FUTURE
CIRCULAR
COLLIDER

FCC-ee Design Project

Presented by:

- Seb Wilkes
- Florian Stummer
- Johannes van de Wetering
- Maria Maxouti
- David McMahon
- Bethany Spear
- Alec Clapp

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

Seb

Florian

Maria

David

Johannes

Bethany

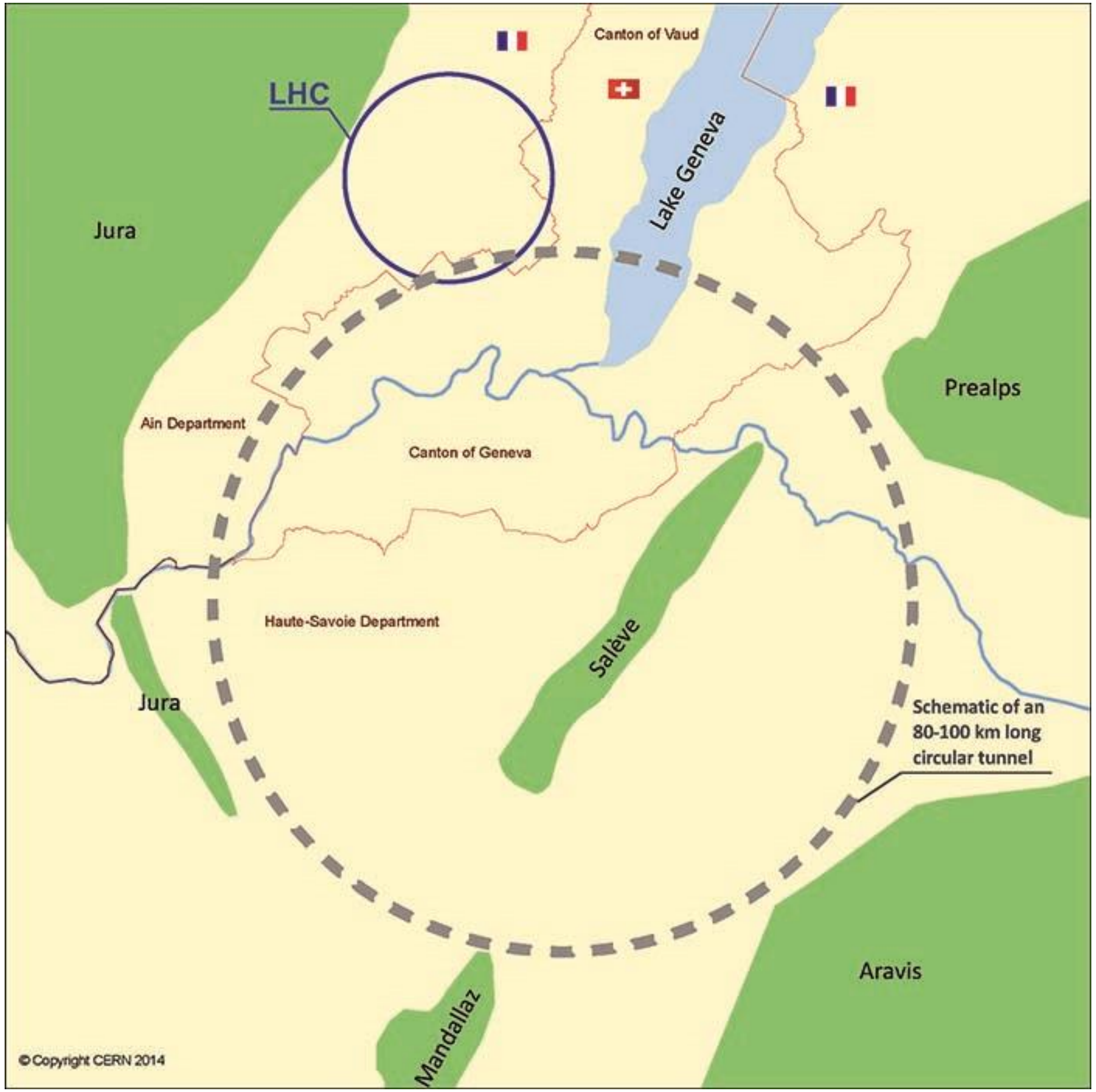
Alec

Introduction

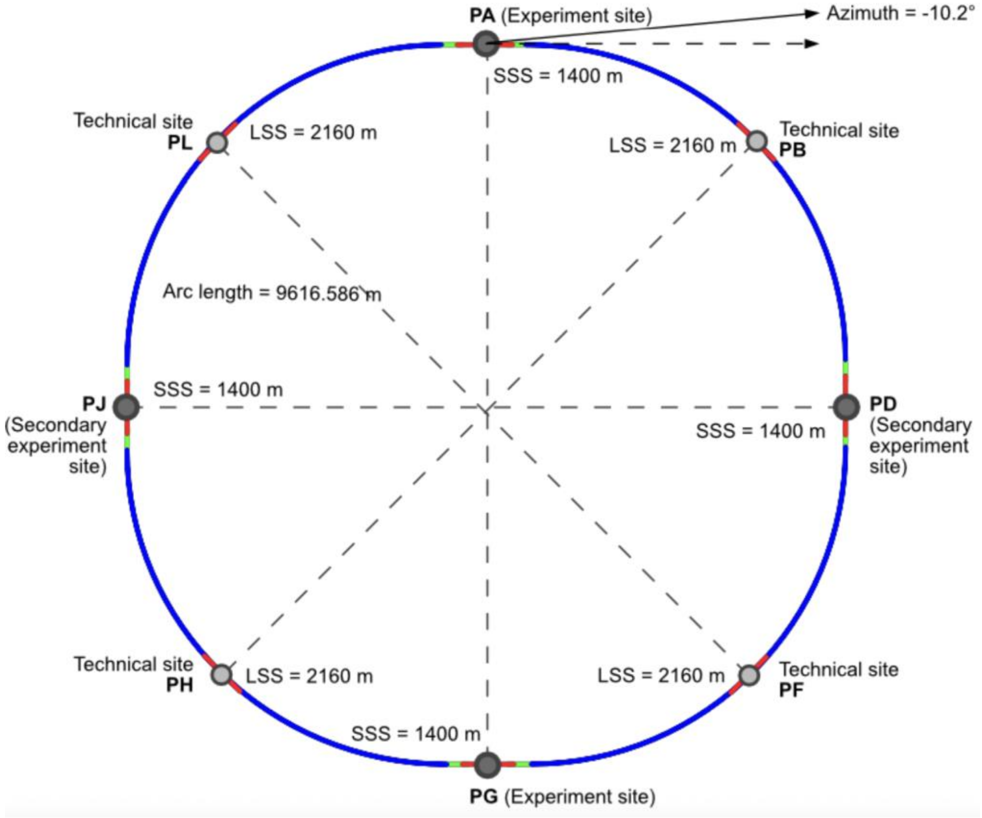
- Geneva region
- >~90 km circumference
- 4 collision points
- Double-ring configuration
- Collision energies between 90 and 365 GeV

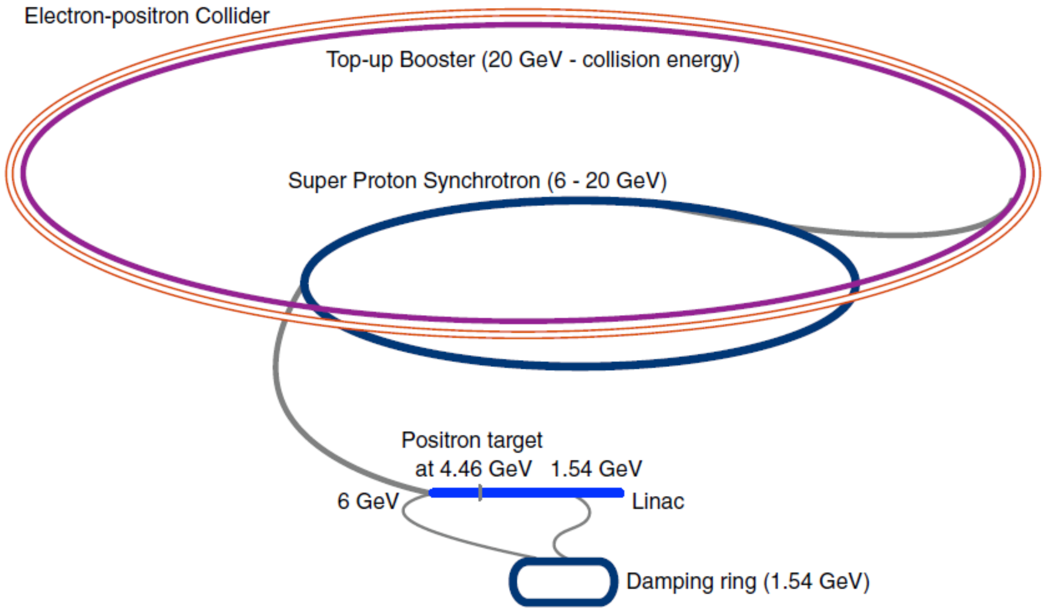
Goals to extend current research at LHC:

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

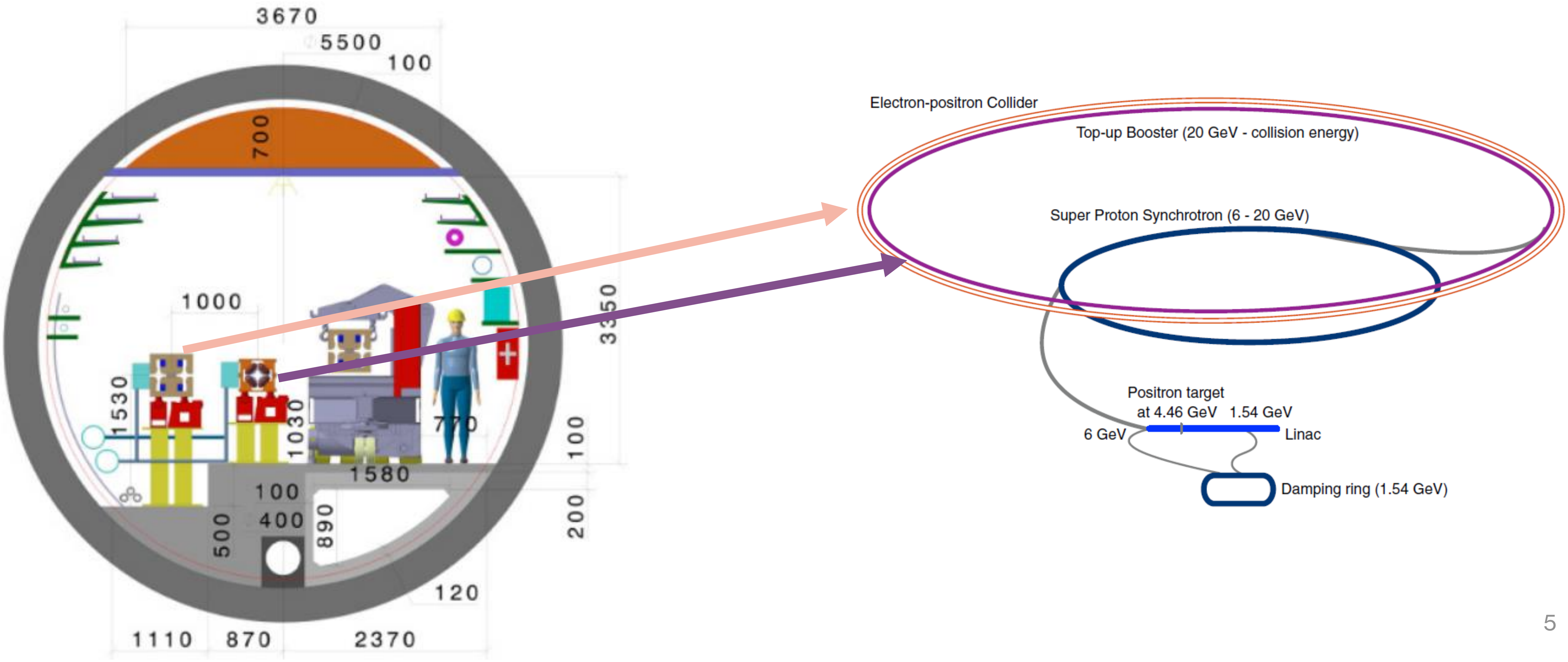


FCC-ee layout





FCC-ee layout



FCC-ee Design Parameters

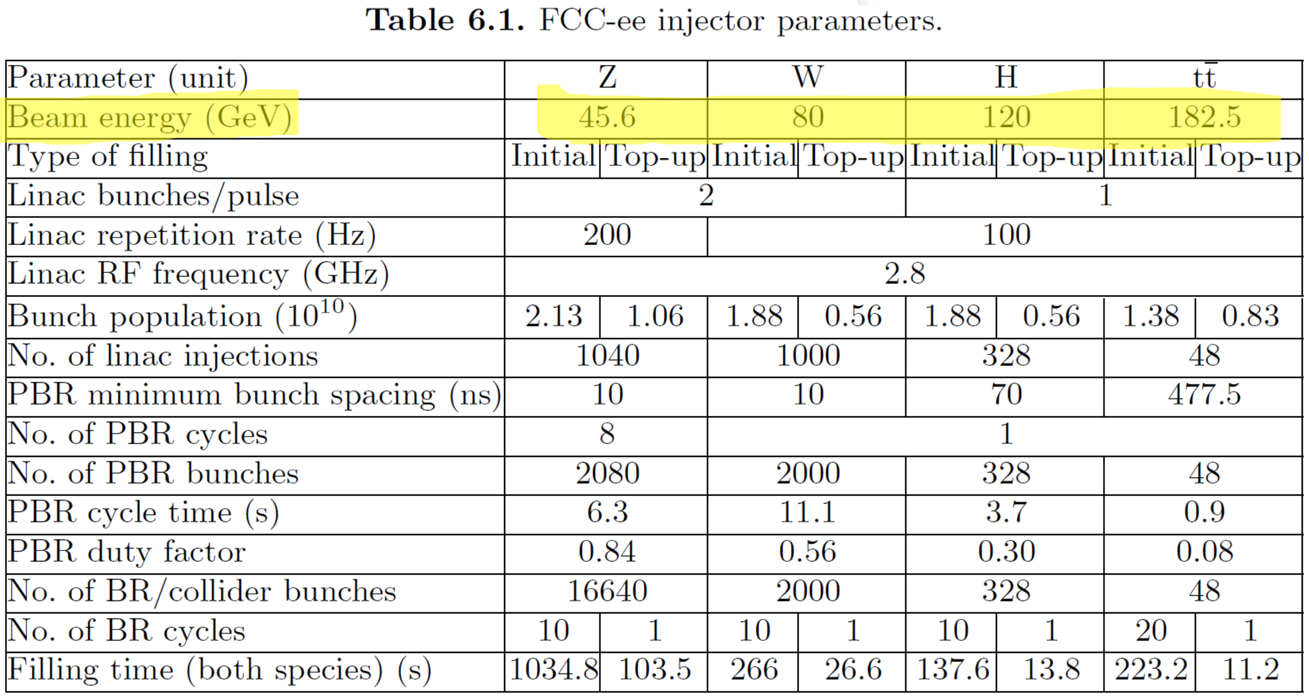


Table 6.1. FCC-ee injector parameters.

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

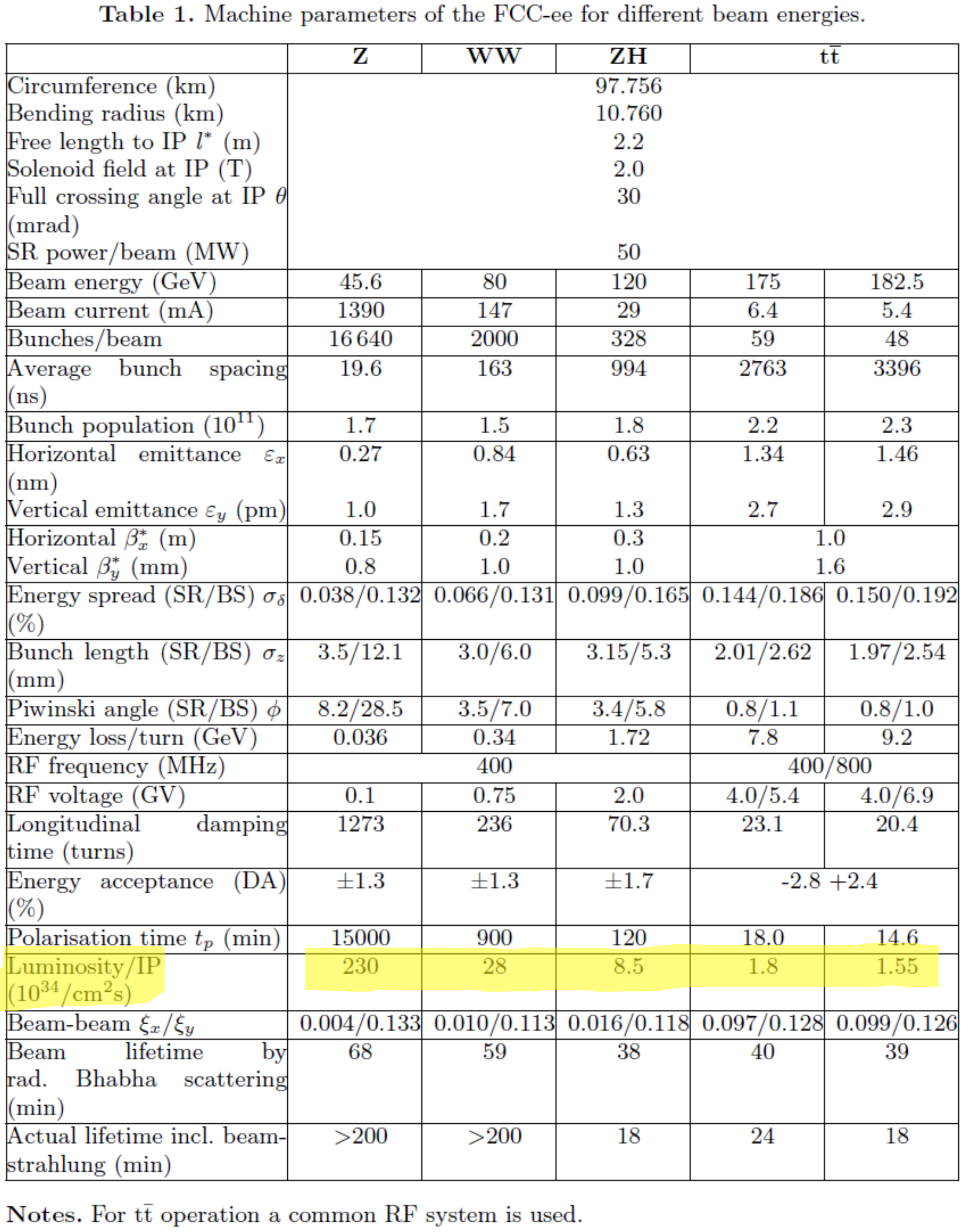


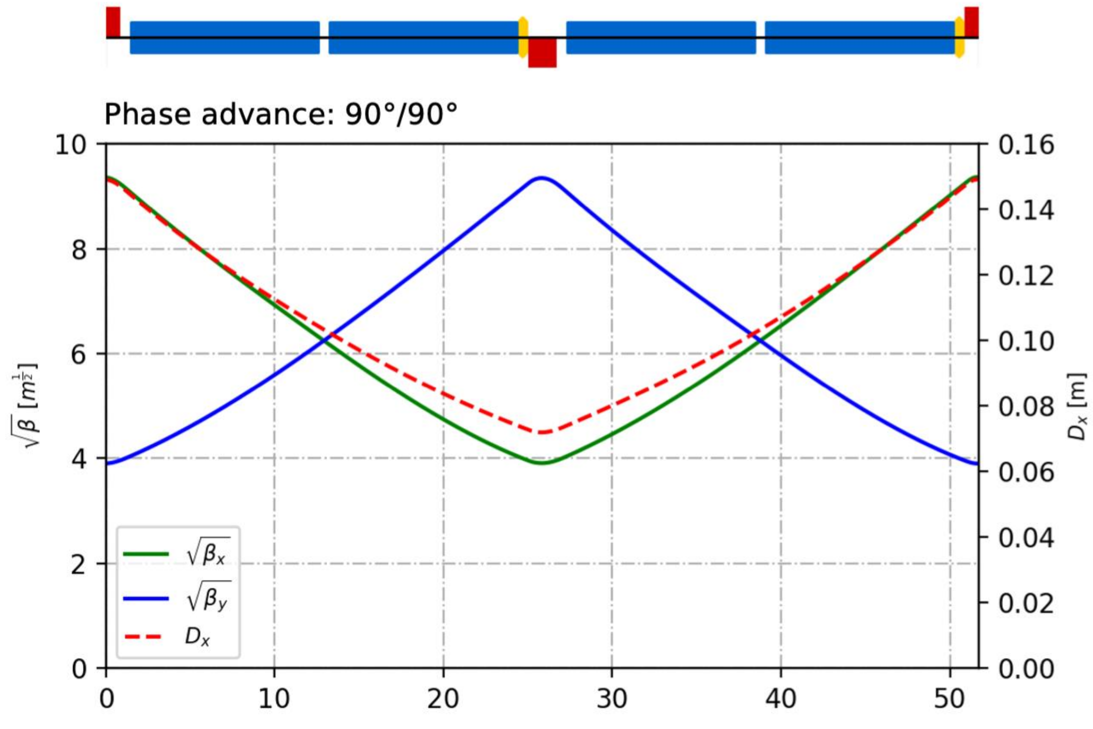
Table 1. Machine parameters of the FCC-ee for different beam energies.

	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. beamstrahlung (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:

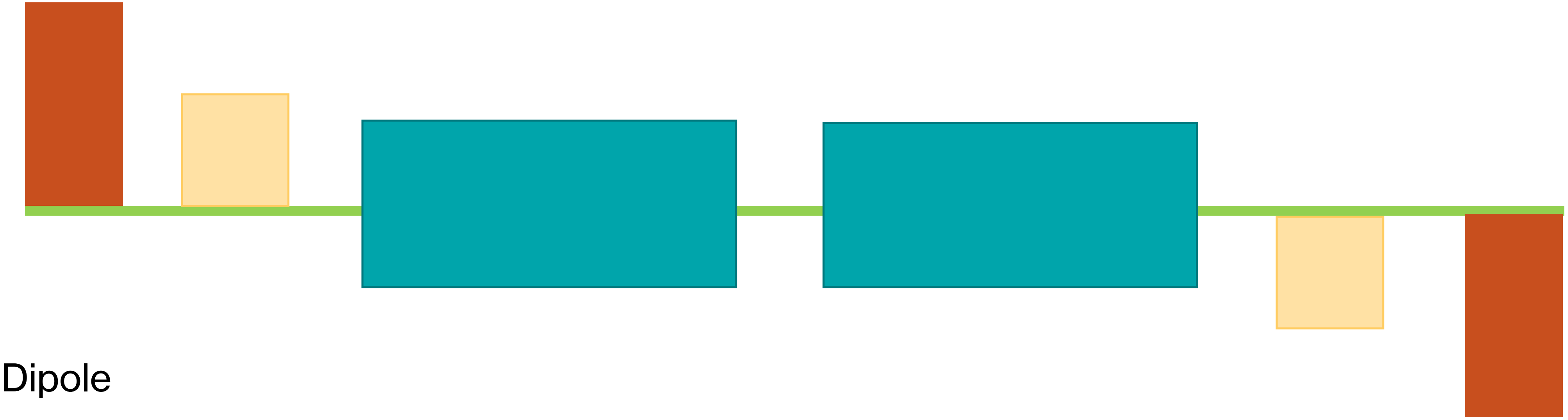
  $B_{1,max}$ = 22.63 T/m (from matching)

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*



Key:

🟦 Dipole

🟥 Quadrupole

🟨 Sextupole

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 20-30

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

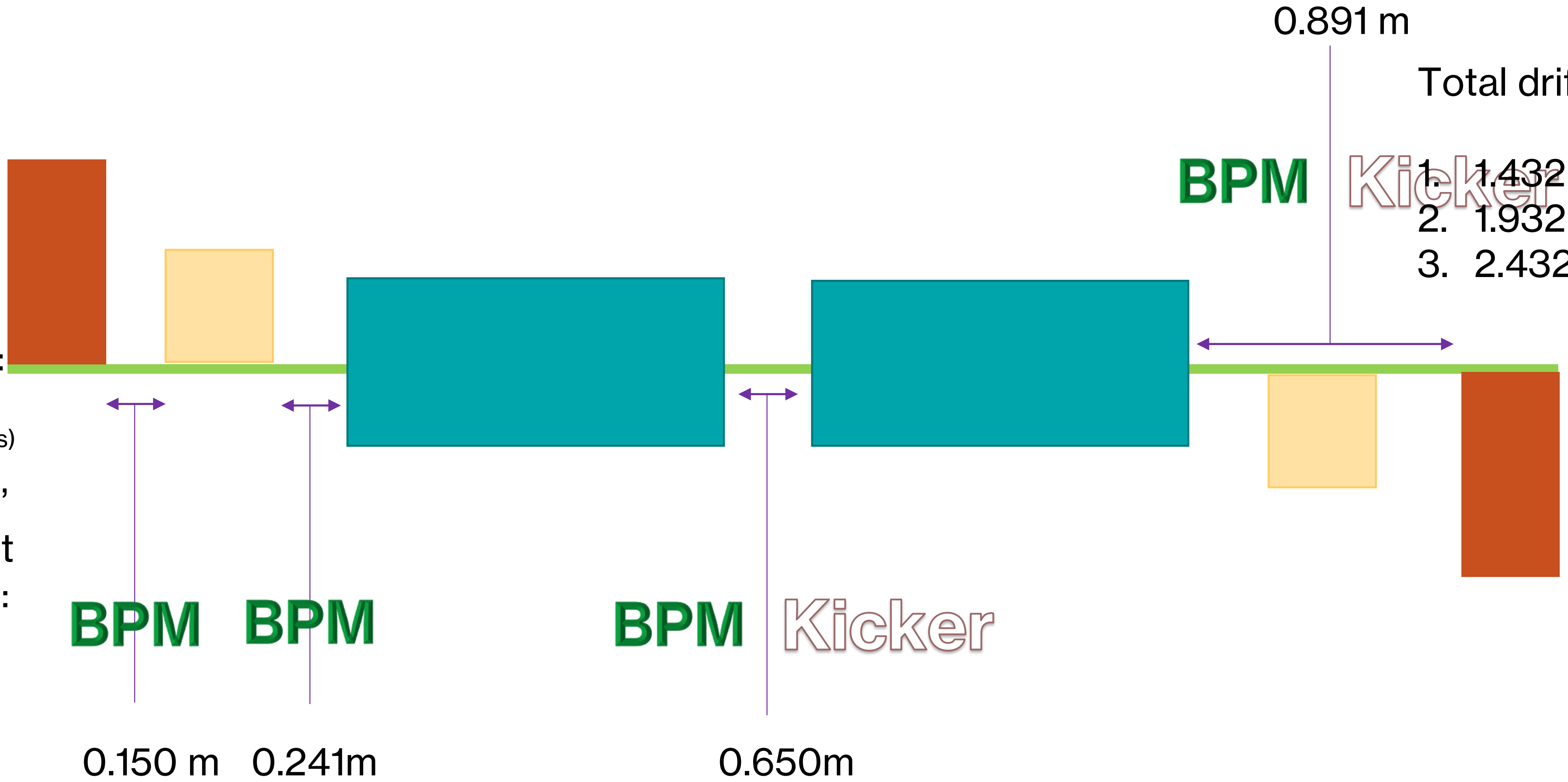
- ➔ estimate 35-45cm

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

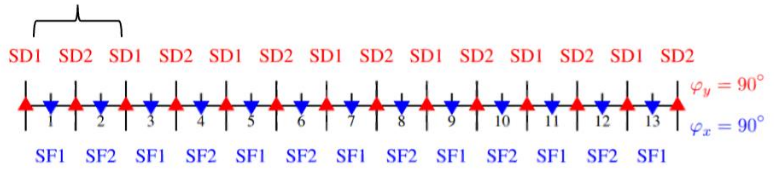


Fig. 6: Schematic of an interleaved sextupole scheme for a FODO cell lattice with $\varphi = 90^\circ$ phase advance in both planes. After every quadrupole a sextupole magnet is installed leading to a maximum number of sextupoles. The sextupoles that are separated by a phase advance of π form a family.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

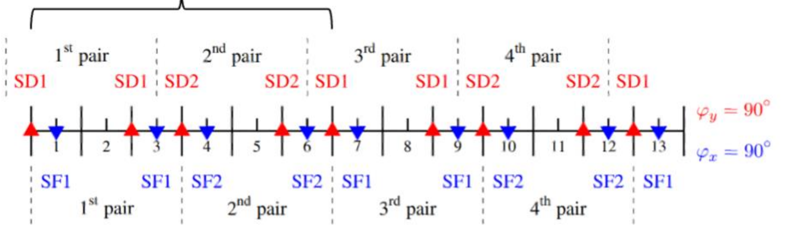
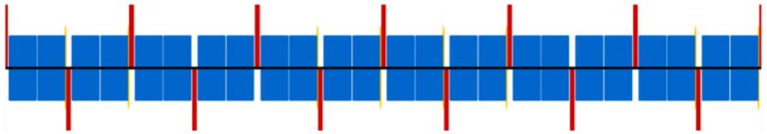


Fig. 7: Schematic of a non-interleaved sextupole scheme for a FODO cell lattice with $\varphi = 90^\circ$ phase advance in both planes. In each plane sextupole pairs are installed with a distance of π phase advance. The sextupoles are considered to only act in one plane and are interlaced with the ones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

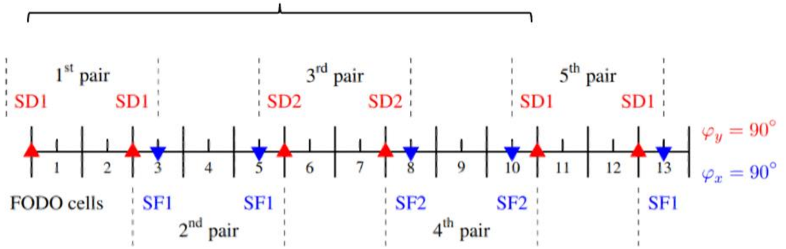
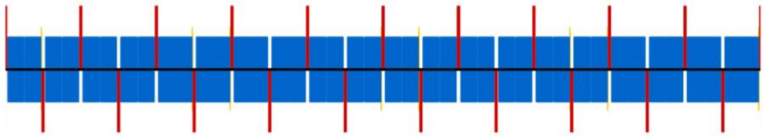


Fig. 8: Completely non-interleaved sextupole scheme for a FODO cell lattice with $\varphi = 90^\circ$ phase advance in both planes. In order to optimise the cancellation of the sextupole's geometric effect, only linear elements are installed between two sextupoles forming a pair.



Max. field for E = 182.5 GeV:

$k_{2,max}$ = 5.273

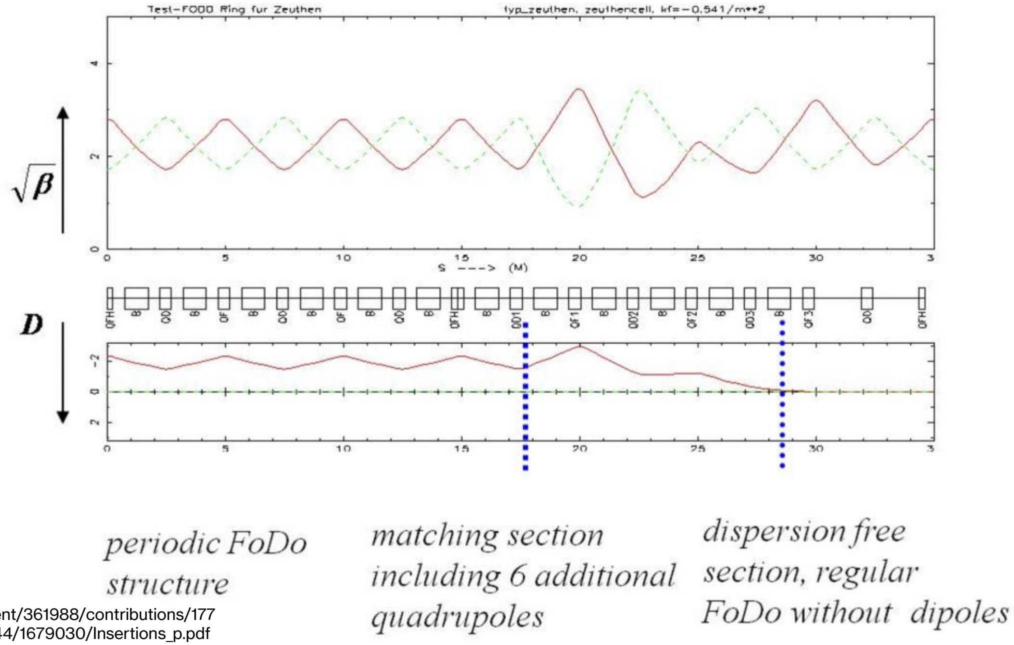
$B_{2,max}$ = 3207.5 T/m^2

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

Comparison of Dispersion Suppressor Schemes

Quadrupole scheme

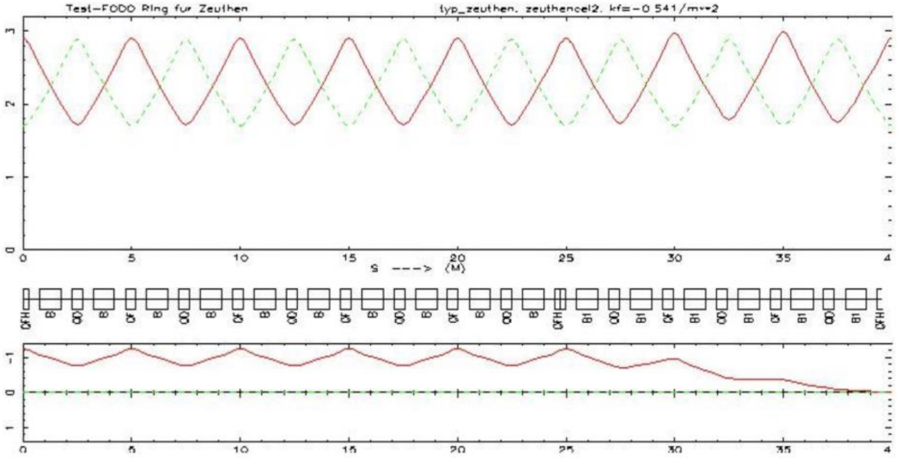
Introduce 6 flexible quadrupole magnets that correct for the six boundary conditions at the end:
-> DX=DDX=0 (no dispersion)
-> $\beta_{x/y}$- & $\alpha_{x/y}$-functions must be continuous



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

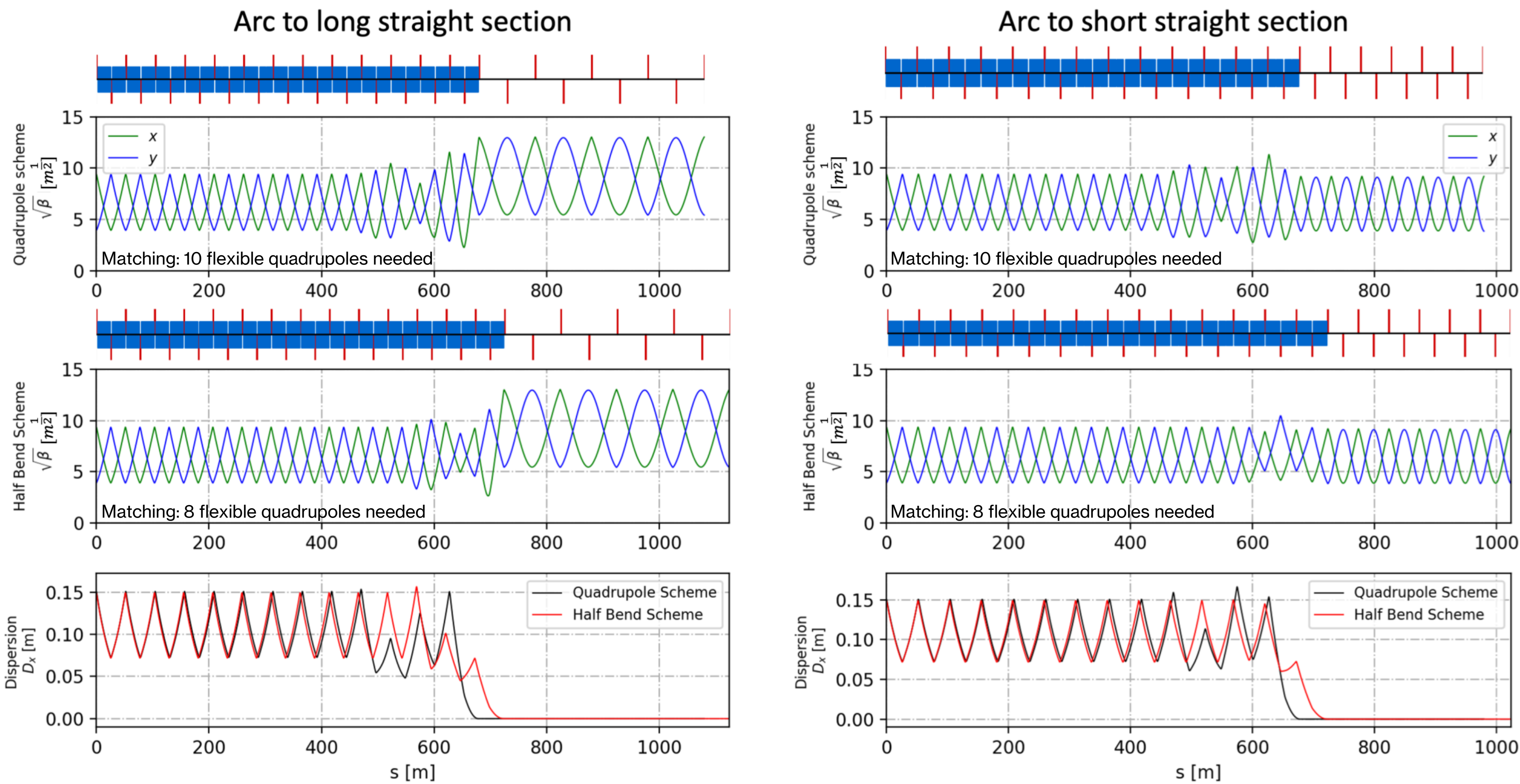
Half Bend Scheme

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.

Comparison of Dispersion Suppressor Schemes

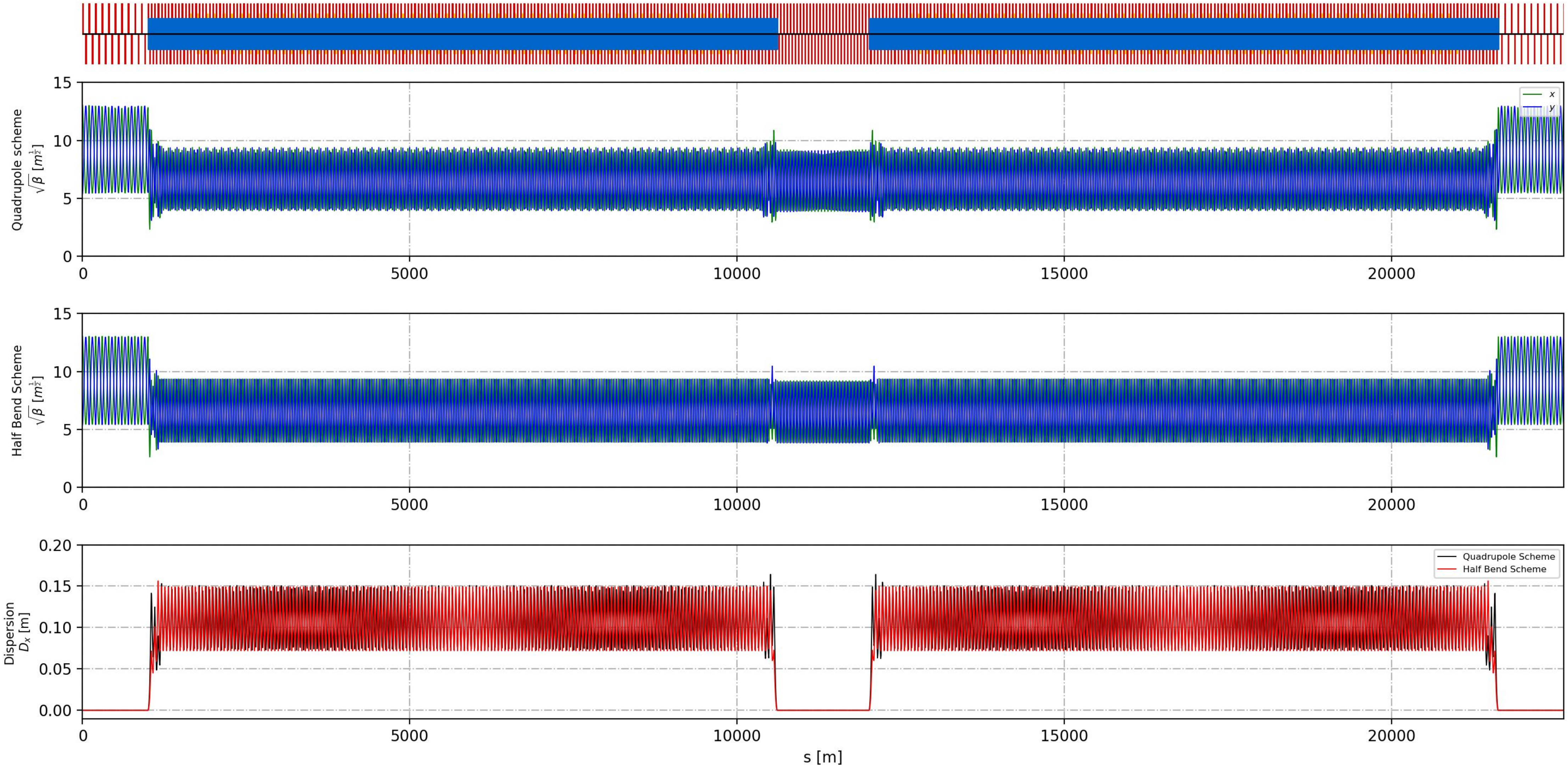

Arc to long straight section

Arc to short straight section

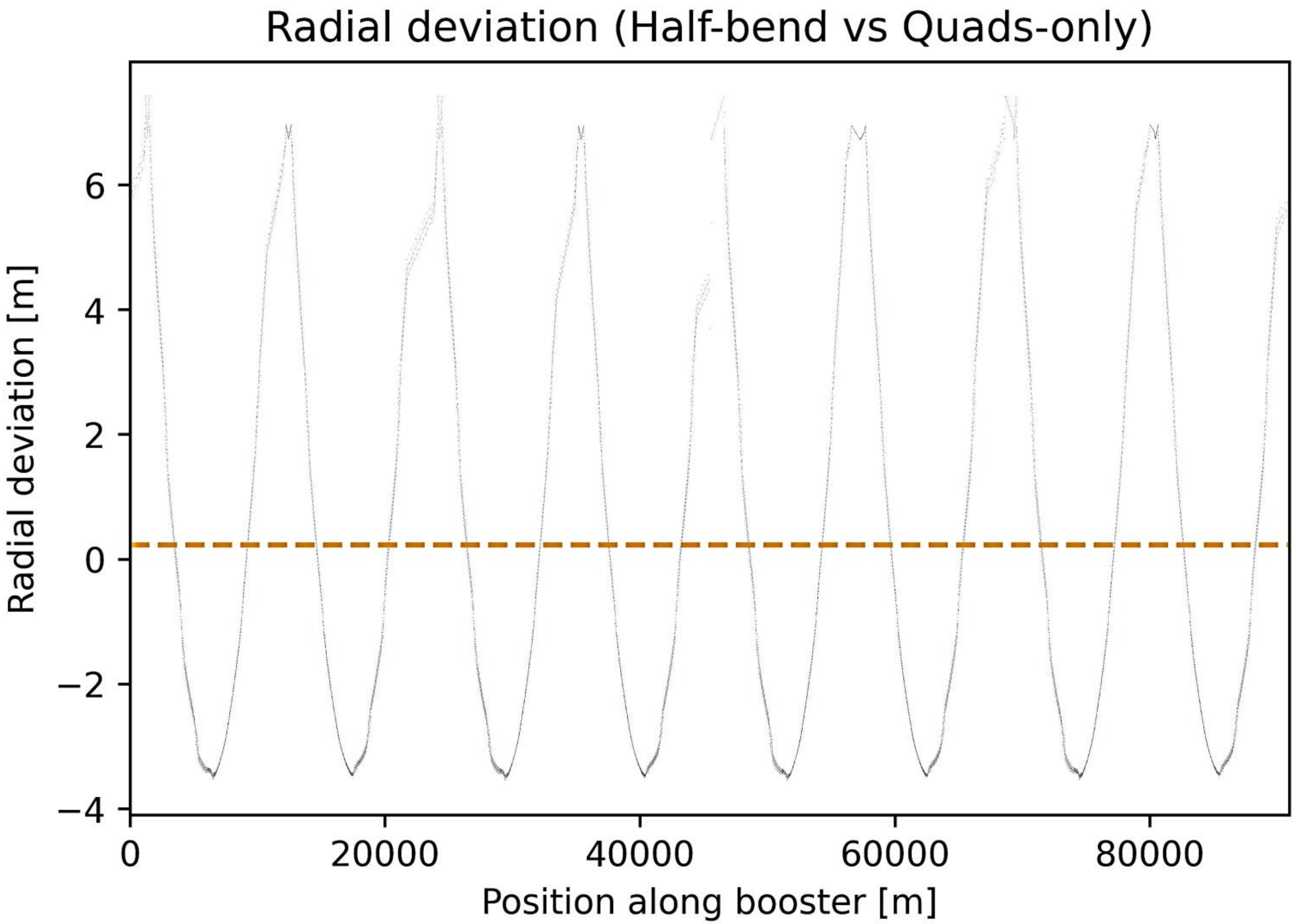
Matching: 10 flexible quadrupoles needed

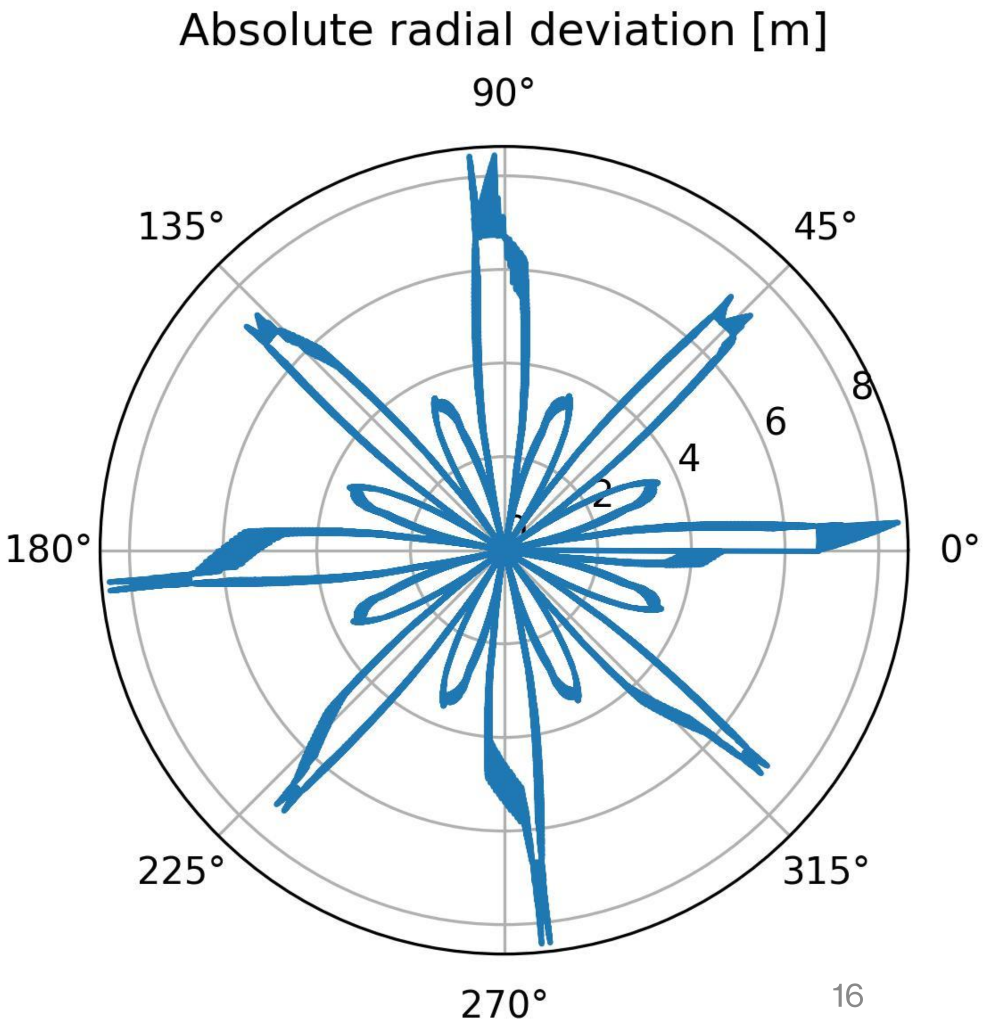
Matching: 8 flexible quadrupoles needed

Quarter of FCC-ee booster ring



Changes in Geometry by choice of Dispersion Suppressor scheme

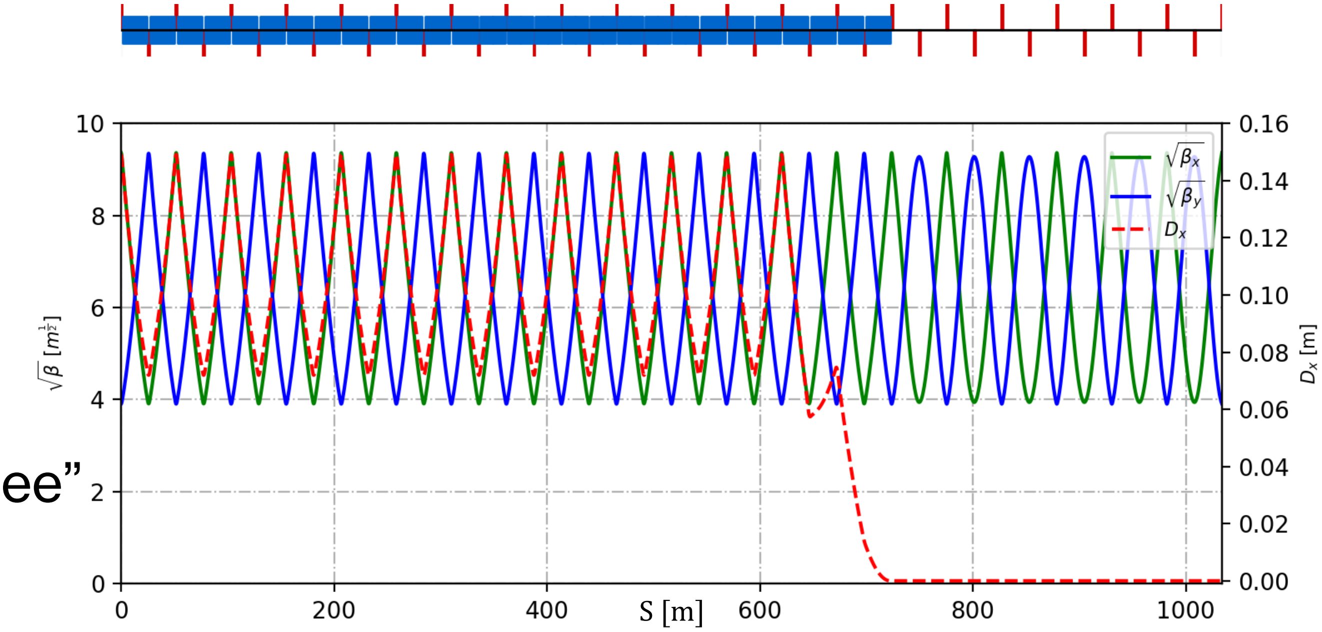




How to further improve Half-Bend scheme

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

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

All GFRs must have a 46.67mm diameter:

- At reference aperture diameter 70mm.
- SPS → Booster injection energies 10 GeV, 15 GeV, 20 GeV.
- Booster → Collider injection energies 45.6 GeV, 80 GeV, 120 GeV, 175 GeV, 182.5 GeV.

Magnets introduction

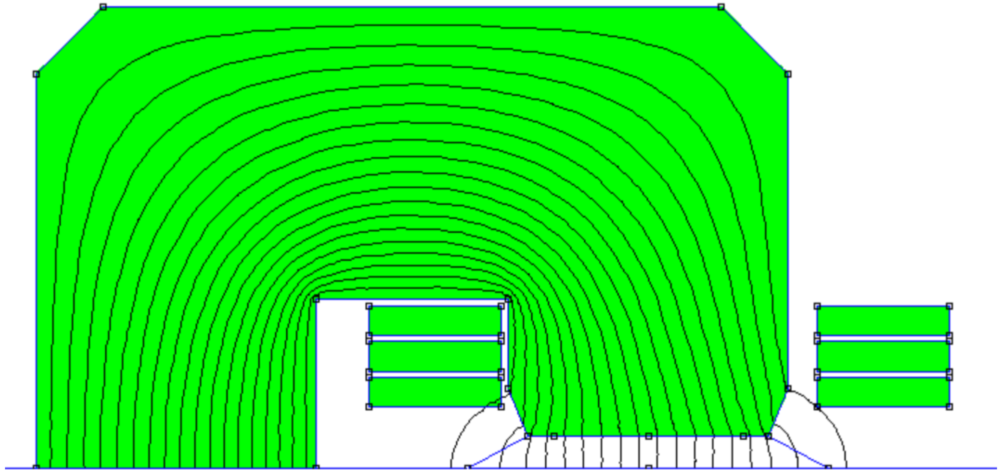
Software & toolkits:

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

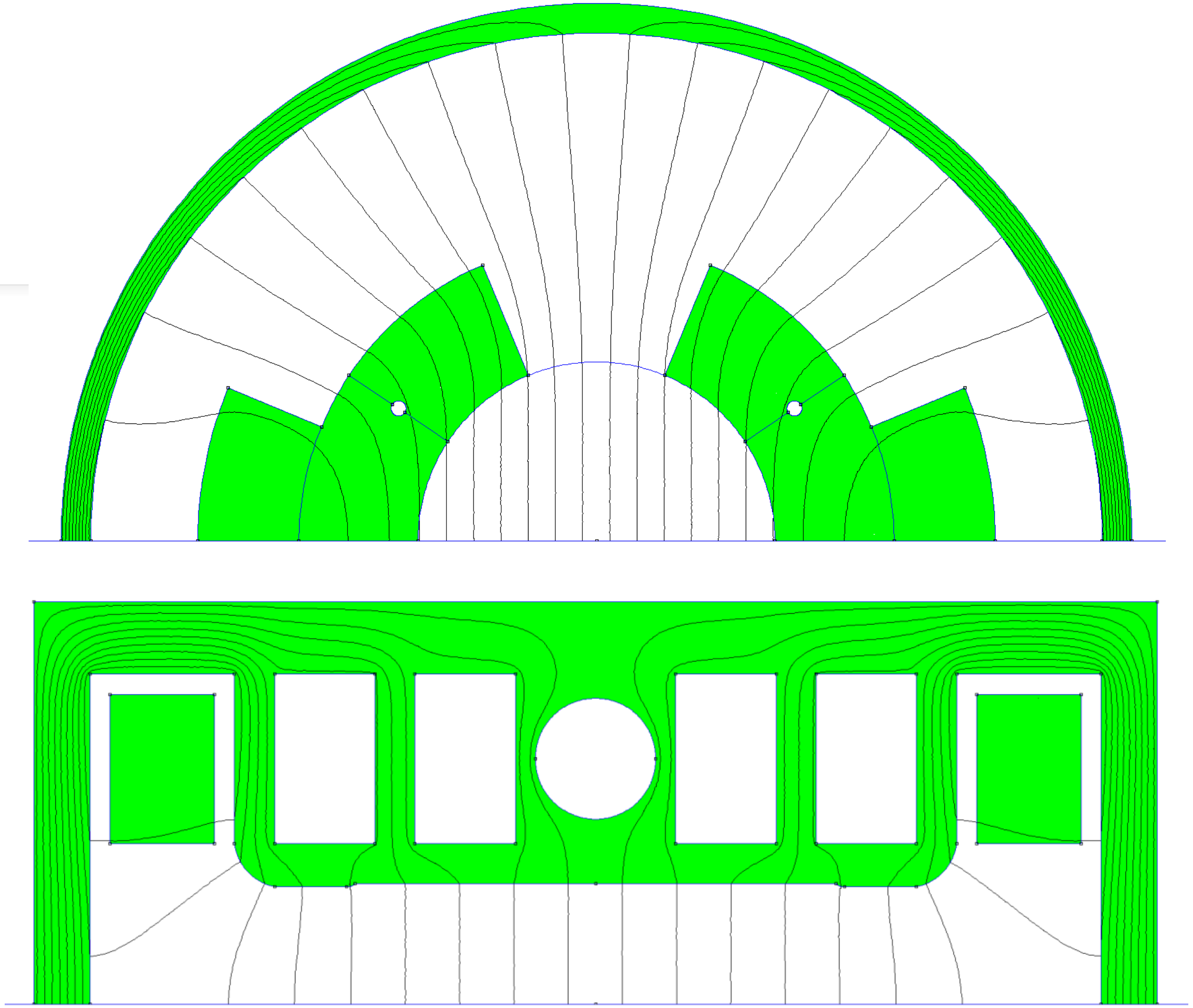
Benefits of non-saturating fields:

- 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

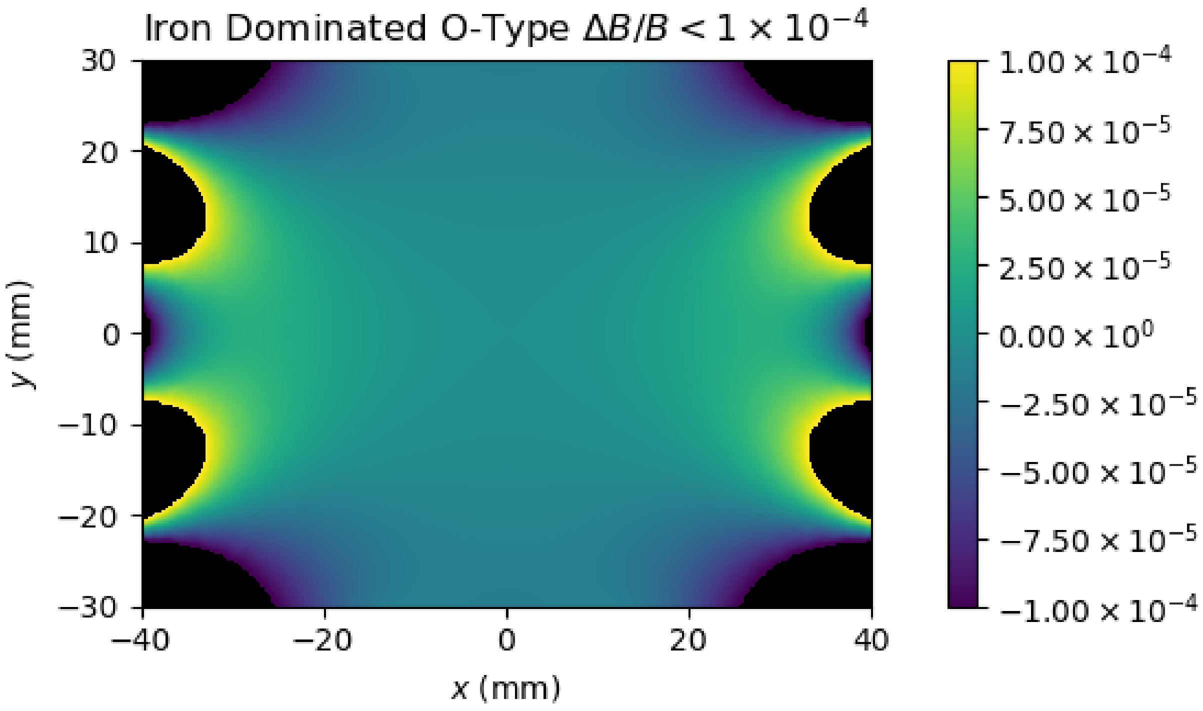


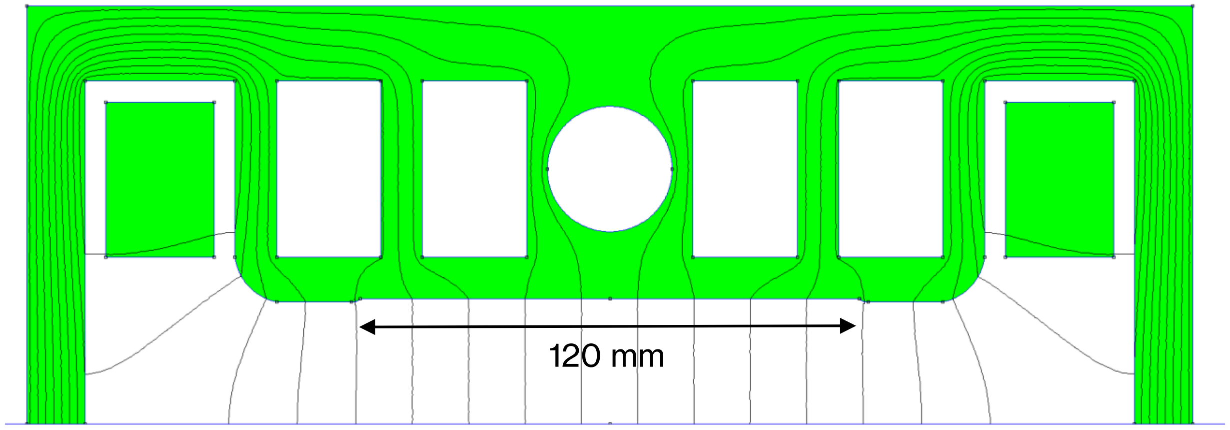
Based on JAI 2021-22
C-type example



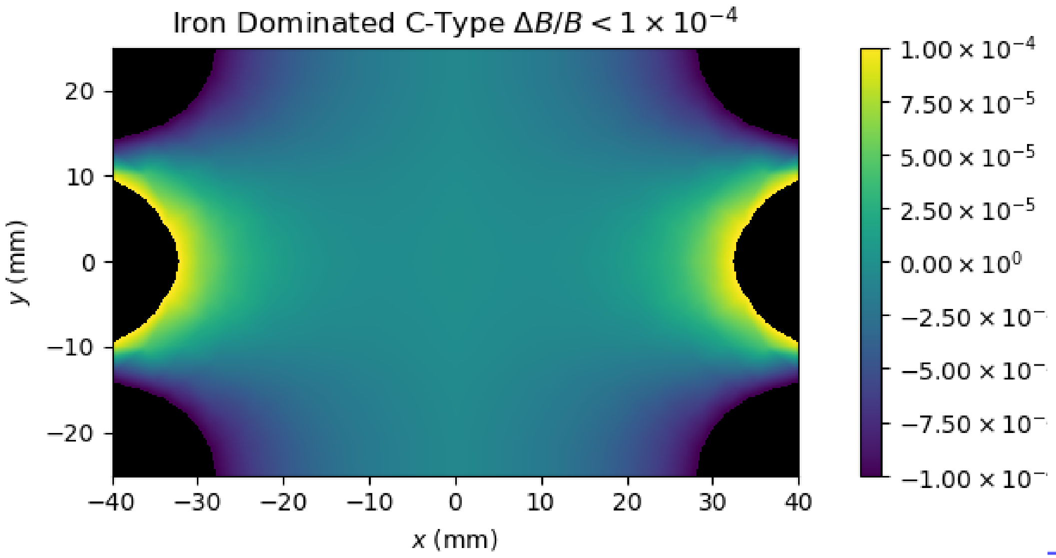
Based on IHEP CAS
designs

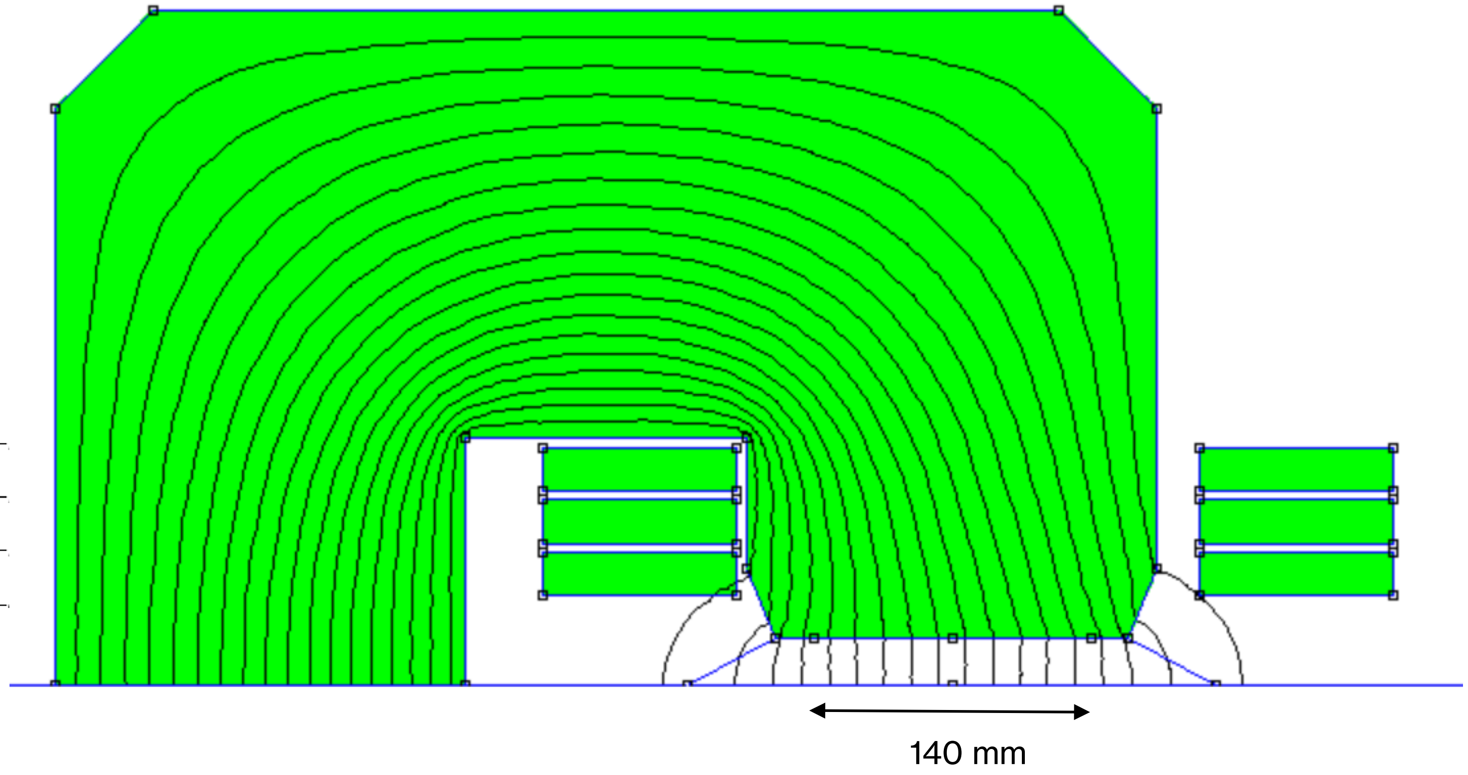
Iron dominated O-type



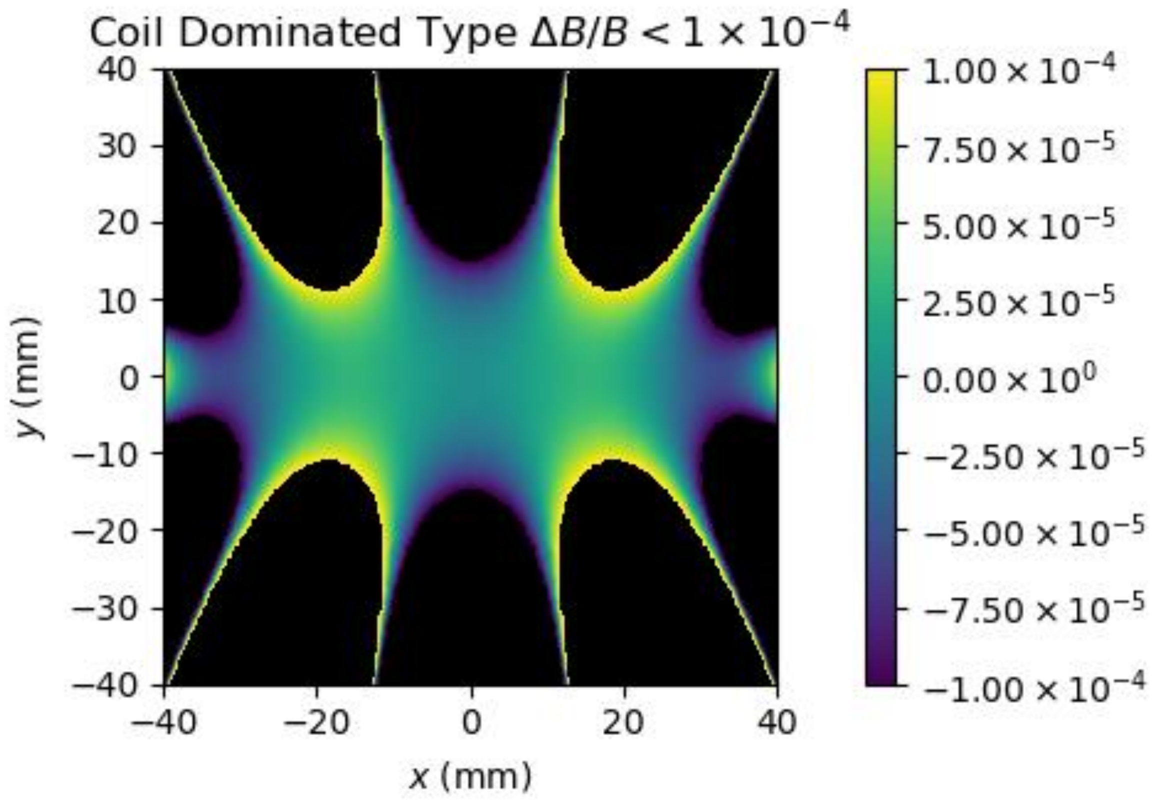


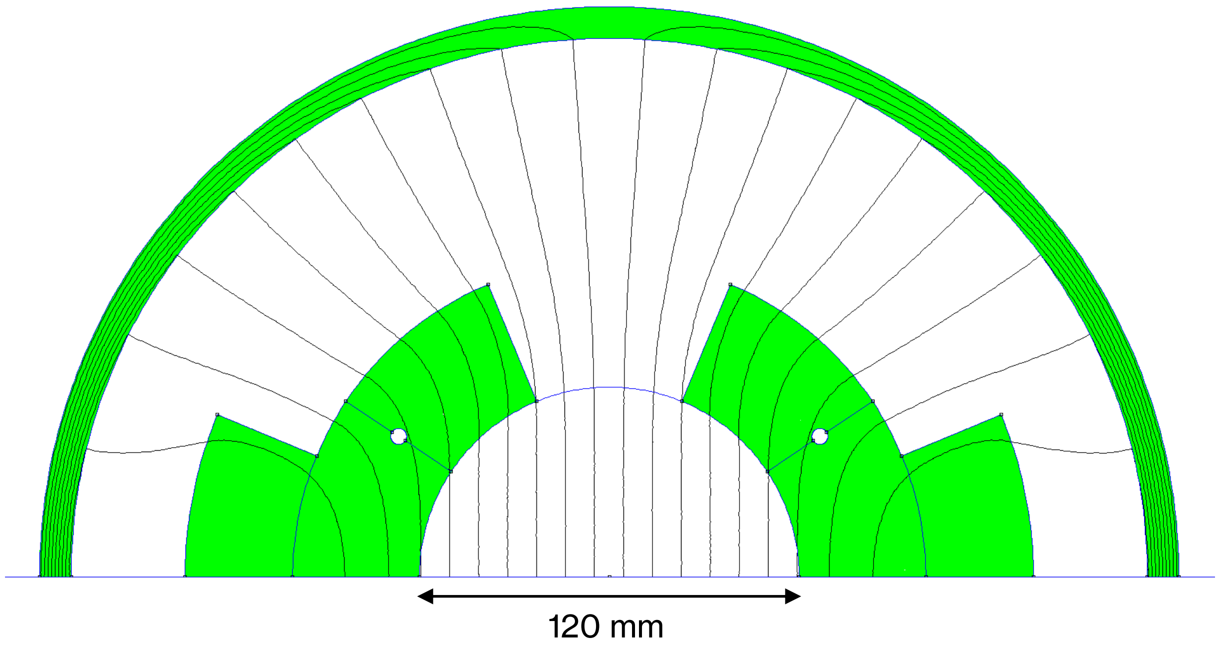
Iron dominated C-type





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

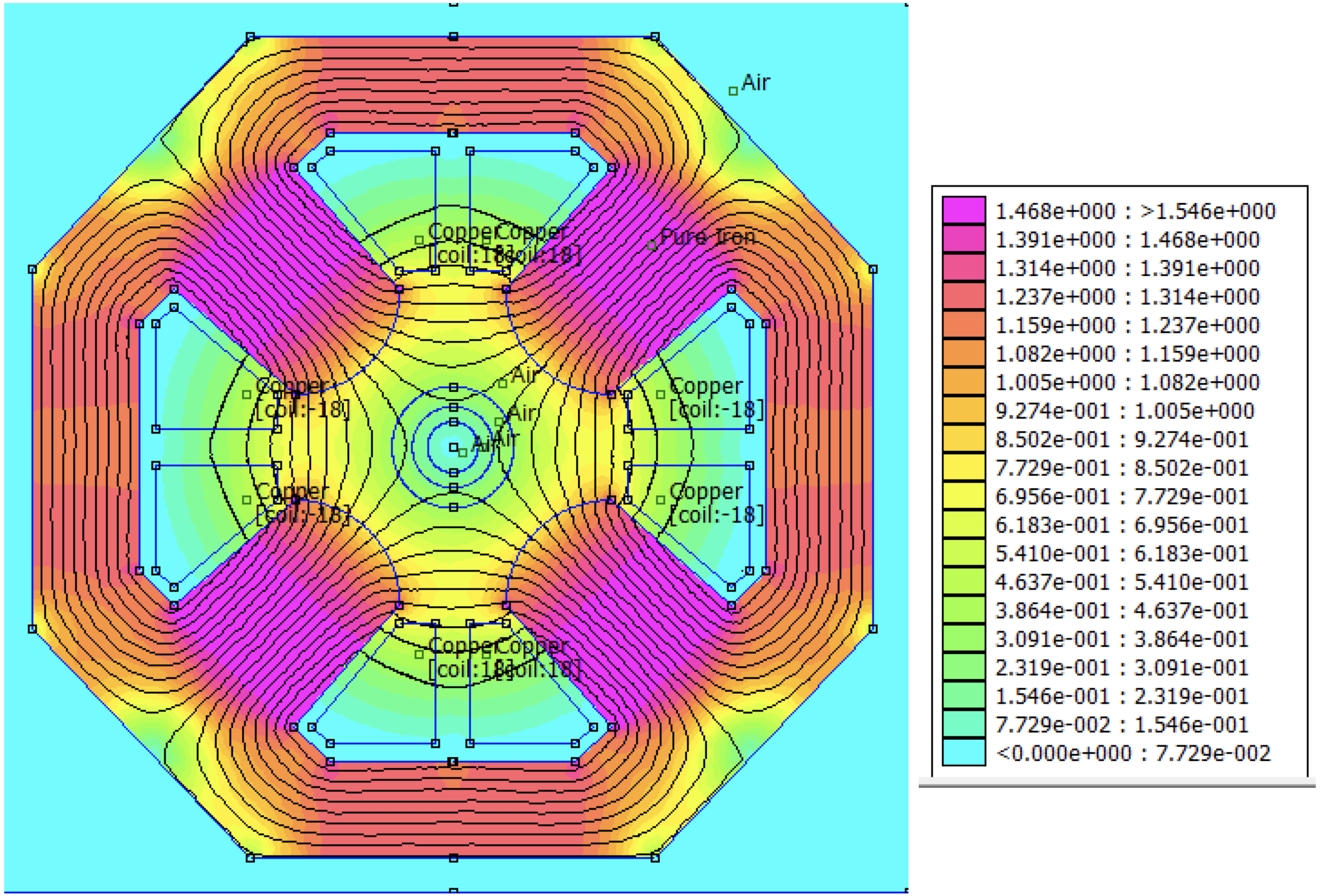
Goals:

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

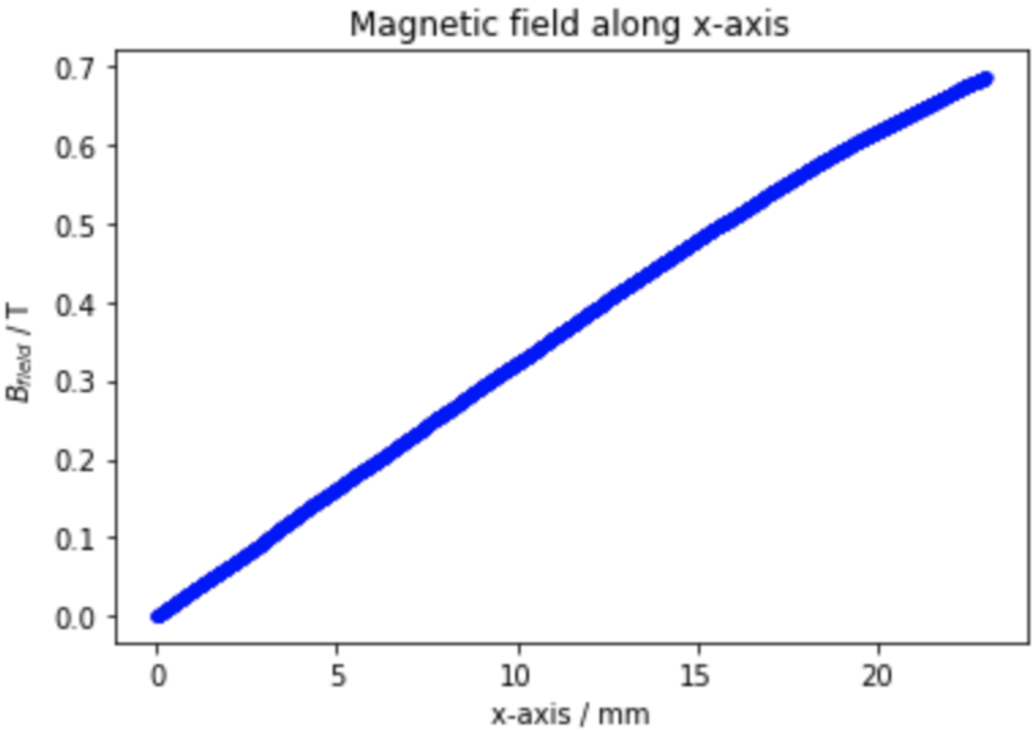
Varied:

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

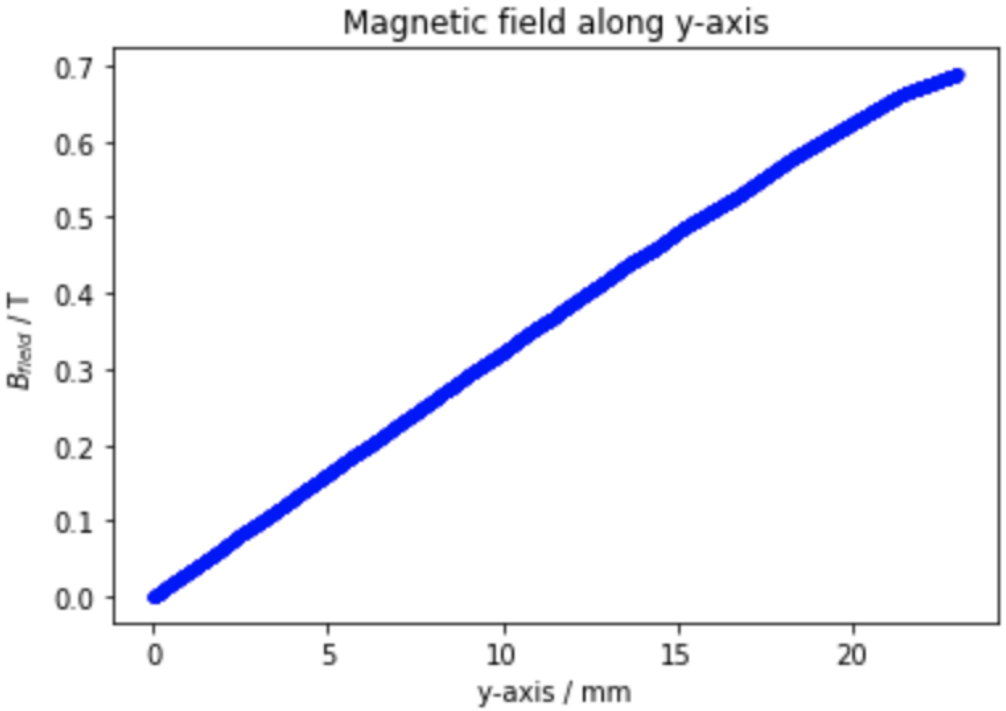
Final design



Quadrupole field analysis



Magnetic field along x-axis



Magnetic field along y-axis

Quadrupole - Summary

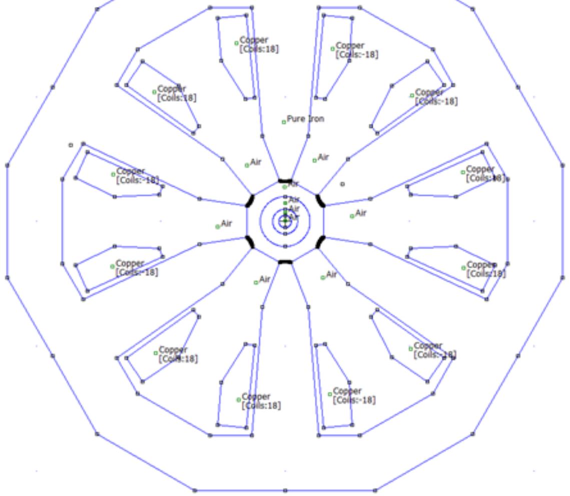
Final design:

- 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

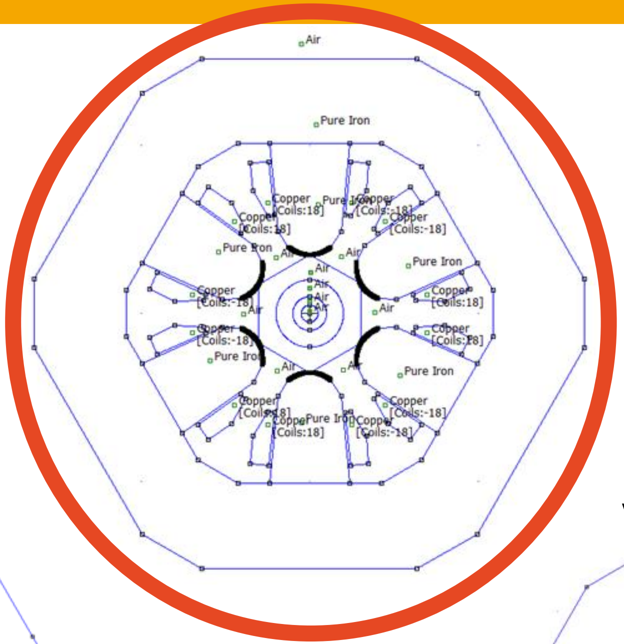
Sextupole - designs

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

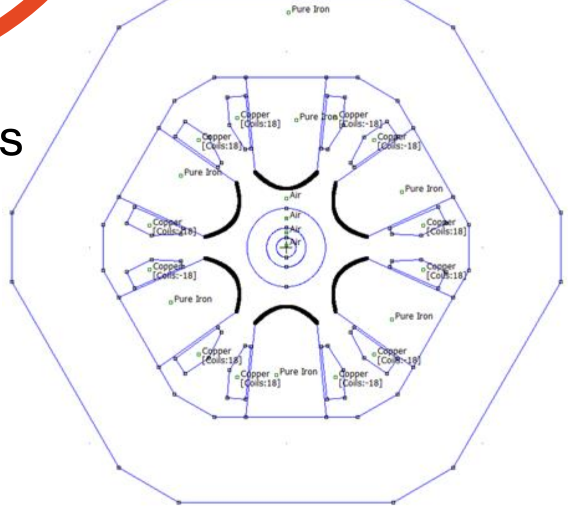
Iranian Light Source Sextupole



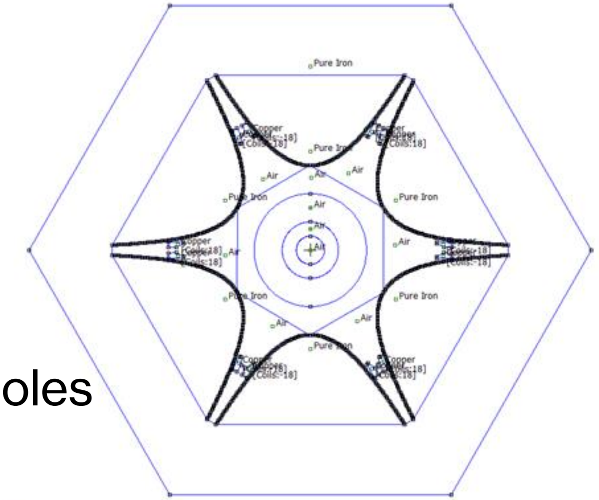
Iranian design + Hyperbolic tip



Hyperbolic poles v1



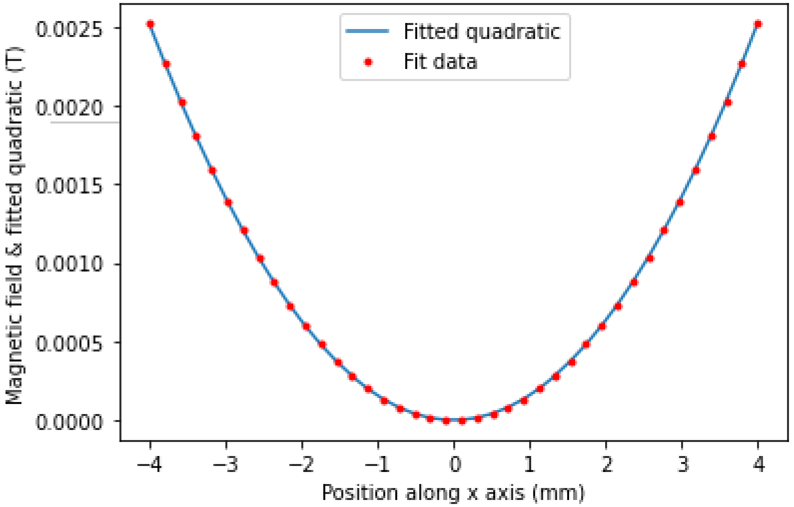
Hyperbolic poles v2



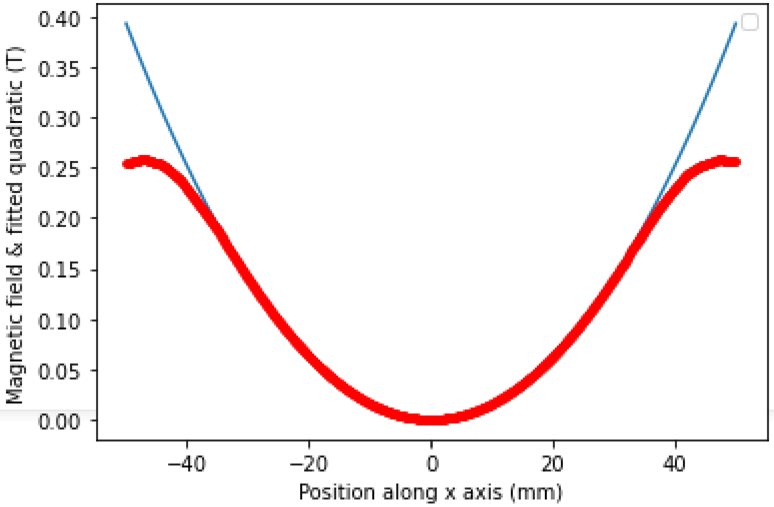
Idealised poles

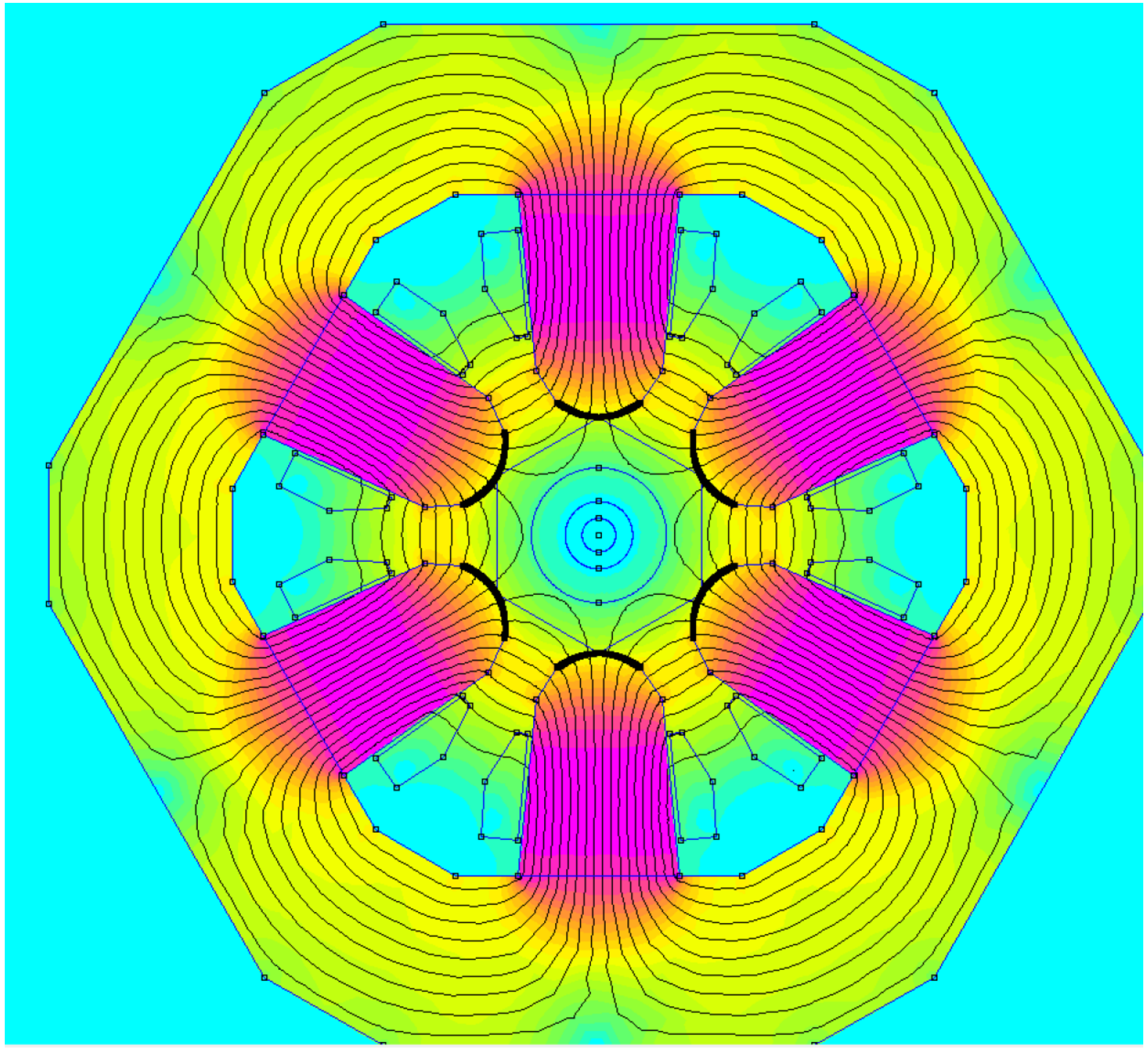
Best design

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

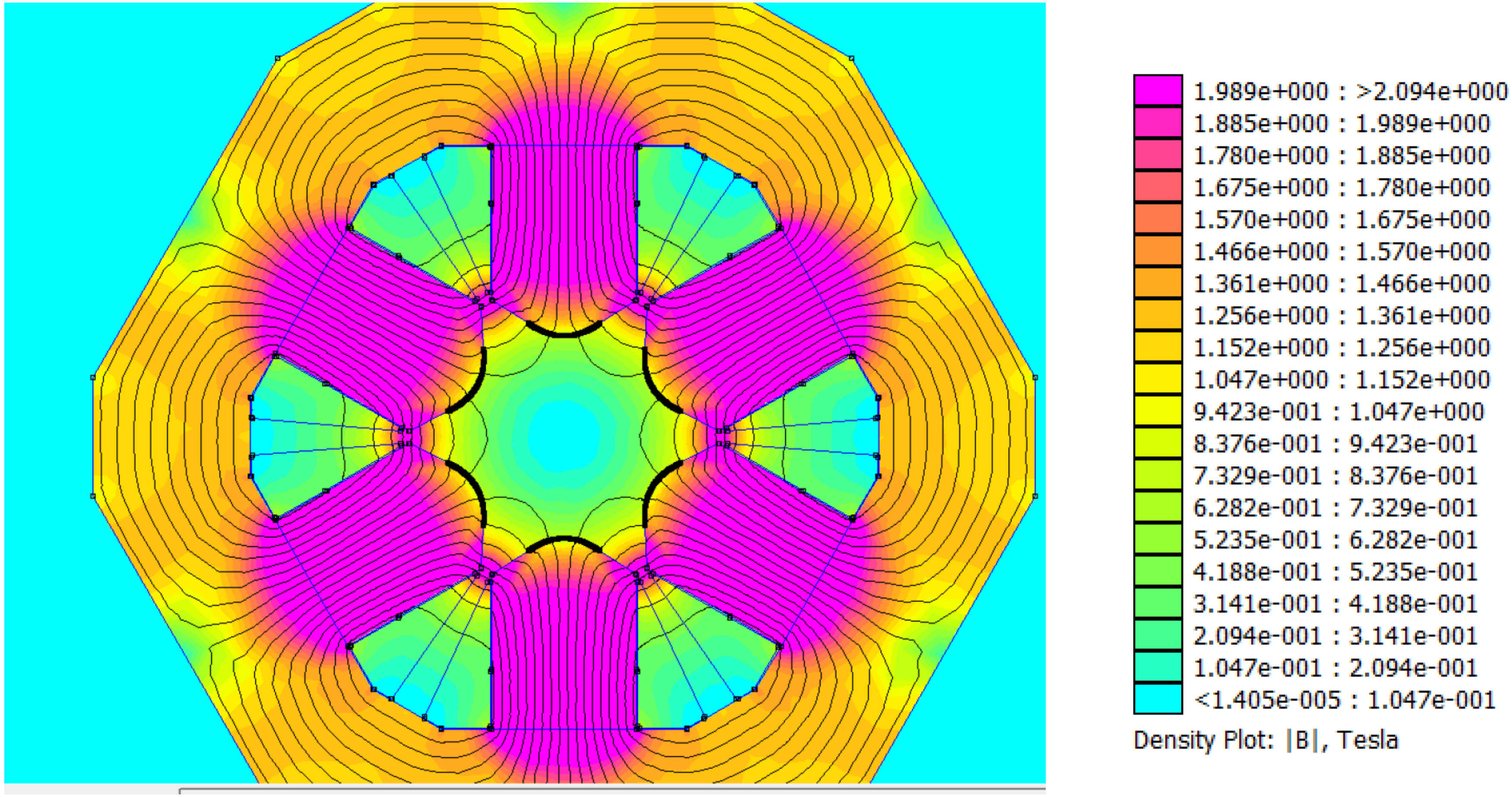


Partial hyperbola 1 - full design - 35mm radius.ans: Plot of all B field data vs fitted quadratic





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

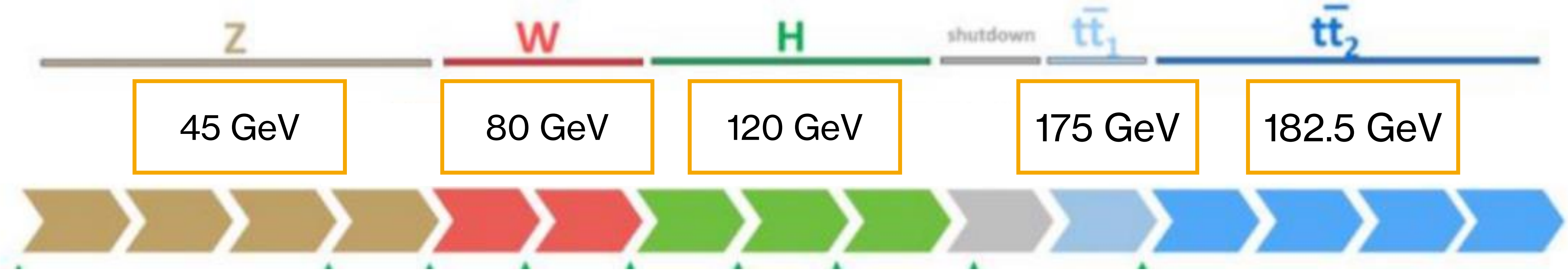
3D work:

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

FCC-ee RF Cavity design

RF Cavity Design

Available for every operation energy



45 GeV | 80 GeV | 120 GeV | 175 GeV | 182.5 GeV

- 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

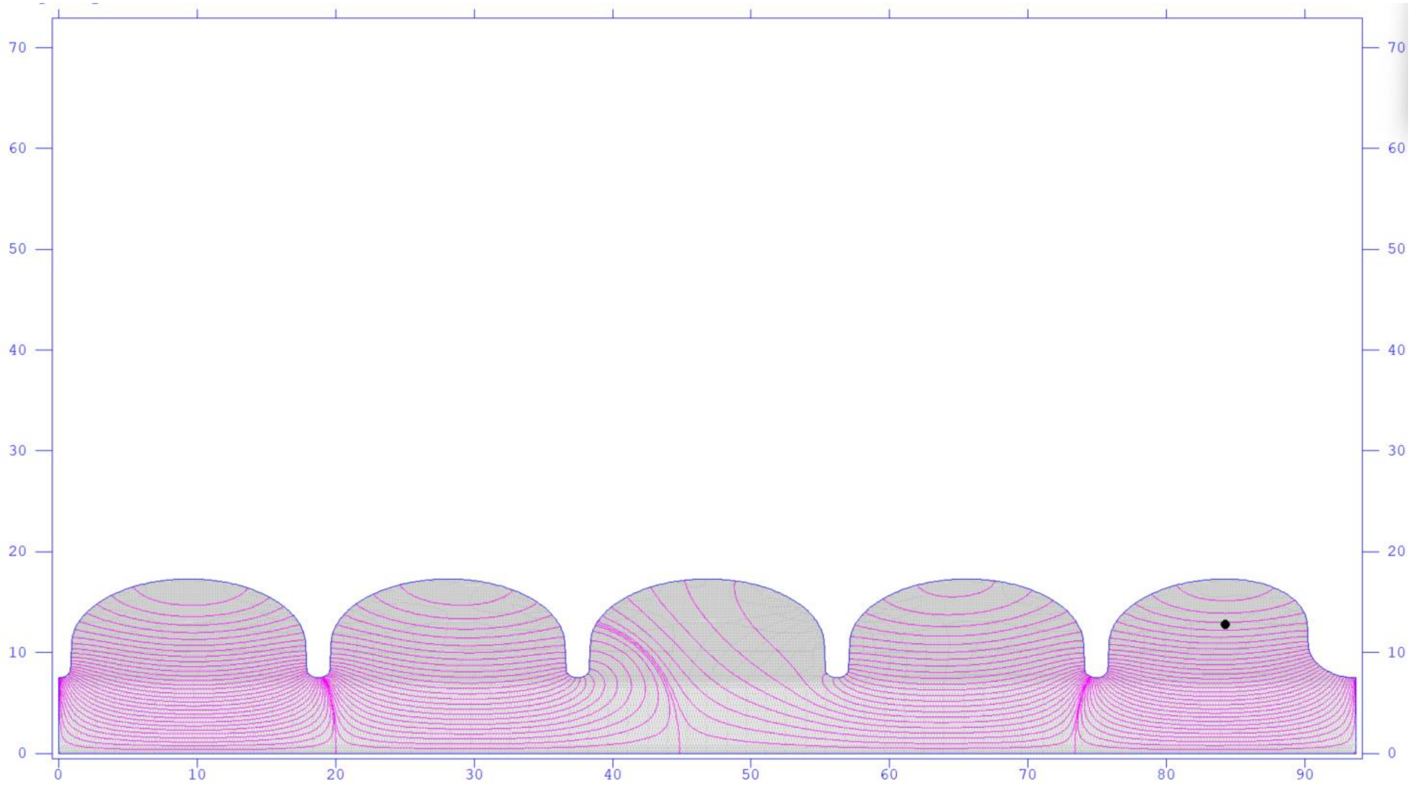
Electromagnetic Considerations

- **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?

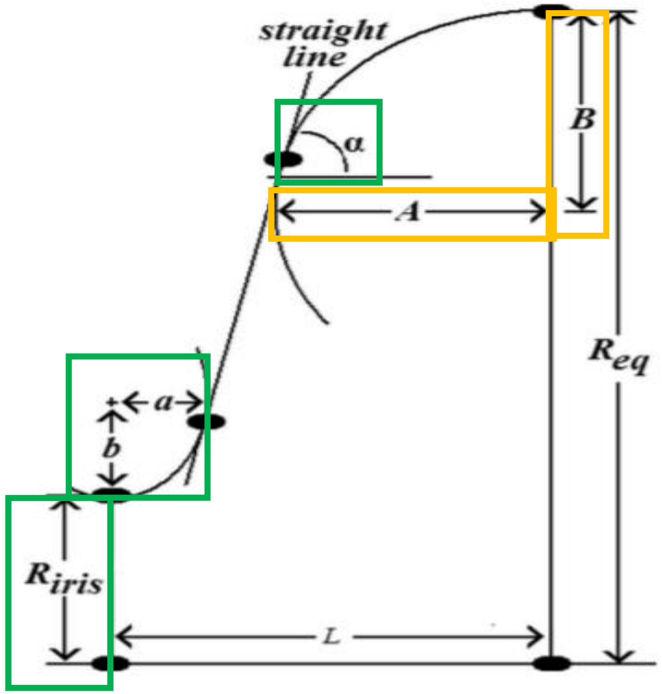
Tuning…. to satisfy

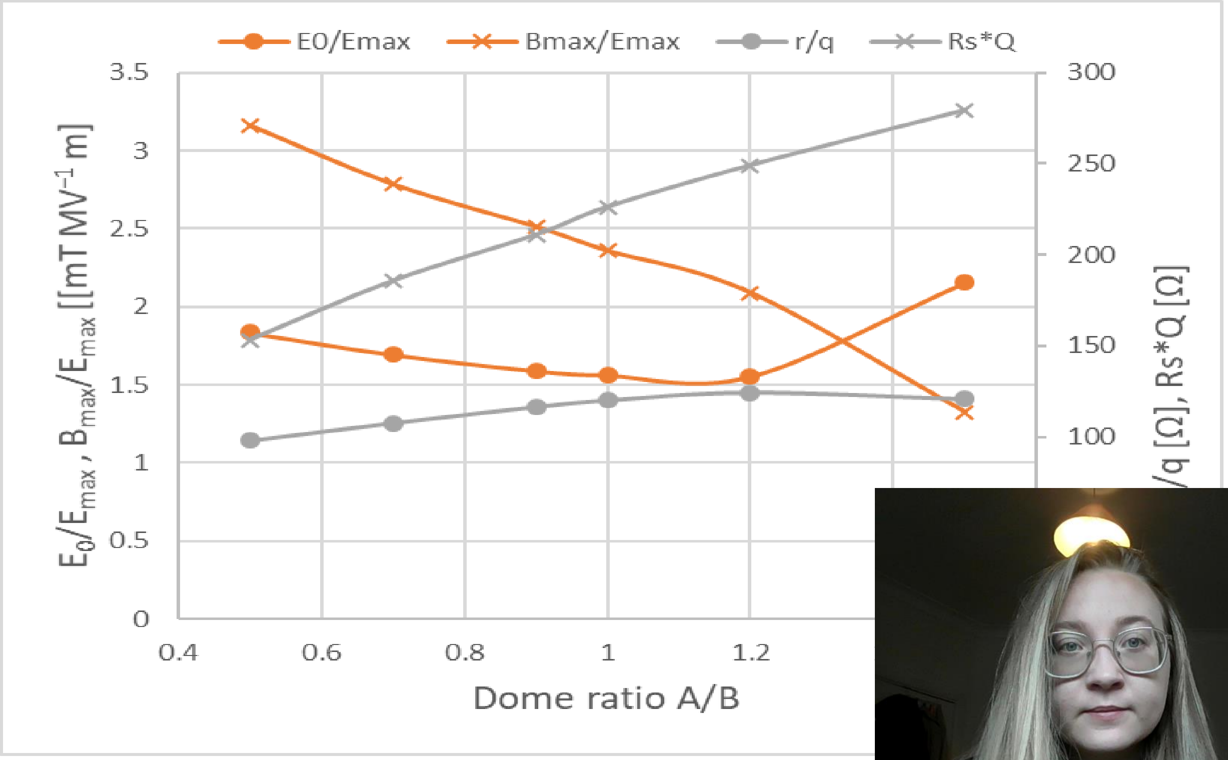
L[m] =v/2f[Hz]

Diameter tuning to match desired frequency

Maximising Electromagnetic Parameters

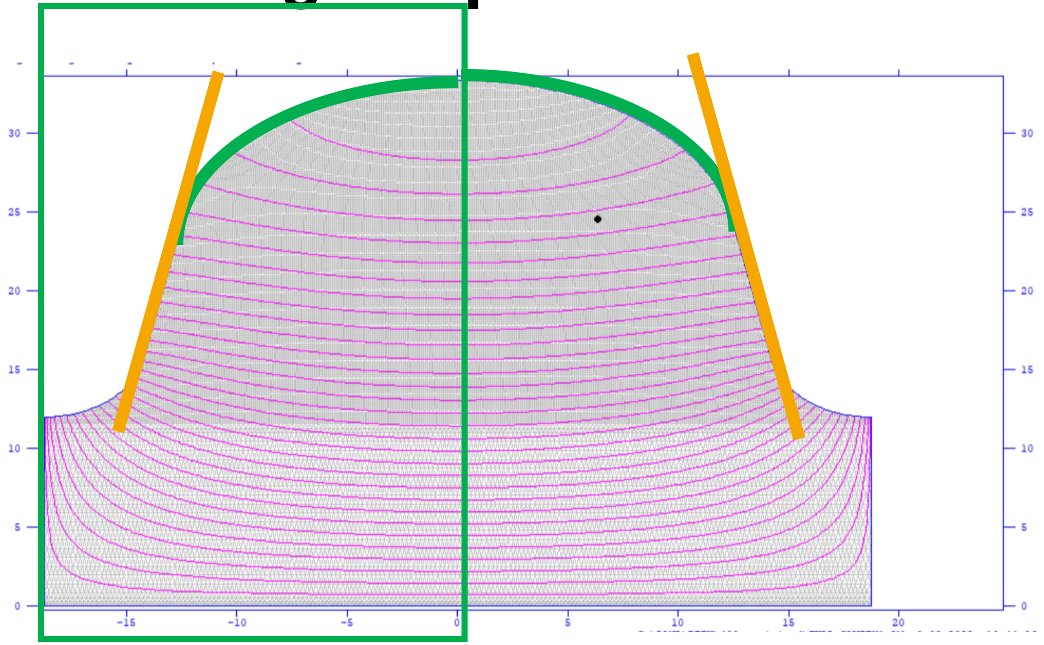
- Optimisation for a single cell done in SUPERFISH
- 5 MV/m
- 400MHz





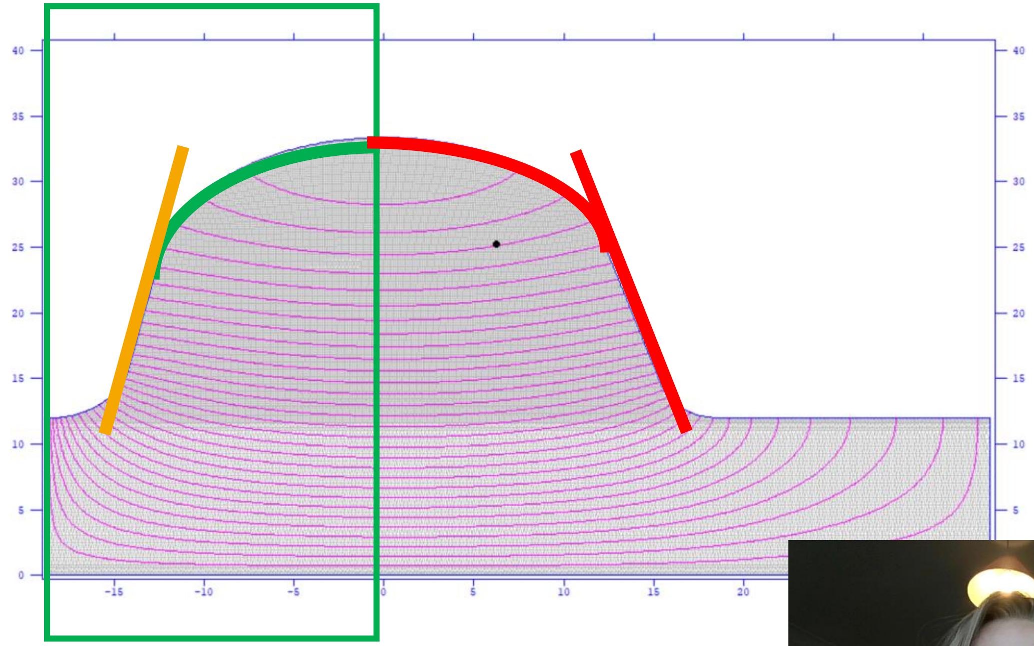
Mid cell + End cell Optimisation at 10MV/m

After Tuning Freq = 400.00541 **MHz**



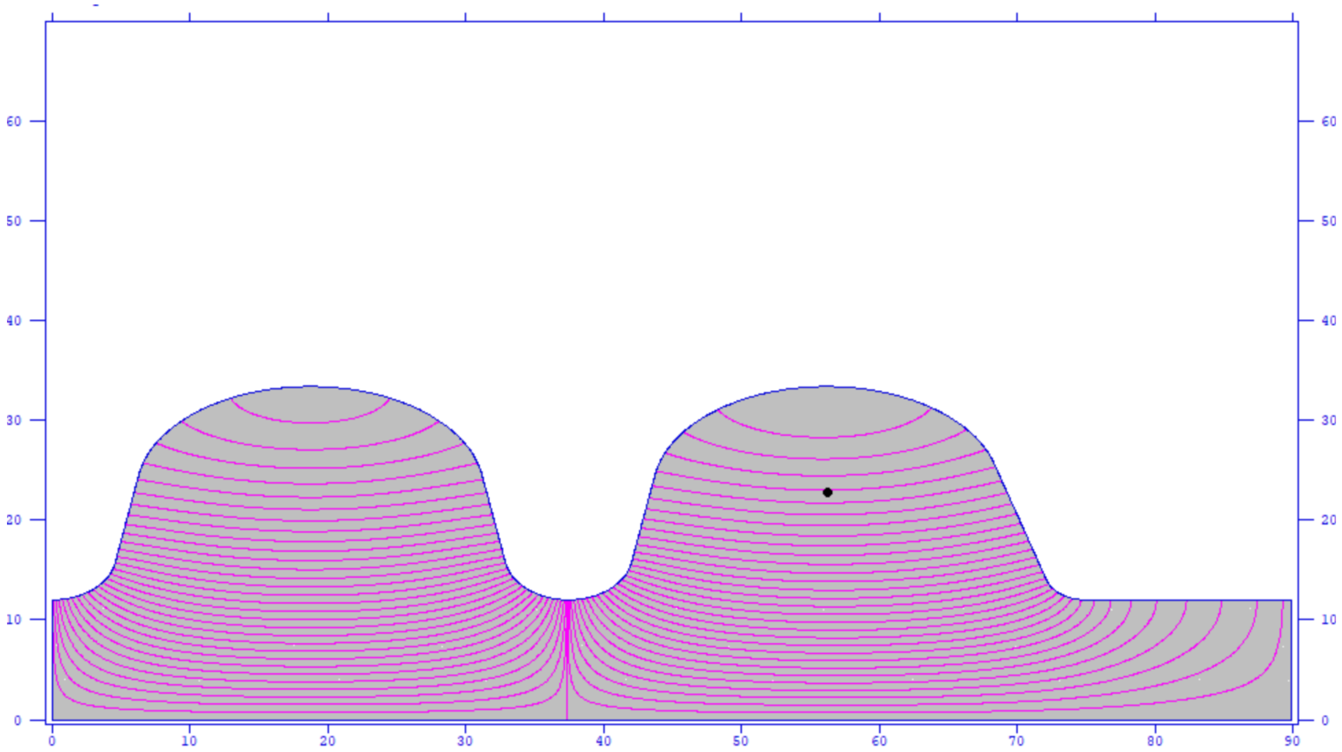
Symmetrical

After Tuning Freq = 400.13717 **MHz**



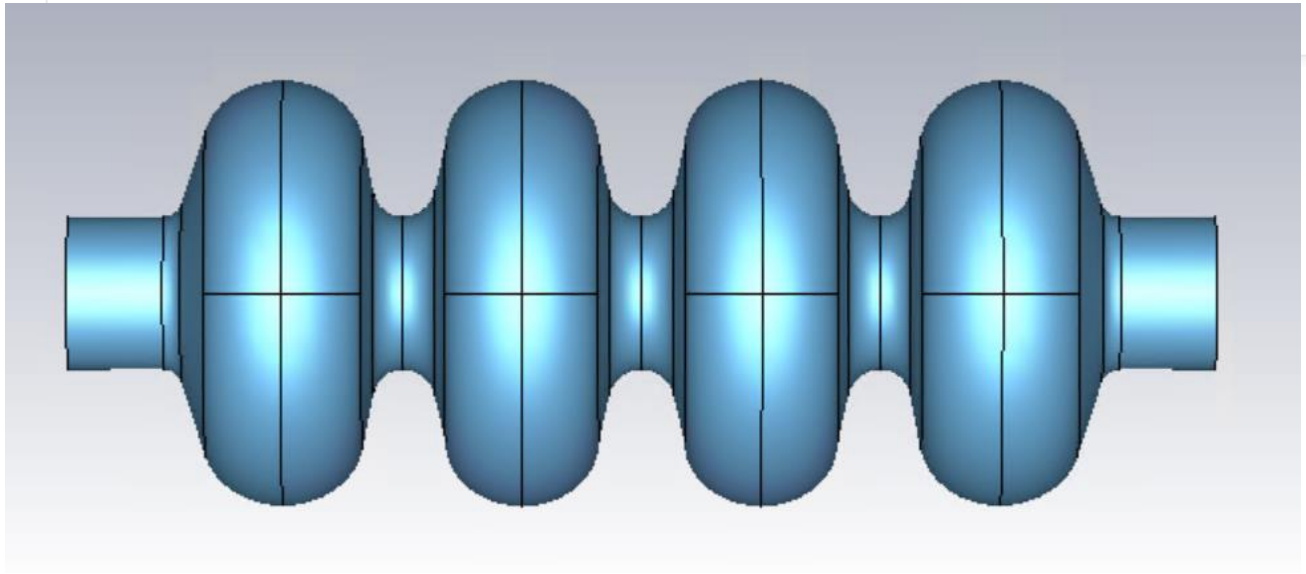
Asymmetrical

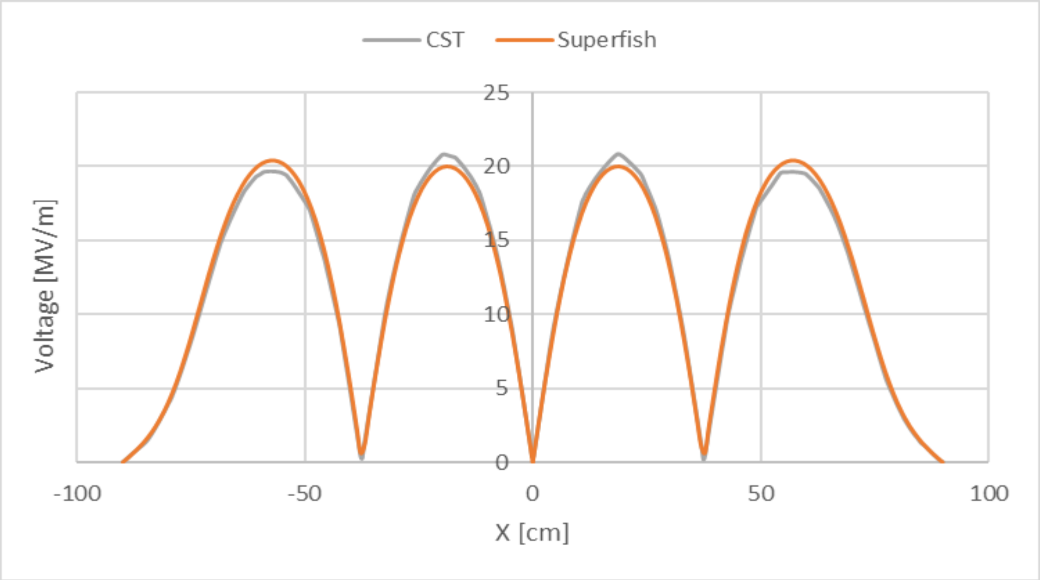
Final 4-cell design



	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)	2.075

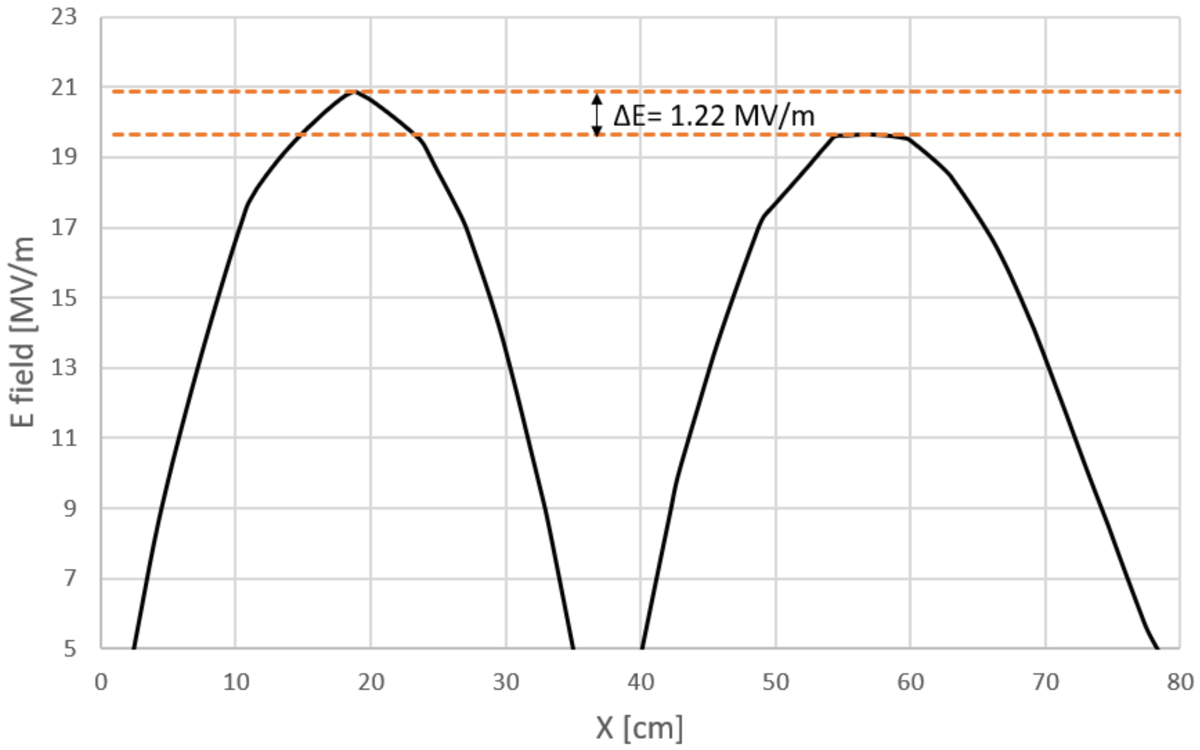
400MHZ 4-cell cavity CST





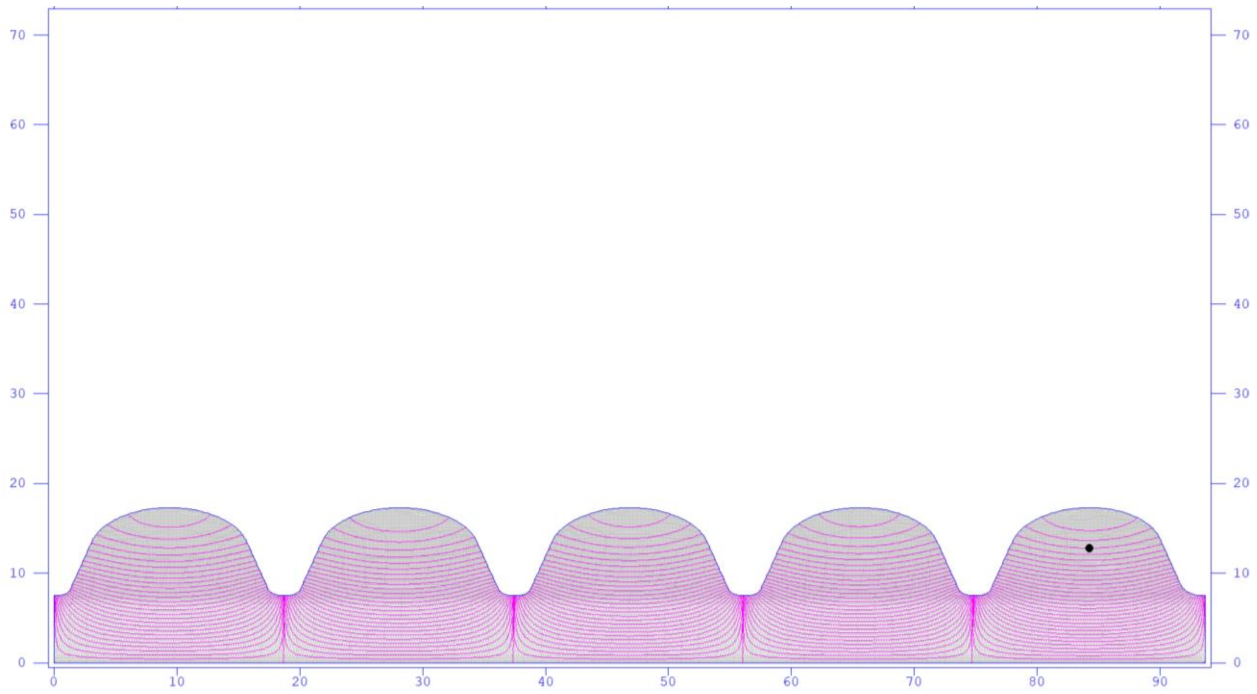
	SUPERFISH	CST
Frequency (MHz)	400.13867	400.0255
r/Q (ohm)	449.098	451.511
Voltage (MV)	2.075	2.224

Field Flatness



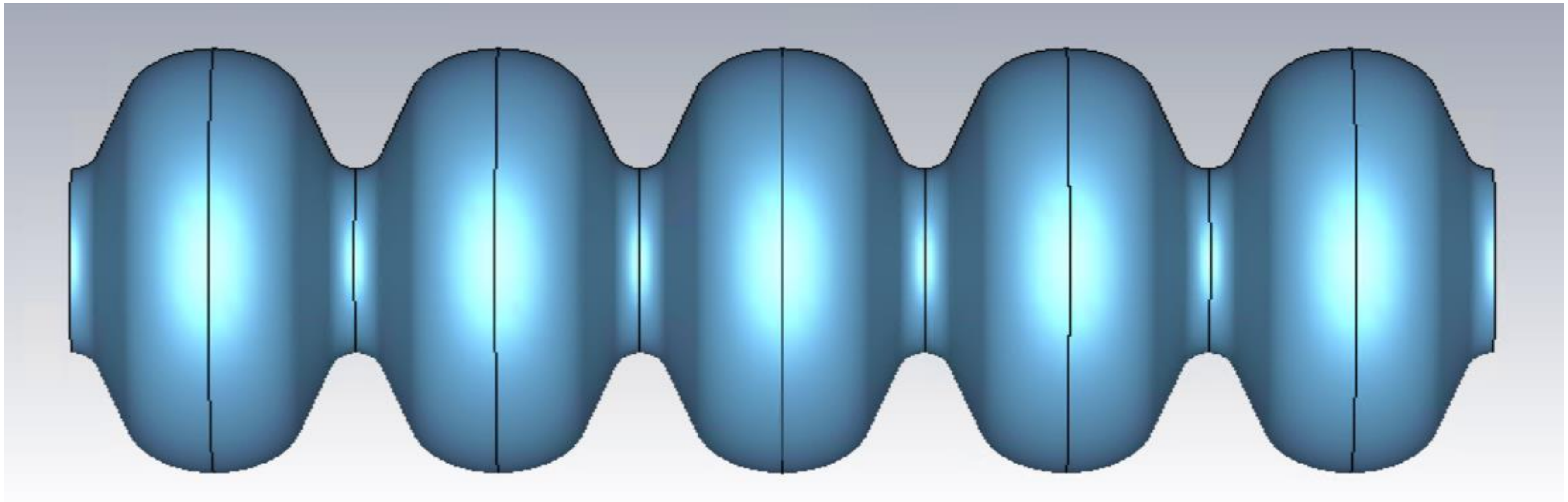
Discrepancy >5 %

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



Parameter	SUPERFISH	CST	Percentage Error
Frequency [MHz]	799.996	800.609	<1%
E_max/E_0	1.8520	1.960	6%
B_max/E_max [mT MV/ m]	2.0156	1.801	12%
R/Q [Ω]	436.043	432.139	<1%

RF Cavities Future Work

- Improve field flatness
- Power demands
- Higher order modes

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

Project Acknowledgements

We would like to thank:

- Emmanuel Tsesmelis
- Léon Van Riesen-Haupt
- Ciprian Plostinar
- Jeremie Bauche
- Stewart Boogert
- Various staff at *Diamond Light Source*

FUTURE
CIRCULAR
COLLIDER

Questions?