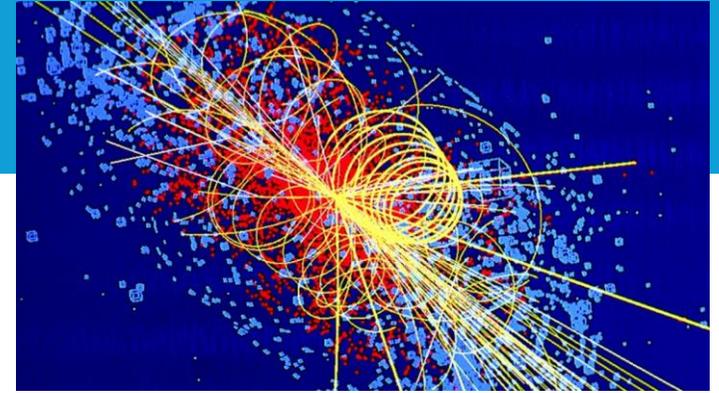




# John Adams Institute Accelerator Design Project 2025

Hybrid Asymmetric Linear Higgs  
Factory (HALHF)

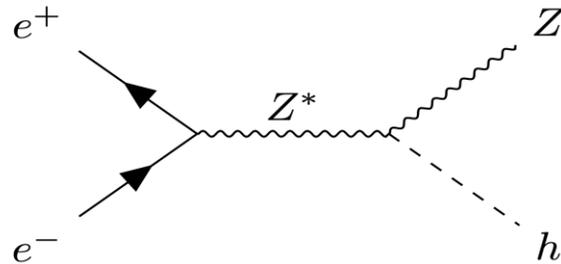
# The Need for a Higgs Factory



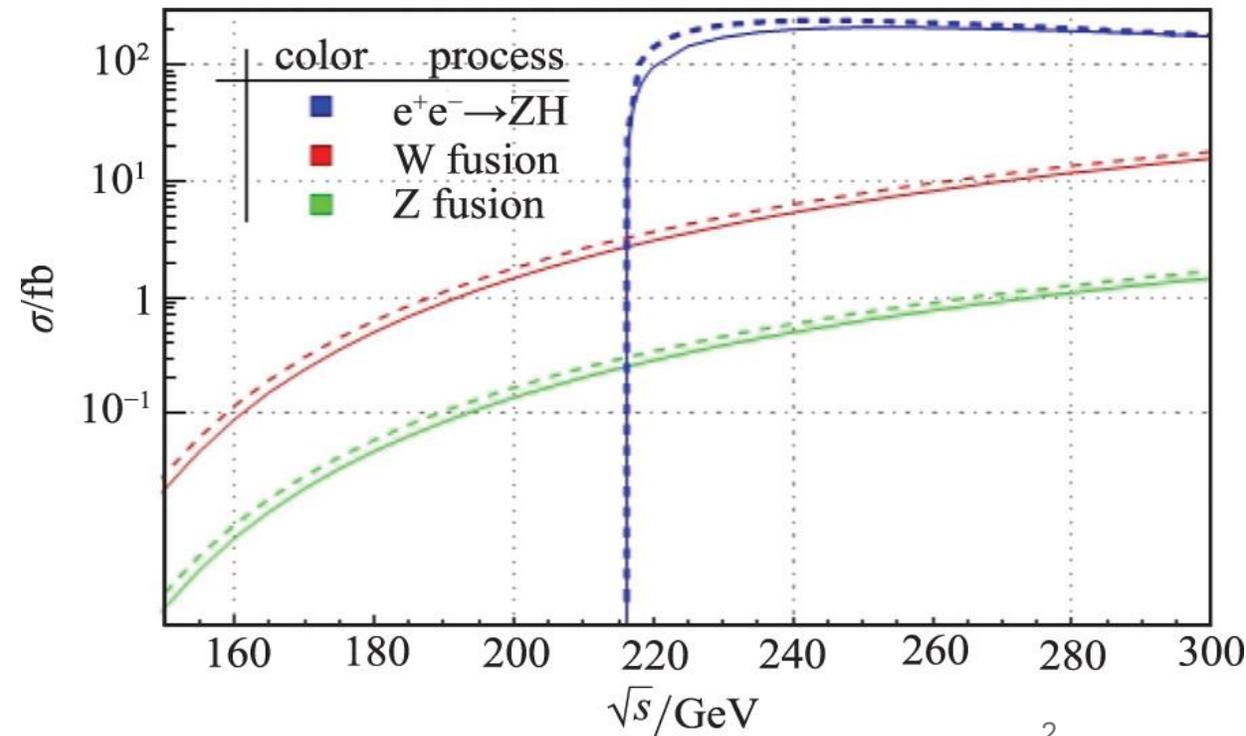
In 2012, the Higgs Boson was discovered!

Next: Precision measurements with leptons

- Minimise QCD background
- High precision using elementary particles
- Can resolve momenta accurately
- Higgsstrahlung:



→ Peak cross-section at 250 GeV CoM



# Higgs Factory Proposals

## Linear Accelerators

- Acceleration = simple
- Focusing = simple
- "One Pass"
- One interaction point
- No synchrotron radiation

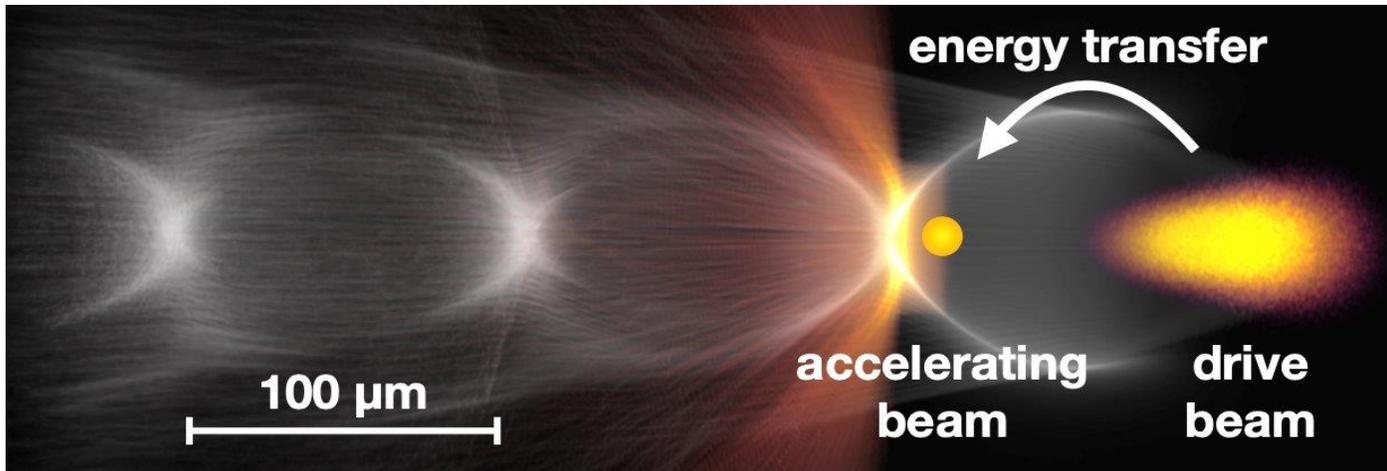
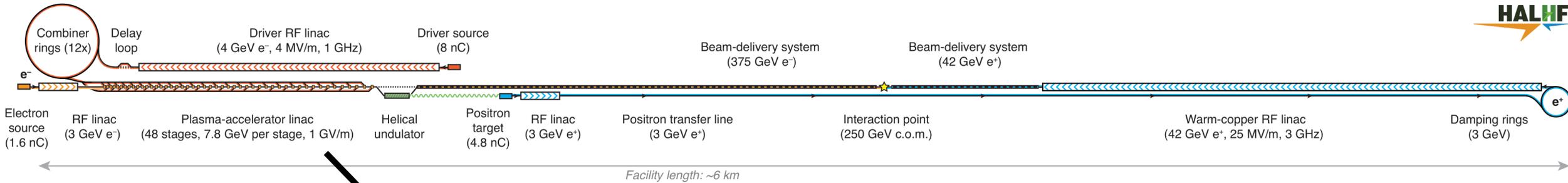


## Circular Accelerators

- Acceleration = simple
- Focusing = more complex
- "Multiple Passes"
- Multiple interaction points



# Hybrid Asymmetric Linear Higgs Factory



## Novelty of HALHF:

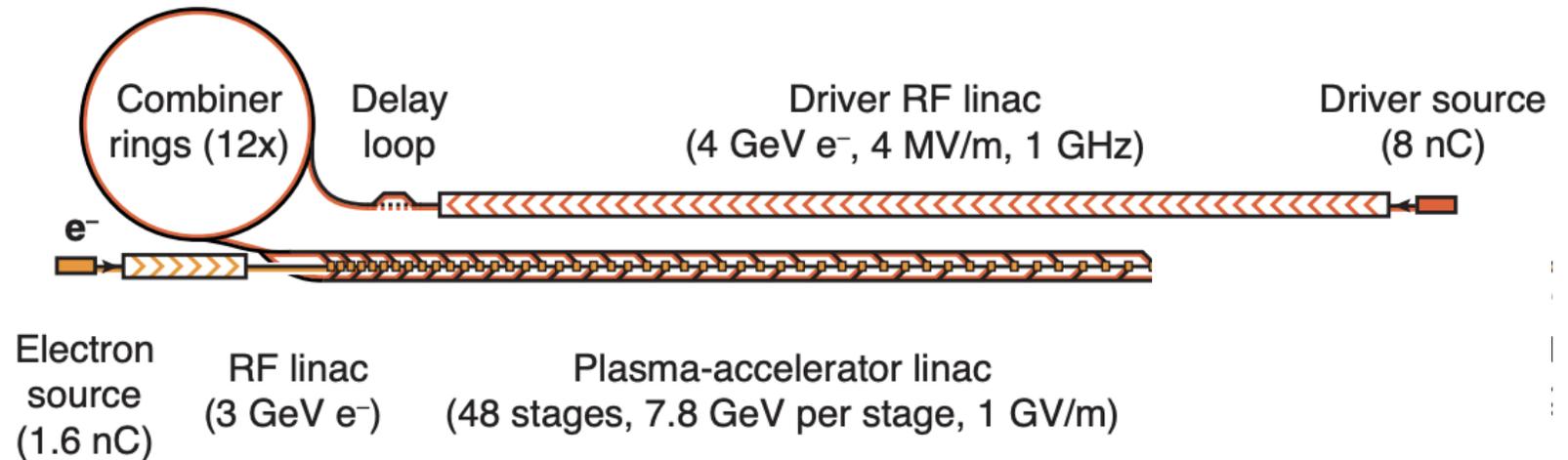
- Plasma based Accelerator Linac
- Asymmetry
- Small overall footprint

# HALHF: Drive-Beam Complex

Primary objective: Accelerate particles to **4 GeV** for **plasma-wakefield seeding**

Perform necessary bunch train manipulations:

- Pulse compression
- Phase manipulation

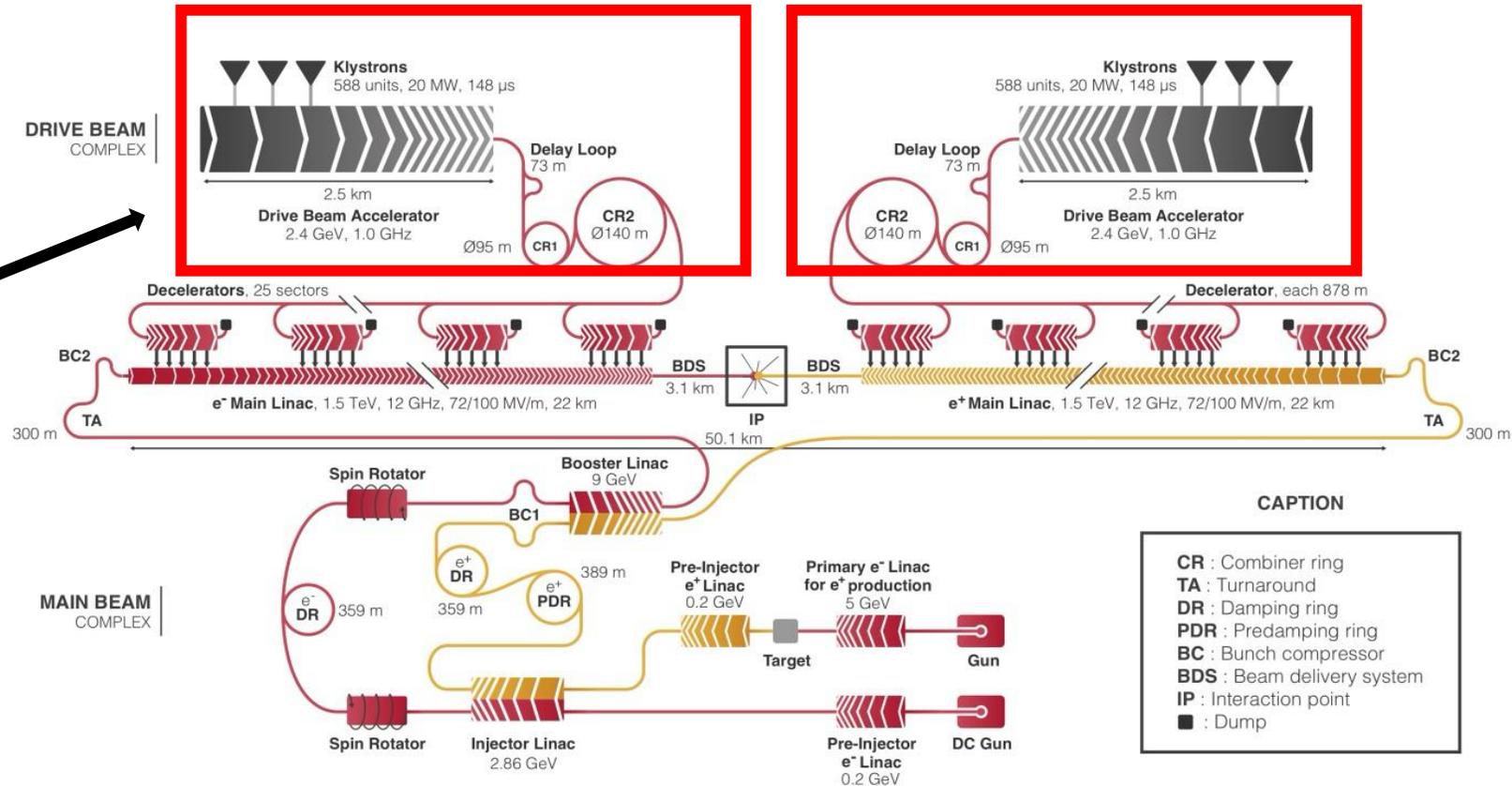


# Using CLIC as a Baseline for HALHF



Why can we use CLIC as the baseline?

- Utilises a drive beam complex for conventional RF accelerators
- Needs to heavily modify bunches



3 TeV

# HALHF: Drive-Beam Complex Objectives

## Lattice / Optics Team:

- Minimise emittance growth
- Best control energy spread
- Maximise filling factor of the RF system

## Radio-Frequency Sources Team:

- Use simulations to design an RF Cavity that is suitable while respecting the power/size limitations

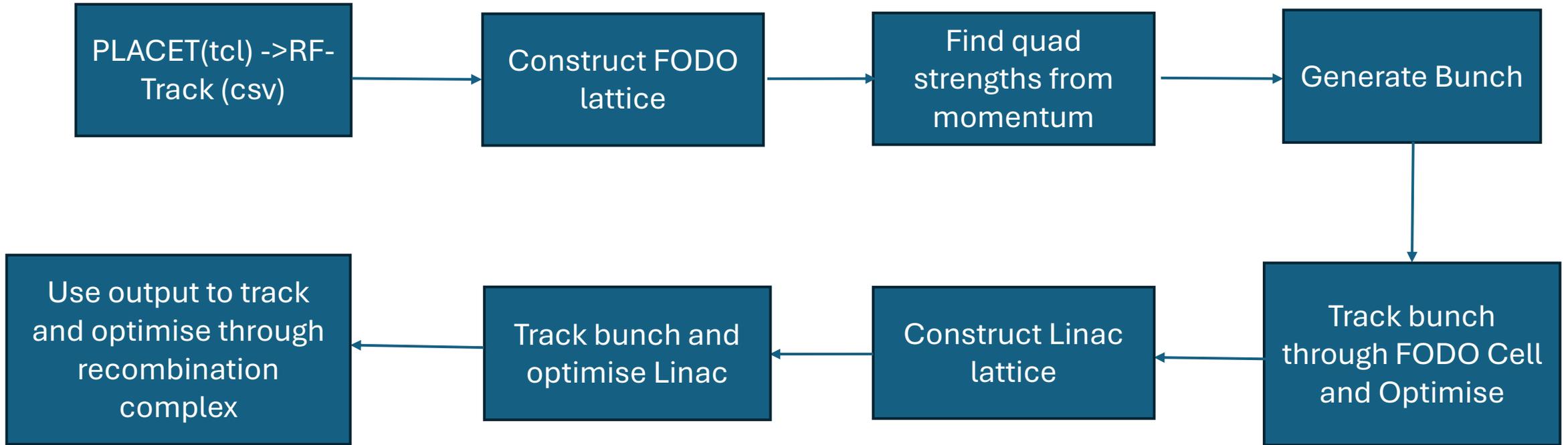
## Magnets Team:

- Design quadrupole and dipole magnets for the linac and combiner ring

# Lattice Team

Joshua Appleby, Louis Forrester,  
Nela Sedlackova

# Design Process

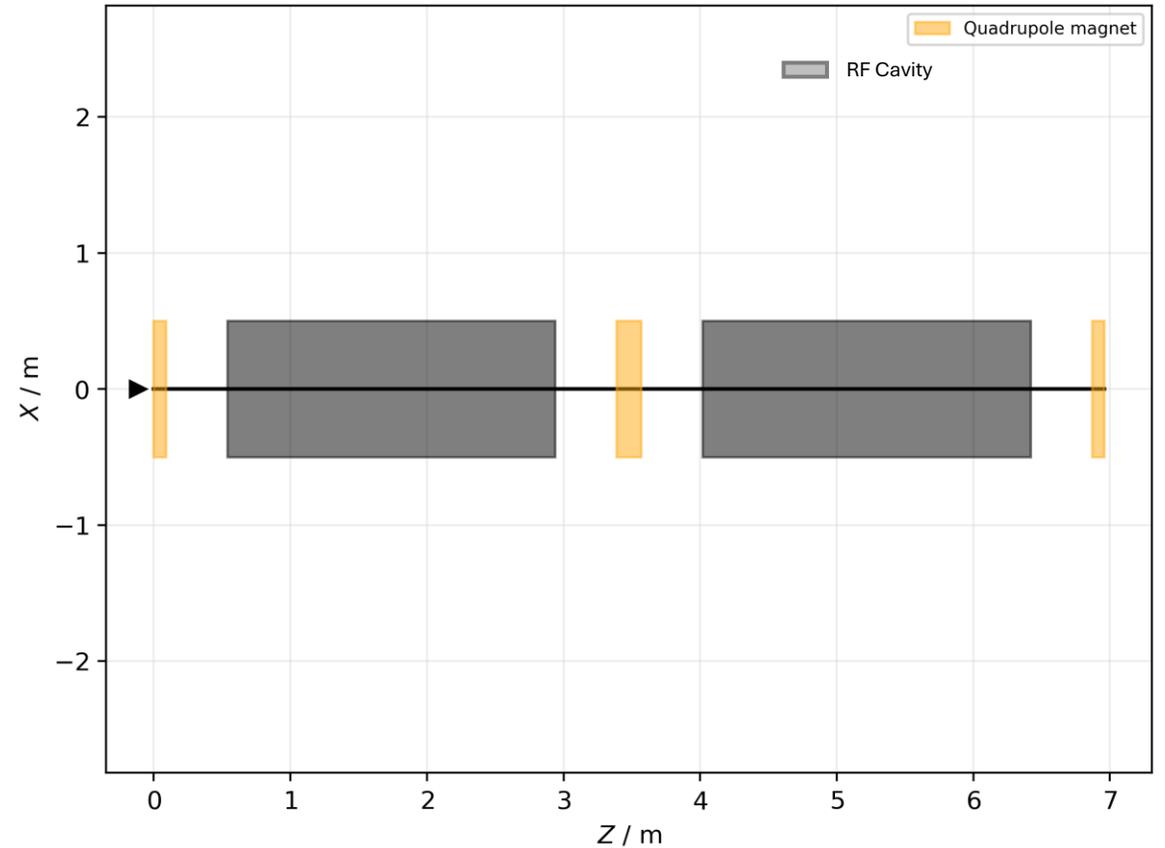


# FODO Cell

Using CLIC baseline and improved gradient:

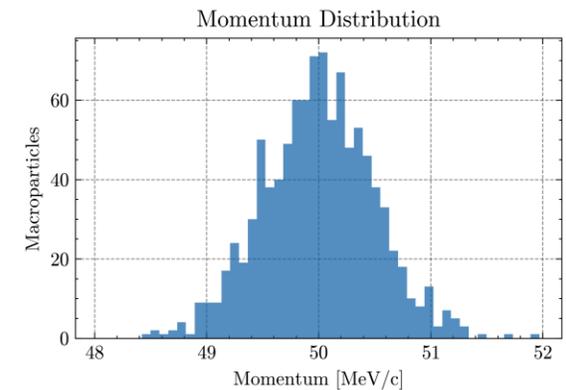
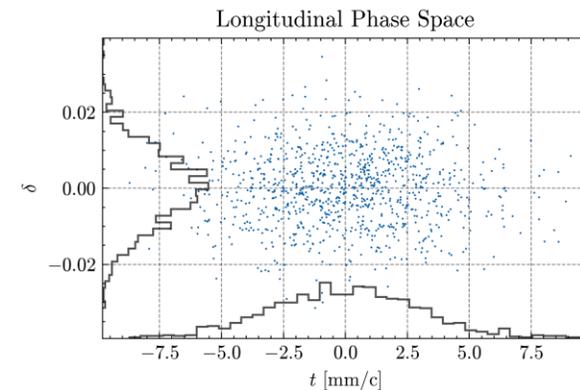
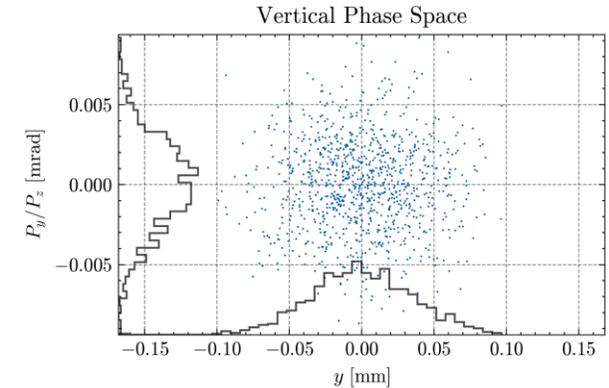
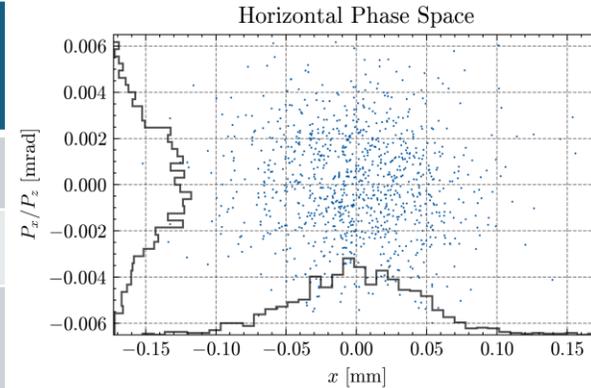
1. Focusing Quadrupole (0.18m)
2. Drift (0.45m)
3. Cavity (2.4m) (12 MV/m)
4. Drift (0.45m)
5. Defocusing Quadrupole (0.18m)
6. Drift (0.45m)
7. Cavity (2.4m) (12 MV/m)
8. Drift (0.45)

But...split the focusing quadrupole



# Bunch Parameters for Drive Beam

Parameter [unit] (Input / Output)	CLIC [1, 2]	HALHF [3, 4]
Energy [MeV]	50 / 2400	<b>50</b> / 4000
Bunch Charge [nC]	8.4	<b>8</b>
Bunch Separation [ns]	0.5 / 0.0167	4 / 0.167
Bunches per Train	312 /	2 / 48
Normalised Horizontal Emittance [ $\mu\text{m.mrad}$ ]	50 / 0.5	<b>10</b> / 50
Normalised Vertical Emittance [ $\mu\text{m.mrad}$ ]	50 / 0.005	<b>10</b> / 50
RMS Bunch Length [mm]	<b>3</b> / 10	0.253 /
Normalised Energy Spread [%]	<b>&lt; 1</b> / 0.5	Assumed CLIC values



Calculated using RF-Track

[1] CLIC Conceptual Design Report, 2012

[2] A. Aksoy, 2014

[3] B. Foster. et al, 2023

[4] B. Foster. et al, 2025

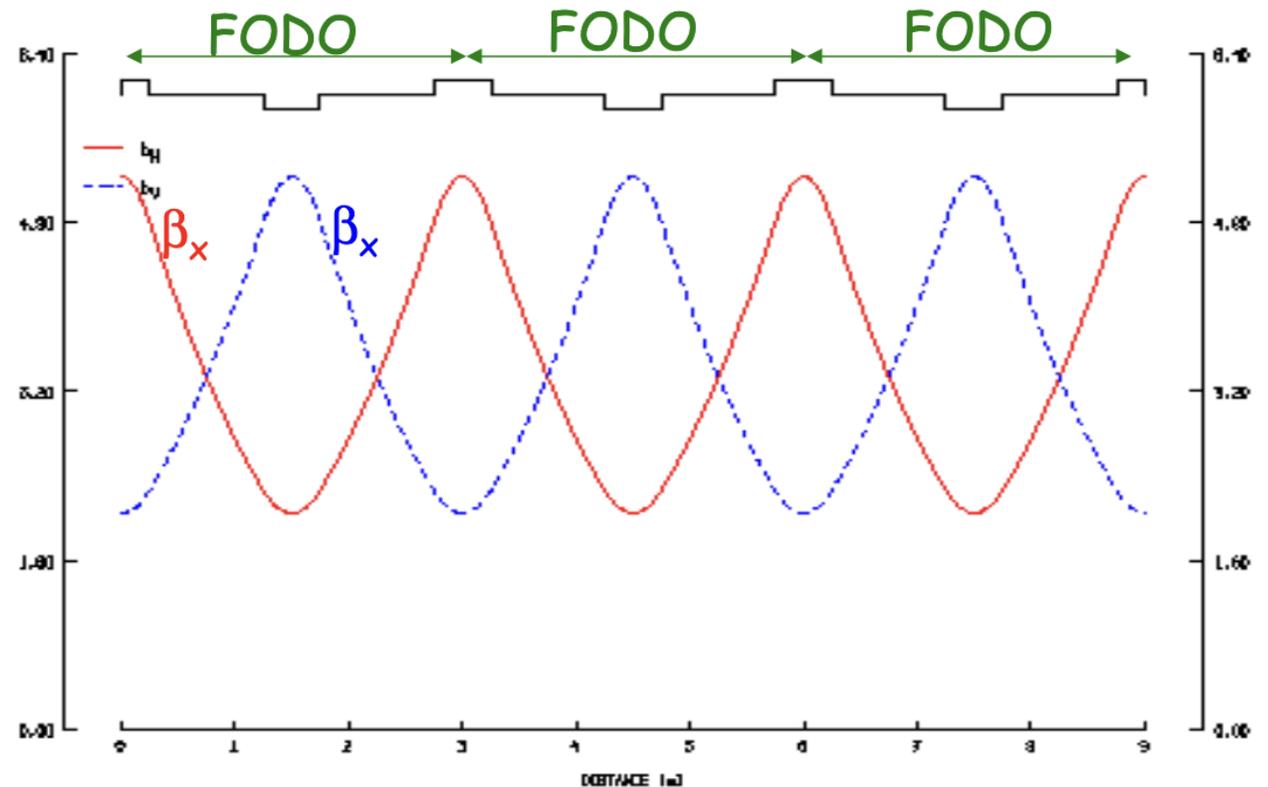
# Optics Tracking and Matching

From a perfect FODO cell, the betafunction should be:

- Periodic across a cell
- Symmetric in X and Y

HALHF also requires:

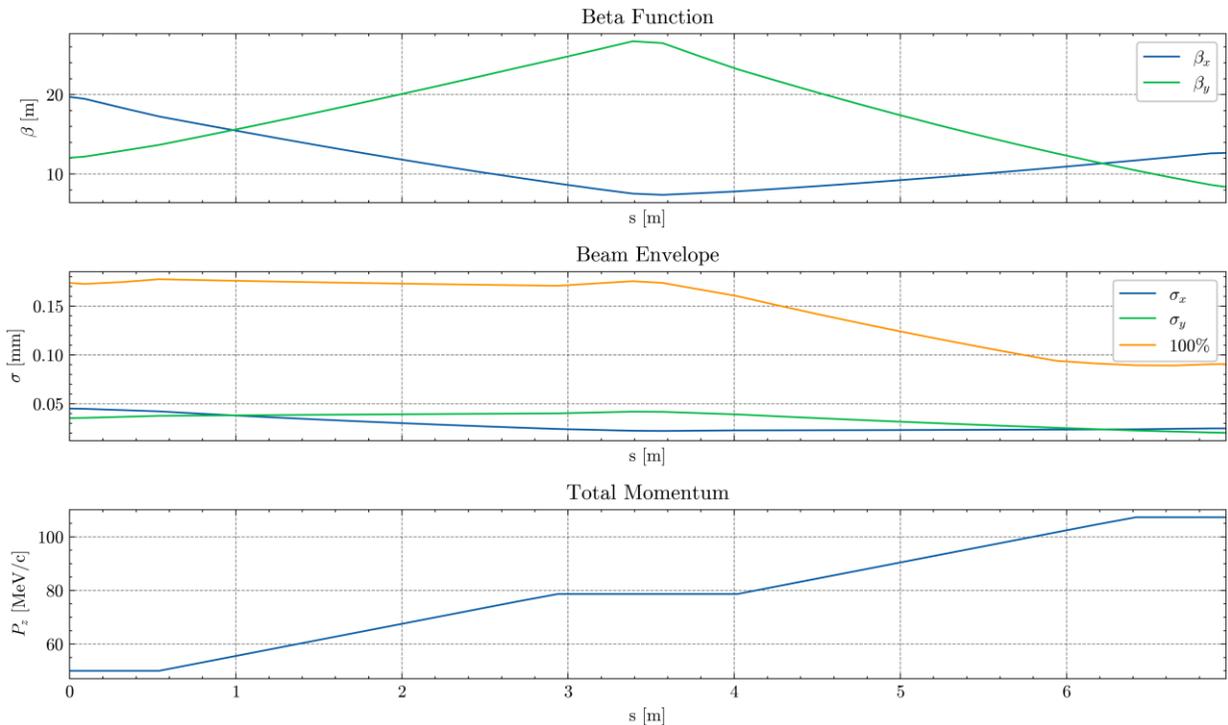
- Minimised transverse emittance
- Bunch shape ideally preserved through the linac



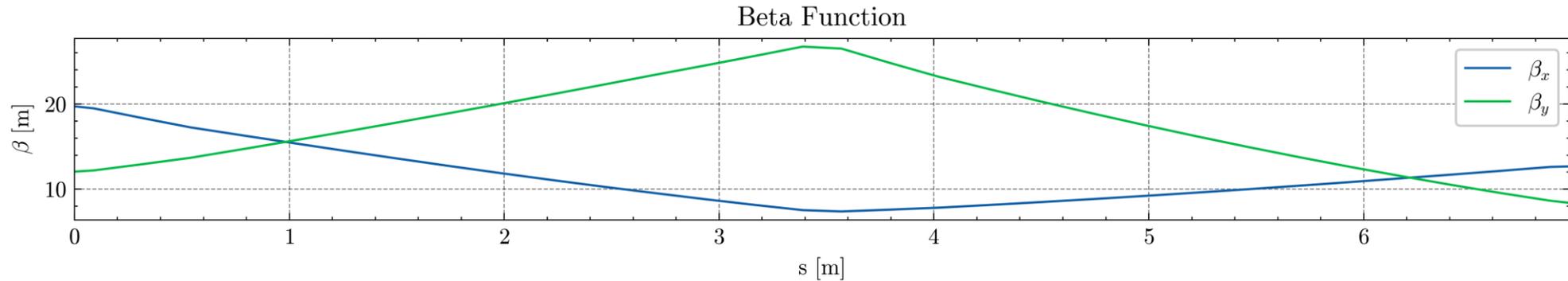
# FODO Cell

When we track and match the FODO:

- Betafunction is periodic
- Betafunction is not symmetric
- Emittance is unchanged (technical issues with plotting)
- Beam envelope is reduced
- Momentum is increased to approx. 107.6 MeV/c



# FODO Issues

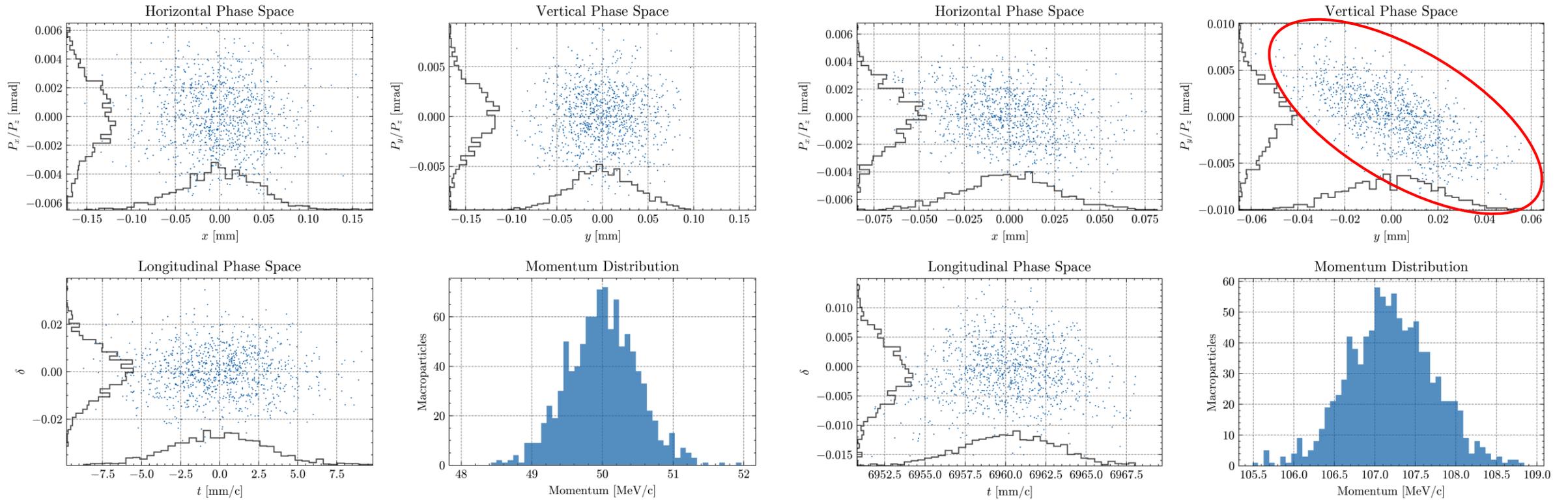


Initial betafunction calculation:

$$\beta_{x,y} = \frac{L (1 \pm \sin \frac{\mu}{2})}{\sin \mu}$$

1. Assumes a “thin” lens quadrupole
2. Assumes FODO cell has no accelerating elements
- 3a. Initial betafunction required to create a bunch (distributions)
- 3b. Tracking then matching yields a different final beta value each time
- 3c. Therefore, hard to optimise.

# Phase Space of FODO: Before / After



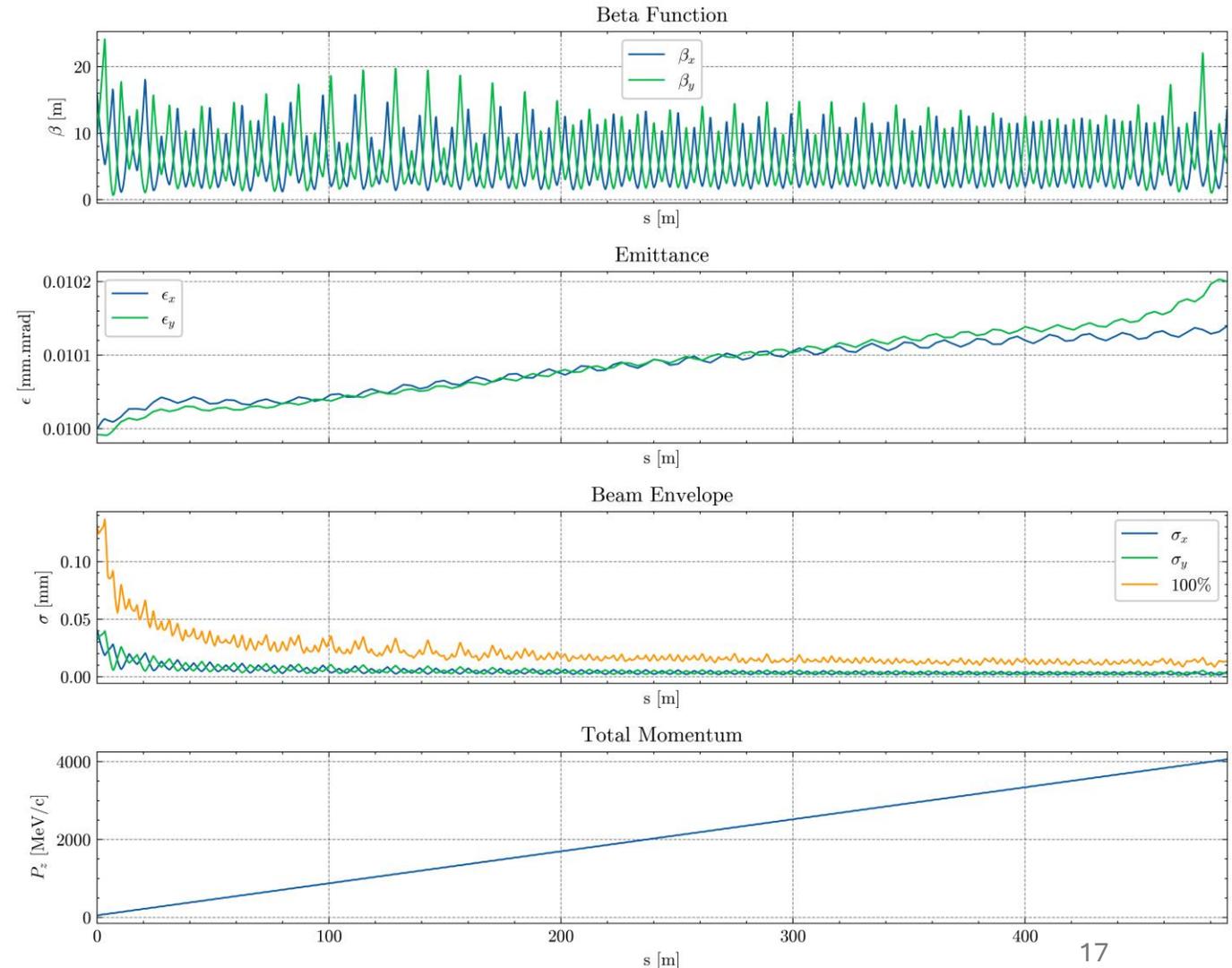
# Linac

- Using the optimised FODO as the starting cell
- Add new (not optimised) FODO's with quadrupole strengths calculated from the momentum at that point
- Replace half quadrupole pairs with a single quadrupole
- Results in a 487.2 m linac with a final momentum of 4 GeV/c
- RF Filling factor of 69%

# Linac

When we track and match the linac:

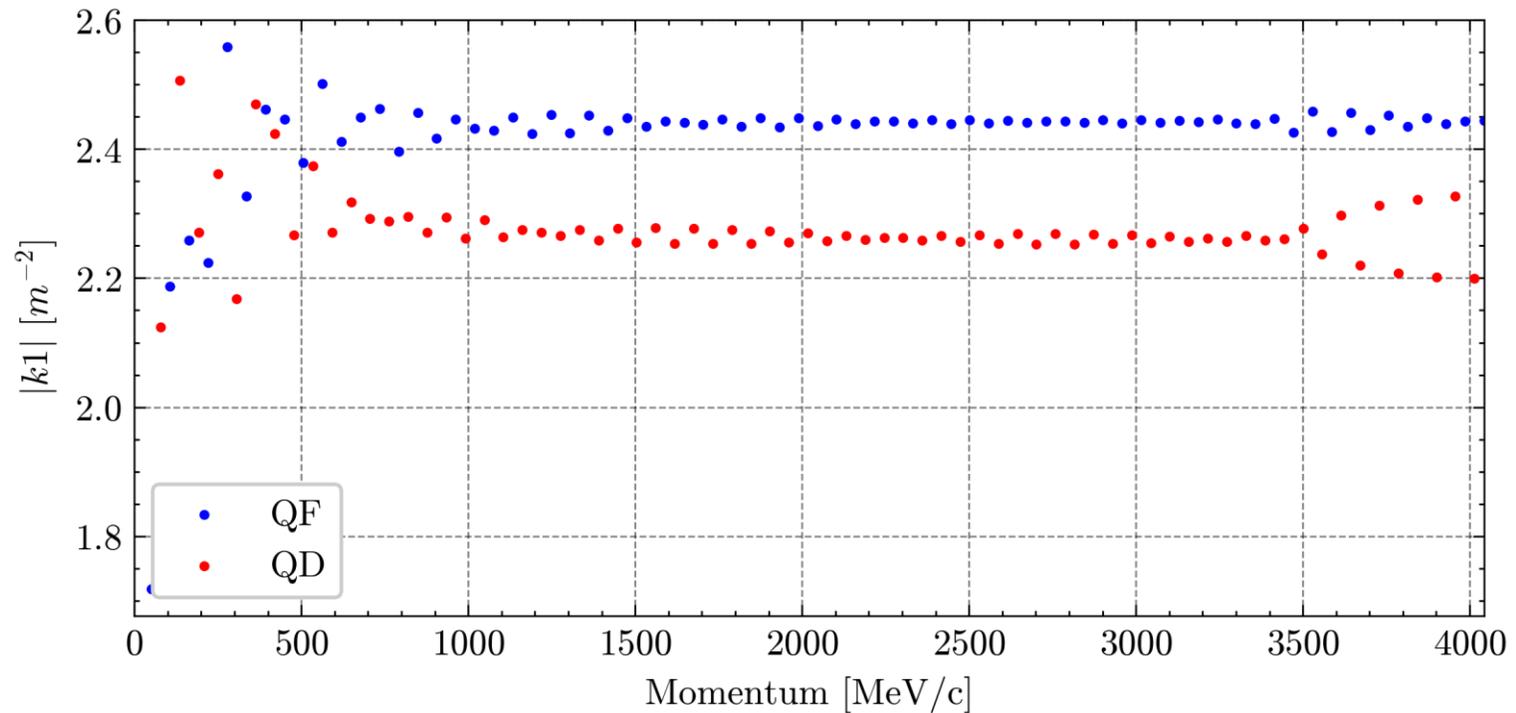
- Betafunction is periodic
- Betafunction is not symmetric, and varies a lot
- Emittance is increasing, but still very small (far below the 0.05 mm.mrad limit)
- Beam envelope is reduced and stable
- Momentum  $\geq 4$  GeV/c reached



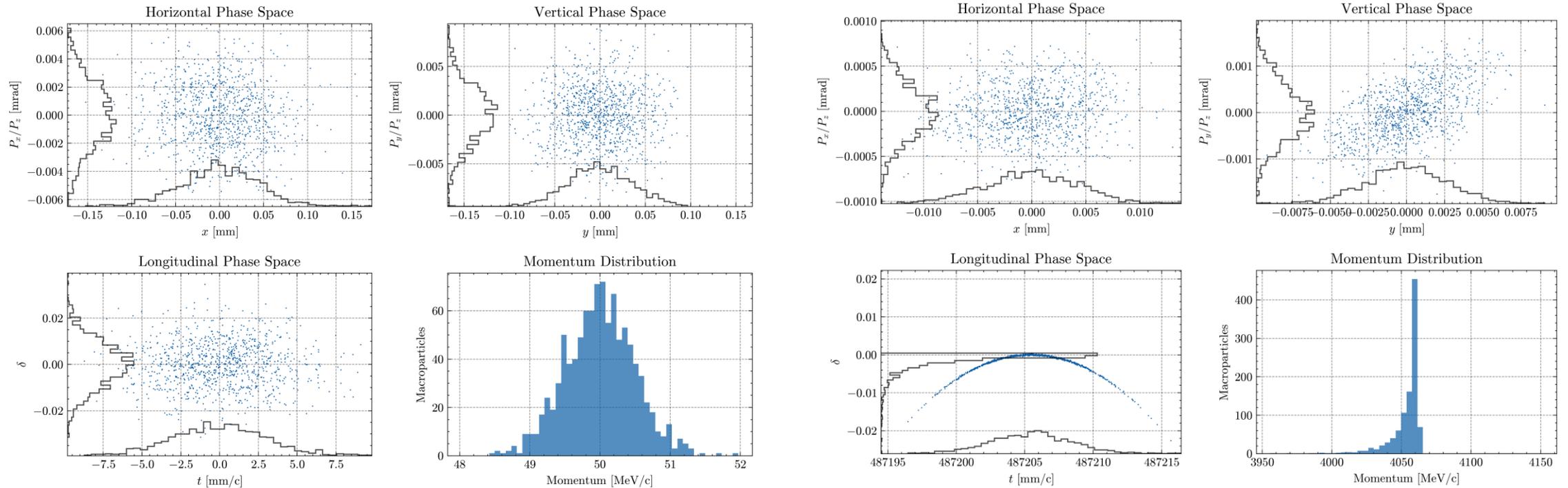
# Linac: Quadrupole Focusing Strengths $k_1$

The optimised quadrupole focusing strengths:

- $k_1$  values mostly stabilise
- QD  $k_1$  values are all negative
- Unsure why QF and QD have different "stabilised" values
- Note the divergence on QD above 3500 MeV/c (to be investigated)



# Linac Bunch Phase Space

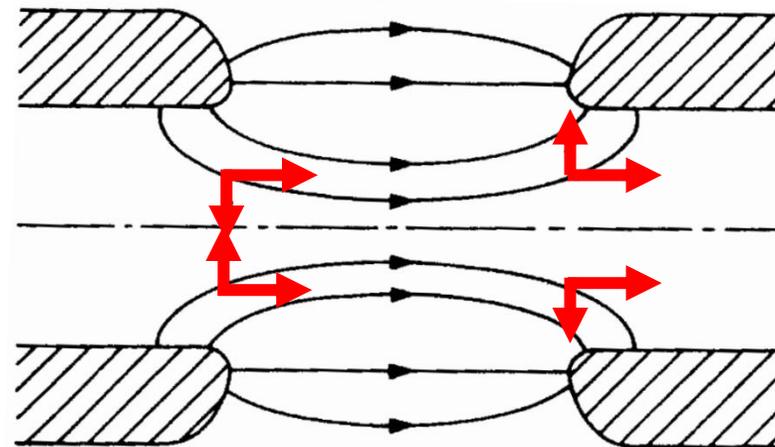
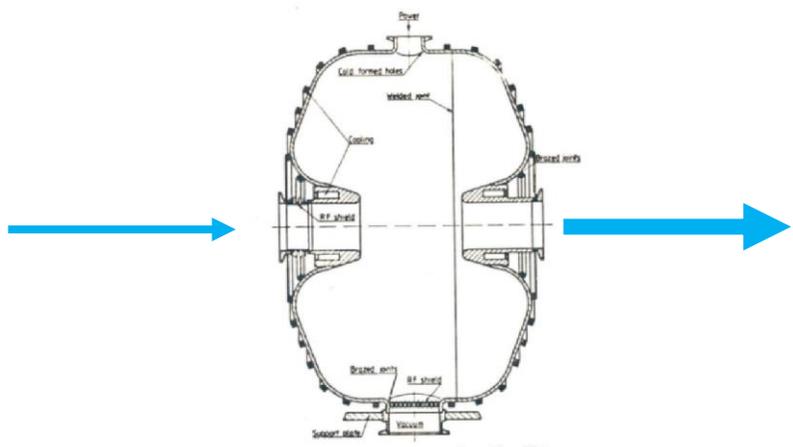
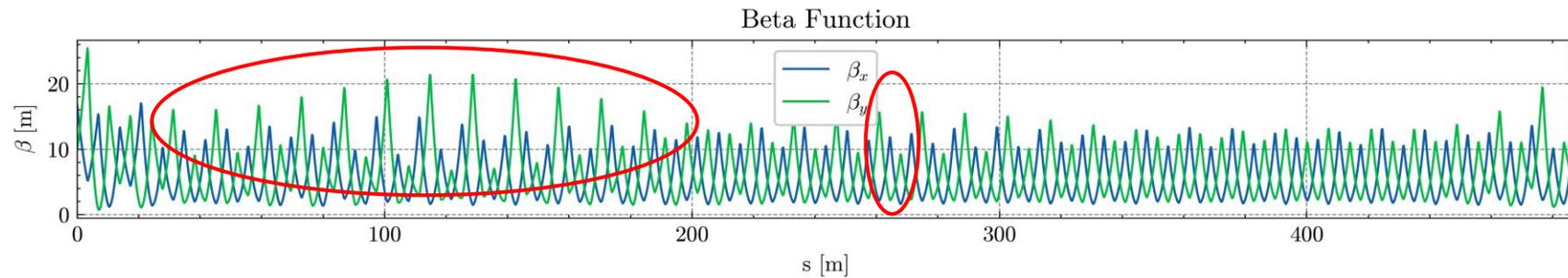


# Linac Successes

- Accelerated to above 4000 MeV/c
- Emittance stays below 0.0103 mm.mrad
- Beam Envelope Range: 0.15 mm to 0.012 mm
- Can be extended higher than 4 GeV/c, dependant on length and power limitations

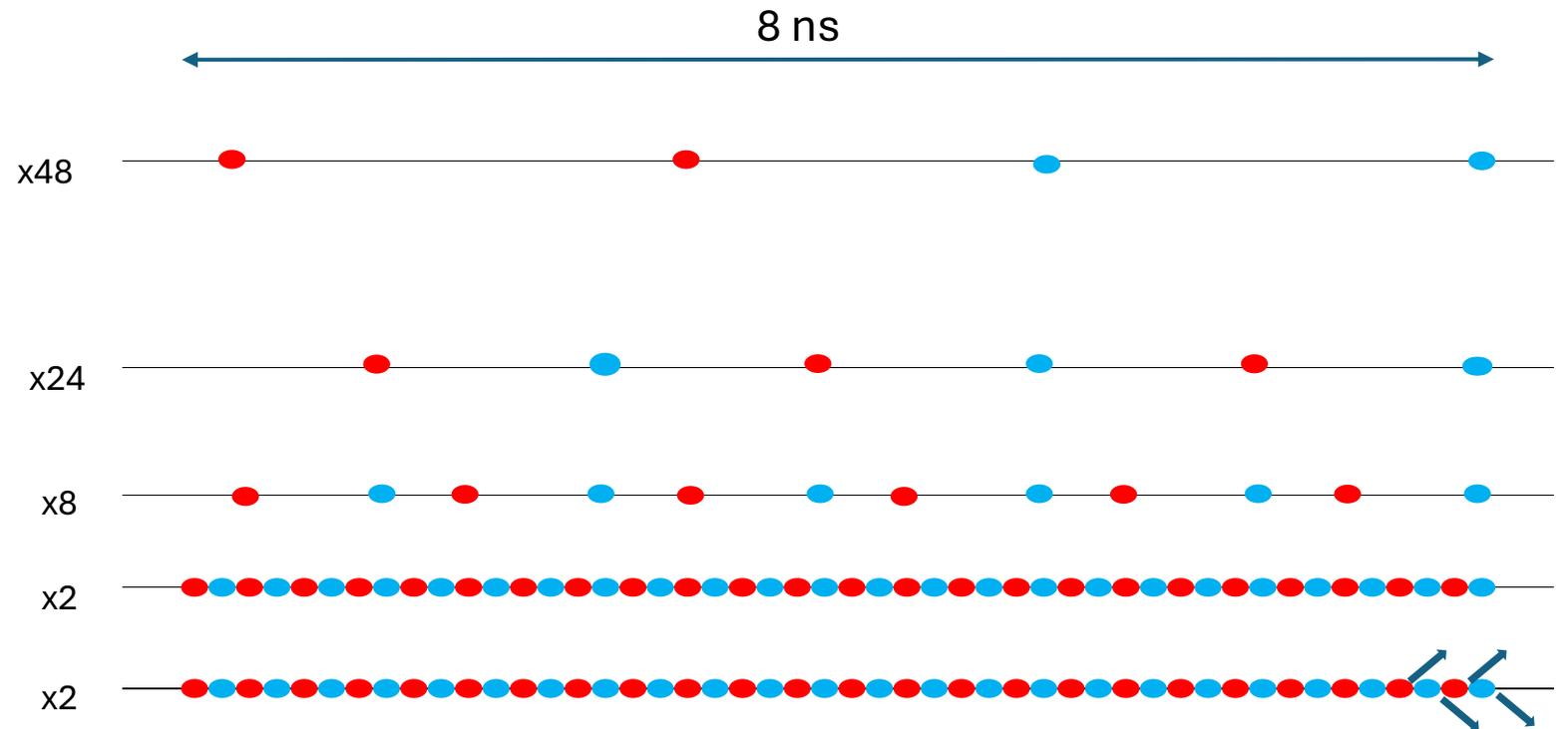
# Linac Issues

- Optimising for 141 independent quadrupoles
- Beta-beating from transverse focusing (RF Track)



# Bunch Manipulation: Delay Loop and Combiner Rings

- Bunch train created from electron gun
  - 96 pulses total (384ns)
  - 4ns bunch separation
- Accelerated by RF Linac
  - Unchanged
- Delay Loop x2
  - 2ns bunch separation
- Combiner Ring x3
  - 0.667ns bunch separation
- Combiner Ring x4
  - 0.167ns bunch separation
- Seeding of plasma acceleration stages



# Delay Loop and Combiner Rings

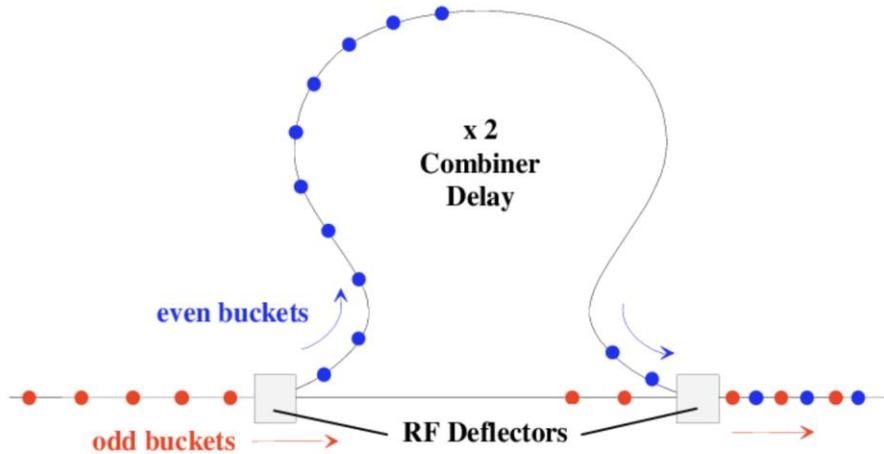
Delay Loop	CLIC	HALHF
Bypass Length [m]	73	1.5
Loop Length [m]	146	3
Recomb multiplier	x2	x2

- DL combines odd and even bunches in alternation
- CR1 & CR2 decreases the bunch separation

	CLIC		HALHF	
Component	CR1	CR2	CR1	CR2
Circumference [m]	292.2	438.3	766.5	766.5
Recomb multiplier	x3	x4	x3	x4

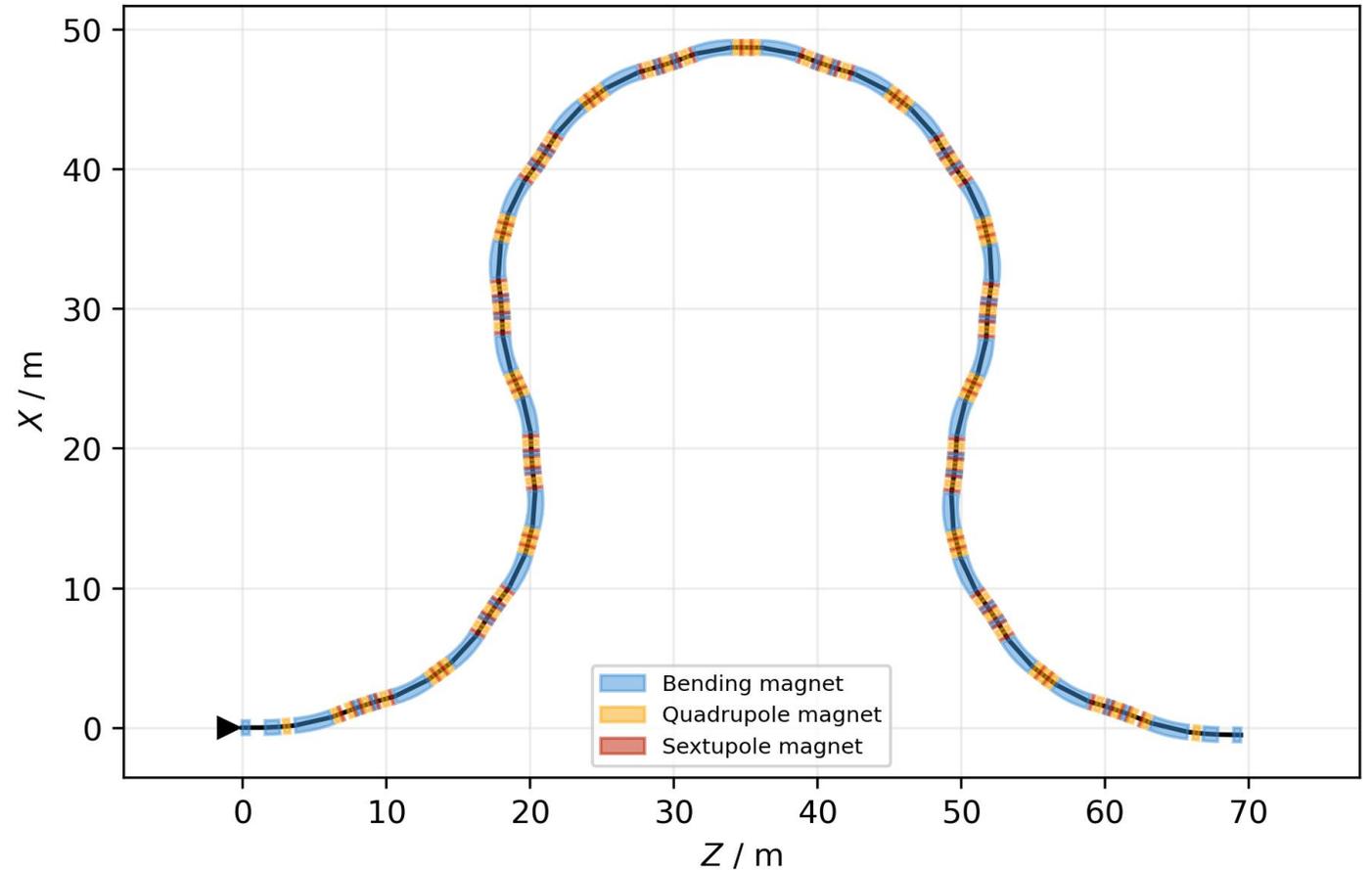
- The Bypass Length is determined by the final bunch train duration
- The Loop Length needs to be 2x Bypass Length
- CR1 & CR2 need to be multiples of the train length

# Delay Loop



[1] Rainer, P

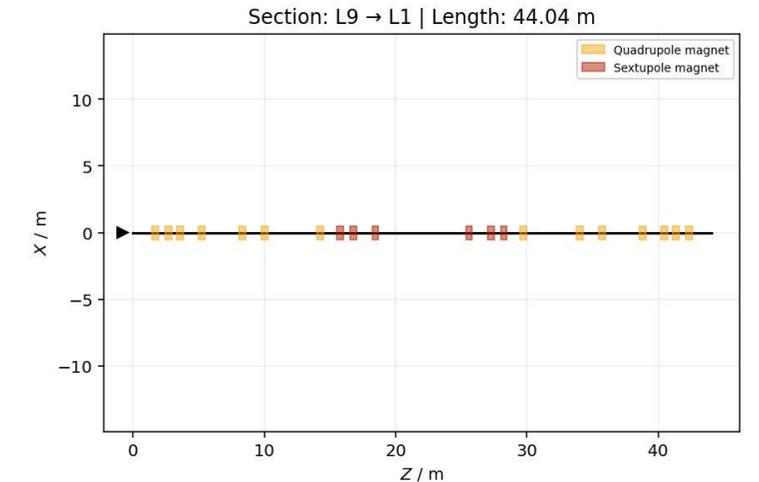
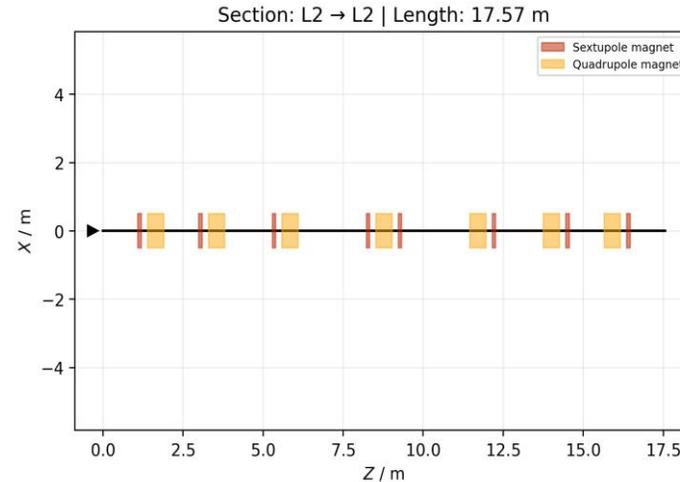
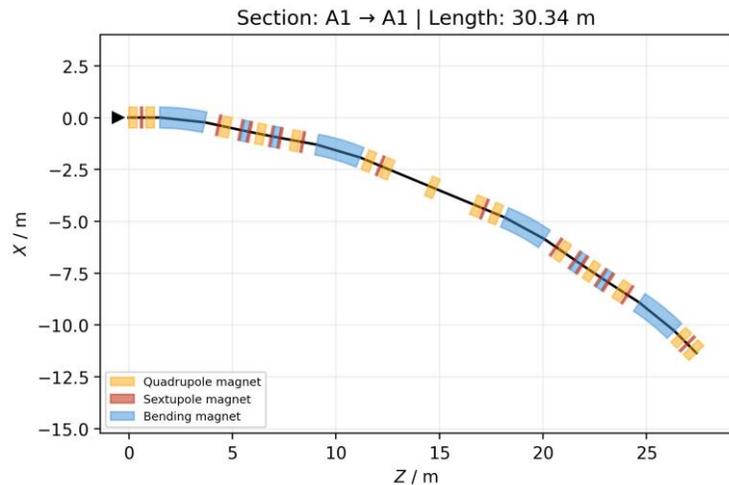
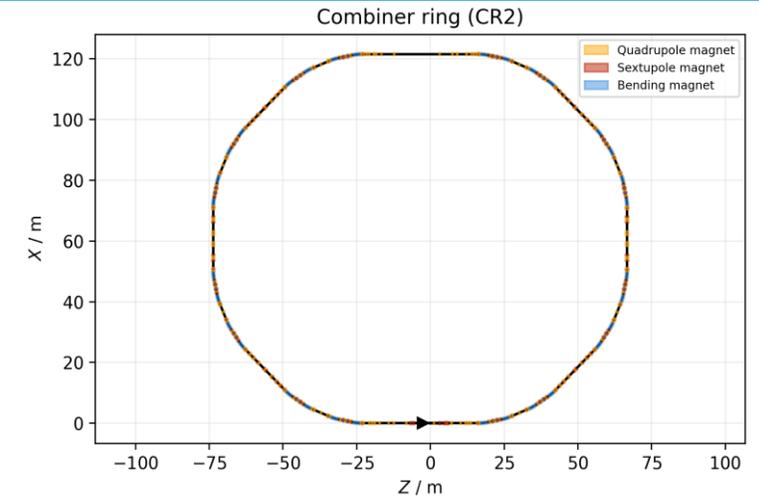
- Odd & Even buckets alternatively recombine
- RFD halves the frequency of buckets entering the delay line



CLIC DL design plotted using Xsuite

# Combiner Ring

- HALHF combiner rings are larger than CLIC due to the higher driver energy and longer bunch separation
- CR1 & CR2 are identical in HALHF as opposed to in CLIC



# Future Work

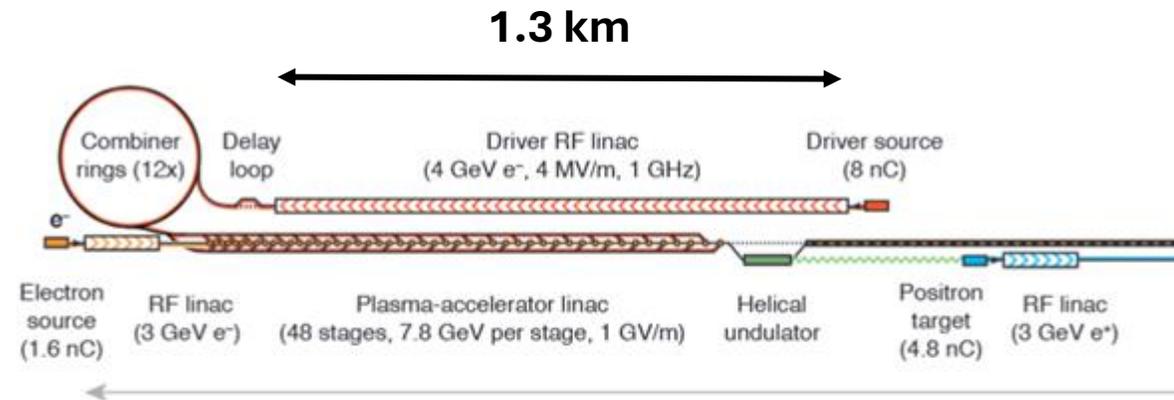
- Investigating if sextupoles are needed for linac
- Tracking and optimising the loop and ring, but it would require bunches from the previously optimised section
- RF-track implementing RF deflectors/kickers
- Incoherent Synchrotron Radiation calculation

# RF Team

Alexander Harrison, Ibrahim Najmudin,  
James Thistlewood

# Motivation and Parameters

- Driver linac requires at least **4 MV/m accelerating gradient**
- Chosen frequency is **1 GHz**
- Electrons from driver source are relativistic ( $\sim 50$  MeV,  $\beta \approx 1$ )
- Uses klystrons with **peak power  $\sim 21$  MW** (requiring 409 klystrons)
- Higher gradient desirable because shortens linac, reduces cost, relaxes limitations



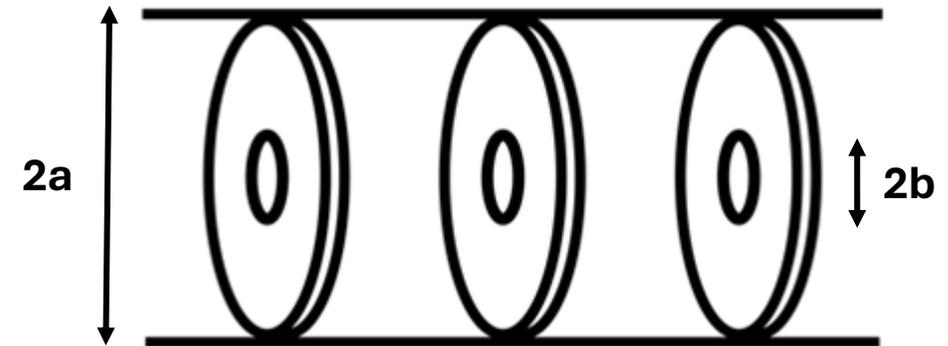
## *Driver linac RF parameters (L-band)*

Average cavity gradient	MV/m	4
Average gradient	MV/m	3
Wall-plug-to-beam efficiency	%	55
RF power usage	MW	42.9
Klystron peak power	MW	21
Number of klystrons		409
RF frequency	GHz	1
Length	km	1.3

Foster, B. *et al.* Proceedings of the Erice Workshop: A new baseline for the hybrid, asymmetric, linear Higgs factory HALHF. [doi:10.48550/arXiv.2501.11072](https://doi.org/10.48550/arXiv.2501.11072)

# Design Choices

- **Travelling-wave cavity** (vs standing wave):
  - More suitable for relativistic single-pass accelerator [1]
  - More efficient than SW – higher transit time factor, since bunch travels with wave
  - Any waveguide mode will have  $v_p > c$ , so must slow phase velocity with iris-loaded waveguide
- **Warm copper normal conducting cavity:**
  - No cryo-plant needed
  - Suitable for the low accelerating gradient required
  - Wide historical use in linacs (e.g. at SLAC), proven technology, well-studied



Iris-loaded waveguide geometry

[1] Wangler, T. P. *RF Linear Accelerators*. (Wiley-VCH, Weinheim, 2008).

# Design Requirements

## Hard limits:

- Peak Klystron power – 21 MW, limits E field strength
- Overall drive linac power usage – 43 MW, limits E field strength
- Kilpatrick limit at 1 GHz – 29 MV/m (with 'bravery factor' = 1)
- 1 GHz signal – fixes cavity radius via fundamental mode  $J_0$
- Phase advance per cell –  $2\pi/3$  (maximises  $R_s$ )
- Cell length –  $\beta\lambda/3$  (necessary for a correct  $2\pi/3$  phase advance)
- Total cavity length – to fit within the FODO cells with enough breathing room

# Simulation Methods

**Poisson Superfish** – 2D axially symmetric frequency-domain cavity mode solver:

- More suitable for standing-wave cavities
- 'Homemade' Bayesian optimization of parameters via Python, tune frequency by tweaking cavity geometry

**CST Studio** – 3D general microwave EM solver:

- Suitable for wide range of problems, handles SW and TW cavities
- Built-in optimization via Trust Region / Nelder-Mead



# Figures of Merit (FoM)

## Geometric values:

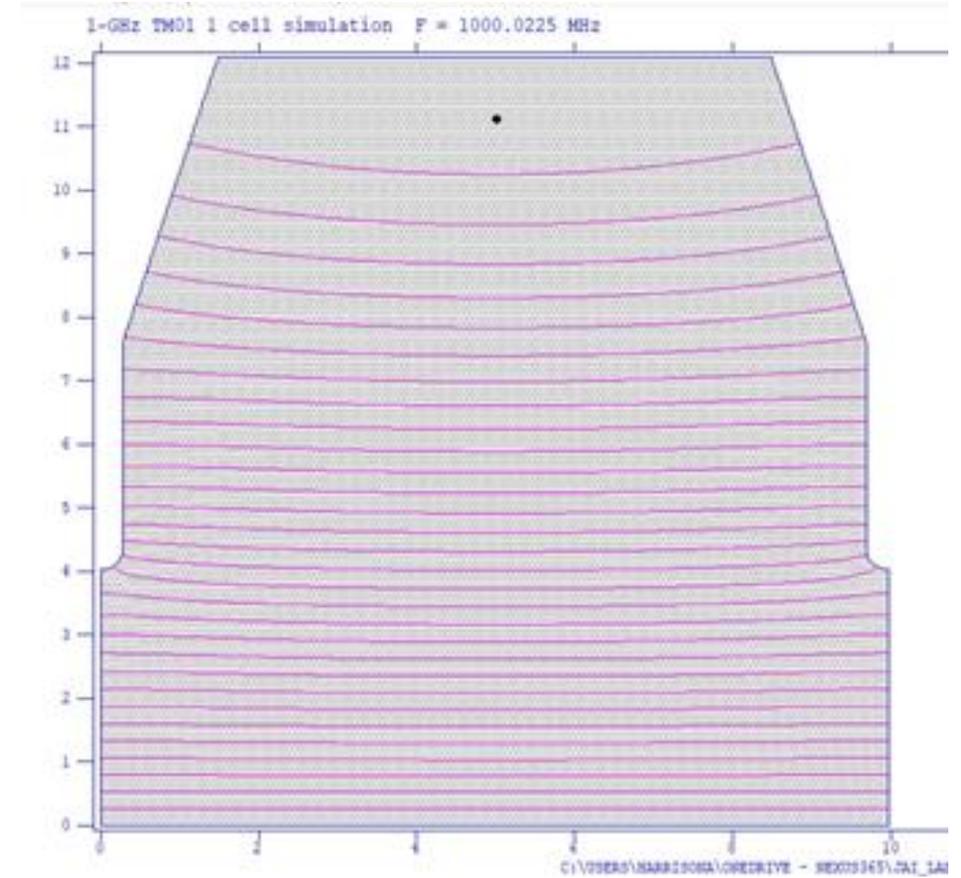
Symbol	Name	Description
<b>Rs</b>	Shunt impedance	Measure of axial voltage vs power dissipated
<b>Q</b>	Quality factor	Ratio of stored energy to loss per period
<b>r/Q</b>		Efficiency of acceleration vs stored energy

## Simulation values:

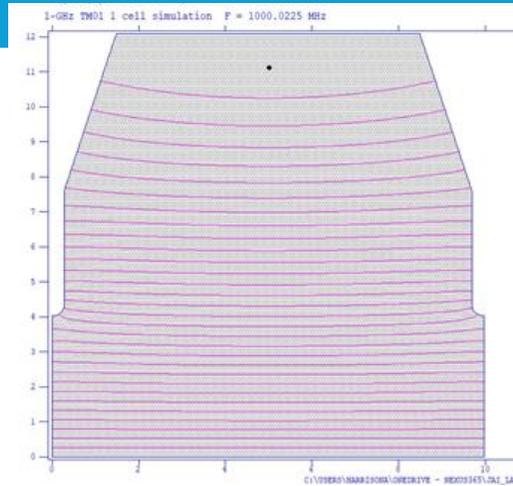
<b>P</b>	Power loss	Power lost to induced currents in cavity walls
<b>T</b>	Transit time factor	Quantifies amount of time beam spends in region of peak accelerating field
<b>Ez</b>	Axial gradient	Avg. z-component of accelerating E field on axis

# How we used Superfish

- Designed a loaded Iris waveguide cell
- Compared different cell designs such as domed roof, pill box, and slanted edge design.
- Optimised design for FOM using a Bayesian black box design
- Investigated the maximum electric field by abiding to the Kilpatrick limit.



# FoM in Superfish



**Example output data:** Electric field ( $E_z$ ) visualisation...

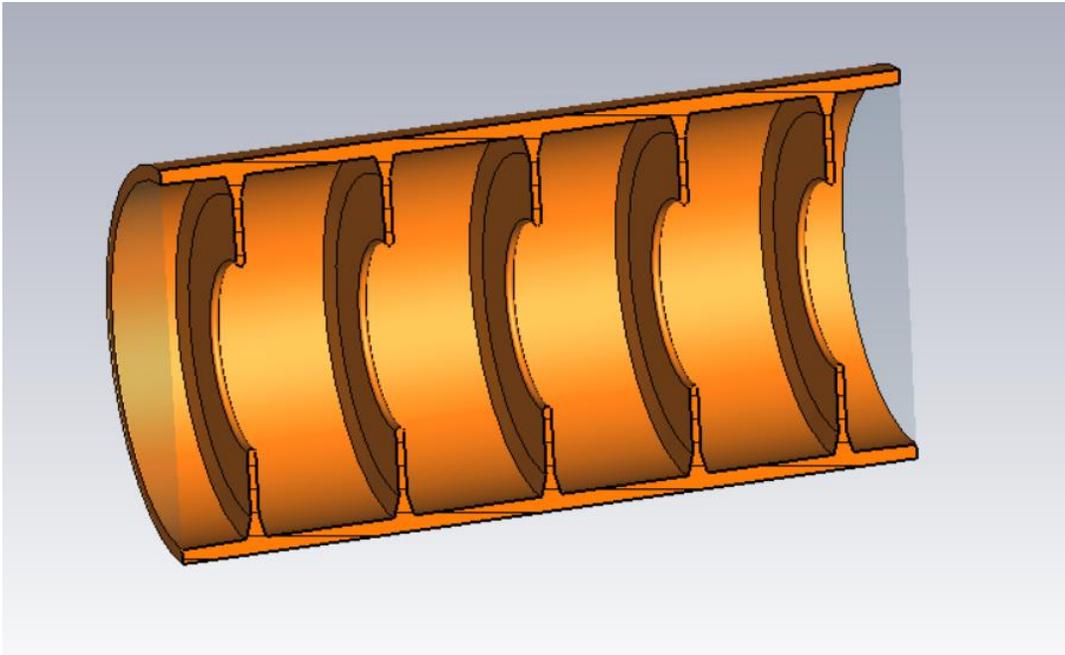
```

All calculated values below refer to the mesh geometry only.
Field normalization (NORM = 0):  EZERO = 12.00000 MV/m
Length used for E0 normalization = 9.97310 cm
Frequency = 1000.02248 MHz
Particle rest mass energy = 0.510999 MeV
Beta = 0.9948770 Kinetic energy = 4.544 MeV
Normalization factor for E0 = 12.000 MV/m = 72096.037
Transit-time factor = 0.4118038
Stored energy = 0.7656258 Joules
Not using standard room-temperature copper.
Surface resistance = 8.25023 milliohm
Normal-conductor resistivity = 1.72410 microhm-cm
Operating temperature = 20.0000 C
Power dissipation = 181.5776 kW
Q = 26493.8 Shunt impedance = 79.092 MOhm/m
Rs*Q = 218.580 Ohm Z*T*T = 13.413 MOhm/m
r/Q = 50.489 Ohm Wake loss parameter = 0.07931 V/pC
Average magnetic field on the outer wall = 17818.7 A/m, 130.975 W/cm^2
Maximum H (at Z,R = 9.10523,9.79044) = 19135.2 A/m, 151.044 W/cm^2
Maximum E (at Z,R = 0.266894,4.25632) = 13.5989 MV/m, 0.475148 Kilp.
Ratio of peak fields Bmax/Emax = 1.7682 mT/(MV/m)
Peak-to-average ratio Emax/E0 = 1.1332
    
```

...and SF0 output

Symbol	Name	Value	Units
<b>f</b>	Resonant frequency	1000.022	MHz
<b>Rs</b>	Shunt impedance	8.25	mΩ
<b>Q</b>	Quality factor	26500	
<b>r/Q</b>		50.5	Ω
<b>E<sub>max</sub></b>	Maximum E field	13.6	MV/m
<b>E<sub>z</sub></b>	Axial gradient	12.4	MV/m

# CST Studio Suite - Modelling



## Iris loaded waveguide in CST

- Multi cell design required for the  $TM_{01}$  mode to propagate
- Slanted/curved edges lead to solver problems in the geometry
  - Increases mesh resolution to define the curves
- 3D simulation greatly increases running time
- 3D modelling is more difficult than 2D
- Time domain solver does not have tools to extract multi variable values out of 3D data

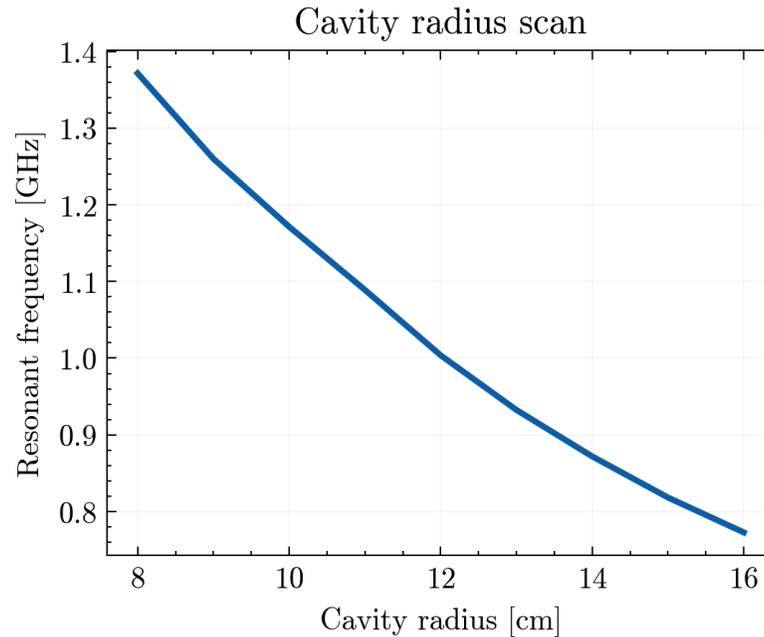
# Parameter scans

Theory of cylindrical waveguides gives us the cavity modes

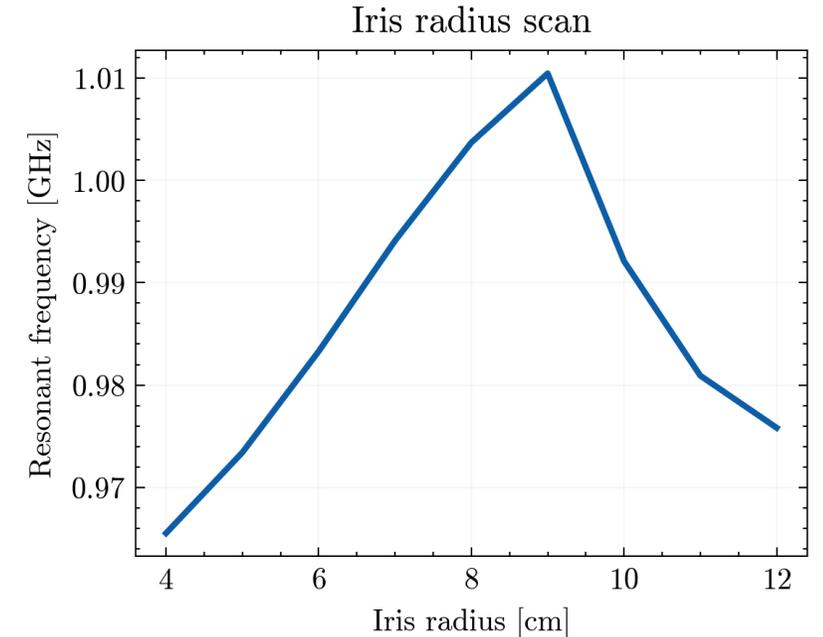
$$\omega_{\text{cav}} = \frac{2.405c}{a}$$

Predicting,

$$a = \frac{2.405c}{2\pi(1 \text{ GHz})} \simeq 11.5 \text{ cm}$$

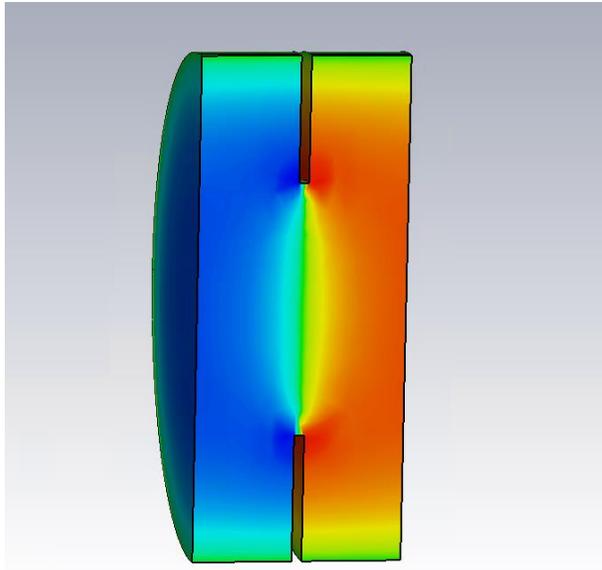


Varying cavity radius keeping iris radius at a constant ratio  $a:2a/3$



And with fixed  $a$ , the cavity frequency is relatively insensitive to the iris's radius

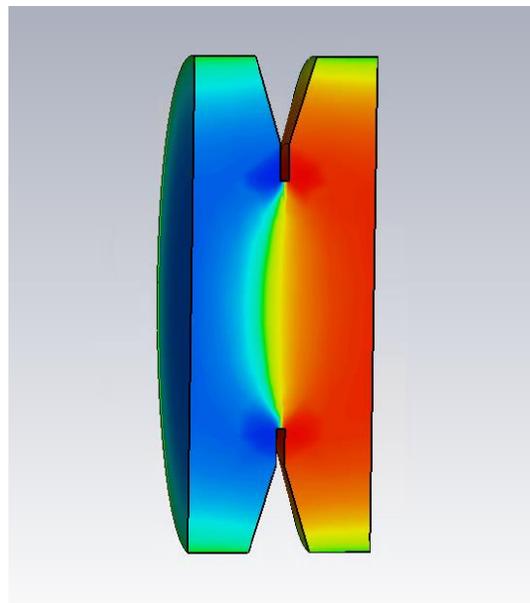
# CST: single-cell geometries, $2\pi/3$ mode



## **Pillbox cavity**

Radius = 12.88 cm  
Iris radius = 6.44 cm

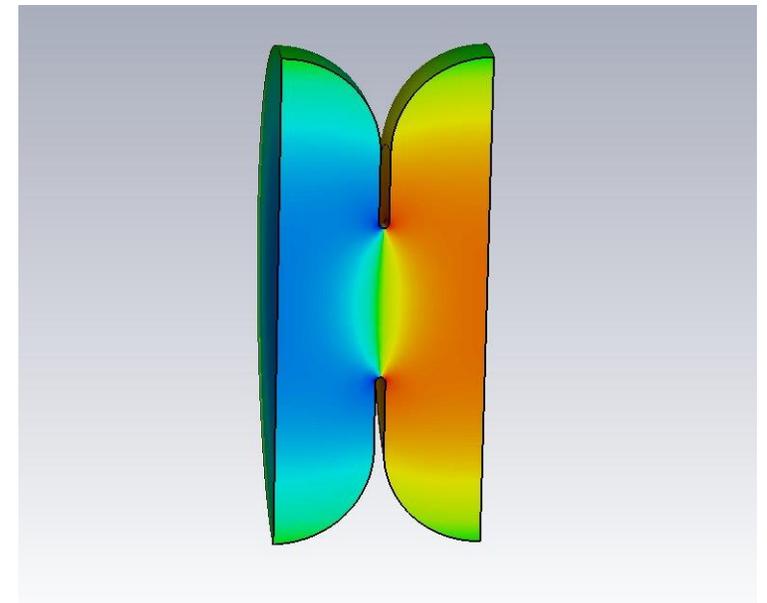
$f = 1000.310$  MHz  
 $Q = 27000$   
 $r/Q = 53.0 \Omega$



## **Chamfered cavity**

Radius = 13.69 cm  
Iris radius = 6.84 cm

$f = 999.921$  MHz  
 $Q = 28700$   
 $r/Q = 48.25 \Omega$



## **Domed cavity**

Radius = 12.94 cm  
Iris radius = 3.97 cm

$f = 999.981$  MHz  
 $Q = 29600$   
 $r/Q = 68.9 \Omega$

# CST v Superfish

## Superfish variant

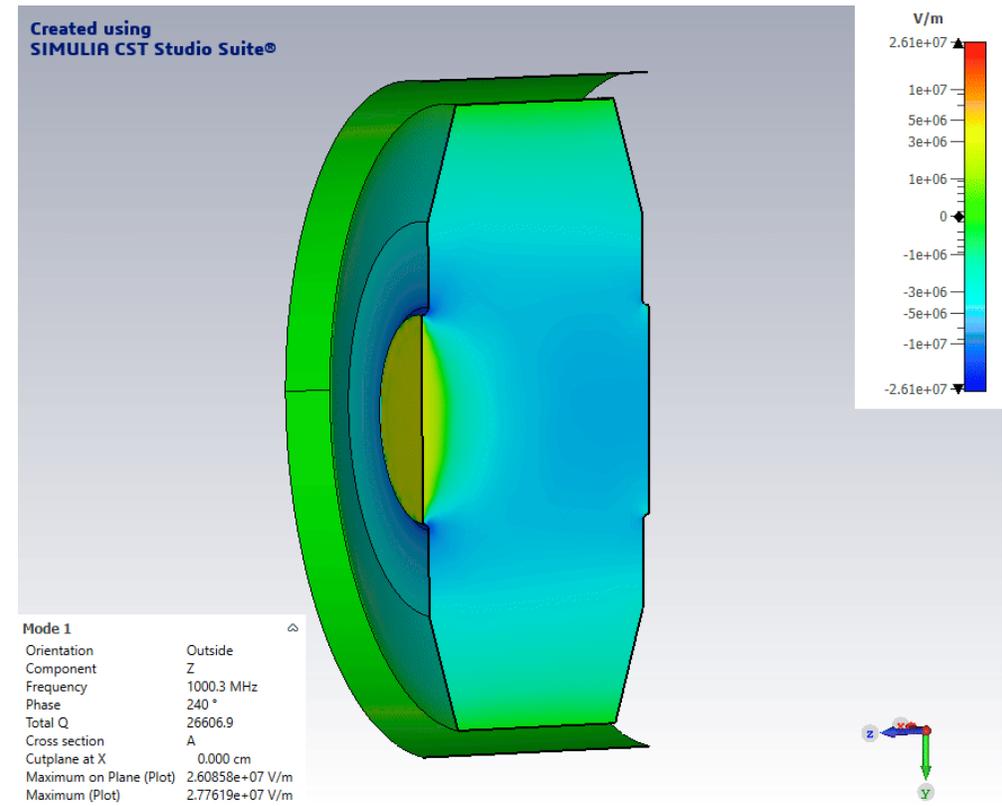
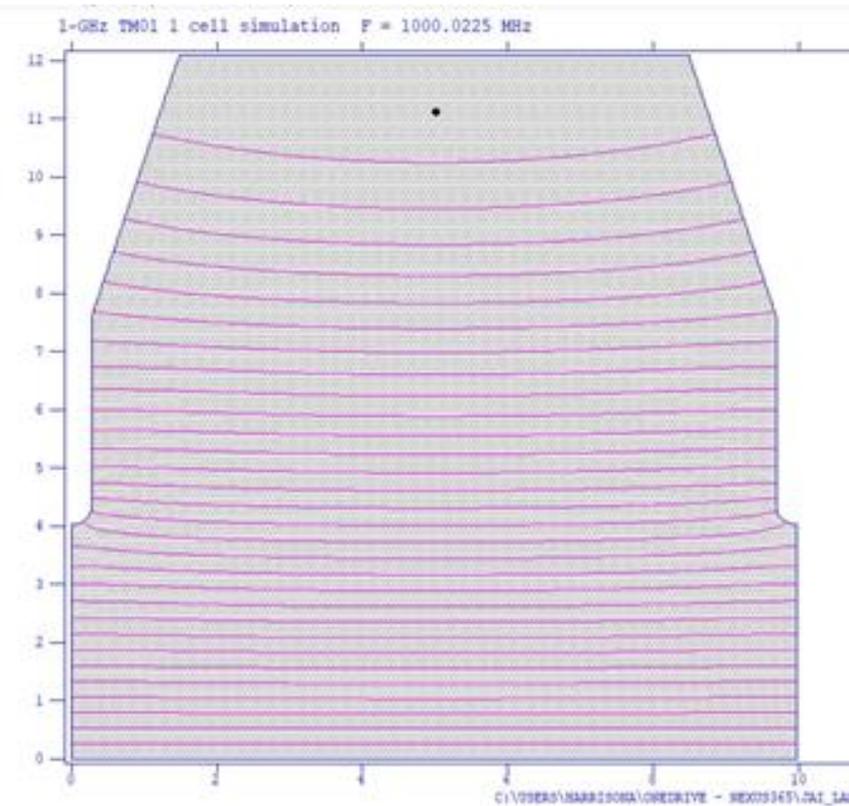
Radius = 12.08 cm  
Iris radius = 4.03 cm

$f = 1000.310$  MHz  
 $Q = 26500$   
 $r/Q = 53.0 \Omega$

## CST variant

Radius = 12.54 cm  
Iris radius = 4.18 cm

$f = 1000.296$  MHz  
 $Q = 26600$   
 $r/Q = 120 \Omega$



# RF Results

- Iris-loaded waveguide structure *is* feasible
- Obtainable minimum parameters

Symbol	Value	Units
<b>E<sub>z</sub></b>	6-9	MV/m
<b>Q</b>	27000	
<b>r/Q</b>	50	Ω

- Further optimization of geometry and full structure still required
  - Full design in CST will require a consideration of input/output waveguides

# Future Work

## Needed for HALHF:

- Acquire accurate travelling wave power dissipation value
  - Requires modelling of coupling cells
  - Will determine if a Superconducting cavity is required instead
- Adapt model into constant gradient structure
  - Variable Iris size to match field attenuation

## Finner additional work:

- Model longitudinal beam dynamics – wake effects
- Beam loading considerations on accelerating field
- Calculate time of flight value for the travelling wave cavity

# Magnet Team

Diya Dipac, Calvin Dyson, Sabrina Wang

# DB Linac Goals and Parameters

- Aim:
  - Test feasibility of scaling up dipoles from CLIC
  - Design compact quadrupole for all field strengths in linac
- Given:
  - 139 full size quadrupoles, 2 half sized quadrupoles at either side

Beam Envelope	0.37 mm with misalignments
Minimum Field Gradient	0.3 T/m ( $k_1 = 1.799 \text{ m}^{-2}$ )
Maximum Field Gradient	30.2 T/m ( $k_1 = 2.264 \text{ m}^{-2}$ )
Full size quadrupole length	0.18 m

# Linac Quadrupole Requirements

Parameter	Value
$B_{\max}$	2.0 T
GFR field purity	$\geq 99.9\%$
Quadrupole length	$>5^*$ aperture radius

- Radius aperture = 7.5 mm (0.3 mm beam envelope + 3-5 mm beam pipe and chamber + 2.2 mm errors)

# Coils

- Air-cooled so current density = 1 A/mm<sup>2</sup>
- Maximum current needed is 70.7 A
  - Minimum area of 70.7 mm<sup>2</sup>
- 2.5 mm gap between coils and yoke:
  - 0.5 mm of conductor insulation
  - 1 mm of ground insulation
  - 1 mm of shimming.
- Extra space:
  - Insulators between turns of coil (1 mm)
  - Additional layer of insulator outside all coils

$$NI = \frac{Bh}{\eta\mu_0}$$

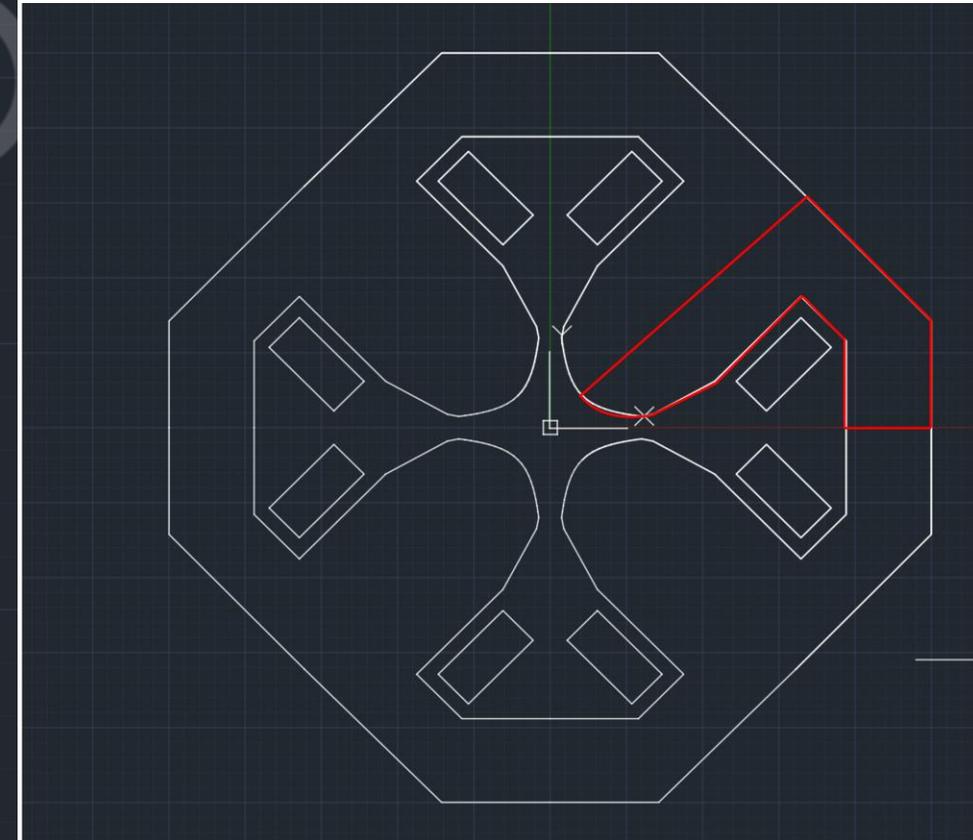
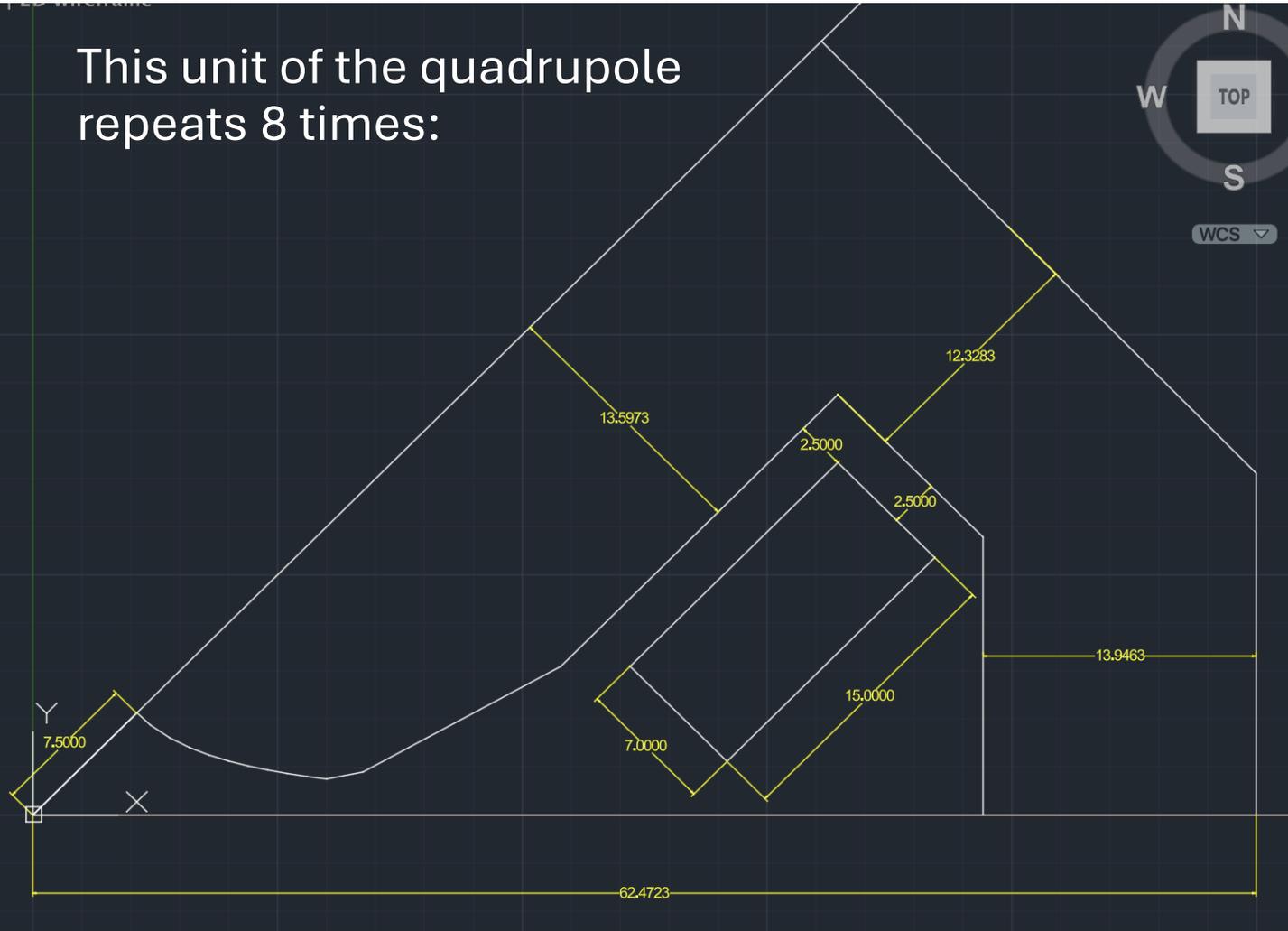
$$I = \frac{(NI)}{N}$$

# Magnet Design Process

- Made a hyperbolic curve using Microsoft Excel (Quad only)
- Imported the curve into AutoCAD and drew the rest of the magnet.
- Imported the AutoCAD magnet design into FEMM 4.2.
- Labelled materials, currents and boundaries.
- Set mesh to obtain fields.

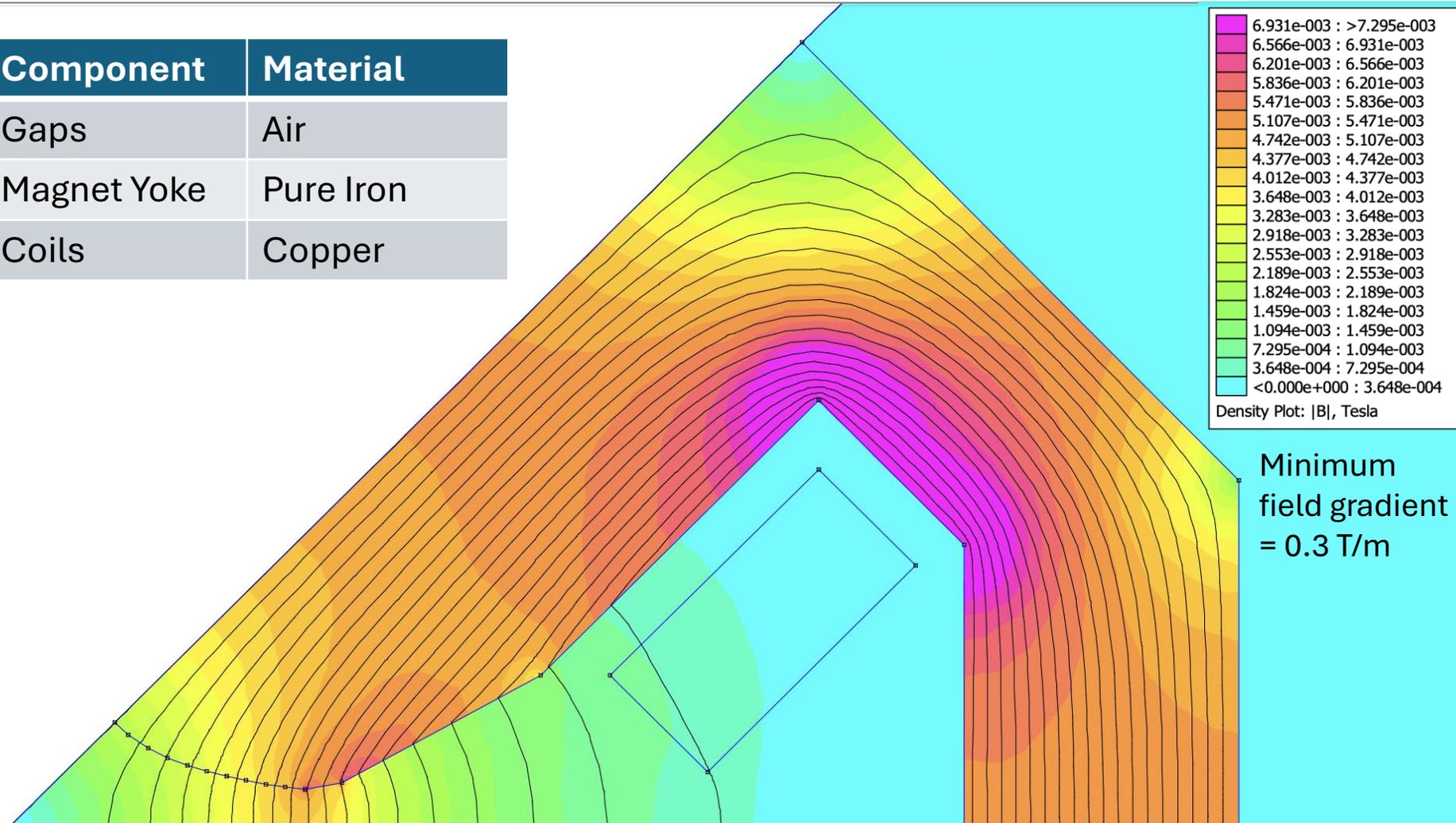
# Linac Quadrupole AutoCAD Design

This unit of the quadrupole repeats 8 times:

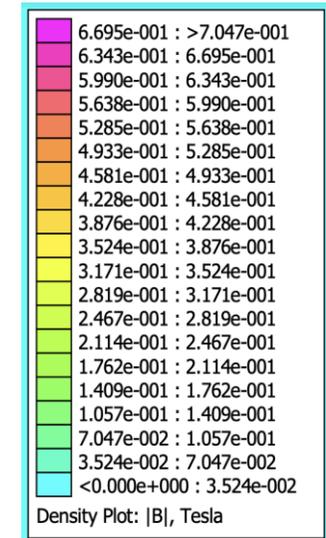


# Field Densities

Component	Material
Gaps	Air
Magnet Yoke	Pure Iron
Coils	Copper



Minimum  
field gradient  
= 0.3 T/m



Maximum  
field gradient  
= 30.2 T/m

# Linac Quadrupole Final Parameters

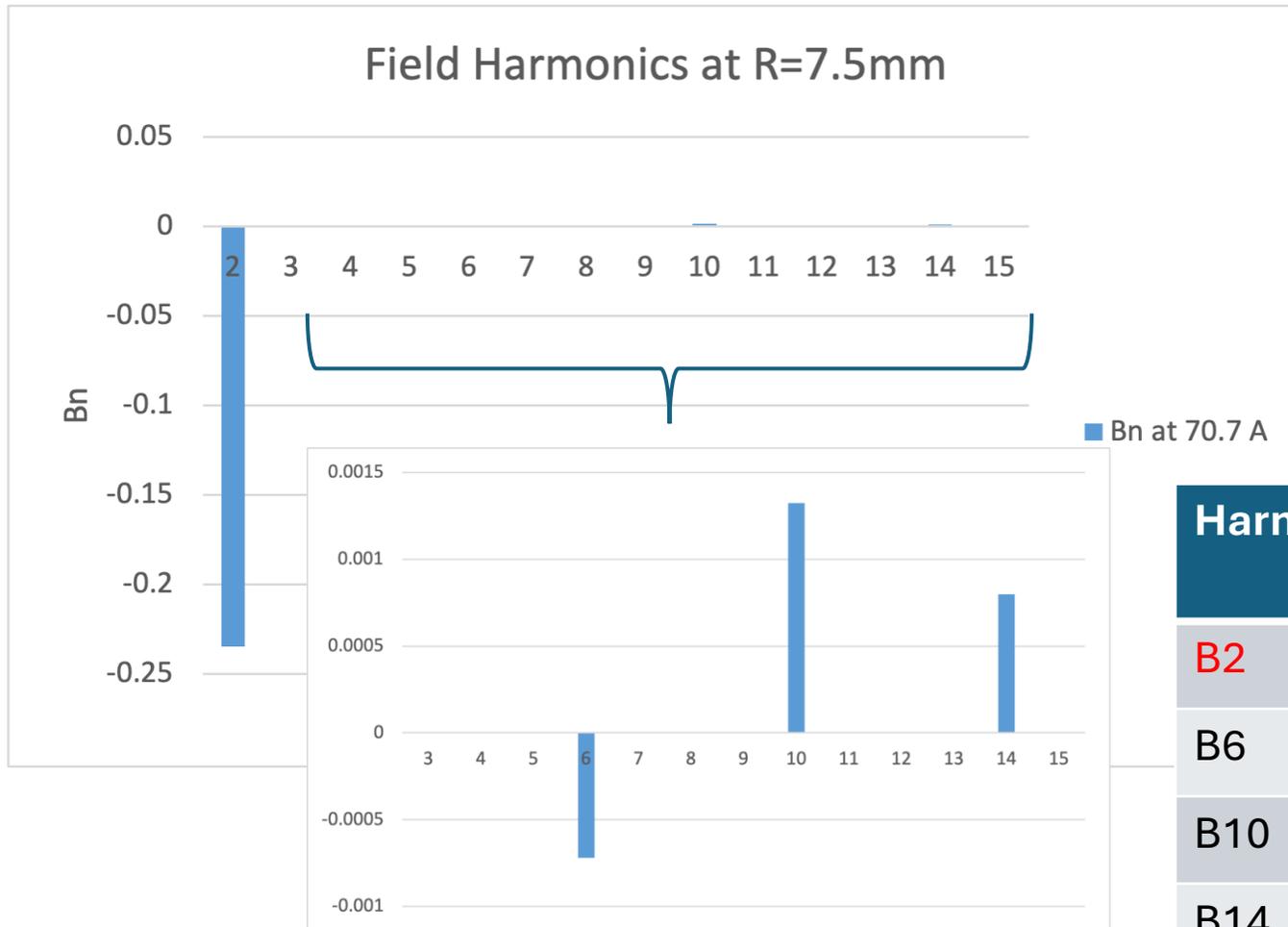
Parameter	Value
Magnet Radius	63 mm
B field energy	2.37021 Joules
Inductance	0.0759 H/m
H	625.142 A/m

# Coil Parameters

Parameter	Value
Current Density	1 A/mm <sup>2</sup>
Dimensions	7*15 mm <sup>2</sup>
Current for min field	0.707 A
Current for max field	70.67 A
Turns	10
Voltage Drop	1.045 Volts
Flux Linkage	0.0671 Webers
Flux/Current	0.000948 Henries
Voltage/Current	0.0148 Ohms
Power	73.87 Watts
Lorentz Force on coil	x-component: 16.42 N y-component: 12.37 N

At maximum field

# Harmonics

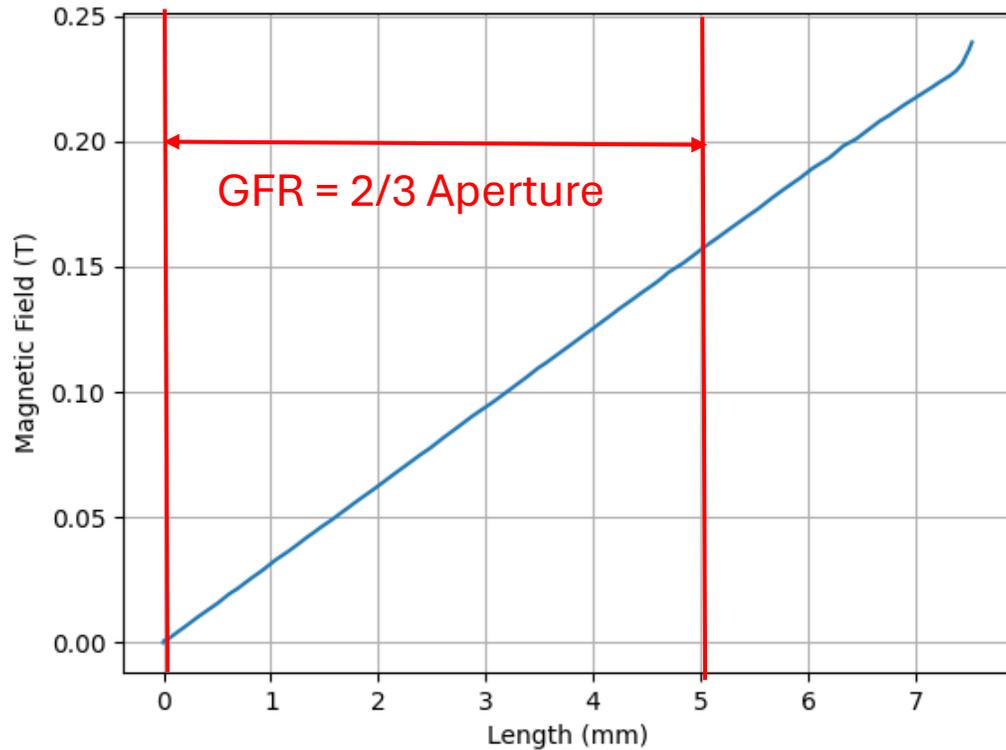


Computed by potential A,  
Skew components =0 here for  
ideal magnets

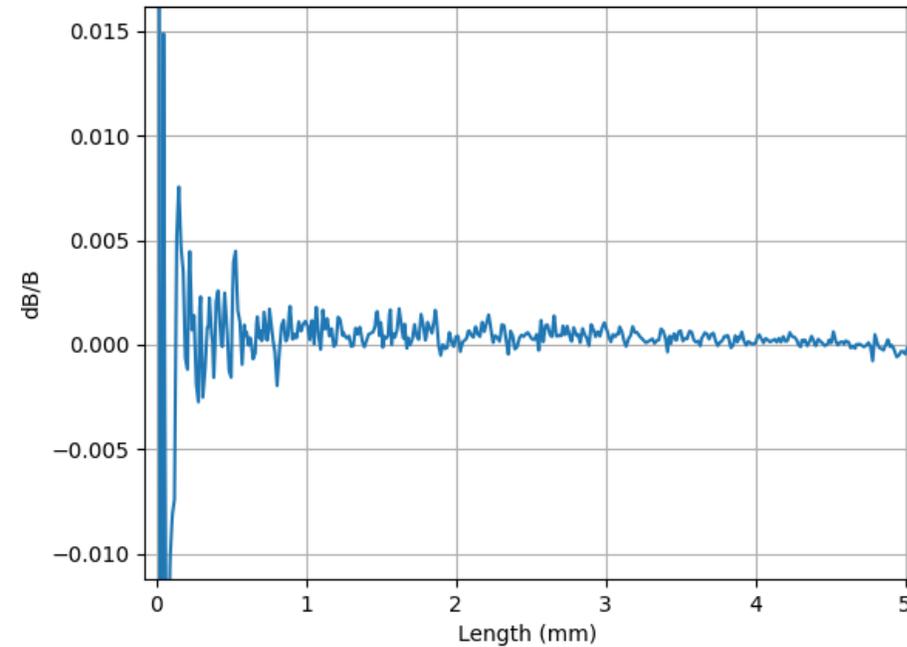
$$B_y(x) = B_2(x/R) + B_6(x/R)^5 + B_{10}(x/R)^9 + B_{14}(x/R)^{13} + \dots$$

Harmonics	Field Strengths (T) (normal)
<b>B2</b>	<b>-0.2349</b>
B6	-7.203 * 10 <sup>-4</sup>
B10	1.3252*10 <sup>-3</sup>
B14	7.970*10 <sup>-4</sup>

# Magnetic Field in Aperture



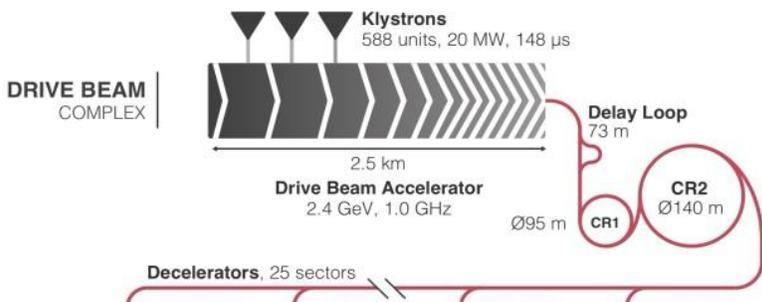
Fitted field gradient  $G = 31.307$  T/m



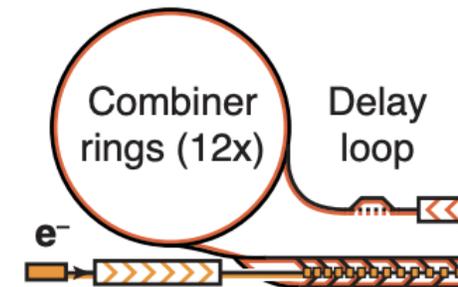
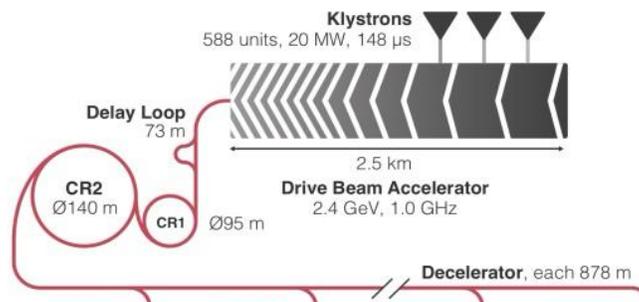
Relative residuals mostly  $<0.1\%$  inside GFR, higher residuals near 0 due to small B

# Combiner Ring Dipole

- Aim: Determine feasibility of CLIC dipoles at HALHF
- 2 types of C-type dipoles at CLIC.
- Dipole lengths,  $L$ , and bending angles,  $\theta$ , extracted from the CLIC PLACET file
- Calculated dipole magnetic field strengths,  $B = B_p * \theta / L$ :
  - $B_1 = 0.679T$
  - $B_2 = 1.29T$



Snapshot of CLIC Drive Beam Complex

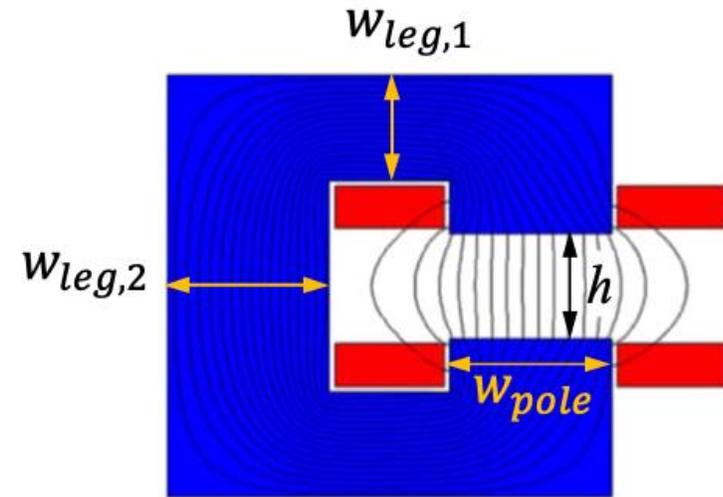


Electron source (1.6 nC)      RF linac (3 GeV e<sup>-</sup>)      (4)

Snapshot of CLIC Recombination Stage

# Iron Yoke Dimensions

- Width of Good Field Region = 60 mm [1]
- Dipole height gap = 30 mm [1]
- 5 mm gap between coil and yoke for insulation
- Air-cooled: current density = 1 A/mm<sup>2</sup>
- Copper Capacity: 70%



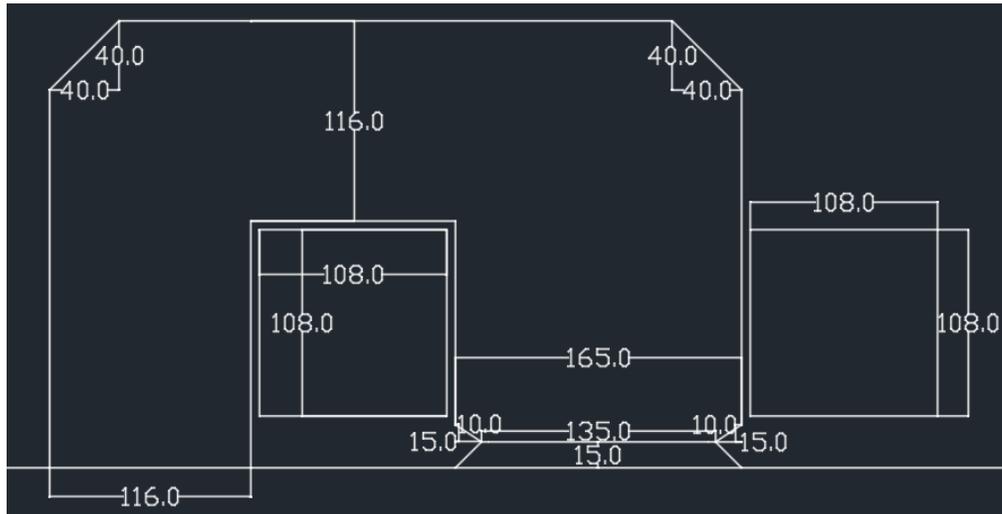
$$NI = \frac{Bh}{\eta\mu_0}$$

$$w_{pole} \cong w_{GFR} + 2.5h$$

$$B_{leg} \cong B_{gap} \frac{w_{pole} + 1.2h}{w_{leg}}$$

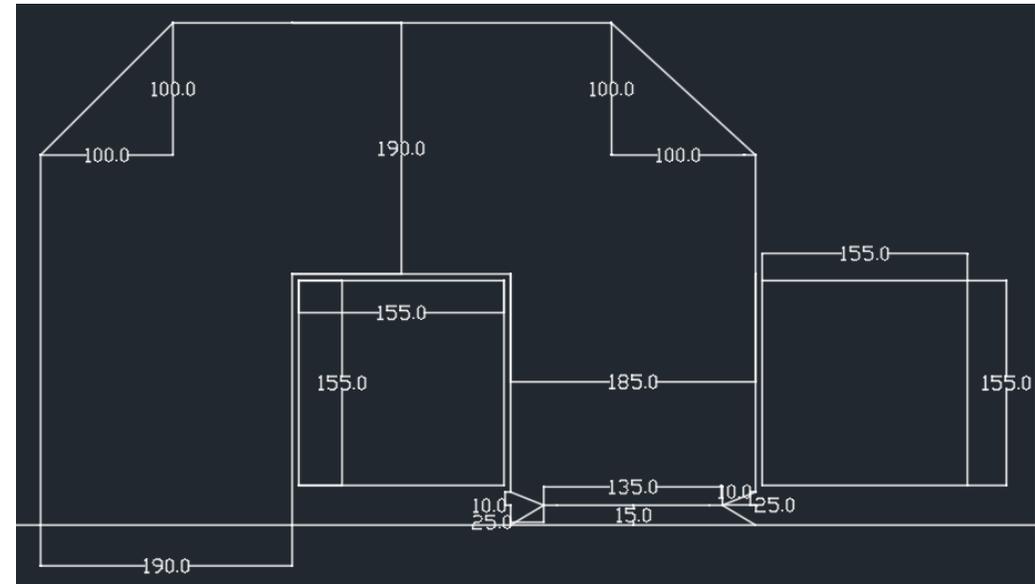
# Combiner Ring Dipole AutoCAD Design

D1: B = 0.679T



Generated from AutoCAD

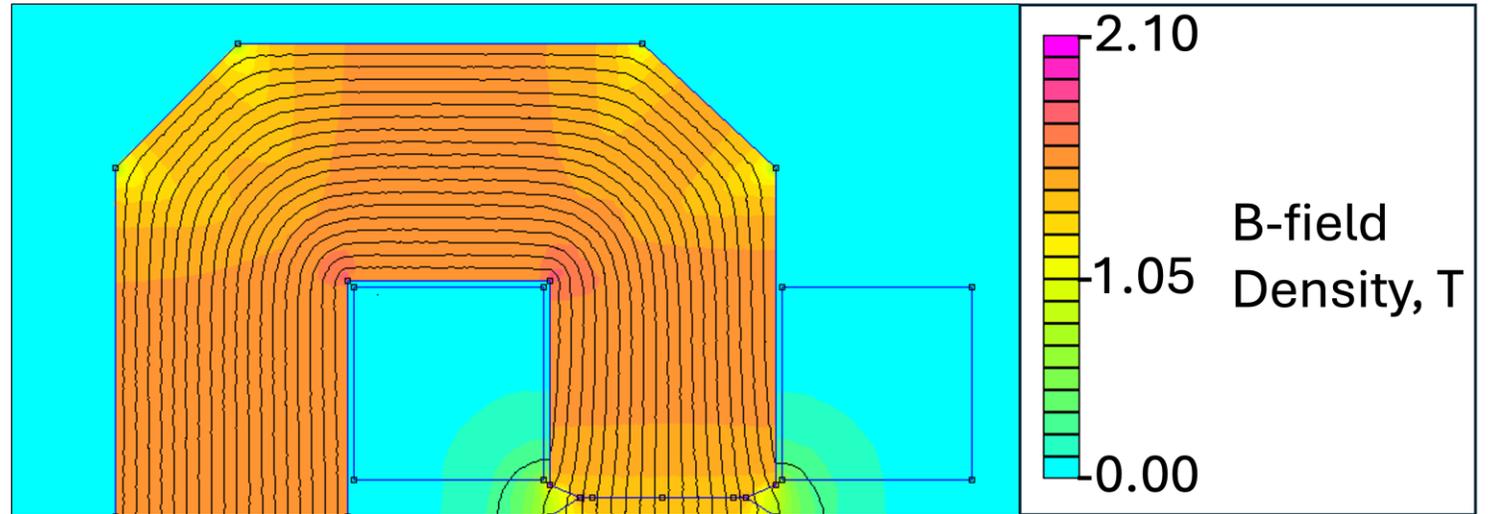
D2: B = 1.29T



Generated from AutoCAD

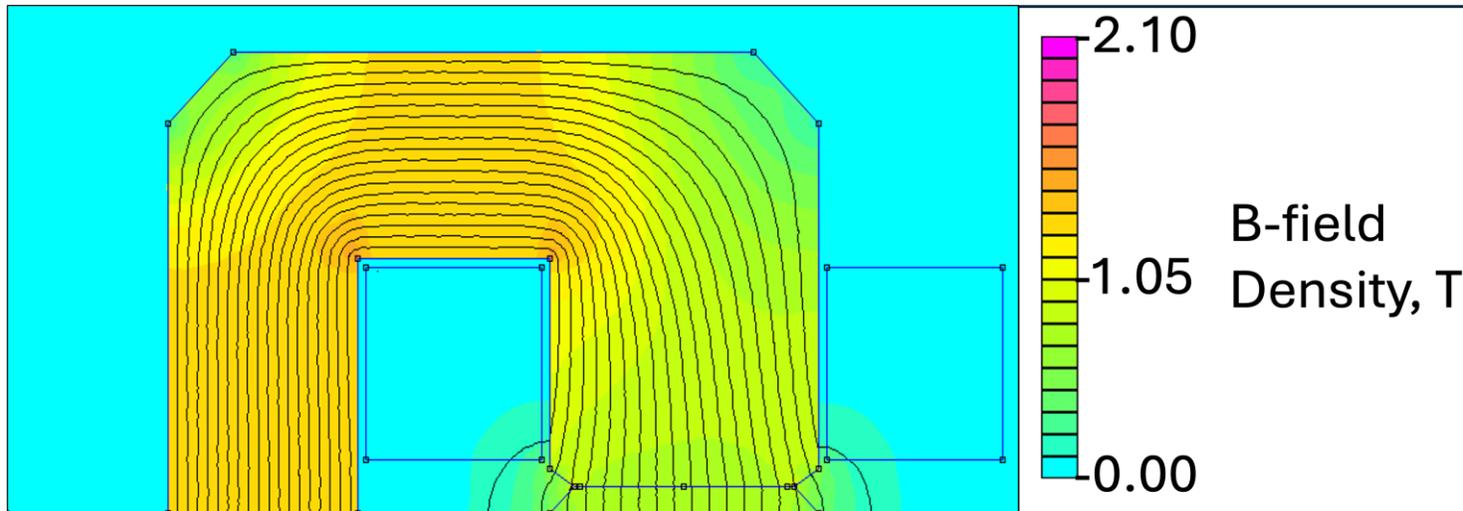
# Field Density Maps

D2 B-field strength: 1.29 T



Generated in FEMM

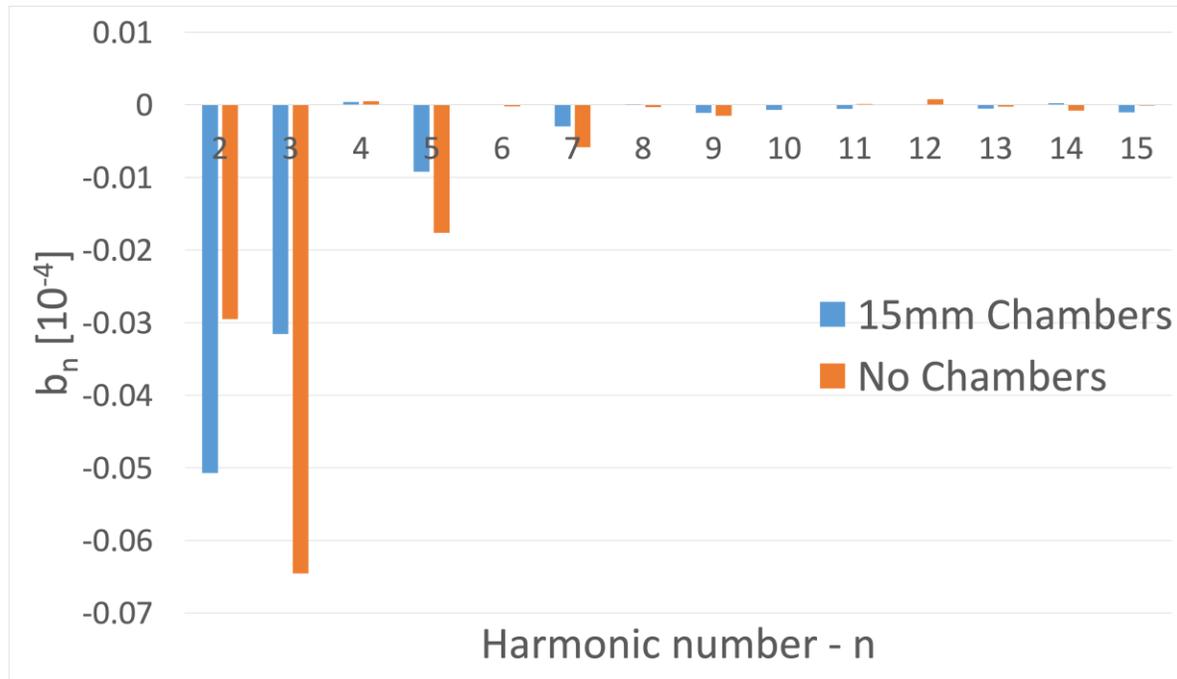
D1 B-field strength = 0.679 T



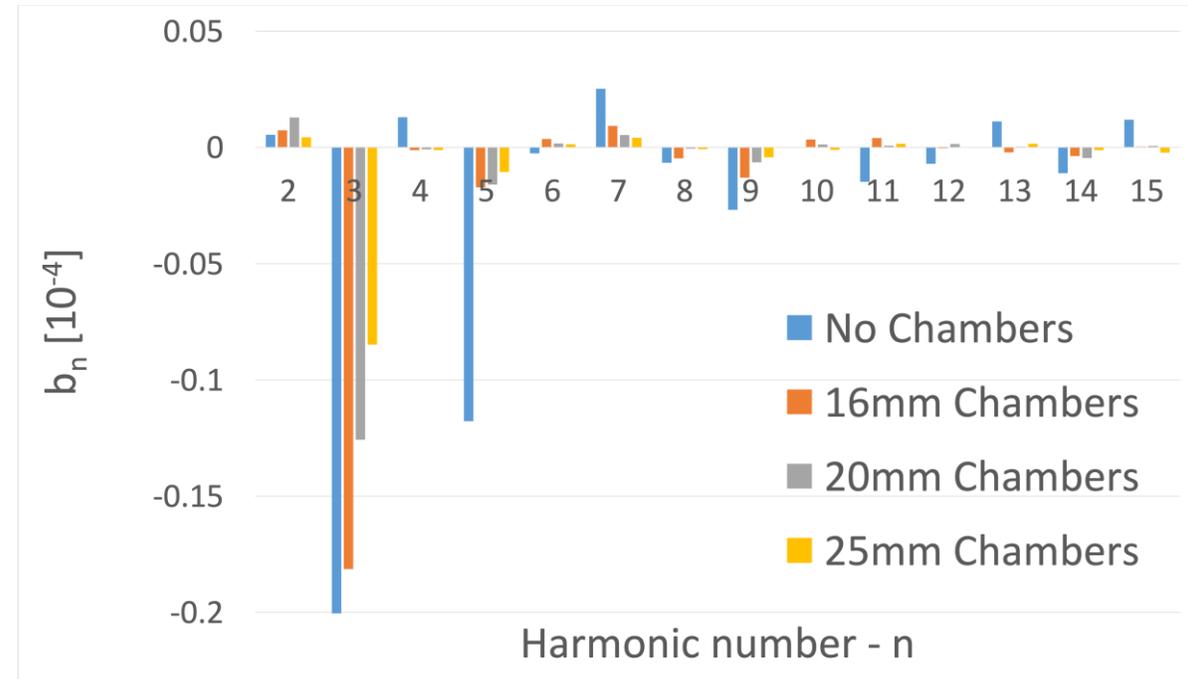
Generated in FEMM

# Field Harmonics

D1: B = 0.679T

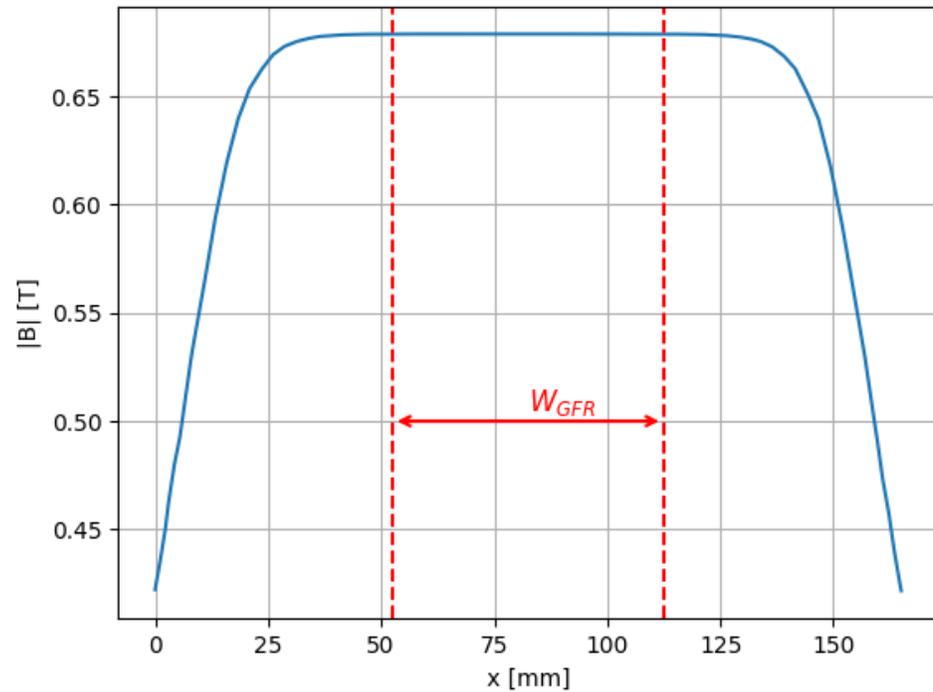


D2: B = 1.29T

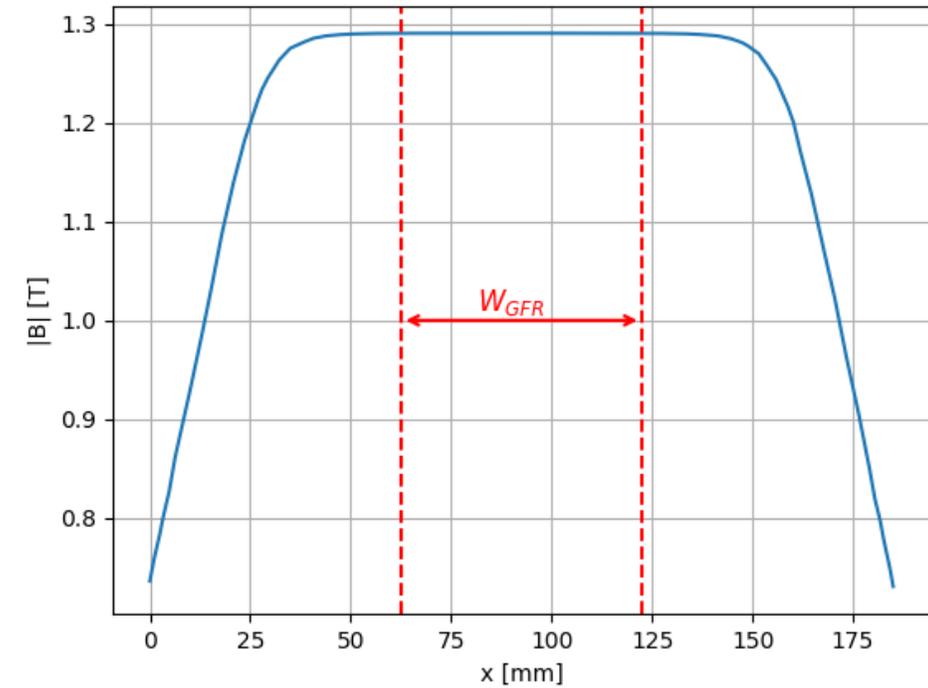


# B field across the Gap

D1:  $B = 0.679\text{T}$

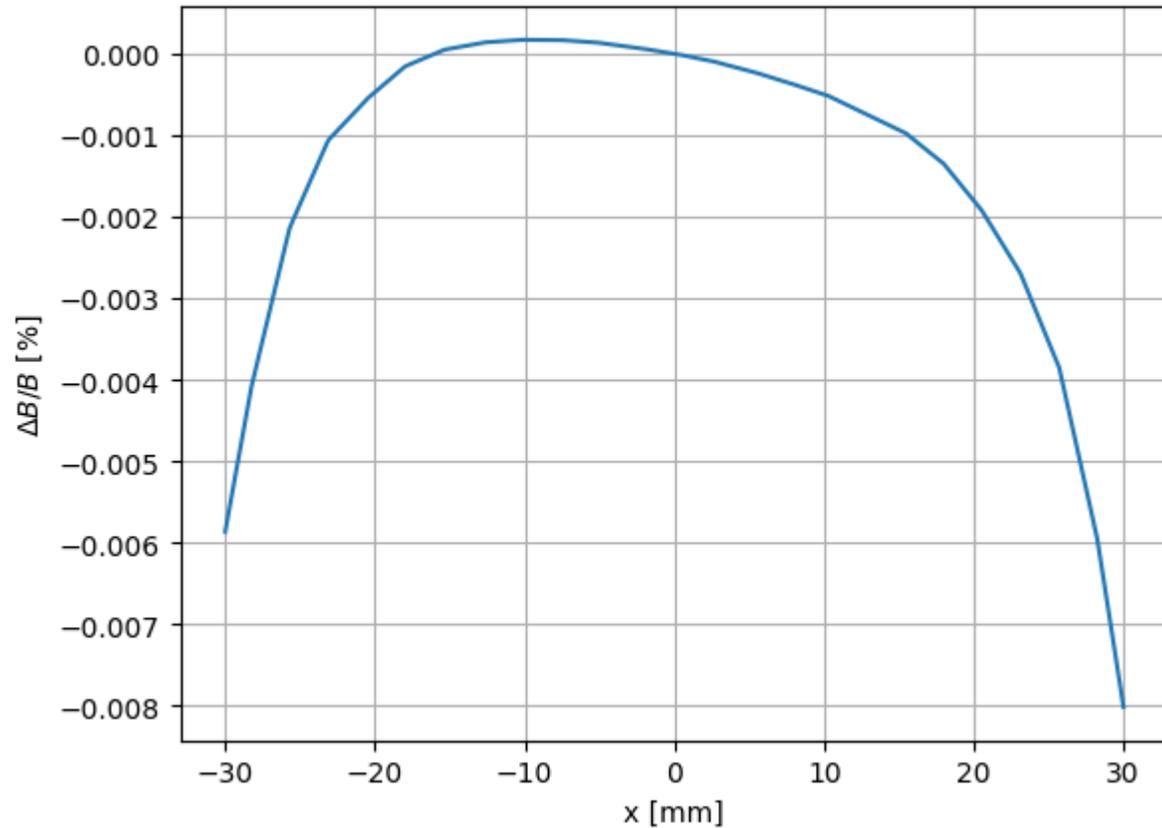


D2:  $B = 1.29\text{T}$

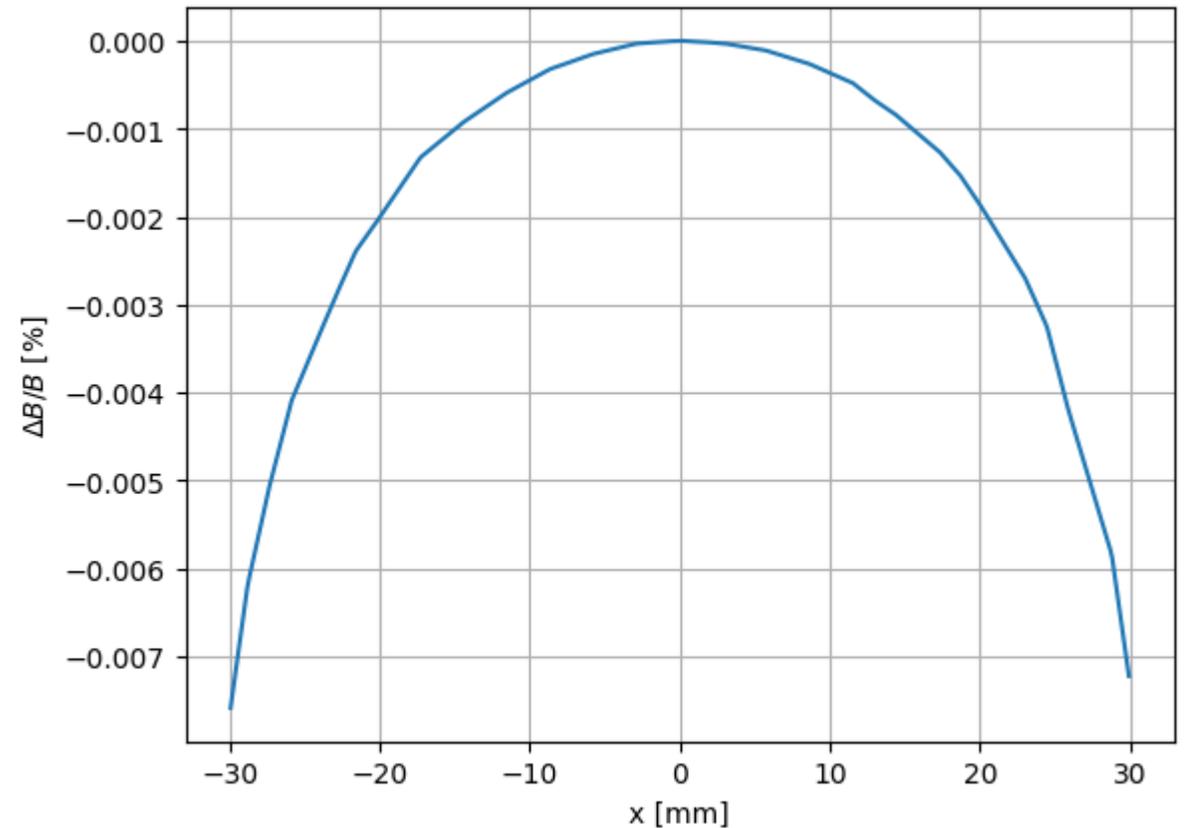


# Magnetic Field in Aperture

D1:  $B = 0.679\text{T}$



D2:  $B = 1.29\text{T}$



# Future Work

- Design the sextupoles in the drive-beam linac
- Design the quadrupoles in the combiner ring
- Design the sextupoles in the combiner ring
- 3D design of magnets in OPERA for edge effects
- Obtain a better understanding of the beam optics to accurately determine whether the CLIC CR2 can be scaled up for the requirements of HALHF

# Sustainability

- Air-cooling coils use less energy than water-cooling coils
- Total power required for quadrupoles in linac: **5.54 kW**
- Total power required for dipoles in combiner ring: **36.4 kW**
- Normal-conducting magnets and RF cavities, so no need for cryogenic cooling
- Minimum power required for RF acceleration:
  - 4 nC to 4 GeV in roughly 10  $\mu$ s >> **1.5 MW**

# Conclusion

- Lattice / Optics Team:

- Designed and optimised a LINAC from a single FODO cell based on CLIC design.
  - Ensured that 4 GeV/c is reached
  - Preserved low emittance and beam size

- Radio-Frequency Team:

- Iris-loaded waveguide design suitable for cavity, accelerating gradient above specification ( $> 4$  MV/m) achievable
- Need further work to design input/output couplers and more accurately determine power dissipation

- Magnets Team:

- Designed two types of quadrupoles for the drive-beam linac: lengths = 0.18 m and 0.09 m; magnetic field gradient = 0.3 T/m to 30.2 T/m
- Designed two types of dipoles for the combiner ring: magnetic field strengths = 0.679 T and 1.29 T