

Development of the Rapid Cycling Synchrotron 1 (RCS1) for the Muon Collider

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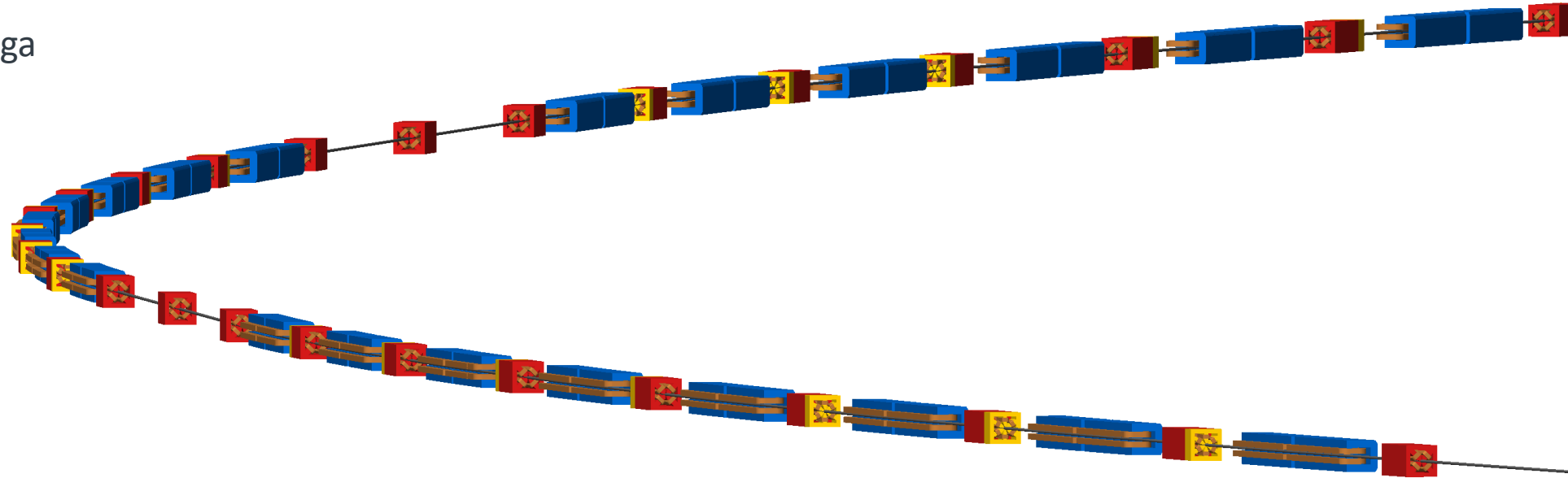
M. Savage

F. Straniero

G. Weis

A. Yousif

12th March 2026



Overview

Introduction

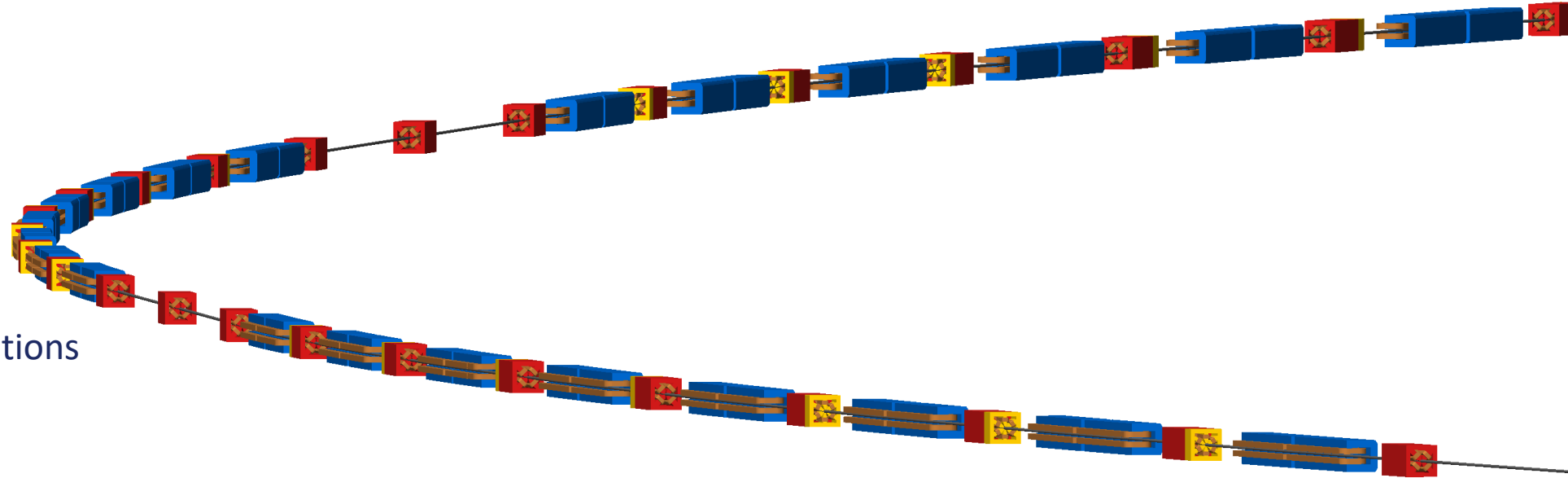
Lattice

Magnets

RF Cavities

Environmental
and Societal Considerations

Conclusions



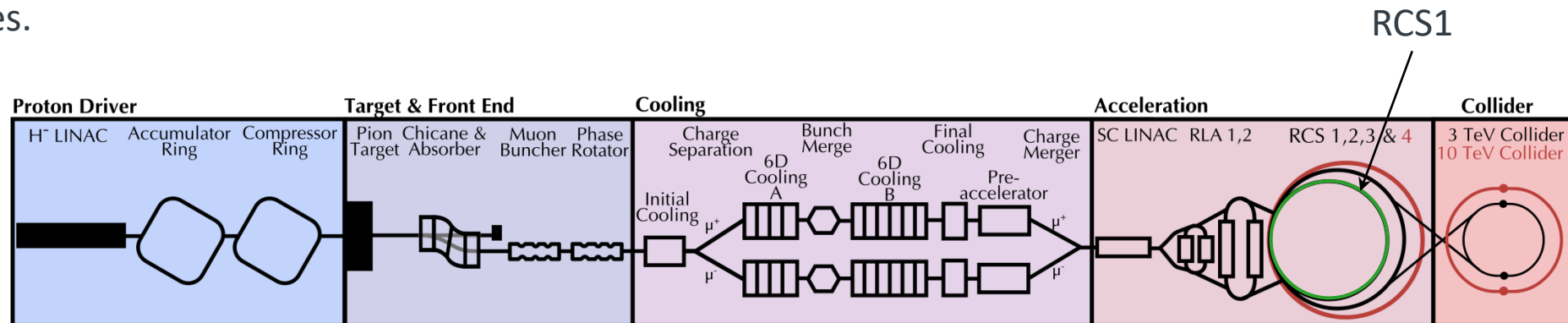
Introduction

Why a Muon Collider?

- 10TeV CM energy collider with broad physics potential (Higgs coupling, electroweak studies, BSM).
- Muon collider ‘best of both worlds’ combining benefits of lepton and hadron colliders.
- Higher energy reach and less synchrotron radiation than electron-positron collider.
- Point-like collisions at the full centre-of-mass energy with clean initial states.

Key Challenges

- Muon beam production is a tertiary process (protons->pions->muons) so need high intensity proton beam
- Muon beams require cooling to reduce emittance
- Short muon lifetime (2.2 μ s) means high accelerating gradients are required



Source: R. Taylor, MuCOL consolidated parameters report (Oct 2025)

R. Taylor v1.5 (2025)

Introduction

Rapid Cycling Synchrotrons

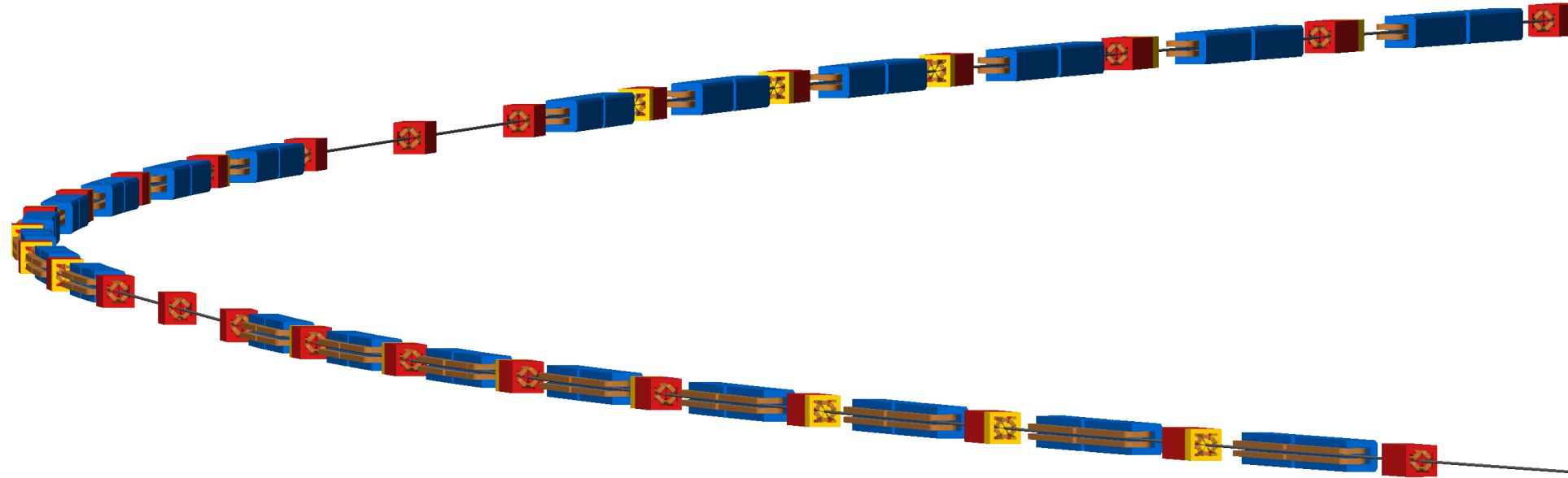
- Due to short muon lifetime, muons must be produced, cooled, and accelerated extremely quickly to higher energies where lifetimes are longer due to time dilation.
- The current design uses a chain of four ‘Rapid Cycling Synchrotron’ (RCS) rings to rapidly accelerate the muons in early stage of the chain before injection into main collider ring.
- This design study focuses on the RCS1 ring, considering lattice, magnet and RF cavity design.

RCS1 Parameters	
Repetition Rate	5Hz
Circumference	5990m
Injection Energy	63GeV
Extraction Energy	314GeV
Assumed survival rate	0.9
Acceleration time	0.34ms
Revolution period	20 μ s
Number of turns	17
Required energy gain per turn	14.8GeV
Average accel. gradient	2.44 MV/m
Inj. bunch population	2.7×10^{12}
Ext. bunch population	2.4×10^{12}
Beam current per bunch	21.67mA
Vert. norm. emittance	25 μ m
Horiz. norm. emittance	25 μ m
Long. norm. emittance	0.025eVs
Bunch length at injection	31ps
Bunch length at extraction	20ps

RCS1 Parameters specified by MuCOL consolidated parameters report (Oct 2025)

Lattice Design

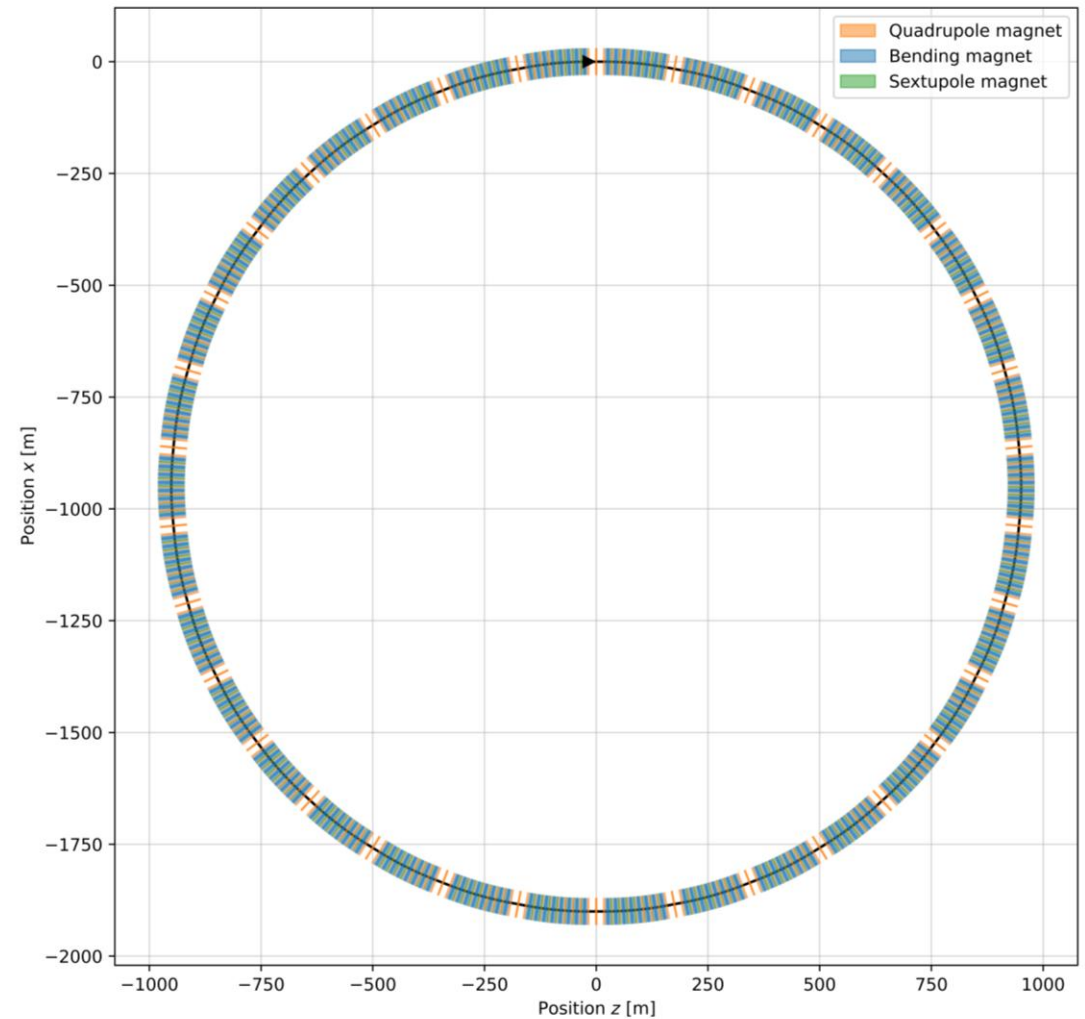
*T. Fernandes de
Nobrega
M. Savage*



Lattice

Overview

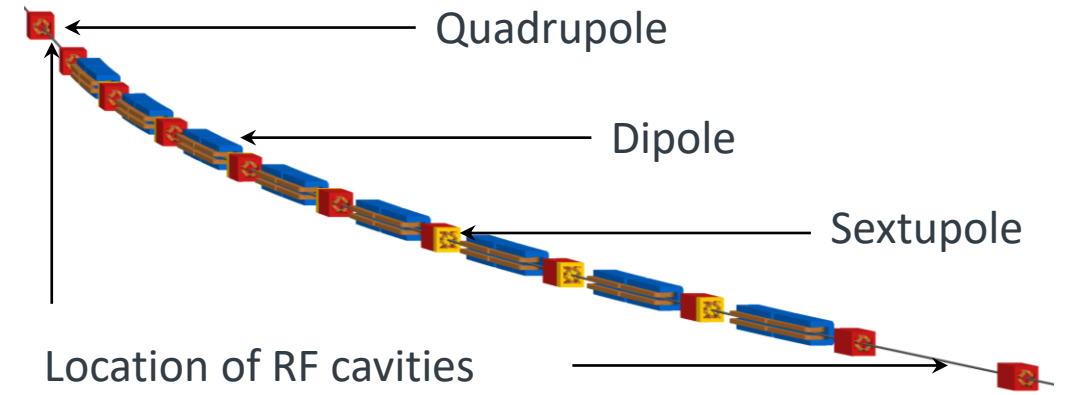
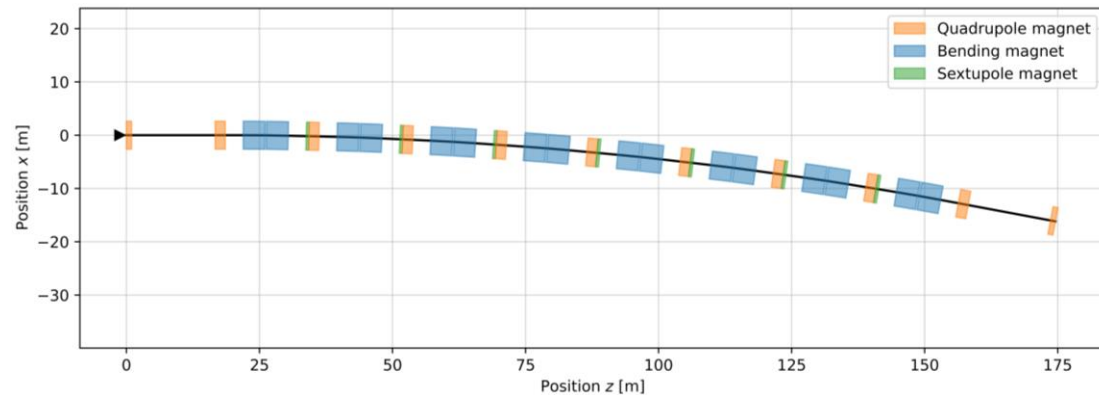
- Started with lattice file from a previous RCS1 design study and analysed using Xsuite.
- Ring consists of 34 repeating cells.
- 2 RF cavities per cell.
- Analysed beam aperture and optics to inform magnet and RF cavity design.
- Performed particle tracking on single muon and example muon bunch to assess lattice performance.



Lattice

The Single Arc Cell

- The single arc cell consists of 16 dipole magnets, 10 quadrupole magnets and 7 sextupole magnets.



- Plot (left) of the RCS1 arc created using Xsuite.
- Visualisation (right) of the RCS1 single arc cell were created using Beam Delivery Simulation (BDSIM) software.



Lattice

Lattice Parameters (from MuCol):

- Here are some of the notable parameters of the lattice that we are expecting to achieve in our Xsuite model.

Ensuring Reachable Accelerating Gradient:

- RF voltage of a cavity, (10 cavities per linear section):

$$V_{\text{cav}} = 21.58 \text{ [MV]}$$

- Total number of linear sections:

$$n_{\text{lin}}(\text{arc}) \cdot n_{\text{arc}}(\text{ring}) = 2 \cdot 34 = 68$$

- Acceleration per turn:

$$G = 10 \cdot 68 \cdot 21.58 \text{ [MV]} \approx 14.67 \text{ [GV]}$$

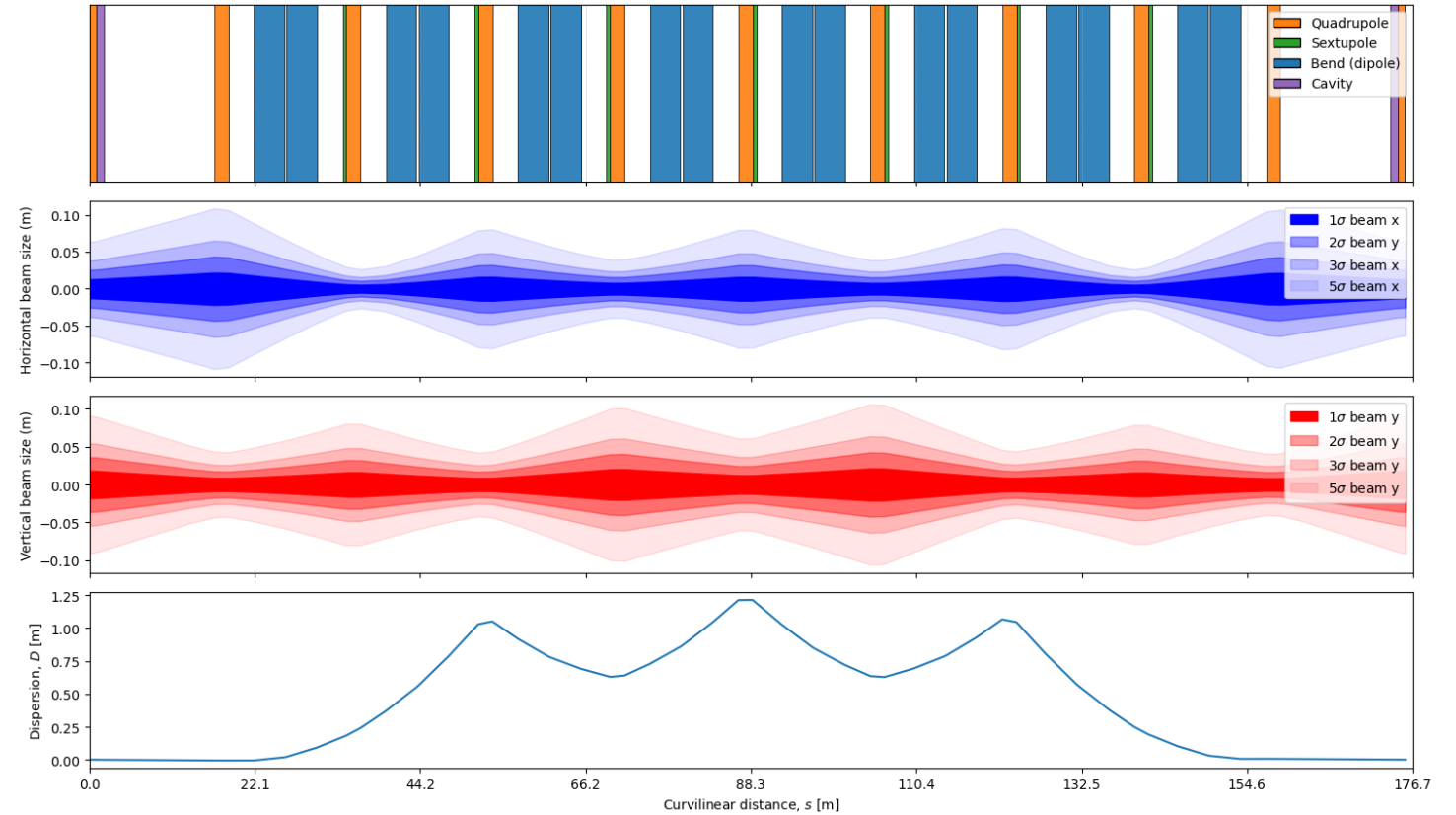
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RCS1 Parameters specified by MuCOL consolidated parameters report (Oct 2025)

Lattice

Beam Aperture and Optics

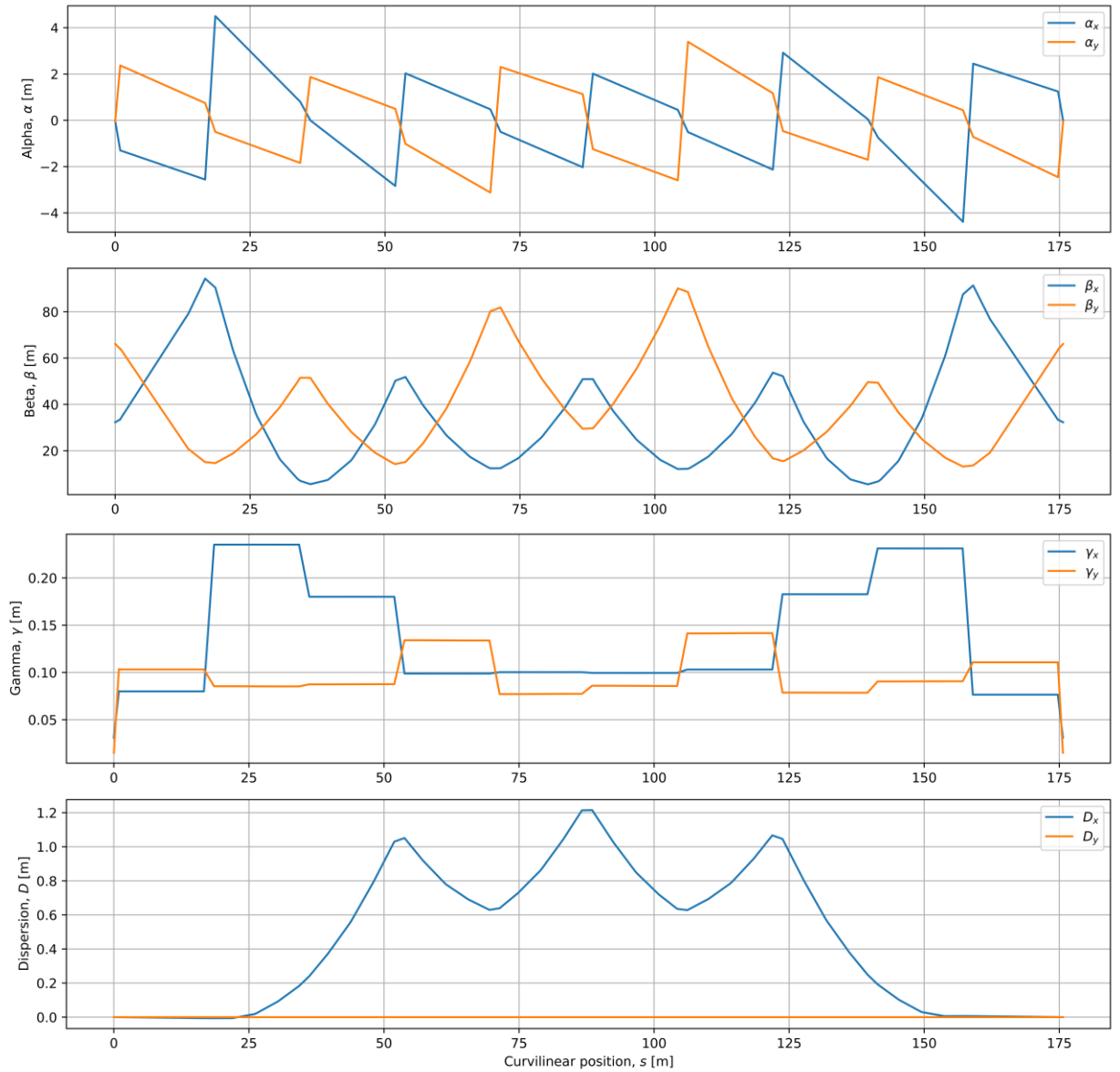
- Beam size in the horizontal (blue) and vertical (red) transverse components for 1σ , 2σ , 3σ and 5σ .
- 2σ beam size chosen to ensure reasonable aperture size for magnets and RF cavities.
- Ideally would an aperture size to contain 5σ of the beam.



Lattice

Twiss Parameters for the Single Arc Cell

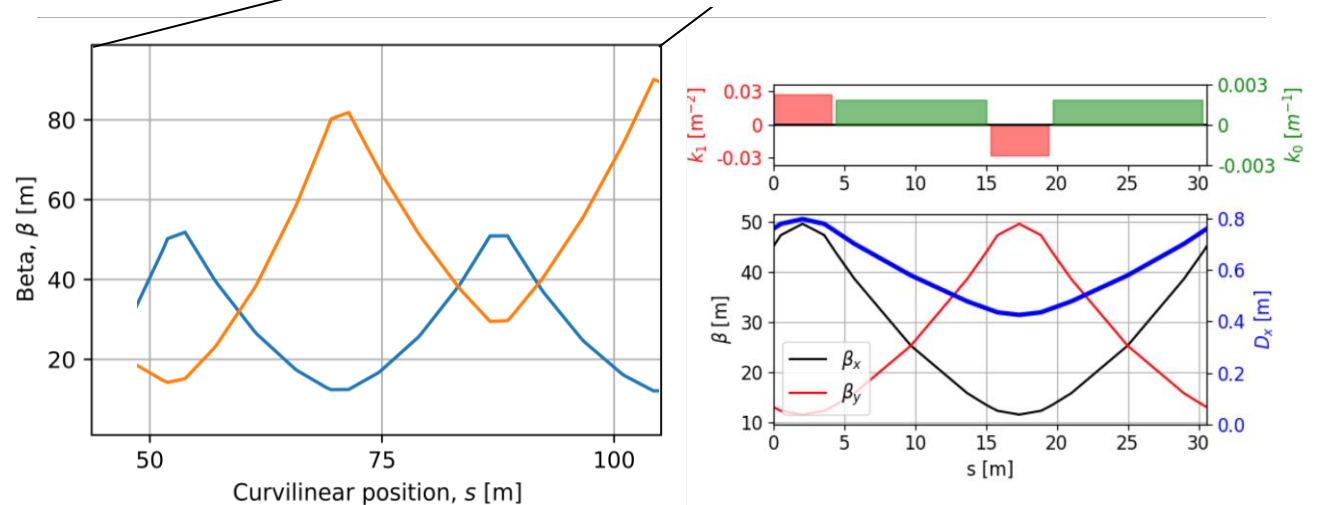
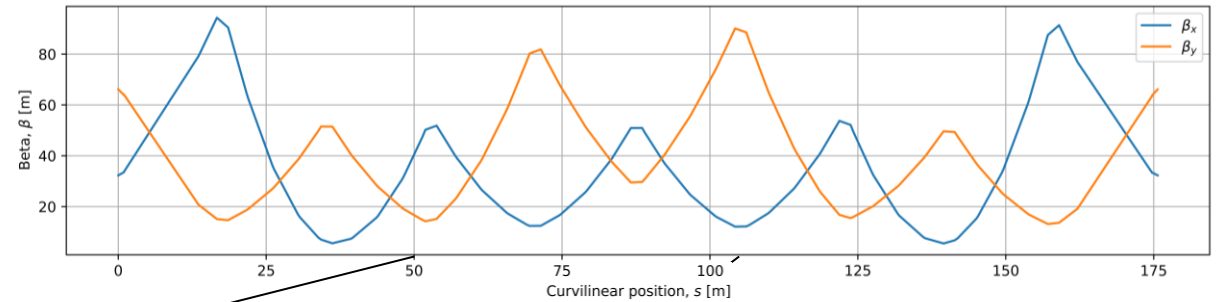
- Alpha is as expected focusing in one direction and defocusing in the other.
- Beta is as expected comparing with lattice results produced by L. Soubirou.
- Gamma larger in x-direction than in the y-direction, suggesting larger angular spread in horizontal plane, as expected.
- Short arc length requires dispersion suppression, hence explaining the fluctuations.



Lattice

Twiss Parameters for the Single Arc Cell

- Beta is as expected comparing with lattice results produced by L. Soubirou.
- Zooming in on the section for which we have the lattice optics from L. Soubirou.
- Can see very similar β_x , and a β_y with a similar shape but a slightly higher expected amplitude.

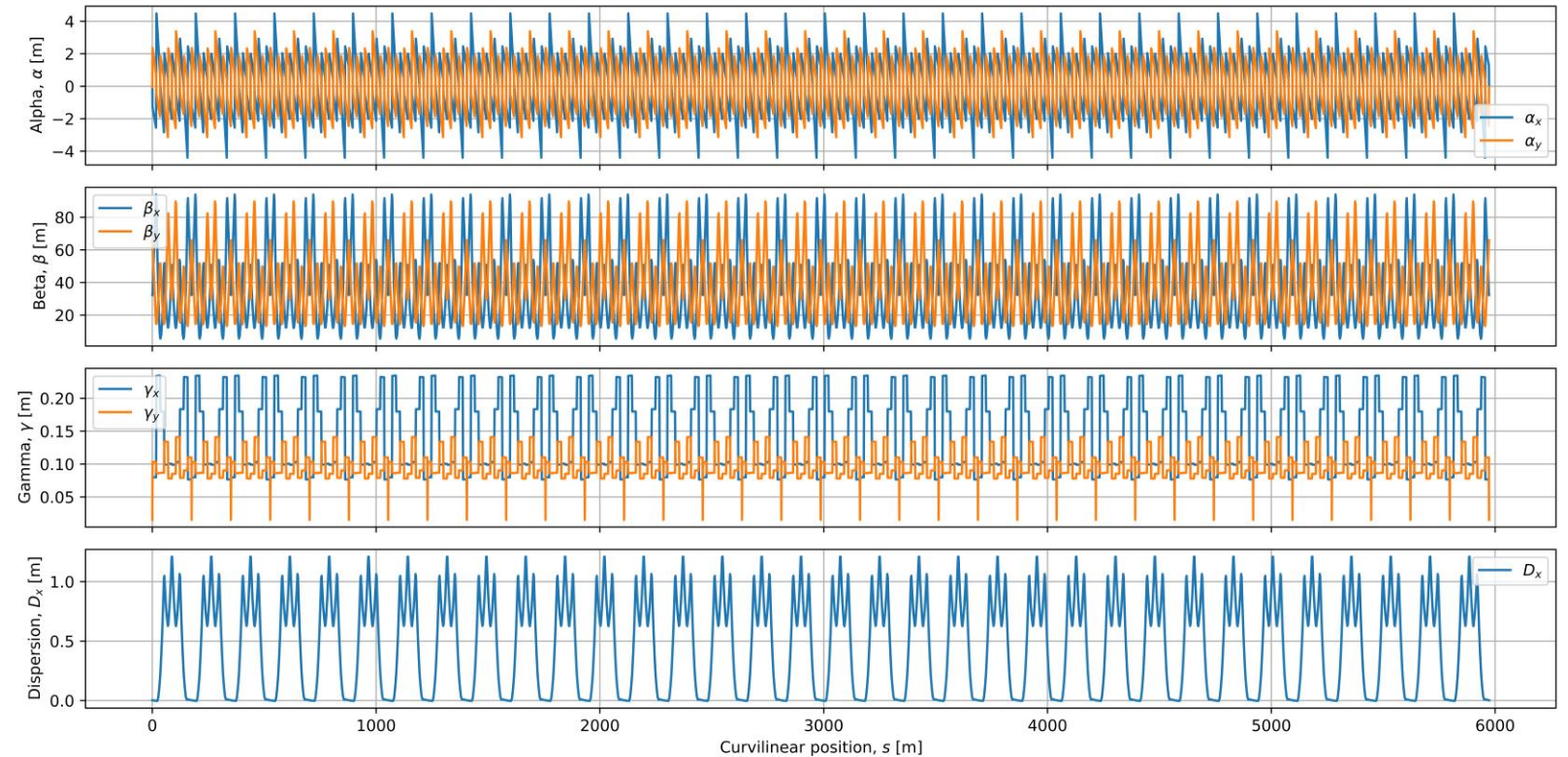


Soubirou L, et al. Optics design status for the muon collider rapid cycling synchrotrons (2025) doi:10.1088/1742-6596/3094/1/012004.

Lattice

Twiss Parameters for the Full Ring

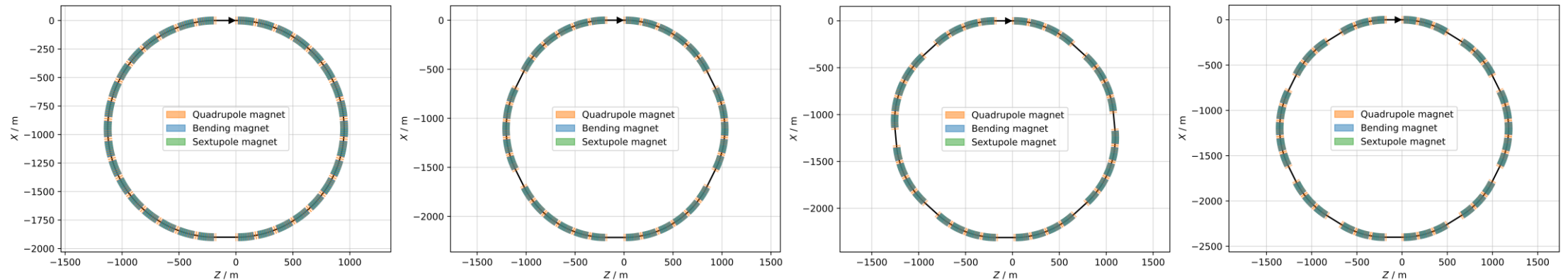
- Twiss parameters α , β and γ plotted in x - and y -directions for the full 6km ring.
- Twiss parameters are periodic and stable closed orbit is produced.
- Start and end points of the plots match.



Lattice

Investigating the Introduction of Straight Sections

- Other variations of ring structure were considered to have dedicated locations for the RF cavities.

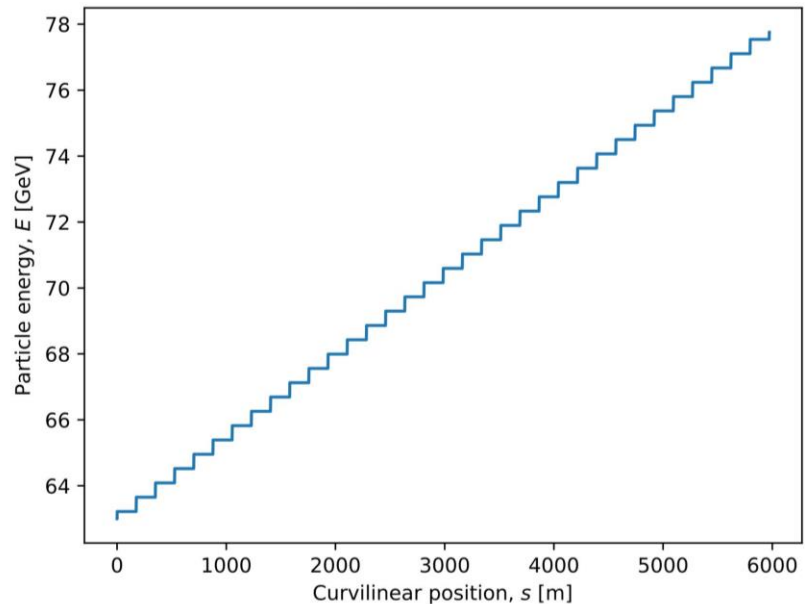


- The cavities under consideration have lengths that allow them to fit within the zero-dispersion region of the lattice.
- Therefore, straight sections no longer needed to be considered.

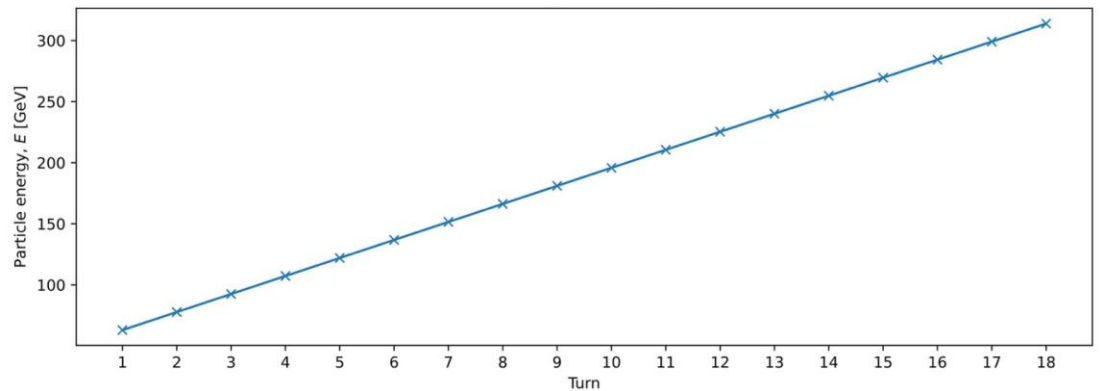
Lattice

Single Particle Tracking

- Particle energy evolution over a single turn.
- Energy gained only at locations of the cavities, as expected.
- For first turn, energy starts at 63 GeV and reaches 78 GeV.



- Particle energy evolution over multiple turns.
- Require 17 turns to reach energy of 314 GeV.

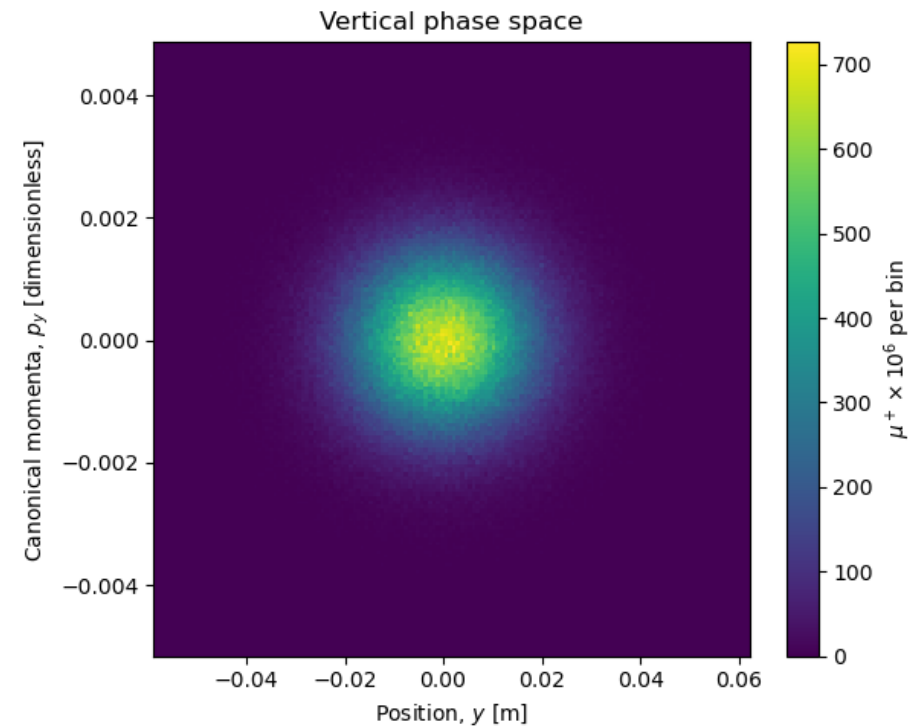
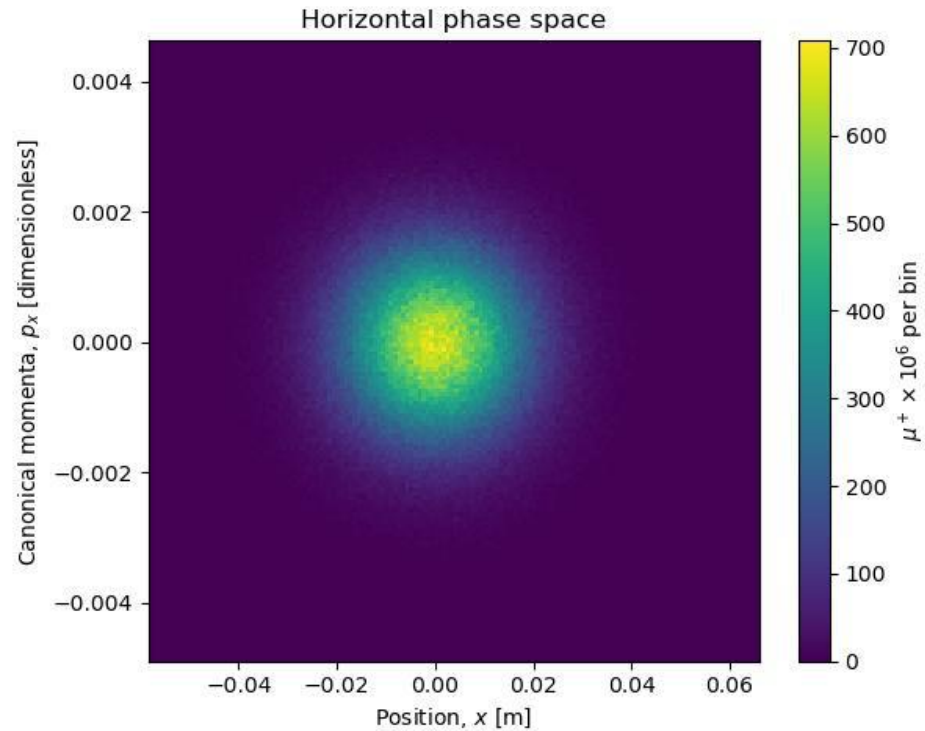


- Both plot show the expected energy gains required per turn.
- Suggests that the lattice can reach its expected performance.

Lattice

Multiple Particle Tracking

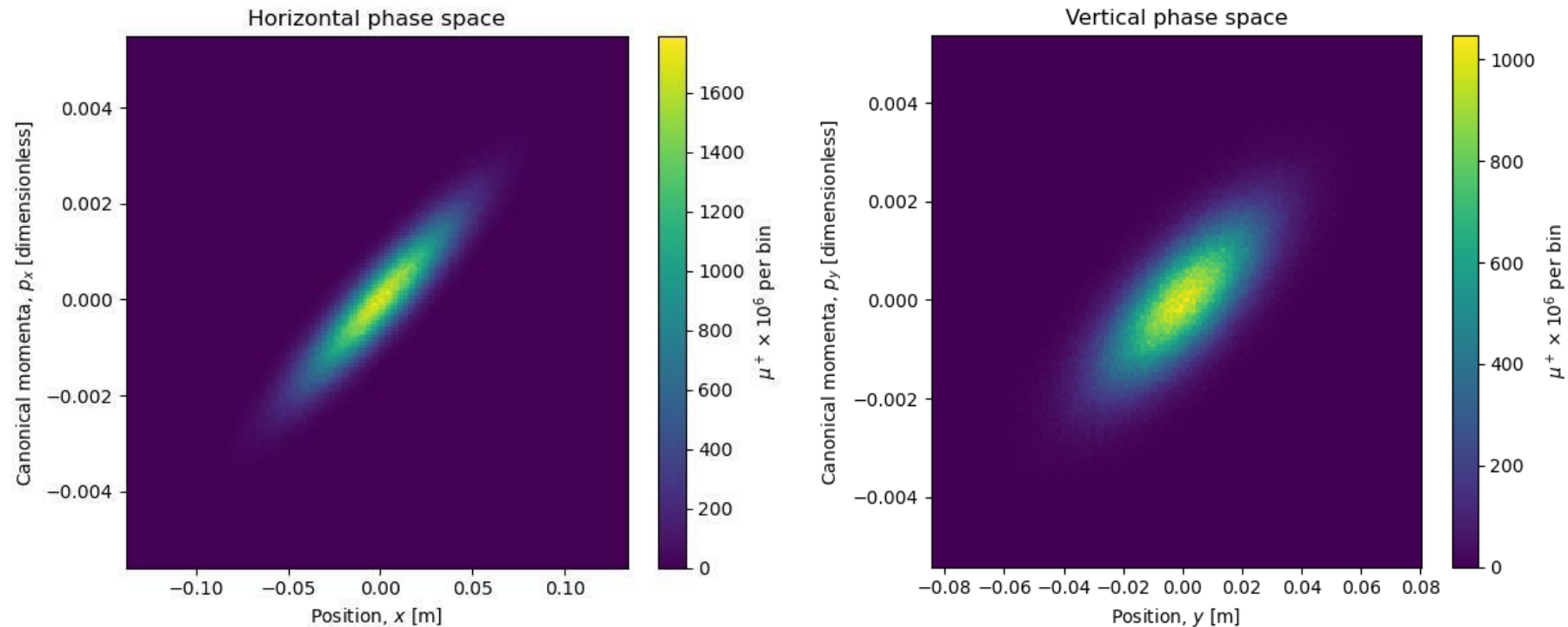
- The horizontal and vertical phase spaces of the muon beam *before* tracking through the RCS1.
- Momentum spread 10^{-3} modelled (specified from MuCOL parameters report).



Lattice

Multiple Particle Tracking

- The horizontal and vertical phase spaces of the beam *after* tracking through the RCS1 (17 turns).
- Beam is diverging at the end of tracking (not ideal for closed loop).
- No significant emittance growth visible.



Lattice

Conclusions

- Single particle tracking successfully performed showing expected optics.
- Transverse beam size determined to provide aperture sizes for magnet and RF teams.
- Expected energy gains over a single turn and over all turns needed to reach ejection energy.
- Beam is seen to be diverging after tracking through the RCS1 but showing no significant emittance growth.

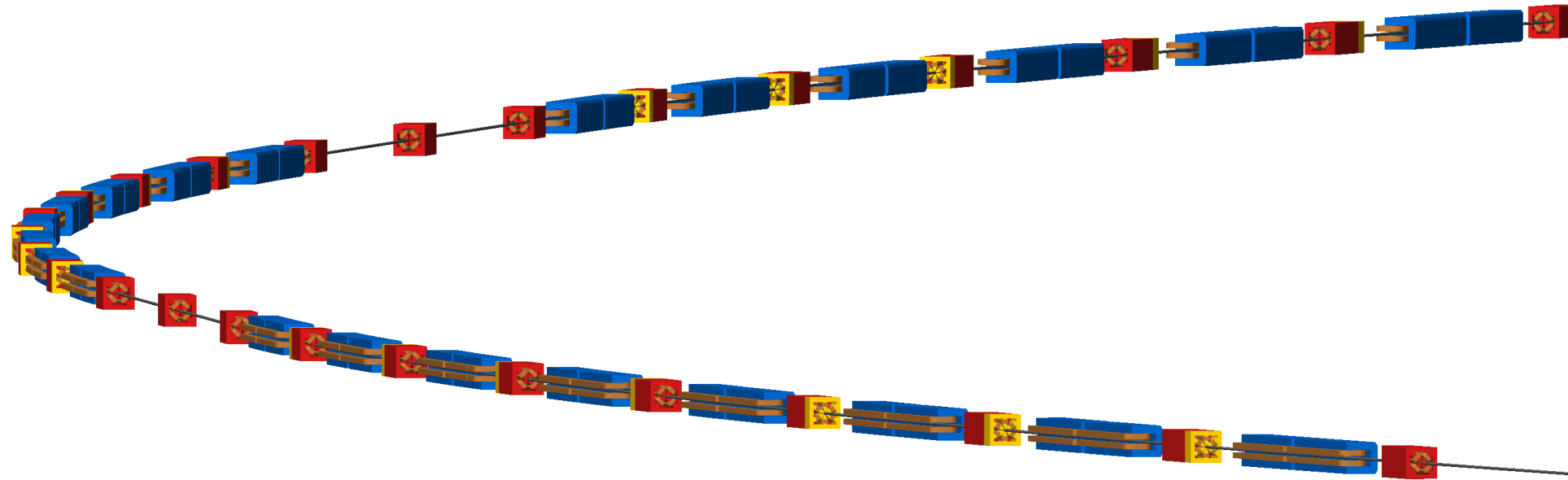
Future work

- Optimisation of the lattice to produce more realistic beam size to minimise the aperture size.
- Further investigation with multiple particle beam tracking.
- Considering other lattice designs such as the hybrid-FODO and combined-function cells*.

*Soubirou L, et al. Optics design status for the muon collider rapid cycling synchrotrons (2025) doi:10.1088/1742-6596/3094/1/012004.

Magnet Design

*T. Hirt Madden
G. Weis*



Dipole Magnet – Specification

Requirements for RCS1

Initial requirements from the muon collider annual meeting (Breschi et. al):

- Magnetic field in aperture 1.8T
- Good Field Region (GFR) 30x100mm
- 1ms ramp from -1.8T to 1.8T

This work focusses on a dipole with H-topology.

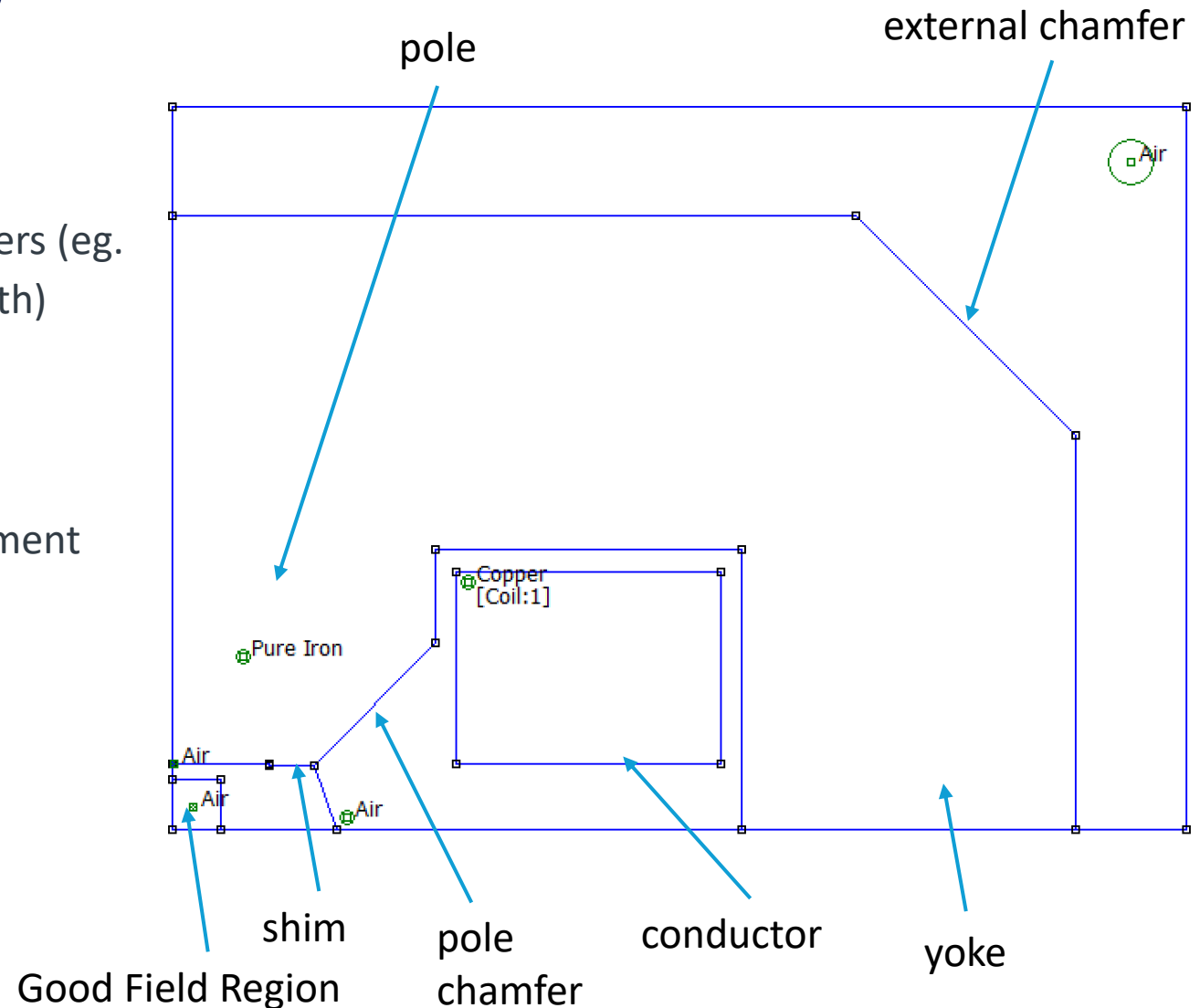
GFR was updated to 43.4x43.4mm towards the end of the project after updates from the lattice team.



Breschi, M. 2025 et.al (2025) , NC magnet configuration (dipoles and quadrupoles) [PowerPoint]. IMCC and MuCol Annual Meeting. May 13th

Dipole Magnet – Geometry

- Only one quadrant of magnet required
- Coordinates generated using 12 input parameters (eg. pole height, aperture height, pole chamfer width)
- Magnet simulation created in FEMM using the pyFEMM interface
- Visualisation produced using FEMM (Finite Element Method Magnetics) software.



Dipole Magnet - Analysis

Post process analysis

Method to extract central field strength and field quality.

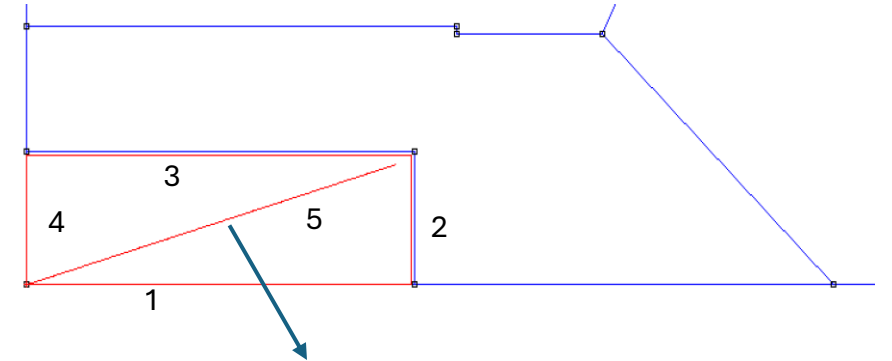
$$\frac{\Delta B}{B} = \frac{B_{max} - B_{min}}{B_{centre}}$$

Similar approach used to measure:

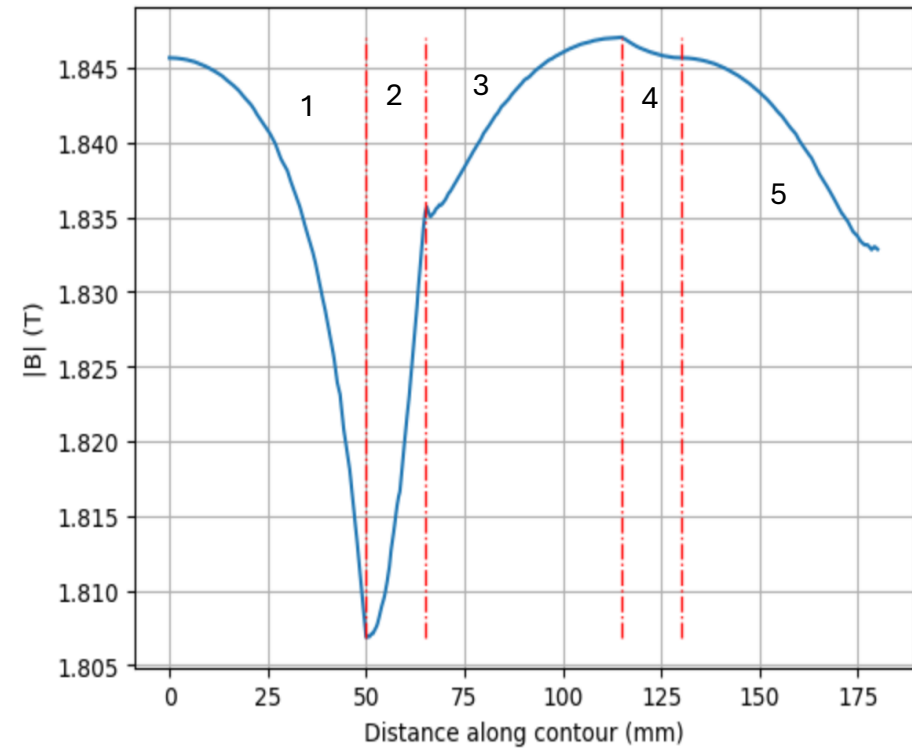
- Field parallelism
- Yoke saturation

Block integrals used to measure:

- Magnet/coil area
- Magnetic field energy



Contour traced in red



Dipole Magnet – Optimisation process

- Cost function designed, with minimum at desired outcomes.
- Bayesian optimisation (gp_minimize from skopt) used to vary parameters and optimise cost function.

Example cost function

$$\omega_1 \frac{\Delta B}{B_{cent}} + \omega_2 \frac{\max(B.t)}{B_{cent}} + \omega_3 (B_{cent} - 1.8)^4 + \omega_4 (B_{yoke} - 1.4)^4 + \omega_5 \times \left(\frac{E_{mag}}{5 \times 10^3} \right)^2 + \omega_6 (J - 7)^2$$

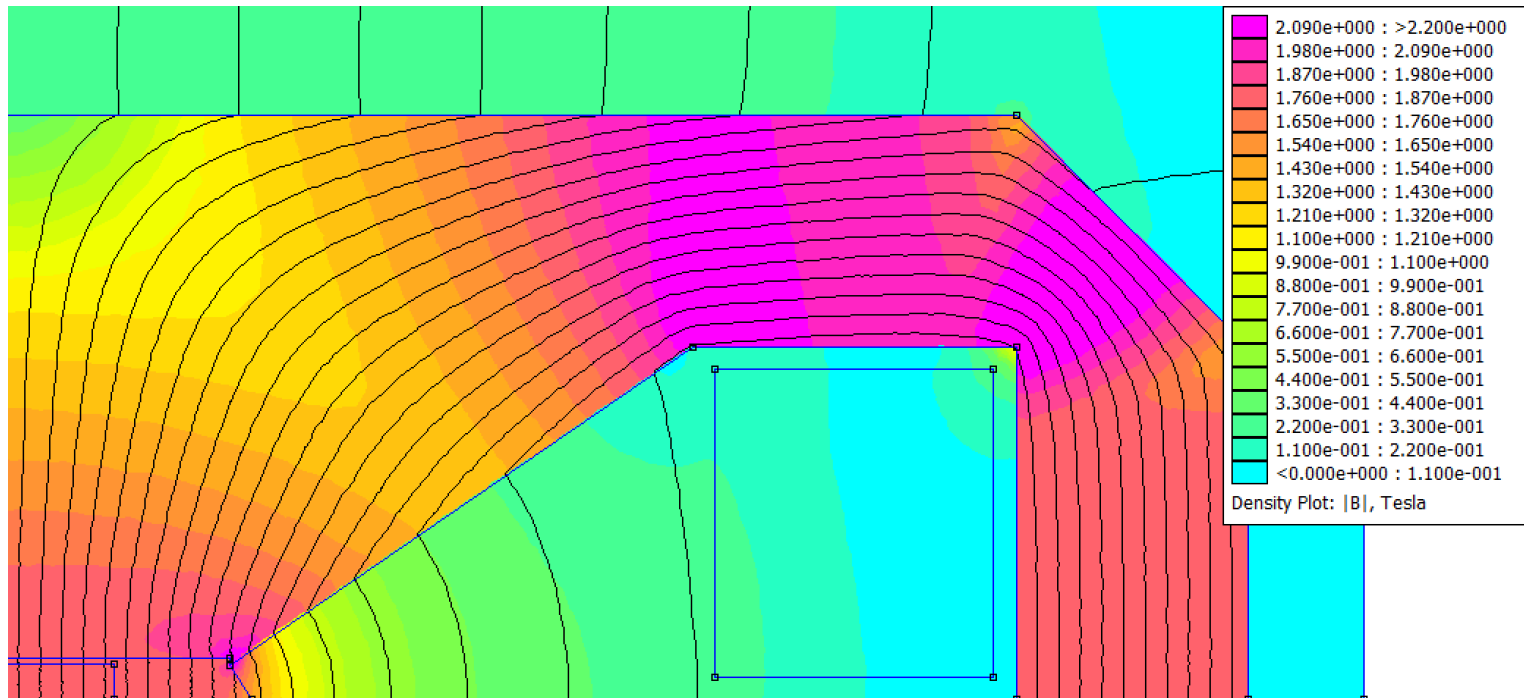
Field quality Field direction Field strength Yoke saturation Magnetic energy Current density

T. Head et al., *scikit-optimize: Sequential model-based optimization in Python*, 2018. <https://scikit-optimize.github.io/>

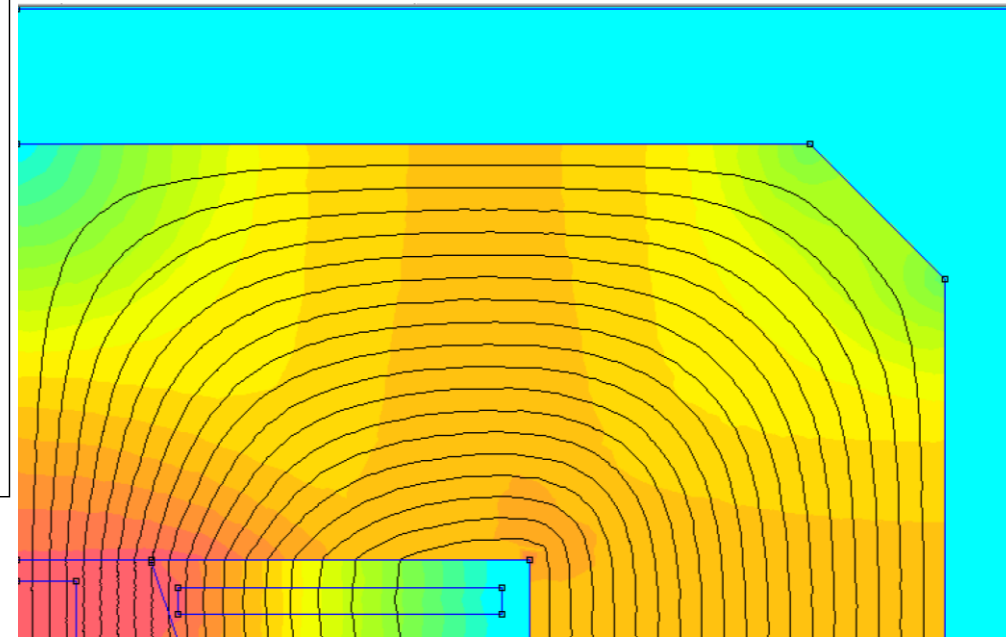
Dipole Magnet - Results

Failed optimisations

- Weights and forms of the penalties had to be constantly adjusted
- Input parameters and search ranges had to be altered



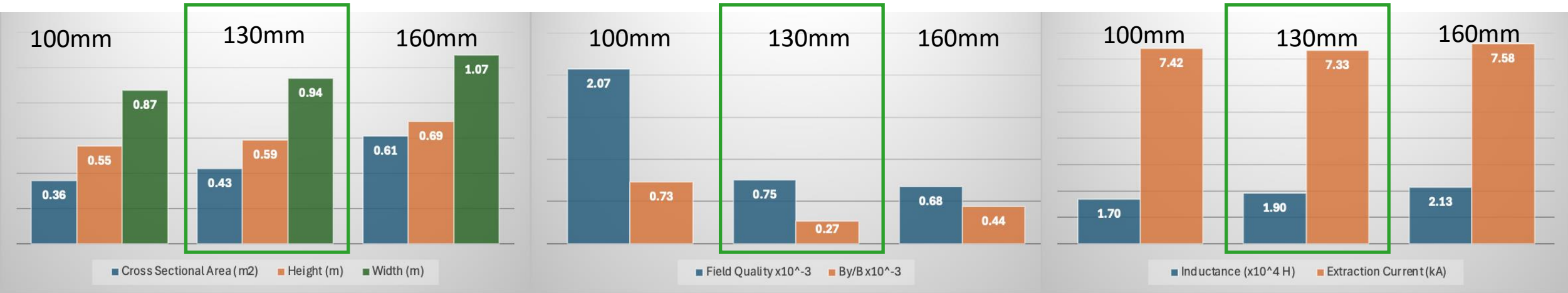
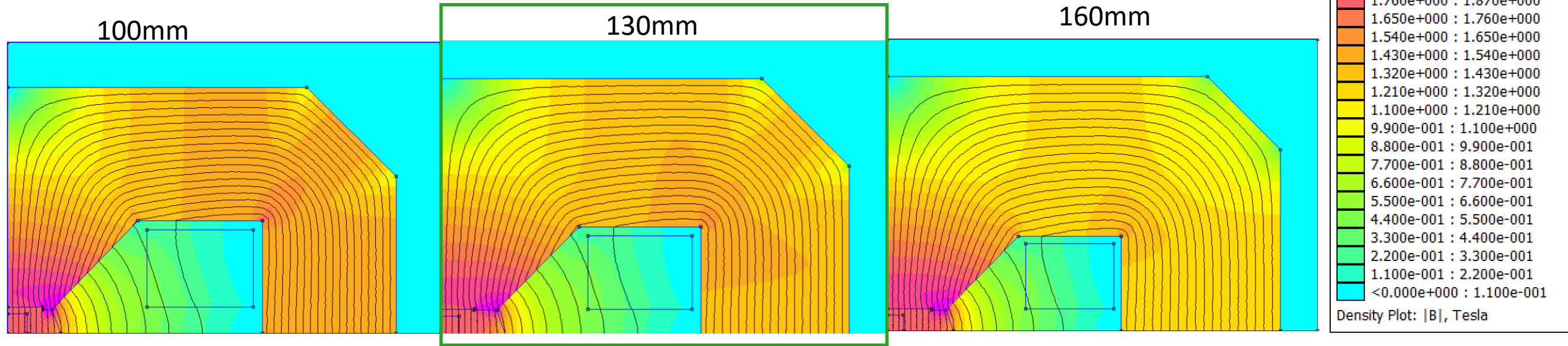
Yoke oversaturation penalty too low



No penalty for current density

Dipole Magnet – Results

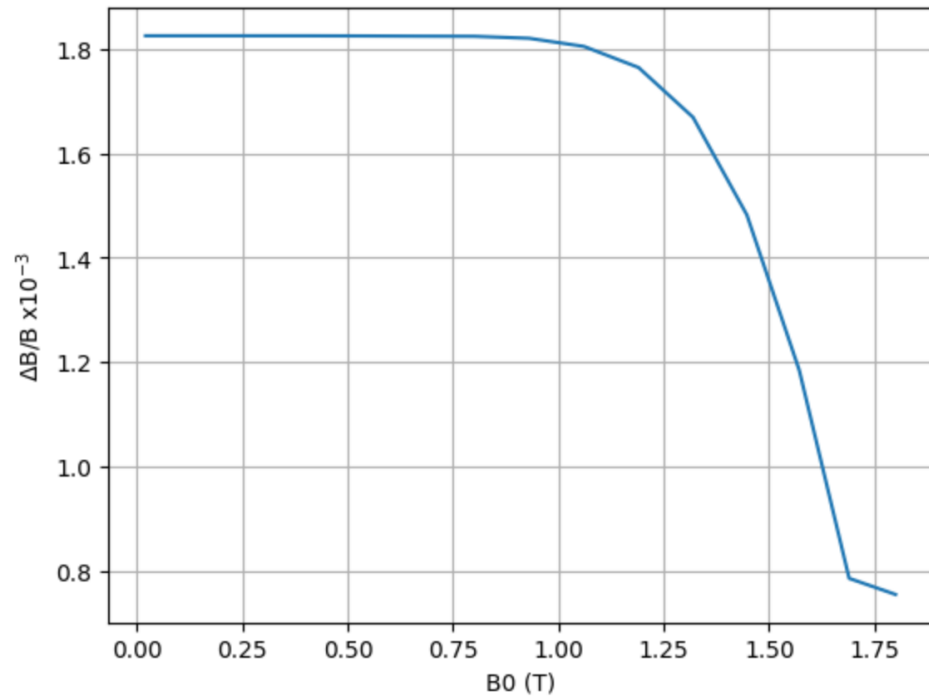
Optimisation outcomes with new GFR specification with various Pole Widths



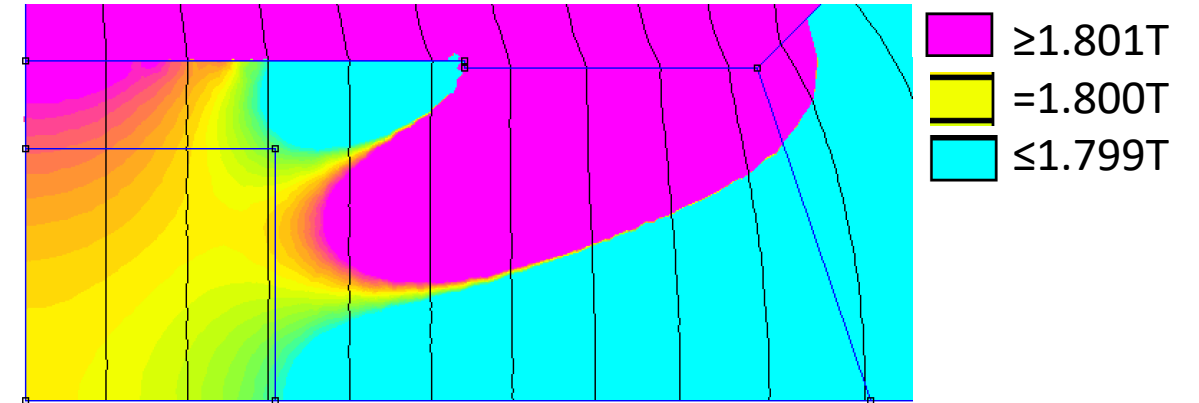
Dipole Magnet

Ramping considerations

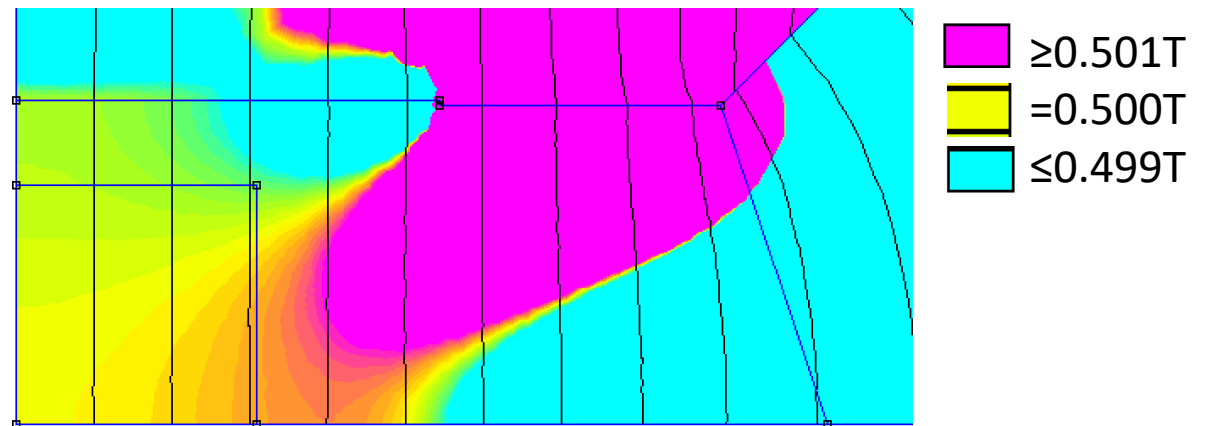
Using optimal 130mm design



Field quality worsens at lower B-Fields



At B = 1.800T



At B = 0.500T

Dipole Magnet

Conclusions

- Optimisation process developed for dipole magnet
- Optimal parameters found at various pole widths for H-shaped dipole with tapered pole
- Best parameters found for 130mm pole width with:
 - Field strength of 1.8T
 - Field quality $\frac{\Delta B}{B} \approx 10^{-3}$ over the good field region.
 - Minimised Magnetic field energy

Future work

- Add penalty for non-constant field quality at lower B-fields
- Explore different yoke and pole geometries (Hourglass topology)
- Dynamic analysis with power requirements

Quadrupole

Design Parameters

Muon Collider annual meeting*

- Field Gradient of approx. 30[T/m]
- Field homogeneity of at least 10^{-3}
- Ramp times of about 1[ms]
- Aperture size 40[mm]

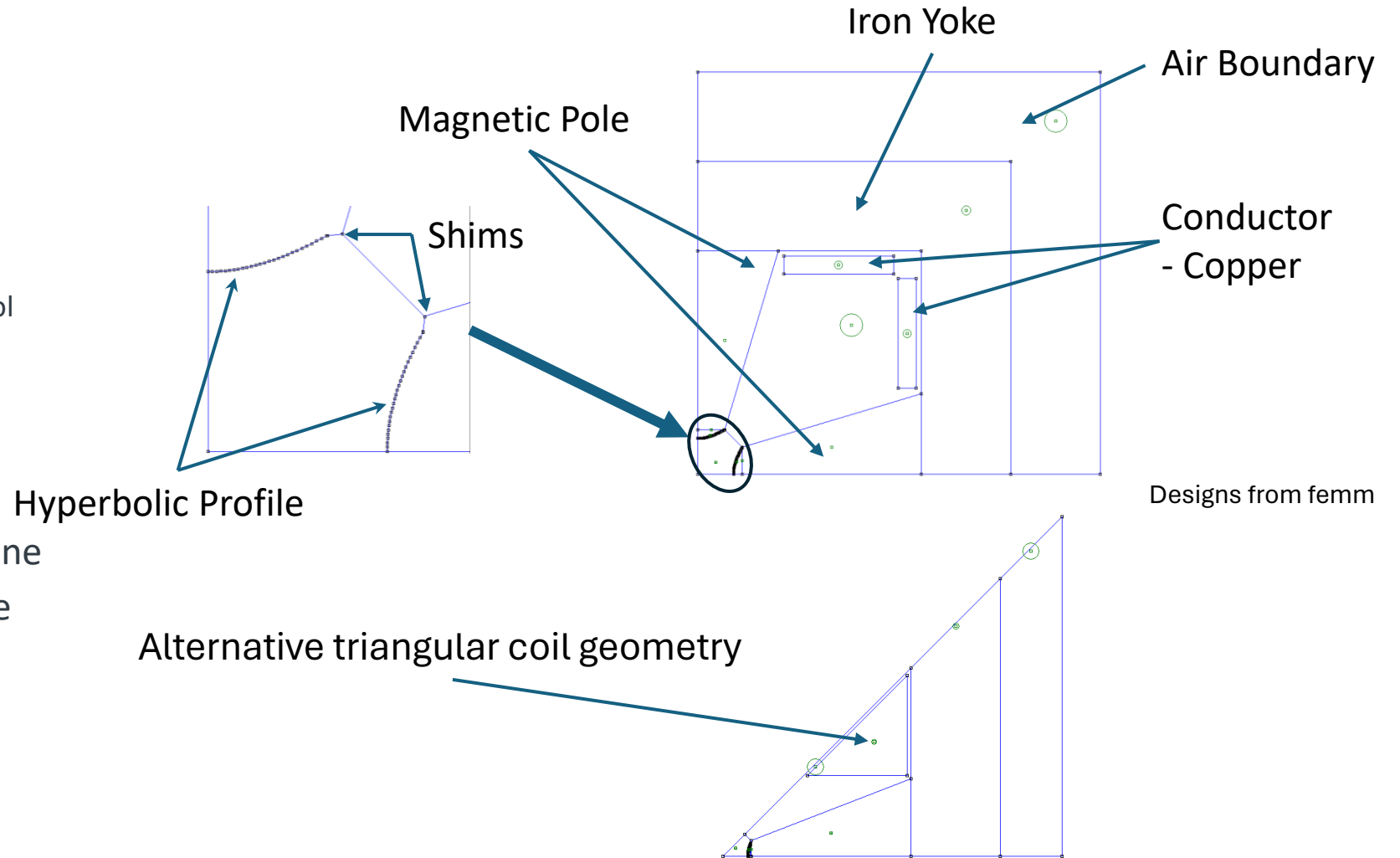
- Lattice team 2σ beam size – 45[mm]

*Breschi, M., A. Macchiagodena, P. L. Ribani, et al. NC Magnet Configuration (Dipoles and Quadrupoles). IMCC and MuCol Annual Meeting, 13 May 2025.
<https://indico.desy.de/event/45968/contributions/186232/>

Quadrupole

Configuration

- MAP Configuration
 - Based on a design at MuCol annual meeting*
- Built in Python
- 7 Varying parameters define whole geometry (e.g. pole width, nose width, yoke width)



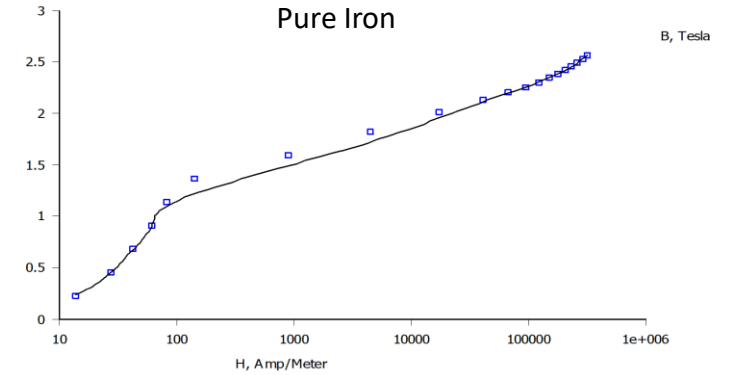
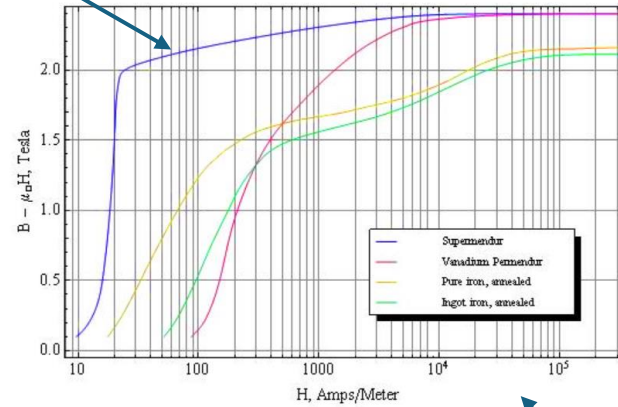
*Breschi, M., A. Macchiagodena, P. L. Ribani, et al. NC Magnet Configuration (Dipoles and Quadrupoles). IMCC and MuCol Annual Meeting, 13 May 2025.
<https://indico.desy.de/event/45968/contributions/186232/>

Quadrupole

Design Considerations

- Good field region
 - $\frac{2}{3} \cdot$ aperture size (r)
- Gradient = G [T/m]
- Pole tip field = Gr
 - $40[\text{mm}] \rightarrow 30 \cdot 40 \cdot 10^{-3} = 1.2[\text{T}]$
 - 2σ beam width = $45[\text{mm}]$
 - $r = \frac{3}{2} \cdot 45 = 67.5[\text{mm}] \rightarrow 30 \cdot 67.5 \cdot 10^{-3} = 2.03[\text{T}]$
- Use Supermendur for magnetic poles
 - 49% cobalt
 - 49% iron
 - 2% vanadium

Supermendur*



Possible pole saturation

Choose a higher saturation material for Poles

Saturation!

*'DC Magnetization Curves of Soft Magnetic Materials: Finite Element Method Magnetics'. Accessed 8 March 2026. <https://www.femm.info/wiki/SoftMagneticMaterials>.

Quadrupole

Multi Objective Bayesian Optimisation with Optimas^[*, **]

5 Objectives

1. Maximise field gradient [T/m]

- Maximise Quadrupole Coefficient from multipole expansion over radius of measurement - $\frac{B_2}{R_{ref}}$

2. Maximise field homogeneity

- Minimise the largest higher multipole harmonic coefficient relative to the quadrupole coefficient - $\max \left| \frac{B_n}{B_2} \right|$

3. Minimise total magnetic energy[J/m]

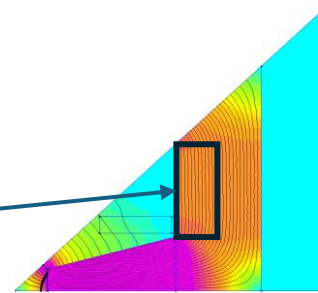
- Calculated by Femm

4. Minimise average yoke density [T] to 1.4[T]

- Average over shown region of yoke

5. Minimise Current Density [A/mm²] to 8[A/mm²]

- Measured with area of coil $\times 0.6$ to account for cooling etc



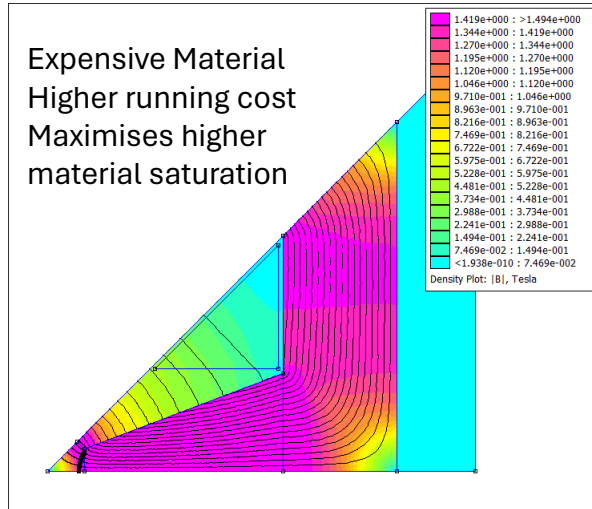
*Ferran Pousa, A., S. Jalaš, M. Kirchen, et al. 'Bayesian Optimization of Laser-Plasma Accelerators Assisted by Reduced Physical Models'. Physical Review Accelerators and Beams 26, no. 8 (2023): 084601. <https://doi.org/10.1103/PhysRevAccelBeams.26.084601>.

**Hudson, Stephen, Jeffrey Larson, John-Luke Navarro, and Stefan M. Wild. 'libEnsemble: A Library to Coordinate the Concurrent Evaluation of Dynamic Ensembles of Calculations'. IEEE Transactions on Parallel and Distributed Systems 33, no. 4 (2022): 977–88. <https://doi.org/10.1109/TPDS.2021.3082815>.

Quadrupole 40mm Aperture Design

Supermendur poles max gradient

Expensive Material
Higher running cost
Maximises higher material saturation

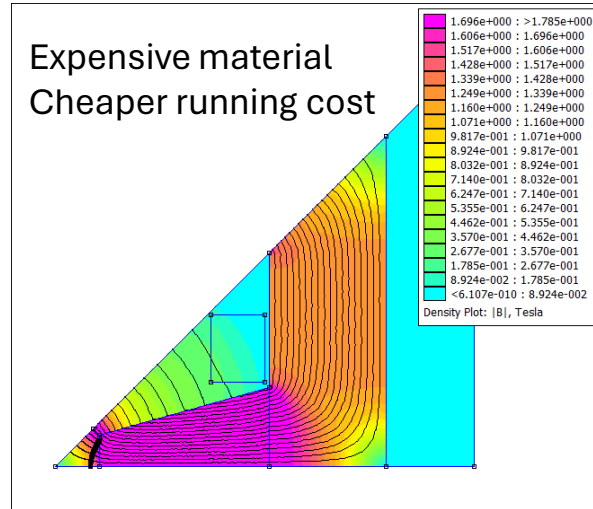


Objective	Value
Field Gradient [T/m]	35.1
Field Homogeneity[$10^{\wedge}x$]	-3.37
Total Magnetic Energy [J/m]	2324
Yoke Density [T]	1.42
Current Density [A/mm ²]	3.41

Parameter	Value	Parameter	Value
yw [mm]	144.7 ss		0.125
nw [mm]	57.2 sg		5.58
pw [mm]	249.1 mpf [T]		1.49
cw [mm]	156 NI [A]		24989
x [mm]	886.8		

Supermendur poles 30 [T/m]

Expensive material
Cheaper running cost

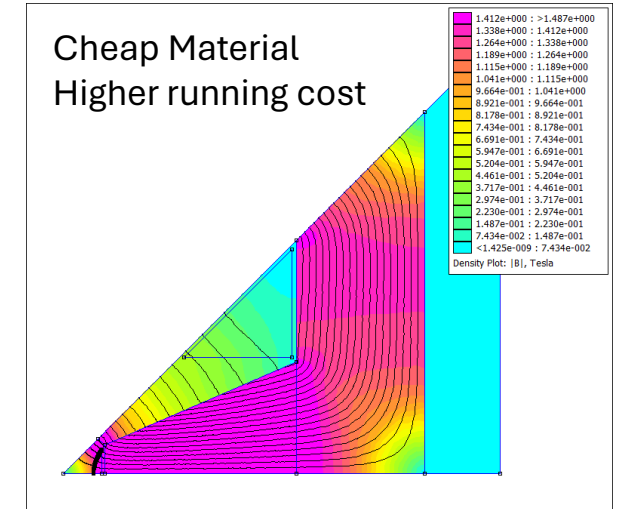


Objective	Value
Field Gradient [T/m]	30.9
Field Homogeneity[$10^{\wedge}x$]	-3.33
Total Magnetic Energy [J/m]	1703
Yoke Density [T]	1.33
Current Density [A/mm ²]	7.6

Parameter	Value	Parameter	Value
yw [mm]	132 ss		0.1498
nw [mm]	72.49 sg		10
pw [mm]	180.2 mpf [T]		1.241
cw [mm]	60 NI [A]		20786
x [mm]	750		

Iron Poles 30 [T/m]

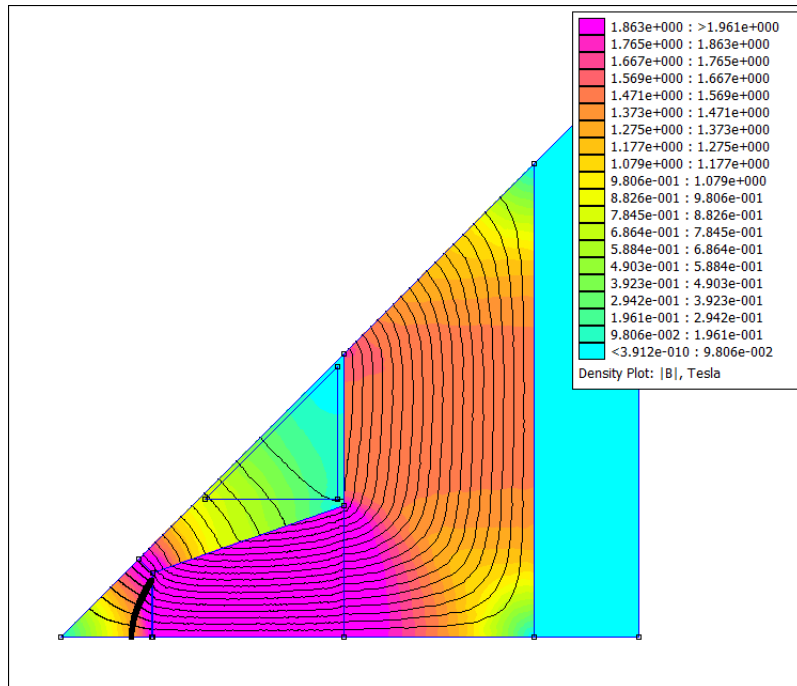
Cheap Material
Higher running cost



Objective	Value
Field Gradient [T/m]	30.1
Field Homogeneity[$10^{\wedge}x$]	-3.67
Total Magnetic Energy [J/m]	2496
Yoke Density [T]	1.27
Current Density [A/mm ²]	4.16

Parameter	Value	Parameter	Value
yw [mm]	171.5 ss		0.142
nw [mm]	76.3 sg		1
pw [mm]	297.2 mpf [T]		1.57
cw [mm]	145 NI [A]		26135
x [mm]	965.5		

Quadrupole 67.5 mm Aperture Design



Objective	Value
Field Gradient [T/m]	19.5
Field Homogeneity [$10^4 \times$]	-3.73
Total Magnetic Energy [J/m]	4800
Yoke Density [T]	1.46
Current Density [A/mm ²]	8.27

Parameter	Value
yw [mm]	191
nw [mm]	123
pw [mm]	250
cw [mm]	126
x [mm]	920.6
ss	0.0951
sg	5.516
mpf [T]	1.4
NI [A]	39579

- Larger aperture size not able to reach target gradient
- Approx. twice magnetic energy
- Almost twice the current turns compared to 40mm
- This is the trade off for a larger aperture

Quadrupole

Post Analysis – Fitting Magnets into Lattice

- Peak Beam Rigidity $\approx 1000[\text{Tm}]$
- Lattice design magnet lengths $\approx 1.89[\text{m}]$
- Lattice peak specified $k_1 \approx 0.0502$

$$k_1 = \frac{G}{B\rho}$$

Lattice Specifying 50[T/m] gradients!

3.38T pole tip field at 67.5mm aperture

$$\frac{1}{f} = k \cdot l \approx 0.09476[\text{m}^{-1}] \rightarrow f \approx 10.5\text{m}$$

Best parameters for apertures:

- 40mm
 - $G=30.9[\text{T/m}]$
 - $k_1 = 0.0309[\text{m}^{-2}]$
 - $L = 3.06[\text{m}]$
 - 67.5mm
 - $G=19.5[\text{T/m}]$
 - $k_1 = 0.0195[\text{m}^{-2}]$
 - $L = 4.85[\text{m}]$
- Magnet Length
-

Quadrupole

Conclusion

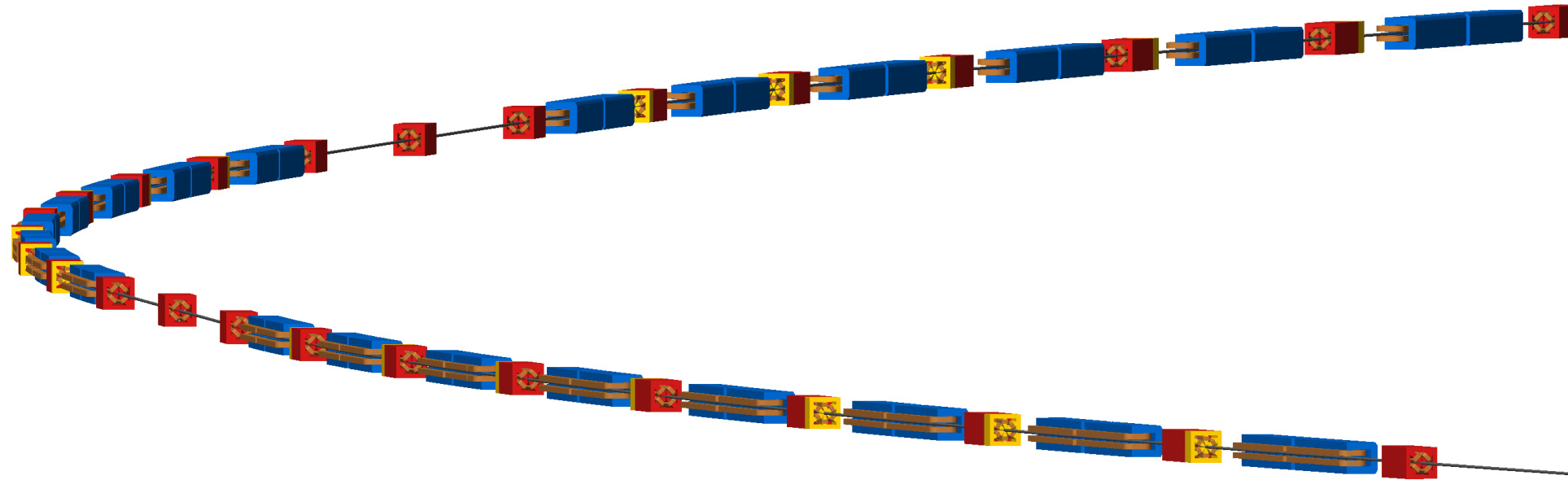
- Developed a Python generated quadrupole geometry
- Optimised quadrupole parameters
 - Achieved 30[T/m] at 40[mm] Aperture
 - Achieved 19.5[T/m] at 67.5[mm] Aperture
 - Achieved field homogeneity to $< 10^{-3}$

Next Steps

- Full parameter and objective space to be further explored
 - More iterations required for convergence
- Consideration of the ramping effect – AC magnet problem
- Consider alternative geometries
 - minimising airgap inside magnet – alternate coil geometry
 - Chamfer corner of Yoke – reduce B field density bunching at corners

RF Cavity Design

*F. Straniero
A. Yousif*



Why Superconducting Elliptical Cavities?

Advantages

- High gradient is necessary to quickly accelerate muons.
- Well established technology, so no need for much R&D.
- Lower breakdown rate, compared to normal-conducting.

Disadvantages

- Much higher energetic cost, due to higher currents and refrigeration.
- Require extra-space for cryomodule.



Experimental Investigations on Superconducting Niobium Cavities at Highest Radiofrequency Fields, L. Lilje et al,
https://www.researchgate.net/publication/48409802_Experimental_Investigations_on_Superconducting_Niobium_Cavities_at_Highest_Radiofrequency_Fields

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Disadvantages

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- Require extra-space for cryomodule.

Frequency (MHz)	Bore radius (cm)	Length cell(cm)	Previous designs:	Notes
352	8.52	37.474	LEP*	The cavities would be quite long and large, requiring much refrigeration and space in linear sections
1300	3.5	11.530	TESLA, ILC**	The aperture radius is smaller than 352, hence need a very narrow beam.

*A superconducting 352MHz Prototype cavity for LEP, G. Arnold-Mayer et al., <https://cds.cern.ch/record/878555/files/cer-002551711.pdf>

**The superconducting TESLA cavity, B. Aune et al., <https://cds.cern.ch/record/429906/files/0003011.pdf>

How Much Accelerating Field Do We Need?

- From lattice group: RF cavities distributed along the ring (683 cavities in 6km).
- Need to go from 63GeV to 313.6GeV in 17 turns.
- Each cavity is 1.038m (in the accelerating part) \rightarrow 708.95m of accelerating sections.
- $\langle E_{acc} \rangle = \frac{(313.6-63)GeV}{(17 \times 708.95m \times e)} = 20.79 \text{ MV/m}$ (this is considerable).
- Transit time factor $T = \frac{\int (E(0,z) \cos(kz) dz)}{\int (E(0,z) dz)}$ and $\langle E_{real} \rangle = \langle E_{acc} \rangle / T$
- In Superfish $\langle E_{real} \rangle = E_0$

Superfish vs CST Solvers

Superfish

- 2D solver*
- Finite differences method.
- Optimizes geometry.
- Iteratively directly solves the linearized matrix problem.
- Uses hexagonal 2D meshing.

CST

- 3D solver**
- Finite elements method.
- Does not optimize geometry.
- Solves the eigenvalue problem through Advanced Krylov subspace method.
- Tetrahedral mesh.

*SUPERFISH-A COMPUTER PROGRAM FOR EVALUATION OF RF CAVITIES WITH CYLINDRICAL SYMMETRY, K.Halbach, R.F. Holsinger, Particle Accelerators 1976, Vol. 6, pp 213-222

** <https://www.3ds.com/products/simulia/cst-studio-suite/electromagnetic-simulation-solvers> (last accessed 10/03/2026)

Why 1.3 GHz?

Upsides:

- 1.3GHz cavities are a mature, well-established technology, which has been already modelled and tested for the TESLA cavities and for ILC*.
- Superconducting 1.3GHz cavities allow us to reach some of the highest gradients attainable, which is a strong-requirement in the muon collider, given the muons short lifetime.
- 1.3 GHz cavities require smaller cryomodules, as a rule of thumb the cavity resonant frequency scales with the inverse of the cavity diameter.

Downside:

- Their compactness results in a smaller bore radius, currently set at 35mm. From lattice group the beam size is 45mm at 2σ , hence a good proportions of particles will be lost per cavity.

*The superconducting TESLA cavity, B. Aune et al., <https://cds.cern.ch/record/429906/files/0003011.pdf>

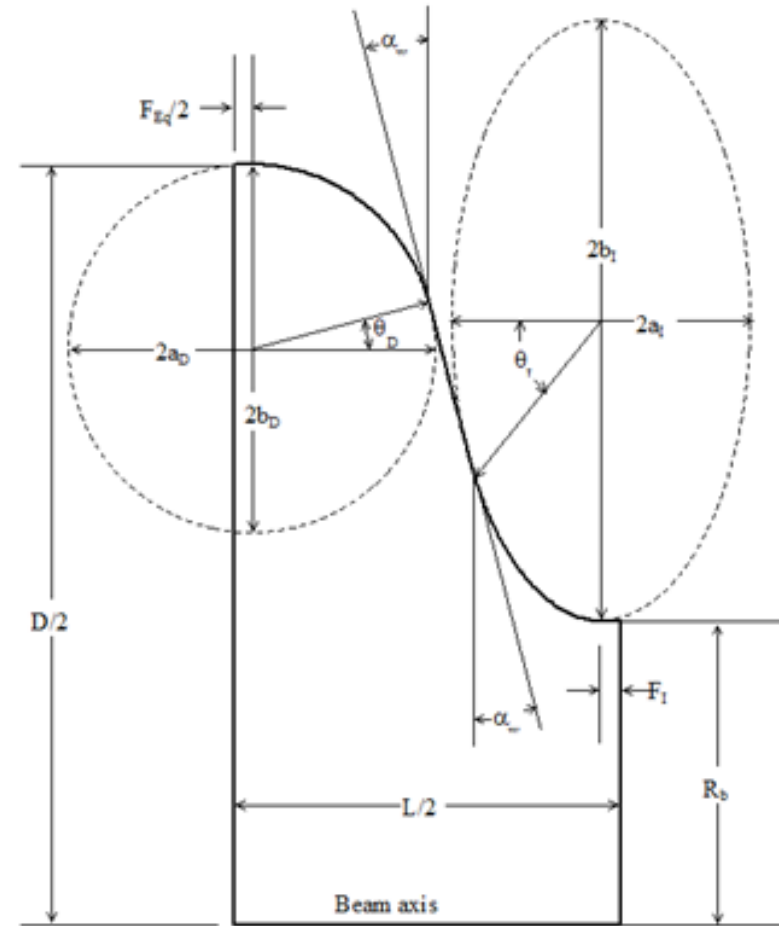
Cavity Geometry – 9 Identical Cells (Except Endcups)

End-cup

- $D/2 = 109.250\text{mm}$
- $B_{\text{dome}} = 15.480\text{mm}$
- $A_{\text{dome}} = 18.576\text{mm}$
- $R_{\text{bore}} = 35.000\text{mm}$
- $B_{\text{iris}} = 77.657\text{mm}$
- $A_{\text{iris}} = 38.829\text{mm}$
- $L/2 = 57.652\text{ mm}$

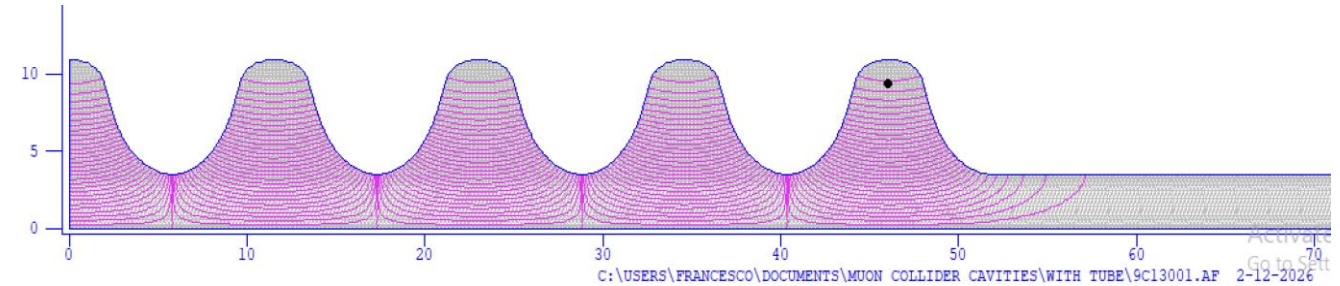
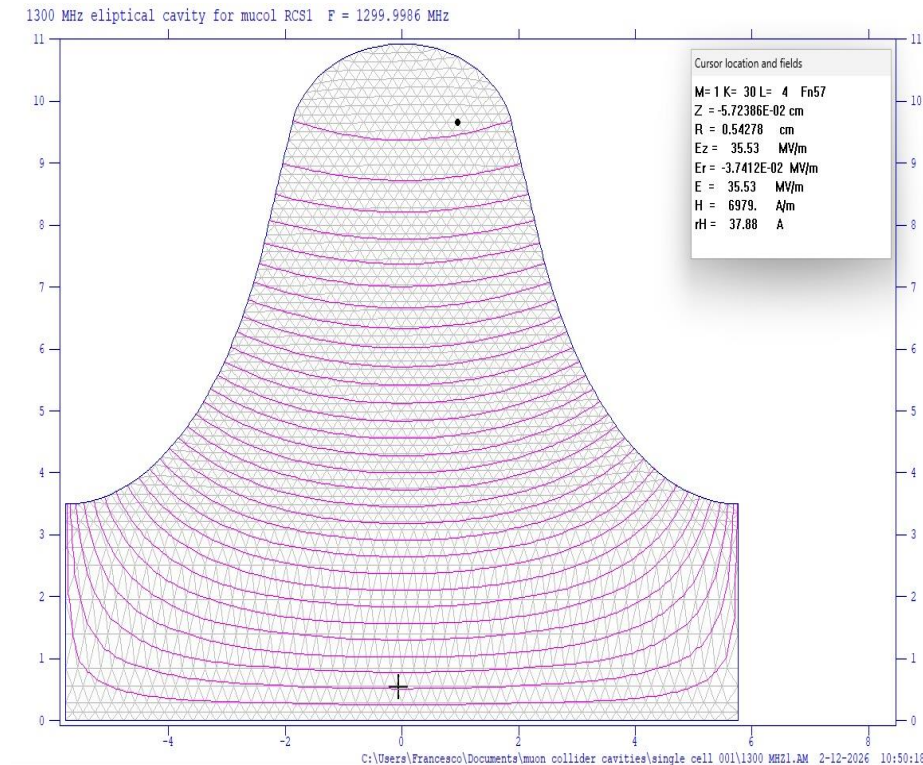
Middle-cup

- $D/2 = 109.250\text{mm}$
- $B_{\text{dome}} = 16.000\text{mm}$
- $A_{\text{dome}} = 19.200\text{mm}$
- $R_{\text{bore}} = 35.000\text{mm}$
- $B_{\text{iris}} = 76.017\text{cm}$
- $A_{\text{iris}} = 38.009\text{mm}$
- $L/2 = 57.652\text{ mm}$



A Design for a 3 TeV Rapid Cycling Synchrotron for Muon Acceleration in the SPS Tunnel. T. Dasalu et al. https://cds.cern.ch/record/2723310/files/JA1%20Muon_RCS.pdf

Superfish Design



Figures of merit:

$$r/Q = 433.455 \text{ Ohm} \quad F = 1300.0015 \text{ MHz}$$

$$Q = 0.728042 \text{E}+10. \quad \text{Shunt Impedance} = 1.055 \text{e}7 \text{ Ohm}$$

$$\text{Maximum H (at Z,R = 0.0,8.92828)} = 94926.5 \text{ A/m,}$$

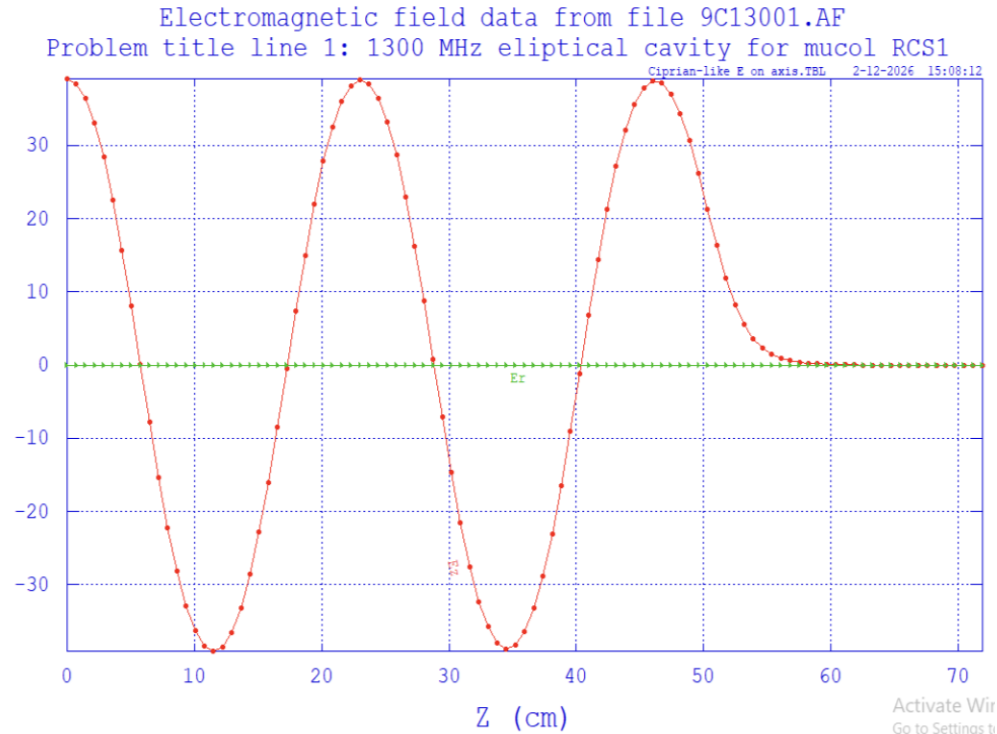
$$\text{Maximum E (at Z,R = 0.0,0.565685)} = 39.0705 \text{ MV/m}$$

$$\text{Ratio of peak fields } B_{\text{max}}/E_{\text{max}} = 3.0531 \text{ mT}/(\text{MV/m})$$

$$\text{Peak-to-average ratio } E_{\text{max}}/E_0 = 1.5077$$

$$\text{Transit-time factor} = 0.7592616$$

Superfish Design



Field properties

- Transit time = 0.7593
- $E_0 = 27.38 \text{ MV/m}$
- $E_{\text{peak}} = 40.44 \text{ MV/m}$

Figures of merit:

$r/Q = 433.455 \text{ Ohm}$

$F = 1300.0015 \text{ MHz}$

$Q = 0.728042 \text{ E}+10$

Shunt Impedance = $1.055 \text{ e}7 \text{ Ohm}$

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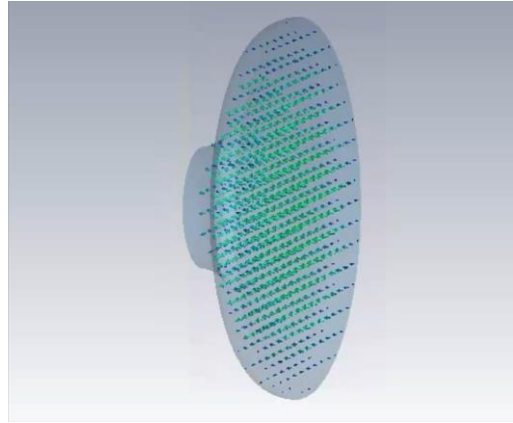
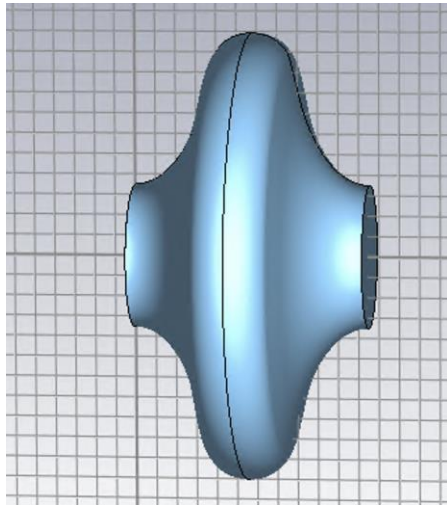
Ratio of peak fields $B_{\text{max}}/E_{\text{max}} = 3.0531 \text{ mT}/(\text{MV/m})$

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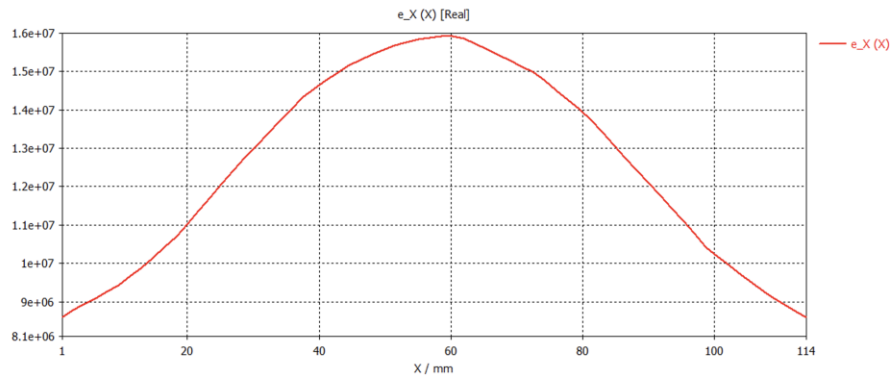
Transit-time factor = 0.7592616

CST Designs

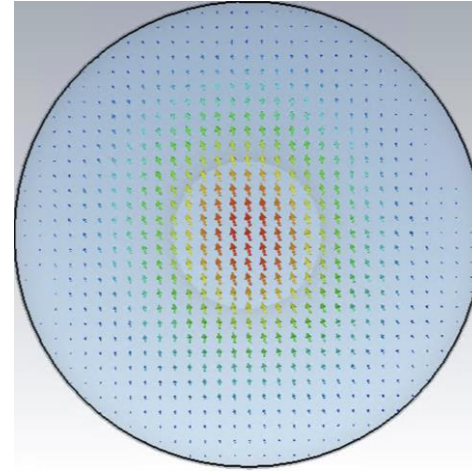
Single cell designs



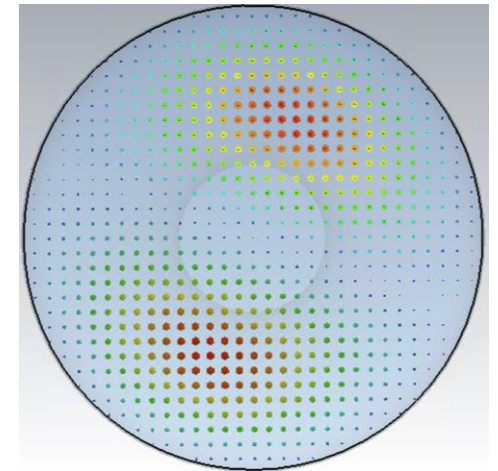
TM010 mode and on axis field



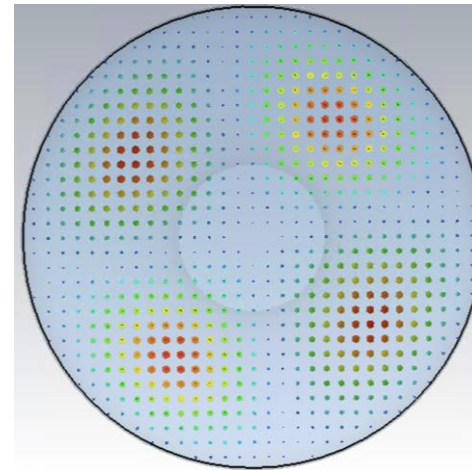
HOM were also observed, far enough from TM01



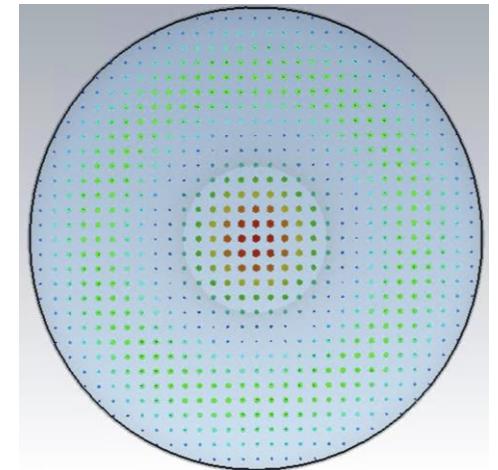
TE11 – 2.042GHz



TM11 – 1.778GHz

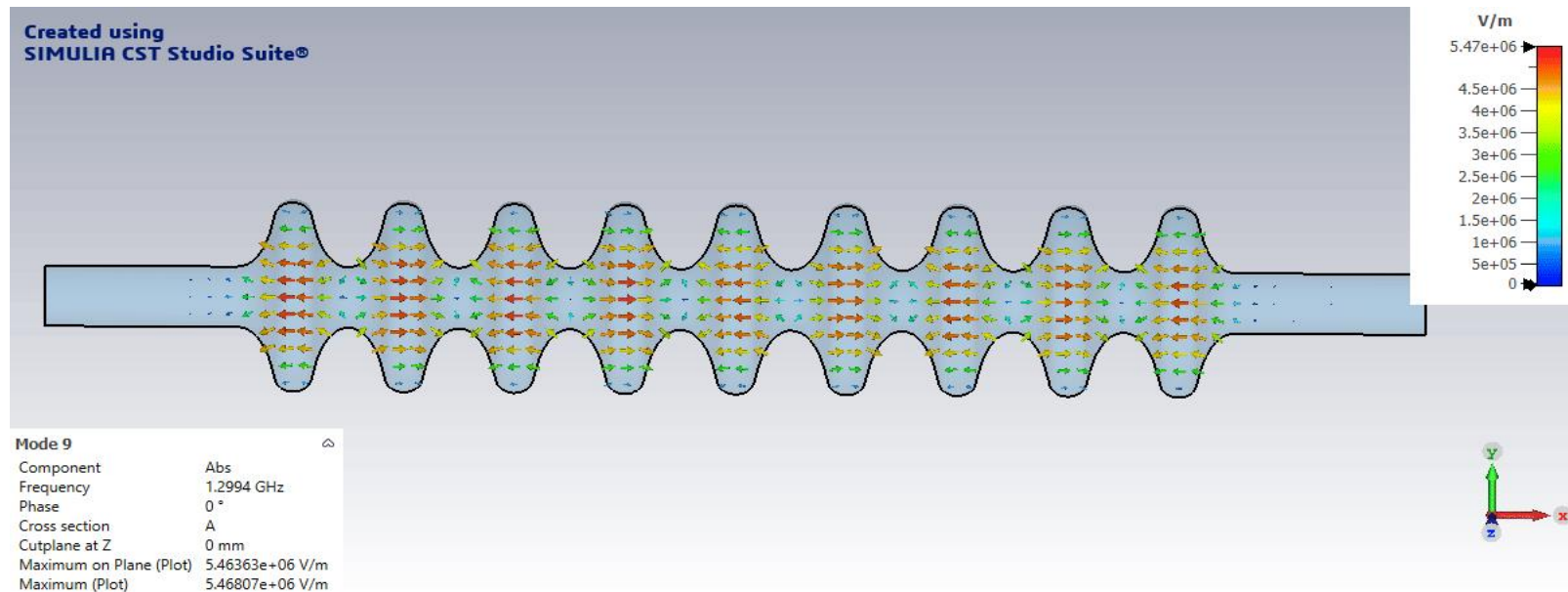
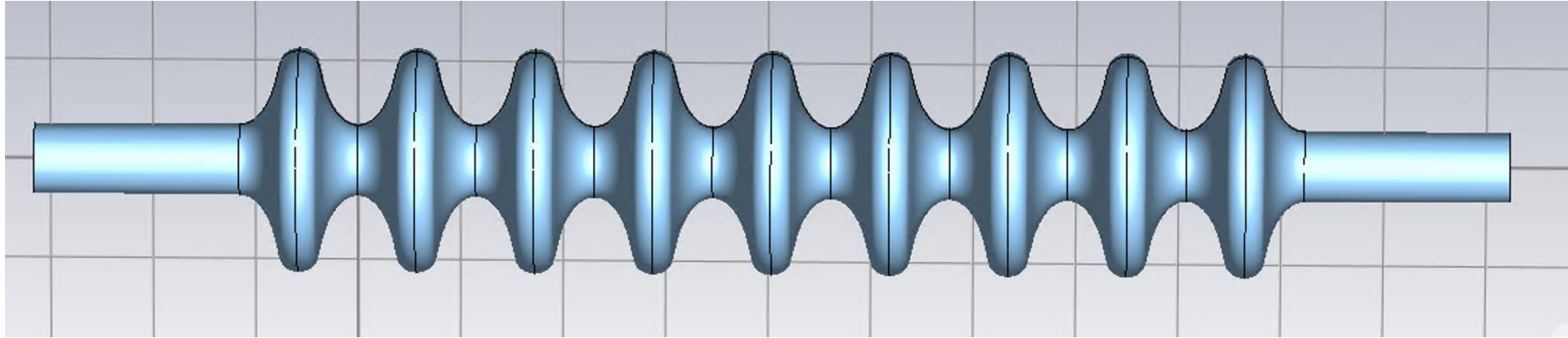


TM – 2.325 GHz



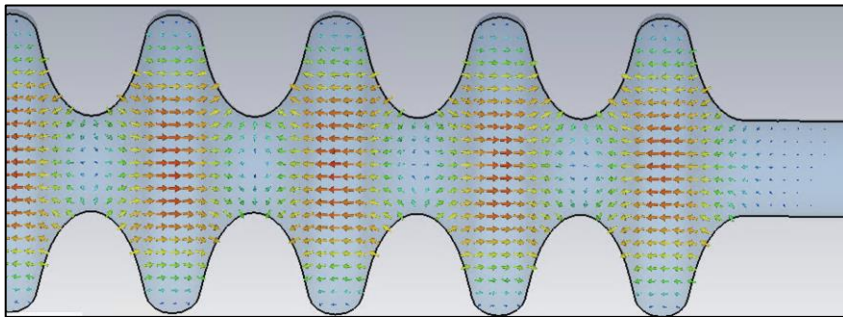
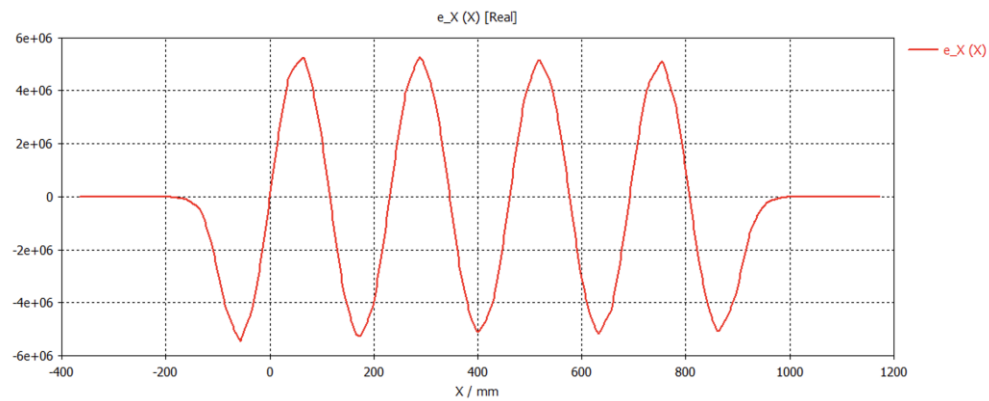
TM – 2.5234 GHz

9 Cell 3D Design – 1299.4 MHz

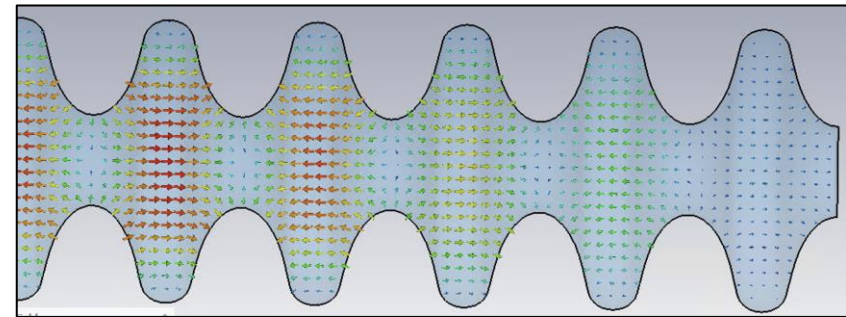
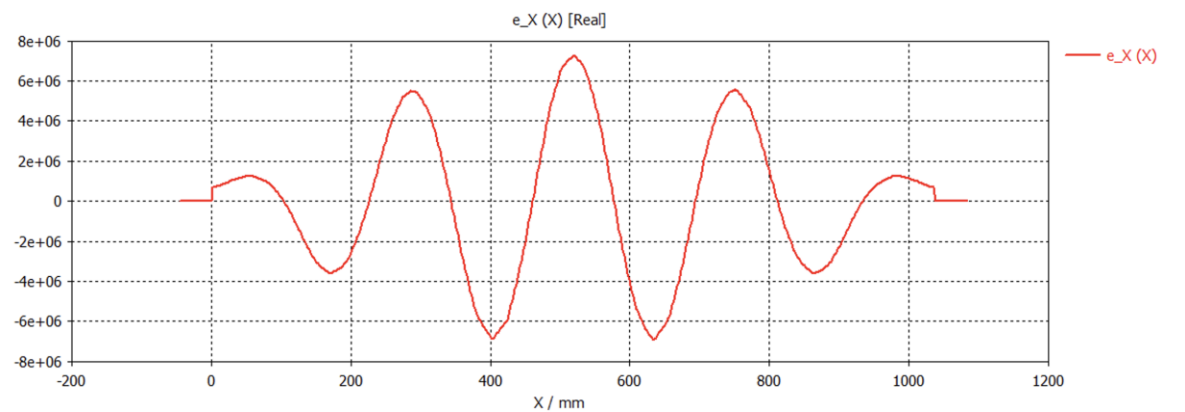


Simulating Right Endcup and Beampipe is Important

Field with beampipe and optimized endcup:

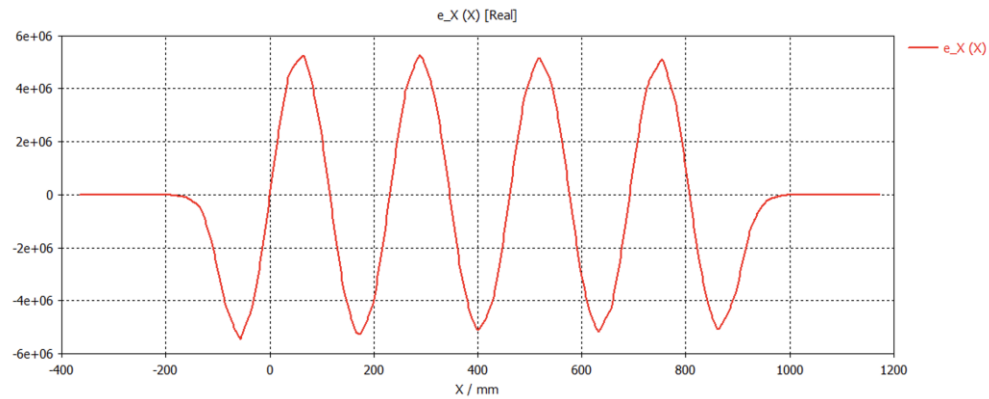


Field without beampipe and no endcup:

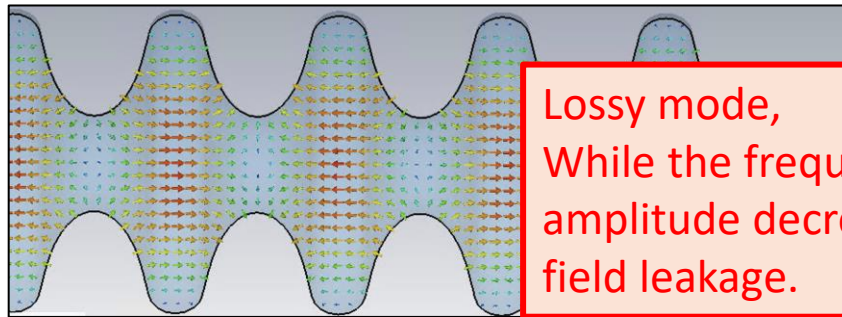
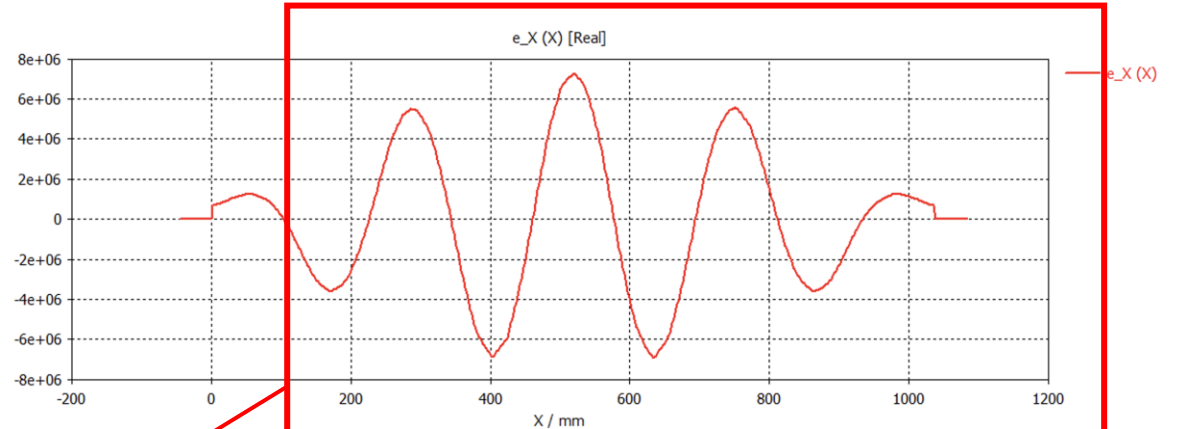


Simulating Right Endcup and Beampipe is Important

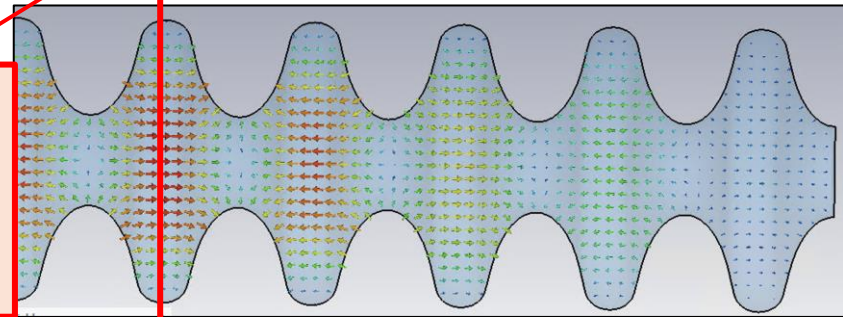
Field with beampipe and optimized endcup:



Field without beampipe and no endcup:

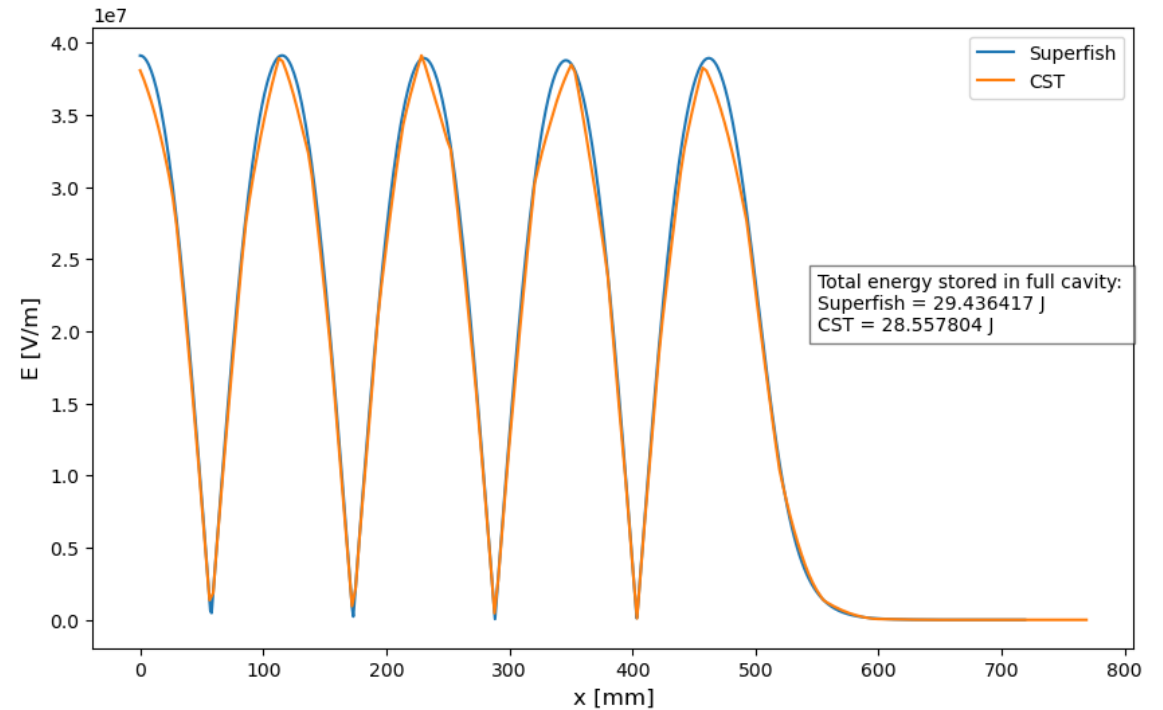


Lossy mode,
While the frequency is right, the
amplitude decreases, showing
field leakage.



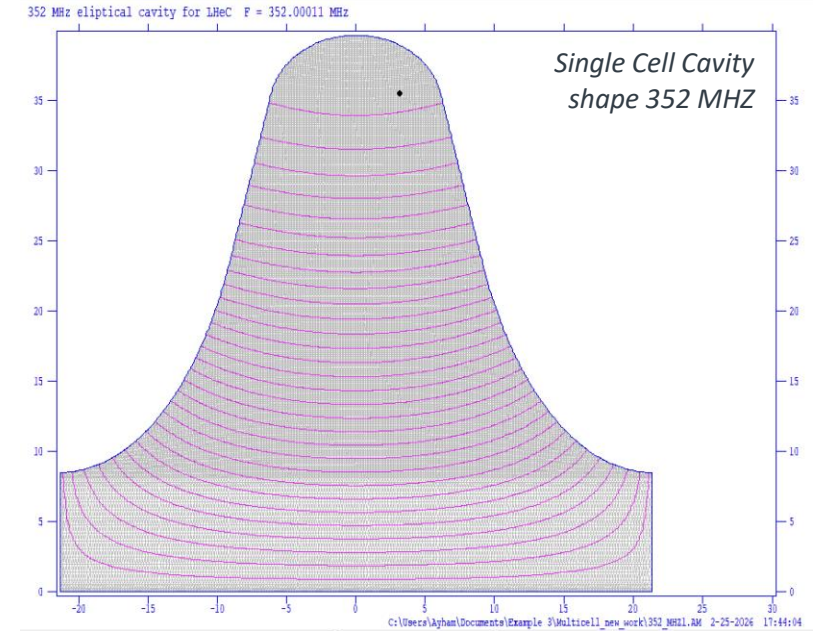
Some Discrepancies Between Field Properties:

Figure	Superfish	CST
Frequency (GHz)	1.3000	1.2994
Shunt Impedance (M Ω)	1.055e7	1.756e7
R/Q (Ω)	433.455	865.101
Peak field/E0	1.5077	2.3994

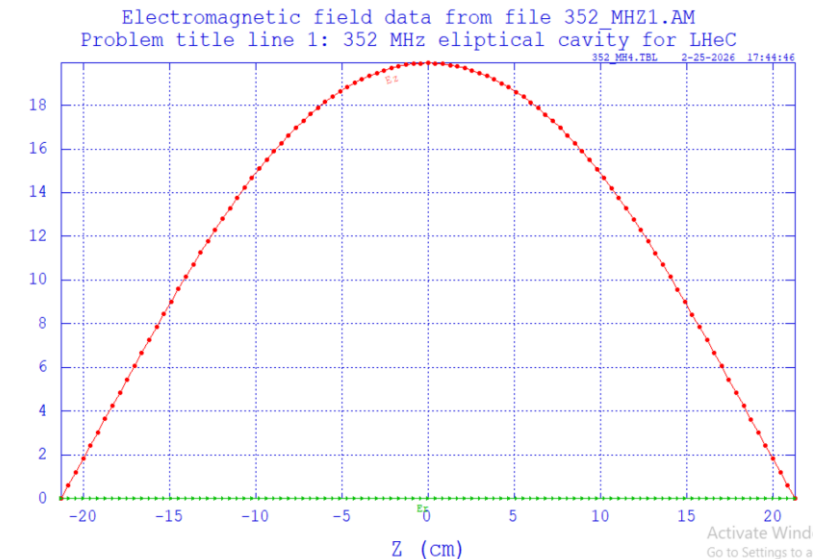


352 MHz Superfish

- We started by existing designs that are relatively close in resonant frequency values to our required values of: 352 MHz.
- List of tuneable parameters:
 - Frequency
 - Diameter
 - DOME_B
 - LEFT_DOME_B
 - RIGHT_DOME_B
 - DOME_A/B
 - LEFT_DOME_A/B
 - RIGHT_DOME_A/B
 - WALL_Angle
 - LEFT_Wall_angle
 - RIGHT_Wall_angle
 - RIGHT_BEAM_tube
 - BORE_radius
- By employing the general relation:
$$\text{frequency} \propto 1/\text{radius}$$
- Tuned the bore radius and cavity diameter.

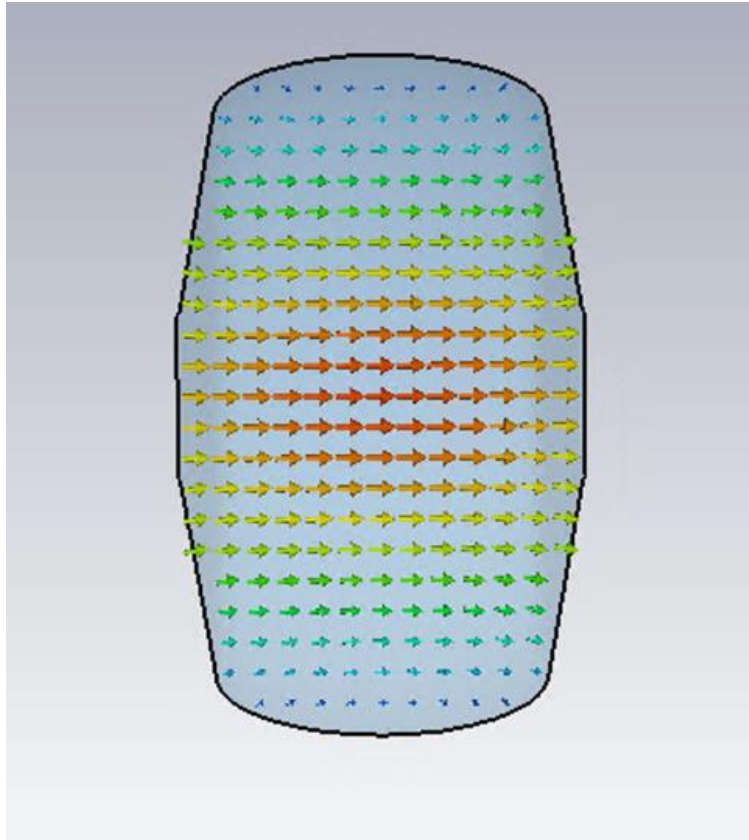


*E-field within Cavity
352 MHz*

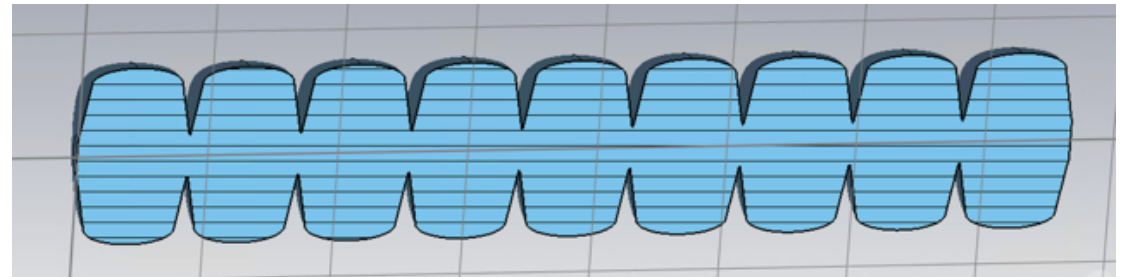
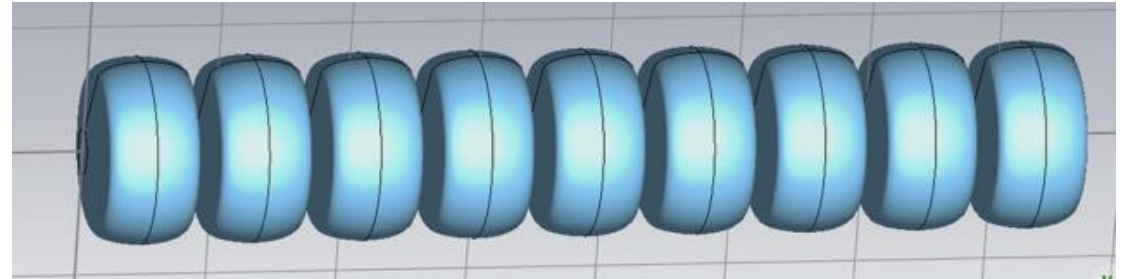


352 MHz CST Design

Single Cell Design



Multicell Design



RF Cavities

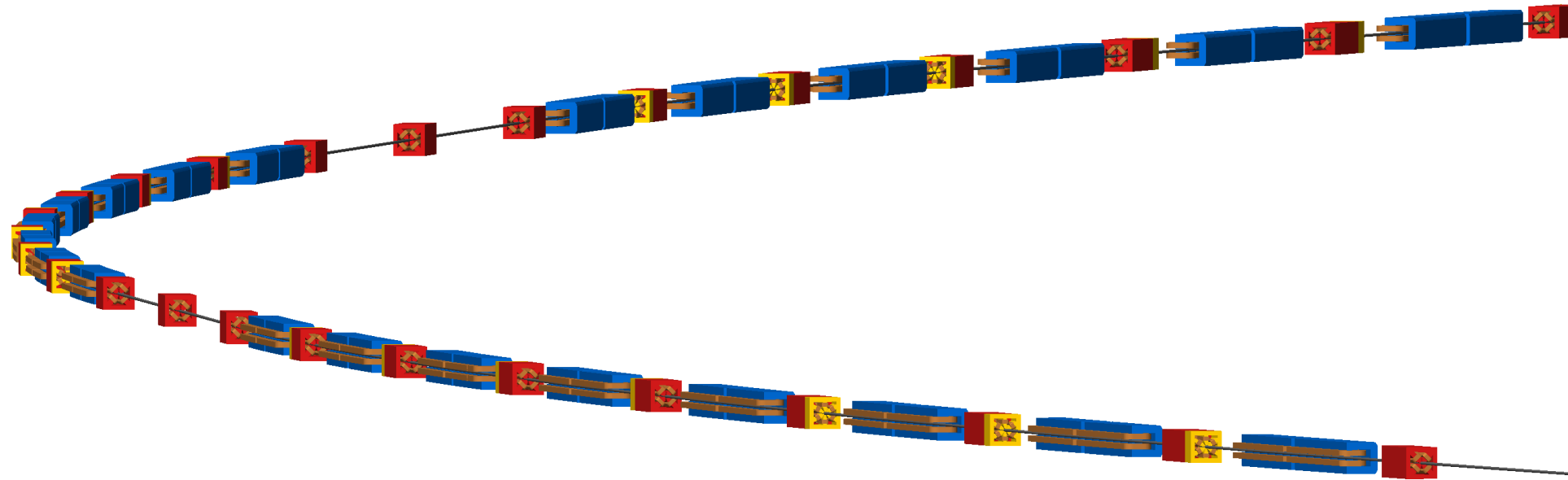
Conclusions

- Both 352MHz and 1300MHz cavities were investigated, with 2D optimization and 3D design to confirm the results. More realistic models with extra beampipe were studied as well.
- Cavities would reach the required gradient to rapidly accelerate muons over 17 turns.
- The ideal cavity, given spatial constraints and previous work, would be the 1300MHz one.

Further Work

- Cryomodule design and study of packing factor for multicell cavities.
- Feasibility study to reuse SPS tunnel, given cryomodule size.
- Study of parasitic higher order modes, which could damage the beam.
- Design of klystron and waveguides complex.
- Further studies on how to reduce environmental impact of RF.

ESG Considerations



Environmental and Social Considerations

- Like any other large experimental project, we must consider the environmental and social impact of a project like the muon collider.
- Capex costs: building new infrastructure, new tunnels, new beamlines, new magnets and RF cavities. Advantages: could reuse already built tunnels (eg SPS)*.
- Opex costs: running continuously superconducting refrigeration, for both magnets and RF, Klystron powering for RF, plus human needed costs (heating, computing etc). Advantages, could reuse heat from to heat homes in winter like at CERN**.
- Radiation safety problems: the decay of muons in the accelerator would produce a significant emission of neutrinos, which would travel to the surface of the earth. Hence the accelerator rings would need to be positioned so that no major human settlement is impacted.

*C. Accettura et al., *Interim report for the International Muon Collider Collaboration (IMCC)*, arXiv:2407.12450 [physics], Jan. 2025. doi: 10.48550 arXiv.2407.12450. Accessed: Jan. 12, 2026. [Online]. Available: <http://arxiv.org/abs/2407.12450>

**<https://home.web.cern.ch/news/news/cern/heating-homes-worlds-largest-particle-accelerator> (last accessed 10/03/2026)

Environmental and Social Considerations – Construction and Capital Expenditure

- Building new infrastructure, new tunnels, new beamlines, new magnets and RF cavities.
- Materials needed to build the components have an associated Global Warming Impact (GWI) index which is the carbon footprint associated with the production of material.
- For example, we estimate that the project requires 16 dipole magnets per arc cell and there are 34 repeating single arc cells, amounting to a total of 344 dipole magnets.
- Hence, calculating the total mass of the dipole magnets to be 12,040 metric tons of steel and steel has a GWI of 2.05kg, which amounts to roughly 25,000 metric tons of carbon dioxide.
- Mitigation: Could reuse already built tunnels (eg SPS)*.
Using steel sourced using renewable power

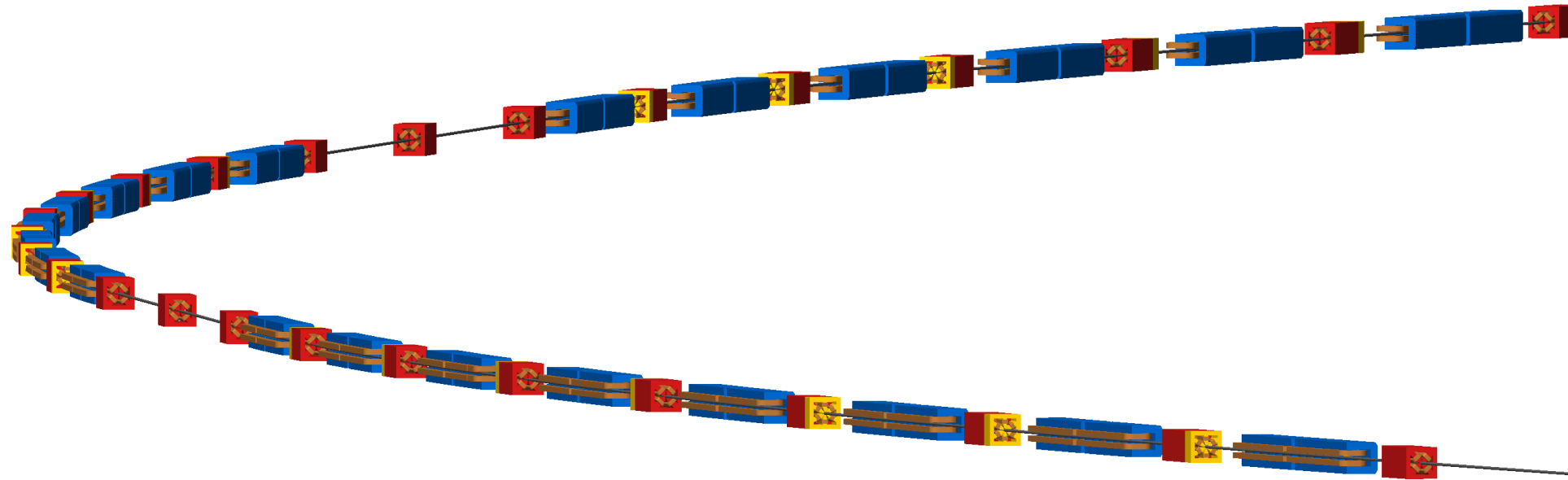
*C. Accettura et al., Interim report for the International Muon Collider Collaboration (IMCC), arXiv:2407.12450 [physics], Jan. 2025. doi: 10.48550 arXiv.2407.12450. Accessed: Jan. 12, 2026. [Online]. Available: <http://arxiv.org/abs/2407.12450>

Environmental and Social Considerations – Operational Expenditure

- Running continuously superconducting refrigeration, for both magnets and RF, Klystron powering for RF.
- It is estimated that LHC consumes 10,000 tonnes of liquid nitrogen to cool its 36,000 tonnes of cold mass magnets to 80 K, which is double the cold mass magnets of this project of 14,325 tonnes.
- Human needed costs such as heating and computing.
- Radiation safety problems: the decay of muons in the accelerator would produce a significant emission of neutrinos, which would travel to the surface of the earth. Hence the accelerator rings would need to be positioned so that no major human settlement is impacted.
- Mitigation: a. Could reuse heat from to heat homes in winter like at CERN**.
b. Using energy recovering linacs where the kinetic energy of beam particles is used to increase the RF intensity of the linac and hence accelerates newly injected particles.

**<https://home.web.cern.ch/news/news/cern/heating-homes-worlds-largest-particle-accelerator> (last accessed 10/03/2026)

Conclusions



Conclusions

Lattice

- Single particle tracking successful with expected optics.
- Determined transverse beam size for aperture constraints for magnet and RF teams.
- Expected energy gains per turn and over 17 turns met.
- Multiple particle tracking achieved showing minimal emittance growth but diverging.

Magnets

- Optimised both dipole and quadrupole magnets.
- For dipole, best configuration with 130mm pole width with field strength of 1.8T, field quality $\Delta B/B \approx 10^{-3}$ over good field region.

For quadrupole:

- achieved 30 T/m at 40mm aperture,
- achieved 19.5 T/m at 67.5mm Aperture
- achieved field homogeneity to $< 10^{-3}$

RF Cavities

- Investigated 352MHz and 1.3GHz, optimised in 2D and confirmed with 3D designs.
- Cavities capable of producing required accelerating gradients achieved.
- Ideal cavity determined to be the 1300 MHz.

Environmental and Social Considerations

- Need to consider effective policies to protect the environment and minimise negative social effects.

Conclusions

Design Study Report

- The report covering the design study of the RCS1 has been completed.
- Not yet available.
- Will be published on the CERN document servers.

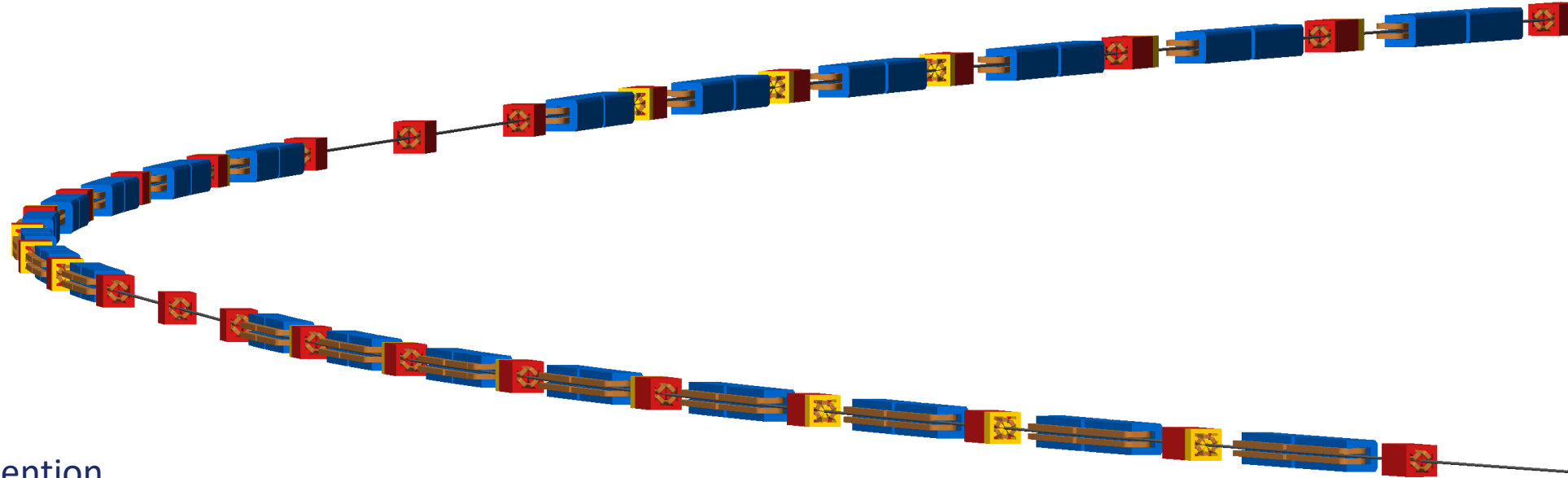


Acknowledgements

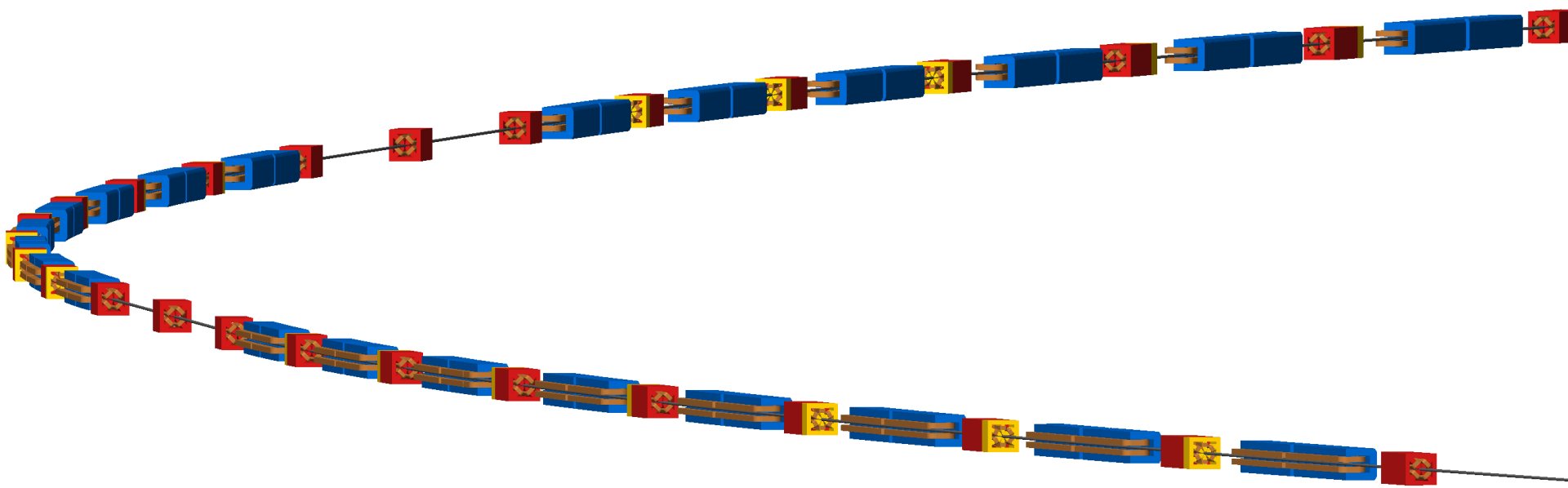
A big thank you to all the following people for time, help and support:

J. Bauche
C. Plostinar
R. Taylor
L. Soubirou
H. Wakeling

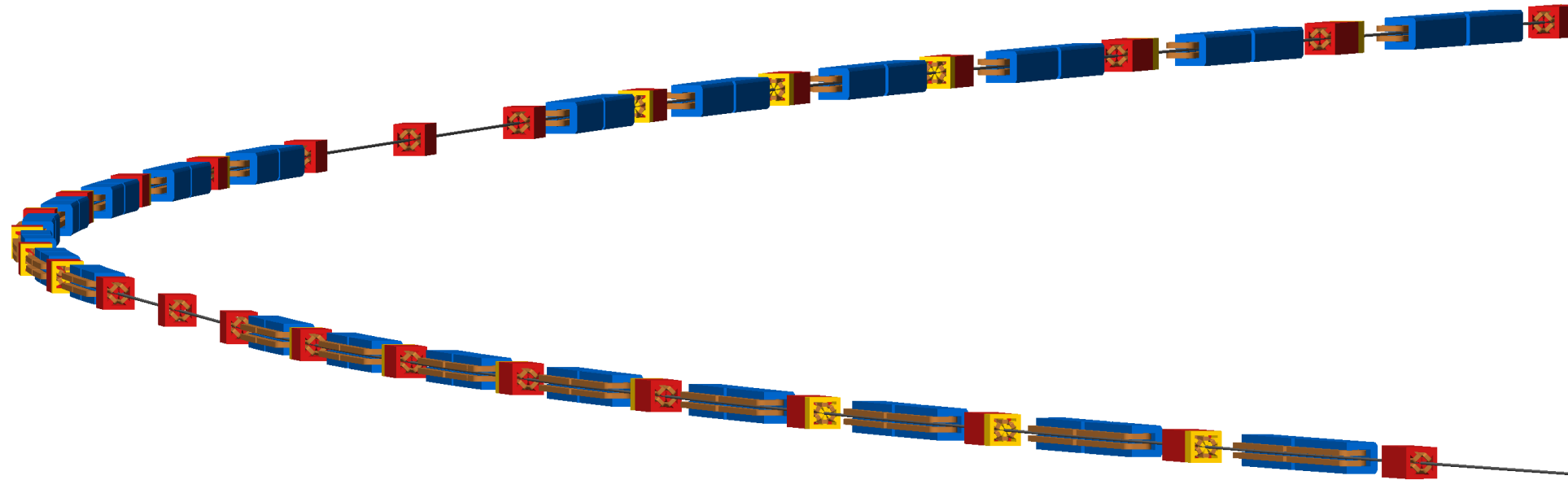
Also, cannot miss to mention
Emmanuel Tsesmelis for his dedication,
help and support throughout the project.



Any Questions?



Backup Slides



Quadrupole

Design Generation in Python

- Hyperbolic nose profile*

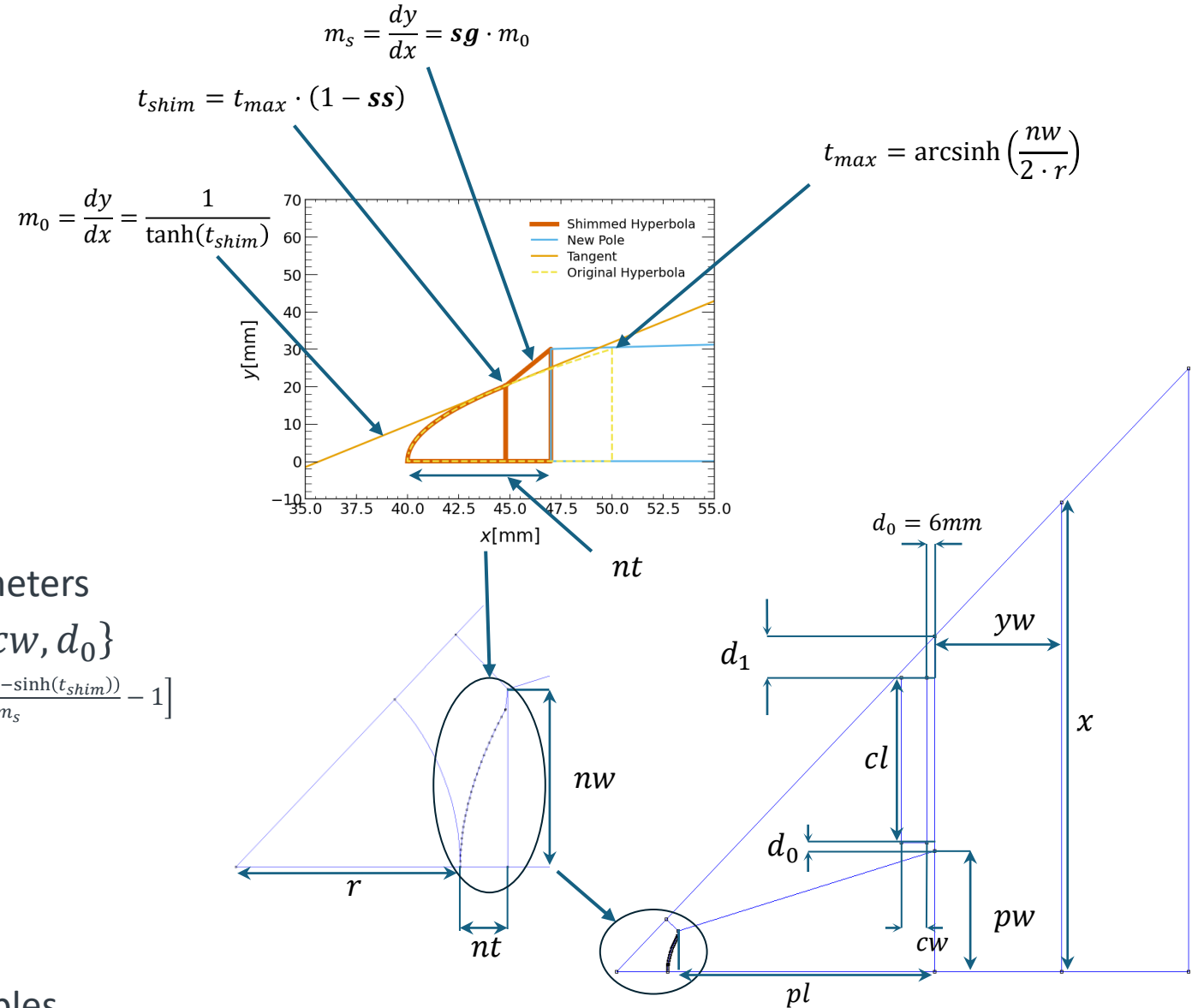
- $2xy = \pm r^2$
- $\begin{pmatrix} x \\ y \end{pmatrix} = \begin{pmatrix} r \cosh(t) \\ r \sinh(t) \end{pmatrix}$

- Geometry Reduced to 9 parameters

- $\{r, x, yw, pw, nw, ss, sg, cw, d_0\}$
 - $nt = r \left[\cosh(t_{shim}) + \frac{(\sinh(t_{max}) - \sinh(t_{shim}))}{m_s} - 1 \right]$
 - $pl = x - yw - nt - r$
 - $d_1 = \frac{2 \cdot d_0 + cw}{x - yw - pw}$
 - $cl = \frac{1 - d_0 - d_1}{x - yw - pw}$

- r and d_0 fixed

- 7 Varying geometry variables



*Bauche, Jérémie. 'An Introduction to Magnets for Accelerators'. <https://indico.cern.ch/event/1621143/contributions/6831399/>

Quadrupole

Multi Objective Bayesian Optimisation with Optimas^[*, **]

- 5 Objectives

1. Maximise Field Gradient [T/m] = $\frac{A_2}{R_{ref}}$

2. Minimise Field Homogeneity = $\max \left| \frac{A_n}{A_2} \right|$

3. Minimise Total Magnetic Energy [J/m] – Calculated by Femm

4. Minimise Yoke Density [T] to 1.4[T] - $\langle |\vec{B}| \rangle - 1.4$

5. Minimise Current Density [A/mm²] to 8[A/mm²] - $|j - 8|$

*Ferran Pousa, A., S. Jolas, M. Kirchen, et al. 'Bayesian Optimization of Laser-Plasma Accelerators Assisted by Reduced Physical Models'. *Physical Review Accelerators and Beams* 26, no. 8 (2023): 084601. <https://doi.org/10.1103/PhysRevAccelBeams.26.084601>.
 **Hudson, Stephen, Jeffrey Larson, John-Luke Navarro, and Stefan M. Wild. 'libEnsemble: A Library to Coordinate the Concurrent Evaluation of Dynamic Ensembles of Calculations'. *IEEE Transactions on Parallel and Distributed Systems* 33, no. 4 (2022): 977–88. <https://doi.org/10.1109/TPDS.2021.3082815>.

$$NI = \frac{Gr^2}{2\eta\mu_0 NI}$$

$$j = \frac{NI}{cw \cdot cl \cdot 0.6}$$

Allow 40% of area for cooling etc

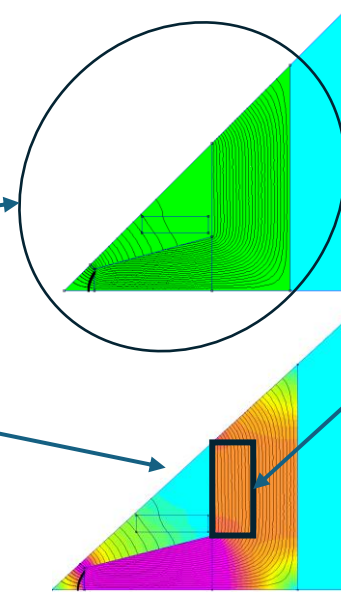
Multipole Expansion^[***, ****]:

$$B_r(r, \theta) = \sum_{n=1}^{\infty} C_n \left(\frac{r}{R_{ref}} \right)^{n-1} \sin(n(\theta - \alpha_n))$$

$$C_n = \sqrt{B_n^2 + A_n^2}$$

Normal Pole Skew Pole

Geometry designed skew ∴ $B_n = 0$



Block integral over entire geometry

$$E = \frac{1}{2} LI^2$$

S defined as rectangle of half yoke width and between the pole base and top part of yoke

$$\langle |\vec{B}| \rangle \approx \frac{1}{m} \sum_{n=0}^m \sqrt{B_x^2(x_n, y_n) + B_y^2(x_n, y_n)}_{\{(x_n, y_n) \in S\}}$$

***Bauche, Jérémie. 'An Introduction to Magnets for Accelerators'. <https://indico.cern.ch/event/1621143/contributions/6831399/>
 ****Breschi, M., A. Macchiagodena, P. L. Ribani, et al. NC Magnet Configuration (Dipoles and Quadrupoles). IMCC and MuCol Annual Meeting, 13 May 2025. <https://indico.desy.de/event/45968/contributions/186232/>