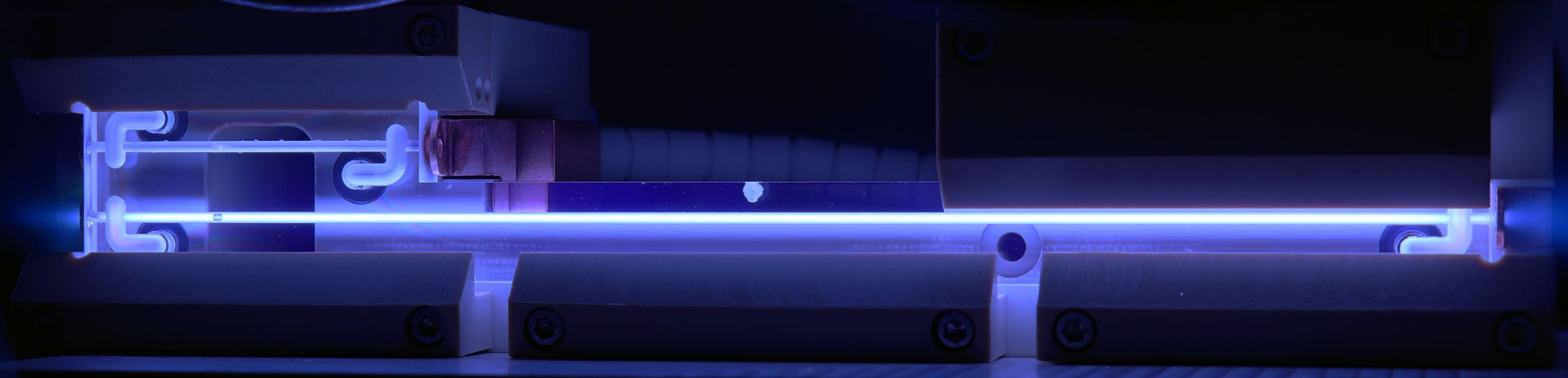
JAI Postgrad Project Progress Report:
Design of the HALHF Drive-Beam Complex



Richard D'Arcy

John Adams Institute, University of Oxford

on behalf of the JAI 1st yr PhD students

UNIVERSITY OF OXFORD

27th Feb 2025 | HALHF Workshop | Online / DESY, Hamburg

JAI Postgraduate Project

Accelerator project for 1st yr PhD students (Oxford, Imperial, RHUL)

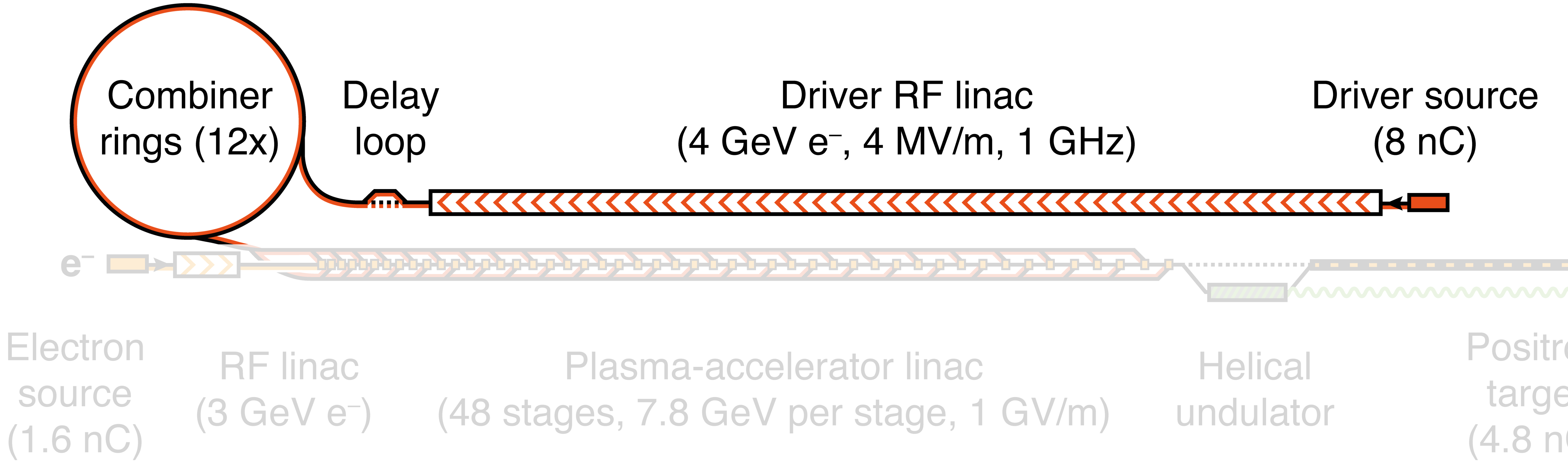
- The project is the focus of the 2nd term of work for the 1st yr PhD students
- An accelerator concept is chosen
  - Previous examples include the FCC, HL-LHC, etc.
  - This year HALHF
- The team is broken down in to small groups with each group working on a subsystem

The Drive-Beam Complex

The main (non-plasma) area of developmental need for HALHF

> The drive-beam linac is the cost driver of the HALHF facility (~40% of the total cost) ➞ klystrons, cavities, rings

> Design and beam parameters are intrinsically linked to the plasma accelerator and its operation



> Very similar to the CLIC drive-beam complex

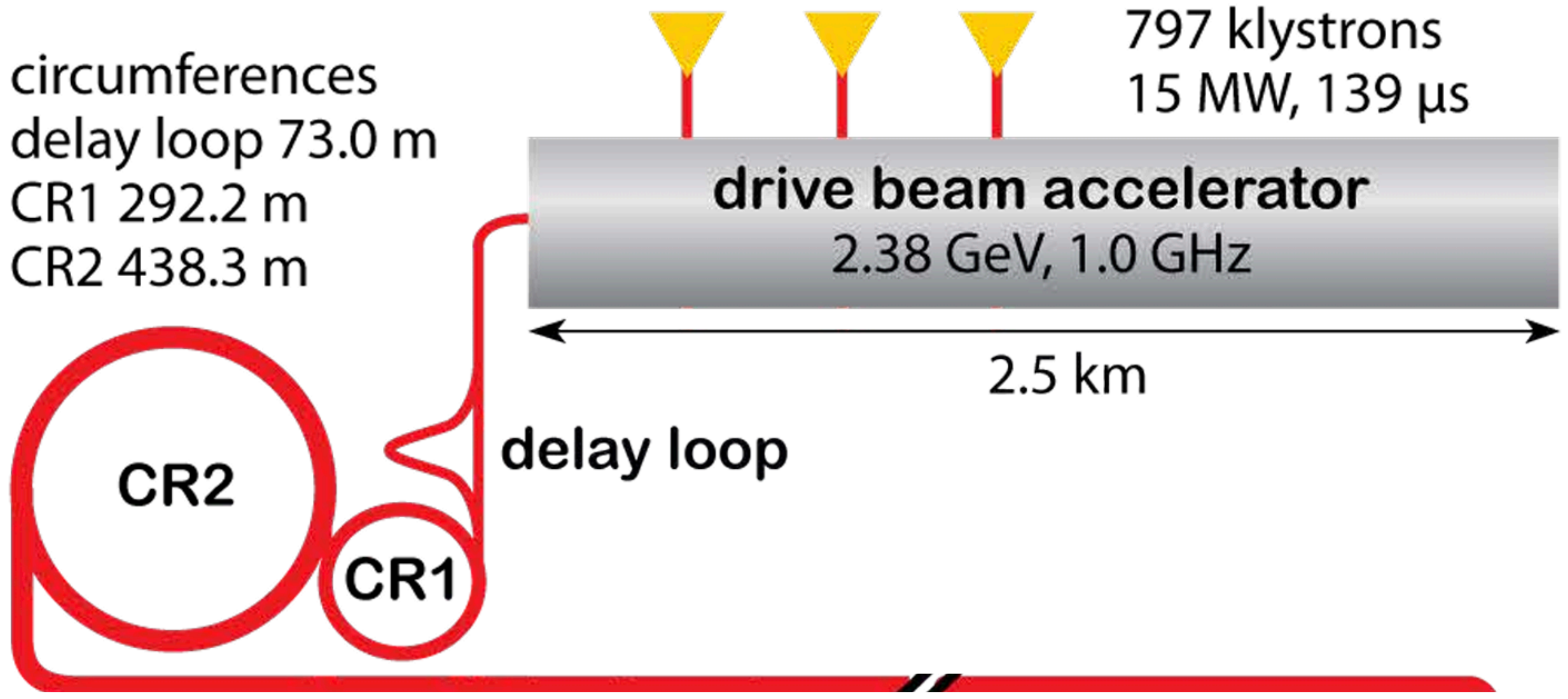
> Drive-beam energy: 2.4 GeV (CLIC) ➞ 4 GeV (HALHF)

> Accelerating gradient (average): 1 MV/m ➞ 3 MV/m

> Linac length: 2.5 km ➞ 1.3 km

> Bunch charge: 8.4 nC ➞ 8 nC

> Final bunch spacing: 0.0167 ns ➞ 0.167 ns

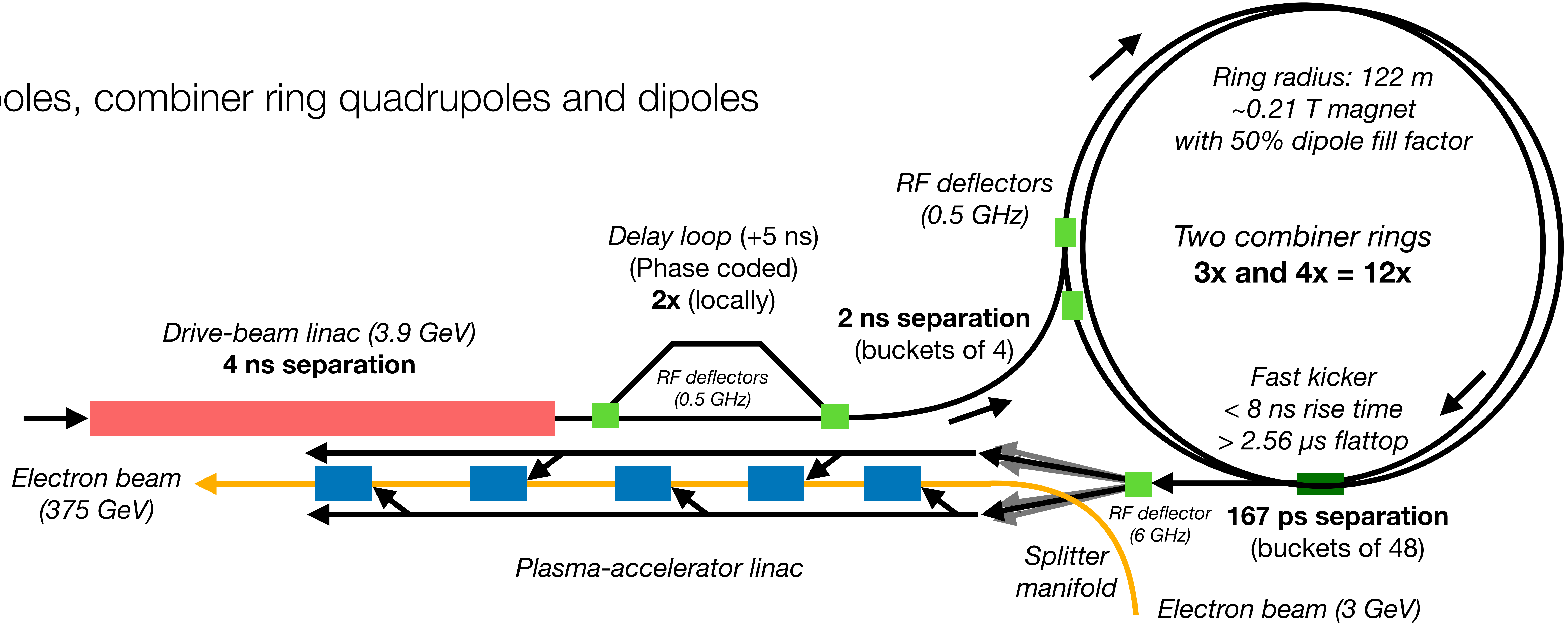


CLIC Drive-Beam Complex. Source: CLIC CDR

Three overlapping subsystems require attention

Optics, RF, and magnets

- **Beam optics**: linac, delay loop, combiner rings
- **RF**: accelerating cavities
- **Magnets**: linac quadrupoles, combiner ring quadrupoles and dipoles



- **General strategy**: Use CLIC as baseline ➞ develop according to CLIC parameters ➞ adjust for HALHF

Optics studies

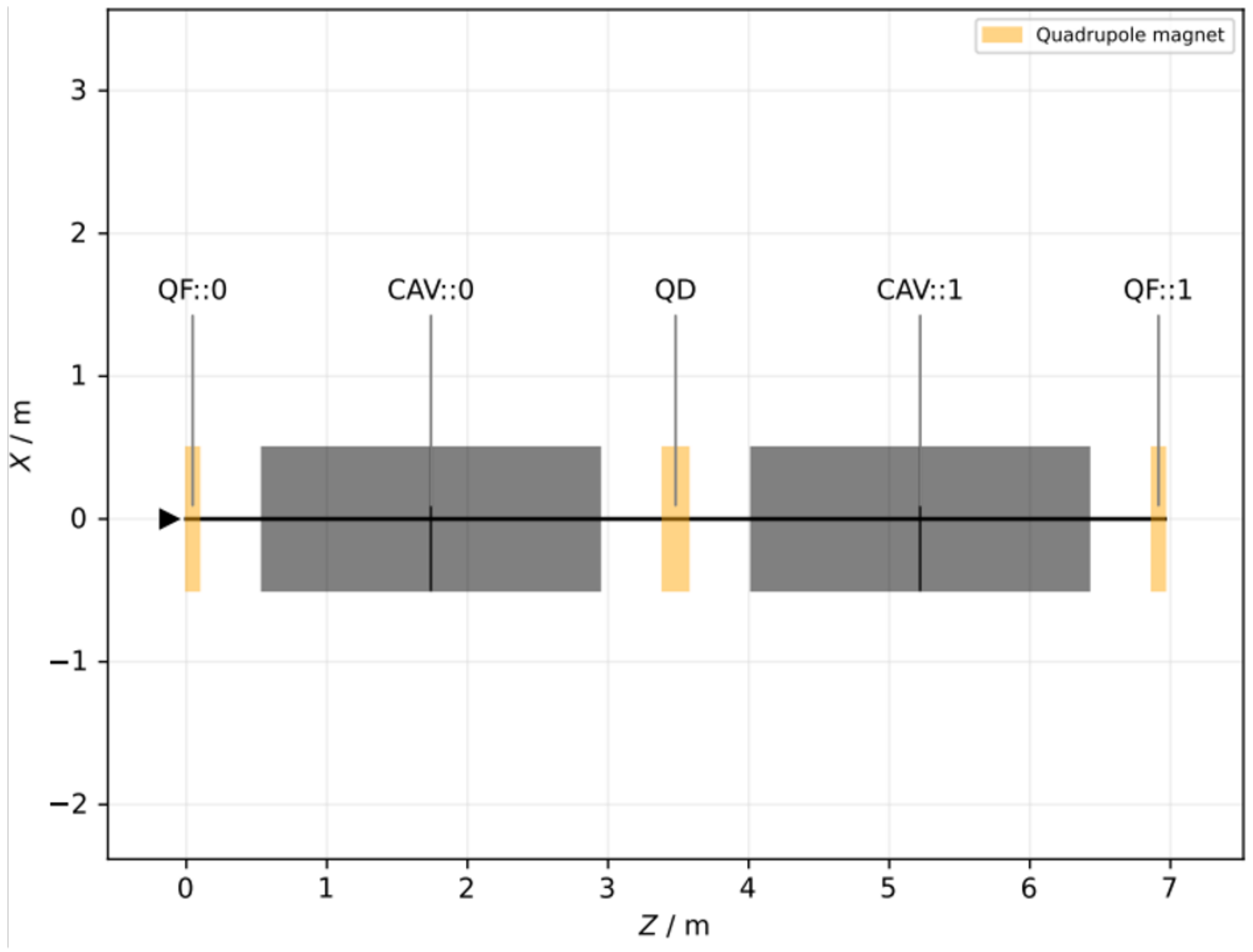
Joshua Appleby, Louis Forrester, Nela Sedlackova

- **Goals**
  - Optimise for optics and beam parameters
  - Transport beams with minimal losses
  - Minimise emittance growth
  - Control energy spread
  - Maximise the filling factor of the RF system (relative to magnet system)
  - Considers physical limitations

Driver linac

Optics studies

- Initial designs for FODO cell and subsequent linac
- Mapped out FODO, delay loop, and combiner rings (XSuite)
  - Cavity 2.4 m, Quad 0.18 m, Drift 0.45 m
  - 6.96 m FODO cell
- Require 206 FODO cells to accelerate the particles fully
  - 206 x 6.96 = 1.434 km
- Physical constraints sent to the RF team



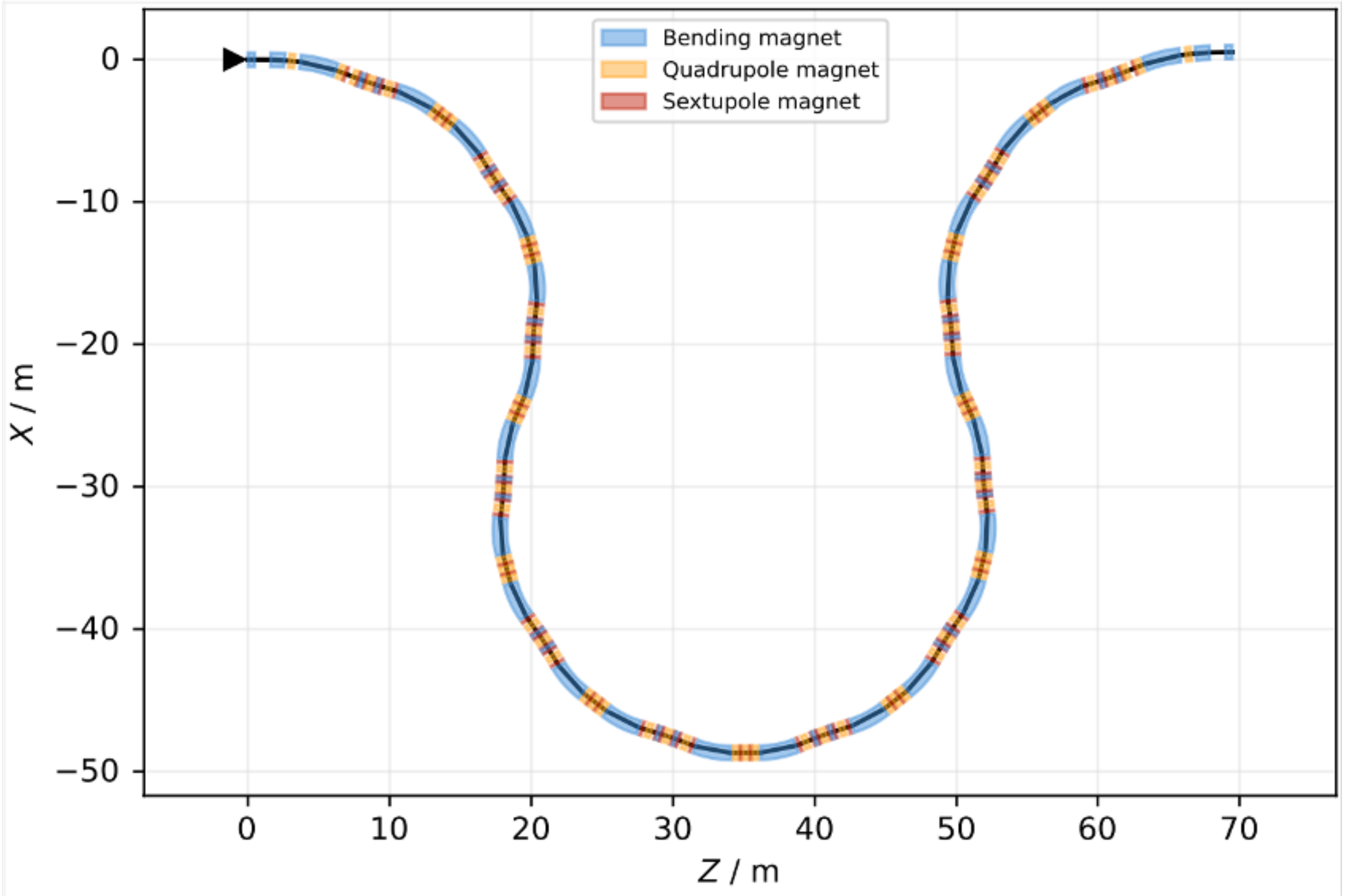
Delay Loop and Combiner Ring

Optics studies

> Start with CLIC delay loop with length of 144 m

> One symmetry point in the centre of the loop

> Use X-Suite to rescale to 1.5 m and reappropriate for 4 GeV electrons



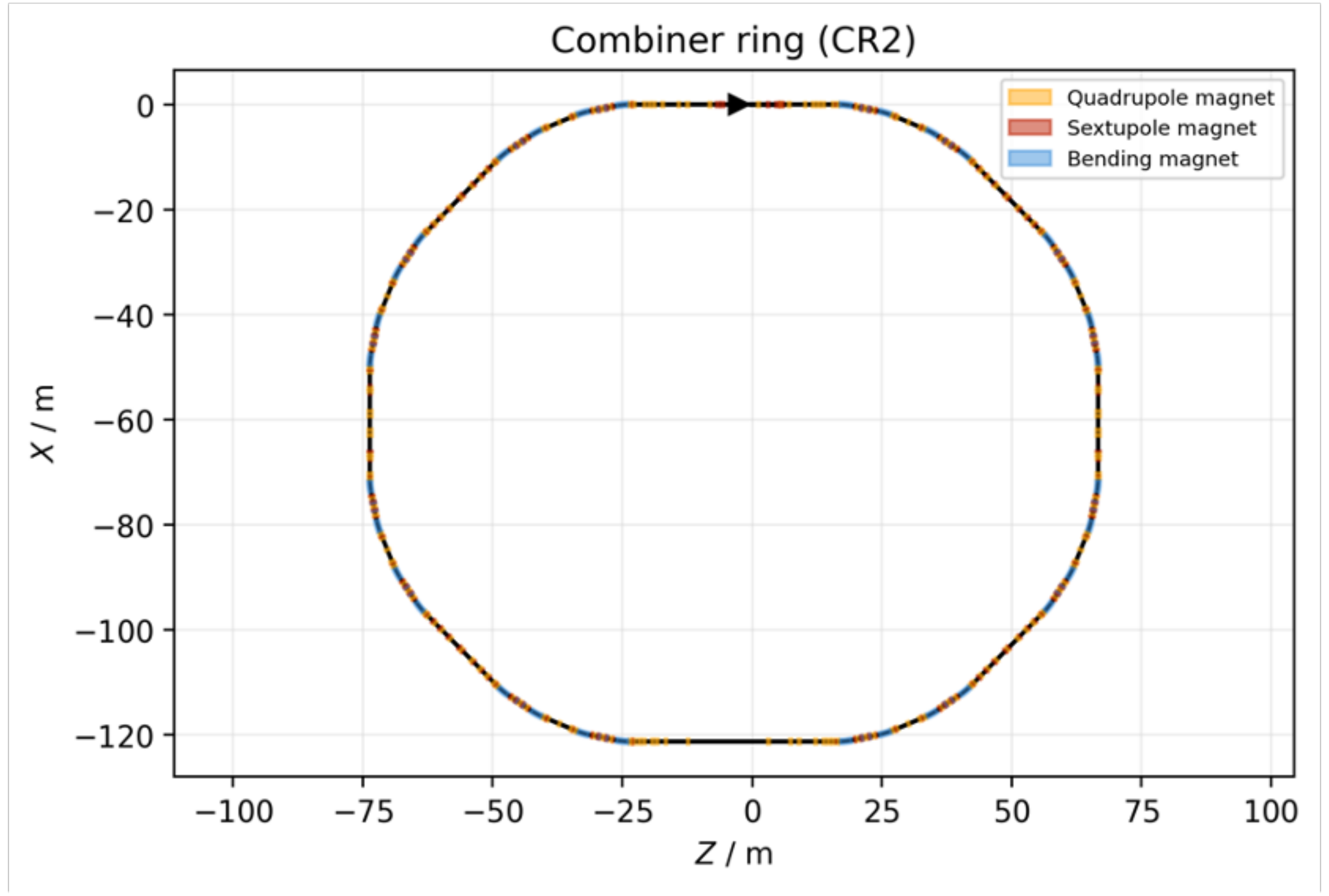
> 8x Arcs

> 4x Corner Linacs

> 2x Side Linacs

> 1x Top Linac

> 1x Bottom Linac



Next steps

Optics studies

- Use RF_Track to enable full simulation of linac ➞ delay loop ➞ combiner ring
  - Will have the ability to load and save the parameters in human readable files
  - This will also include optics matching and chromaticity matching functions
- Introduce misalignments
- Rescale delay loop and combiner ring for a 4 GeV system
- Incorporate RF design and Magnet design using RF_Track interface

RF design

Alex Harrison, Ibrahim Najmudin, James Thistlewood

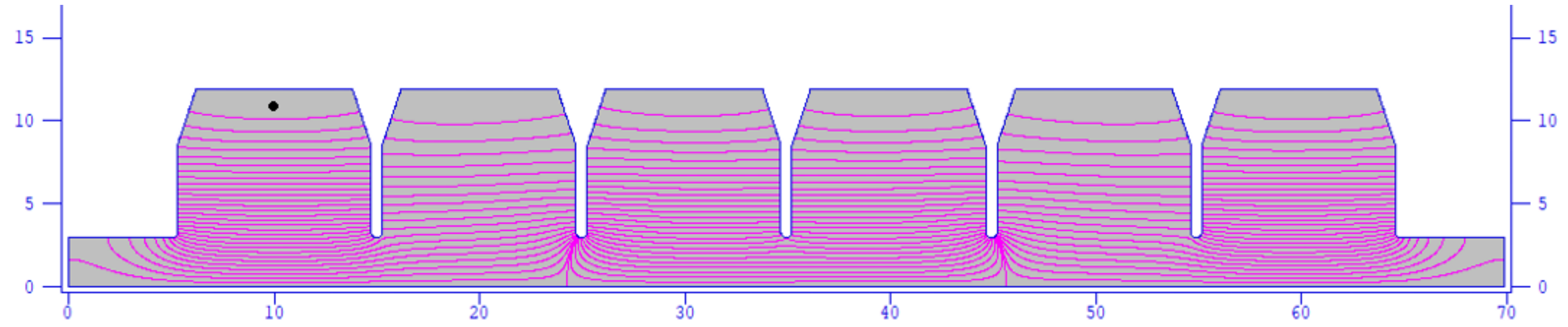
> **Goals**

- Model an appropriate iris-loaded travelling wave (TW) cavity structure over the 2.4 m cavity sections (defined by the optics team)
- Model iris aperture decrease to keep E_z field constant over the cavity
- Increase average accelerating gradient to shorten driver linac
- Optimise key parameters such as quality factor , shunt impedance, and others whilst keeping build tolerances feasible

Superfish simulations of RF cavities

RF design

- **Physical constraints**
  - FODO cell length: 7m
  - Average accelerating gradient: 3 MeV/m
- **Acceleration constraints**
  - Starting energy: 50 MeV
  - Final energy: 4 GeV
  - Wave type: Travelling wave
  - Total cavity length: 890 m (of 1.3 km total length)
  - Accelerating length: 2x 2.4 m of TW cavity per FODO
  - Matched beta: 0.994877 (start), 0.999936 (end)



Design of an initial 6 cell cavity with input/output beam pipe

- **Current design parameters**
  - Radius (b) = 11.73 cm
  - Iris aperture (a) = 2.93 cm
  - Beam pipe = 5cm input/output
  - Phase advance per cell = $2\pi/3$
  - Frequency = 1000.01777 Hz
  - Q = 26198
  - Rs = 58.9
  - r/Q = 4.09

Next steps

RF design

> Calculate necessary aperture variation for constant E field, variable impedance structure

> Try multiple geometry types with increased area/volume for large impedance, increasing aperture size.

> Work with the beam optics team to increase the gradient and reduce beam emittance growth

Magnet design

Diya Dipac, Calvin Dyson, Sabrina Wang

> **Goals**

- Design the quadrupole magnets of the drive-beam linac
- Design the dipole magnets of the combiner ring
- Design the quadrupole magnets of the combiner ring
- Use the baseline design of the CLIC drive-beam complex's delay loop and combiner ring as a starting point by extracting its parameters
- CLIC drive-beam complex is designed for an energy of 2.4 GeV, so its parameters must be scaled up for an energy of 4 GeV for the HALHF drive-beam linac

Drive-beam linac quadrupoles

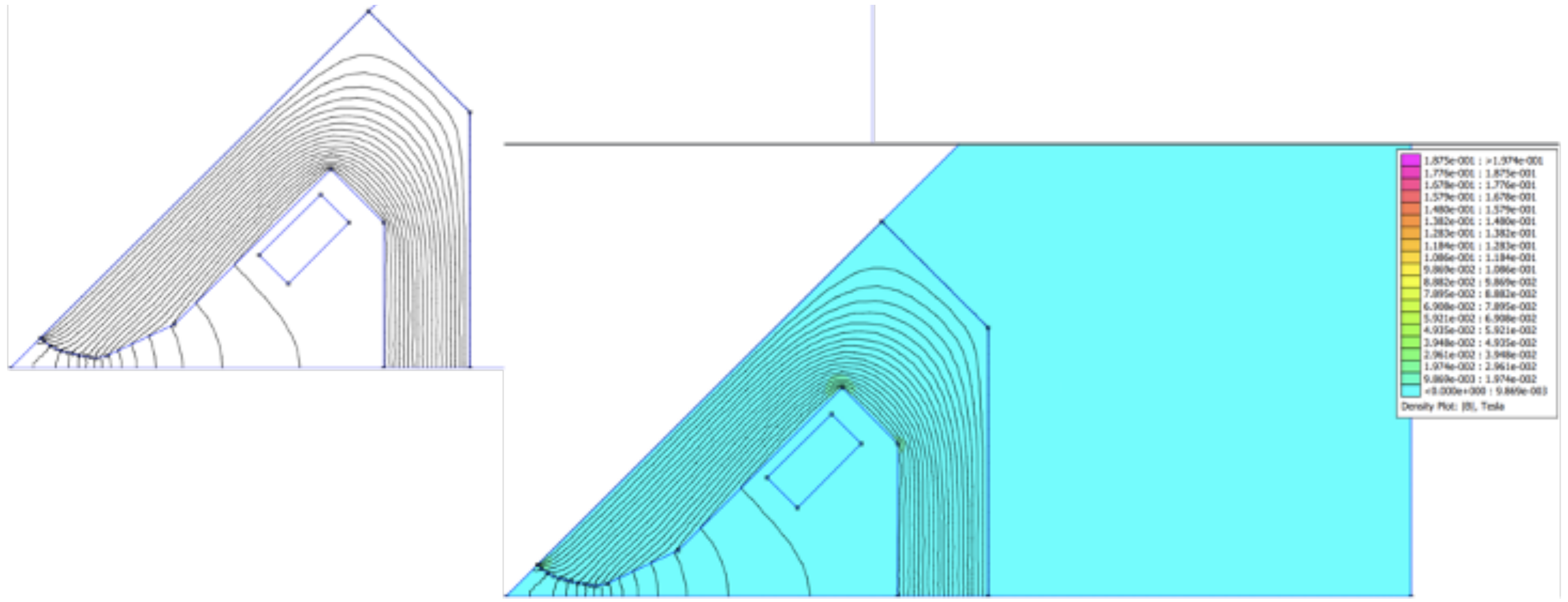
Magnet design

- Radius aperture = 7.5 mm (0.3 mm beam envelope + 3-5 mm beam pipe and chamber + 2.2 mm errors)
- Made a hyperbolic curve using Microsoft Excel
- Imported the curve into AutoCAD and drew the rest of the magnet
- Imported the AutoCAD magnet design into FEMM 4.2, in which the materials, currents, and boundaries were set to obtain fields
- This unit of the quadrupole repeats 8 times and it is 160 mm wide
- The beam optics group provided us with values for the magnetic field gradient of 0.3 Tm^{-1} to 30.2 Tm^{-1}, and quadrupole lengths of 0.09 m and 0.18 m
- Quadrupole length should be greater than at least 5 times the radius of the aperture (> 0.0375 m) to have minimal edge effects, which is satisfied with both of these lengths

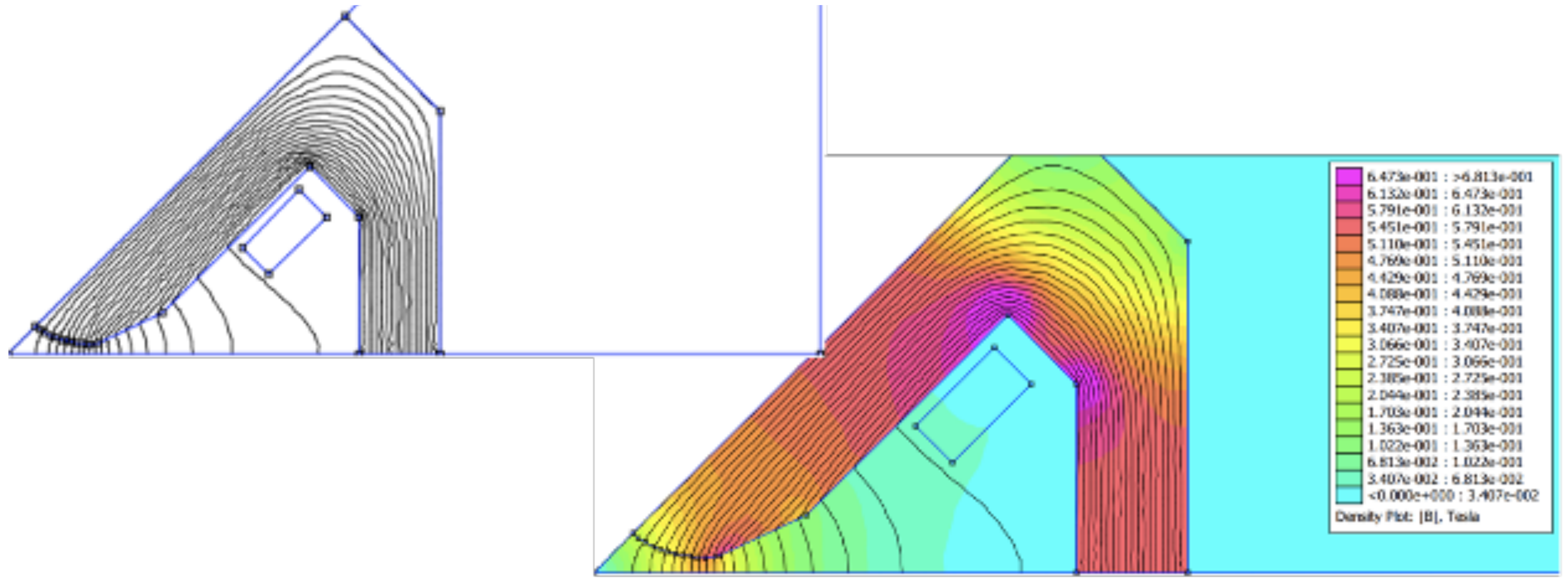
Drive-beam linac quadrupoles

Magnet design

- Calculated coil size using required current
  - Used current density of 1 Amm^{-2} for air-cooling system
  - Chose 10 turns, and needed a minimum area of 72 mm^2
  - Designed coil area of 7*15 mm^2 to allow for some extra margin
- B-field along x-axis shows a linear B-field in position within the good field region, which is what we want



Field vectors (left) and field density (right) for magnetic field gradient of 0.3 Tm^{-1}

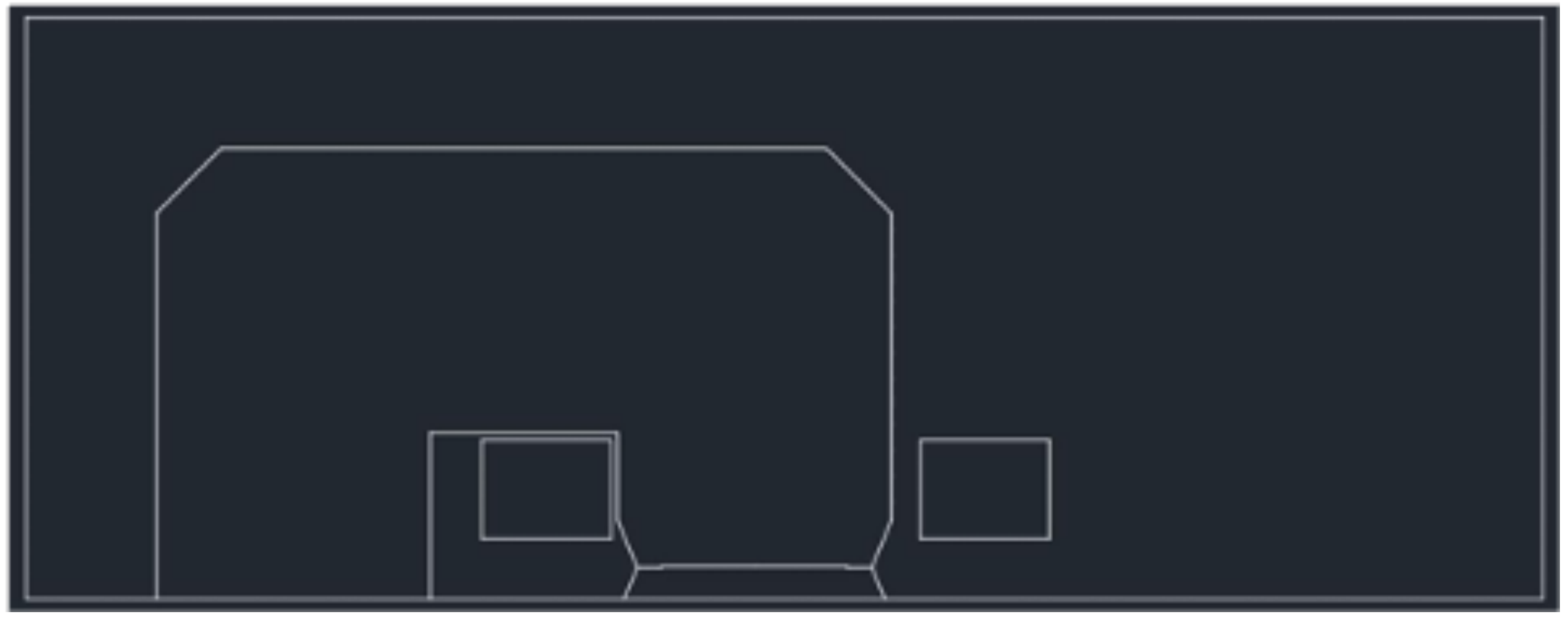


Field vectors (left) and field density (right) for magnetic field gradient of 30.2 Tm^{-1}

Combiner ring dipoles

Magnet design

- Extracted dipole lengths, L, and bending angles, θ, from the CLIC PLACET file. Calculated Bρ using a beam energy of 4 GeV for HALHF
- Calculated dipole magnetic field strengths, B, using the equation $B = B\rho^*\theta/L$:
  - B1 = 0.680 T
  - B2 = 1.289 T
- Created a template for the dipole magnet using AutoCAD
- Working with C-type magnets
- Waiting for required height and good field region width from the beam optics group to calculate the dimensions and coil size of the magnets



Template of the dipole magnet using AutoCAD

Next steps

Magnet design

> Make the drive-beam linac quadrupole magnet’s legs shorter to use space more efficiently

> Wait for beam optics group to provide us with specifications so that we can design the quadrupole and dipole magnets of the combiner ring

Remaining timeline of JAI project

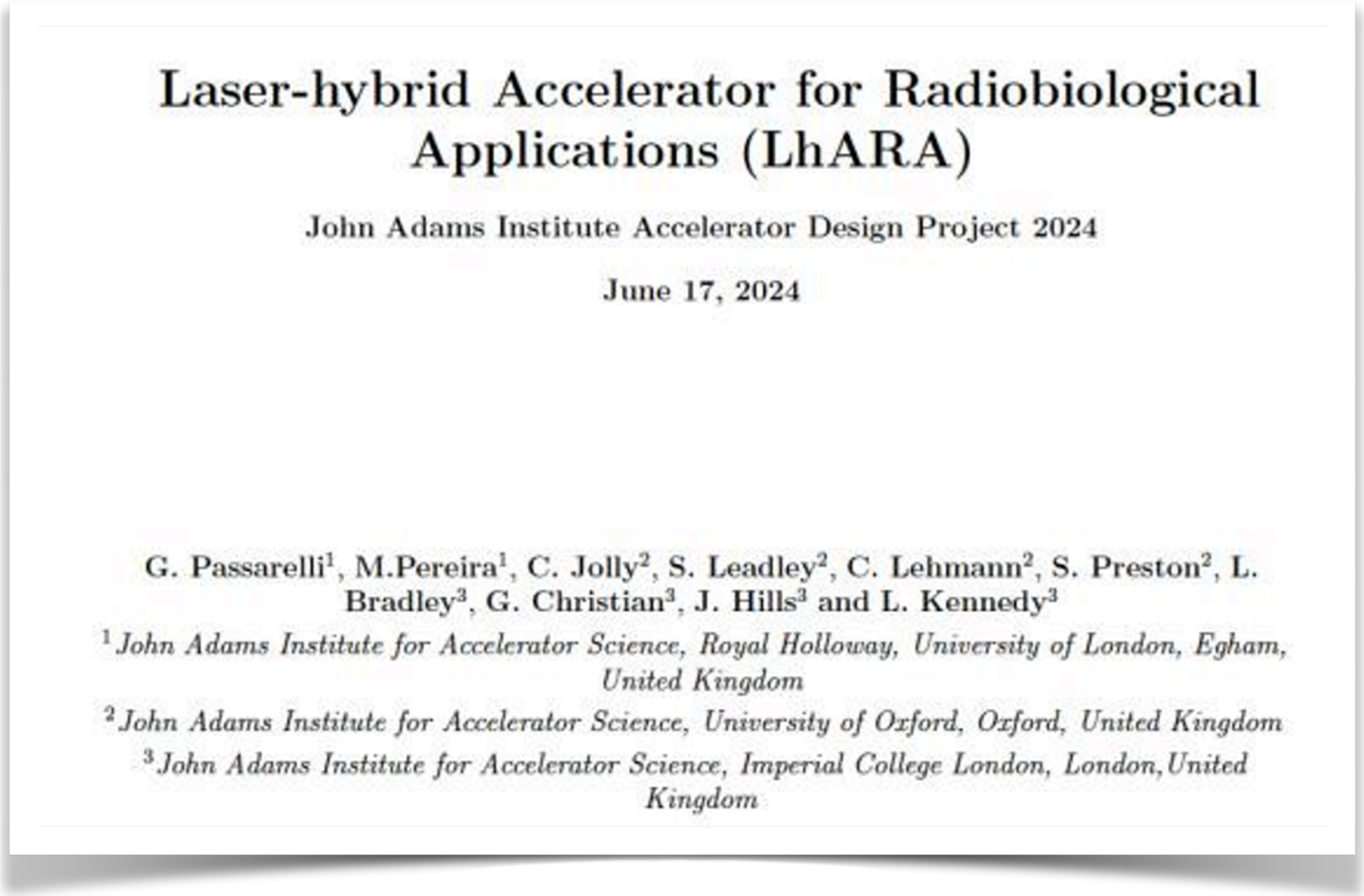
Presentation, written report, and seminar

> Presentation of final findings — 13/03/25

> **Submission of written report** — ~07/04/25

> Seminar at the JAI Advisory Board Meeting — 24/03/25

> Presentation of results at CERN — 11/07/25



Laser-hybrid Accelerator for Radiobiological Applications (LhARA)

John Adams Institute Accelerator Design Project 2024

June 17, 2024

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