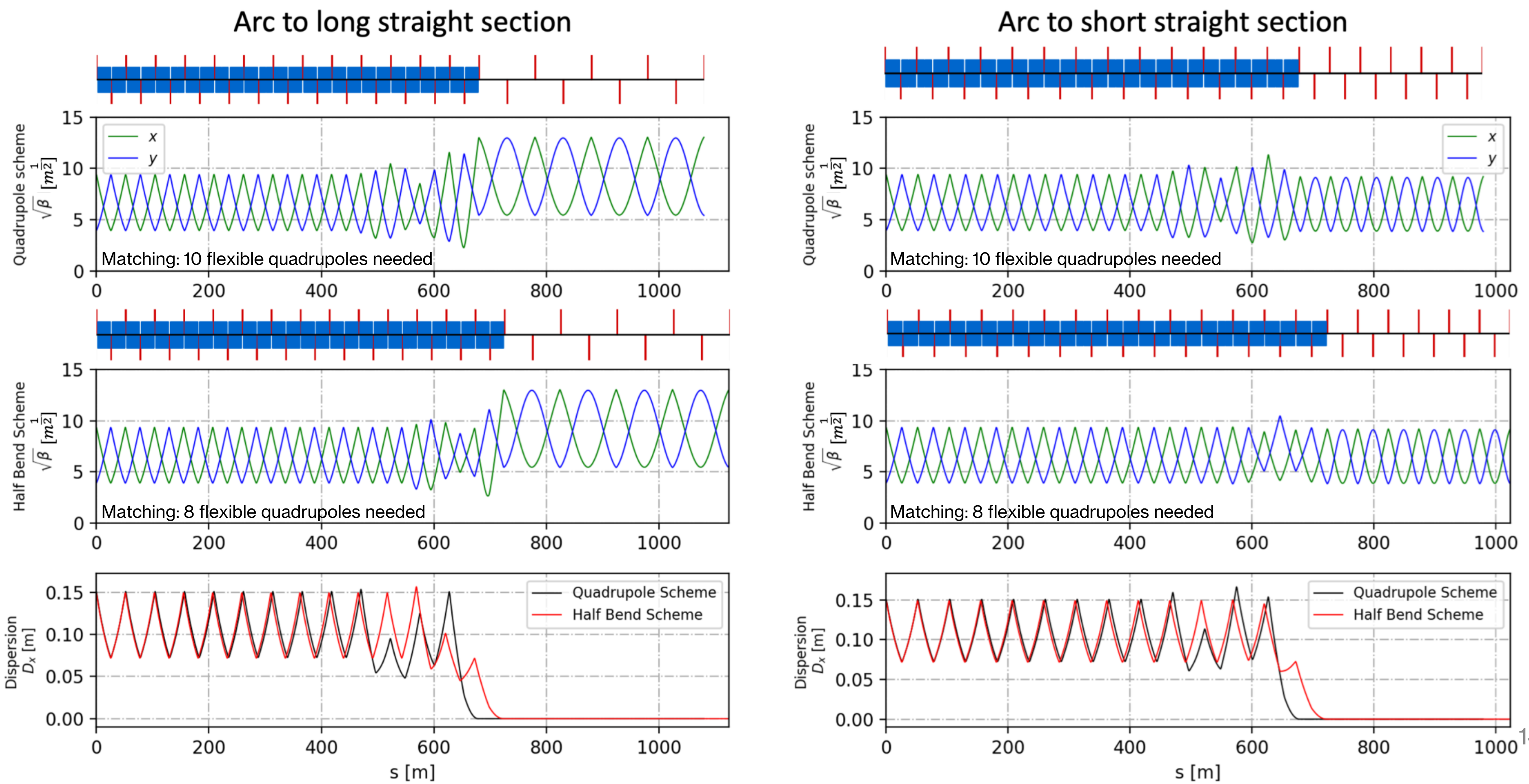
Replace n/2 full arc cells with n arc cells with half the bending field, where n depends on the phase advance (for 90°/90° n=2) to naturally get to zero dispersion.



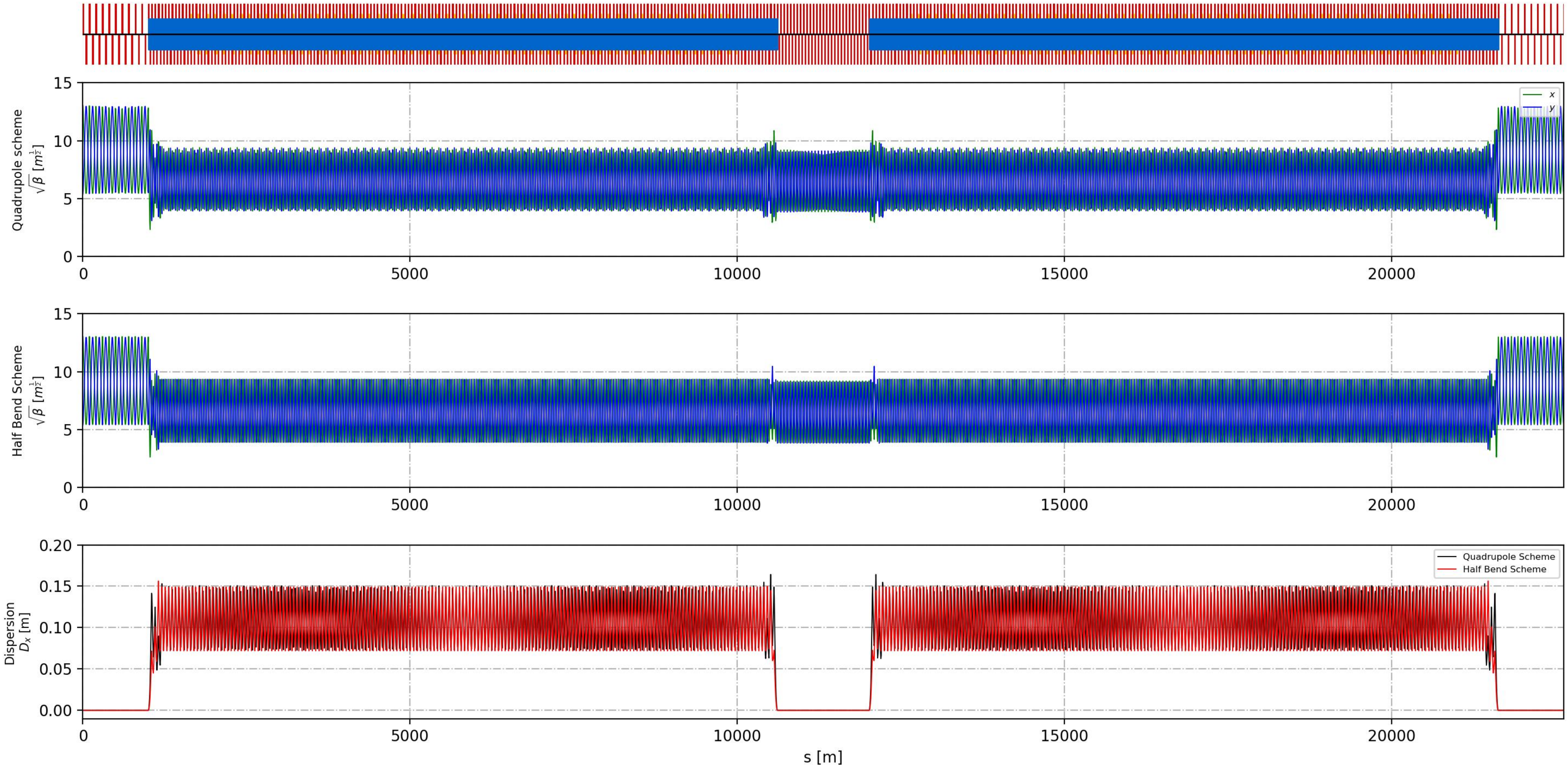
Note: If the cell length also changes, more flexible quadrupoles are needed.

https://indico.cern.ch/event/361988/contributions/1775736/attachments/1151344/1679030/Insertions_p.pdf

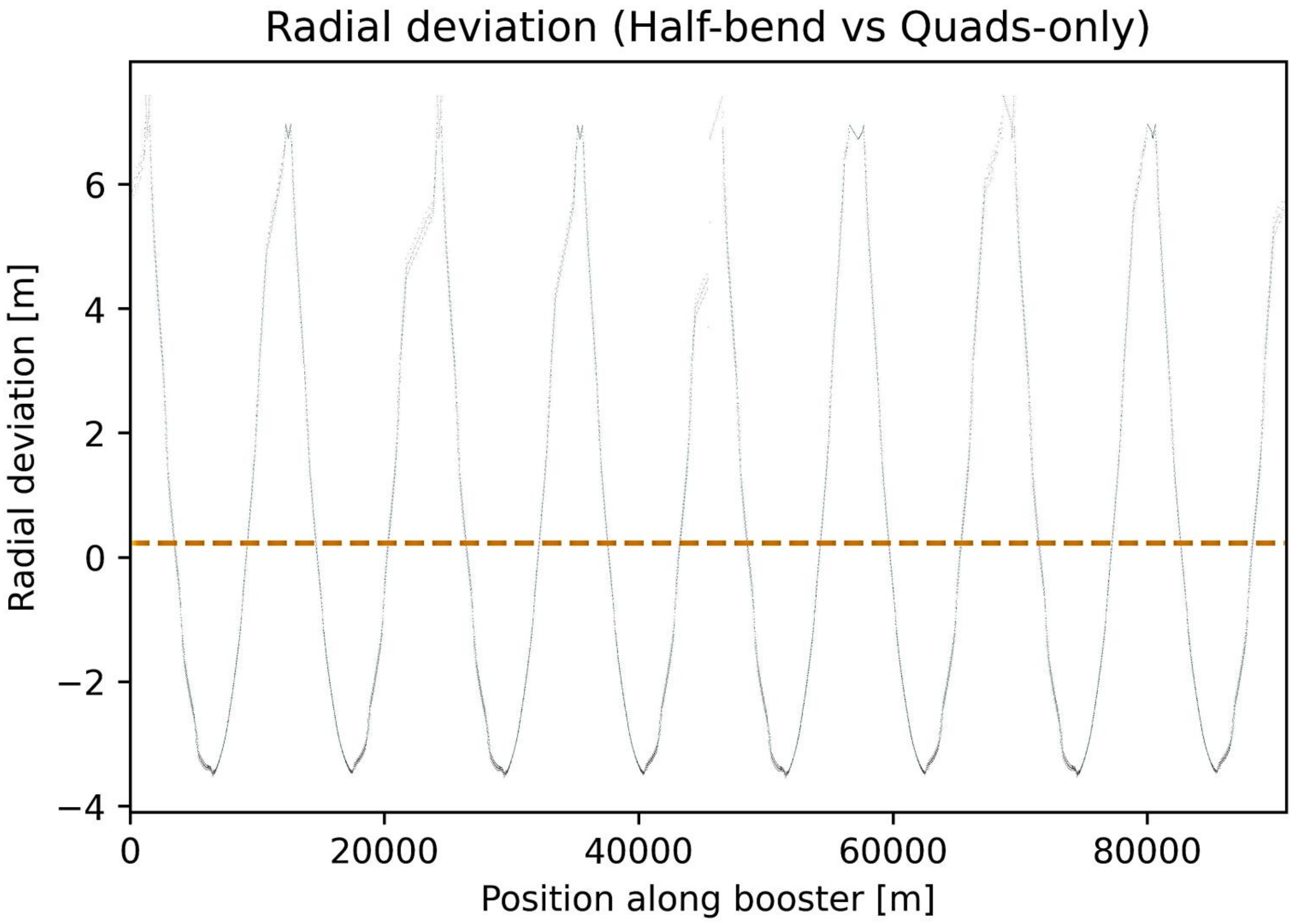
Comparison of Dispersion Suppressor Schemes

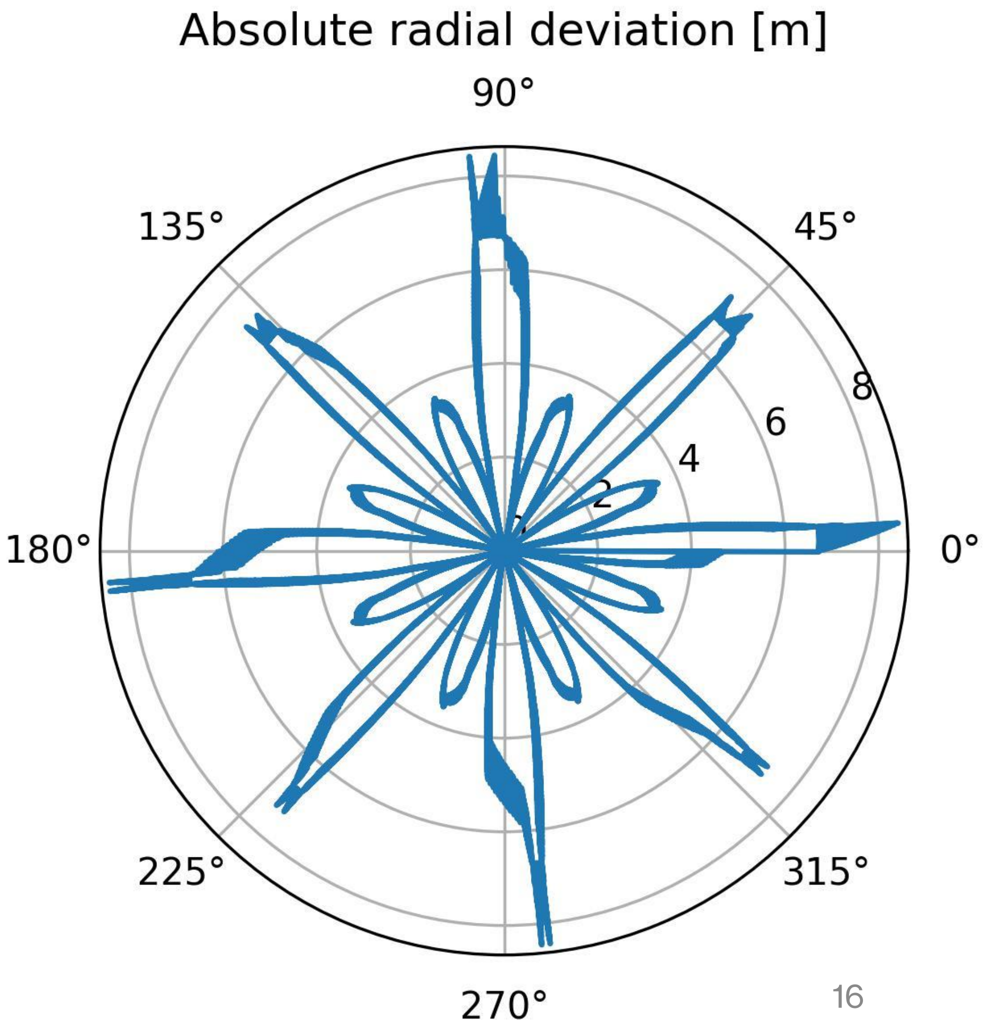


Quarter of FCC-ee booster ring



Changes in Geometry by choice of Dispersion Suppressor scheme

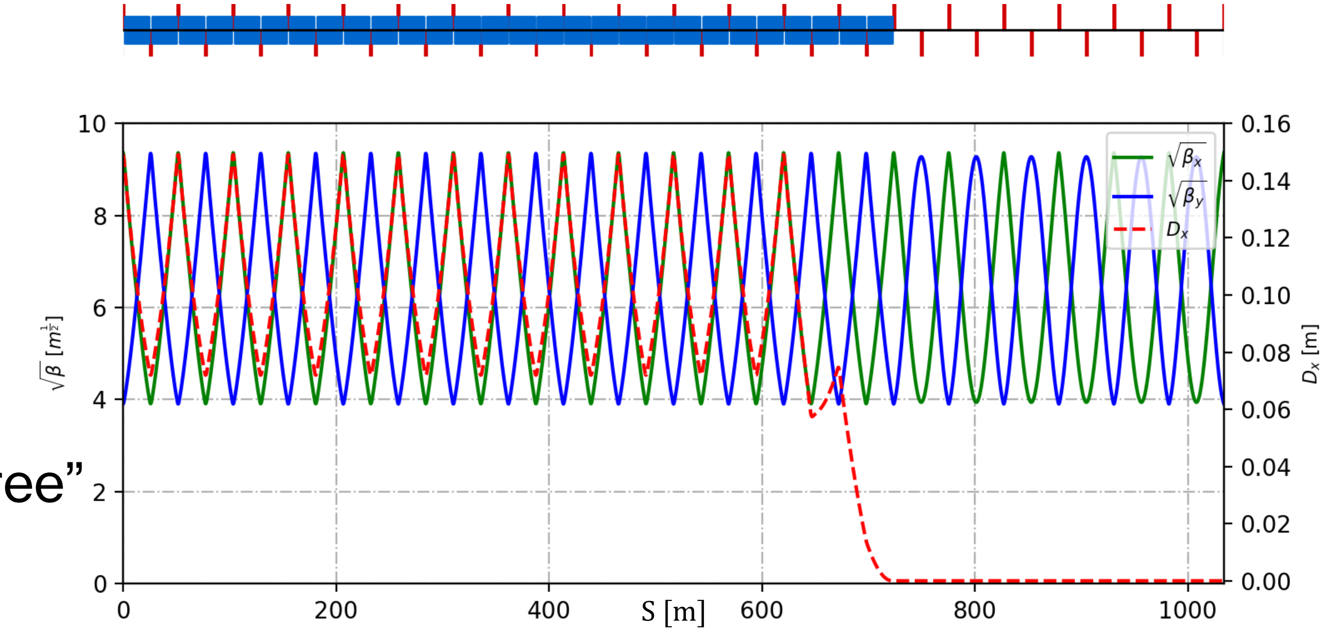




How to further improve Half-Bend scheme

Current improvements:

- $\frac{\varepsilon_{x,HB}}{\varepsilon_{x,Q}} = 0.986$
- $\beta_{x,\max}$ 31% smaller
- $D_{x,\max}$ 9% smaller
- 0.13% less energy loss per turn "for free"
- **Can we do better?**



	ARC FODO length [m]	STR short length [m]	# STR short FODOs per section	Total length STR section [m]	# flexible quads needed
Status quo	51.7	50.0	28	1400	8
Half Bend Optimized	51.7	51.7	27	1395.9	0

Note: These design changes will keep the length of the arc sections and the total circumference of the FCCee booster ring constant.

Lattice Future Work

- Our optics-matching methods have been shown to be adaptable
- We recommend more investigations into the half bend scheme
- Properly ascertain straight section constraints – potential for an even better lattice
- Tapering may be required – how would this affect optics?

FCC-ee Magnet design

Magnet design goals

$$\text{Good field region (GFR)} := \frac{\text{abs}(B_{predicted} - B)}{B_{predicted}} < \begin{cases} 1 \times 10^{-4} \text{ for dipole} \\ 2 \times 10^{-4} \text{ for quadrupole} \\ 1 \times 10^{-3} \text{ for sextupole} \end{cases}$$

All GFRs must have a 46.67mm diameter:

- At reference aperture diameter 70mm.
- At injection energies 45.6 GeV, 80 GeV, 120 GeV, 175 GeV, 182.5 GeV

Magnets introduction

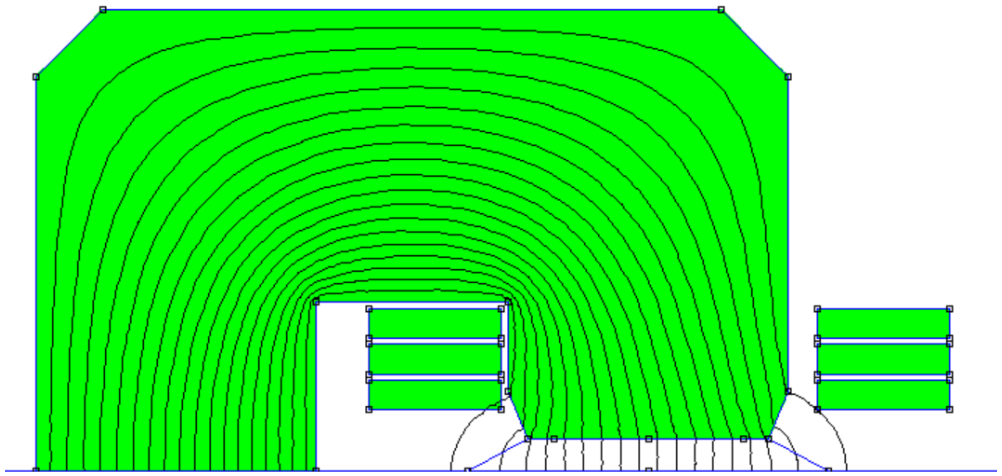
Software & toolkits:

- FEMM: Program for designing and solving electromagnetic problems on two-dimensional planar or axisymmetric domains
- PyFEMM: Python interface to FEMM

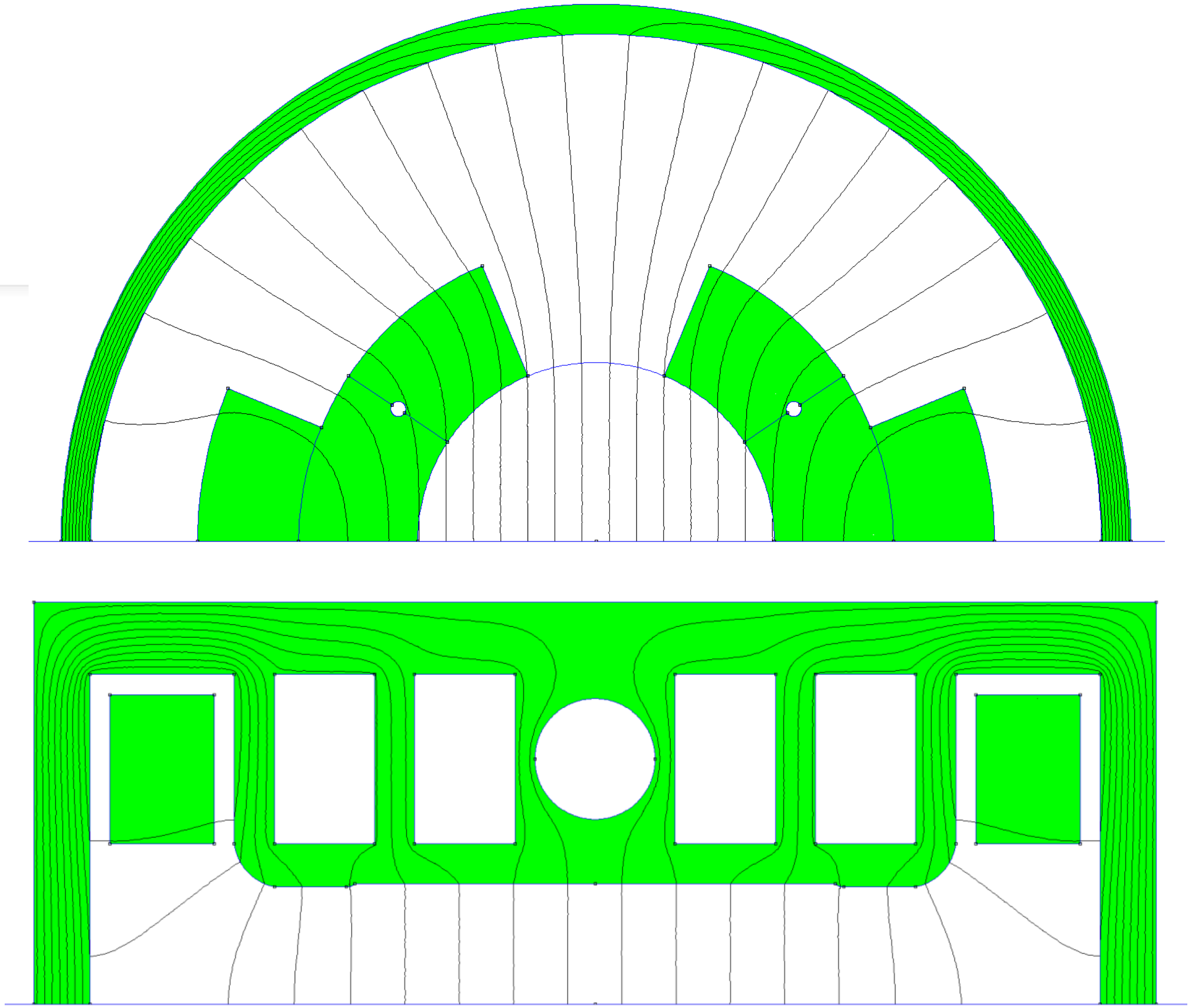
Benefits of non-saturating fields:

- Well-defined linear relation between current & field – design easier.
- GFR does not change with field. Therefore, designs work for all FCC-ee operational energies.

Dipole Designs

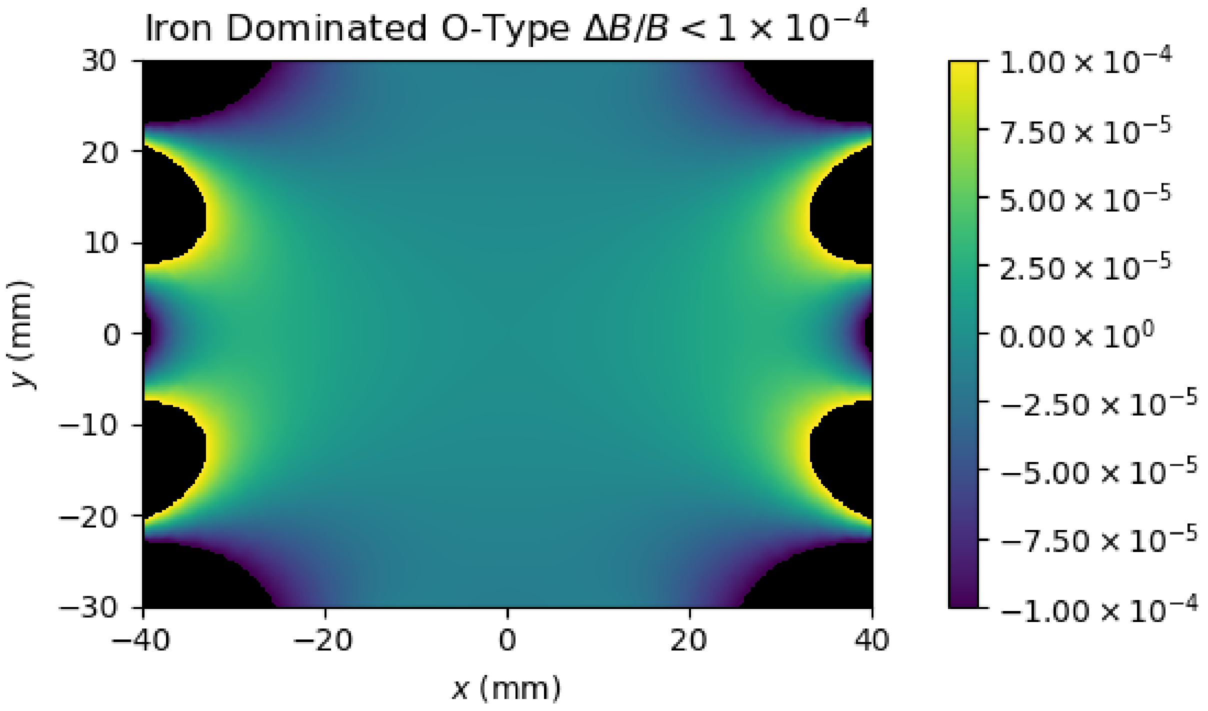


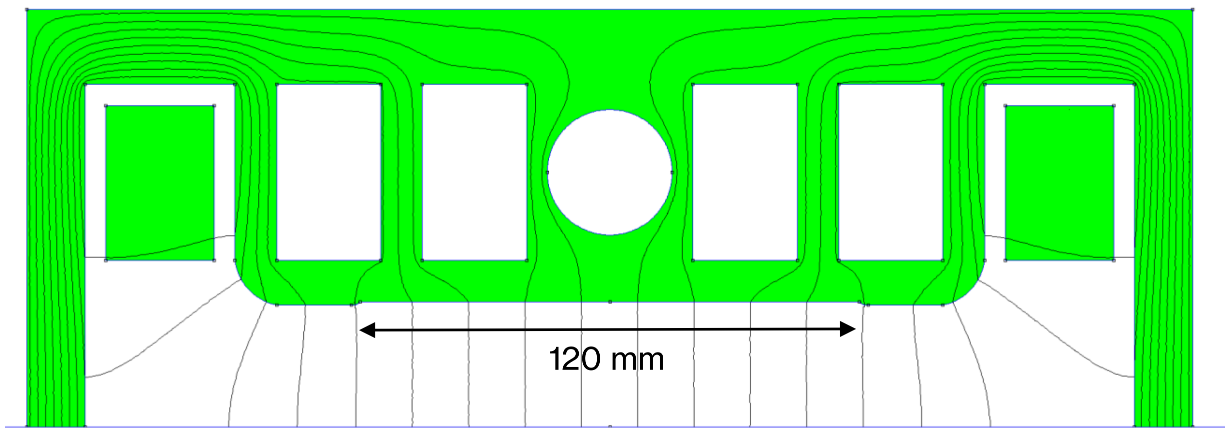
Based on JAI 2021-22
C-type example



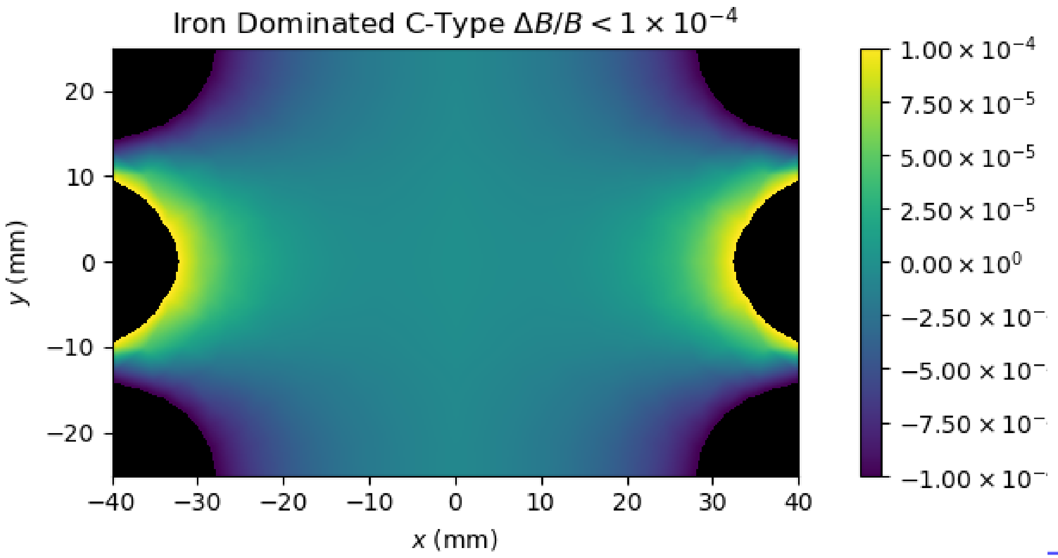
Based on IHEP CAS
designs

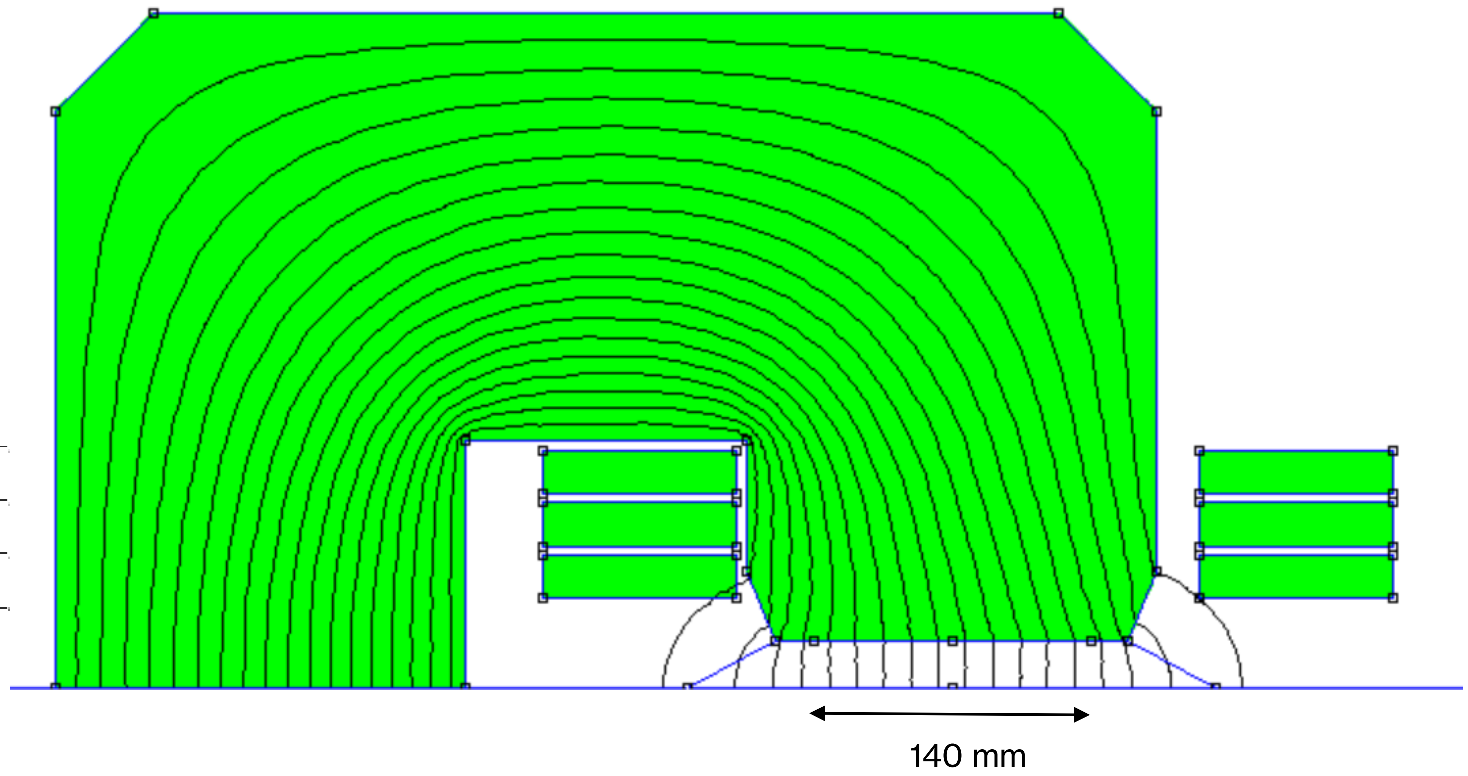
Iron dominated O-type



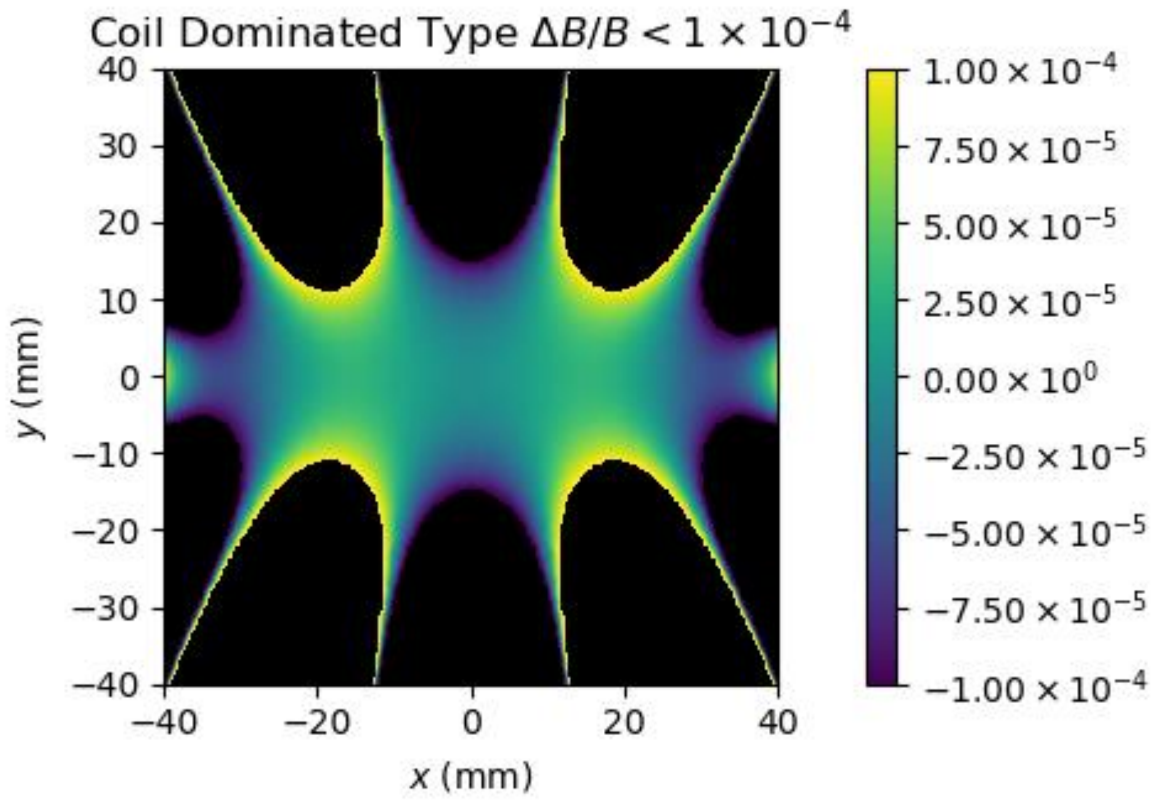


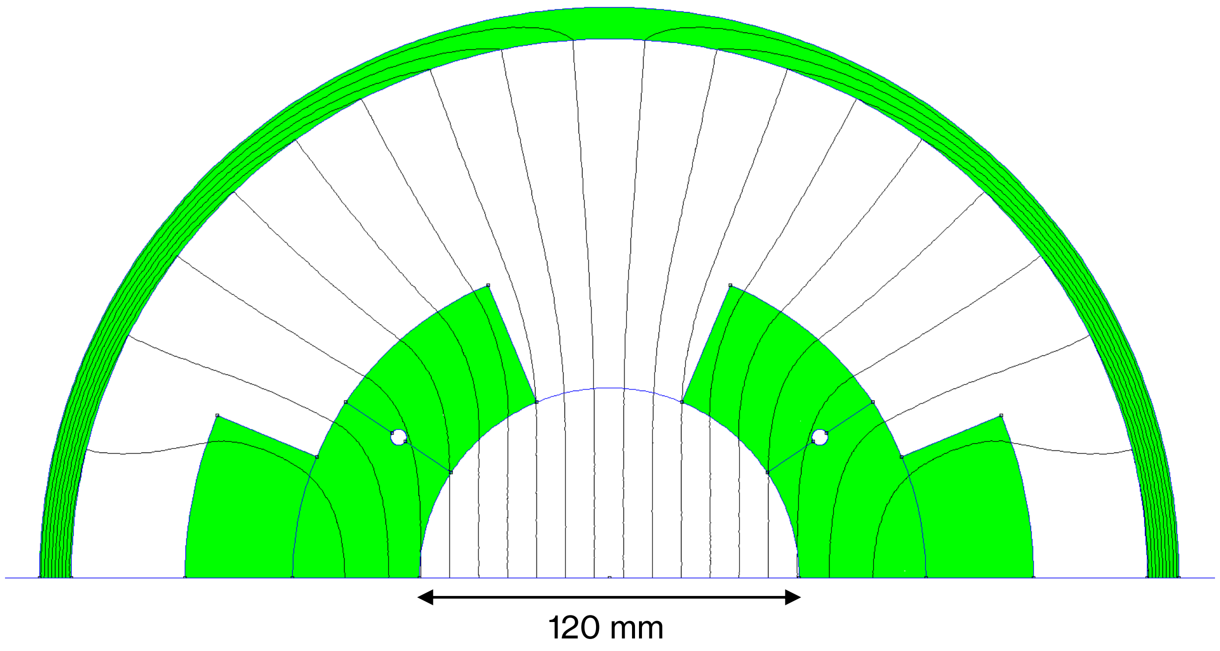
Iron dominated C-type





Coil dominated type





Dipole - Summary

- All designs are far from iron saturation for the full range of injection energies.
- O-type is more compact than the C-type, but the C-type is easier to build/maintain.
- Iron-dominated types are easy to optimize both in FEMM and for real by shimming.
- The coil-dominated type is much trickier to optimize in the vertical direction due to the coil geometry, but its real-life field quality would be less susceptible to imperfections in the iron as it is merely used to shield the dipole.

Quadrupole design

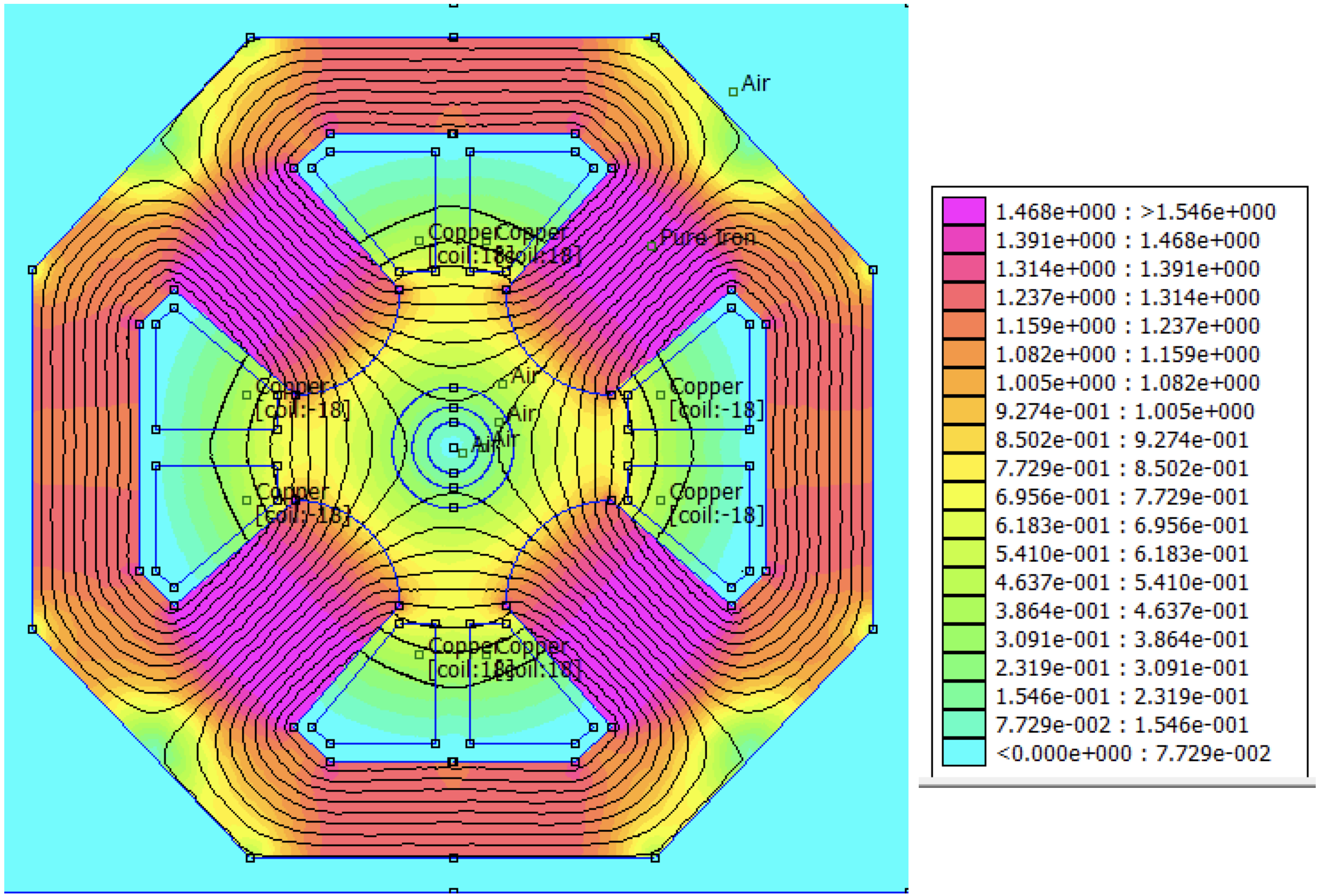
Goals:

- 70 mm aperture
- $\Delta B/B < 2 \times 10^{-4}$ within 20 mm radius
- Work with low current → low power consumption

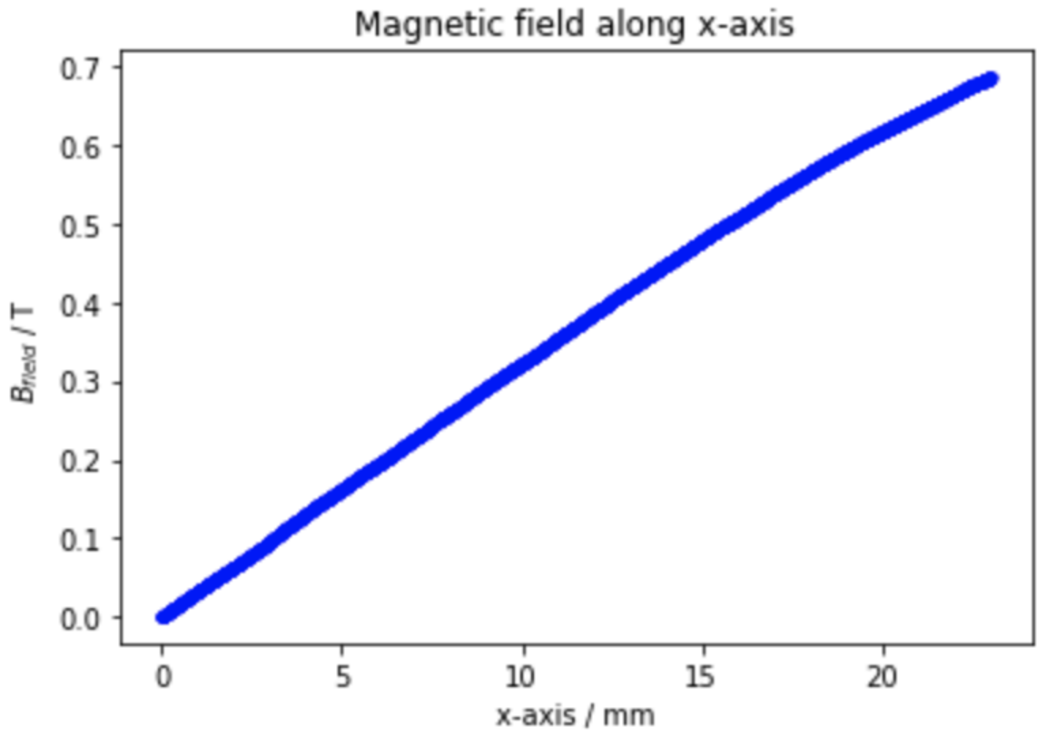
Varied:

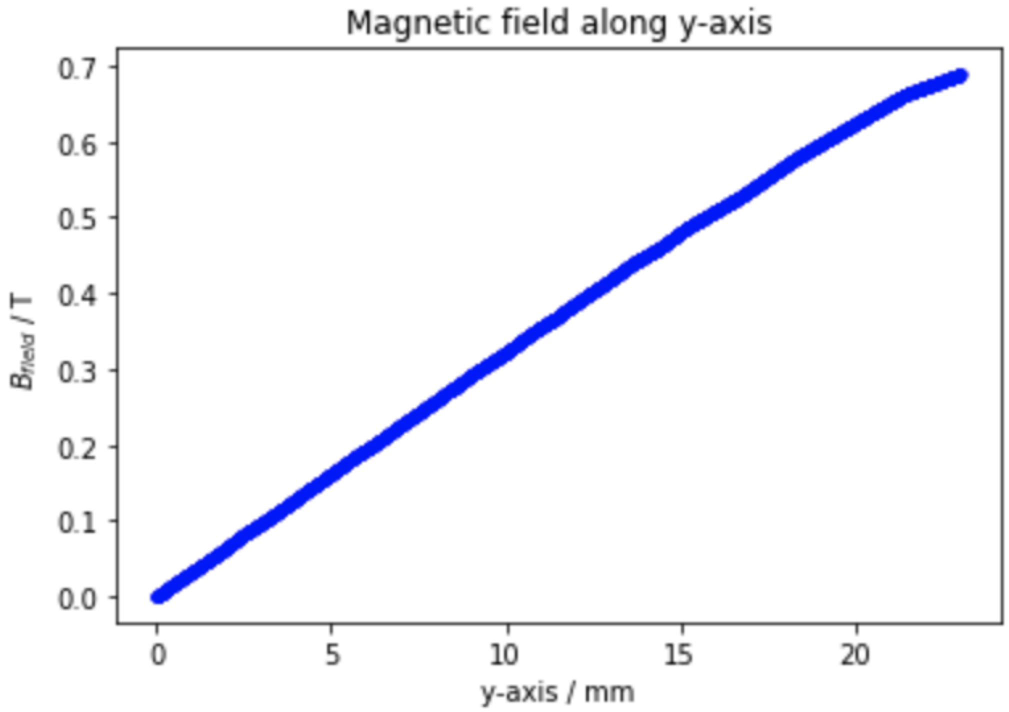
- Pole size
- Current through the coils
- Number of turns
- Materials
- Iron thickness

Final design



Quadrupole field analysis





Quadrupole - Summary

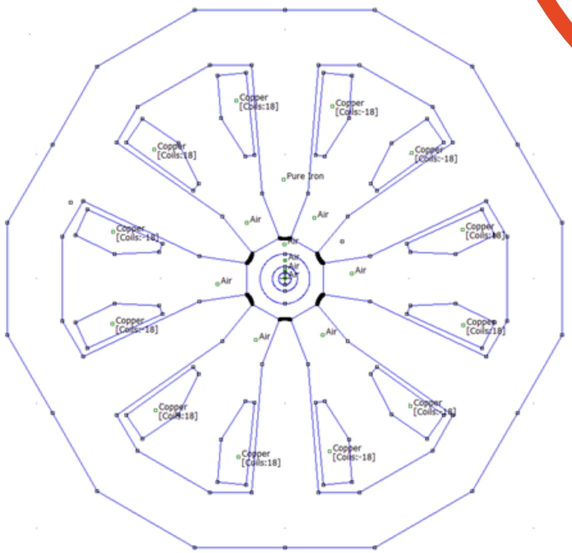
Final design:

- 70 mm aperture, as required
- Good Field Region: 42.42 mm, Target: 46.67 mm
- 1.47 Tesla maximum magnetic field → low current
- Works for all injection energies

Sextupole - designs

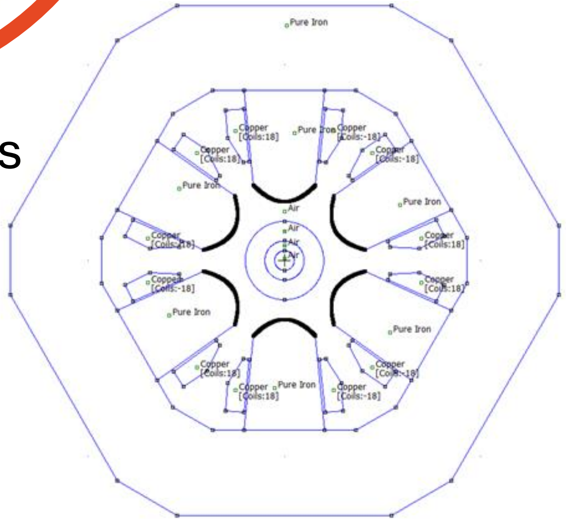
Magnet design for Iranian Light Source Facility storage ring
M. Razazian, F. Saeidi, S. Yousefnejad, J. Rahighi
Aug 7, 2020
Published in: JINST 15 (2020) 08, P08002
Published: Aug 7, 2020
DOI: 10.1088/1748-0221/15/08/P08002

Iranian Light Source Sextupole

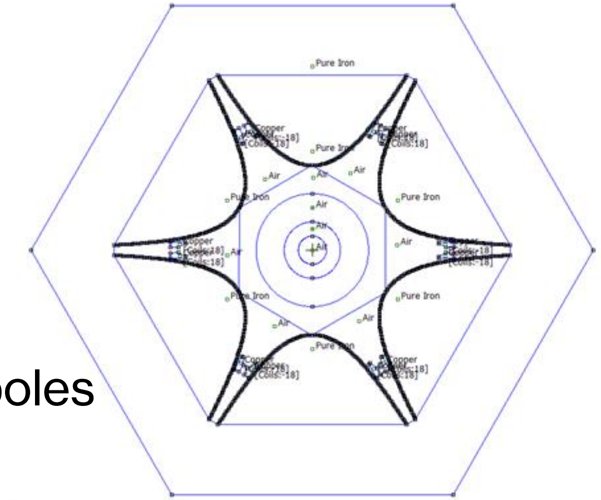


Iranian design + Hyperbolic tip

Hyperbolic poles v1



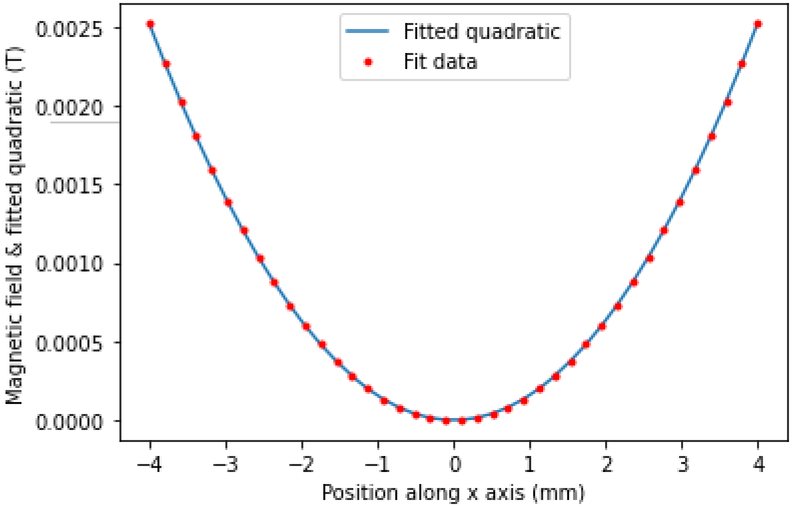
Hyperbolic poles v2



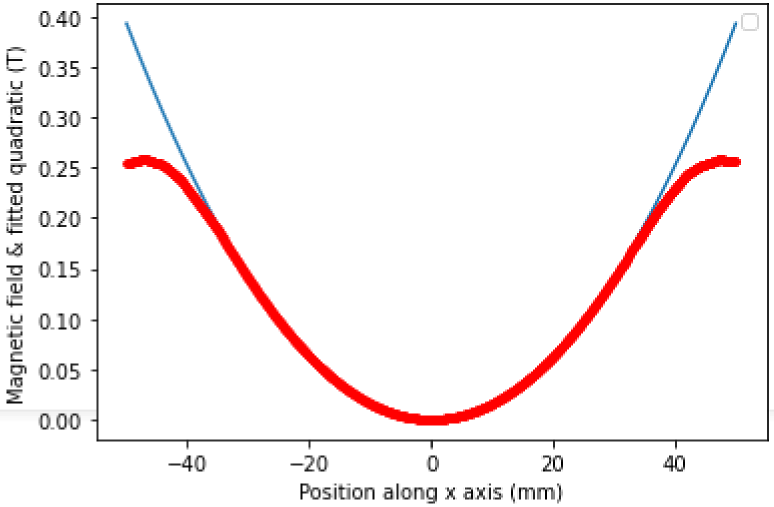
Idealised poles

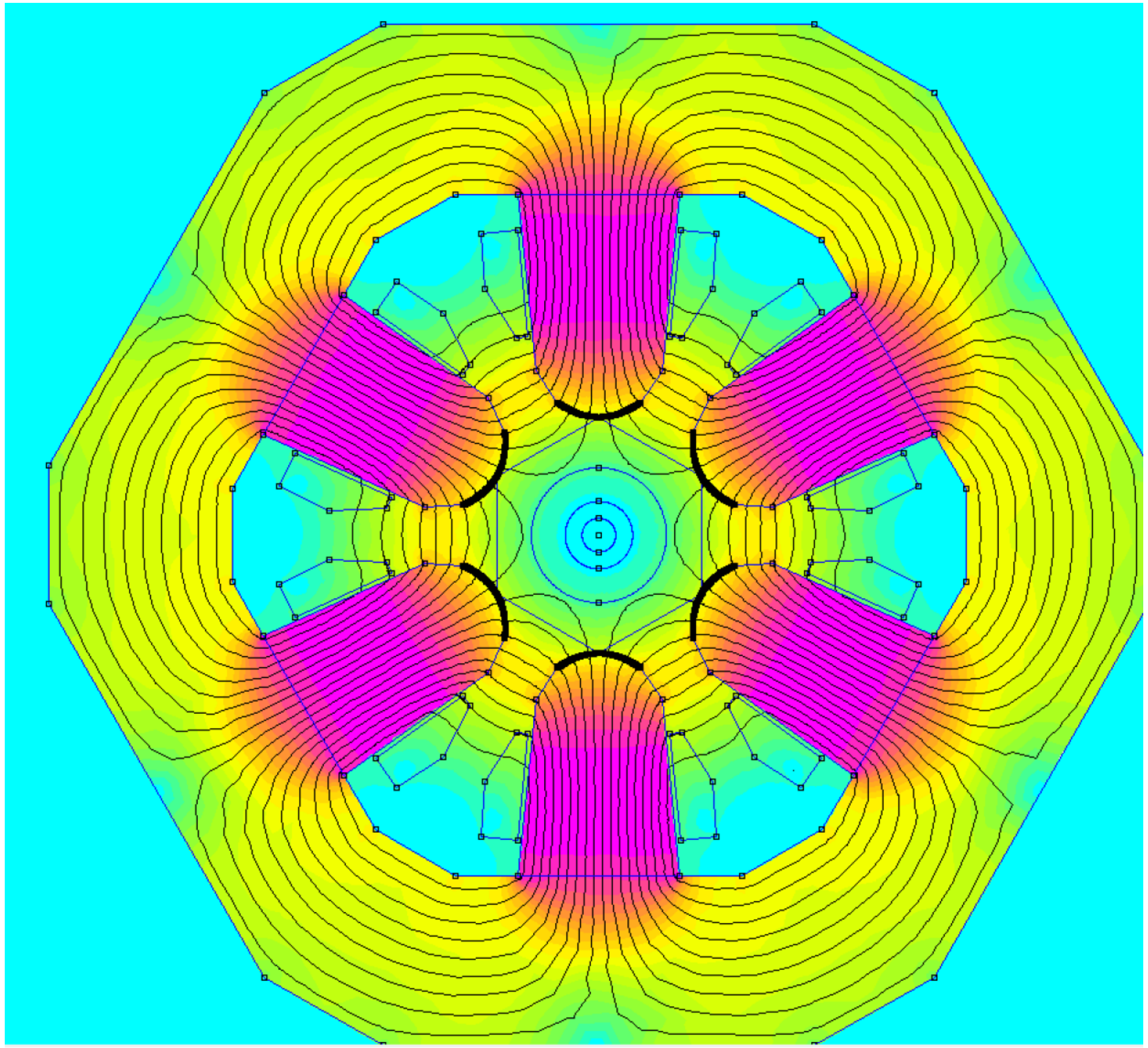
Best design

Partial hyperbola 1 - full design - 35mm radius.ans: Plot of Fit data vs fitted quadratic

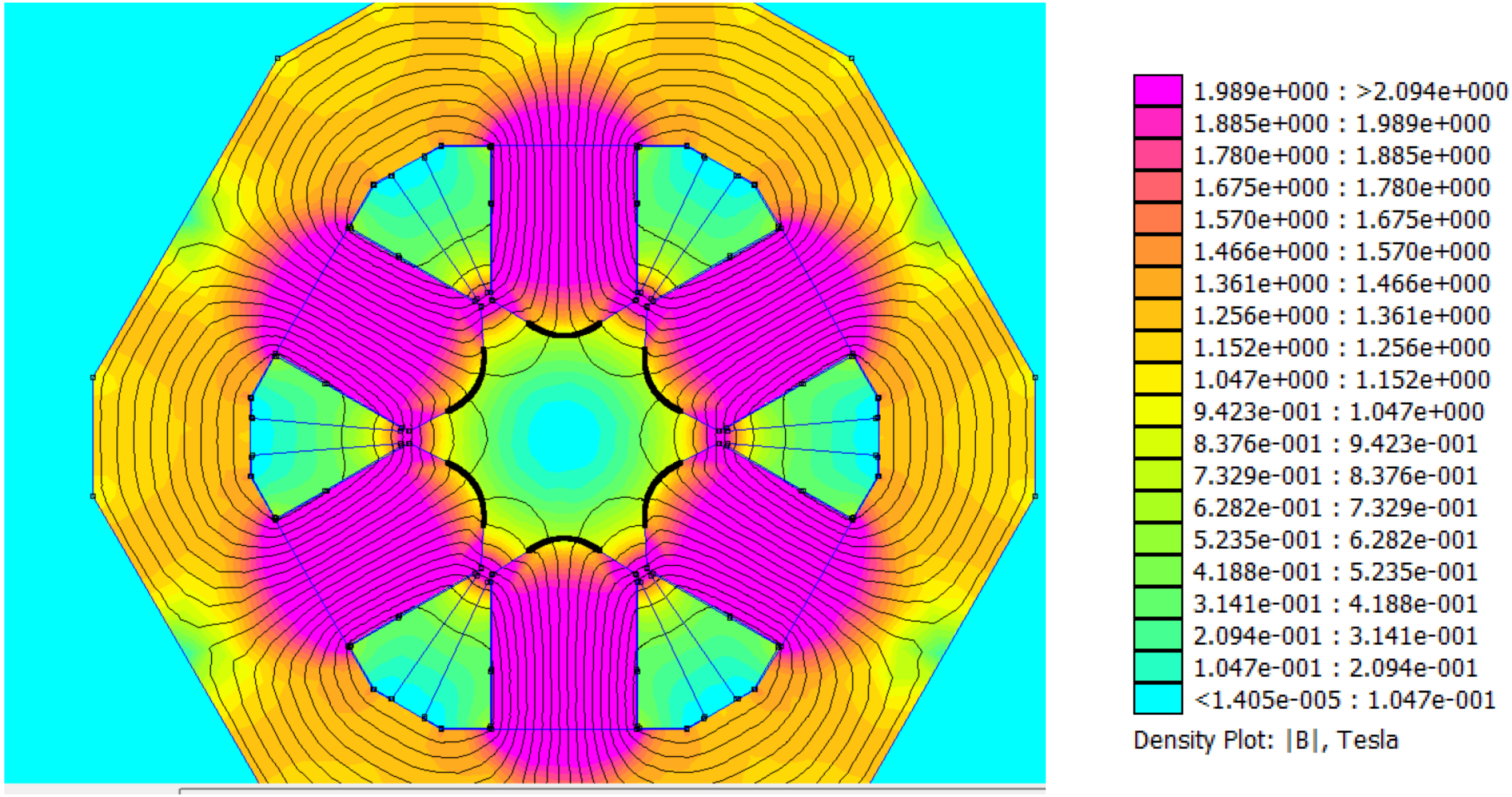


Partial hyperbola 1 - full design - 35mm radius.ans: Plot of all B field data vs fitted quadratic





Removing saturation: Not yet successful



Sextupole - Summary

Target (mm)	GFR diameter (mm)	Maximum field (T)	Saturation?	Works for all injection energies
46.67	39.8	2.6	Yes	No

Magnets Future Work

Further optimisation:

- Quadrupole & Sextupole need better GFR.
  - Shimming
    - Get ~+5mm to GFR diameter.
- Sextupole needs to become unsaturated
  - Widen poles

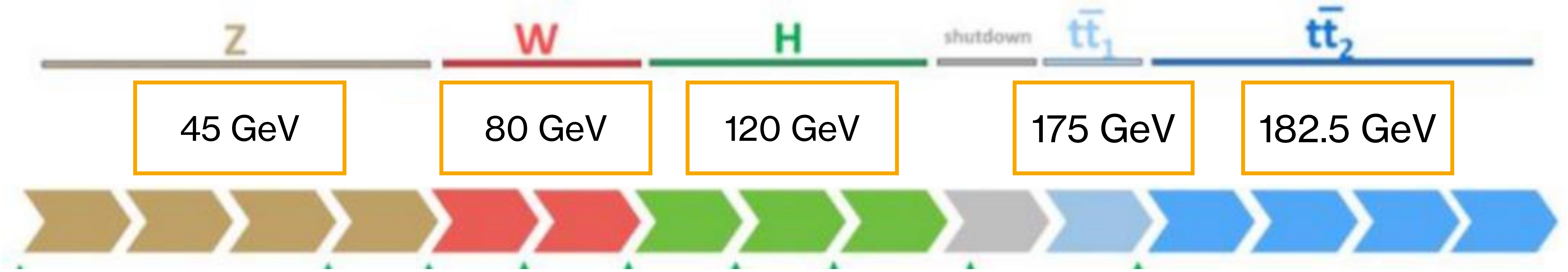
3D work:

- Model magnets in 3D using Opera
- Compare FEMM and Opera designs

FCC-ee RF Cavity design

RF Cavity Design

Available for every operation energy



- Fixed synchrotron radiation power of 50 MW per beam

Voltage requirements

0.4 GV	0.8 GV	3 GV	10 GV	>10 GV

3 types of cavity to cover different requirements

Shape/ Material consideration?

Why elliptical?

- Larger acceleration gradients
- Low ratio of peak surface fields
- Easier to fabricate

Single cell vs multicell?

- Accounts for higher order modes

Why superconducting?

- lower surface resistances
- more efficient (greater portion of the RF energy to accelerate the beam rather than be dissipated as heat)
- Lower power consumption

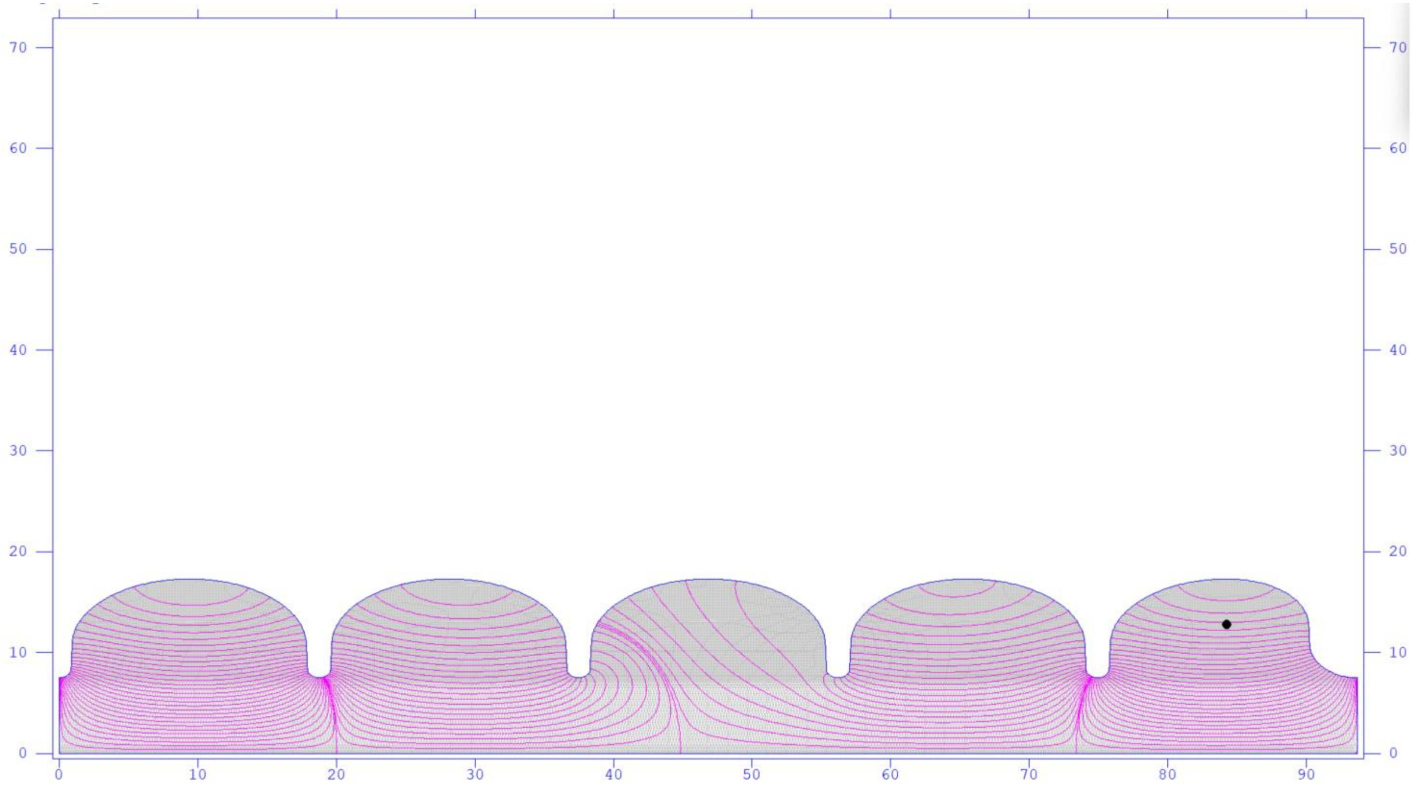
Electromagnetic Considerations

- **Maximise Rs*Q** Geometry factor
- **Maximise r/Q factor**
- **Minimise peak fields**
- **Maximise Transit time**

Superfish Optimisations

SUPERFISH is a Finite Element solver

Utilises symmetries



How to fix a design like this?

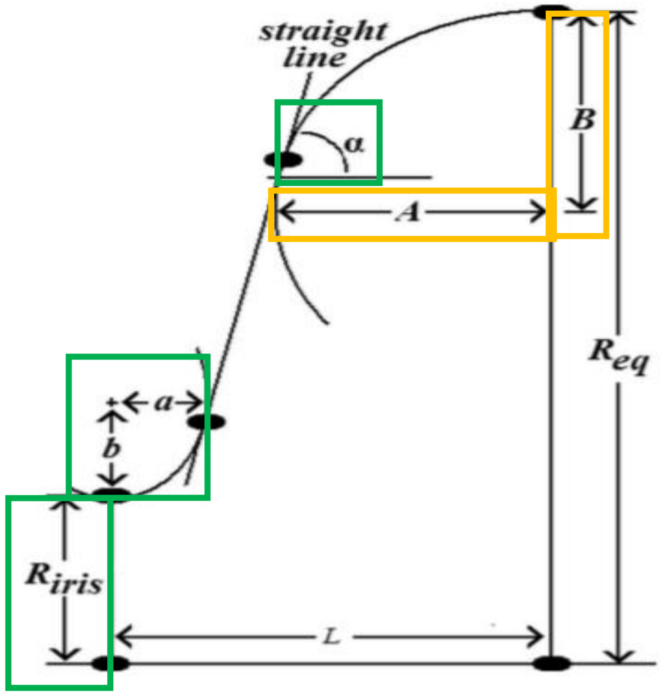
Tuning.... to satisfy

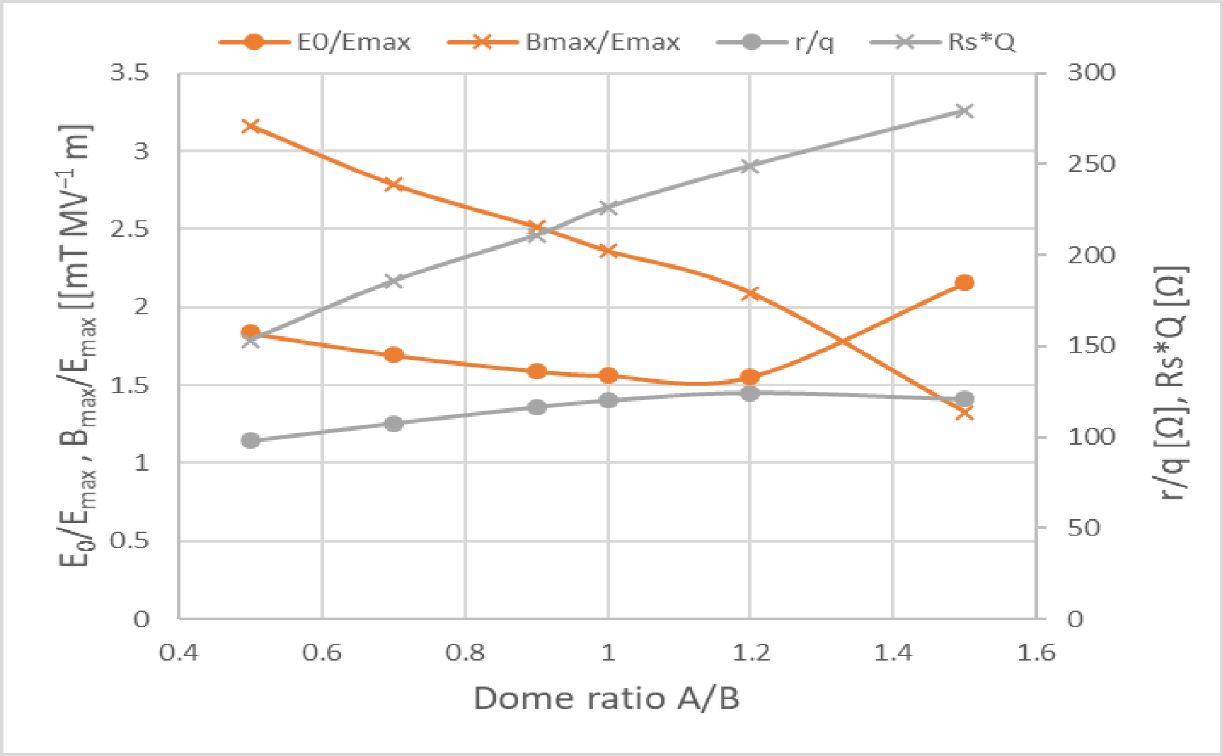
L[m] =v/2f[Hz]

Diameter tuning to match desired frequency

Maximising Electromagnetic Parameters

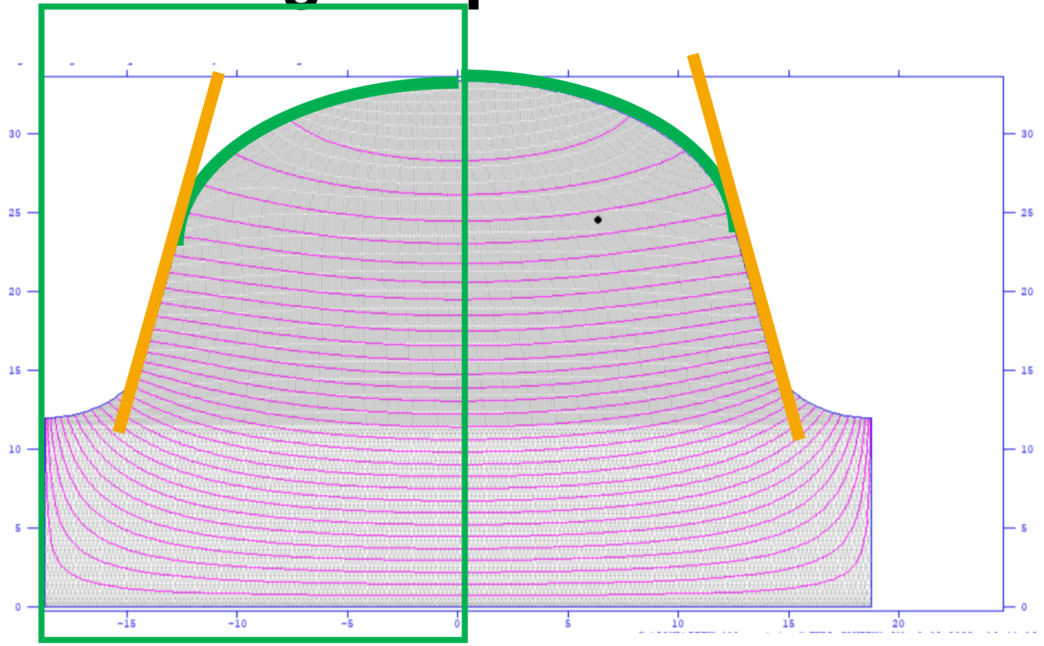
- Optimisation for a single cell done in Superfish
- 5 MV/m
- 400MHz





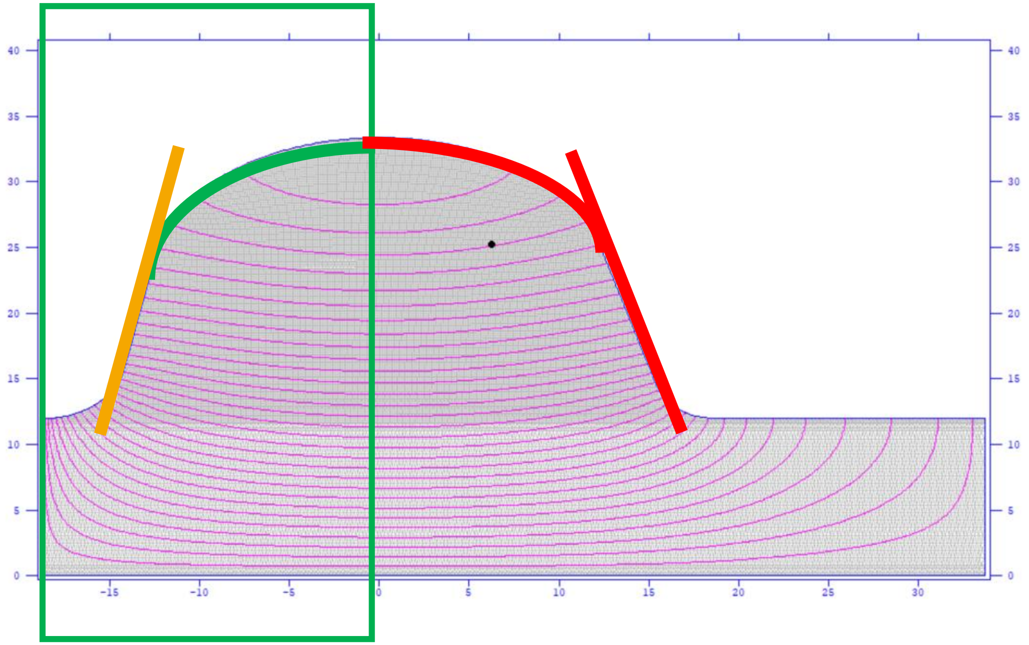
Mid cell + End cell Optimisation at 10MV/m

After Tuning Freq = 400.00541 **MHz**



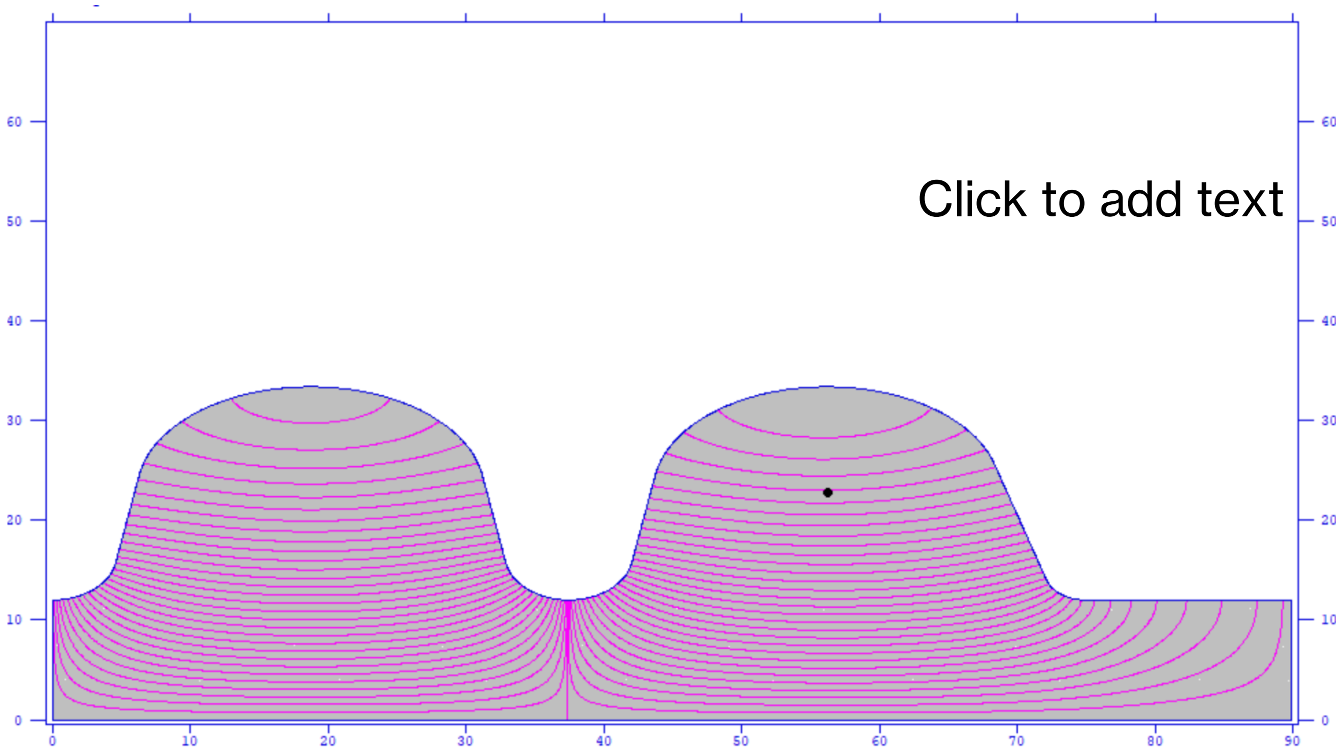
Symmetrical

After Tuning Freq = 400.13717 **MHz**



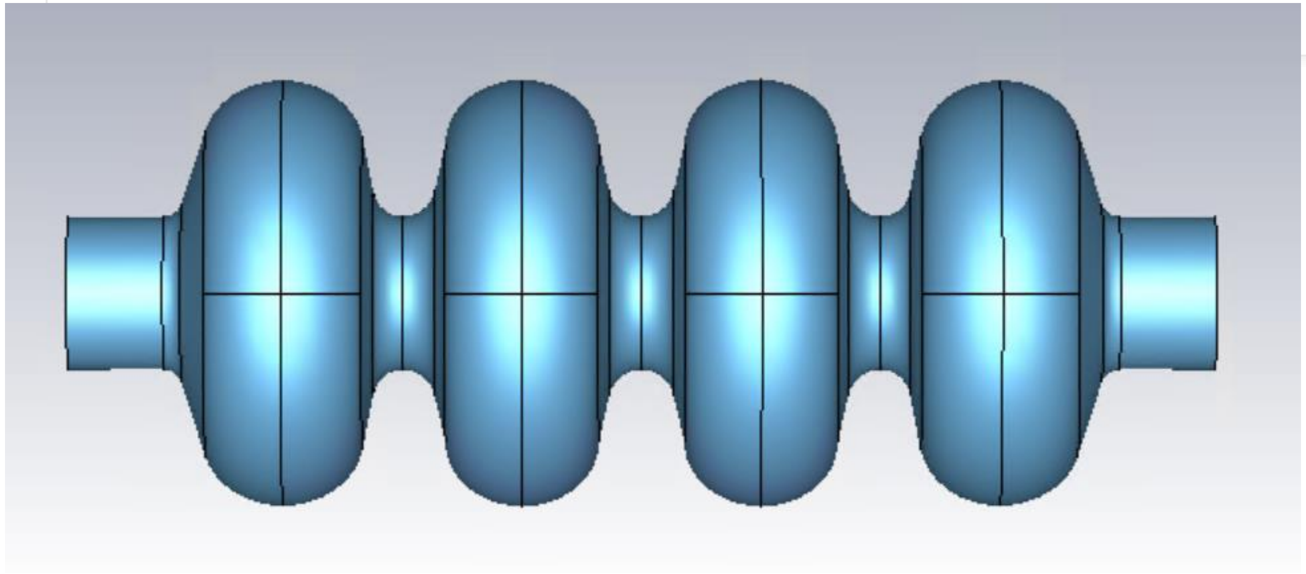
Asymmetrical

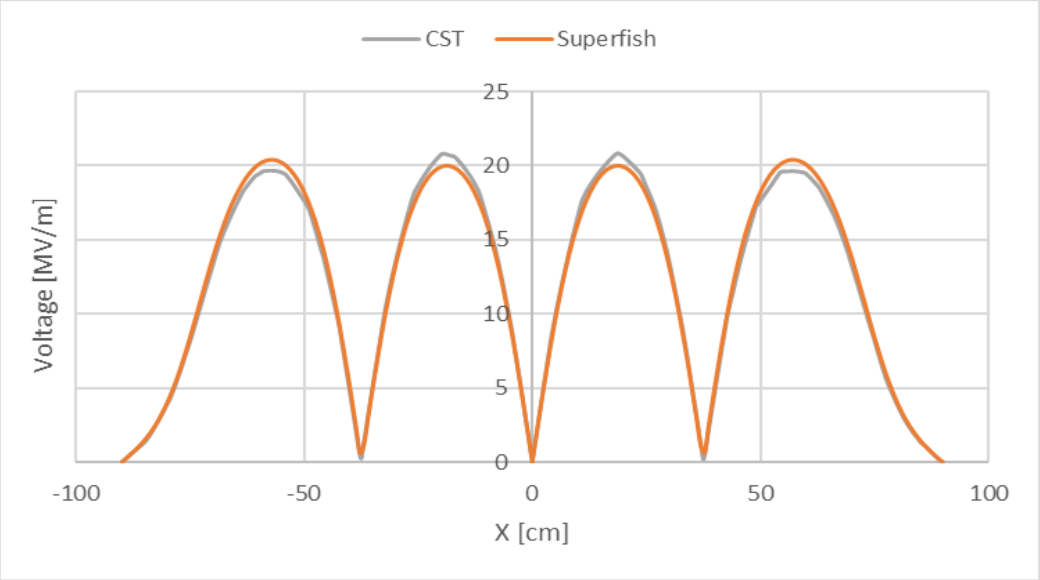
Final 4-cell design



	SUPERFISH
Frequency (MHz)	400.13867
r/Q (Ω)	449.098
Rs*Q (Ω)	705.272
Emax/E0	1.4843
Bmax/Emax (mT/(MV/m))	2.0429
Voltage (MV/m)	20.75

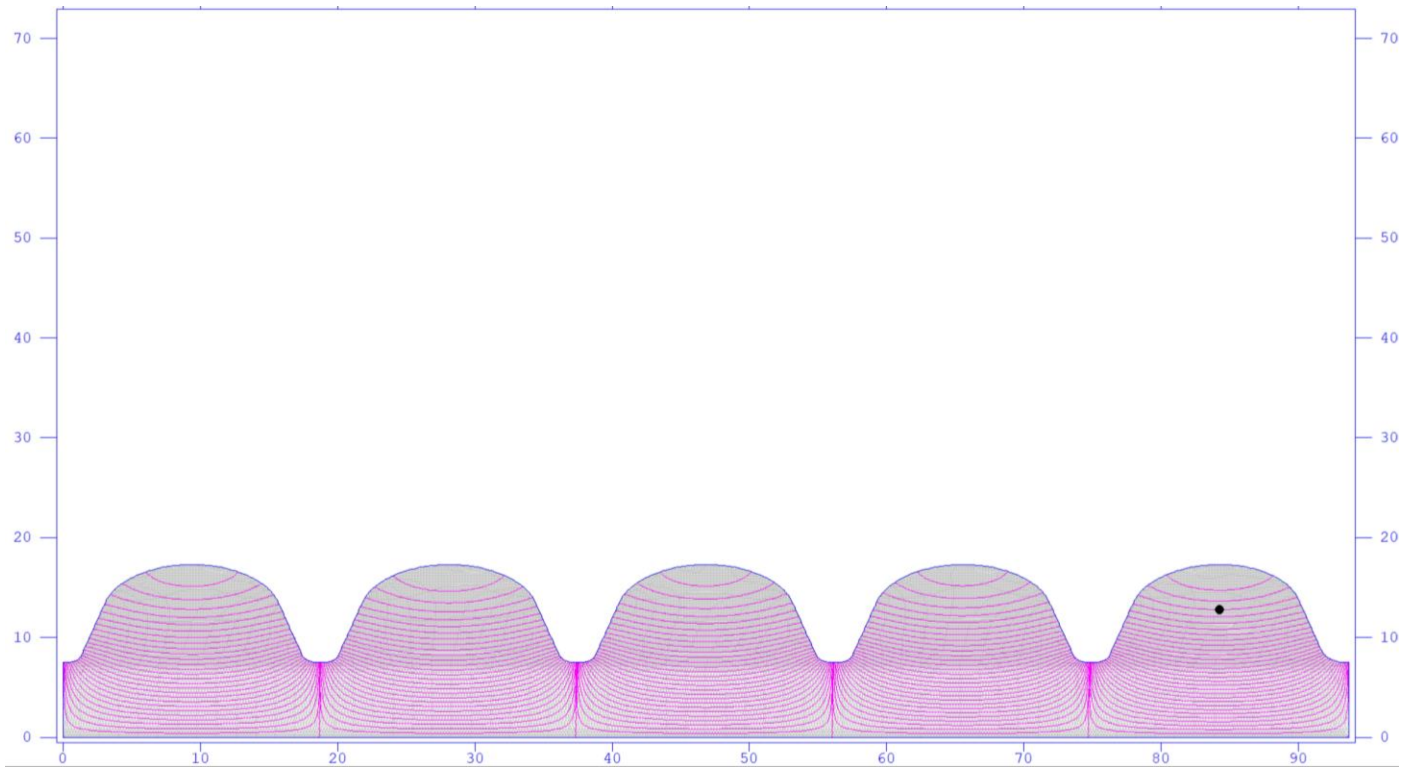
400MHZ 4-cell cavity CST

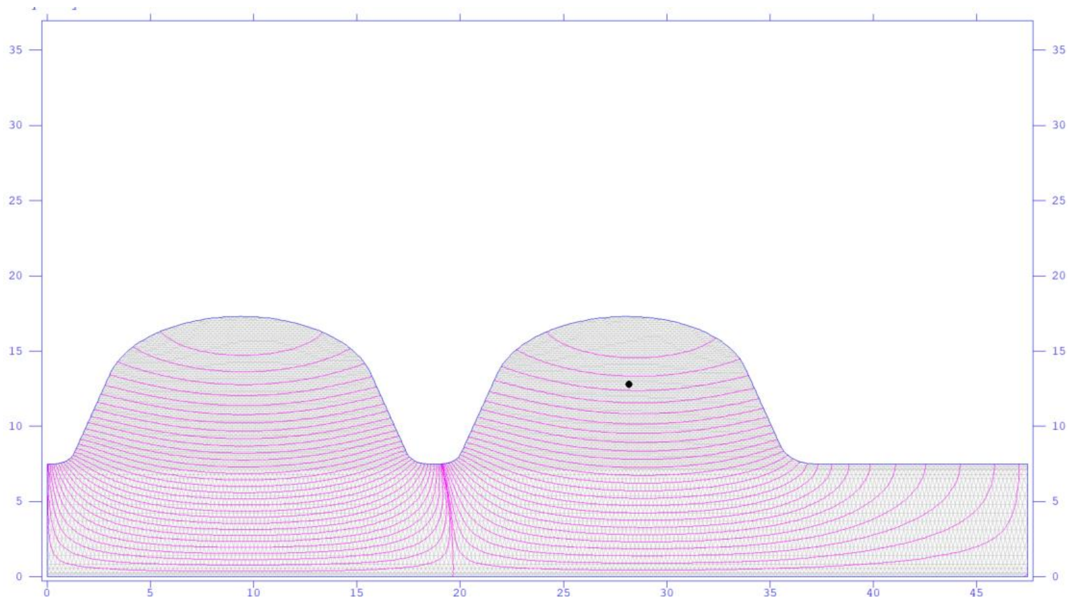




	SUPERFISH	CST
Frequency (MHz)	400.13867	400.0255
r/Q (ohm)	449.098	451.511
Voltage (MV/m)	20.75	22.24

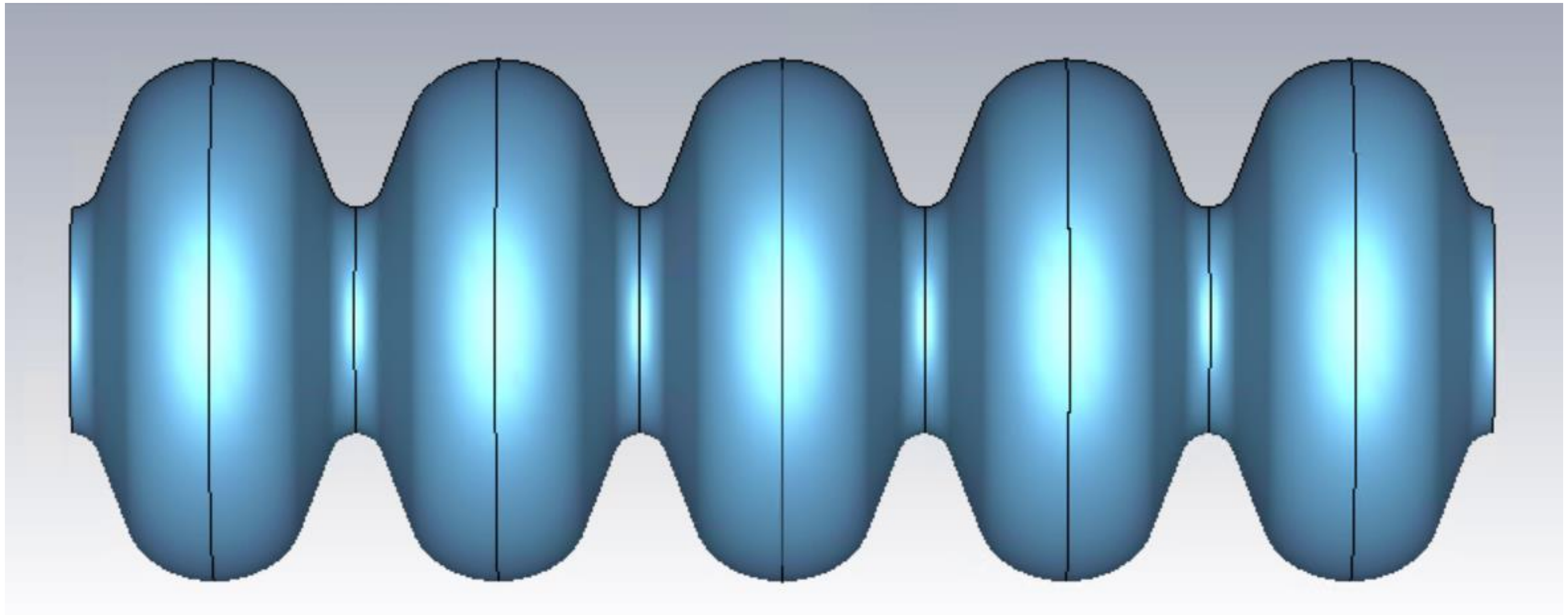
800MHz 5-cell Superfish





Parameter	Value
Frequency (MHz)	799.99633
Q	0.184030E+11
Rs*Q (Ω)	301.085
r/q (Ω)	436.043
Ratio of peak fields (mT/(MV/m))	2.0156
Transit-time factor	0.7771197

800MHz 5-cell cavity



RF Cavities Future Work

- Improve field flatness
- Power demands

Project Conclusions

- Beam optics
  - Adaptable MADX model for FCC-ee booster established
  - Estimate for max. Quadrupole and Sextupole field strengths found
  - Dispersion suppressor options evaluated
- Magnets
  - Different magnets have been designed that will work for all operation energies.
  - Designs need to be optimised to reach the required GFR.
  - Performing full 3D studies using Opera is the next step
- Three RF cavity designs to produce required acceleration gradient and voltage requirements at all operating energies

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FUTURE CIRCULAR COLLIDER

Questions?