FCC-ee Positron Damping Ring and Transfer Line

John Adams Institute Accelerator Design Project 2023

JAI Design Project 2023

- The **John Adams Institute** is a UK research centre for **novel accelerator technology**
- Many different accelerators across the UK and Europe used in many different scientific fields
- Collaboration between **Royal Holloway University of London, Imperial College London and University of Oxford**

Meet the Team

Lattice


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Magnets


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Introducing the FCC

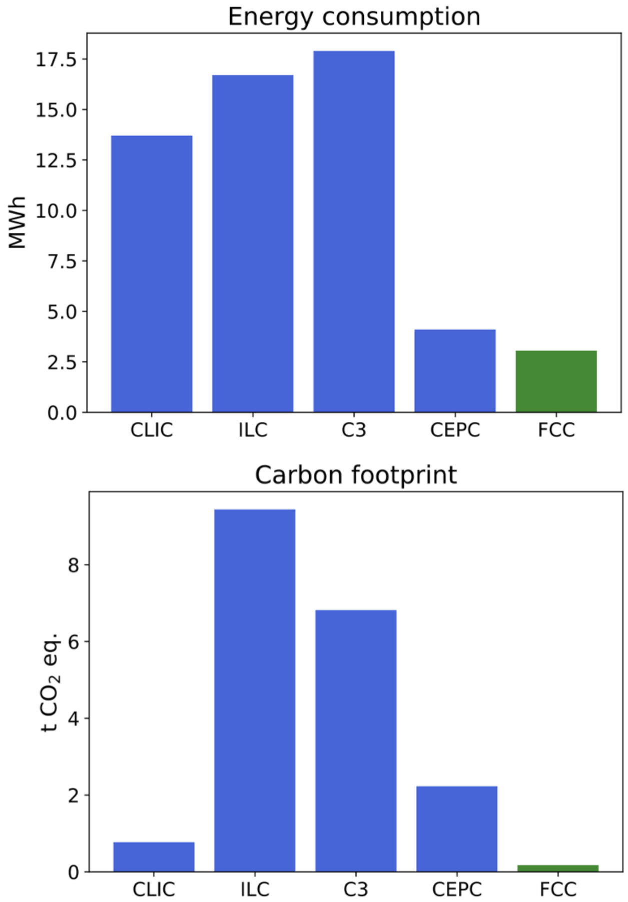
- **Future Circular Collider**
- ~100 km collider proposed by CERN, with higher centre-of-mass energy than any collider to date (100 TeV hh compared to LHC's 13 TeV)
- A century of physics: FCCee, FCChh, FCCeh and heavy ions

Collider	Peak COM energy(GeV)	Luminosity (10^{34} /cm^{2}s)
CLIC	3000	1.5
ILC	500	1.35
C3	2000	4.5
CEPC	240	1.74

FCCee Parameter	COM energy (GeV)	Luminosity (10^{34} /cm^{2}s)
ZZ	90	182
WW	160	19.4
ZH	240	7.3
$t\bar{t}$	365	1.33

FCCee Design Aims

- FCCee provides precision measurements around key resonances (CDR 2019):
    - Z (88-95GeV)
    - WW (158-162GeV)
    - ZH (240GeV)
    - $t\bar{t}$ (340-350, 365 GeV)
- Ambitious aims for:
    - Energy consumption
    - Carbon footprint
    - Cost-effectiveness
- FCChh aims to reach 100 TeV *pp* collisions



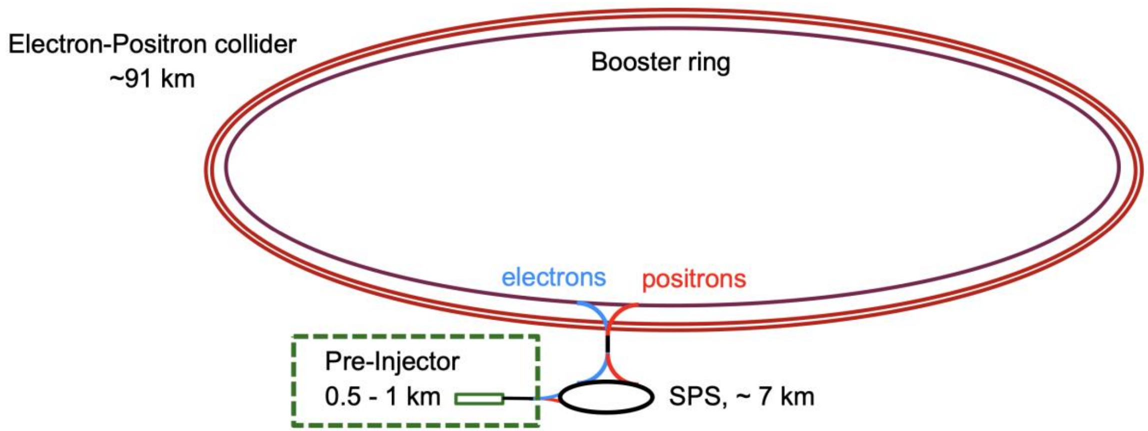
Janot, P., Blondel, A. The carbon footprint of proposed e+e−e+e− Higgs factories. *Eur. Phys. J. Plus* **137**, 1122 (2022). https://doi.org/10.1140/epjp/s13360-022-03319-w

The FCCee Physics Program

Pre-injector complex: currently in development

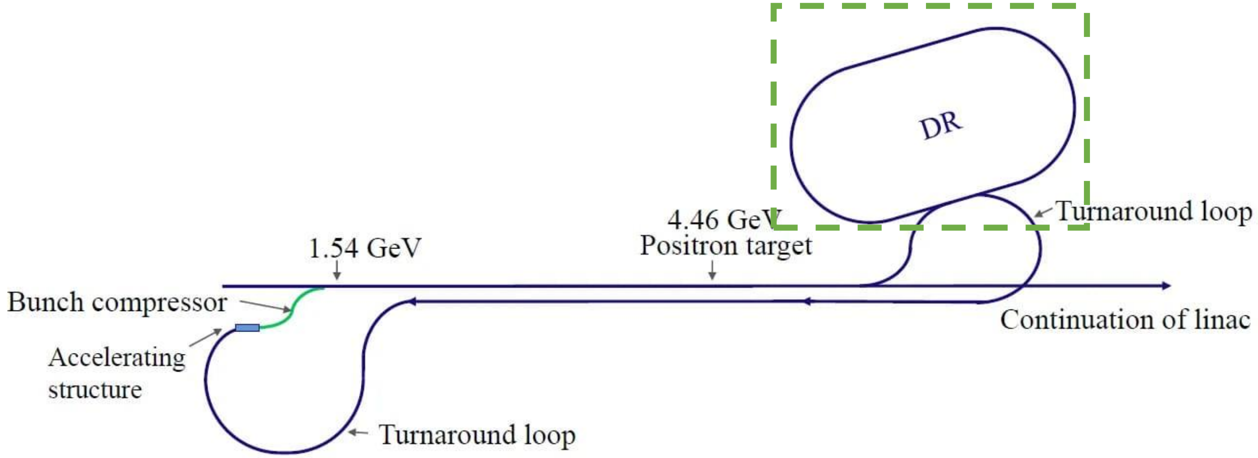
Focus of this project: **positron damping ring** of pre-injector complex

Transfer line of pre-injector complex



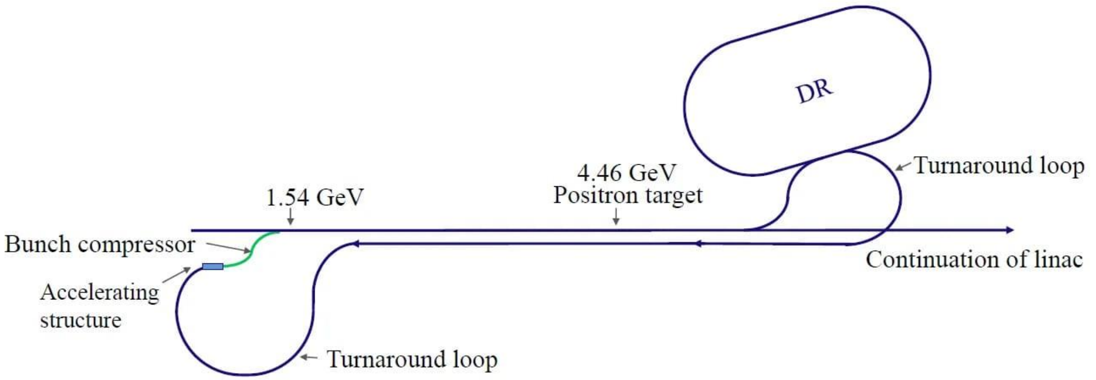
The Positron Damping Ring

- **Positrons** are produced with high emittance
- **Emittance**: spread in position-momentum (or energy-phase) relation
- low spread in position and momentum make the beam more concentrated and more easily steerable
- Damping ring reduces emittance, before further injection



Project Overview

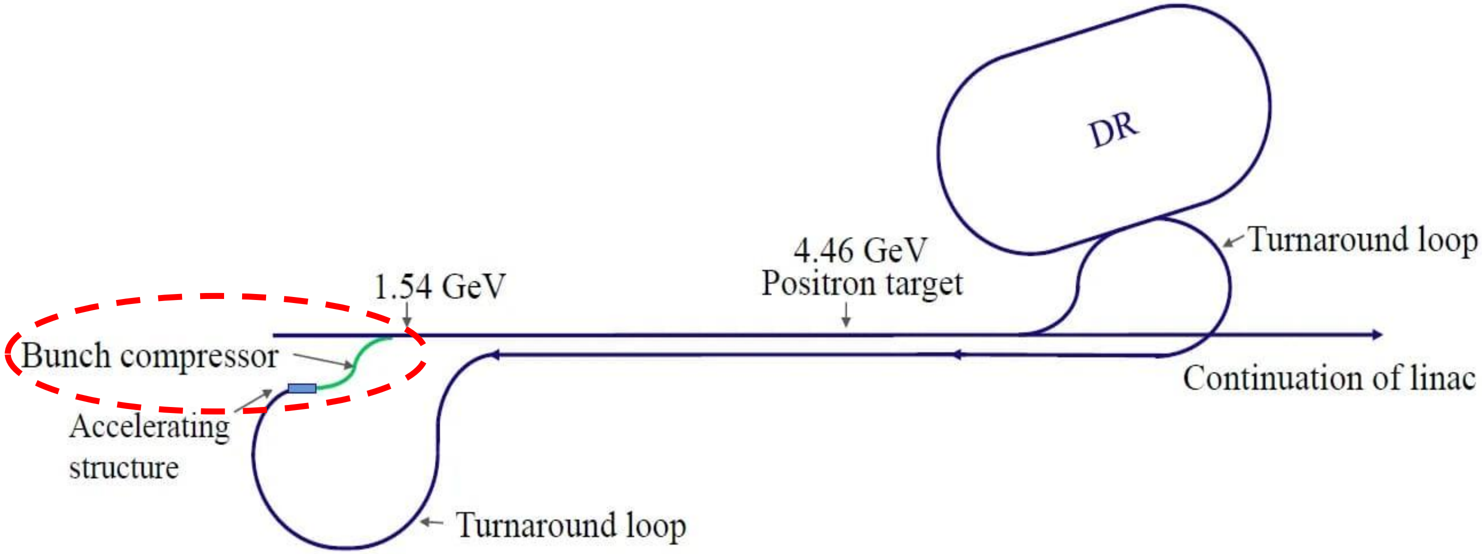
- **Lattice:** description of **general configuration and requirements of a bunch compressor**, including stand-alone bunch compressor configuration in MAD-X at the exit of the transfer line from the pDR to the Common Linac
- **Magnets**: FEMM modelling of main magnets of the pDR – **dipoles, quadrupoles** and **sextupoles**, as well as finding requirements and geometry for **kicker/septa** and **wiggler** magnets
- **RF cavity:** optimization in 2D using Superfish of the **superconducting RF** cavity at 400 MHz and 800 MHz, as well as a **normal conducting RF** cavity, followed by 3D modelling in CST



Lattice

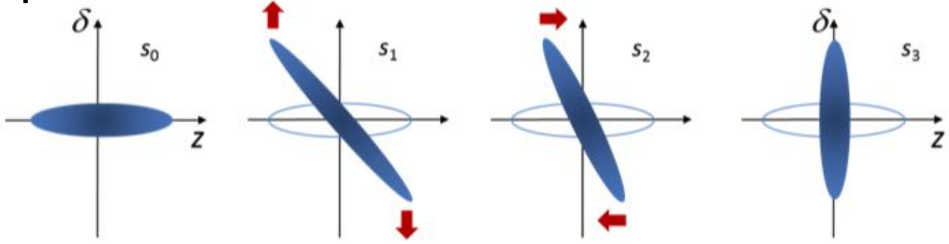
Bunch Compressor Design

Bunch Compressor



A bunch compressor is …

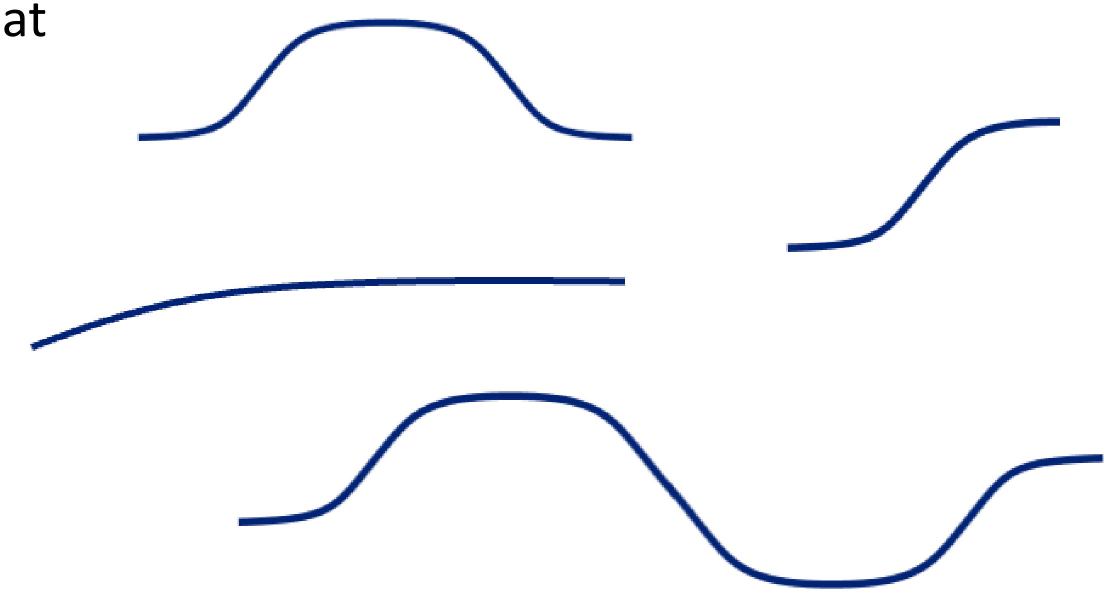
- … needed as high energy accelerators require high peak current, meaning that the bunch must be compressed to lengths in the pico/femtosecond range.
- … necessary because the space charges, in the beam, stretch the bunch length and increase the longitudinal emittance.
- … used to compress a bunch, longitudinally, to reduce the bunch length by rotating the longitudinal phase space.



Distribution of particles 'rotates' in longitudinal phase space (area is conserved).

Types of bunch compressors

- Here are some examples of possible bunch compressor schematics:
  - C-bend Achromat
  - Dog-Leg
  - Arc F0D0
  - S-Chicane



Theory

For particles through an element, the 6D positions are given by:

$$X_i = \boldsymbol{R}_{ij} X_j$$

Where R is the transfer matrix.

For a combination of elements, the $\boldsymbol{R}_{ij}$ matrices can be multiplied. In the bunch compressor, this can be reduced to:

$$X_i = \boldsymbol{R}_{optics} \boldsymbol{R}_{cavity} X_j$$

And since we are working with only the longitudinal plane, we can focus on the R_{55}, R_{56}, R_{65}, R_{66}

Transfer Matrix of a Dipole

A dipole does not change the momentum offset and therefore, R_{65} and R_{66} are 0 and 1. In the context of the bunch compressor, the R_{56} parameter, which corresponds to the change in path length for unit momentum is of importance.

$$R_{56} = \frac{\Delta L}{\delta} = \int_0^L \frac{D(s)}{\rho} ds$$

Where $D(s)$ is the dispersion and ρ is the bending radius.

Transfer Matrix of an RF Cavity

In the longitudinal plane, the transfer matrix can be shown to be:

$$\begin{bmatrix} x'_5 \\ x'_6 \end{bmatrix} = \begin{bmatrix} 1 & 0 \\ R_{65} & R_{66} \end{bmatrix} \begin{bmatrix} x_5 \\ x_6 \end{bmatrix}$$

Where $R_{65} = -\frac{qVk_{rf}}{E_{s,in}} \cos\phi_s$ and $R_{66} = 1 - \frac{qV}{E_{s,in}} \sin\phi_s$. We set the phase $\phi_s = 0, \pi$ to ensure there is no acceleration of the central particle.

Bringing it all together…

Finally, on multiplying the transfer matrices of the optics and the cavity,

$$z_{out} = \left(1 + R_{56}^{optics} R_{65}^{cavity}\right) z_{in} + R_{56}^{optics} \delta_{in}$$

On averaging over all particles in the bunch, the RMS bunch length σ_{out} becomes:

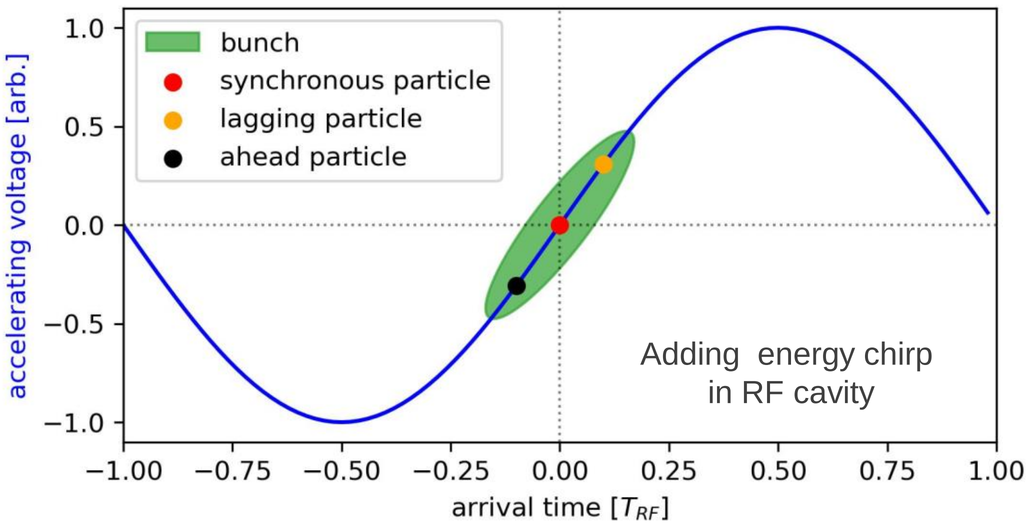
$$\sigma_{out} = \sqrt{\left(1 + R_{56}^{optics} R_{65}^{cavity}\right)^2 \sigma_{in}^2 + R_{56}^{optics^2} \delta_{in}^2}$$

This is minimised when $R_{56}^{optics} = -\frac{1}{R_{65}^{cavity}}$

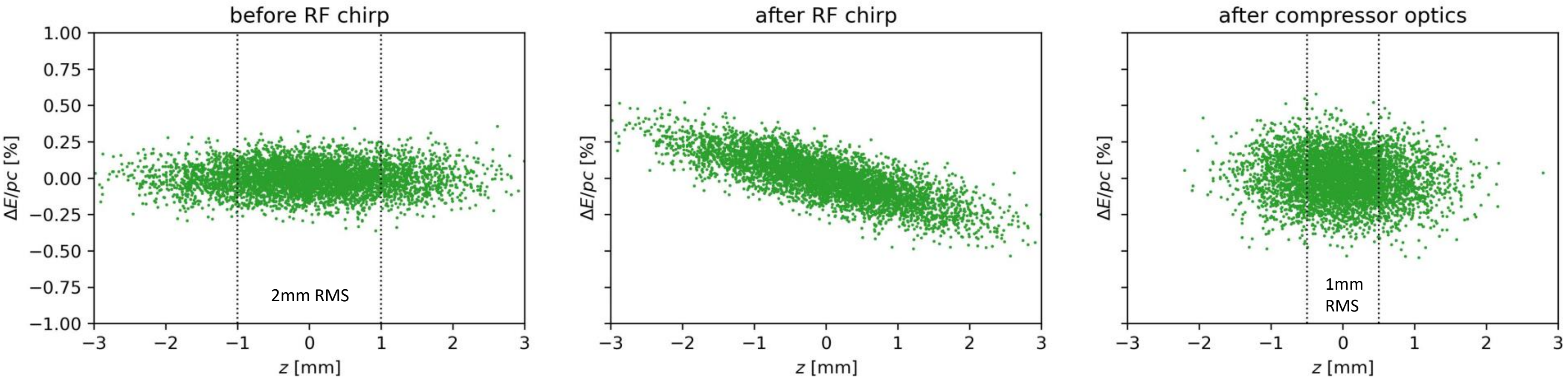
Bunch Compression

Parameters:

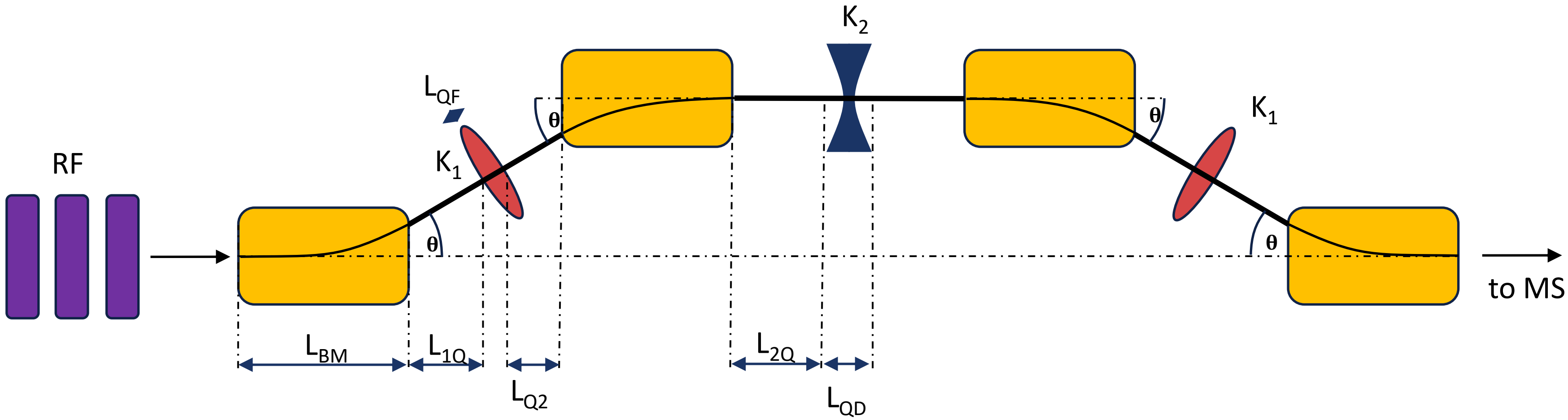
- 1.54 GeV positron beam
- 0.1% momentum spread
- RMS bunch length:
  - 2mm (initial)
  - 1mm (final)



Longitudinal phase space development (with C-Bend Achromat):



C-bend Achromat: Single Cell

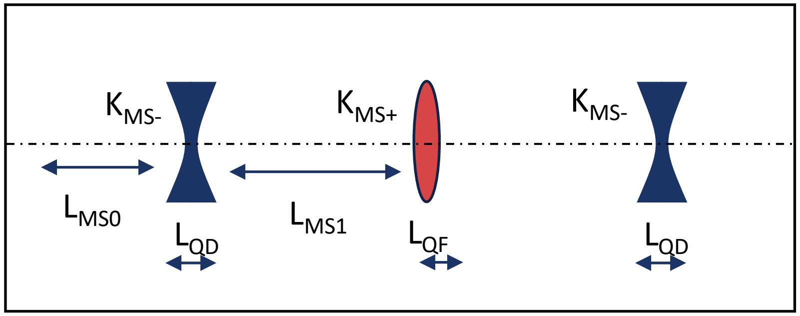


Dimension	Value (m)
L_{BM}	1.5
L_{1Q}	0.45
L_{QF}	0.3
L_{2Q}	0.55
L_{QD}	0.3
L_{MS0}	1.4
L_{MS1}	2.2

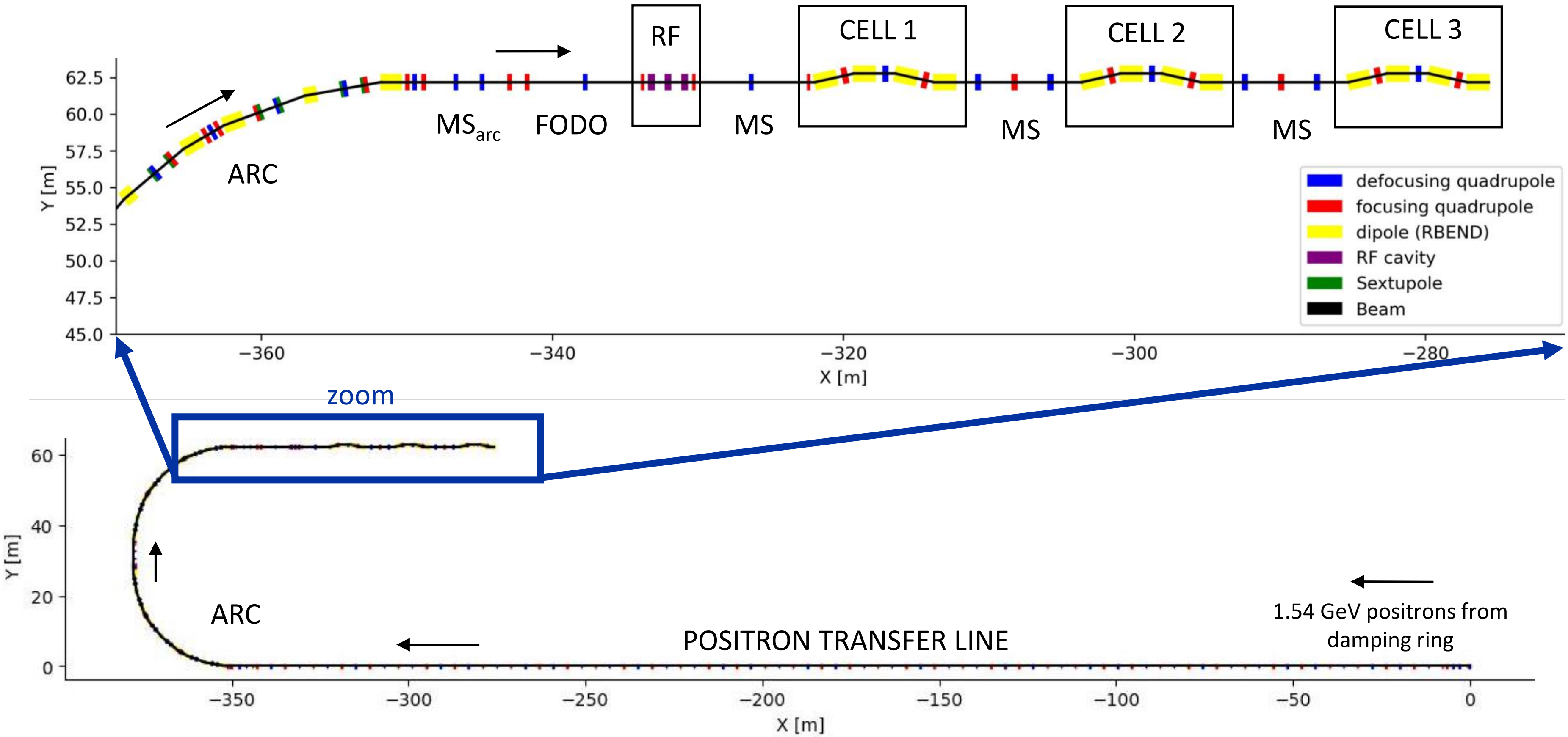
Magnet Parameter	Value
K_1	1.1 m^{-2}
K_2	1.92 m^{-2}
θ	12.5^{O}
K_{MS}	+- 1.5 m^{-2}

RF Parameter	Value
f (accel. frequency)	3 GHz
V (peak accel. voltage)	10 MV

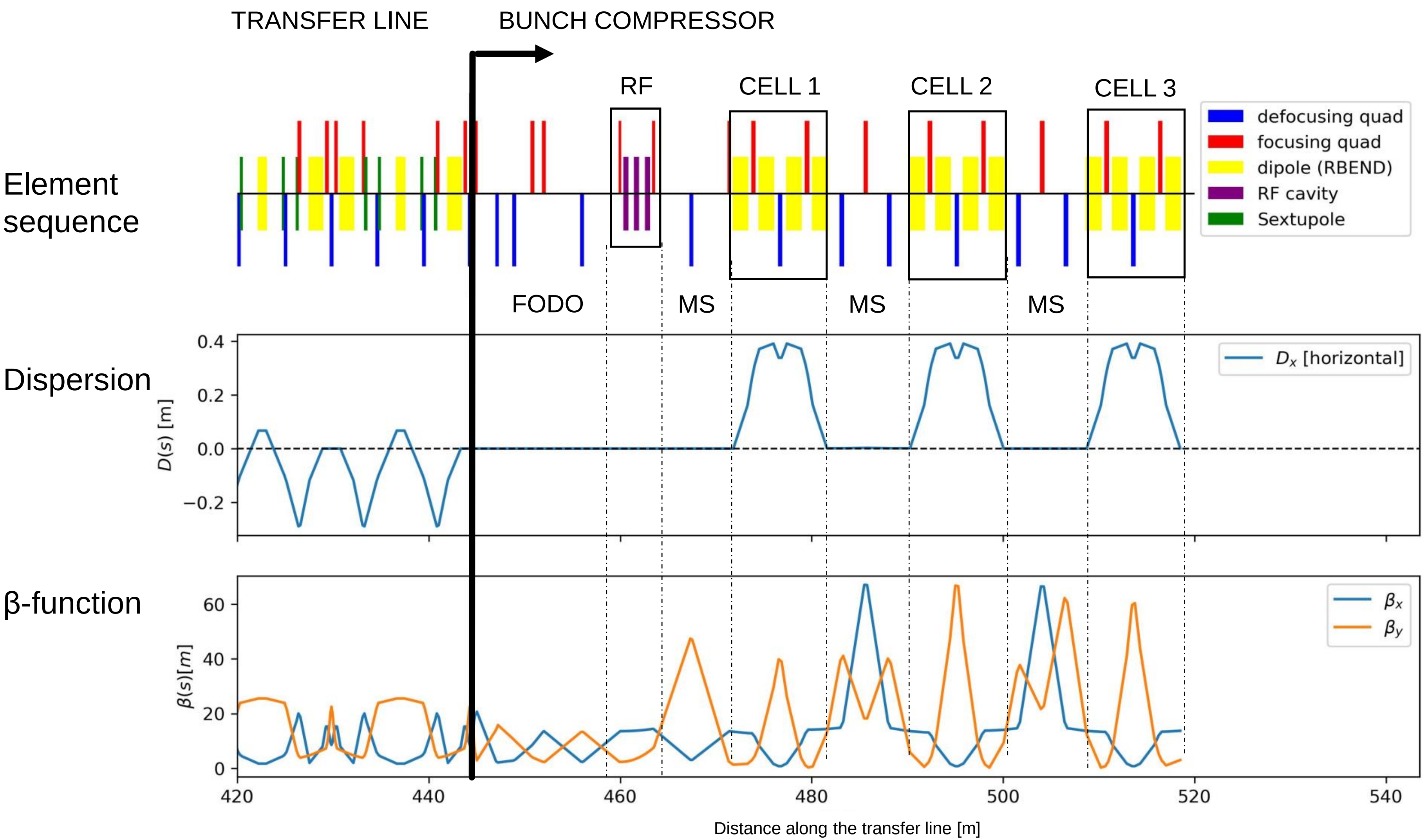
Matching Section (MS):



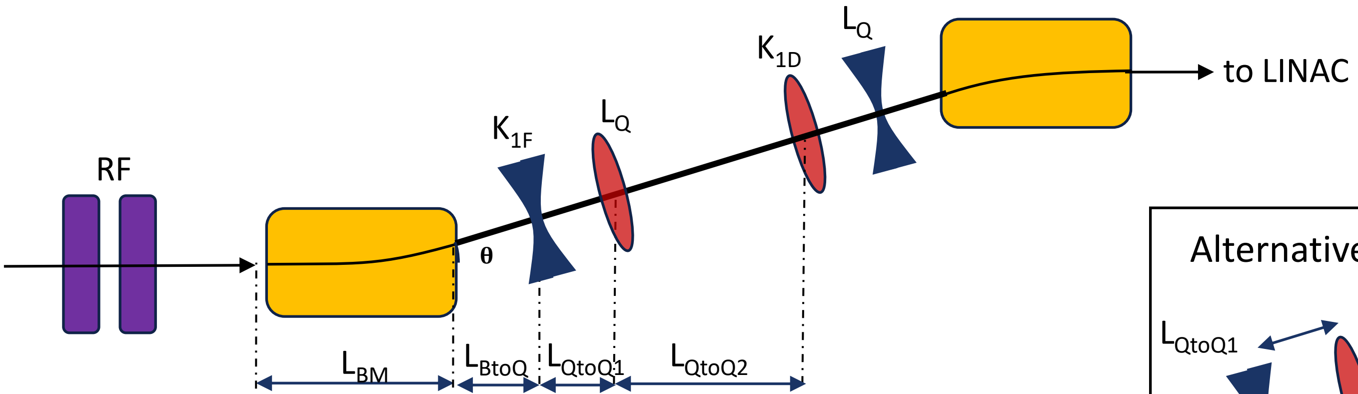
C-Bend Achromat: Global Layout

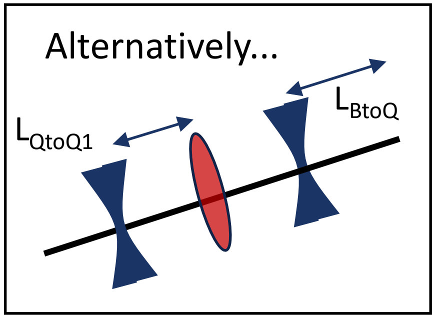


C-Bend Achromat: Lattice Design



FDDF Dog-Leg





RF parameter	Value
f	3 GHz
V	10 MV

Magnet Parameter	Value
K_{1F}	1.02 m^{-2}
K_{1D}	-0.61 m^{-2}
θ	60.0^{O}

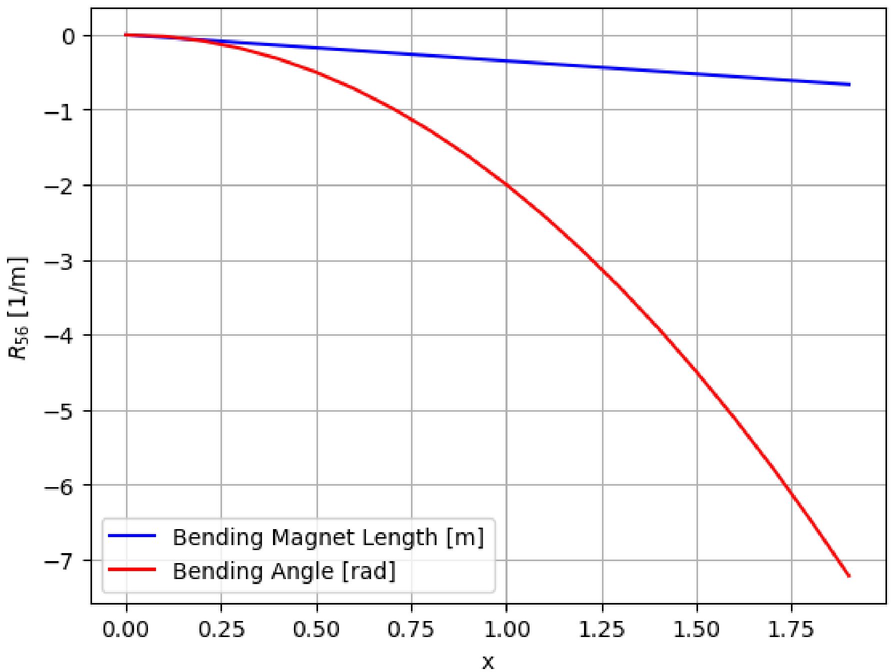
Segment	Value (m)
L_{BM}	1.0
L_Q	0.5
L_{BtoQ}	8.0
L_{QtoQ1}	2.0
L_{QtoQ2}	4.0

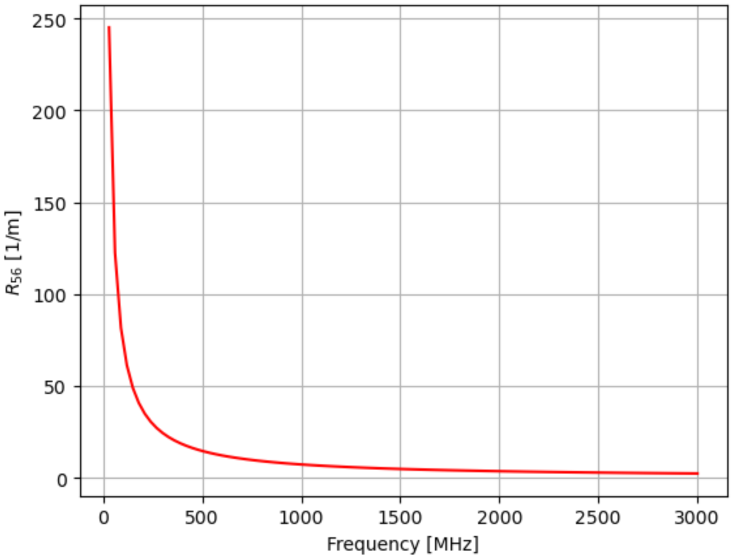
Magnet Parameter	Value
K_1	1.322 m^{-2}
K_2	-1.322 m-2
θ	60.0^{O}

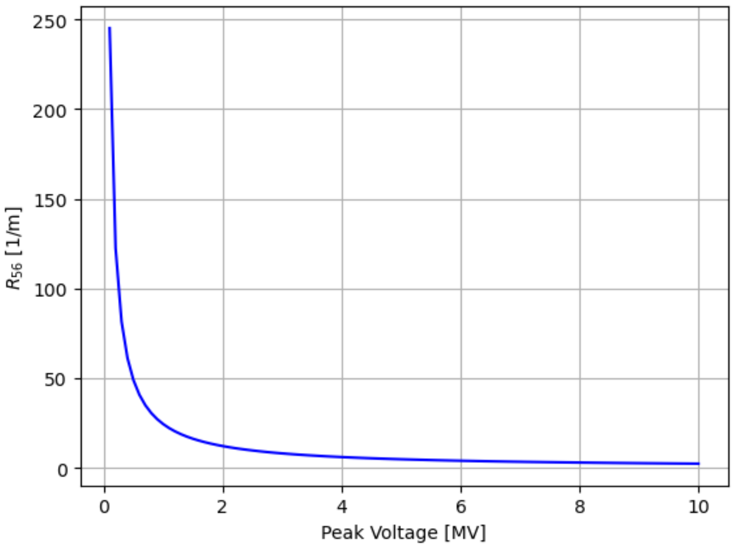
R_{56} Matching for Dog-Leg

In bunch compressor: $$R_{56} \approx -\frac{L_{BM}\theta^2}{3} = -\frac{1}{R_{65}}$$

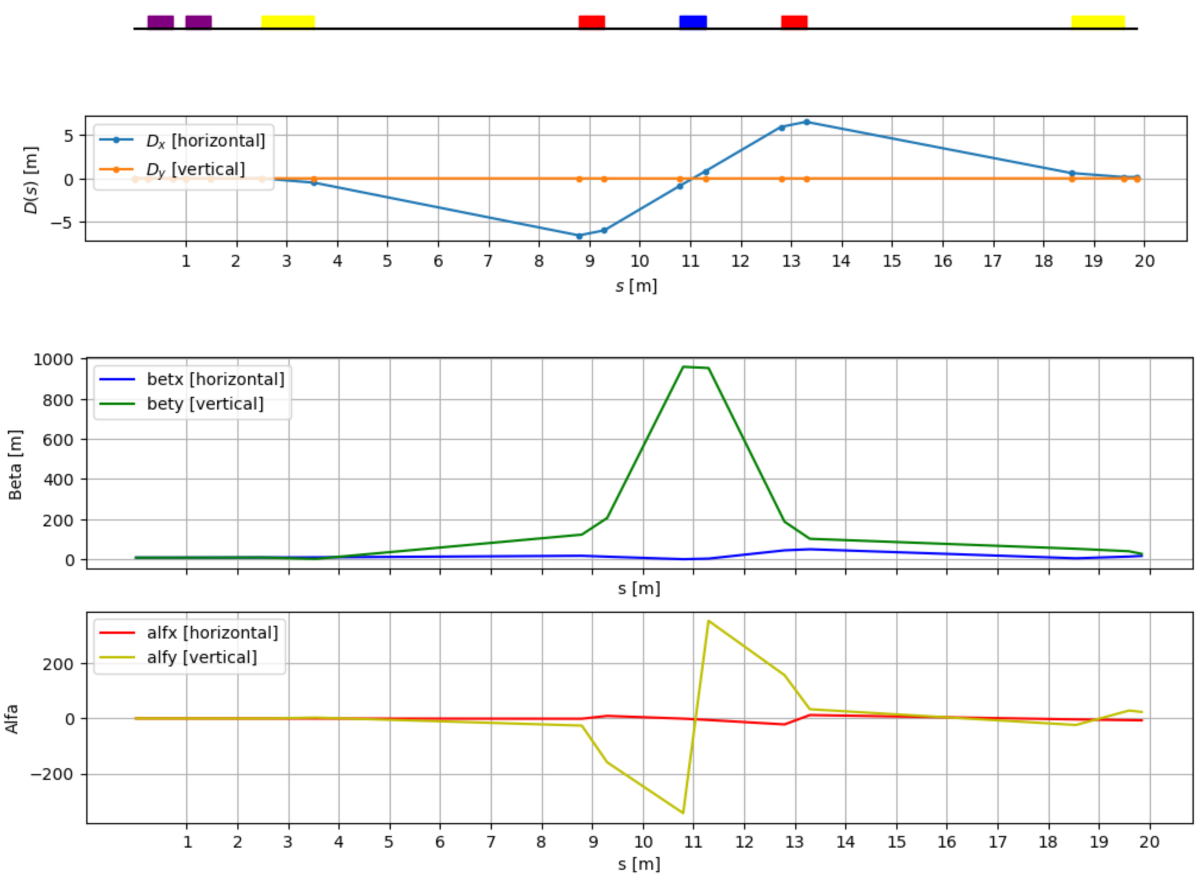
In RF Cavity: $$R_{65} = -\frac{qVk_{rf}}{E_{s,in}}\cos\phi_s$$



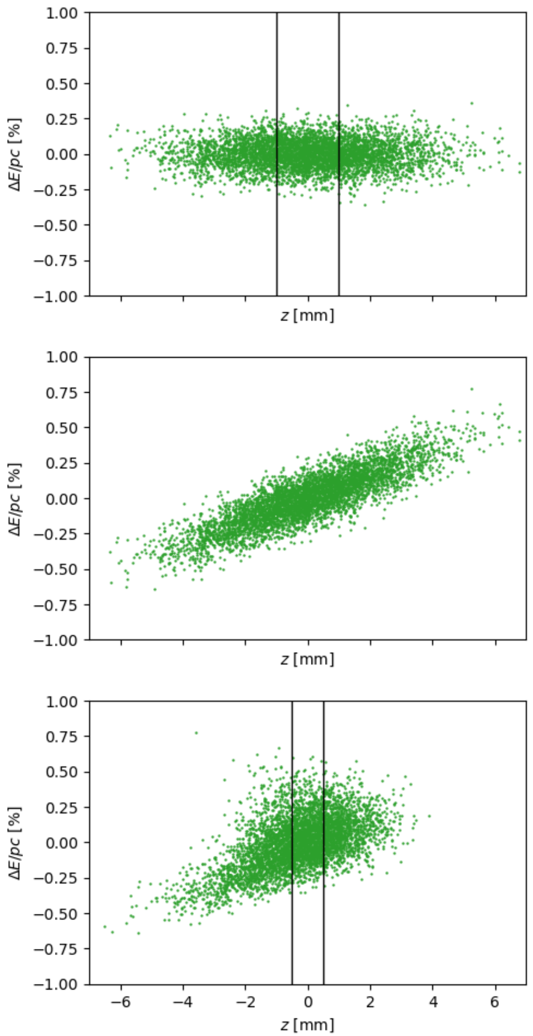




FODO Dog-Leg Results

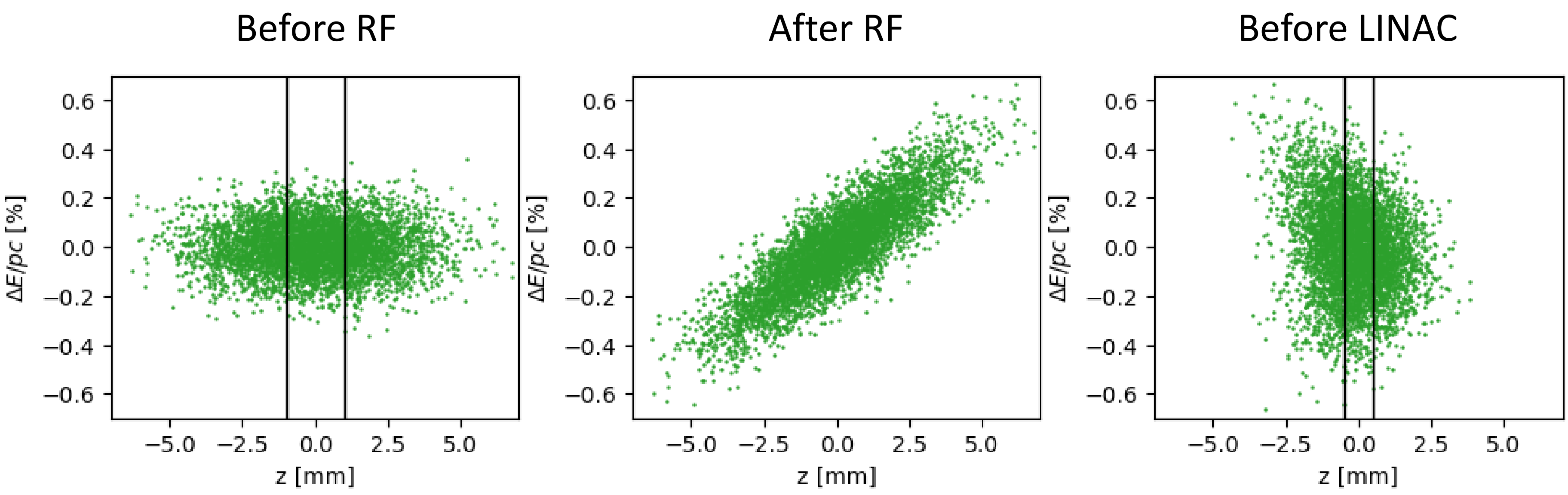


Before RF



After RF

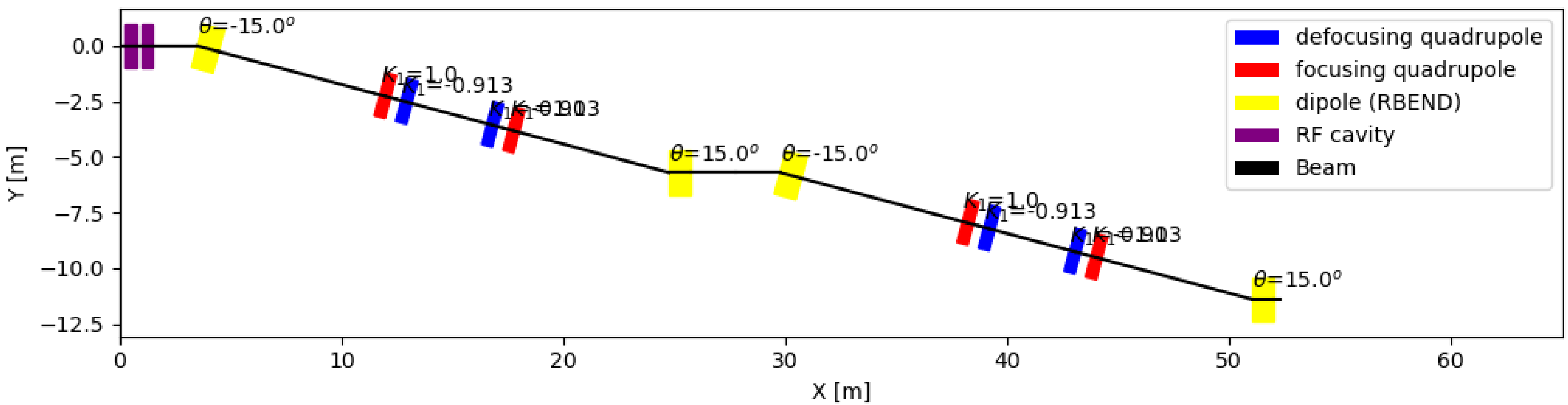
FDDF Dog-Leg Results



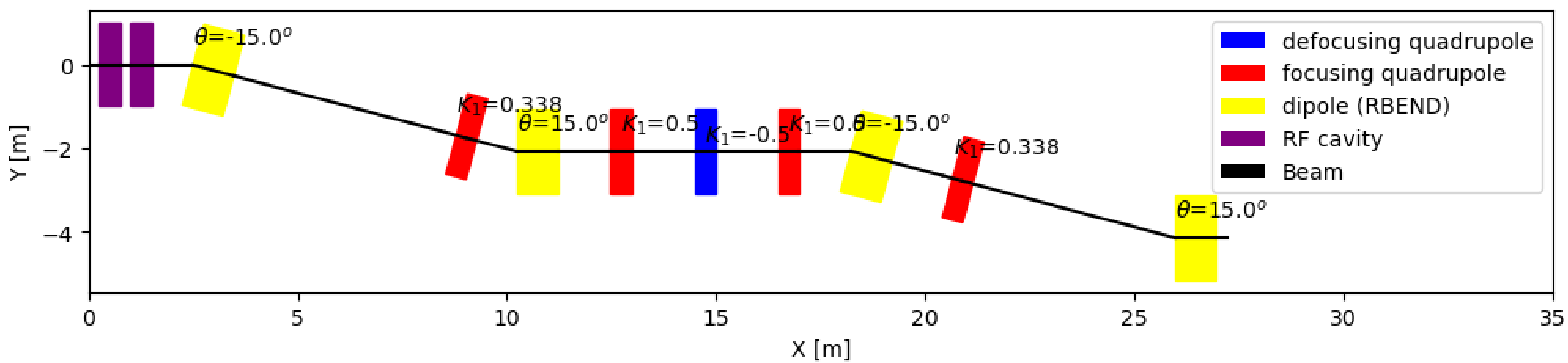
Reducing the Bending Angle by chaining Dog-Legs

$$\theta_n = \frac{\theta}{\sqrt{n}}$$

Coupled dog-legs can contain matching sequences

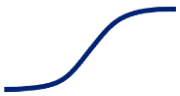


Centre Achromat Dog-Legs allows K1 tuning of R56!



Design Comparison

C-BEND Achromat	
+	-
Tunable R_56	Large size (~80m)
Modular	Additional matching to linac required



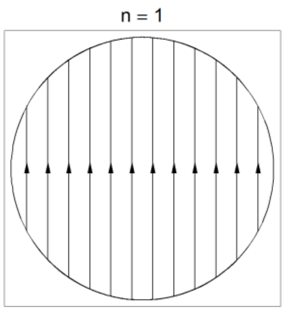
Dog-Leg	
+	-
R_56 tunable in some designs	R_56 tuning is very limited
Simple, with few elements	Larger chromatic effects
Direct matching to linac	

Future Work:

- Synchrotron radiation study required
- Higher order chromaticity corrections (adding sextupoles)
- Matching to Linac
- RF cavity for the compressor requires dedicated design (3 GHz!)

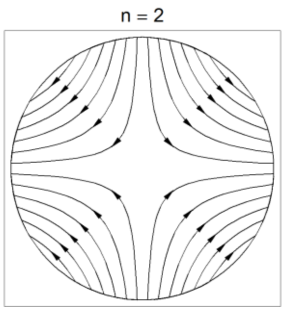
Magnets

What magnets and why?



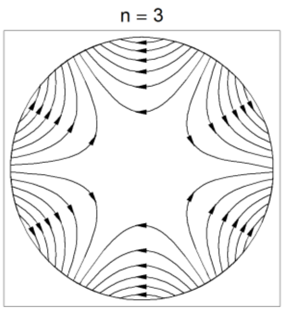
Dipole

Beam Steering



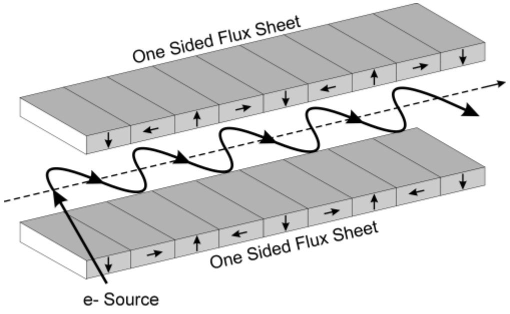
Quadrupole

Beam Focussing



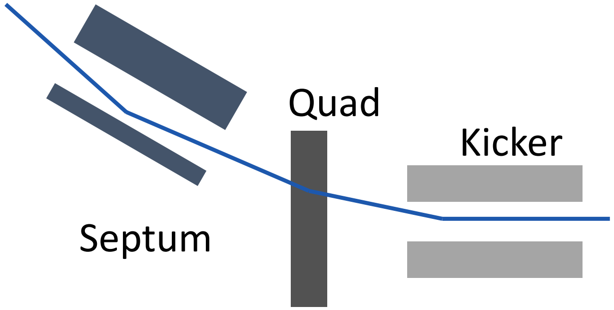
Sextupole

Chromaticity Correction



Wiggler

Emittance damping in pDR



Kicker and Lambertson septum

Injection/Extraction

Darren

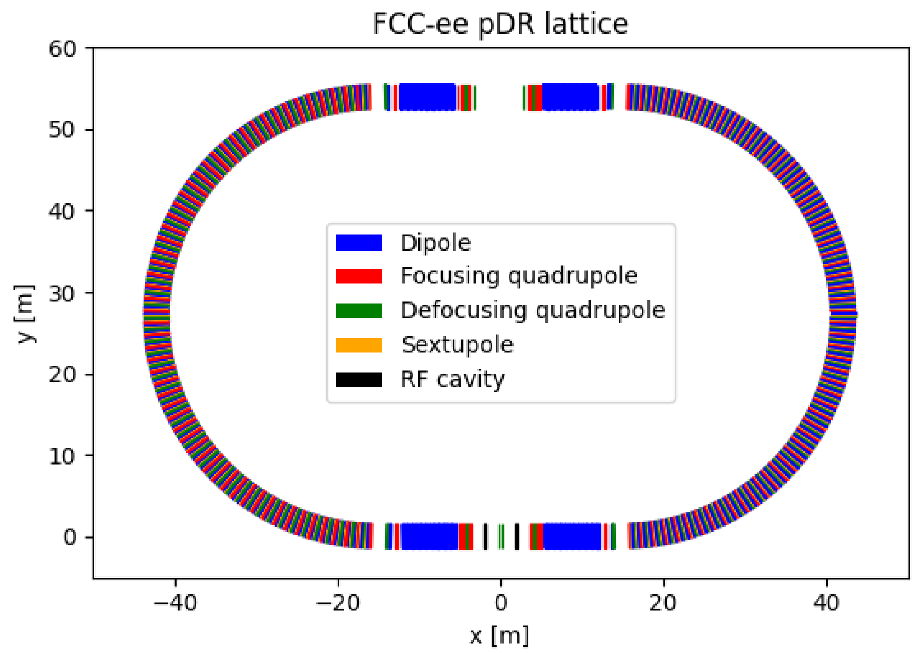
Design Goals

- Aim: High performance **Normal Conducting Magnets**
  - In line with FCC aim: high efficiency to reduce power consumption and running costs
  - Removes the requirement for cryogenic installation
- Lattice requires multiple quadrupole and sextupole configurations, taken to match the MADX file
  - 1 design for each, tuneable by varying current

Enzo

Design Parameters

- Design parameters for all magnets taken from MADX file
  - Match emittance requirements of lattice
- Beampipe: 50mm diameter, 1.5mm thickness steel
- Performance Criteria: Good Field Region >= 2/3 beampipe diameter



$$\left|\frac{\frac{\partial^n}{\partial x^n}(B_{\text{pole}} - B)}{\frac{\partial^n}{\partial x^n}B_{\text{pole}}}\right| \sim \begin{cases} 10^{-4},\ n = 0 \text{ for dipoles} \\ 10^{-3},\ n = 1 \text{ for quadrupoles} \\ 10^{-3},\ n = 2 \text{ for sextupoles} \\ 10^{-3},\ n = 0 \text{ for wiggler} \\ 10^{-1},\ n = 0 \text{ for kicker and septum} \end{cases}$$

Darren

Material Choices

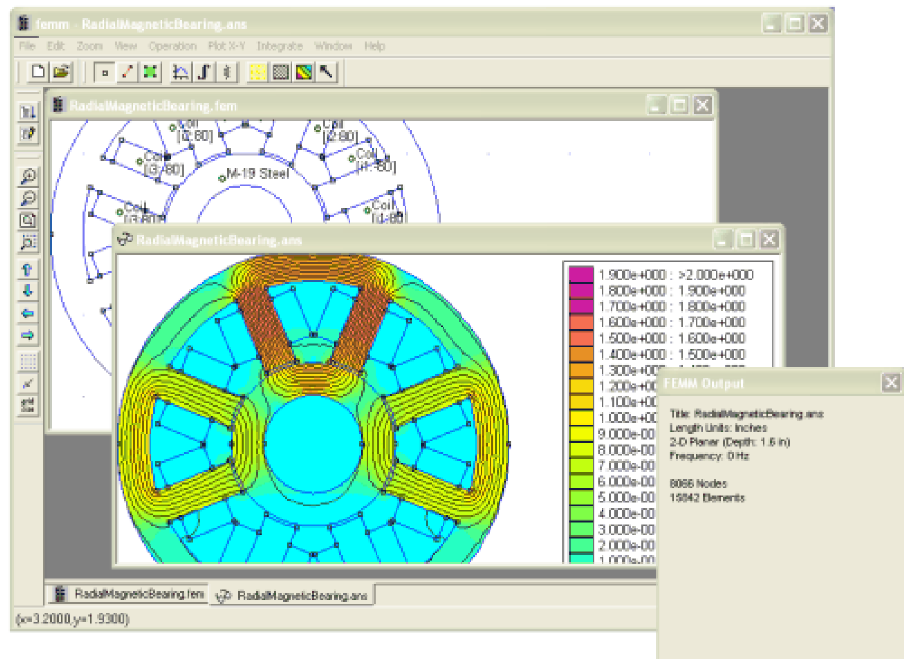
- In line with FCC environmental design philosophy, aim to use readily available, lower carbon footprint materials
- Electromagnets designed using Iron Yokes and Copper Coils
- Wiggler: two options, permanent magnet (ferrite) and electromagnet
- Dipoles, Quadrupoles, Sextupoles and Wiggler all **fixed field**: saturation and ramping is less relevant

Sesame Quadrupole

Jack

Analysis Techniques

- Magnetics Simulations performed in FEMM 4.2 Finite Element Method Magnetics
- Data extraction and analysis using Python with PyFEMM
- Quadrupole and Sextupole results based on **Multipole Analysis**
- Kicker/Septum analysed using **Numerical Derivatives**



Jack

Magnets- results

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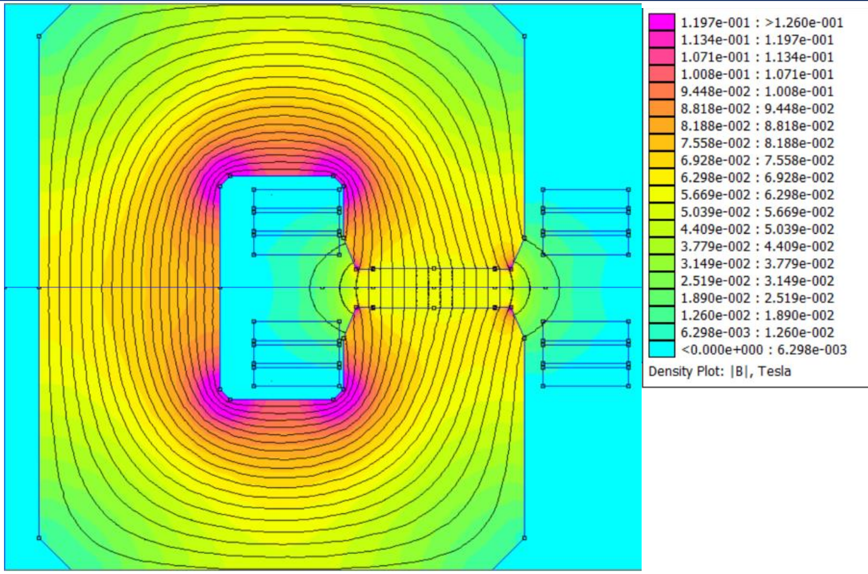
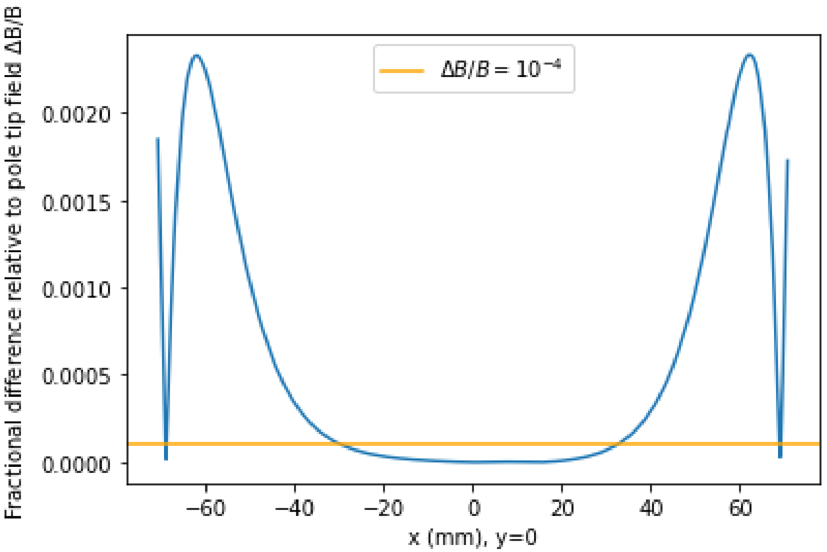
Dipoles

- C-type dipole based on JAI tutorial example
- Electromagnet coils: 18 turns, 21.986 A
- Chamfering to reduce saturation
  - Yoke remains far from saturation magnetization of iron
- Achieved target B-field of 0.0595 T, 30 mm radial GFR covers full extent of beampipe





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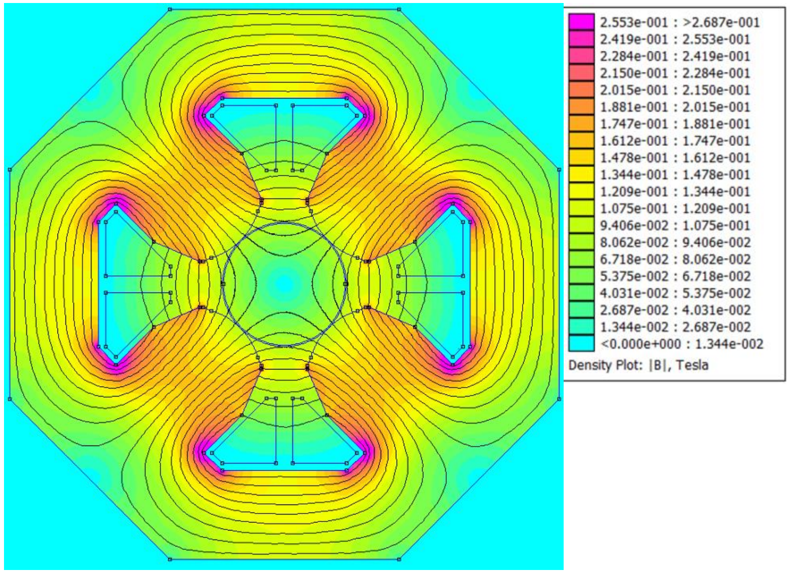
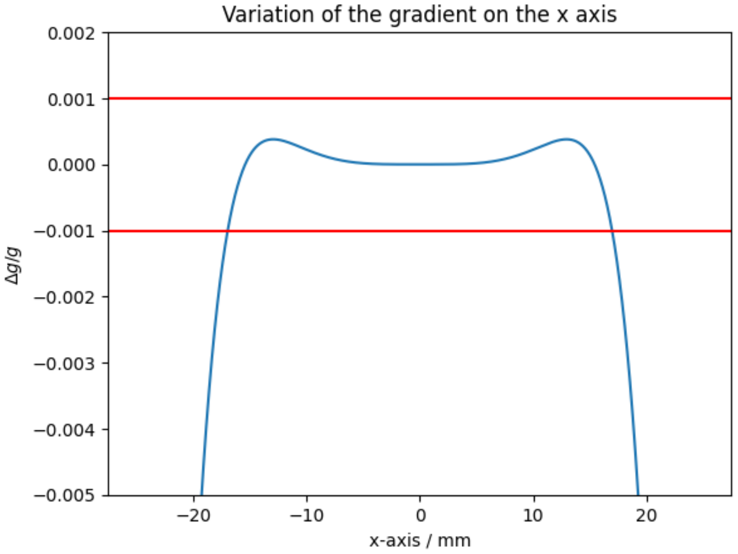
Quadrupoles

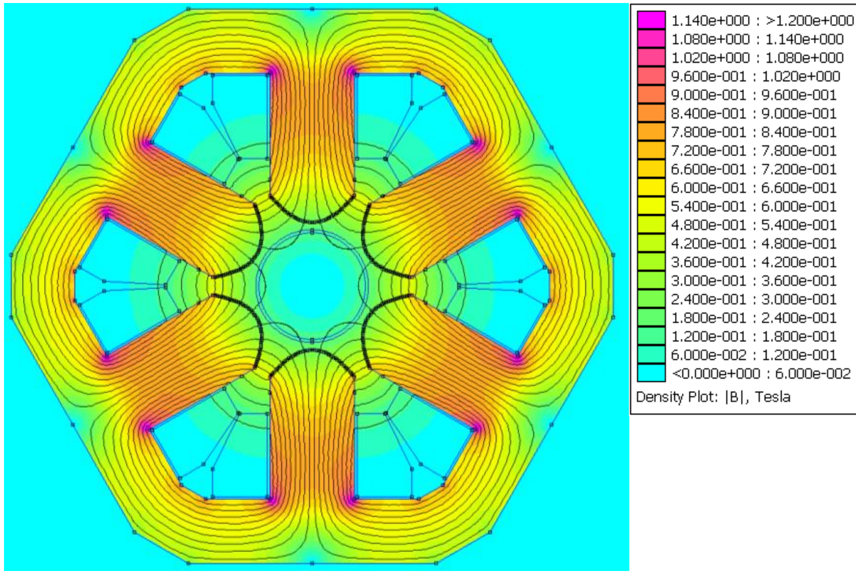
- Good field region: 16.97 mm radial, above the target value of 16.67 mm
- Magnetic gradient: 3.717 T/m matches the target gradient
- Coils: 20 turns, 48.305 A
- Chamfering to reduce saturation
- Shimming: increase GFR

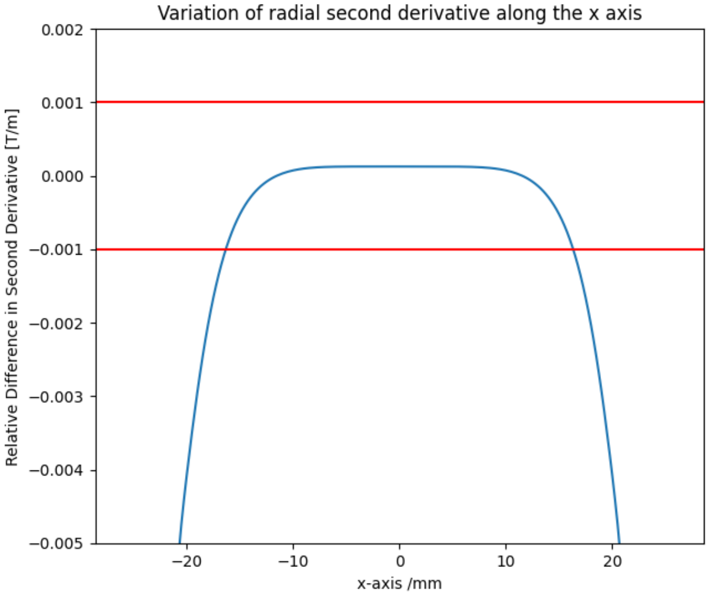




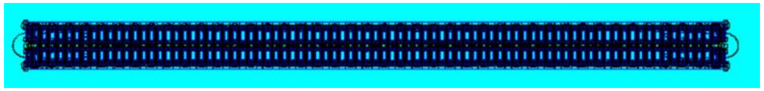
Sextupoles

- 1D Good Field Region: 16.05 mm radial, below target value of 16.67 mm
- 2D Good Field Region: 18.01 mm mean radial, above target value of 16.67 mm
- **GFR is not circularly symmetric**
- Hyperbolic Pole Tips
- 18 coils @ 6.5x6.5 mm^2
- Focussing Sextupole:
  - Target: SF: 523.81 T/m^2
  - Current: 104.7A
- Defocussing Sextupole:
  - Target: -743.74 T/m^2
  - Current: -148.7 A

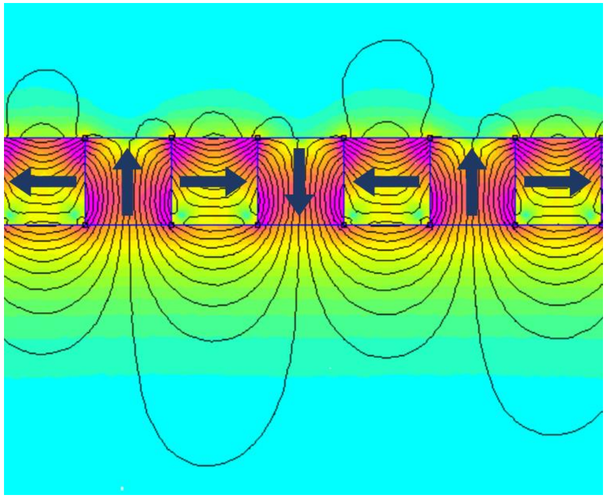


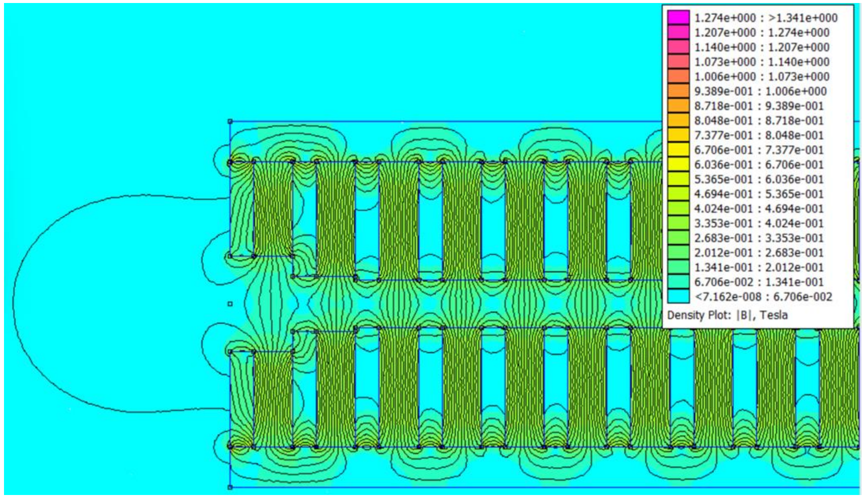


Ferrite Wiggler – Design



- Two Halbach array of permanent magnets – creates strong field inside wiggler and weak field outside.
- Ferrite permanent magnets attached to a steel frame.
- End magnet poles have an increased gap and therefore have weaker fields, meaning the overall particle path in on axis.
- This requires optimisation and simulation of particle paths to verify.



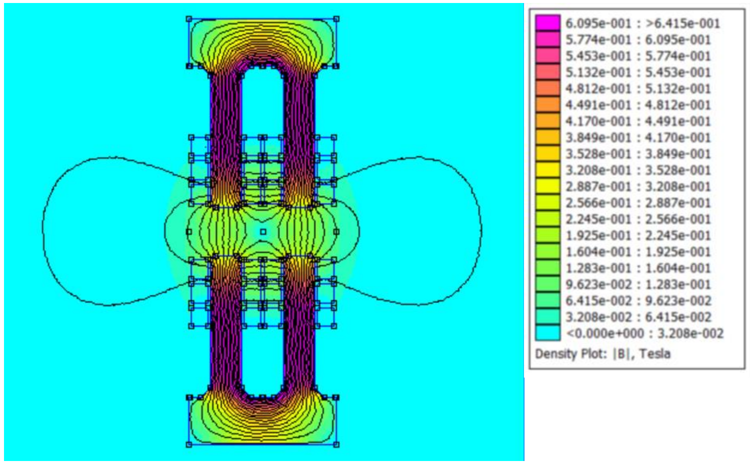


Ferrite Wiggler – Properties

Wiggler Properties	Value
Length	6.75 m
Energy emitted per wiggler per particle	40.7 keV
Magnitude of field max	0.166 T
Wiggler gap	60 mm
Cost of ferrite (Y30) and steel for 1 wiggler	CHF 365

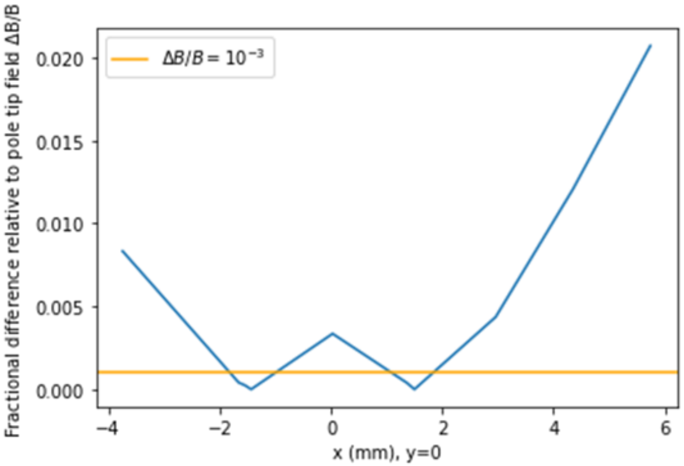
Electromagnetic wiggler

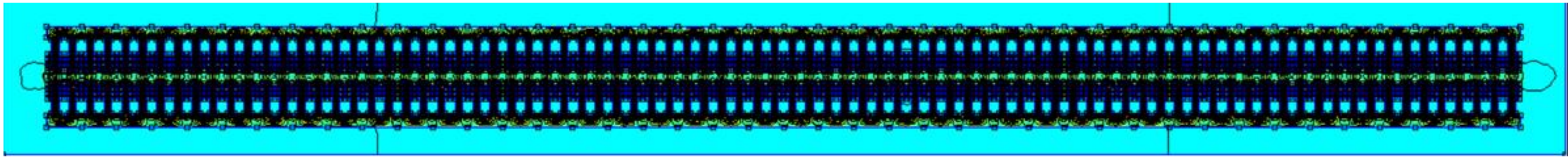
- More tunable and resists demagnetization
- B-field of each dipole was 0.162 T
  - 2 mm total GFR
  - All fields in magnet < 1 T



- 42 two-dipole cells, each 158 mm long
- Coils: 8 turns, 151.198 A

- Cost: For a magnet depth of 10 cm
  - Iron: 4844.40 CHF / m^3, total 741 CHF
  - Copper: 2.02×10^5 CHF / m^3, total 14750 CHF





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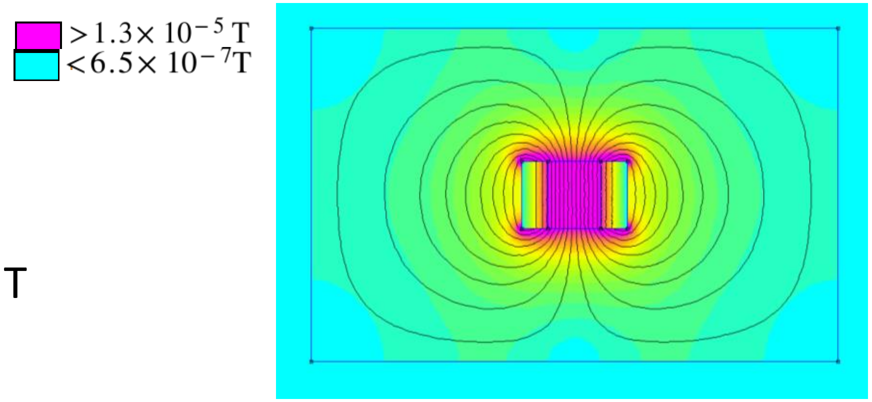
Kicker/Septum

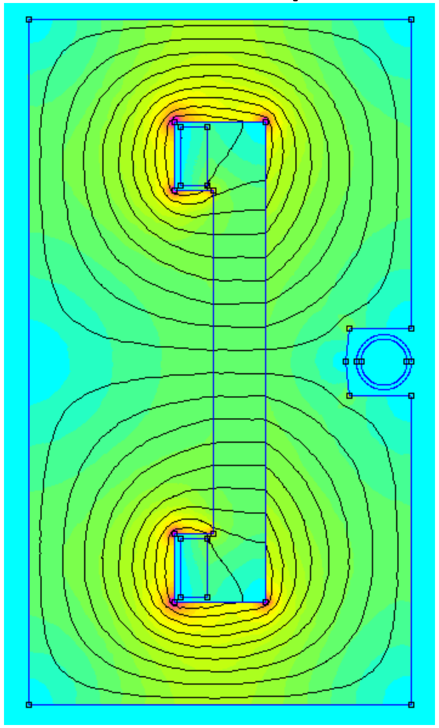
Kicker:
- Average B-field = $1.558 \pm 0.003 \times 10^{-5}$ T
- Coils: 20 turns at 0.025A
- Field outside negligible (10^{-9} T)

Lambertson Septum:
- Average B-field = $1.18 \pm 0.05 \times 10^{-5}$ T
- Coils: 4 turns at 0.025A
- Field in beam pipe negligible (10^{-9} T)

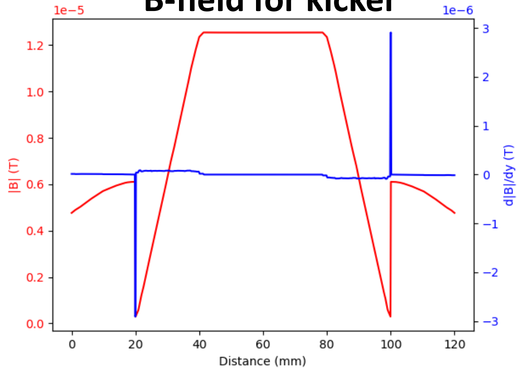
Kicker



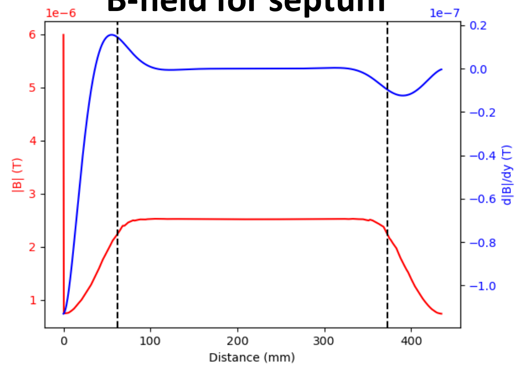
Lambertson septum



B-field for kicker



B-field for septum



Magnets conclusion

- Dipoles, quadrupoles, sextupoles, and kicker/septa were designed with a sufficient GFR
  - For wigglers, GFR analysis requires full 3D simulation
- The B-field of all magnets is always kept below the saturation value
- Two different wiggler designs were explored which provide the desired field
  - Advantage of the electromagnetic wiggler is tunability of the field
  - Permanent magnet wiggler is cheaper to build and run but harder to adjust and may need more maintenance due to demagnetisation – further studies needed

Sasha

Further Work

- Model in 3D (Opera) to establish good field region (edge effects significant, particularly for wiggler)
- Particle tracking
- Look at impacts on lattice (vertical focusing etc)
- More in-depth studies to compare different possible materials
- Structural and thermal analysis
- Calculation of off-axis magnetic fields to validate circular symmetry
- Investigate ramping effects on kicker
- Optimise wiggler ends to have beam on average on-axis
- More in-depth comparison of different kinds of wigglers

Sasha

RF Cavities

Design of the RF cavity

The pDR requires RF cavities:

1. no more than 1.5 m in length
2. with a minimum RF voltage of 4 MV

Cavity types considered:

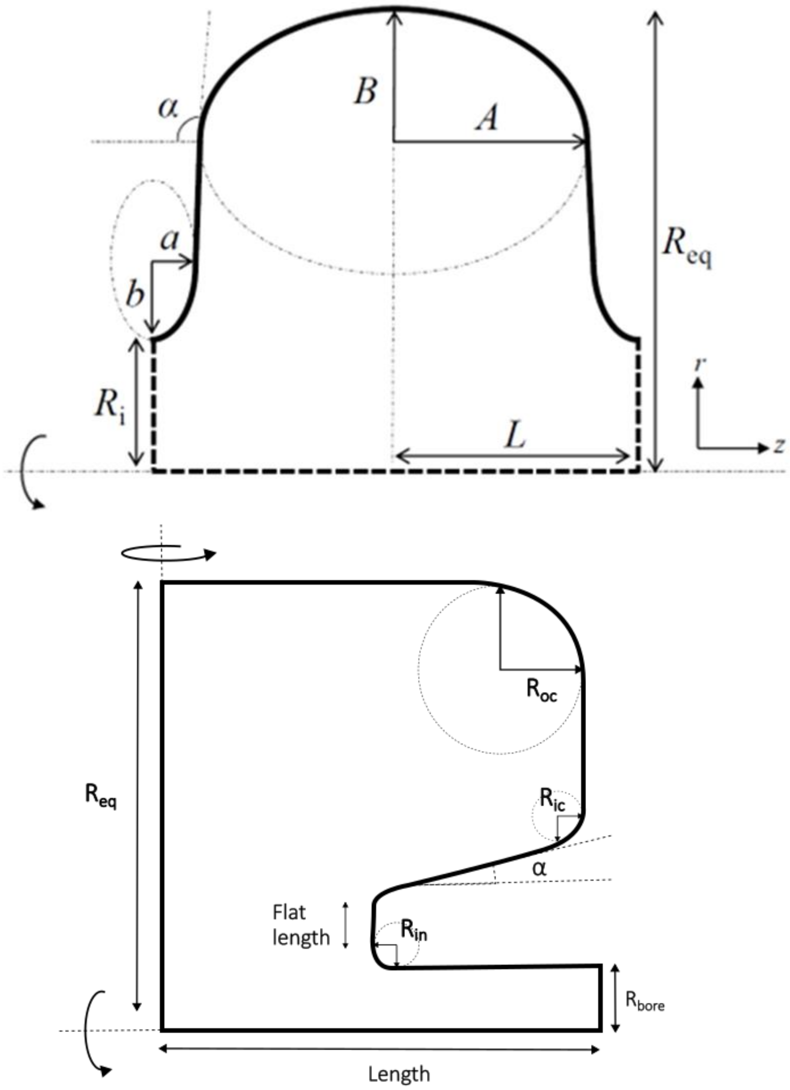
1. Elliptical superconducting (400/800 MHz)
2. Side-coupled normal conducting (400 MHz)

Parameter	Value	Unit
Beam energy	1.54	GeV
Energy loss per turn	0.227	MeV
Total radiated power	16	kW
RF voltage	4	MV
Available length	1.5	m

Cavity optimisation goals

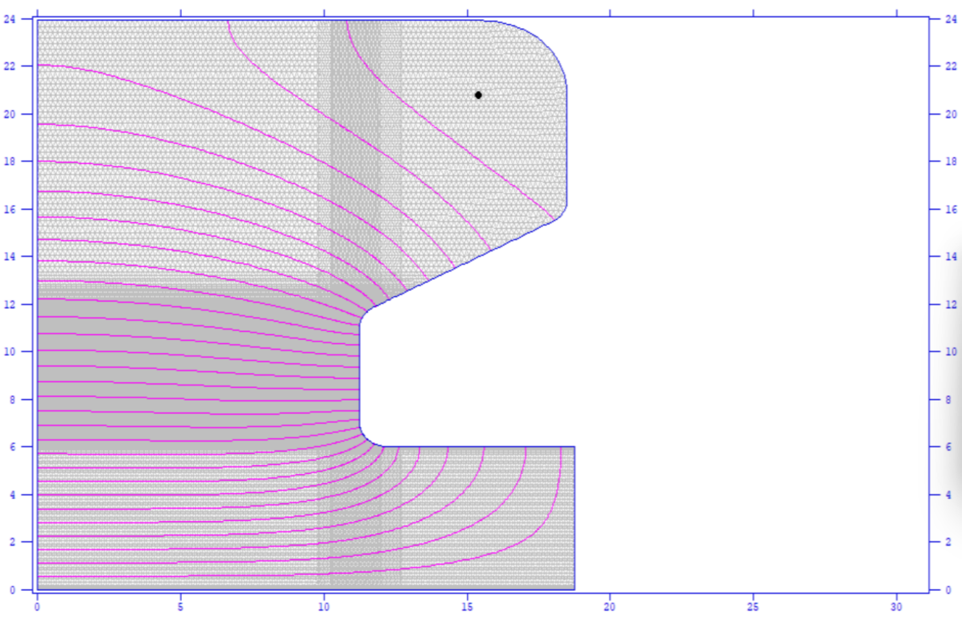
- Maximise:
- 1.G = Rs*Q
- 2.r/Q
- 3.Transit time factor

- Minimise:
- 1.Peak E and H fields
- 2.Bmax/Emax

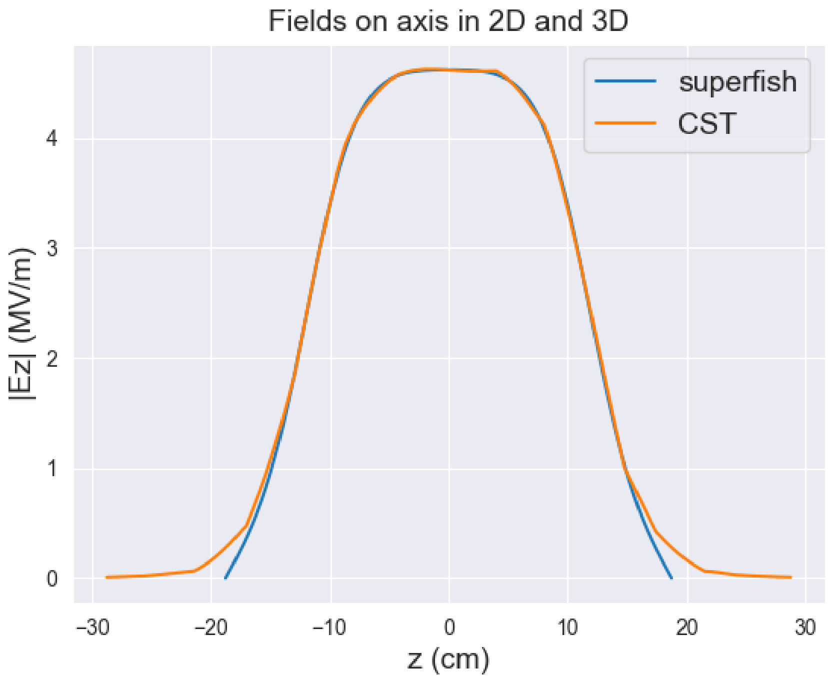


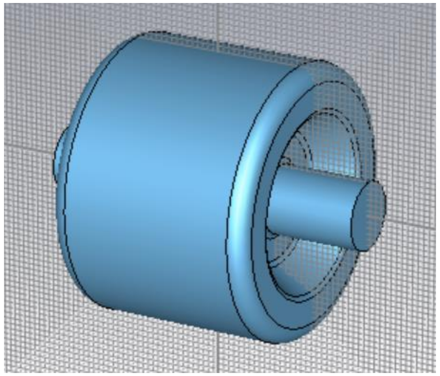
400 MHz NC: 2D optimisation in Poisson Superfish

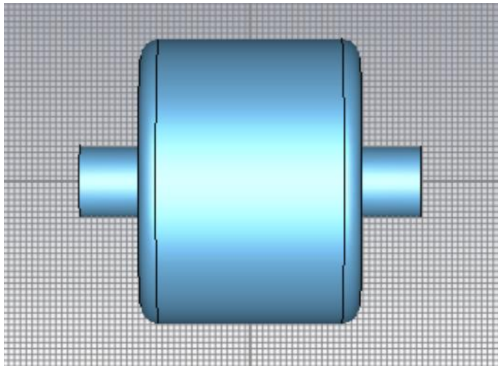
Parameter	Value	Units
Frequency	400	MHz
Gradient	3	MV/m
Length	18.747	cm
Diameter	47.840	cm
Gap length	22.484	cm
Outer corner radius	3	cm
Inner corner radius	1	cm
Outer nose radius	1	cm
Inner nose radius	1	cm
Flat length	4	cm
Cone angle	30	deg
Bore radius	6	cm



3D model in CST Microwave





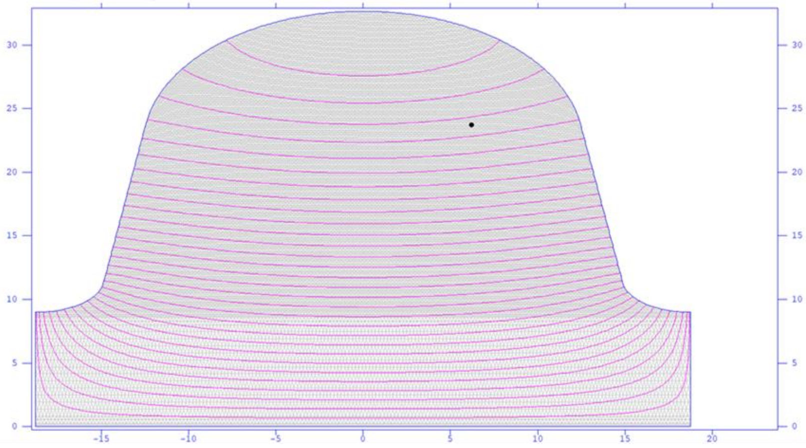


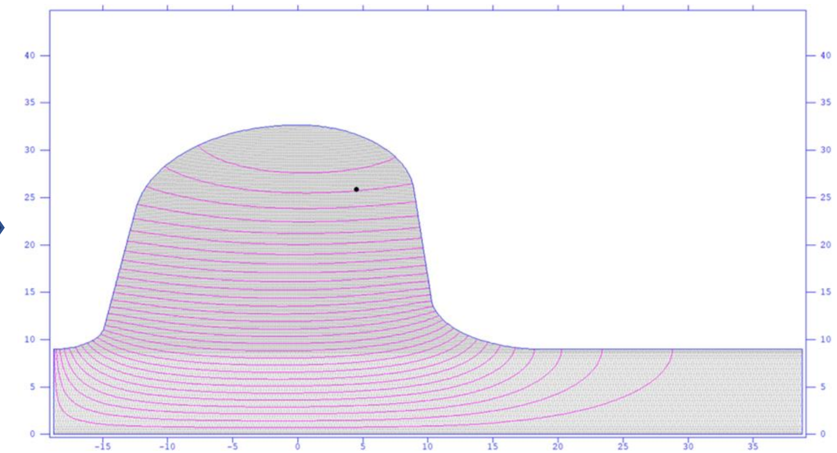
	Superfish parameters	CST parameters	Percentage difference
Frequency	400.0025	399.9596	0.011
Transit time	0.7872	0.8060	2.38
R/Q	108.8700	109.0400	0.16
Max E	8.9330	10.2205	14.41
Max H	9599.8234	9623.7836	0.25
RF Voltage	1.1160	1.1421	2.33

400 MHz SC: 2D optimisation in Poisson Superfish

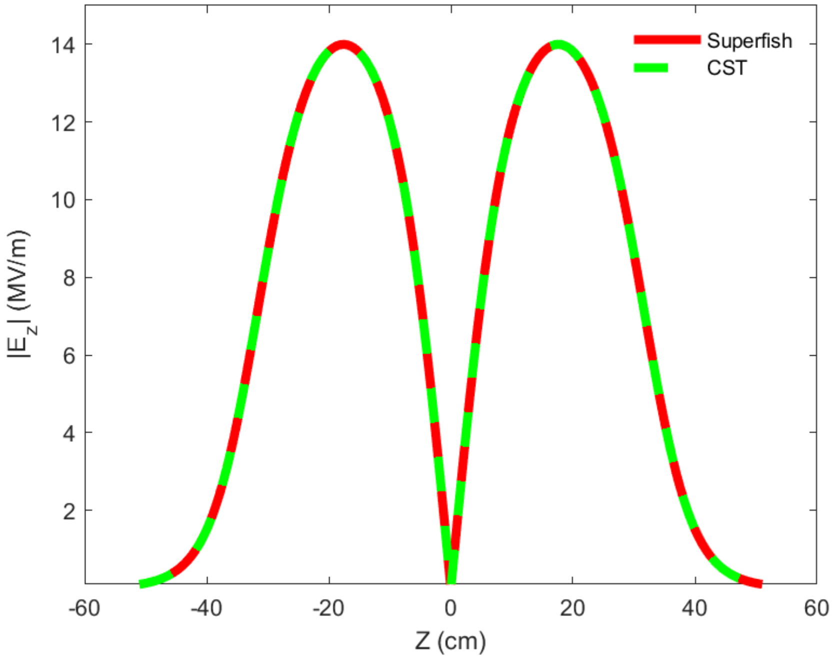
An asymmetrical optimisation was used to mitigate E field extension into the beam pipe and ensure field flatness.

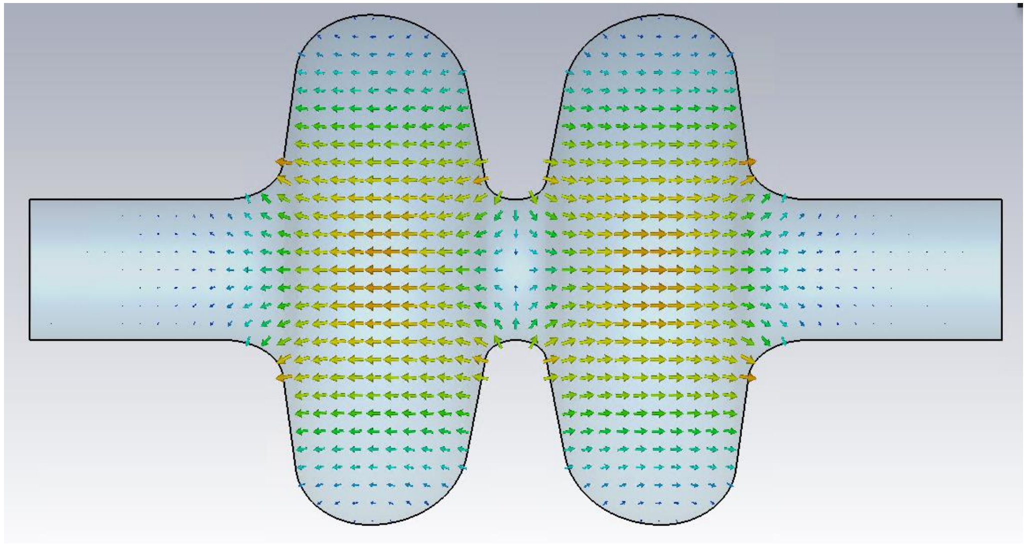
Parameter	Value	Units
Frequency	399.702	MHz
Gradient	10	MV/m
Length	37.47	cm
Diameter	65.31	cm
Left Dome B	10.5	cm
Right Dome B	7.99	cm
Dome A/B	1.2	
Left wall angle	11	deg
Right wall angle	7.8	deg
Iris A/B	1.5	
Bore radius	9	cm





3D model in CST Microwave

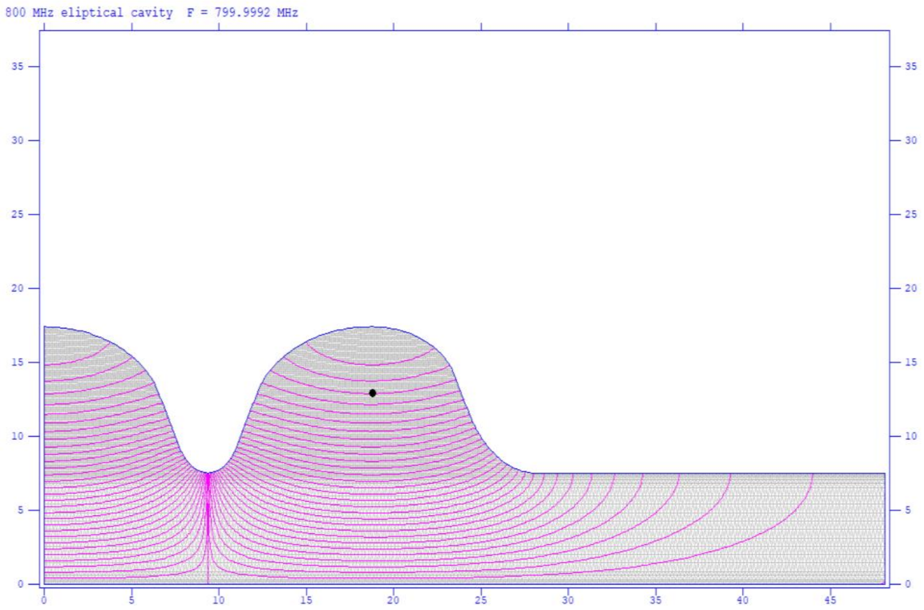




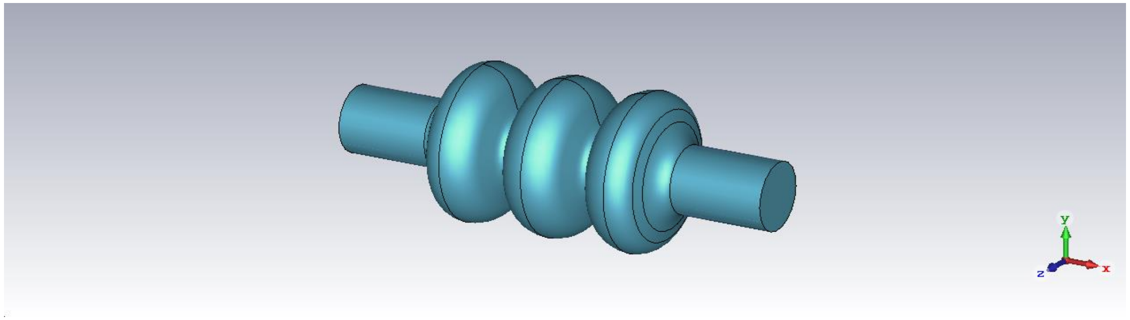
Parameter	Superfish	CST	Unit	Percentage difference (%)
RF voltage	7.4994	7.5019	MV	0.03
Frequency	399.68205	399.67745	MHz	0.0011
R/Q	134.206	134.228	Ohm	0.016
T	0.7280	0.7279		0.024
Max E	16.904	16.870	MV/m	0.20
Max H	25562.2	25565.0	A/m	0.01

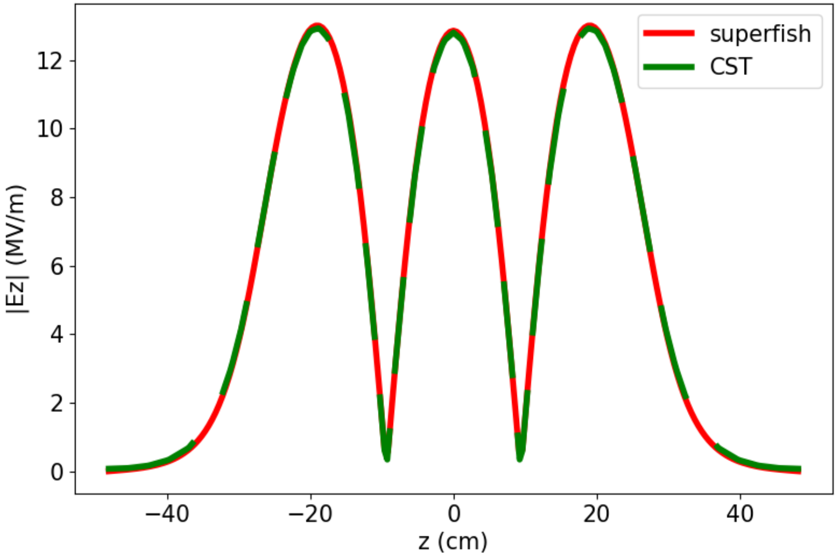
800 MHz SC: 2D optimisation in Poisson Superfish

Parameter	Value	Units
Frequency	800	MHz
Gradient	10	MV/m
Length	18.737	cm
Diameter	34.798	cm
Left Dome B	6.500	cm
Right Dome B	4.470	cm
Dome A/B	1.1	
Left wall angle	18	deg
Right wall angle	18	deg
Iris A/B	0.5	
Bore radius	7.5	Cm



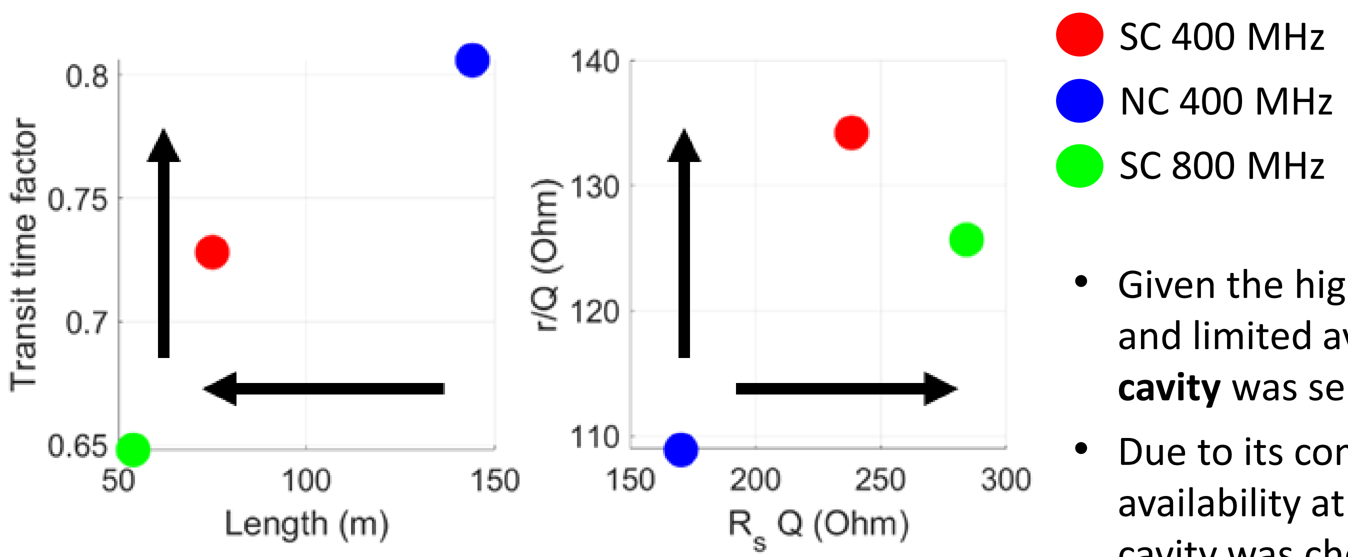
3D model in CST Microwave





Parameter	Superfish	CST	Unit	Percentage difference
RF Voltage	5.622080	5.623472	MV	0.02
Frequency	799.9992	799.8342	MHz	0.02
R/Q	125.656	125.7449	Ohm	0.07
T	0.647773	0.647273		0.08
Max E	18.6329	19.50229	MV/m	4.7
Max H	27642.7	25775.8	A/m	6.8

Conclusion: Cavity choice



- Given the high RF voltage involved and limited available space, a **SC cavity** was selected.
- Due to its compactness and availability at the LHC, the **400 MHz** cavity was chosen for the pDR.

Further work

Superconducting cavities:

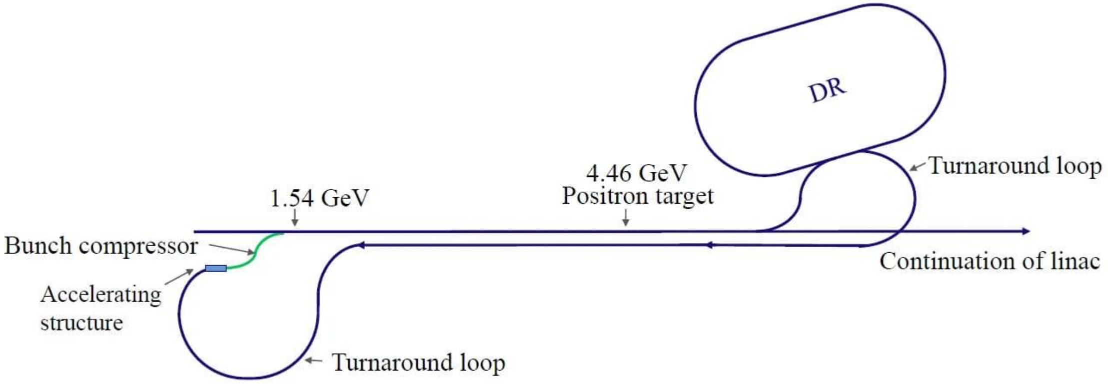
- Cryomodule design
- HOM coupler configuration to limit higher order modes
- Sensitivity study of secondary effects: wake fields, wake potentials, multipacting, field emission

Normal conducting cavities:

- Modelling the full four-cavity LINAC
- Tuning the cavity to 800MHz instead of 400MHz to reduce overall size

Conclusion

- **Lattice:** The **C-Bend Achromat** and **Dog-Leg** successfully demonstrated a bunch length compression from **2mm to 1mm in the pDR transfer line** to the common linac
- **Magnets**: the required magnetic fields were achieved with a **dipole, quadrupole, sextupole, wigglers and kickers/septa**, which were optimised until the fields were sufficiently uniform along the central axis
- **RF cavities:** Given the high RF voltage involved and limited available space, a **SC cavity** was selected. Due to its compact design, and availability at the LHC, the **400 MHz** cavity was selected to be the preferred choice



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- **Lattice:** Rebecca Louise Ramjiawan
- **RF cavities:** Ciprian Plostinar
- **Magnets**: Ian Martin, Zena Patel, Attilio Milanese

And all other lecturers and guests who contributed to the JAI Accelerator Course!

References (1)

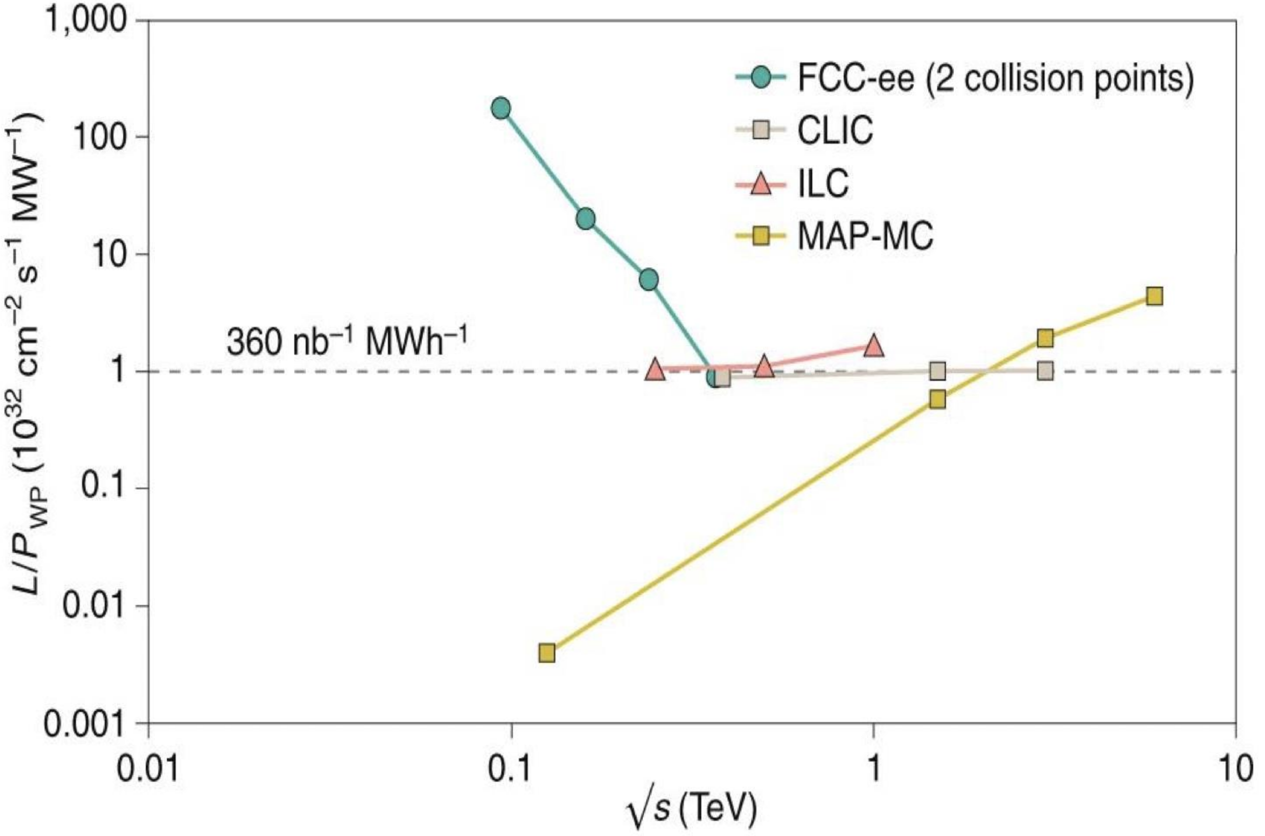
- Zimmerman, F. FCC-ee design overview (2019). FCC Week 2019 Brussels, 24 June 2019. https://indico.cern.ch/event/727555/contributions/3447588/attachments/1867605/3071651/FCC-ee_Overview.pdf
- Barklow, T. et al. C3: An Advanced Concept for a High Energy e+e- Linear Collider (2021). https://www.snowmass21.org/docs/files/summaries/AF/SNOWMASS21-AF3_AF4-EF1_EF2_C3_Collaboration-243.pdf
- Latina, A. CLIC Luminosity Studies (2019). LCWS 2019. https://agenda.linearcollider.org/event/8217/contributions/44778/attachments/34920/53970/CLIC_Luminosity_Latina.pdf
- Yamamoto, H. Luminosity and Site AC Power of the ILC (2019). https://linearcollider.web.cern.ch/sites/linearcollider.web.cern.ch/files/1_NOTE_Luminosity-vs-Energy_HYamamoto_09052019_FINAL.pdf
- Gao, J. The strategy of Accelerator based High Energy Physics of China (2014). Rencontres du Vietnam 2014: Physics at LHC and beyond. https://indico.cern.ch/event/300048/contributions/1661107/attachments/565207/778694/High_Energy_Physics_Strategy_in_China_-_Jie_Gao.pdf
- Raubenheimer, Tor. Accelerator Overview (2022). FCC Week 2022. https://indico.cern.ch/event/1064327/contributions/4891237/attachments/2452429/4202848/220530%20Accelerator%20Overview%20posted.pdf
- Janot, P., Blondel, A. The carbon footprint of proposed e+e−e+e− Higgs factories. *Eur. Phys. J. Plus* **137**, 1122 (2022). https://doi.org/10.1140/epjp/s13360-022-03319-w

References (2)

- Wolski, Andy. "Nonlinear Dynamics: Part 1." CAS: Introduction to Accelerator Physics, Budapest, Hungary (2016).
- SHARMA, AMALENDU. *OPTICS DESIGN AND OPTIMIZATION OF ELECTRON BUNCH COMPRESSOR TRANSFER LINE (WITH A CASE STUDY OF CTF3 BUNCH COMPRESSOR)*. Diss. HOMI BHABHA NATIONAL INSTITUTE, 2013.
- Charles, T. K., et al. "Bunch compression and turnaround loops in the FCC-ee injector complex." *Journal of Physics: Conference Series*. Vol. 1067. No. 6. IOP Publishing, 2018.
- Di Mitri, Simone. "Bunch length compressors." *CERN Yellow Reports: School Proceedings* 1 (2018): 363-363.
- Byrd, John. "Bunch Compressors." *Lecture of Short Bunches in Accelerators: USPAS, Boston, MA, USA* (2010): 21-25.
- Wolski, Andy. "A short introduction to Bunch Compressors for Linear Colliders." *Notes for USPAS Course on Linear Colliders, Santa Barbara* (2003).
- Jacobson, B. T., J. M. J. Madey, and P. Niknejadi. "DESIGN AND COMMISSIONING OF CHASMAN-GREEN DOUBLE BEND ACHROMAT LATTICE LINEAR TRANSPORT LINE AT THE UNIVERSITY OF HAWAI'I MKV ACCELERATOR FACILITY." (2013).

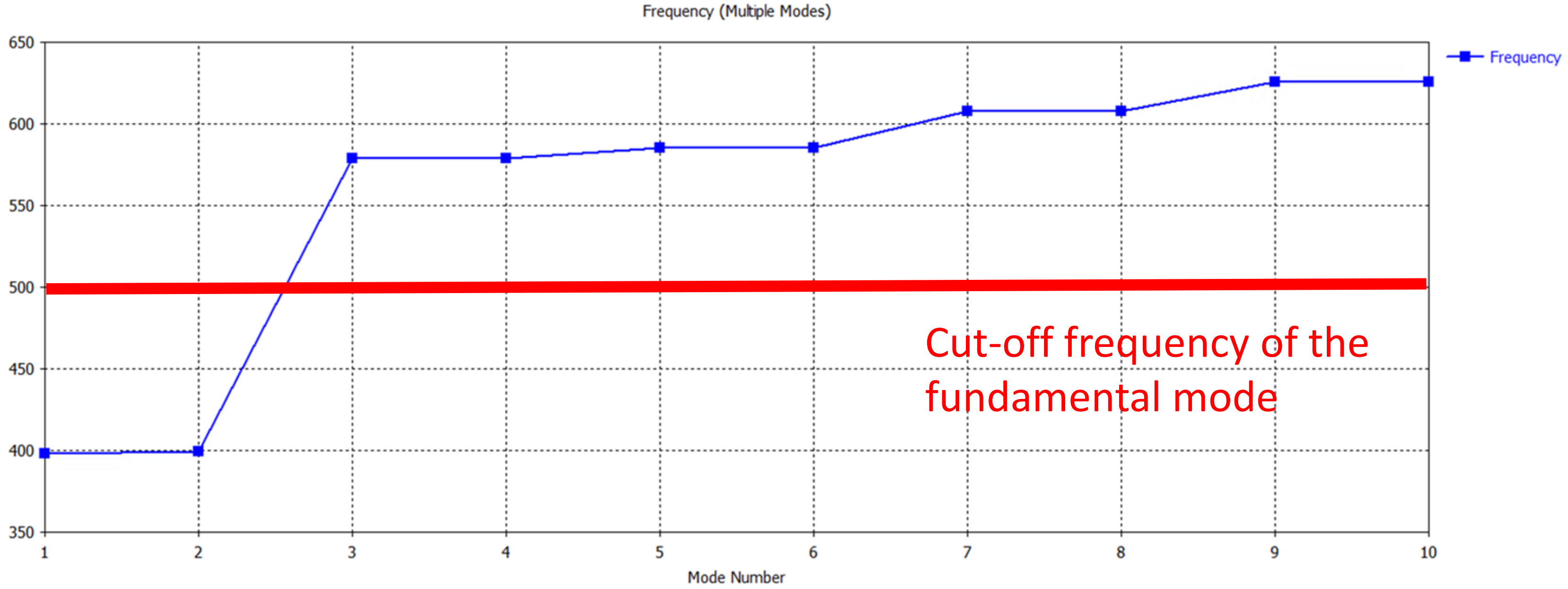
Appendix

Luminosity vs. electricity consumption

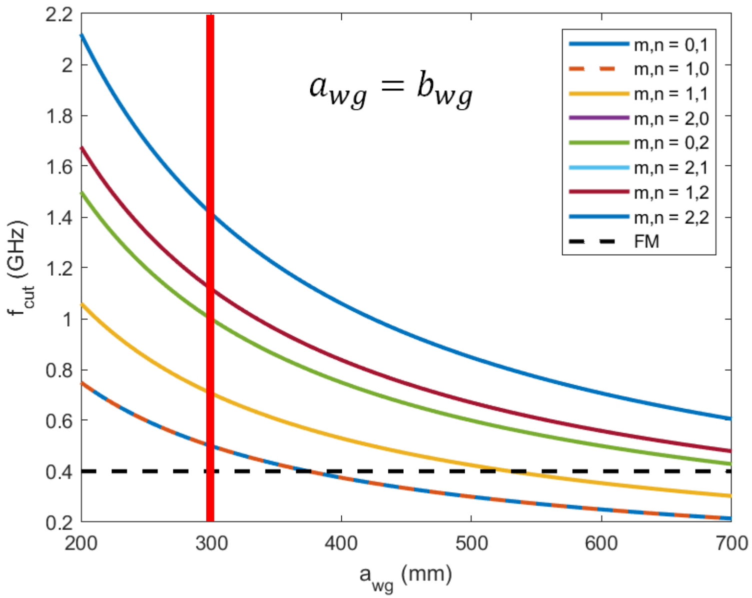


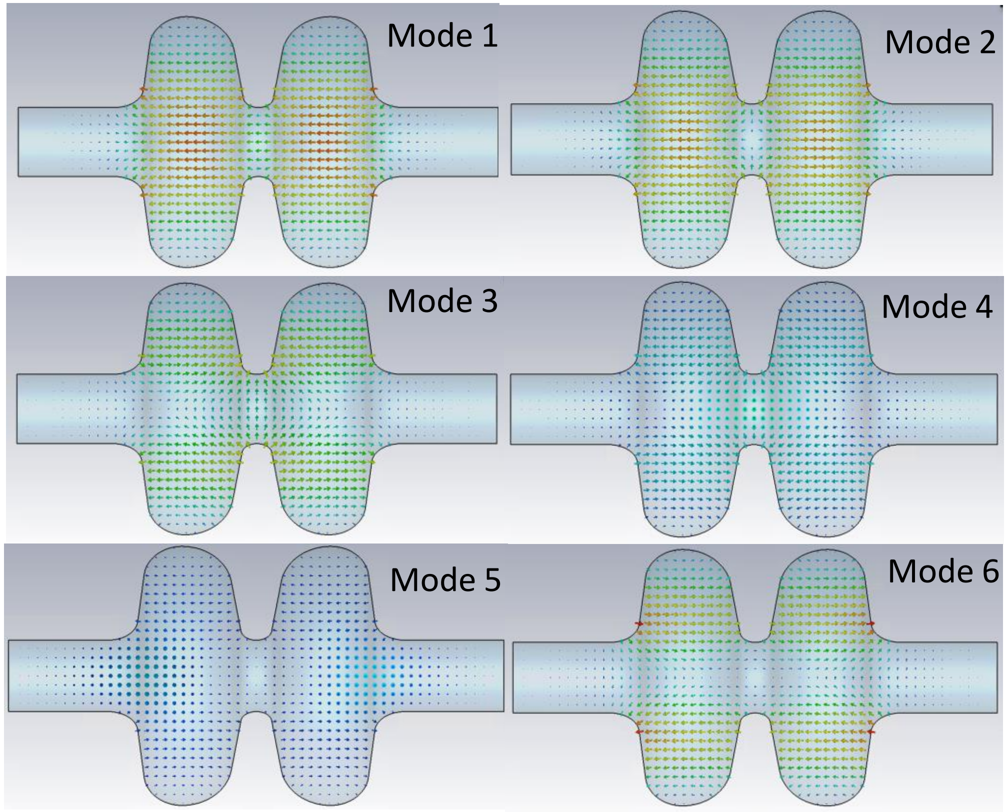
HOM couplers

Dimensions of the HOM coupler are optimised to have a fundamental cut-off frequency larger than the TEM010 mode, and smaller than HOM modes.



Rectangular waveguide





Normal conducting VS superconducting

NC cavities

+ less infrastructure
+ simpler technology
+ simpler tuning

- Higher RF power required
- Lower gradients
- Thermal effects
- Larger cavities

SC cavities

+ no thermal effects
+ efficient use of input power for acceleration
+ larger gradient

- Cryogenic system
- Complex fabrication process
- Less tolerant against beam loss