

Electron Accelerator Lattice Design for LHeC With Permanent Magnets

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Abstract: We present a new 'green energy' approach to the 60GeV electron Energy Recovery Linac (ERL) of LHeC using a single beam line made of combined function permanent magnets, using a Fixed Field Accelerator (FFA) design with very strong linear gradients. We are basing our design on recent successful commissioning results of the Cornell University and Brookhaven National Laboratory ERL Test Accelerator "CBETA" in 2019-20.

INTRODUCTION

- Future Electron Ion Colliders (EICs) could be ‘green energy colliders’ as Energy Recovery Superconducting Linacs (ERLs) can be used to make energy fully recovered.
- Electron beam is brought back to the linac by a single **permanent magnet** beam line **without requiring electric power, reducing the estimated wall power of 100 MW in the present LHeC design to a negligible power for arcs.**
- The single beam line transports all electron energies at once using the Fixed Field Alternating Gradient (FFA) principle with **very strong focusing.**
- The design is based on experience from the successful commissioning of the **Cornell University and Brookhaven National Laboratory Energy Recovery Test Accelerator – “CBETA”.**
- The green EIC of the CERN Large Hadron Collider - **LHeC** is presented, as well as an alternative design for the PERLE ERL.
- The **FFA non-linear gradient design is a racetrack shape**, where, as in CBETA, the arcs are matched by an adiabatic transition to the two straight sections.
- Two 10 GeV superconducting linacs are placed on both sides of the Interaction Region (IR) to reduce the power of synchrotron radiation loss significantly.

OUTLINES

RLA or ERL's advantages for EICs:

- Smaller beam-beam effect in a single pass during every collision,
- Reduced total synchrotron radiation power
- Disruption of stored electrons is not so important, lower operating and building cost.
- Lowest dump energy.

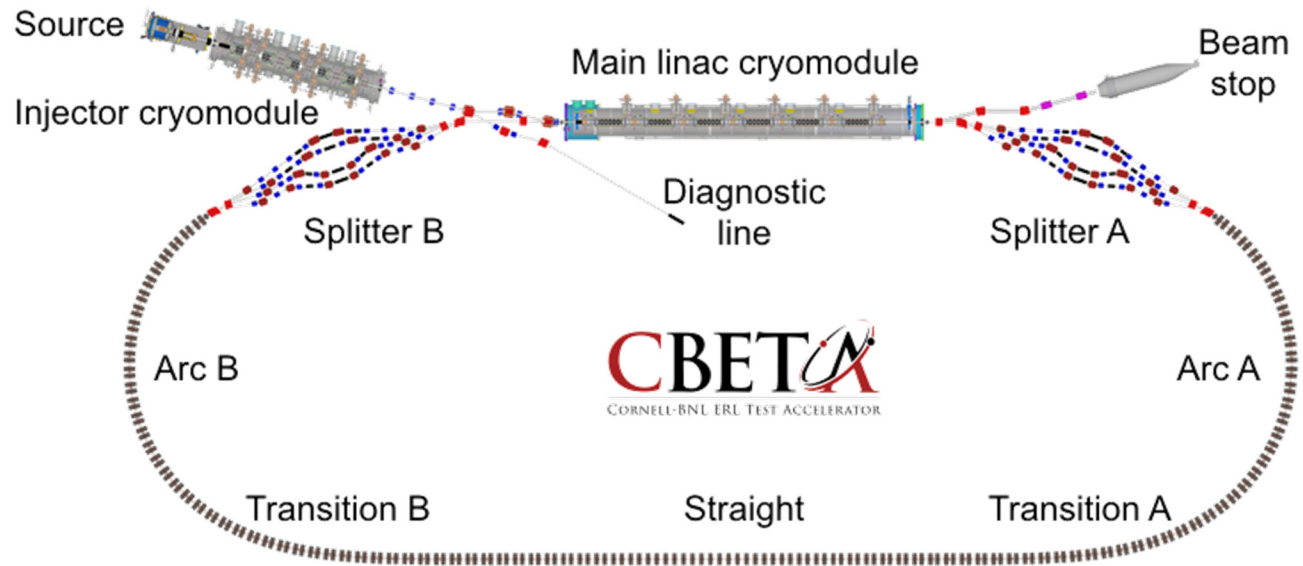
Proposal is based on:

- Already **experimentally** and theoretically shown examples **CBETA**, EMMA, BNL ATF experiment AE-79
- **High quality combined function permanent magnets**
- **CBETA proof of principle for FFA adiabatic transitions.**

Examples of the new FFA lattice designs for: **LHeC** and PERLE lattice designs

SUMMARY: A new combination of the FFA accelerators with the ERL's shows a **novel and very promising combination for multiple applications.**

What is CBETA?



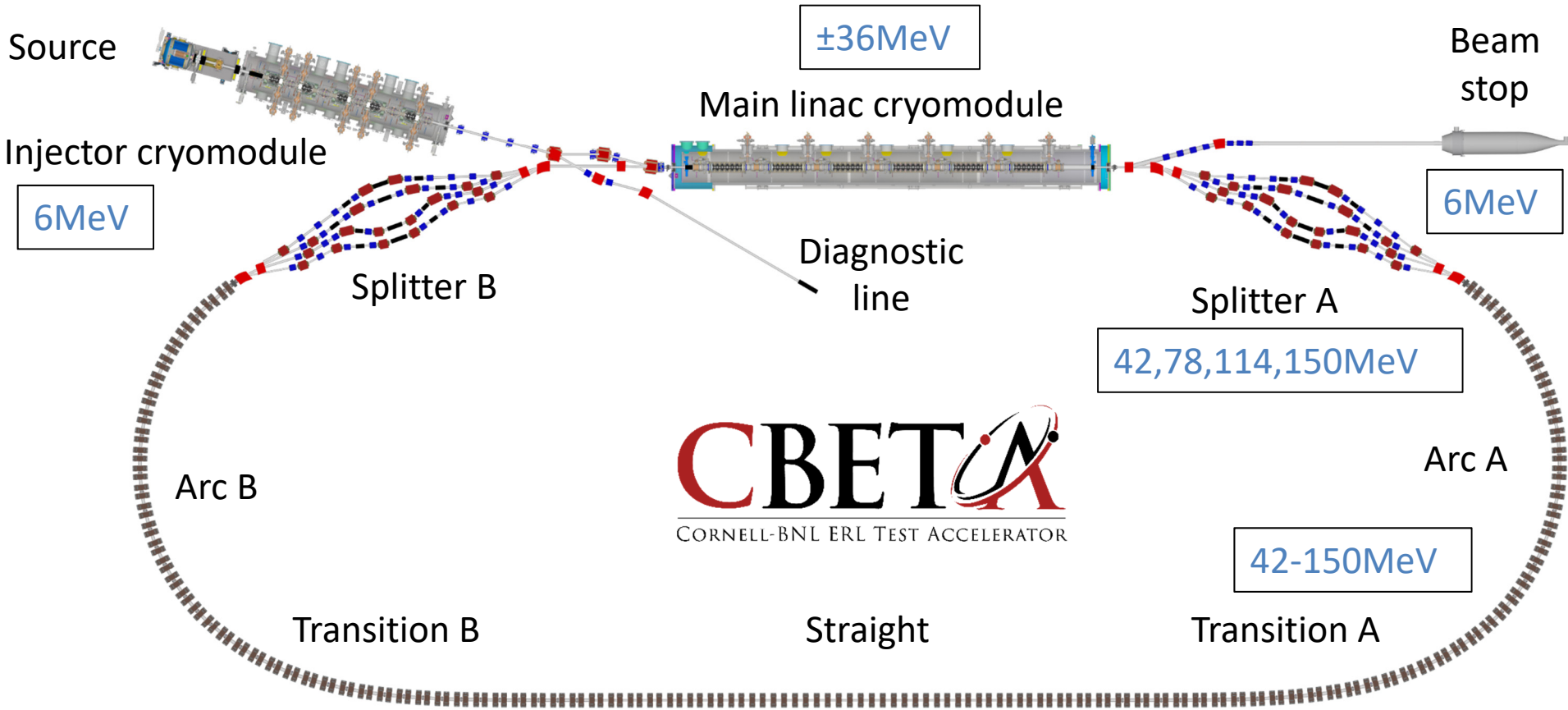
- It's a 4-turn energy-recovery linac (ERL)
 - CW operation with superconducting RF
- The return loop uses FFA (fixed-field accelerator) technology with permanent magnets
 - Returns energies of 42-150MeV in same pipe
 - “Non-scaling FFA” (linear field) focussing
 - Small dispersion (few cm), short cell length (~45cm)

Layout & Parameters

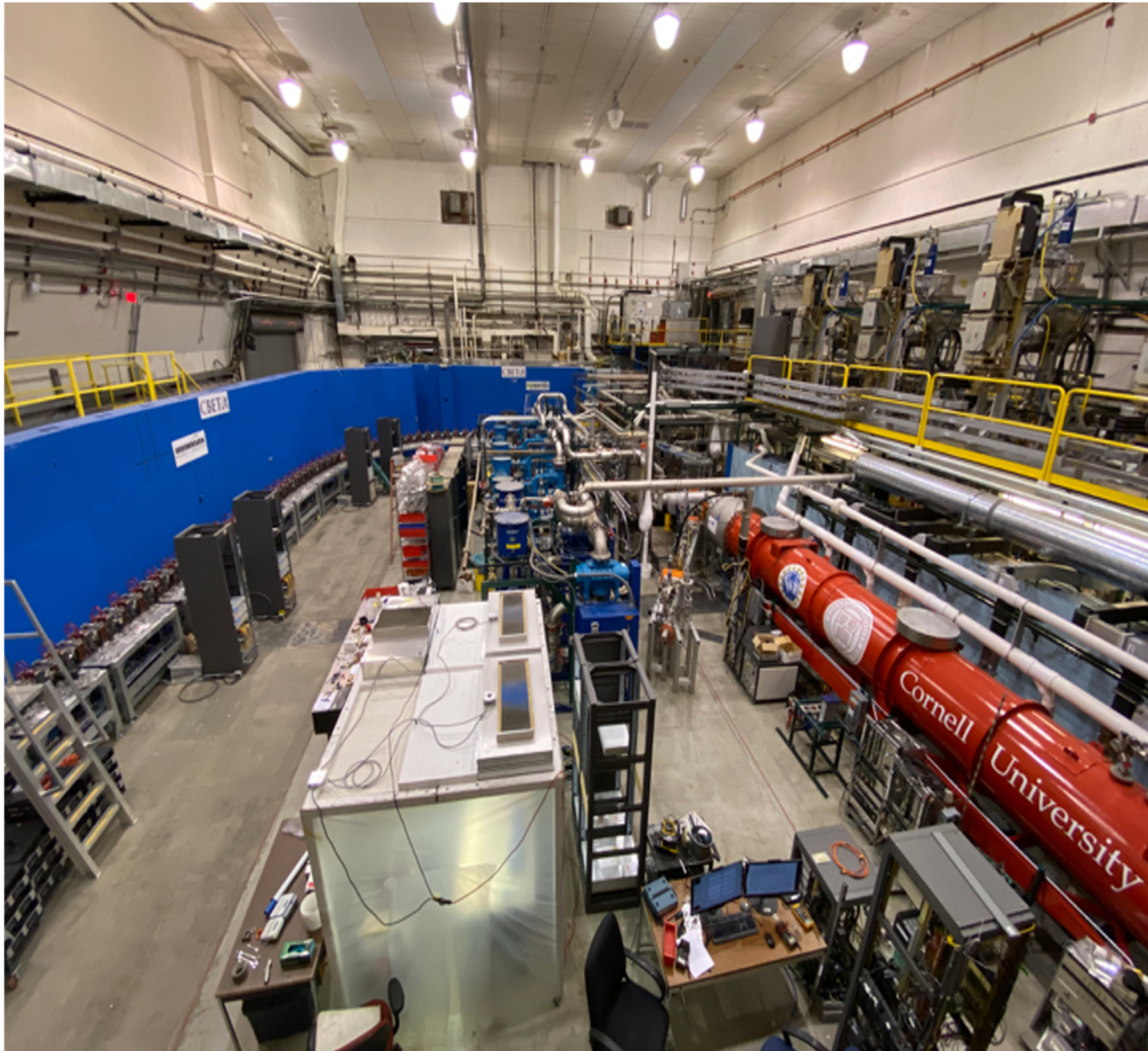
Main linac is a 1.3GHz SCRF module with six 5-cell cavities

Key Performance Parameters (NYSERDA contract Table 1)

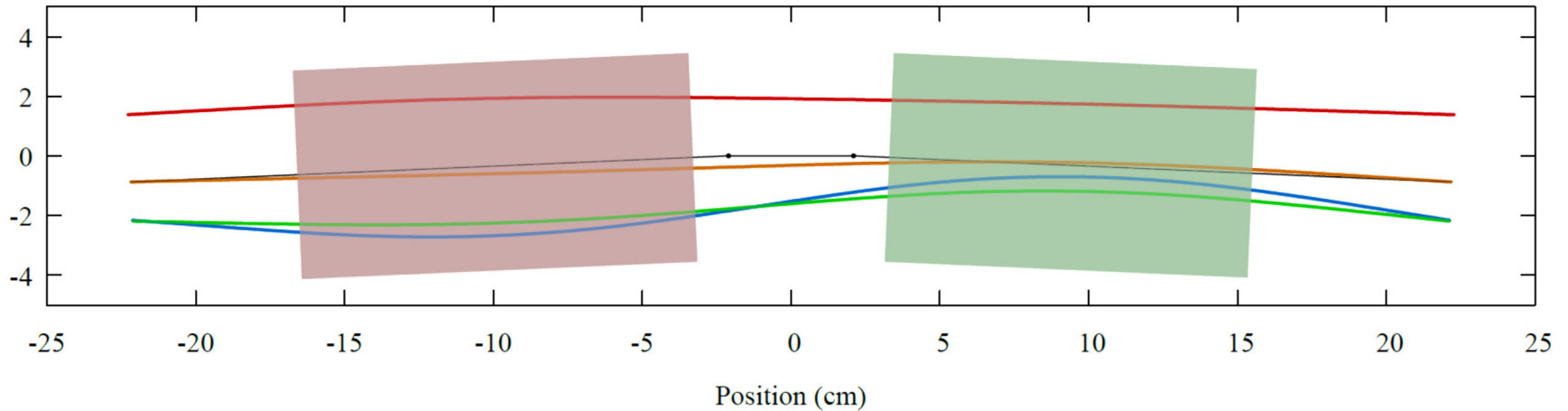
Parameter	Unit	KPP	Design
Electron beam energy	MeV		150
Electron bunch charge	pC		123
Gun current	mA	1	40
Bunch repetition rate (gun)	MHz		325
RF frequency	MHz	1300	1300
Injector energy	MeV		6
RF operation mode			CW
Number of ERL turns		1	4
Energy aperture of arc		2	4



Cornell University Brookhaven ERL Test Accelerator 'CBETA'



Fixed-Field Return Loop Optics

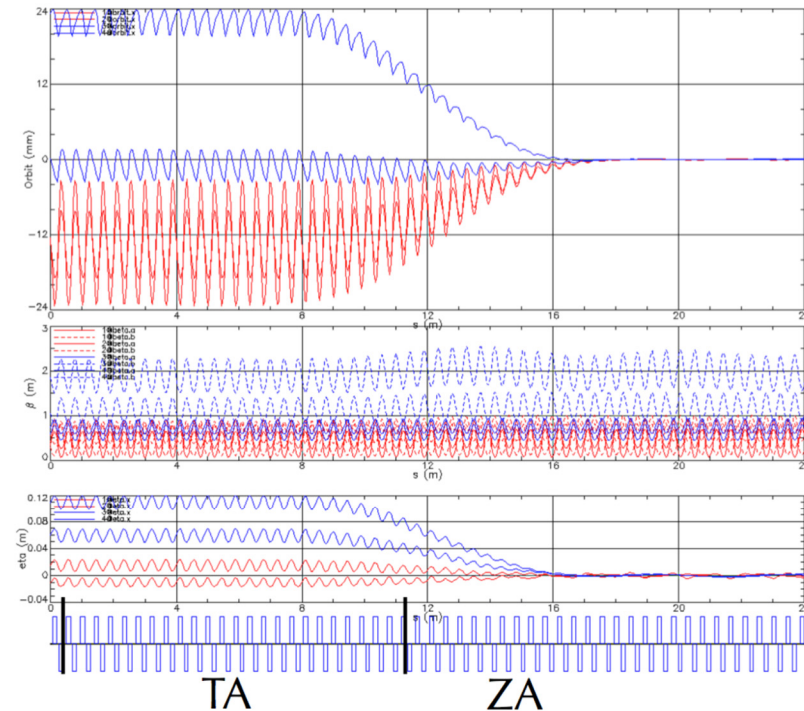


- Beams with 4x rigidity range transmitted through same **overall** radius of curvature in arcs
- Adiabatically merged to zero curvature, separation in straights
- Beam cell tune decreases as a function of energy

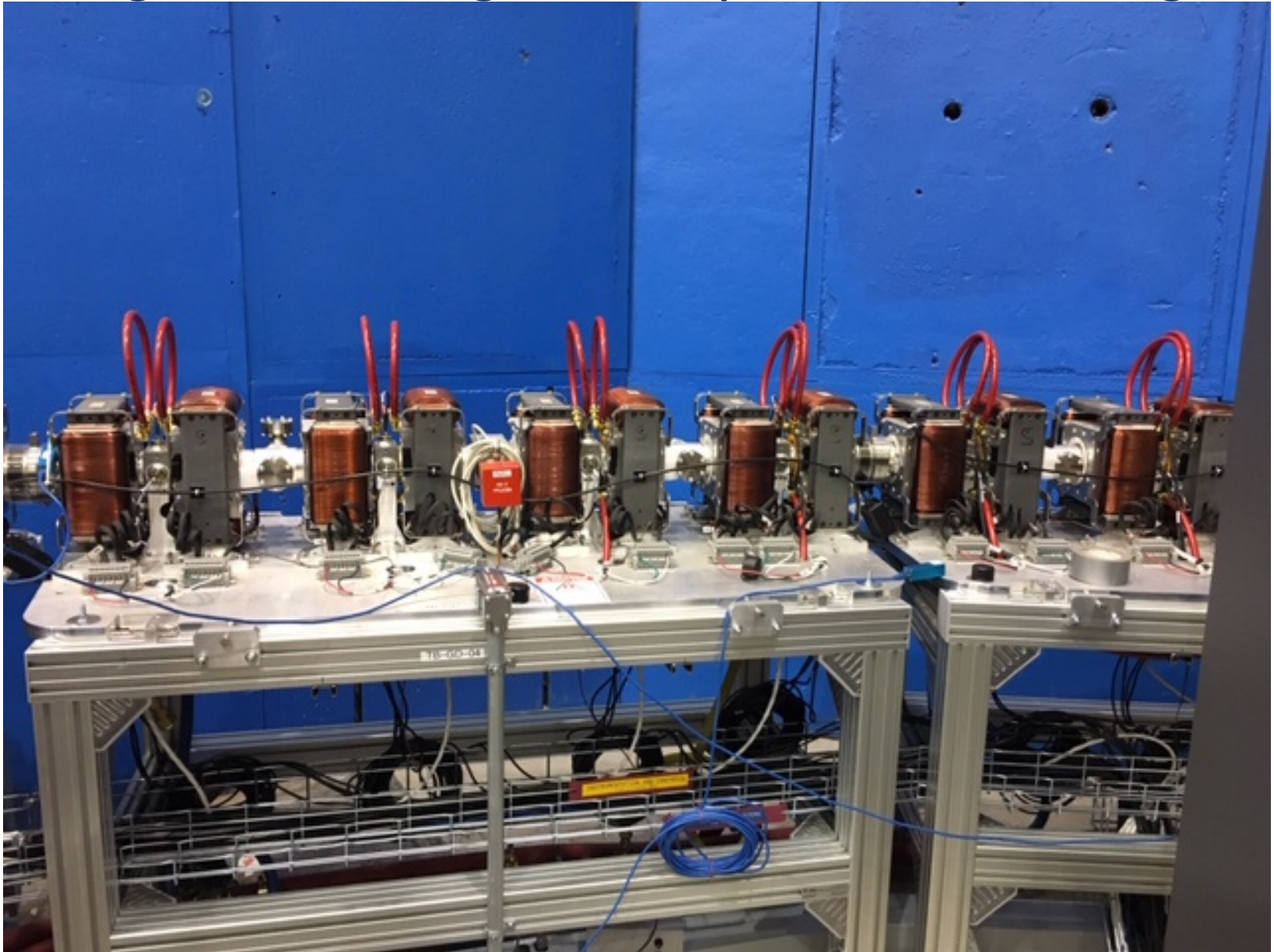
FA

TA

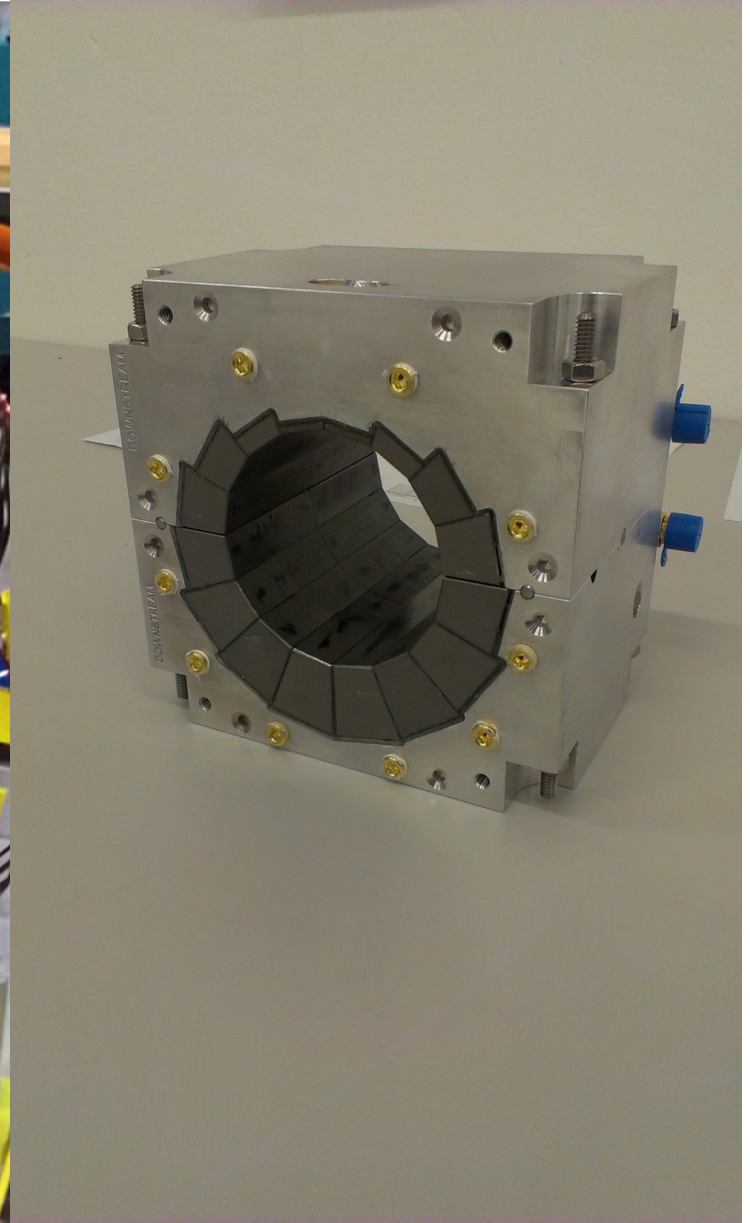
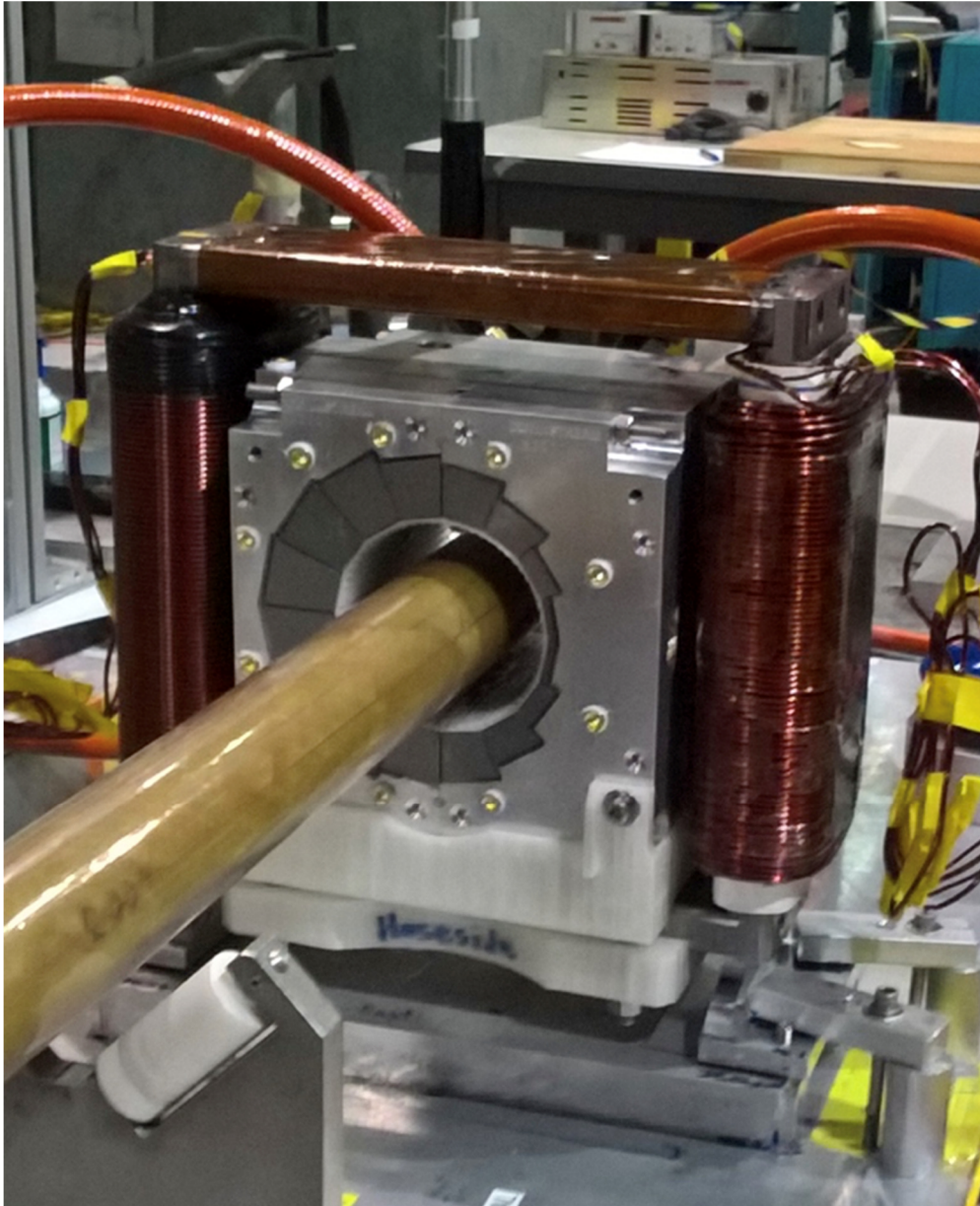
ZA



CBETA girder and High Quality Permanent Magnets

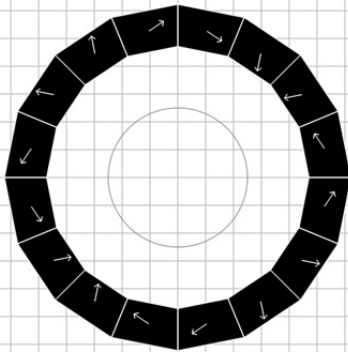


CBETA girder and High Quality Permanent Magnets

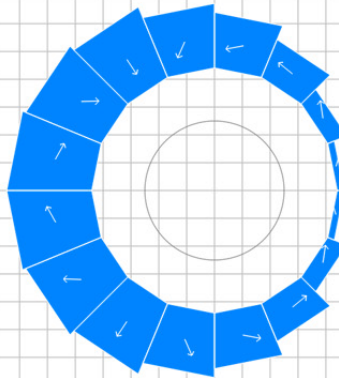


Magnet Types and Parameters

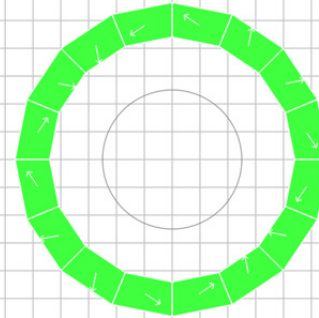
QF



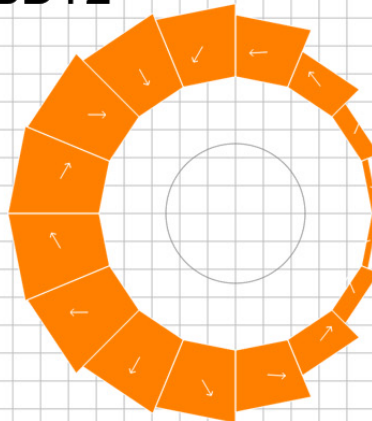
BD



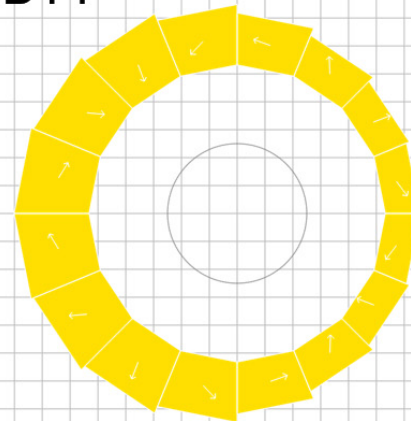
QD



BDT2

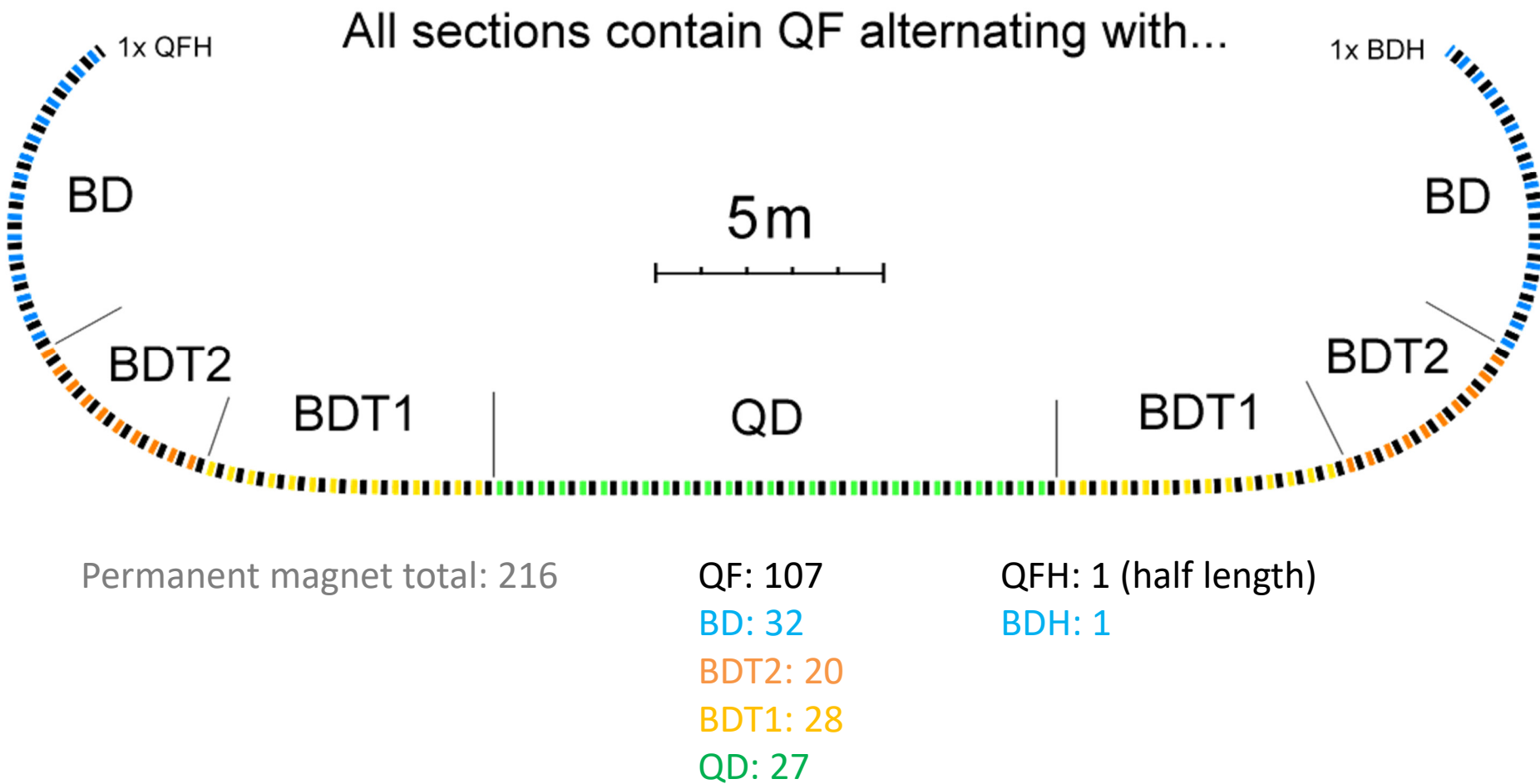


BDT1



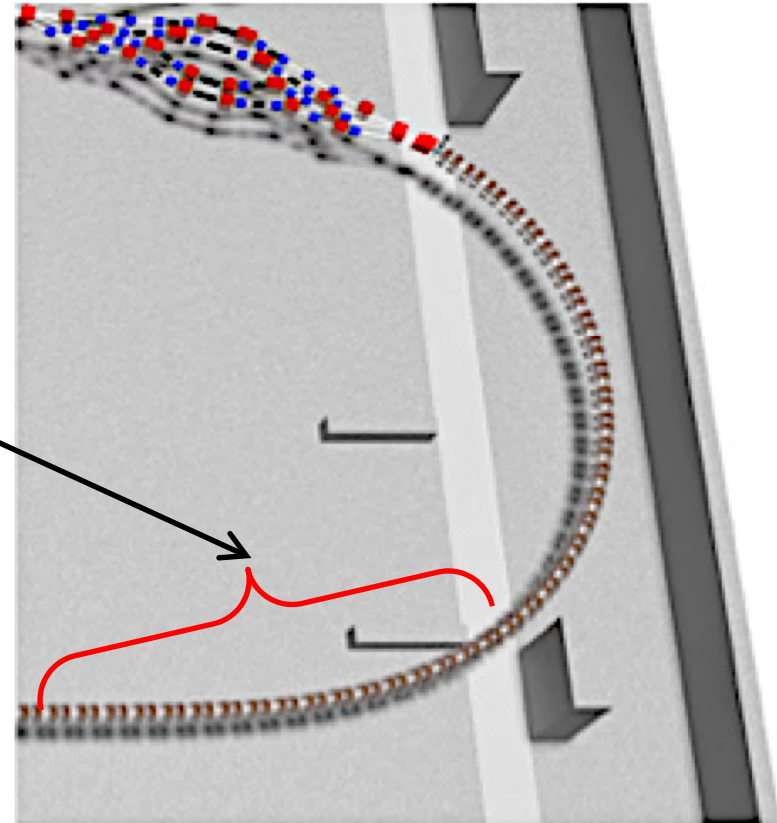
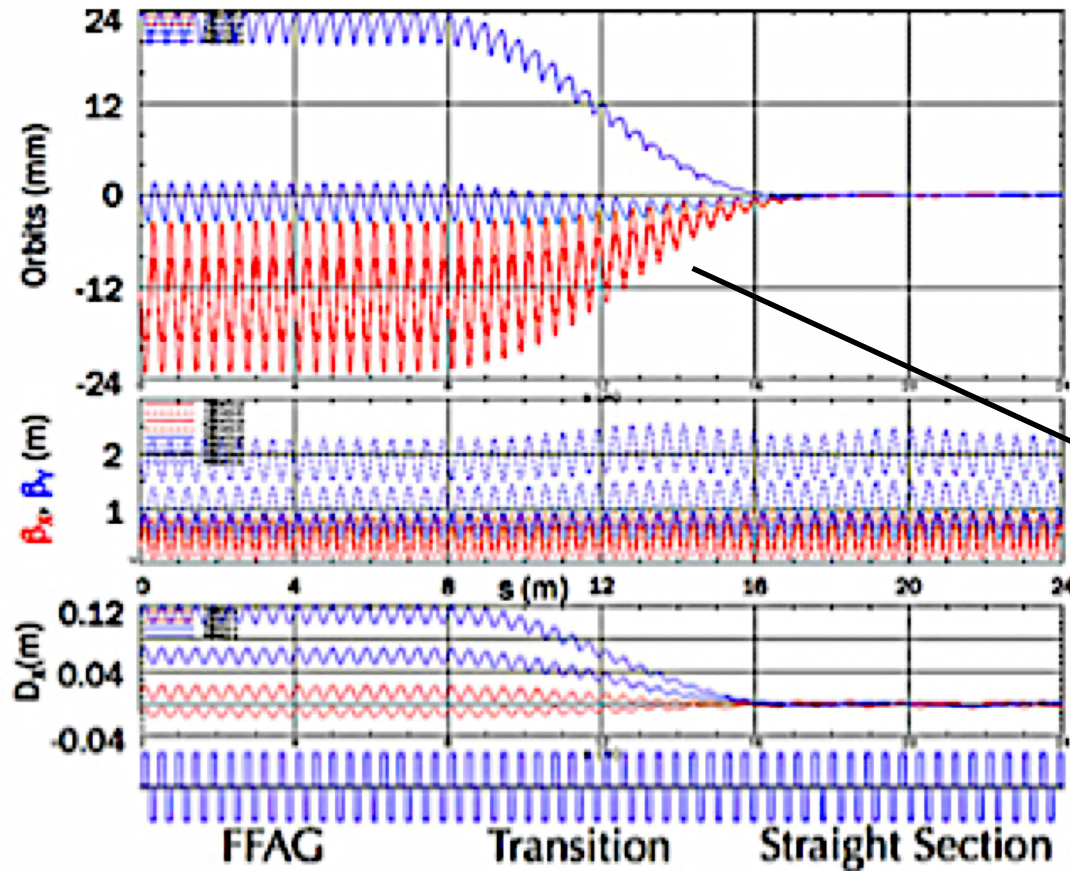
Magnet	Dipole (T)	Quad (T/m)	Good field radius (mm)	Aperture radius (mm)	Max field (T) (good region)	Max field (T) (aperture)
QF	0	-11.5624	25	43.1	0.2891	0.4983
BD	-0.3081	11.1475	25	40.1	0.5868	0.7551
BDT2	-0.2543	11.1475	25	44.938	0.5330	0.7552
BDT1	-0.1002	11.1475	25	49.085	0.3789	0.6474
QD	0	11.1434	25	40.1	0.2786	0.4469

Layout and Magnet Counts

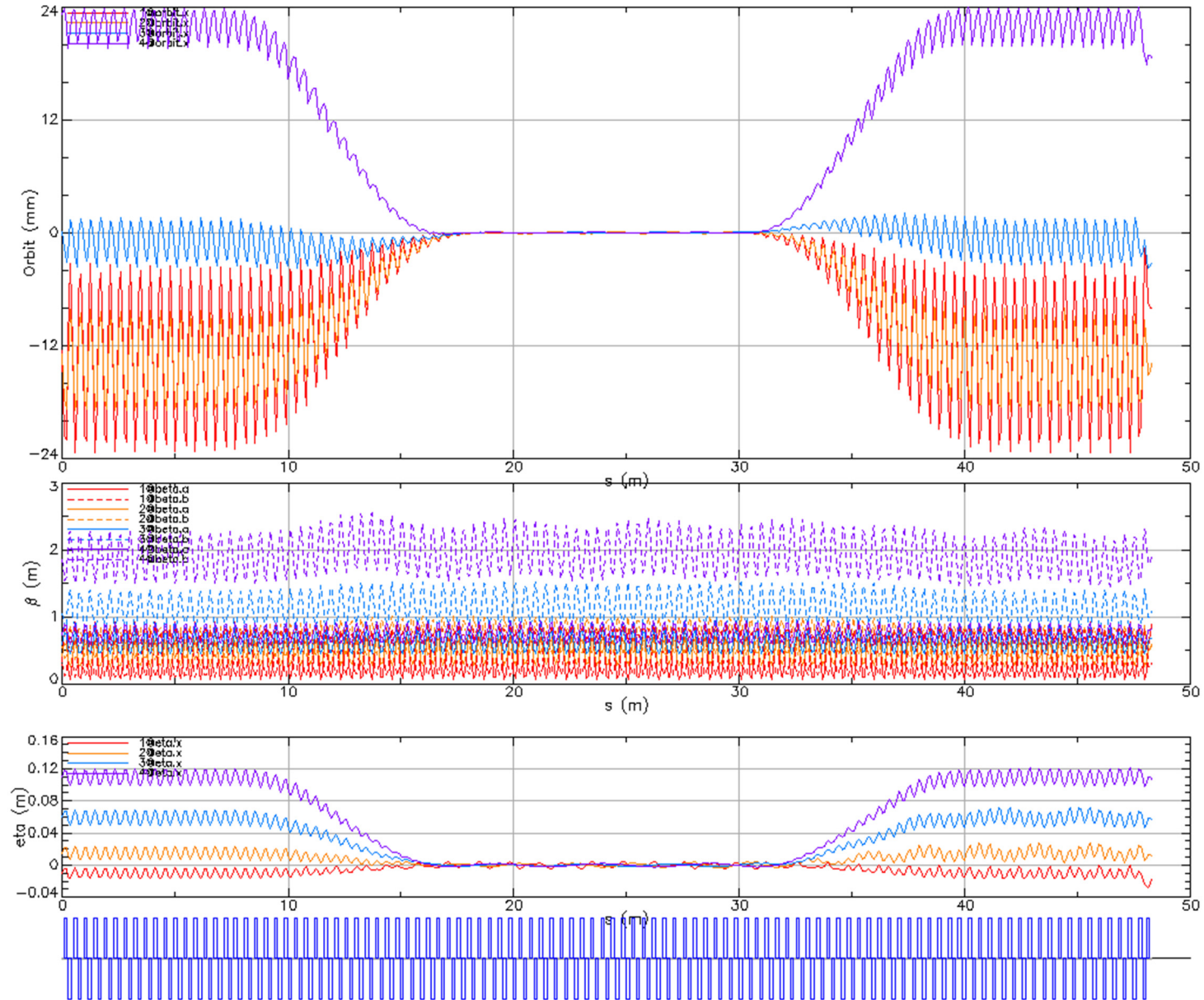


The orbits in the FFA Arc are Adiabatically merged into one

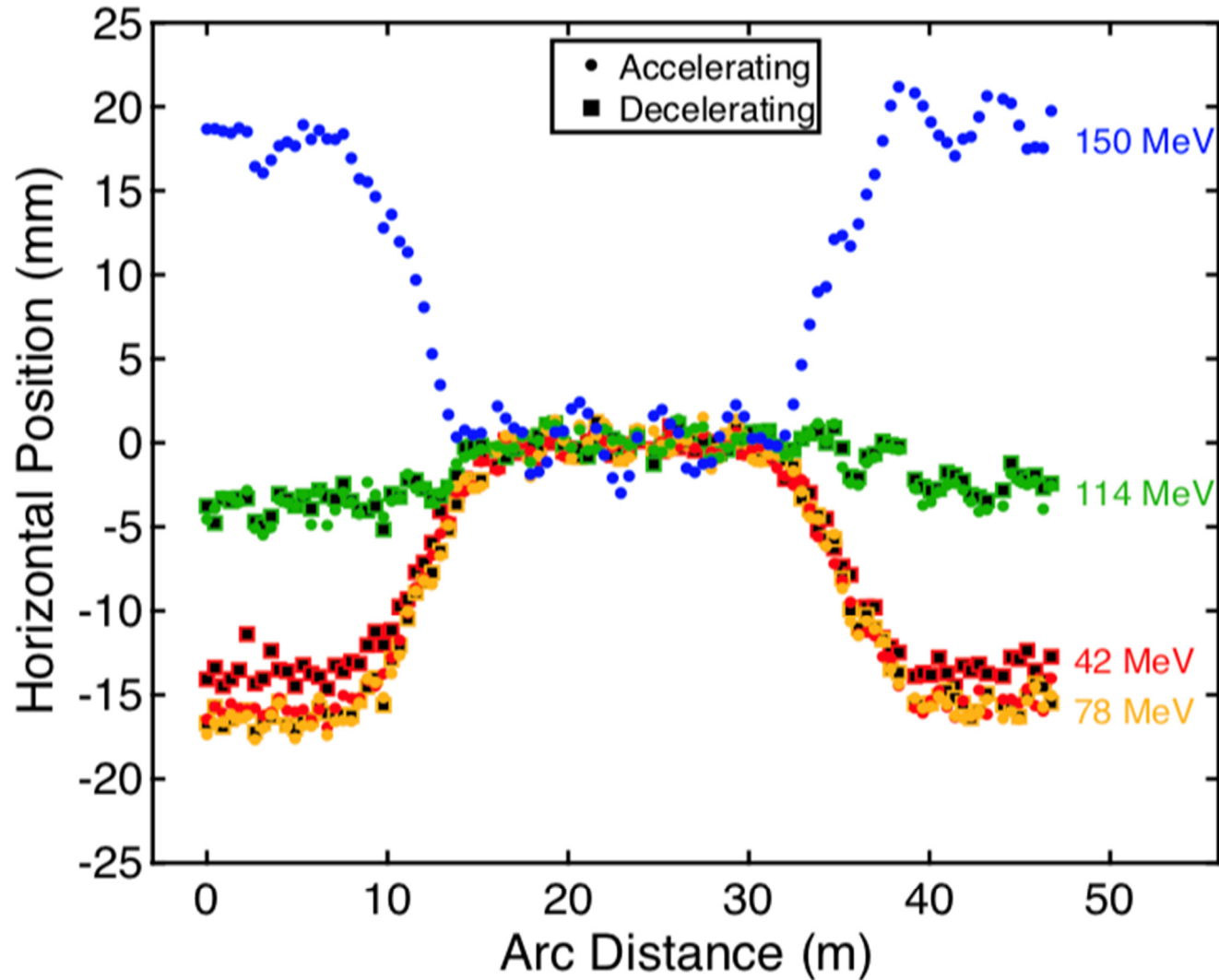
Merging of the orbits at the CBETA project



The orbits in the FFA Arc are Adiabatically merged into one

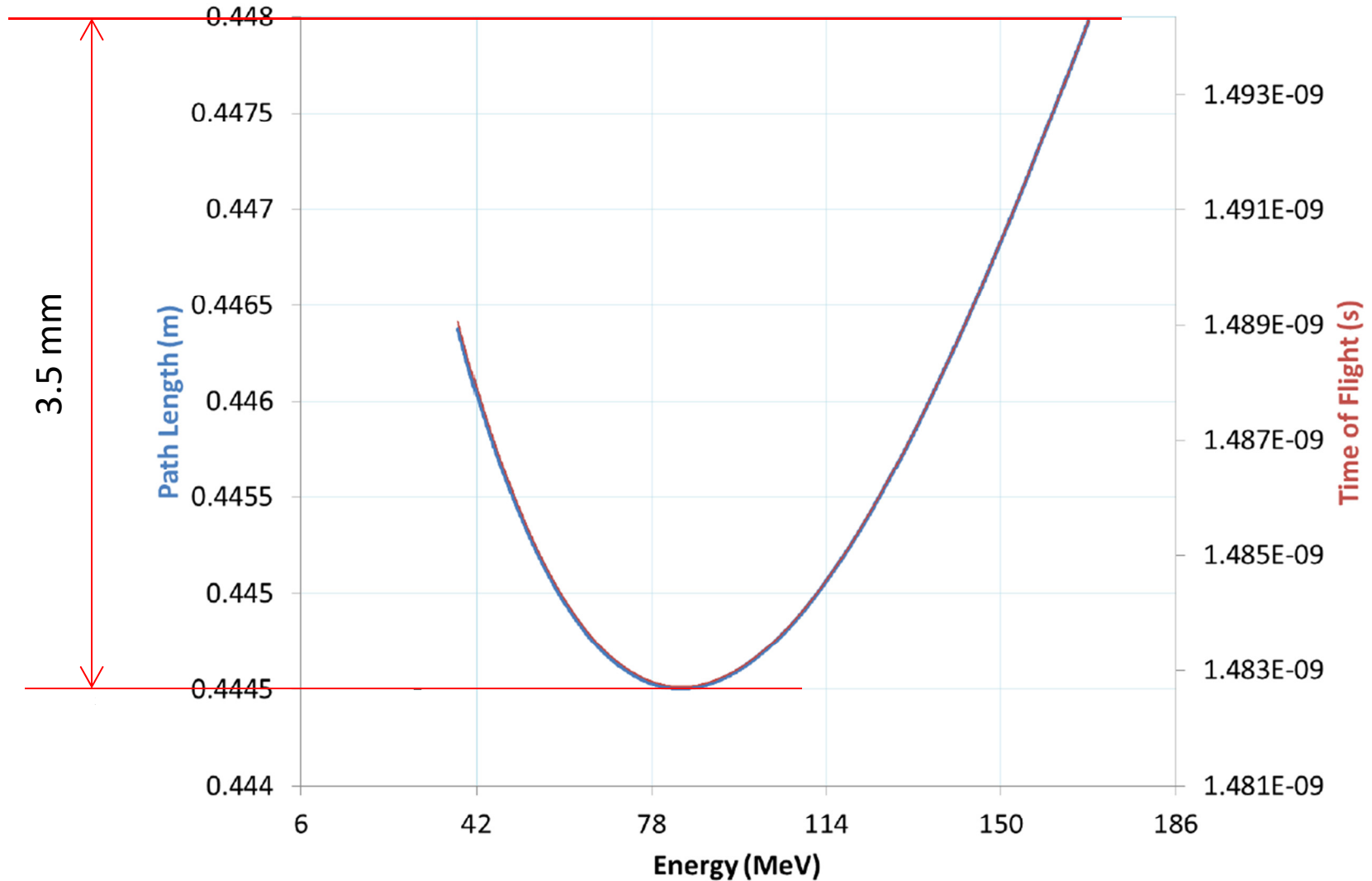


Measurements of Orbits in the CBETA FFA Cells

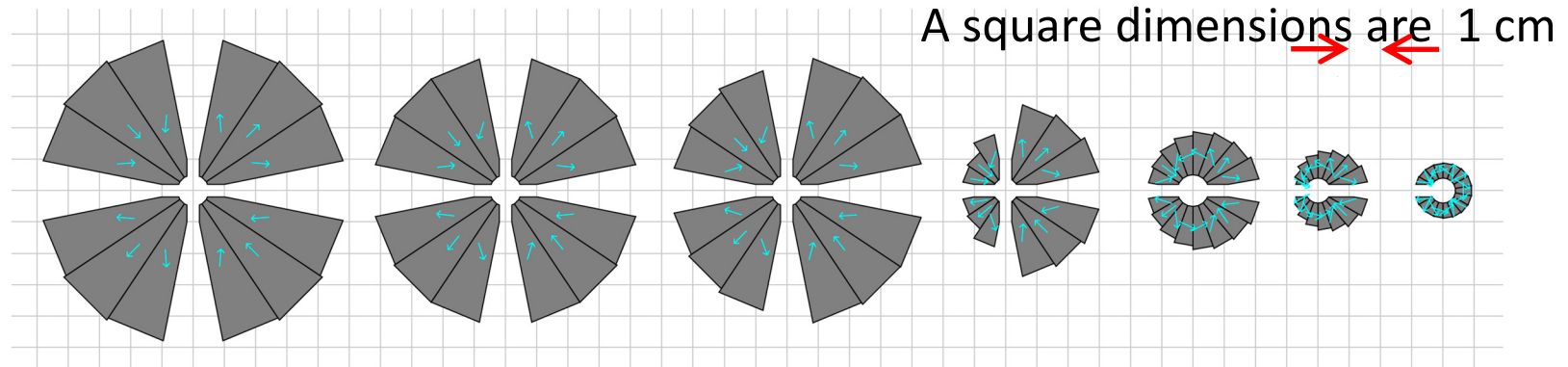


(a) Horizontal FFA orbits

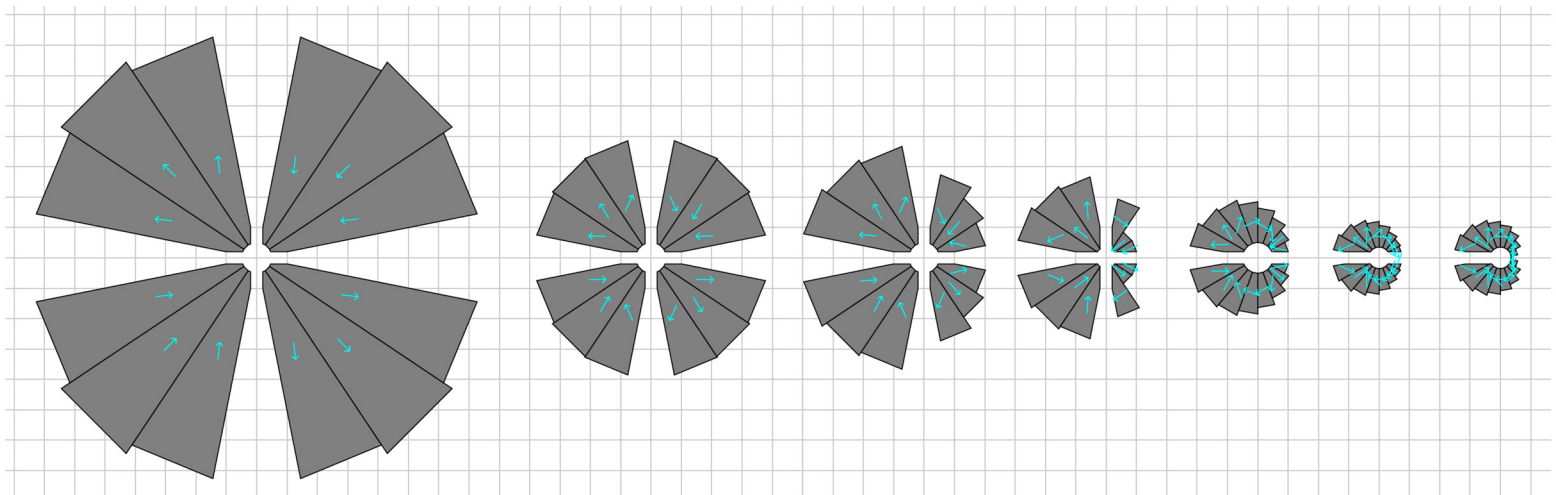
Path length and time of flight in the CBETA arc cell as a function of energy.



Newest Permanent Magnet Designs For Light Sources



Comparisons of the displaced Halbach with open gap with Combined Function **Focusing** magnet by keeping the beam more towards the center of the aperture



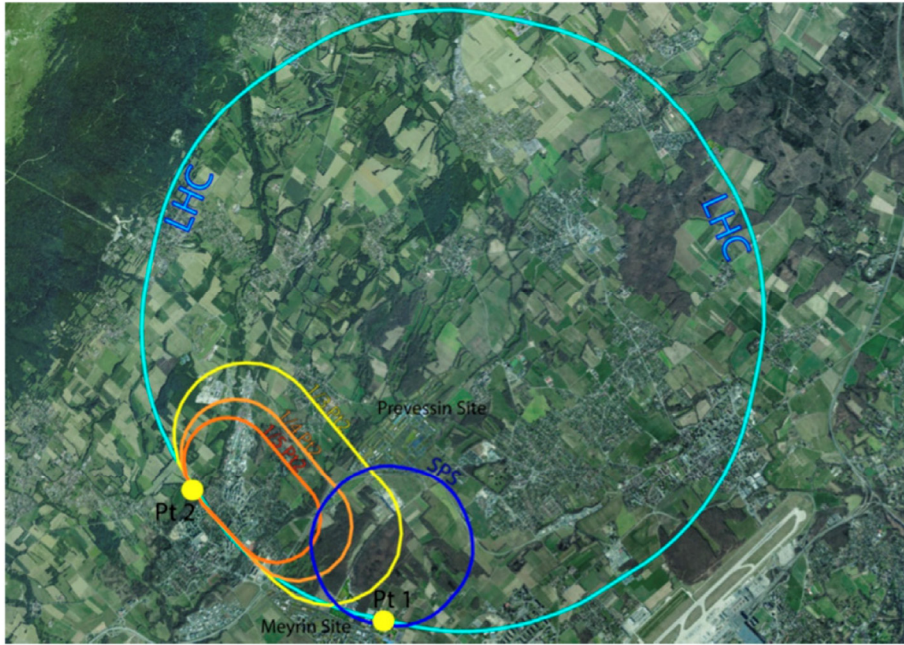
Comparisons of the displaced Halbach with open gap with Combined Function **Defocusing** magnet by keeping the beam more towards the center of the aperture

Layout of the LHeC-LHC-SPS

From Oliver Brüning, Andrei Seryi, and Silvia Verdu-Andres

Frontiers in Physics, 25 April 2022, Electron-Hadron Colliders: EIC, LHeC and FCC-eh

A



B

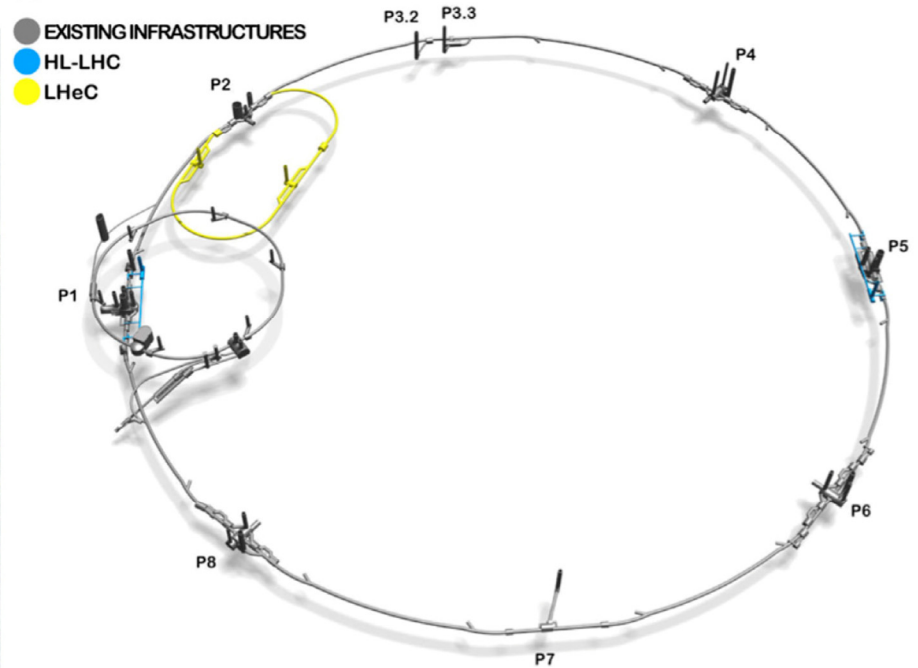
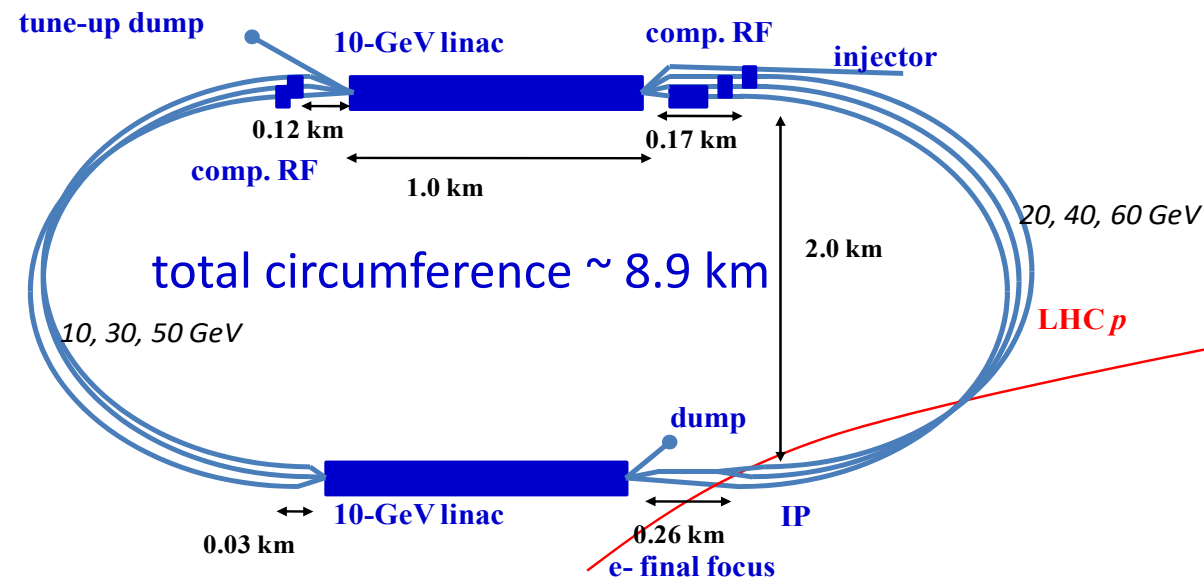


FIGURE 2 | (A) Layout options and footprint of the LHeC in the Geneva basin next to the Geneva airport and CERN. The yellow racetrack corresponds to the LHeC layout that offers optimal performance; in orange, two size variations explored for cost optimization. For reference, the light blue circle depicts the existing tunnel of the LHC; the dark blue circle is the SPS. **(B)** 3D schematic showing the underground tunnel arrangement. The grey sections indicate the existing SPS and LHC tunnel infrastructures and the yellow section the new LHeC installation.

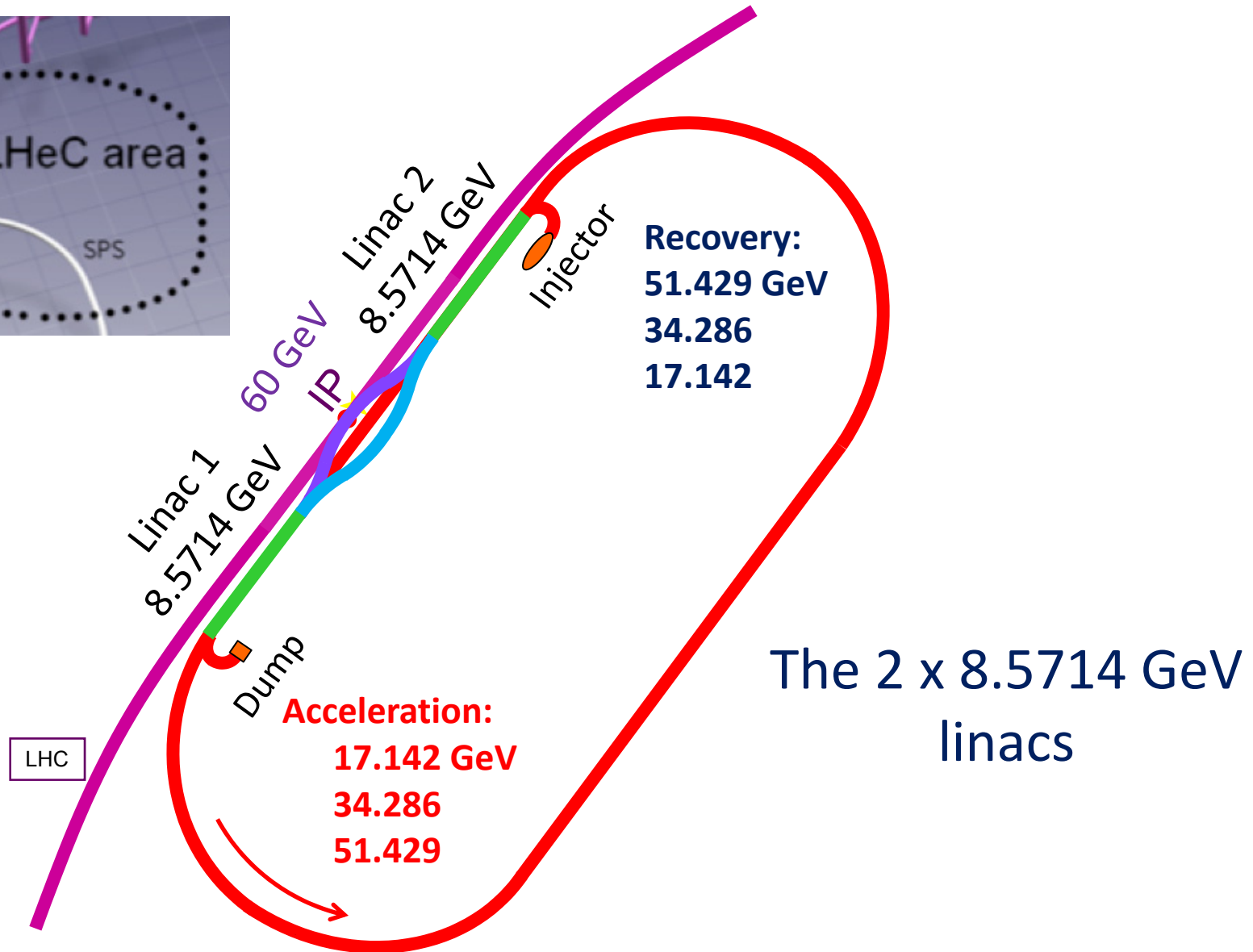
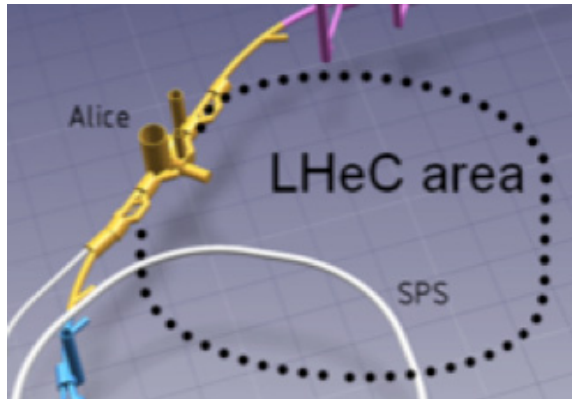
Linac-Ring Option – LHeC Recirculator



	LHeC
Host site	CERN
Layout	ERL linac-ring
Circumference hadron/lepton (km)	26.7/[5.3–8.9]
Number of IRs/IPs	1
Max. CM energy (TeV)	1.2
Crossing angle (mrad)	0
Max. peak luminosity (cm ⁻² s ⁻¹)	2.3×10^{34}
Lepton	Electrons unpolarized
Max. average current (A)	0.02
Max. SR power (MW)	45
Main RF frequency (MHz)	802
No. main RF cavities/cryomodules	448/112
No. crab RF cavities	–
Hadron	Protons unpolarized
Max. average current (A)	1.1
Main RF frequency (MHz)	400
No. crab RF cavities/cryomodules	8/4
No. ERL RF cavities	–

The initial goal of the LHeC was to provide a beam power in excess of 600 MW at the interaction point with a total wall plug power consumption of 100 MW for the electron beam. Later design considerations aiming on pushing the performance reach beyond a peak luminosity of $10^{34} \text{ cm}^{-2} \text{ s}^{-1}$ and minimizing the total installation cost for the LHeC resulted in shorter linacs, a total circumference of about 5.4 km (1/5th of the LHC circumference with 900 m linac length) but with a slightly higher wall-plug power consumption than the initial 100 MW target. The updated LHeC design features a peak current from the source of 20 mA and total currents within the SRF cavities of more than 120 mA ($2 \times 3 \times 20 \text{ mA}$) [5]. **Figure 2** shows the potential LHeC size and layout options in relation to the LHC tunnel.

FFA LHeC Recirculator with Energy Recovery



FFA Arc Lattice Design

Magnet Properties:

Defocusing magnet

$$L_{BD} = 0.696 \text{ m}$$

$$G_D = 106.605 \text{ T/m}$$

$$B_D = -0.16343 \text{ T}$$

$$B_{Dmax} = -0.532 \text{ T}$$

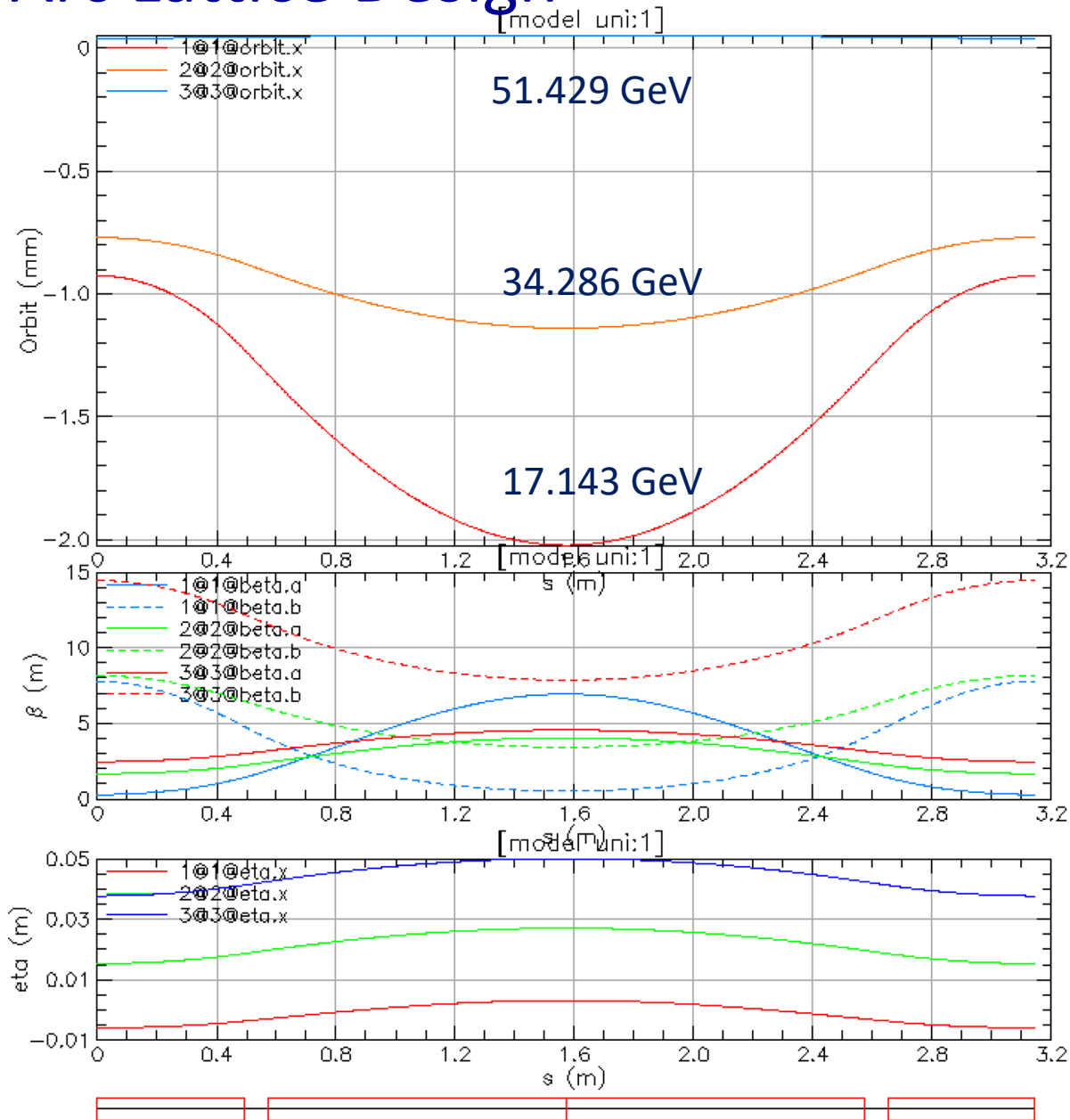
Focusing magnet

$$L_{QF} = 2.0 \text{ m}$$

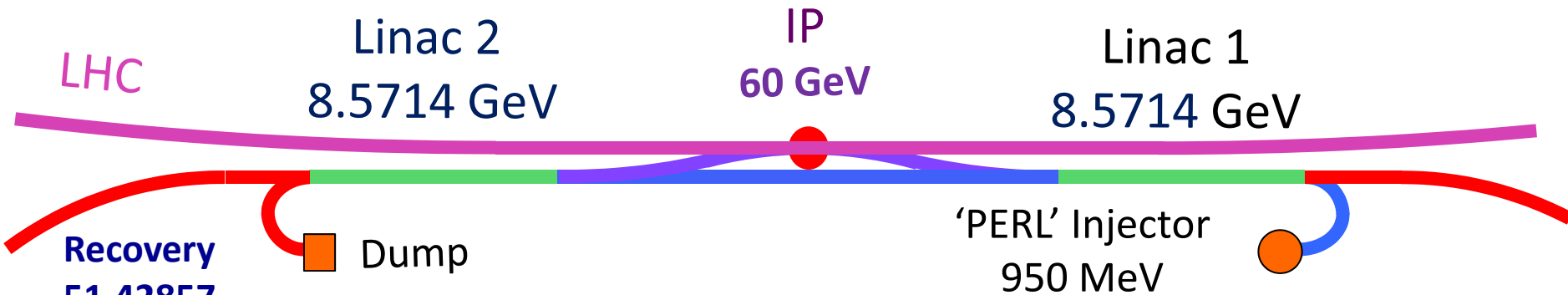
$$G_F = -61.9214 \text{ T/m}$$

$$B_F = -0.16343 \text{ T}$$

$$B_{Fmax} = 0.272 \text{ T}$$



FFA LHeC Recirculator with ER



REDUCING THE SYNCHROTRON RADIATION:
8.92 MW, with 6.6 mA to be compared to 15 MW!

Electron Energy (GeV)	R@QF	R@BD	Power lost in QF	Power lost in BD	Total Synchrotron Power loss for 6.6 mA
51.429	-682.06	-535.13	5.5110	0.0458	5.5568
34.286	746.77	-277.89	0.0054	2.3237	2.3832
17.143	447.35	-117.12	0.1604	0.8144	0.9748
					8.9195

Previous LHeC design set the SR loss limit of 15 MW

Recovery

51.42857

34.28571

17.14286

Arc Orbits

17.14286 GeV

34.28571 GeV

51.42857 GeV

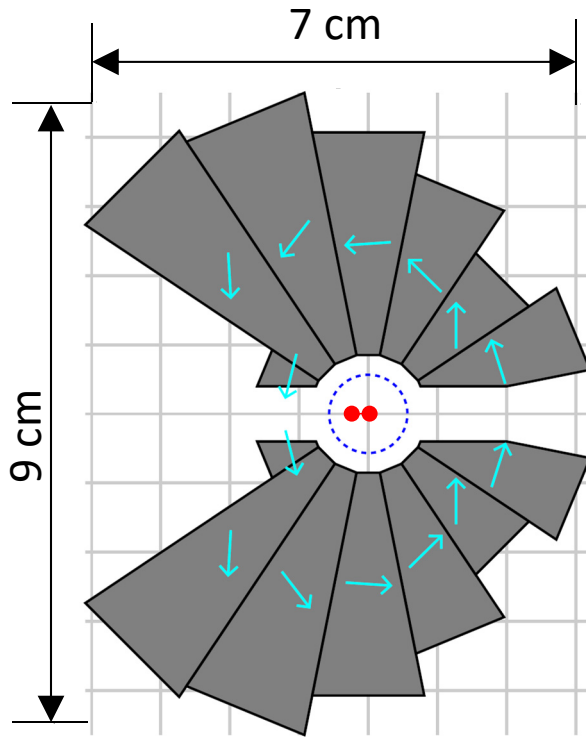
Three times

Energy acceptance

For the new LHeC limit of 20 mA instead of 45 MW synchrotron radiation loss the FFA losses 27 MW !

Gain in luminosity is from 20 mA → 33.6 mA = x 1.68

Magnets for the FFA LHeC arc



Defocusing Magnet

$$L_{BD} = 0.696 \text{ m}$$

$$G_D = 106.605 \text{ T/m}$$

$$B_D = -0.16343 \text{ T}$$

$$B_{Dmax} = -0.532 \text{ T}$$

$$\text{Area} = 34.8 \text{ cm}^2$$

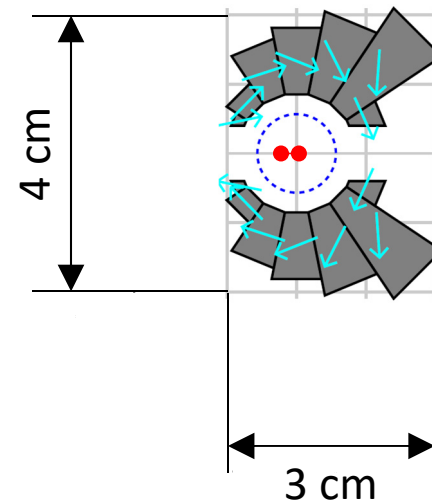
$$\text{Max radius} = 49.2 \text{ mm}$$

NdFeB grade N42EH $B_r = 1.3 \text{ T}$ material

17mm diameter aperture

8mm open midplane slot

$R = 5.67 \text{ mm}$ good field region (blue circle)



Focusing magnet

$$L_{QF} = 2.0 \text{ m}$$

$$G_F = -61.9214 \text{ T/m}$$

$$B_F = -0.16343 \text{ T}$$

$$B_{Fmax} = 0.272 \text{ T}$$

$$\text{Area} = 5.89 \text{ cm}^2$$

$$\text{Max radius} = 25.2 \text{ mm}$$

Expected Magnet Harmonics

Focusing Combined Function Magnet

Table 1: Field harmonics at R=5.66667mm. The reference field component is 106.604 T/m.

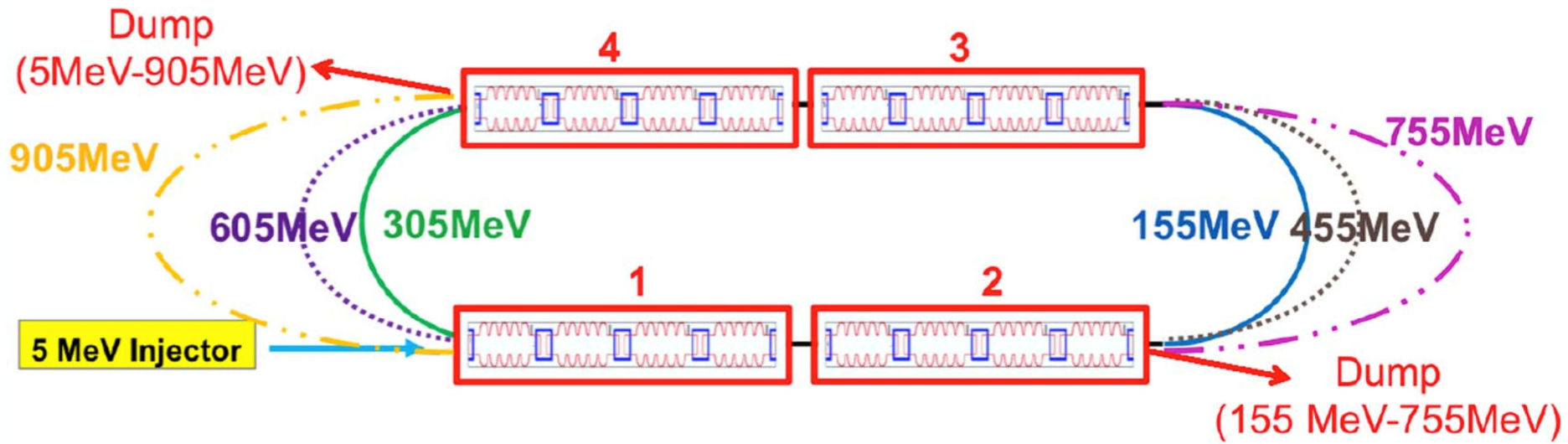
Field harmonic	Normal units	Skew units
Dipole	-2705.10	0.00
Quadrupole	10000.00	-0.00
Sextupole	0.67	0.00
Octupole	-0.69	-0.00
Decapole	0.75	0.00
Dodecapole	-0.22	0.00
14-pole	1.83	0.00
16-pole	1.52	-0.00
18-pole	3.30	0.00
20-pole	-8.35	0.00
22-pole	-0.17	-0.00
24-pole	-8.00	0.00
26-pole	-0.21	0.00
28-pole	-2.50	-0.00
30-pole	-0.06	0.00
32-pole	1.81	0.00
34-pole	0.03	-0.00
36-pole	0.19	-0.00
38-pole	-0.02	-0.00
40-pole	0.23	-0.00

Defocusing Combined Function Magnet

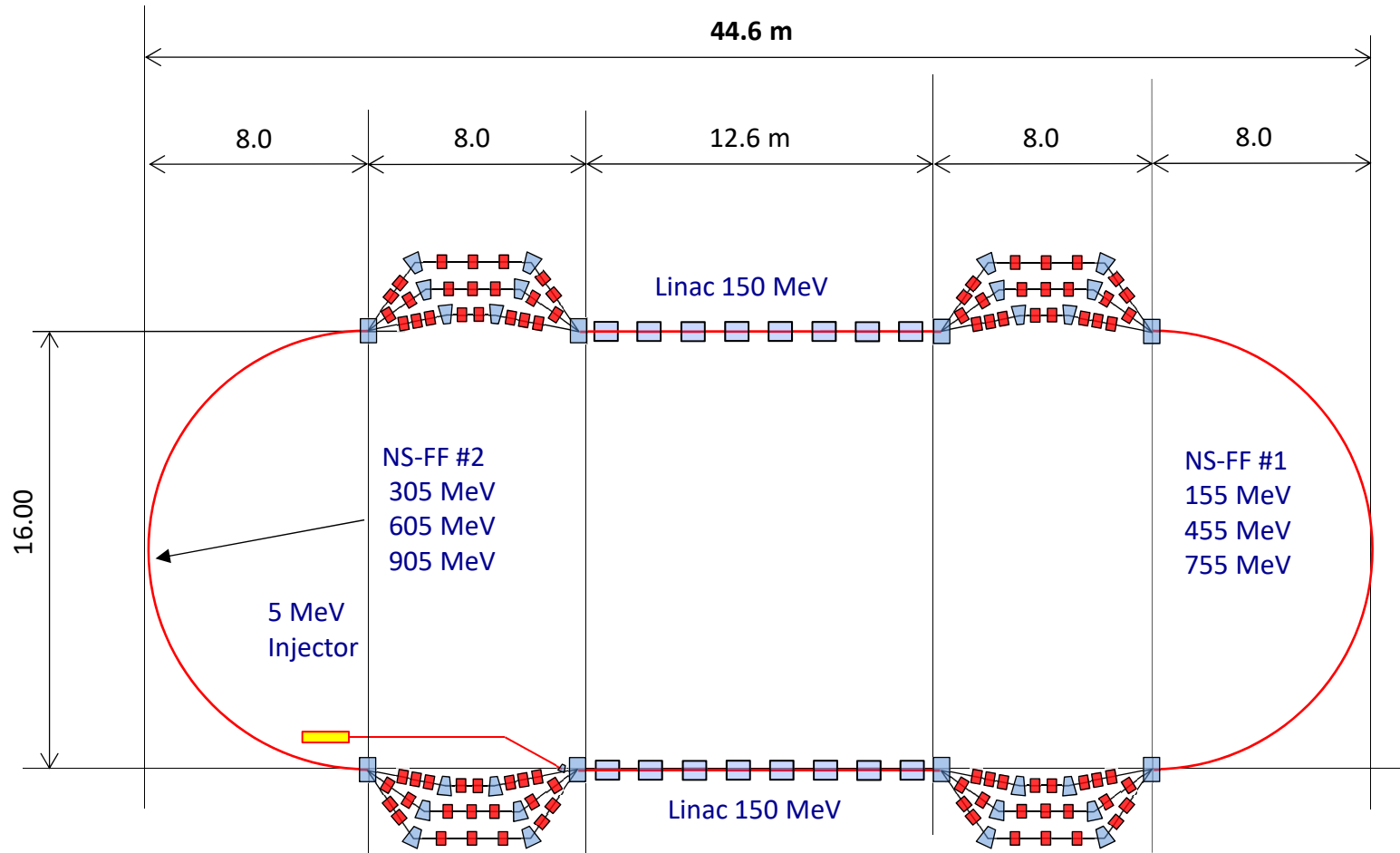
Table 1: Field harmonics at R=5.66667mm. The reference field component is -61.9179 T/m.

Field harmonic	Normal units	Skew units
Dipole	4657.87	0.00
Quadrupole	10000.00	-0.00
Sextupole	-0.56	0.00
Octupole	-1.13	-0.00
Decapole	-0.68	-0.00
Dodecapole	-0.15	-0.00
14-pole	0.19	-0.00
16-pole	0.18	-0.00
18-pole	-0.53	0.00
20-pole	-3.24	0.00
22-pole	-5.82	0.00
24-pole	-6.08	-0.00
26-pole	-2.67	-0.00
28-pole	-6.11	0.00
30-pole	1.80	-0.00
32-pole	0.41	0.00
34-pole	0.55	-0.00
36-pole	0.36	-0.00
38-pole	0.15	-0.00
40-pole	0.54	-0.00

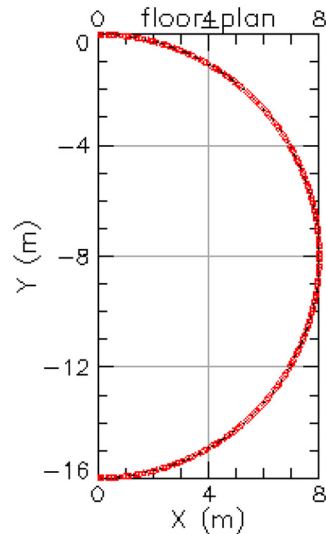
PERLE Present Design



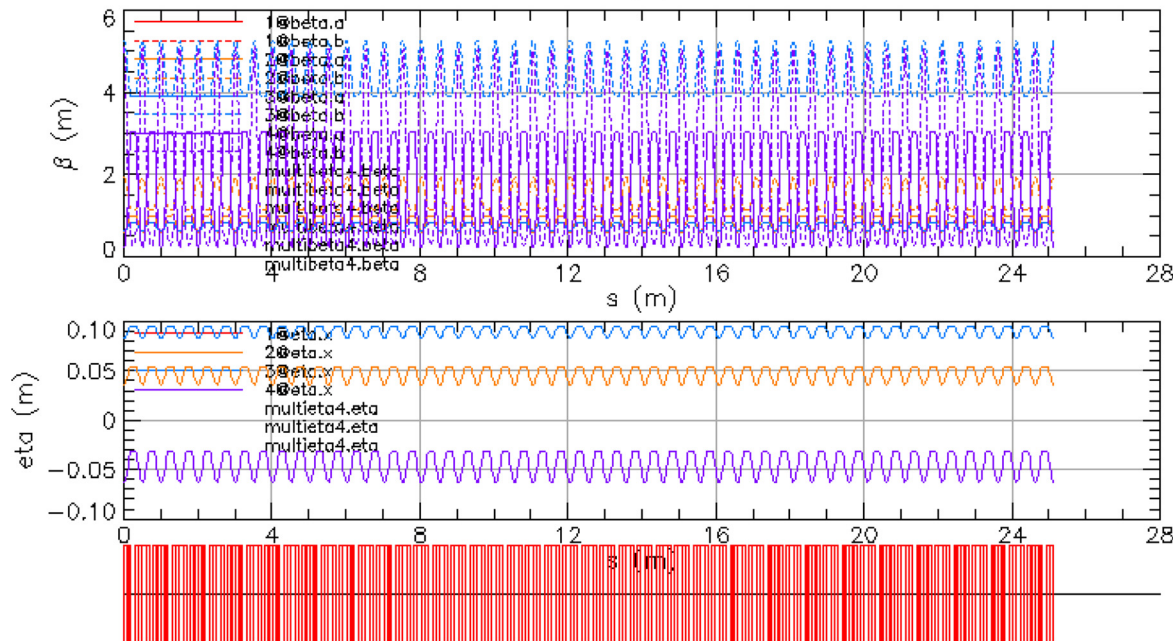
Fixed Field Arc for PERLE – similar to CBETA



Fixed Field Arc for PERLE 155-755 MeV – like CBETA

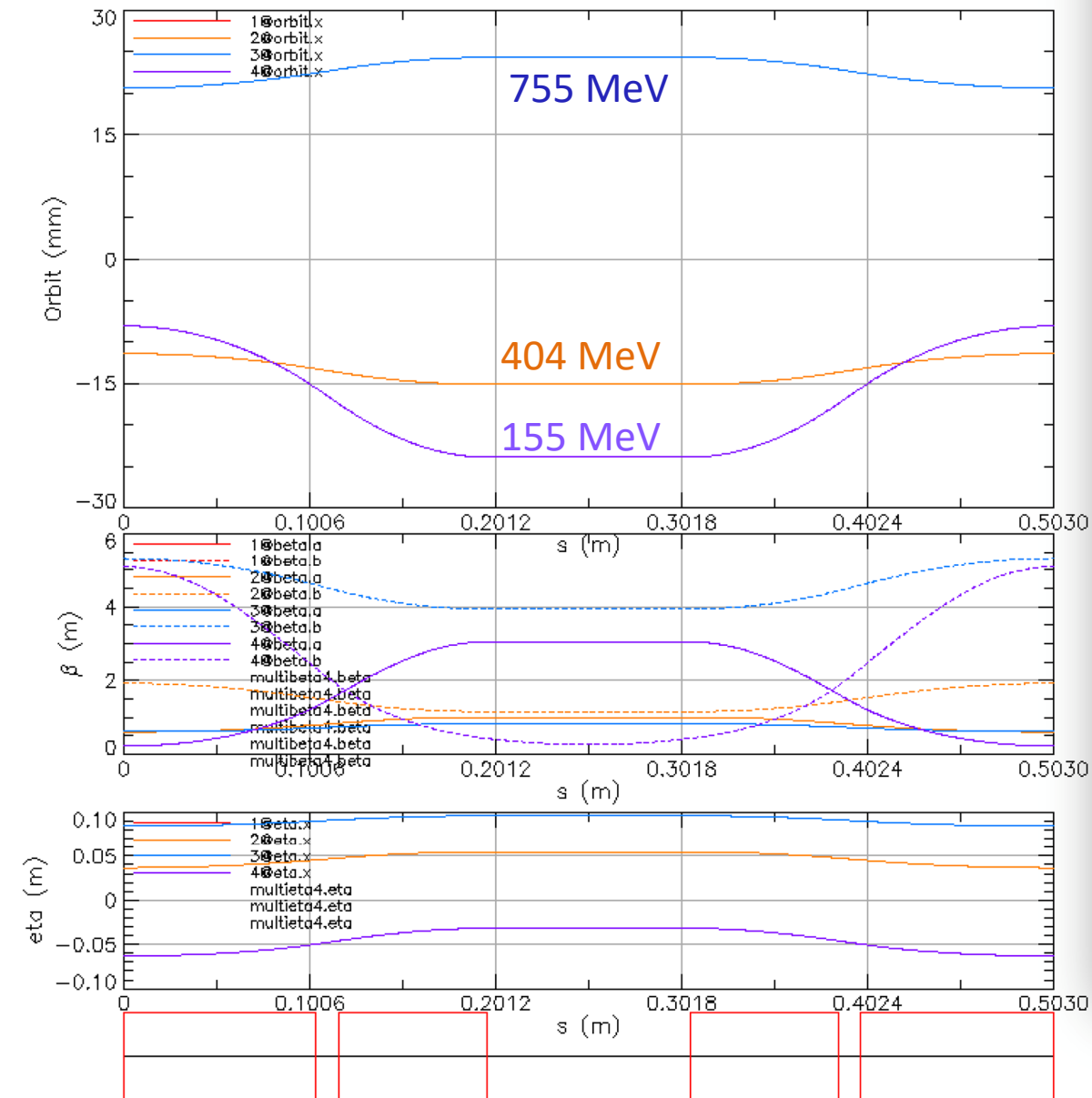


A single right-side arc covering the energy range between 155-755 MeV with the betatron and dispersion functions for all three energies

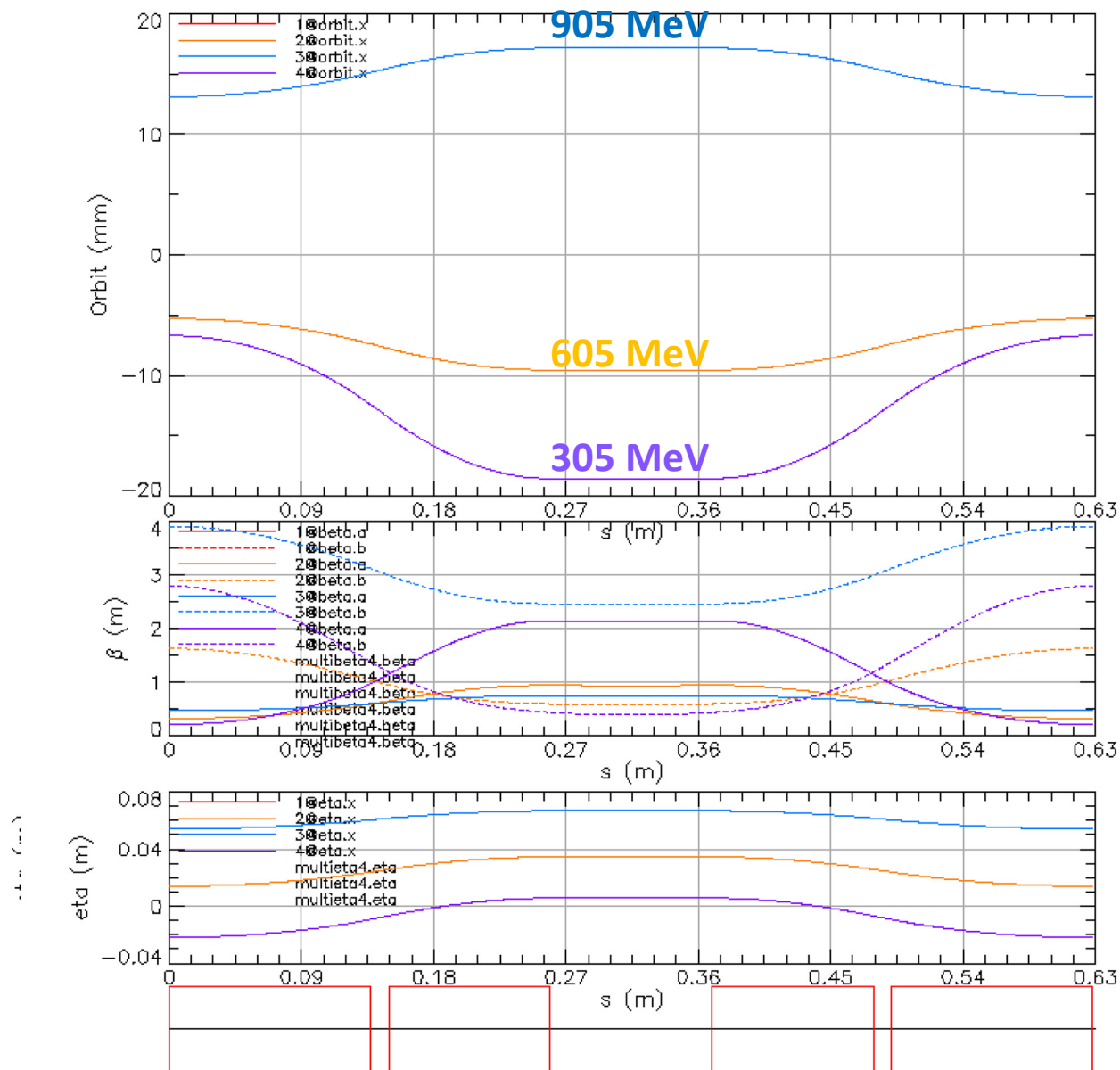


'PERLE' 155-755 MeV FFA arc

Orbit Offsets and
Lattice functions for the
single right side arc cell.



Fixed Field Arc for PERLE 305-905 MeV– like CBETA



CONCLUSION

- Lattice solutions are proposed for the PERLE design with a single arc line and for LHeC.
- A new LHeC proposal replaces the 2 x 10 GeV linacs and three arcs, with 2 x 8.57 GeV linacs and one arc per side
 - This is a cost-effective solution
 - No magnet power, power supplies or cabling
 - Single arc to transport all three energies
 - 14% less linac
 - It reduces the synchrotron radiation in arcs
 - **8.9MW instead of 15MW for 6.6 mA current**
 - Hence provides 1.68 times larger luminosity for the same limit on the total power loss from synchrotron radiation.
 - At 45 MW limit, instead of 20 mA the FFA solution can provide 33.6 mA