New approach for Electron-Ion Colliders (EIC) with Fixed Tunes Non-Scaling FFA

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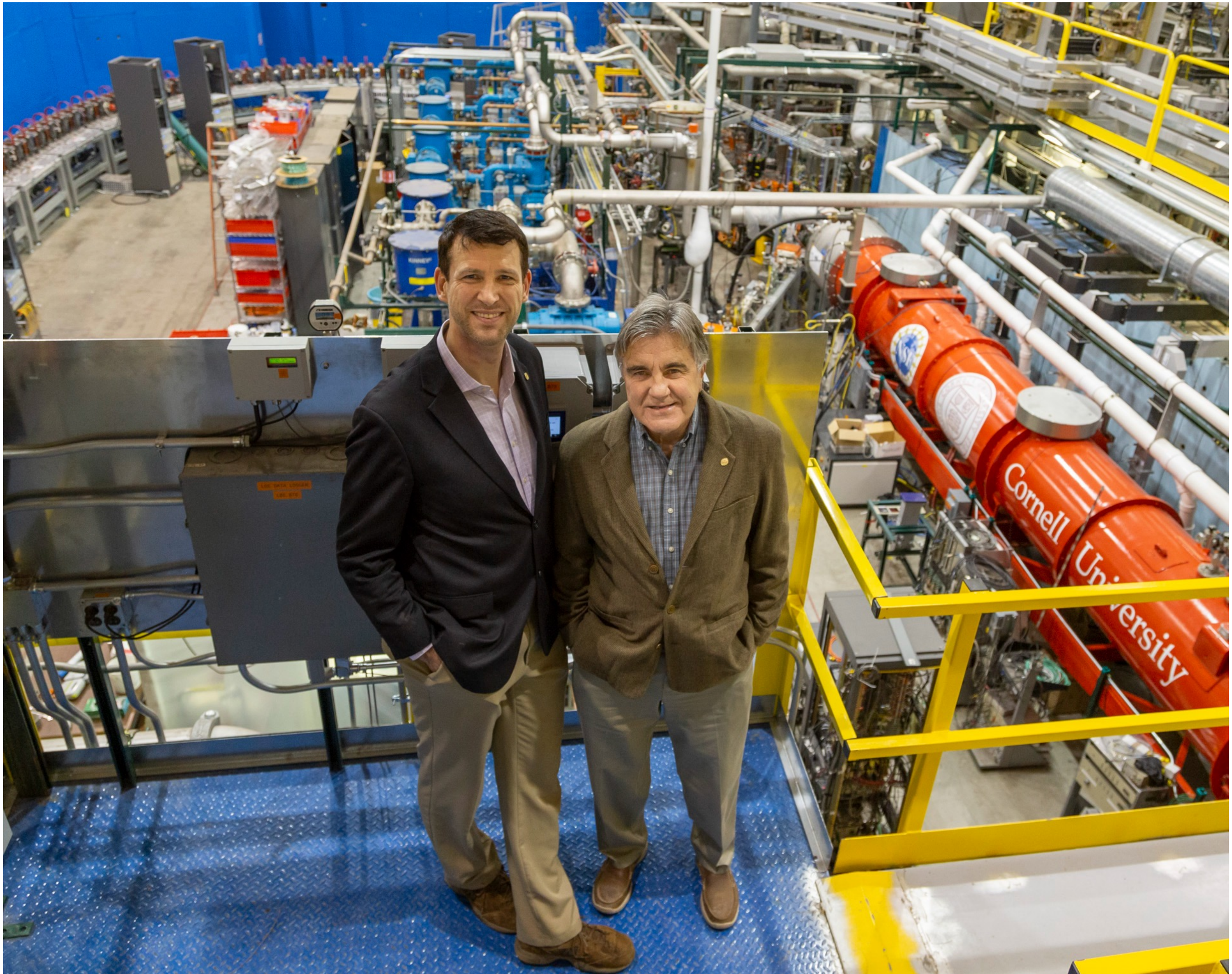
The future Electron Ion Colliders (EIC) could be the 'green energy colliders' as the Energy Recovery Superconducting Linacs 'ERLs' are used to make the energy fully recovered. After collisions electron beam is brough back to the linac by **a single permanent magnet beam line** without requiring electric power.

The single beam line transports all electron energies at once as it uses the Fixed Field Alternating Gradient (FFA-LG) principle with a very strong focusing but this time **with fixed horizontal and vertical betatron tunes**.

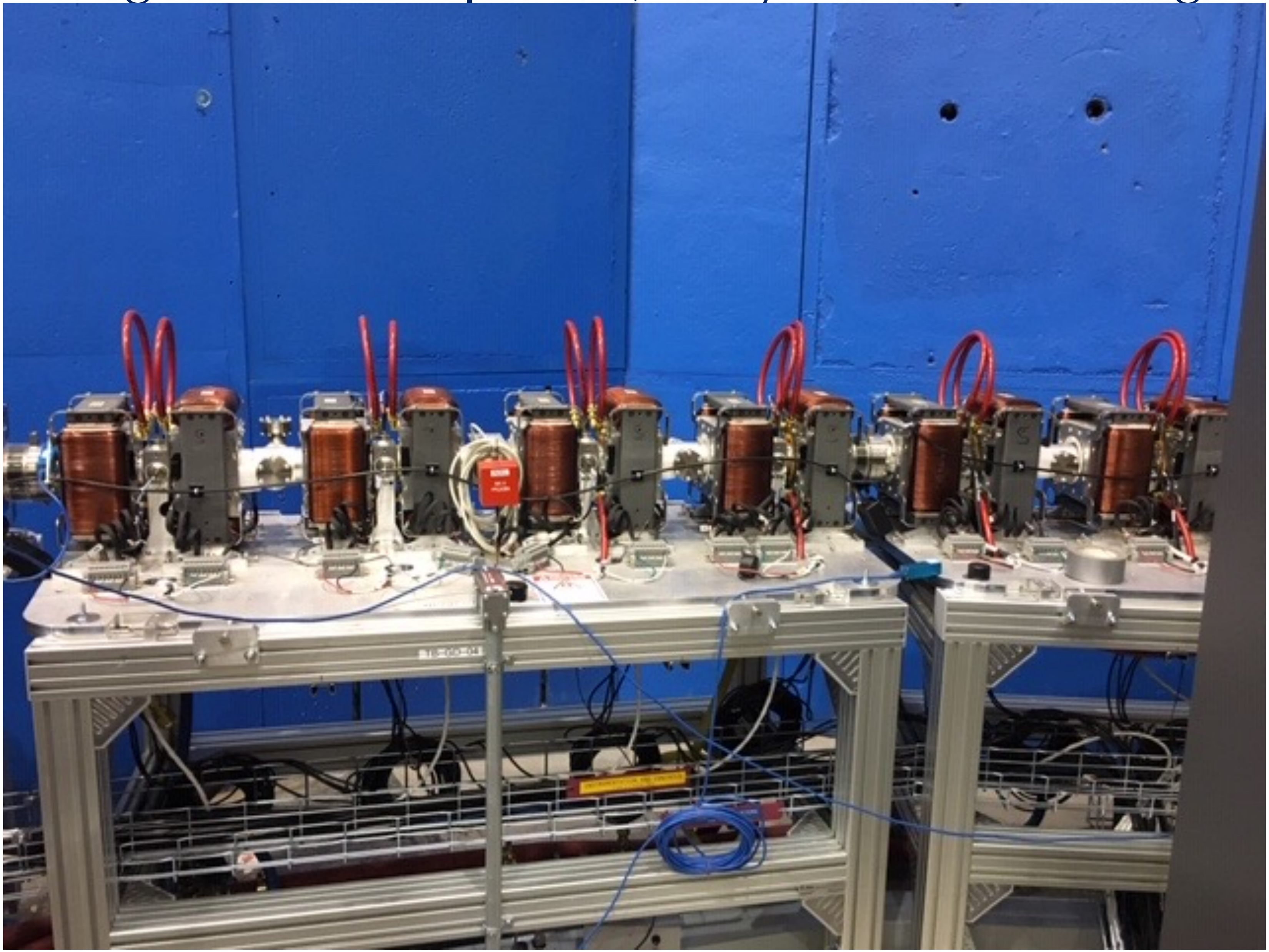
The electron rings for EIC at BNL and at CERN-LHeC are based on the experience from a very successful commissioning of the **Cornell University and Brookhaven National Laboratory Energy Recovery Test Accelerator – 'CBETA'**.

The **FFA non-linear gradient design is a racetrack shape**, with arcs matched by adiabatic transition to the two (LHeC) or multiple straight sections (EIC in the RHIC tunnel) as in the CBETA example. The straight sections are used to place the superconducting linacs.

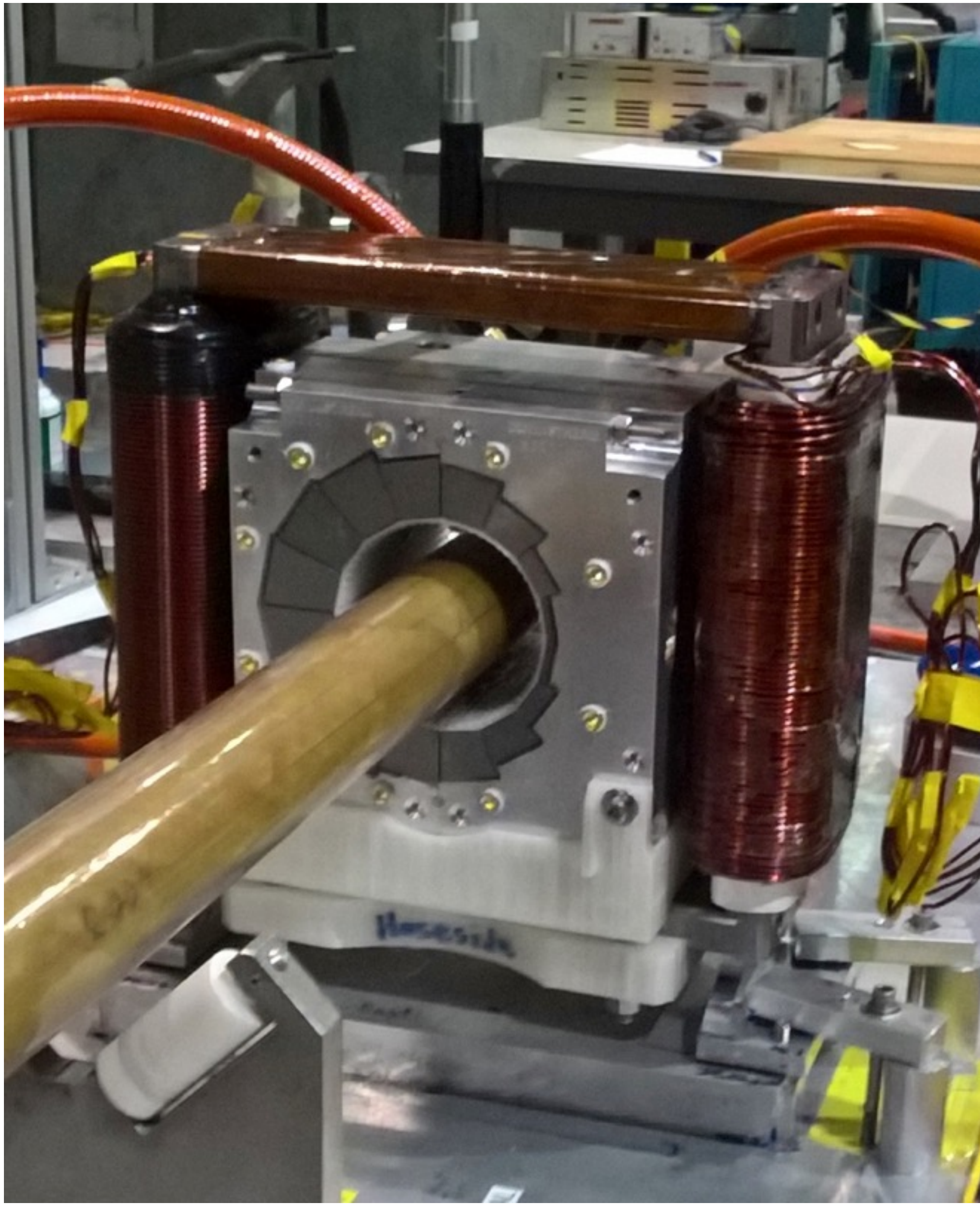
Cornell University Brookhaven ERL Test Accelerator ‘CBETA’

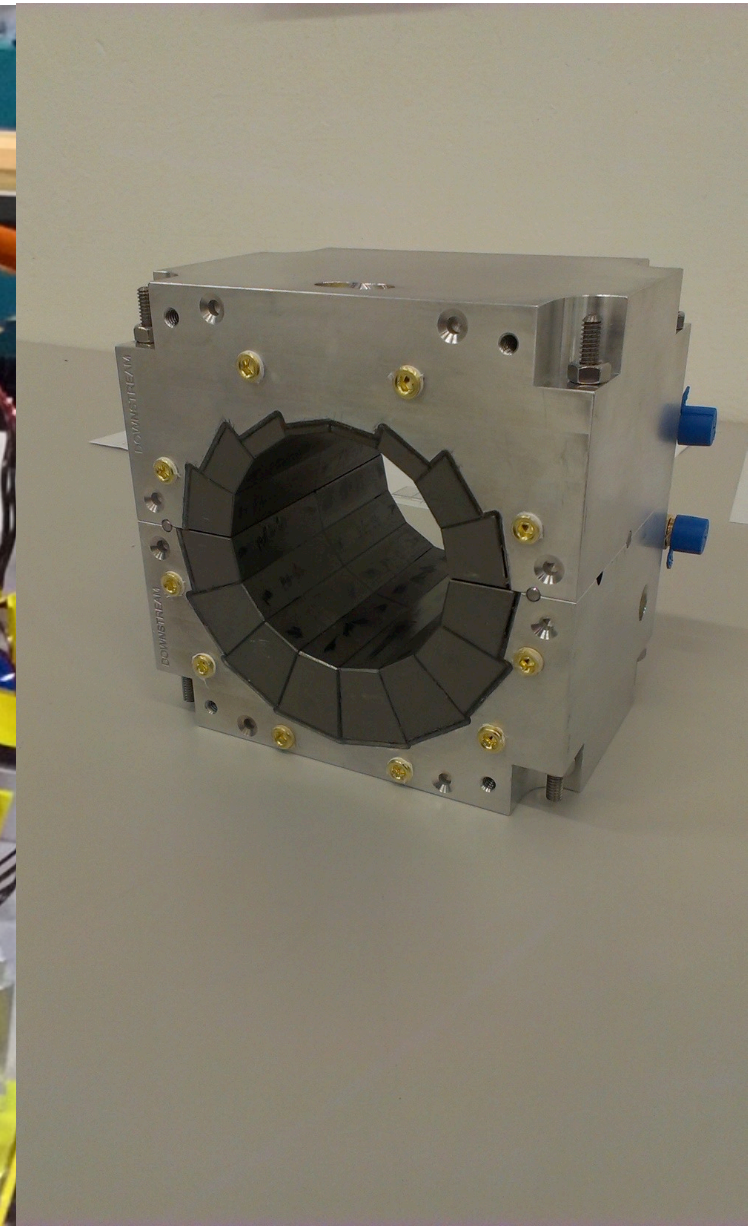


CBETA girder and Superb Quality Permanent Magnets



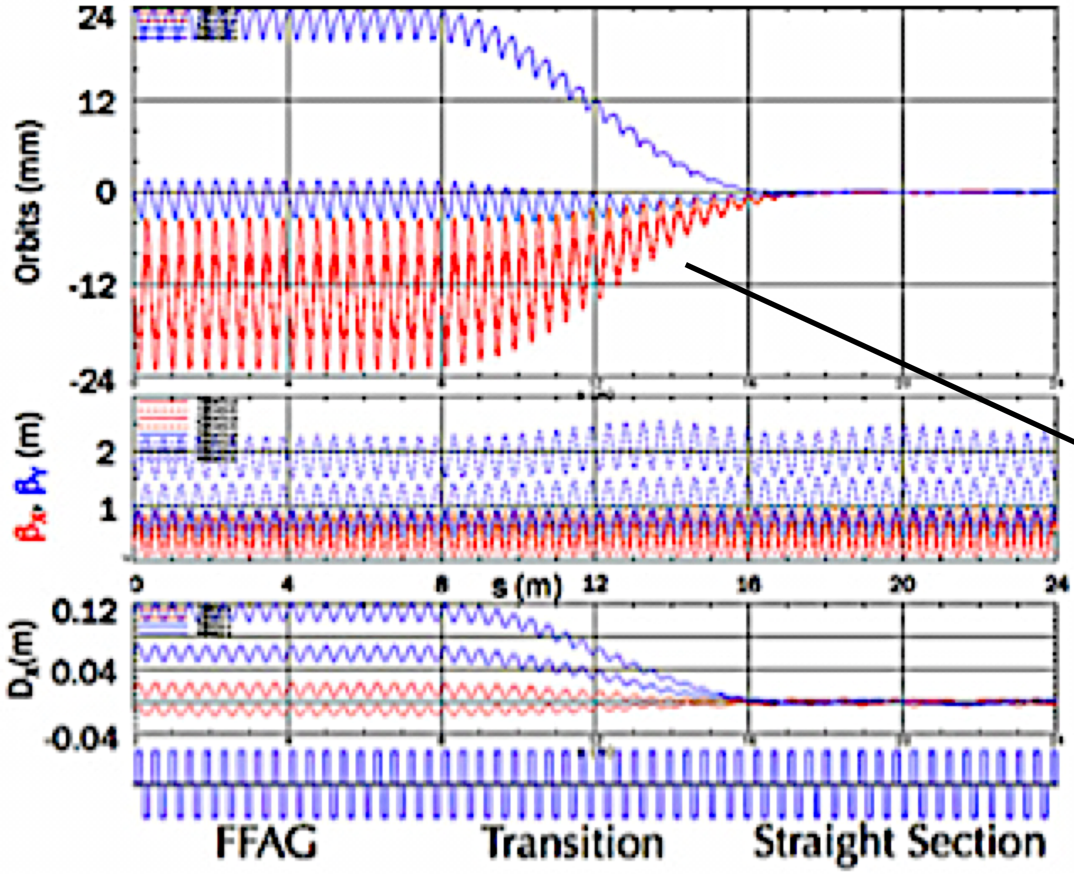
CBETA girder and Superb Quality Permanent Magnets

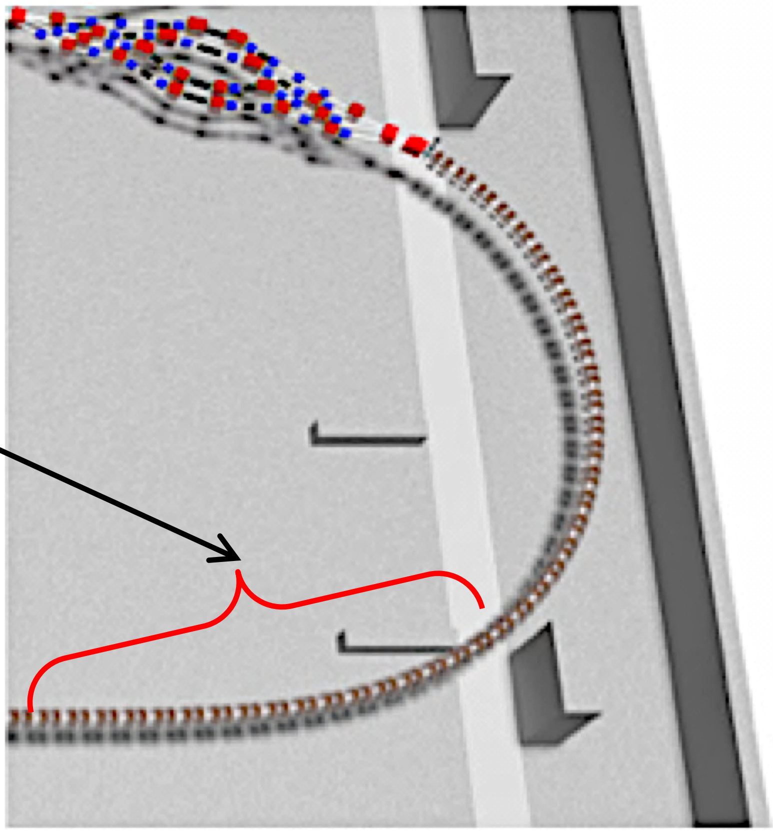




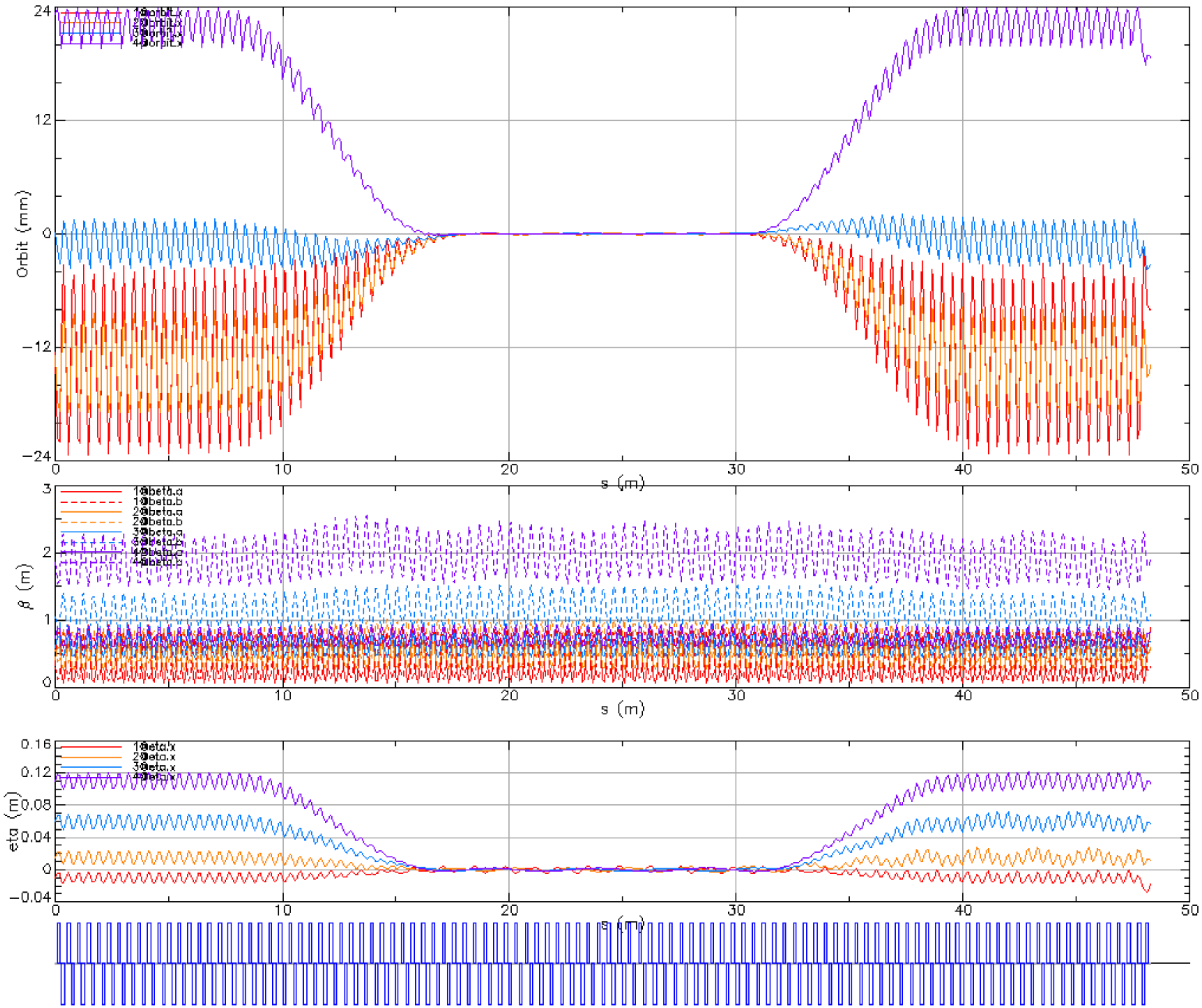
The orbits in the FFA Arc are Adiabatically merged into one

Merging of the orbits at the CBETA project

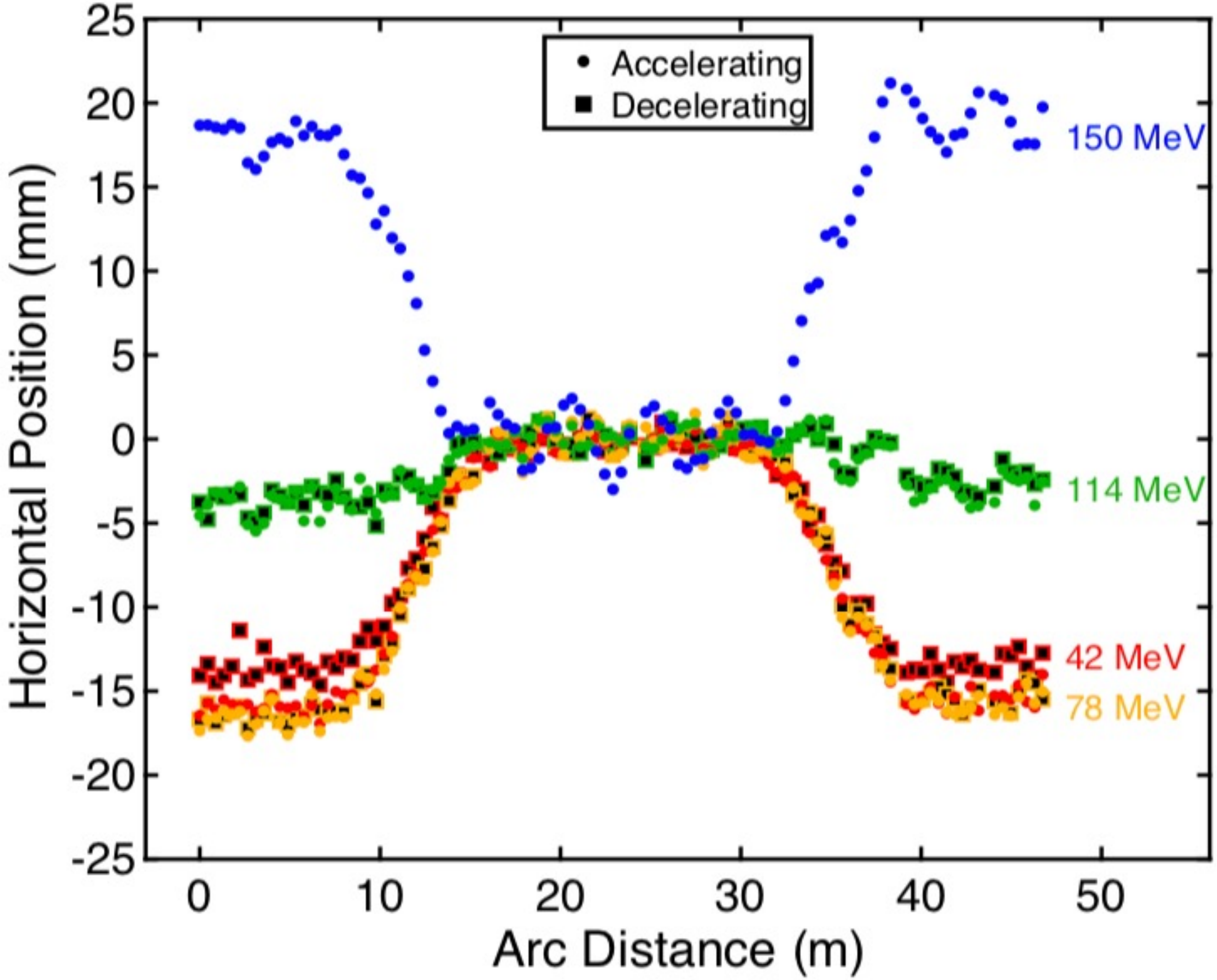




The orbits in the FFA Arc are Adiabatically merged into one

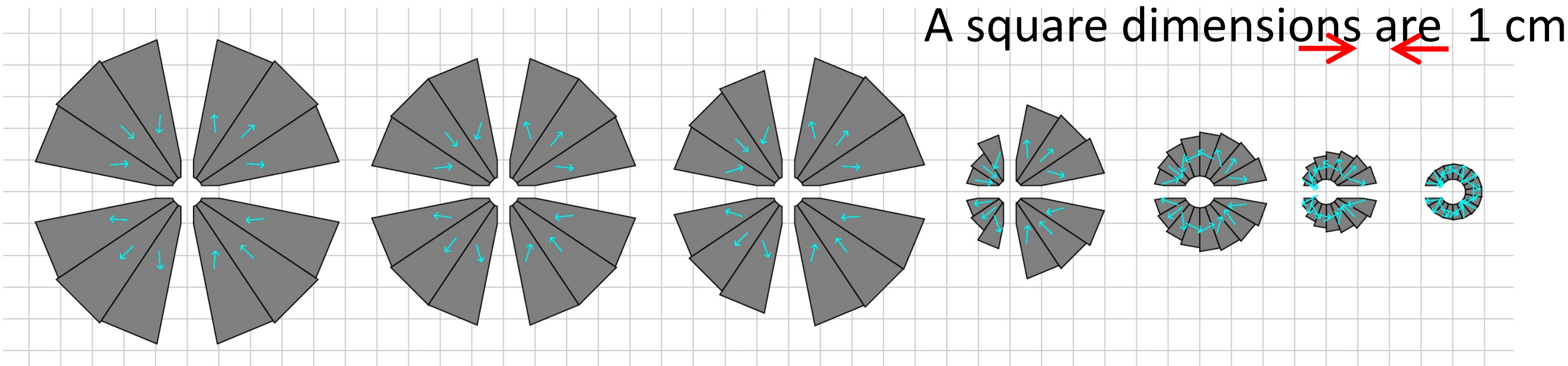


Measurements of Orbits in the CBETA FFA Cells

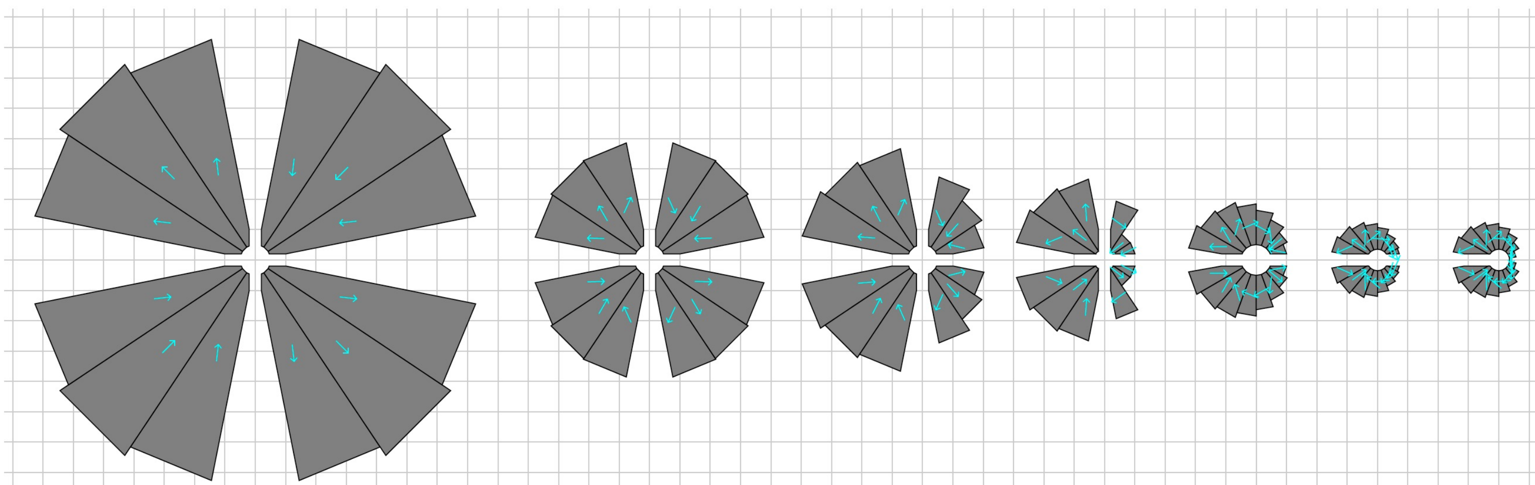


(a)Horizontal FFA orbits

Newest Permanent Magnet Designs For Light Sources

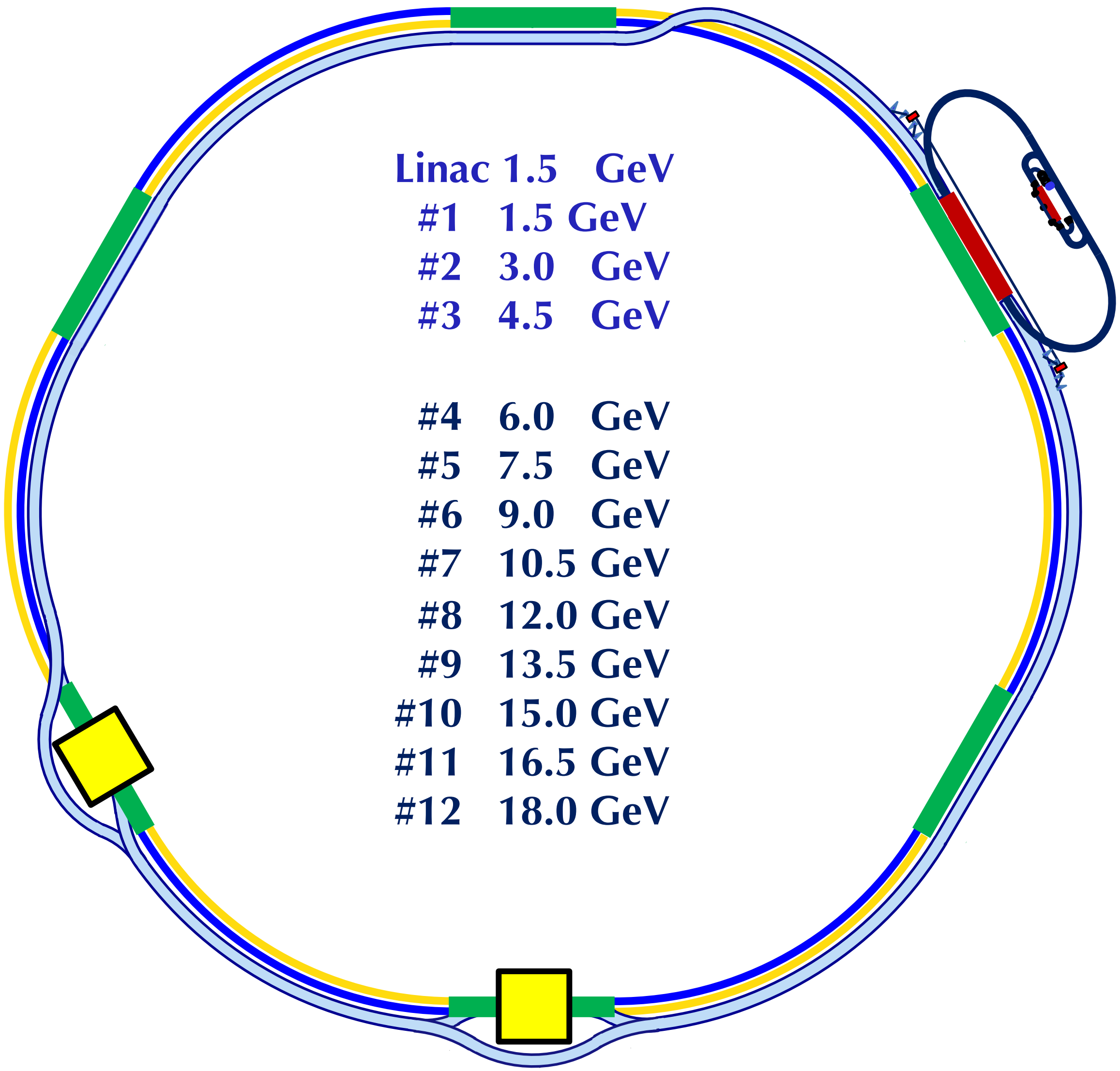


Comparisons of the displaced Halbach with open gap with Combined Function **Focusing** magnet by keeping the beam more towards the center of the aperture

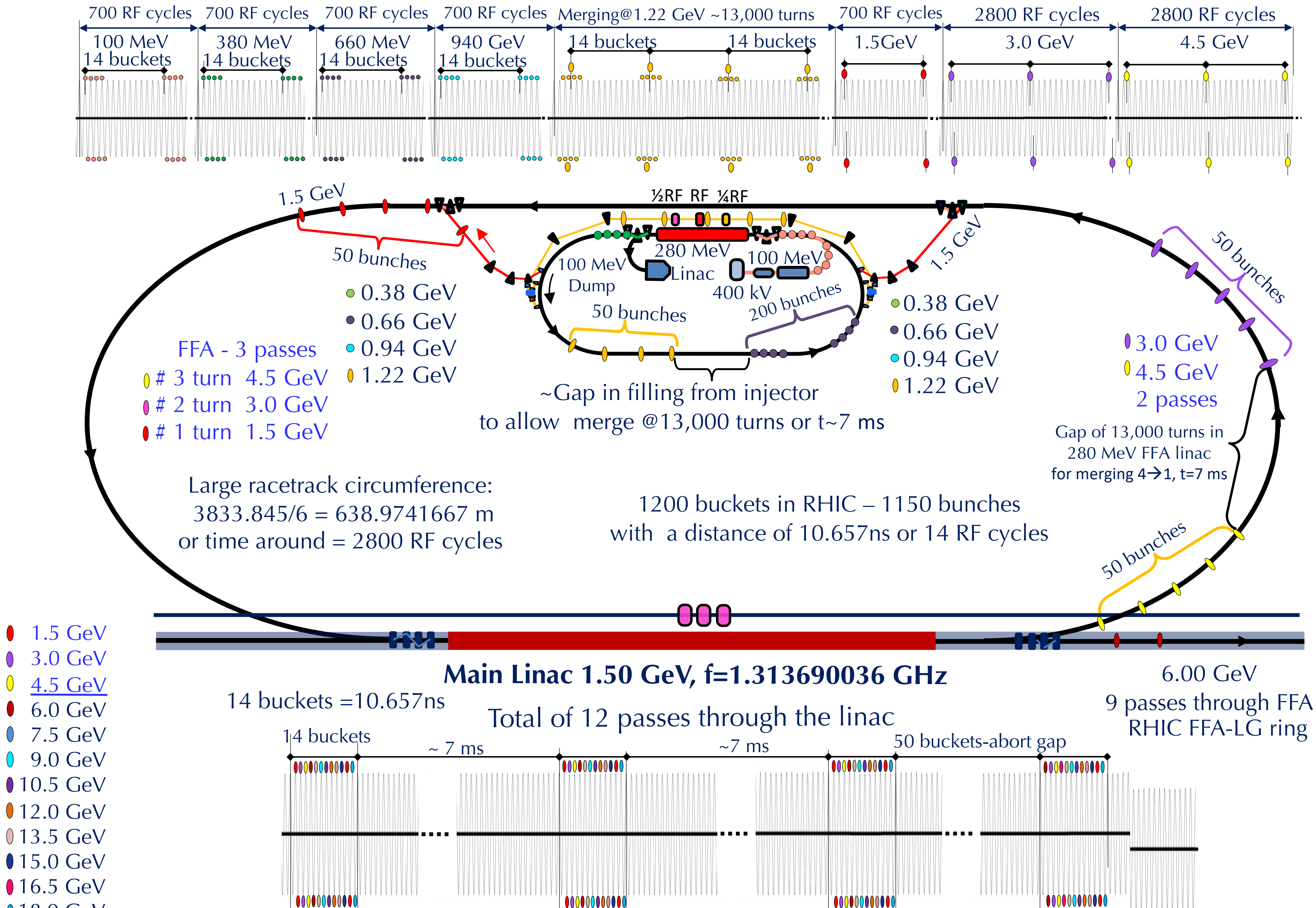


Comparisons of the displaced Halbach with open gap with Combined Function **Defocusing** magnet by keeping the beam more towards the center of the aperture

Layout of the Electron Ion Collider in RHIC

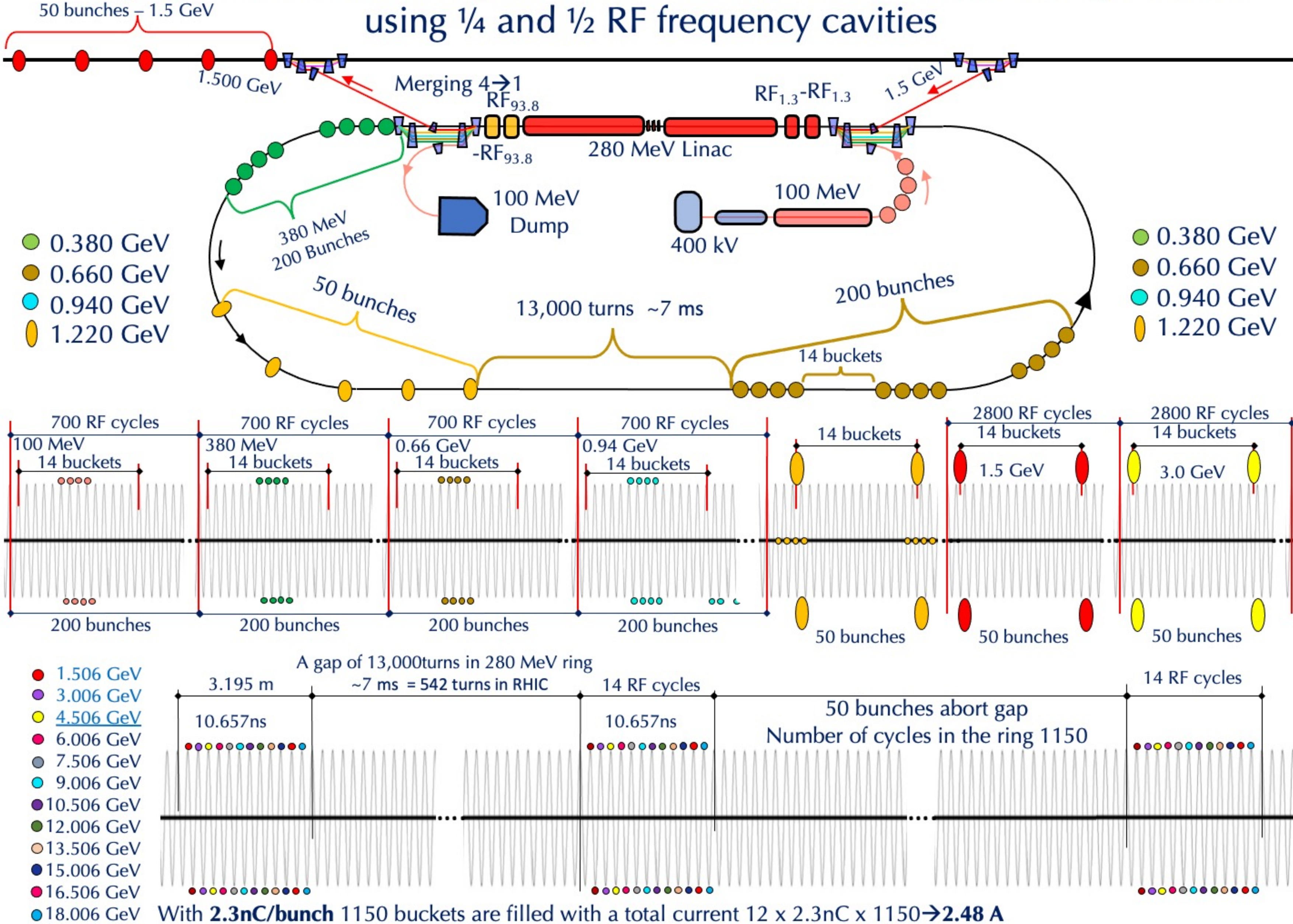


INJECTOR with 280 MeV linac and 1.5→4.5 GeV Racetrack



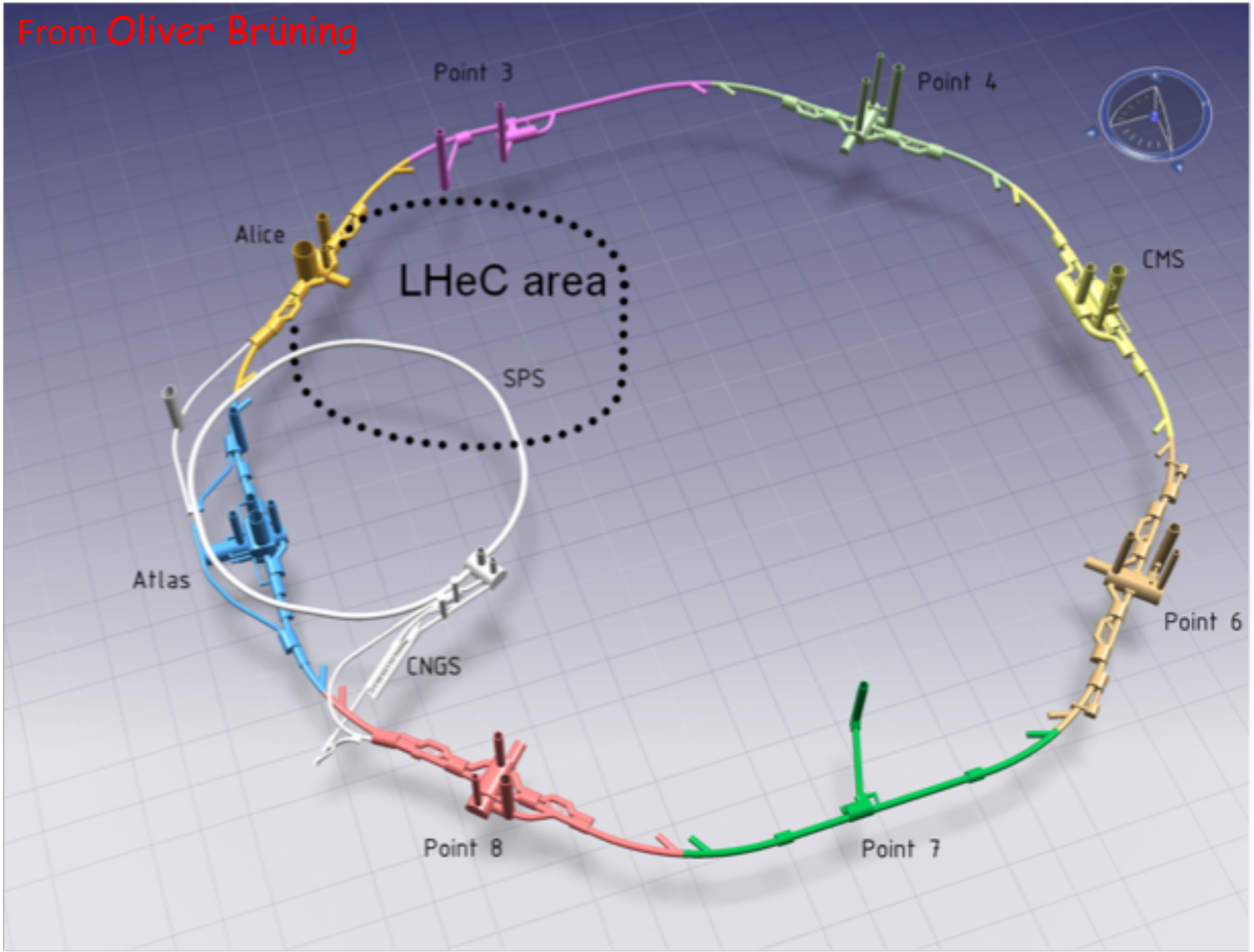
With **28nC/bunch** every 12th of 1150 buckets are filled with a total current 12 x 28nC x 100 = **2.48A**

Merging four bunches at injection first into two and then into a single bunch using ¼ and ½ RF frequency cavities

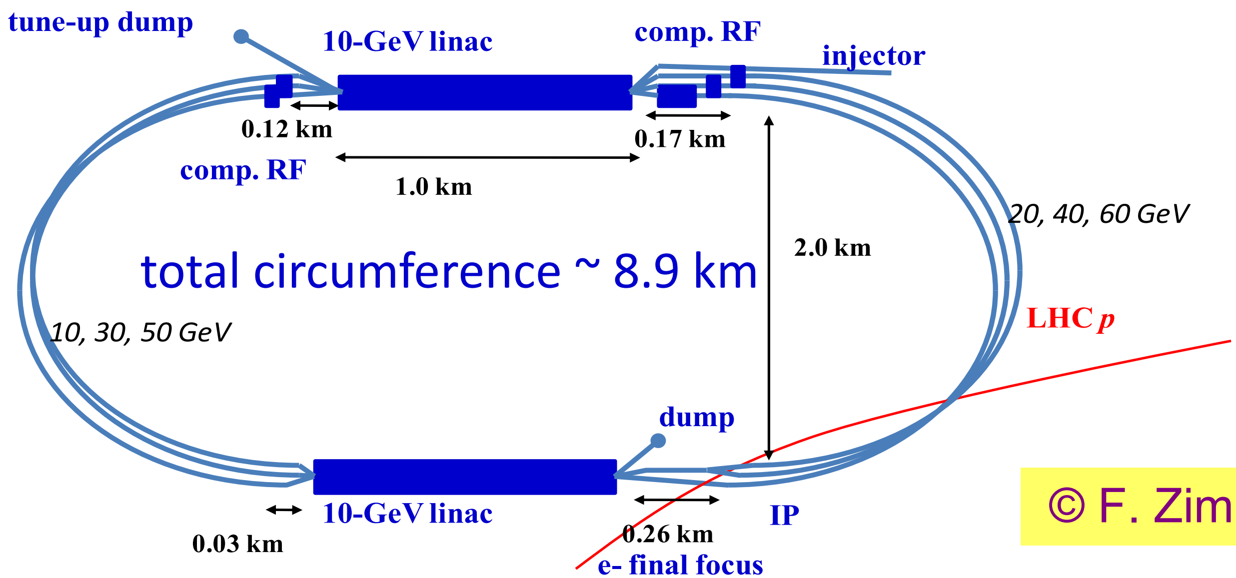


With **2.3nC/bunch** 1150 buckets are filled with a total current 12 x 2.3nC x 1150→**2.48 A**

Layout of the LHeC-LHC-SPS



Linac-Ring Option – LHeC Recirculator



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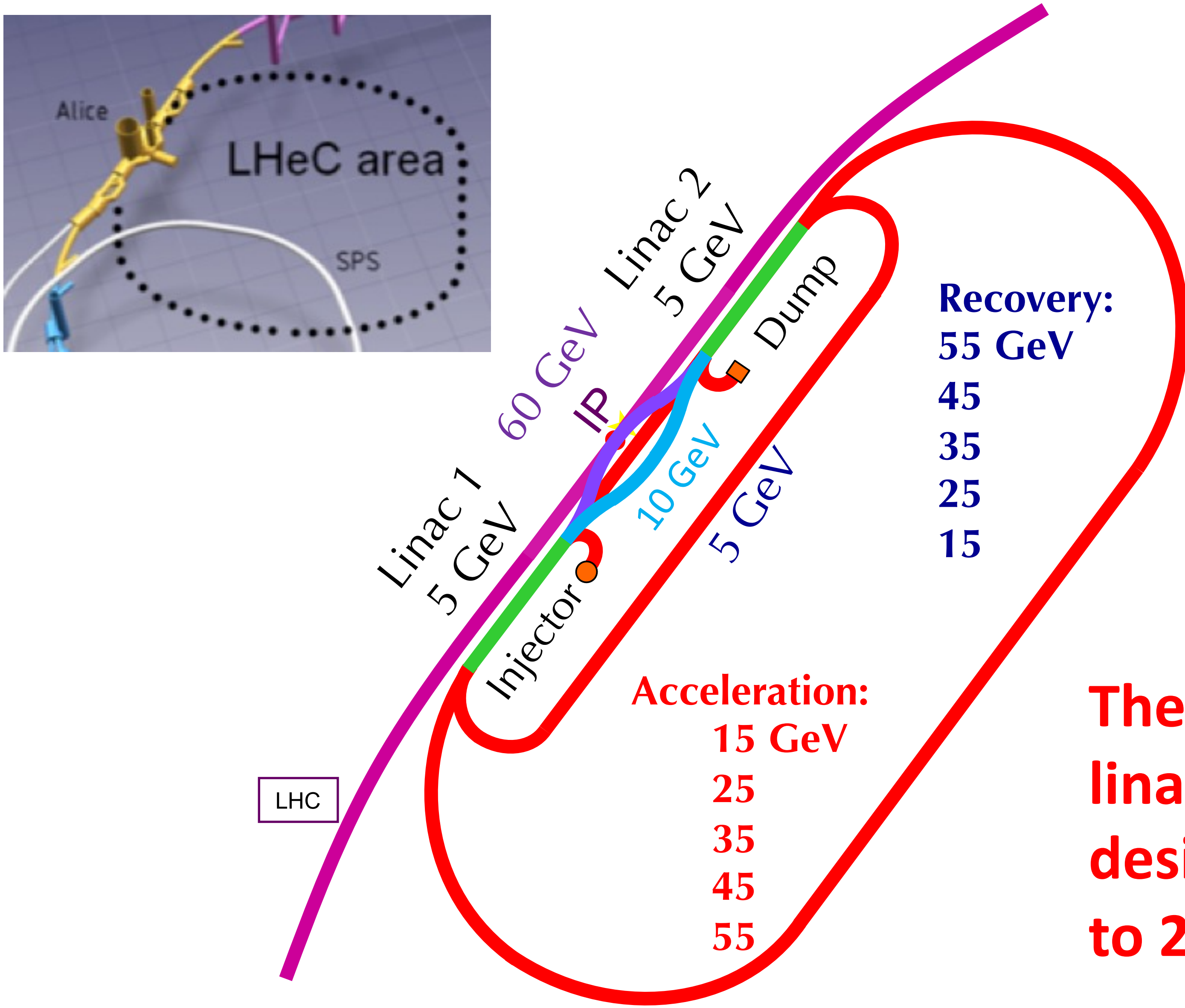
RECIRCULATOR COMPLEX

1. 0.5 Gev injector
2. Two SCRF linacs (10 GeV per pass)
3. Six 180° arcs, each arc 1 km radius
4. Re-accelerating stations
5. Switching stations
6. Matching optics
7. Extraction dump at 0.5 GeV

	PROTONS	ELECTRONS
Beam Energy [GeV]	7000	60
Luminosity [$10^{33}cm^{-2}s^{-1}$]	1	1
Normalized emittance $\gamma\varepsilon_{x,y}$ [μm]	3.75	50
Beta Function $\beta^*_{x,y}$ [m]	0.10	0.12
rms Beam size $\sigma^*_{x,y}$ [μm]	7	7
rms Divergence $\sigma'_{x,y}$ [μrad]	70	58
Beam Current [mA]	(860) 430	6.6
Bunch Spacing [ns]	25 (50)	25 (50)
Bunch Population	$1.7*10^{11}$	$(1*10^9)$ $2*10^9$

The baseline 60 GeV ERL option proposed can give an e-p luminosity of 10^{33} $cm^{-2}s^{-1}$ (extensions to 10^{34} $cm^{-2}s^{-1}$ and beyond are being considered)

FFA-LG LHeC Recirculator with Energy Recovery



The 2 x 10 GeV linacs in LHeC design are reduced to 2 x 5GeV linacs

6-18 GeV Lattice Design

3.09 mm

Magnet Properties:

Defocusing magnet

$L_{BD} = 0.81573$ m

$G_D = 73.953$ T/m

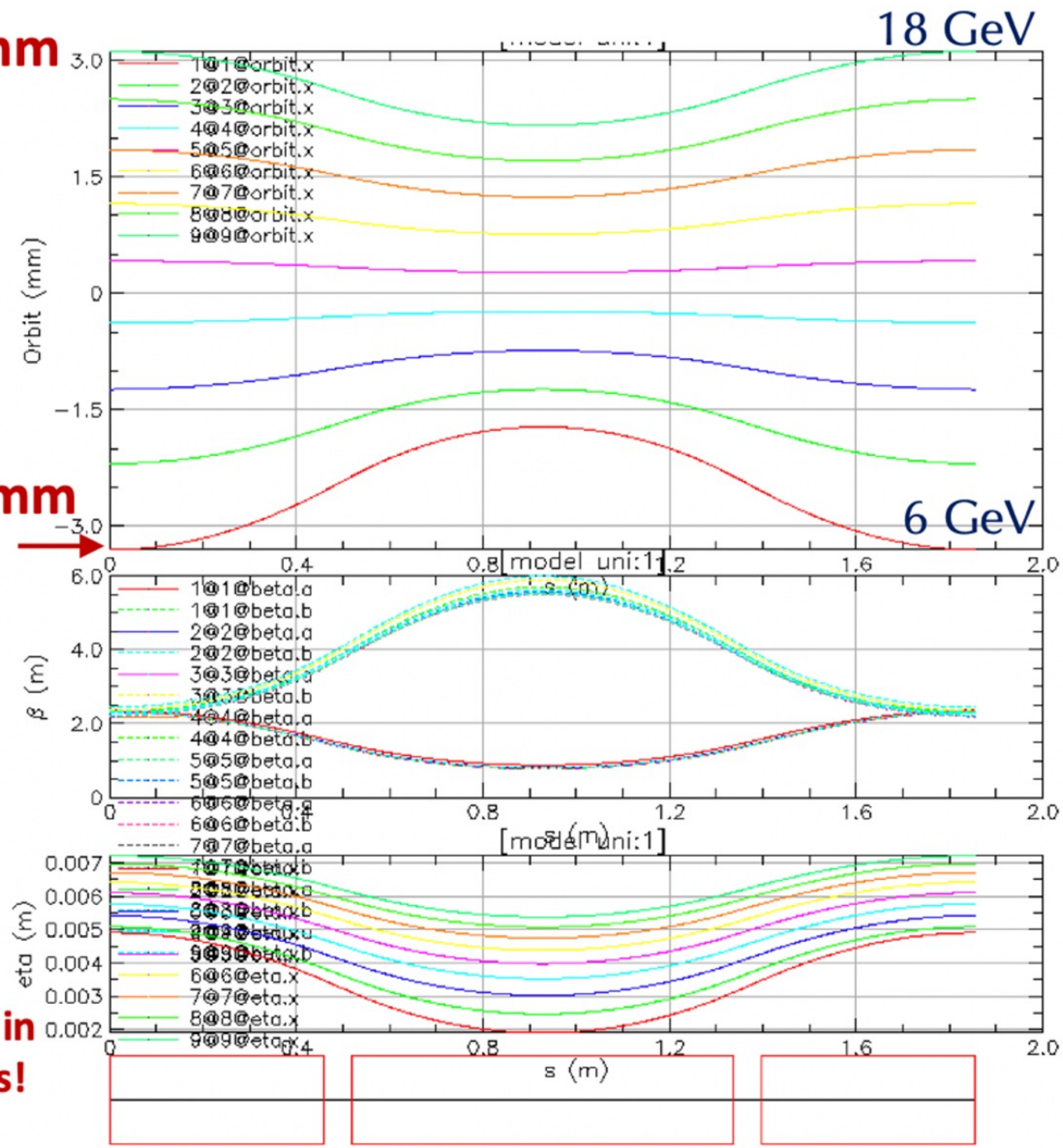
$G_{SXD} = 7407.9$ T/m^2

$O_{XD} = 2.5E3$ T/m^3

$B_D = -0.104525$ T

$B_{Dmax} = 0.363$ T

-3.22 mm



Focusing magnet

$L_{QF} = 0.92$ m

$G_F = -82.79$ T/m

$G_S = -7407$ T/m^2

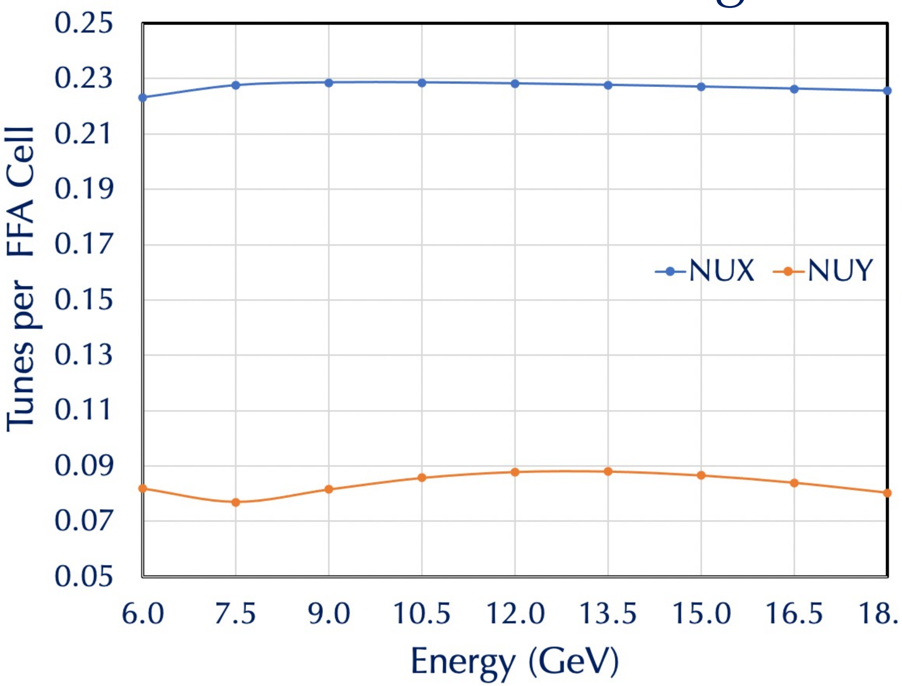
$O_{XF} = 168050.$ T/m^3

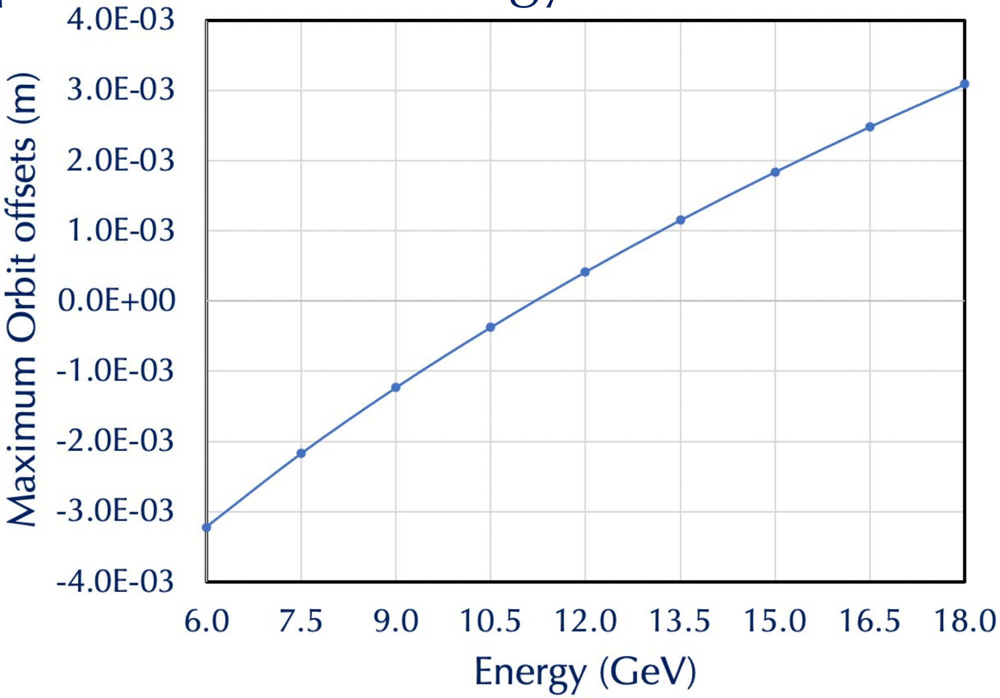
$B_F = -0.104525$ T

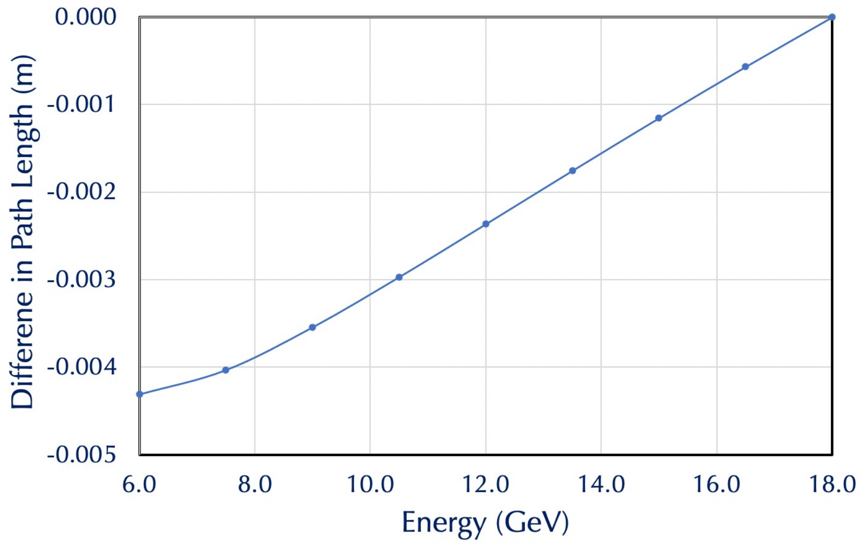
$B_{Fmax} = -0.436$ T

Dispersion is in
In millimeters!

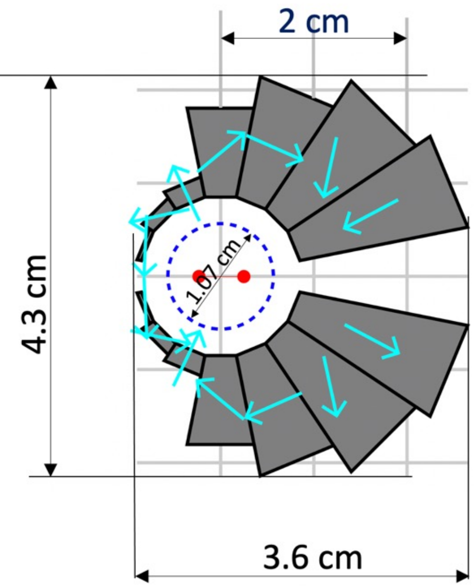
Tunes, Maximum Orbit offsets, and Time of Flight Dependence on Energy



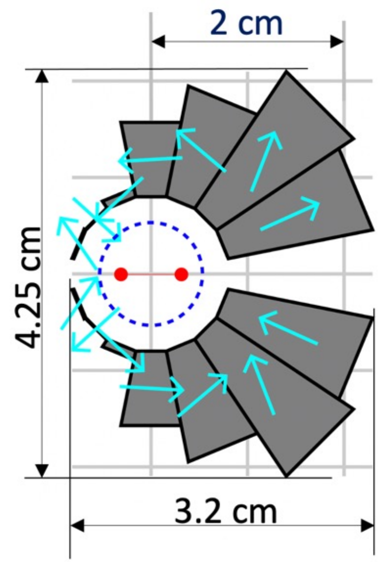




Magnets for the Large FFA ring in RHIC tunnel



For EIC@RHIC
$L_{BD} = 0.81573$ m
$G_D = 96.6$ T/m
$B_D = -0.104525$ T
$S_{XD} = 7407.9$ T/m^2
$O_{XD} = 2.5E3$ T/m^3
$R_{BD} = 357.419$ m
Good Field Region
$R_{BD} = 5.33$ mm
Maximum Orbit Offsets in B_D
x_{MIN} = - 2.28mm,
x_{MAX} = 2.52 mm
Maximum field =-0.363 T



$L_{QF} = 0.92$ m
$B_F = -0.104525$ T
$R_{QF} = 357.419$ m
$G_{QF} = -82.789$ T/m
$S_{XF} = -7407.9$ T/m^2
$O_{XF} = -168050$ T/m^3
$R_{QF} = 357.419$ m

Good Field Region R = 5.33mm
Maximum Orbit Offsets QF:
x_{MIN}= -3.22 mm, x_{MAX}=3.09 mm
Maximum field = -0.436 T

Multipoles in the permanent magnets

Multipole components in the defocusing magnet with the field harmonics at R = 5.33 mm with the reference field component of G_D=96.6 T/m.

Field harmonic	Normal units	Skew units
Dipole	-2650.13	-0.00
Quadrupole	10000.00	-0.00
Sextupole	6780.24	0.00
Octupole	-95.91	0.00
Decapole	0.05	-0.00
Dodecapole	0.10	0.00
14-pole	0.49	0.00
16-pole	0.78	0.00
18-pole	-0.22	-0.00
20-pole	-4.55	-0.00
22-pole	-9.76	0.00
24-pole	-9.98	0.00
26-pole	-3.43	-0.00
28-pole	-2.72	-0.00
30-pole	-0.50	0.00
32-pole	0.00	0.00
34-pole	0.74	-0.00
36-pole	-1.62	0.00
38-pole	-1.04	0.00
40-pole	0.21	-0.00

Multipole components in the focusing magnet with the field harmonics at R = 5.33 mm with the reference field component of G_F= - 82.7876 T/m.

Field harmonic	Normal units	Skew units
Dipole	2367.22	-0.00
Quadrupole	10000.00	-0.00
Sextupole	4772.21	-0.00
Octupole	57.74	-0.00
Decapole	0.07	-0.00
Dodecapole	0.23	-0.00
14-pole	0.45	-0.00
16-pole	0.42	-0.00
18-pole	-0.89	-0.00
20-pole	-4.07	0.00
22-pole	-8.34	0.00
24-pole	-9.63	0.00
26-pole	-6.40	0.00
28-pole	0.54	-0.00
30-pole	-1.02	0.00
32-pole	-0.00	0.00
34-pole	-0.11	-0.00
36-pole	-1.31	-0.00
38-pole	-0.57	-0.00
40-pole	0.11	-0.00

Low Energy 1.5 - 4.5 GeV EIC@RHIC FFA-LG Cell

Max orbit offset =1.6 mm

Magnet Properties:

Defocusing magnet

L_{BD} = 0.1856 m

G_D = 222.3713 T/m

B_D = 0.2406 T

B_{Dmax} = 0.57583 T

-2.4 mm

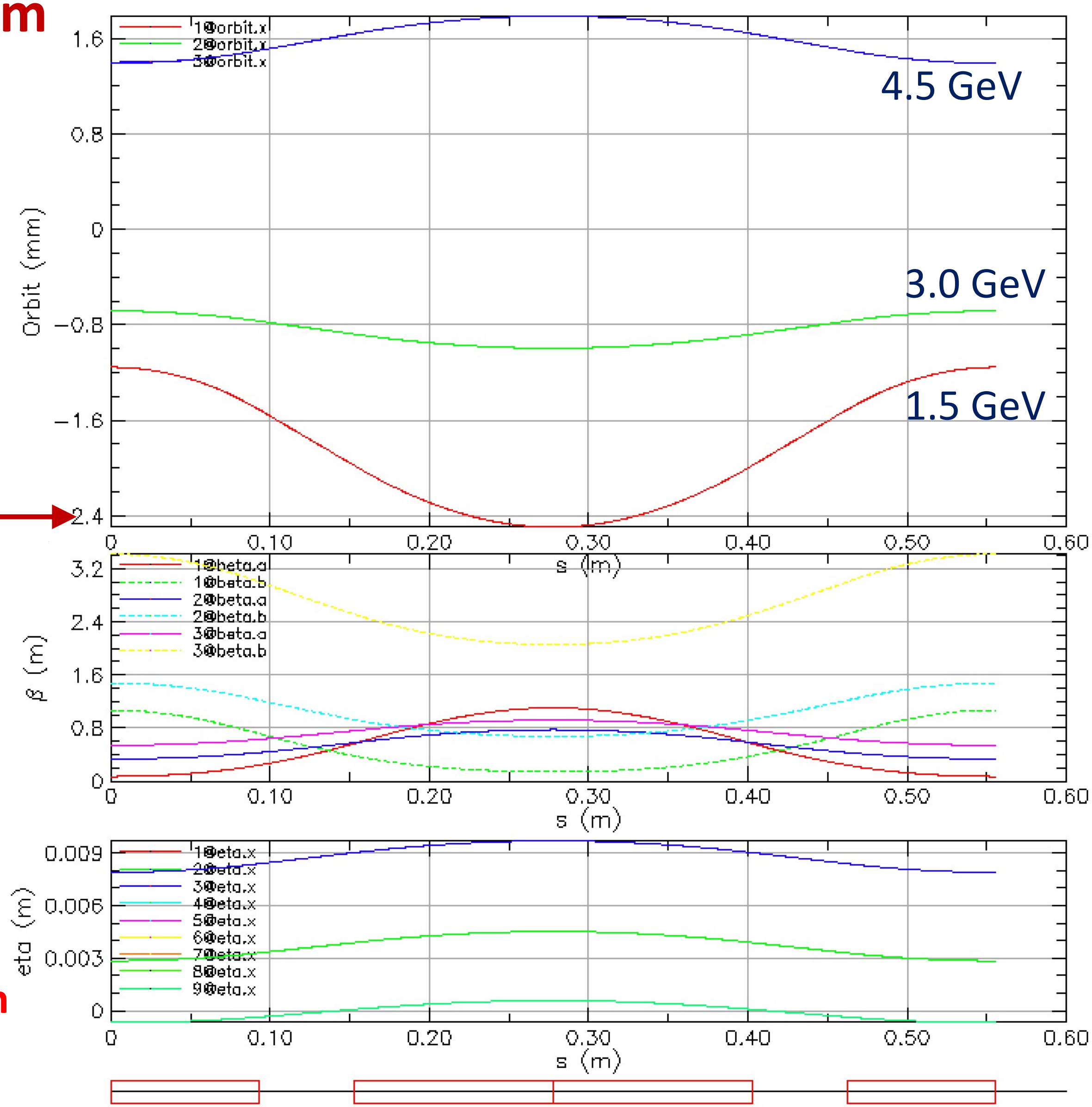
Focusing magnet

L_{QF} = 0.25 m

G_F = -195.8831 T/m

B_F = 0.2406 T

B_{Fmax} = 0.5907 T



Dispersion is in millimeters!

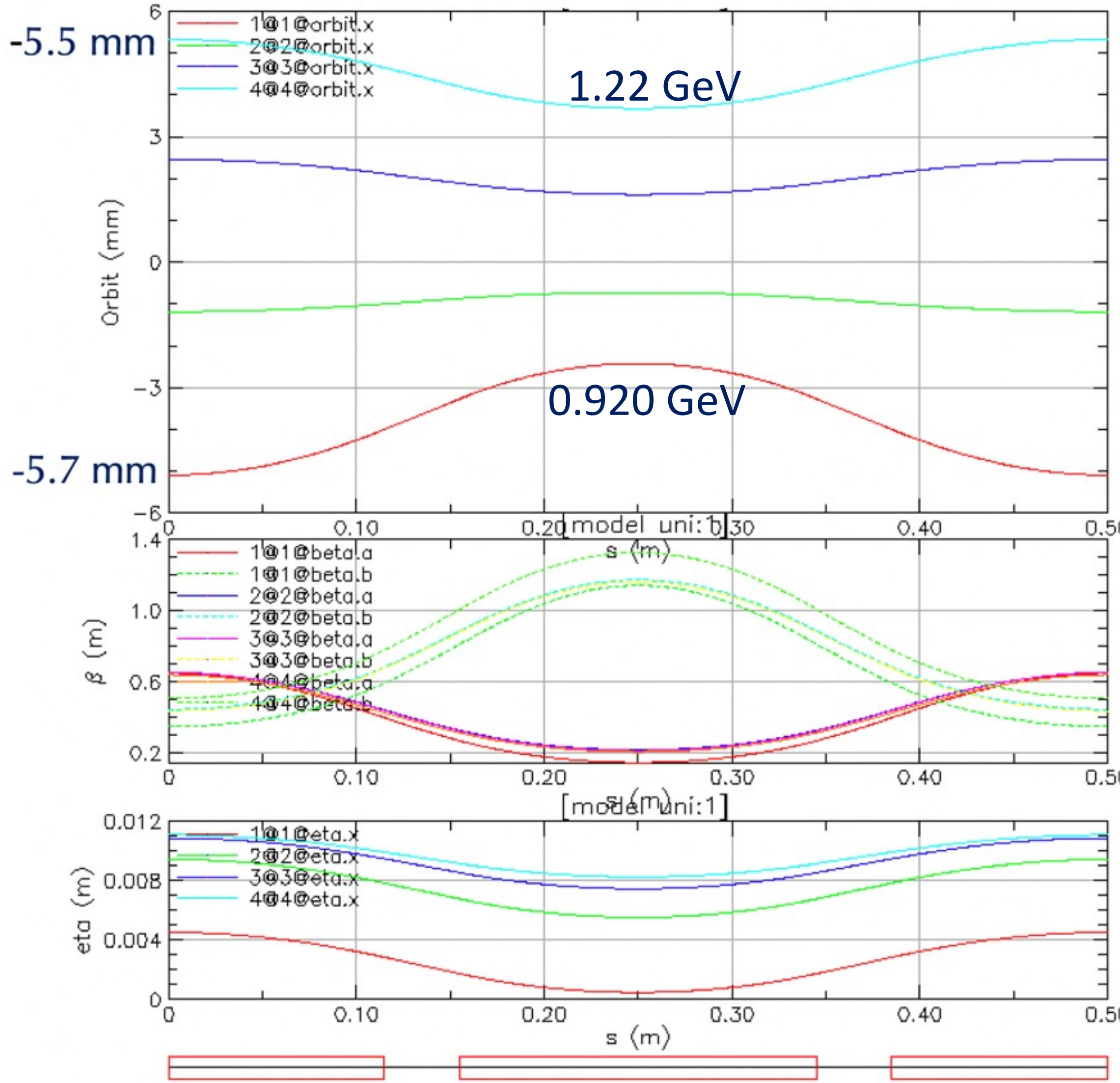
Lattice functions and orbits in the single arc cell of the small 159m racetrack with the permanent combined function magnet properties

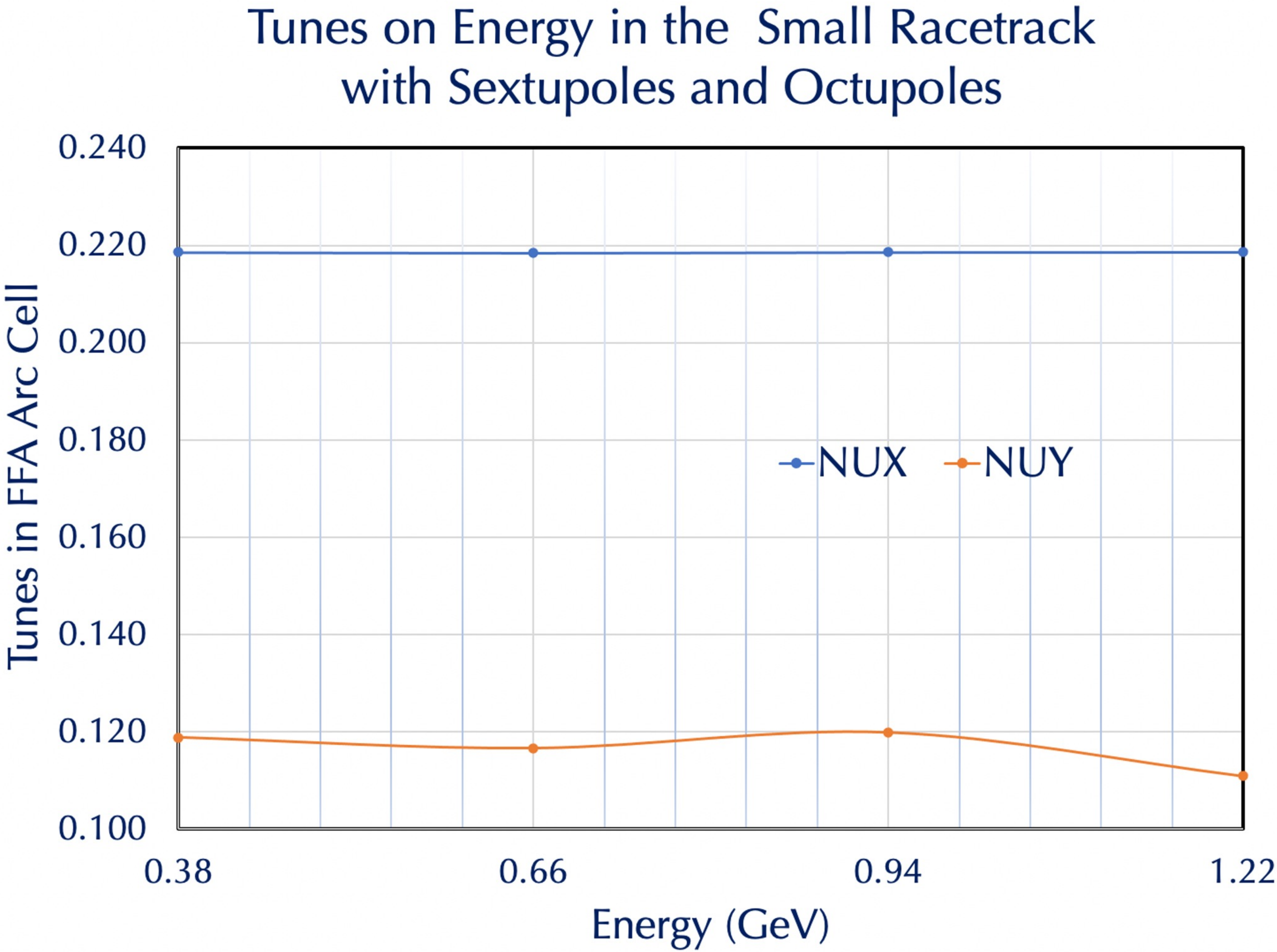
Defocusing Combined Function Magnet:

L_{BD} = 0.170 m
B_D = -0.16596556 T
R_D = 14.9733 m
G_D = 75.71 T/m
$Sextp_D$ = 5840.3 T/m^2
$Octp_D$ = 2.9x10^4 T/m^3
Maximum field:
B_{max} = -0.527 T

Focusing Combined Function Magnet:

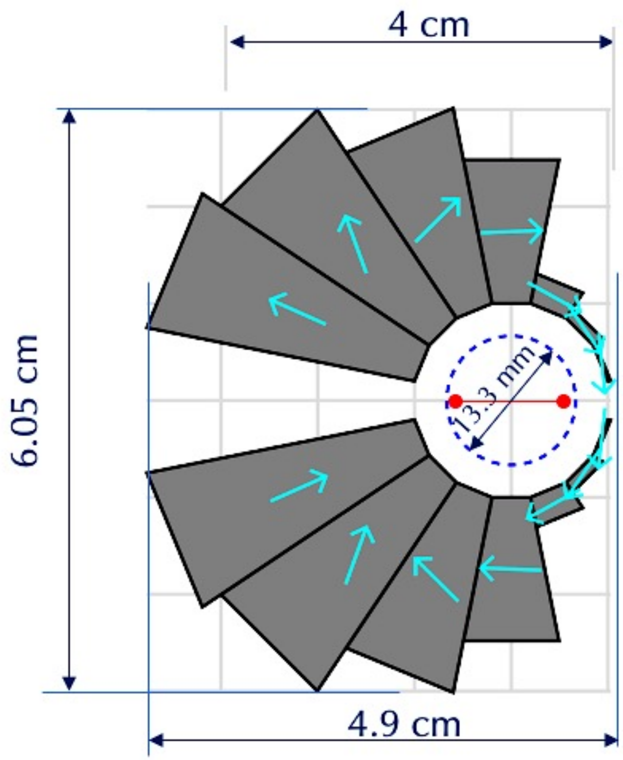
L_{BD} = 0.250 m
B_D = -0.16596556 T
R_D = 14.9733 m
G_D = -75.43 T/m
$Sextp_D$ = -3968.0 T/m^2
$Octp_D$ = 5.8x10^4 T/m^3
Maximum field:
B_{max} = -0.703 T




Tunes on Energy in the Small Racetrack
with Sextupoles and Octupoles
Tunes in FFA Arc Cell
0.240
0.220
0.200
0.180
0.160
0.140
0.120
0.100
NUX
NUY
0.38
0.66
0.94
1.22
Energy (GeV)

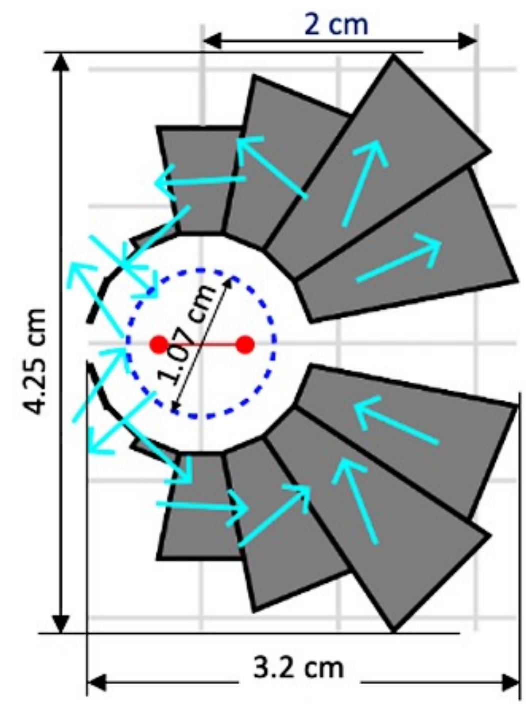
Extraordinary Magnets → Fixed Tunes

For EIC@RHIC, L_{BD}=0.81573 m, **G_D=96.6 T/m**, **B_D=–0.104525 T**, S_{XD} = 7407.9 T/m^2, O_{XD} = 2.5E^3 T/m^3 , R_{BD}=357.419 m



Good field region with R_{BD} = 5.33 mm, with maximum orbit offsets in the defocusing magnet **B_D** of **-2.28mm< Δx_{OFFSET}< 2.52 mm** with the maximum field **B_{DMAX}= – 0.363 T**

L_{QF} = 0.92 m, **B_F =–0.104525 T**, R_{QF}=357.419 m, **G_{QF}=–82.789 T/m**, S_{XF} = –7407.9 T/m^2, O_{XF}=–168050 T/m^3, R_{QF} = 357.419 m



Good field region at the radius of R =5.33 mm with the maximum orbit offsets at the focusing magnet **Q_F** of **-3.22 mm< Δx_{MAX}<3.09 mm**, with a maximum field of **B_{FMAX}= –0.436 T**

Field multipoles in the Small Racetrack

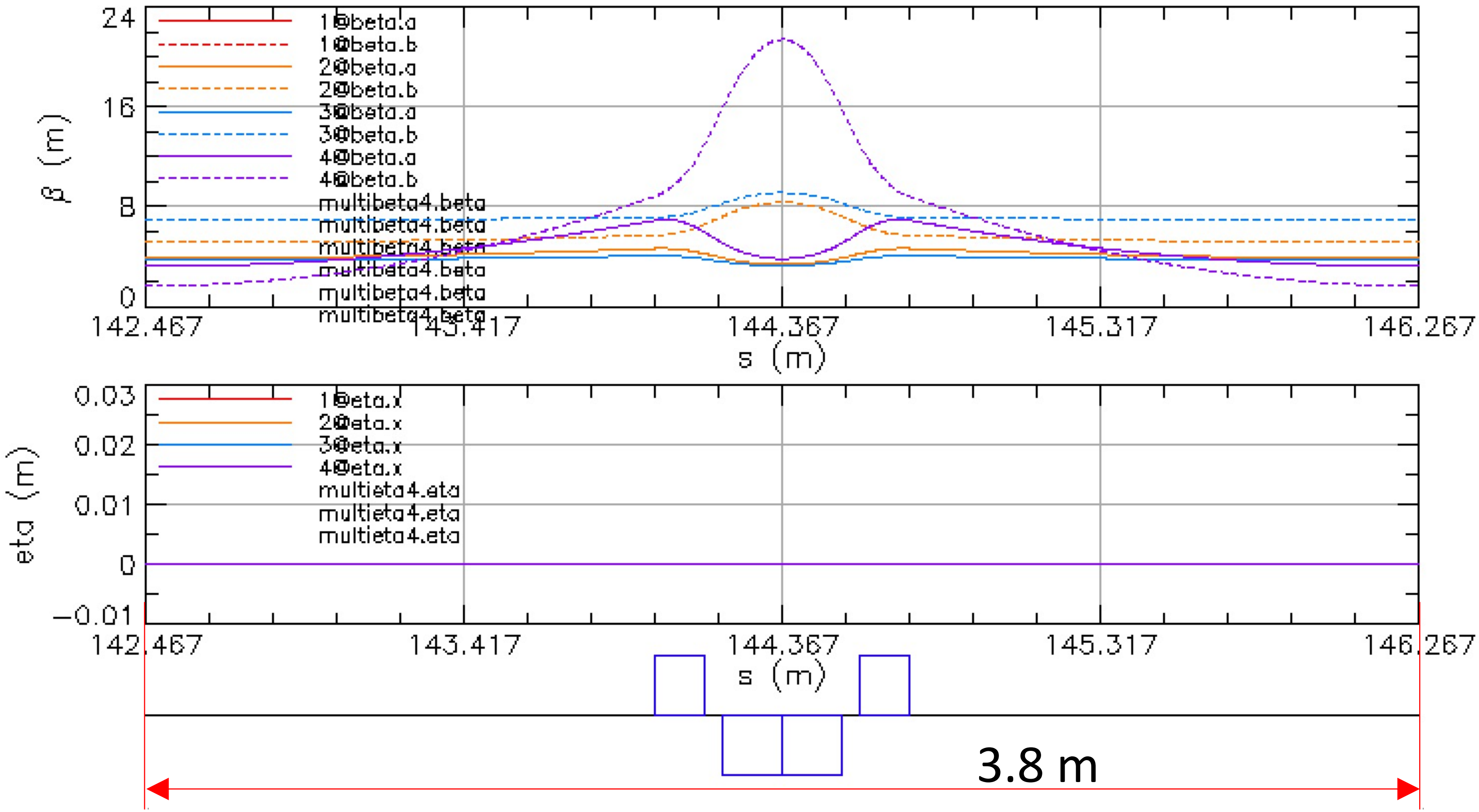
Field harmonics at R=6.66667mm. The reference field component is 74.996 T/m.

Field harmonic	Normal units	Skew units
Dipole	3341.55	-0.00
Quadrupole	10000.00	-0.00
Sextupole	3318.52	-0.00
Octupole	343.63	-0.00
Decapole	-0.32	-0.00
Dodecapole	0.01	-0.00
14-pole	0.31	0.00
16-pole	0.20	0.00
18-pole	-1.77	-0.00
20-pole	-5.49	-0.00
22-pole	-8.33	0.00
24-pole	-6.51	-0.00
26-pole	-4.88	-0.00
28-pole	-0.39	-0.00
30-pole	-0.40	0.00
32-pole	0.00	0.00
34-pole	-0.33	-0.00
36-pole	-1.16	0.00
38-pole	-0.17	0.00
40-pole	-0.18	-0.00

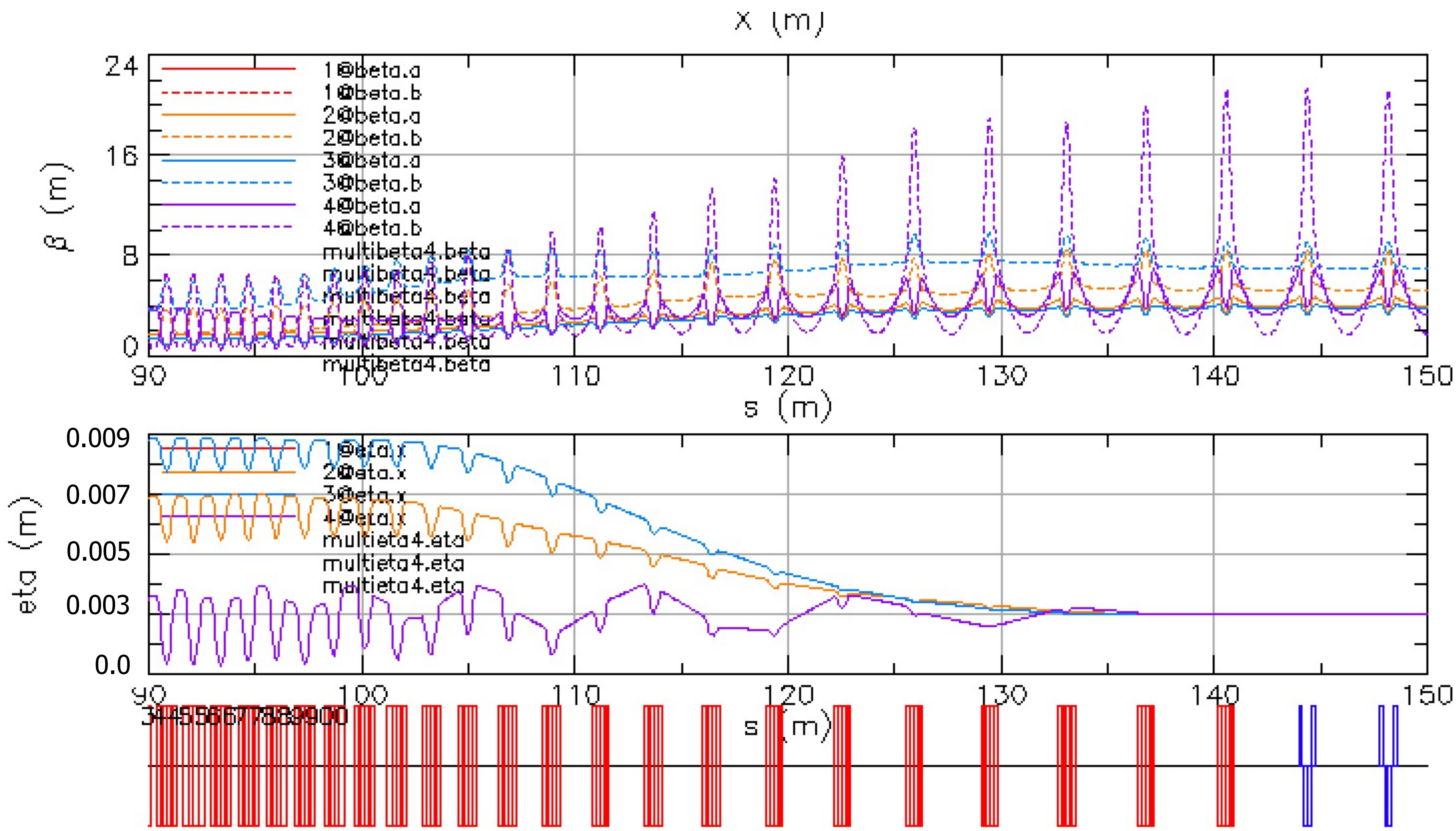
Field harmonics at R=6.66667mm. The reference field component is -75.6993 T/m.

Field harmonic	Normal units	Skew units
Dipole	-3310.65	0.00
Quadrupole	10000.00	0.00
Sextupole	5790.70	0.00
Octupole	-170.21	0.00
Decapole	0.08	-0.00
Dodecapole	0.13	-0.00
14-pole	0.33	0.00
16-pole	0.63	0.00
18-pole	-0.04	-0.00
20-pole	-3.85	-0.00
22-pole	-8.23	-0.00
24-pole	-7.27	0.00
26-pole	-1.69	-0.00
28-pole	-3.01	-0.00
30-pole	-0.06	0.00
32-pole	0.00	0.00
34-pole	0.58	-0.00
36-pole	-1.30	0.00
38-pole	-0.67	0.00
40-pole	0.05	-0.00

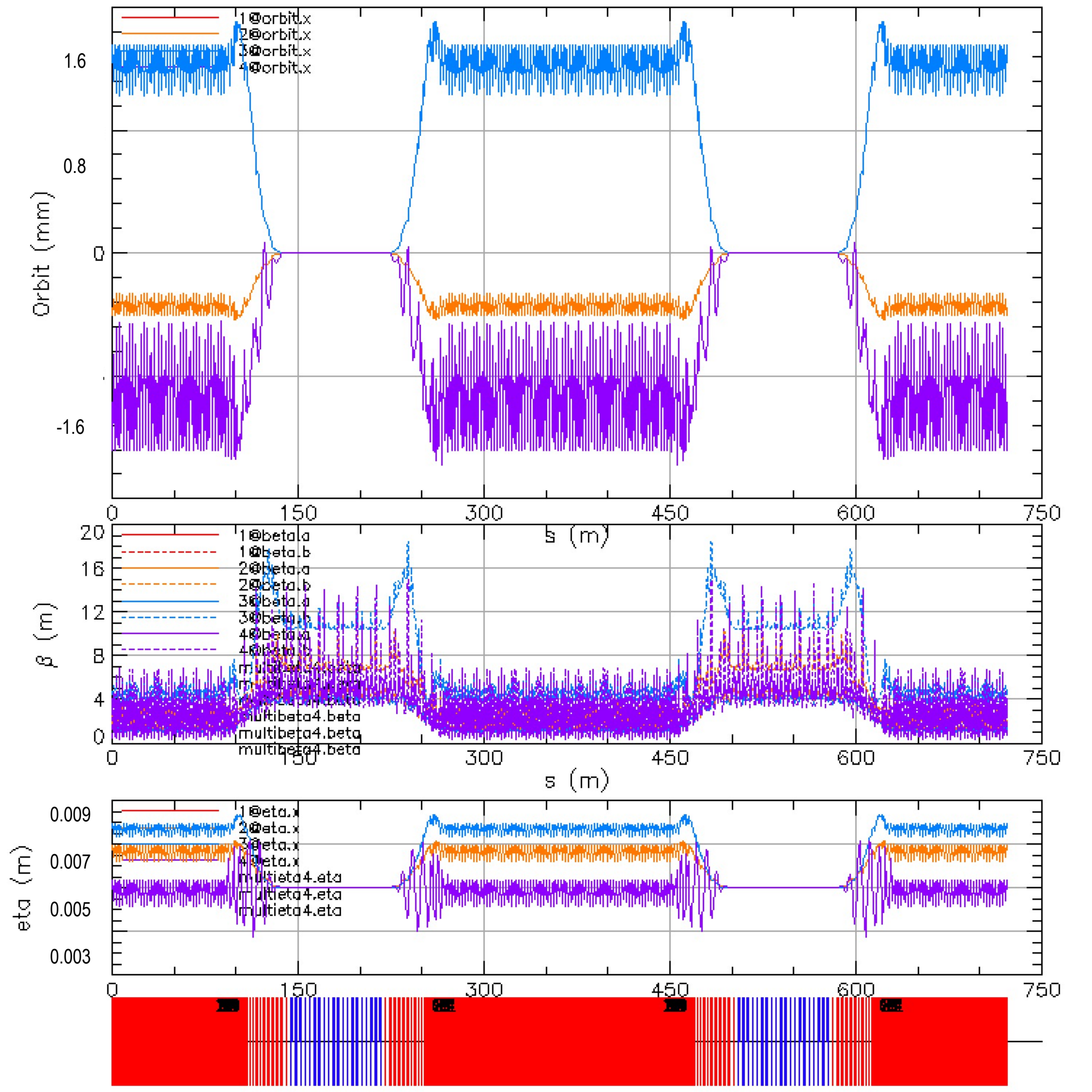
Straight Section Cells



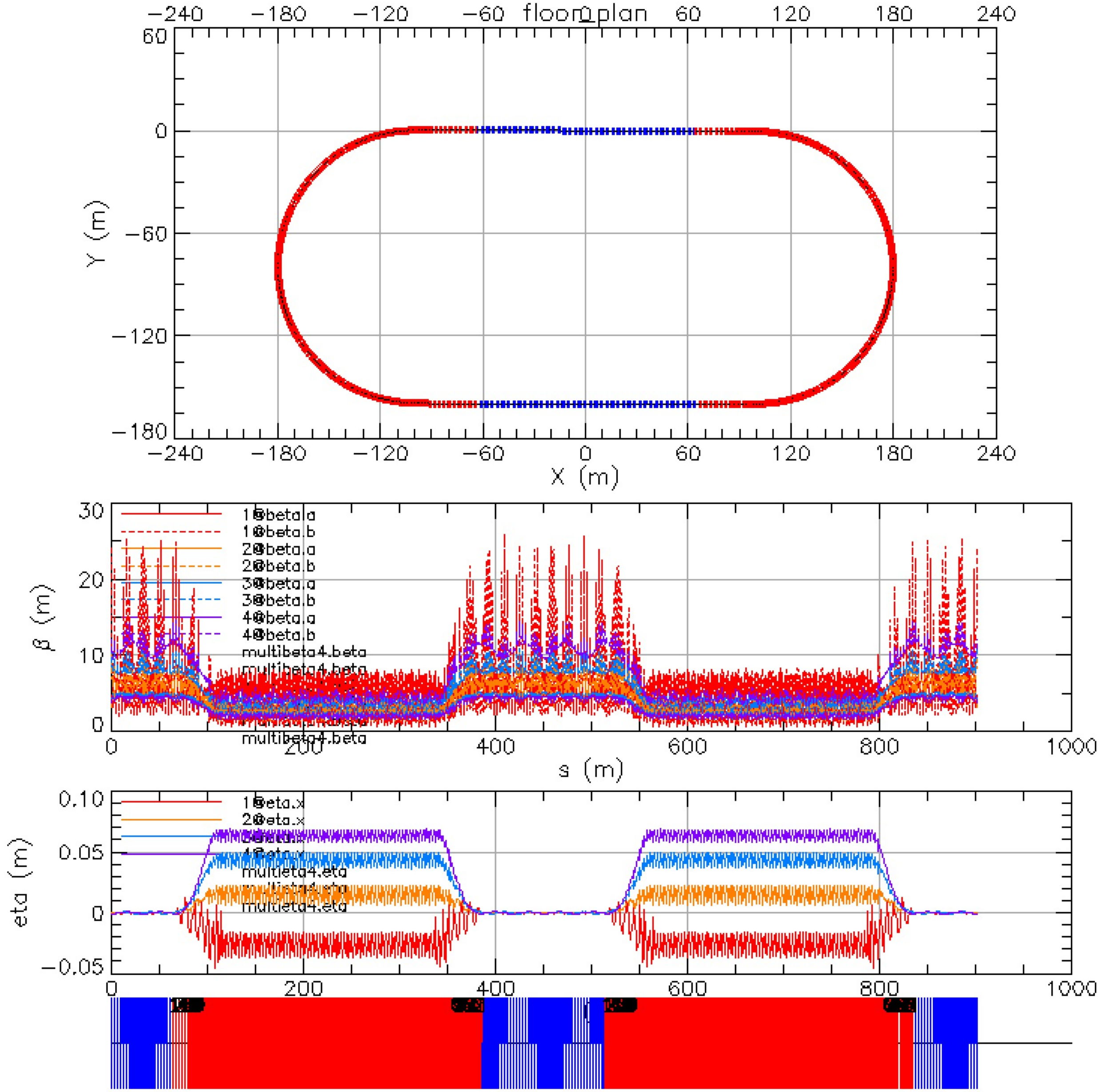
Matching Transition From the FFA-ARC to the Straight



1.5 GeV Linac for eRHIC Linac-Ring Solution



Fixed Field racetrack with linac



0.01

Lattice Function in the LHeC FFA arc

2 mm

Magnet Properties:

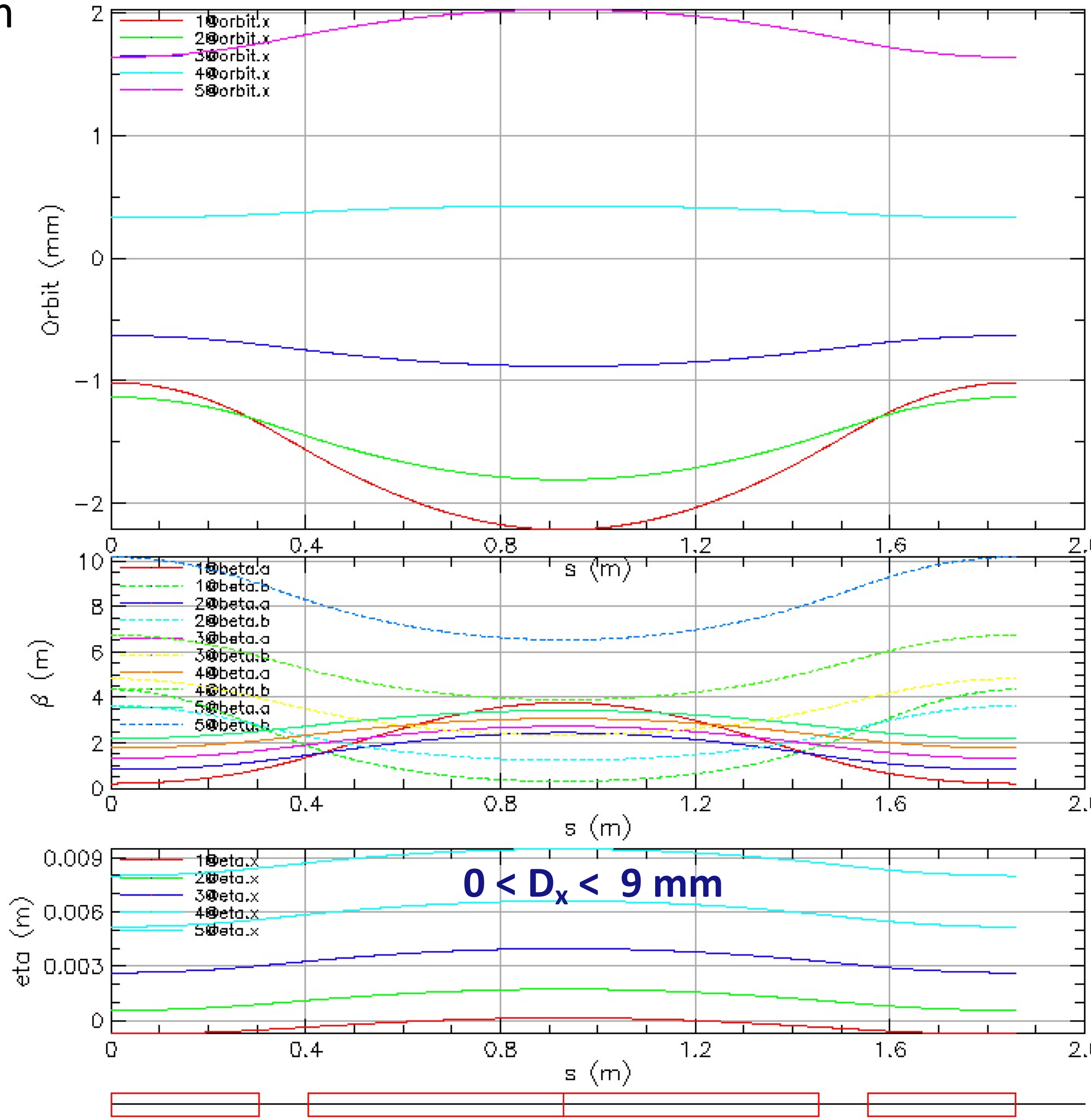
Defocusing magnet

L_{BD} = 0.609 m

G_D = 241.253 T/m

B_D = 0.157 T

B_{Dmax} = 0.481 T



Focusing magnet

L_{QF} = 1.05 m

G_F = -158.8124 T/m

B_F = 0.157 T

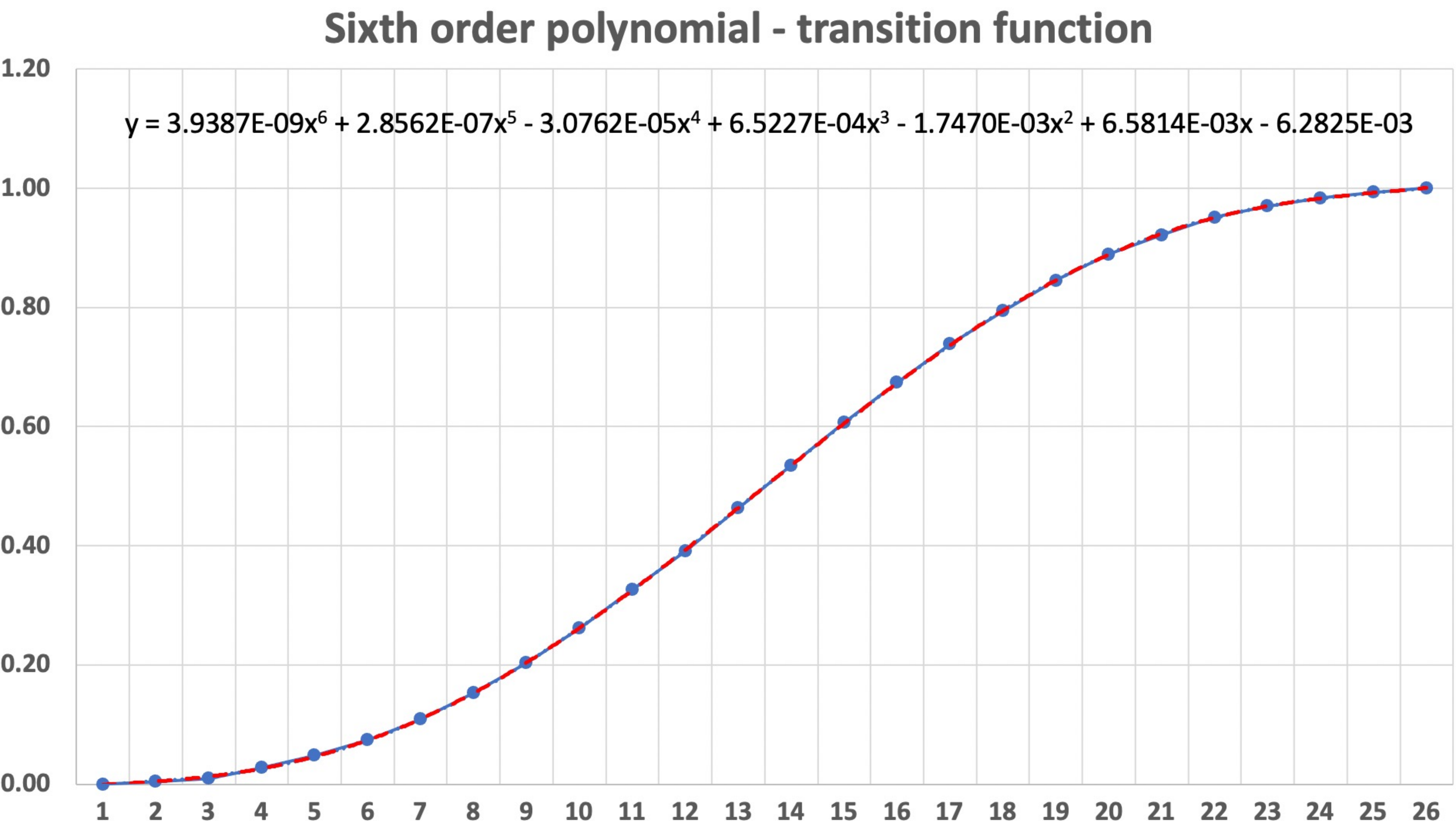
B_{Fmax} = 0.476 T

CONCLUSION

- High gradient permanent magnet design reduces significantly the magnet size and the required beam aperture to within diameter of 2-5 mm providing fixed horizontal and vertical betatron tunes.
- FFA-LG Lattice solutions are developed for EIC@RHIC and LHeC
- A new proposal could replace the two rings: the fast-cycling synchrotron and the storage ring with a single beam line using the 1.5 GeV SFR linac with 12 passes preserving the polarization. This is a ‘green’ accelerator as there is not need for electrical power due to permanent magnets and the energy is recovered

Back Up Slides

Adiabatic transition from the arc to the straight with expanding the transition cell lengths



Extraction from the FFA-arc to Collisions

Magnet Properties:

Defocusing magnet

L_{BD} = 2.8231 m

G_D = 7.725T/m

B_D = 0.2383 T

B_{Dmax} = 0.5023 T

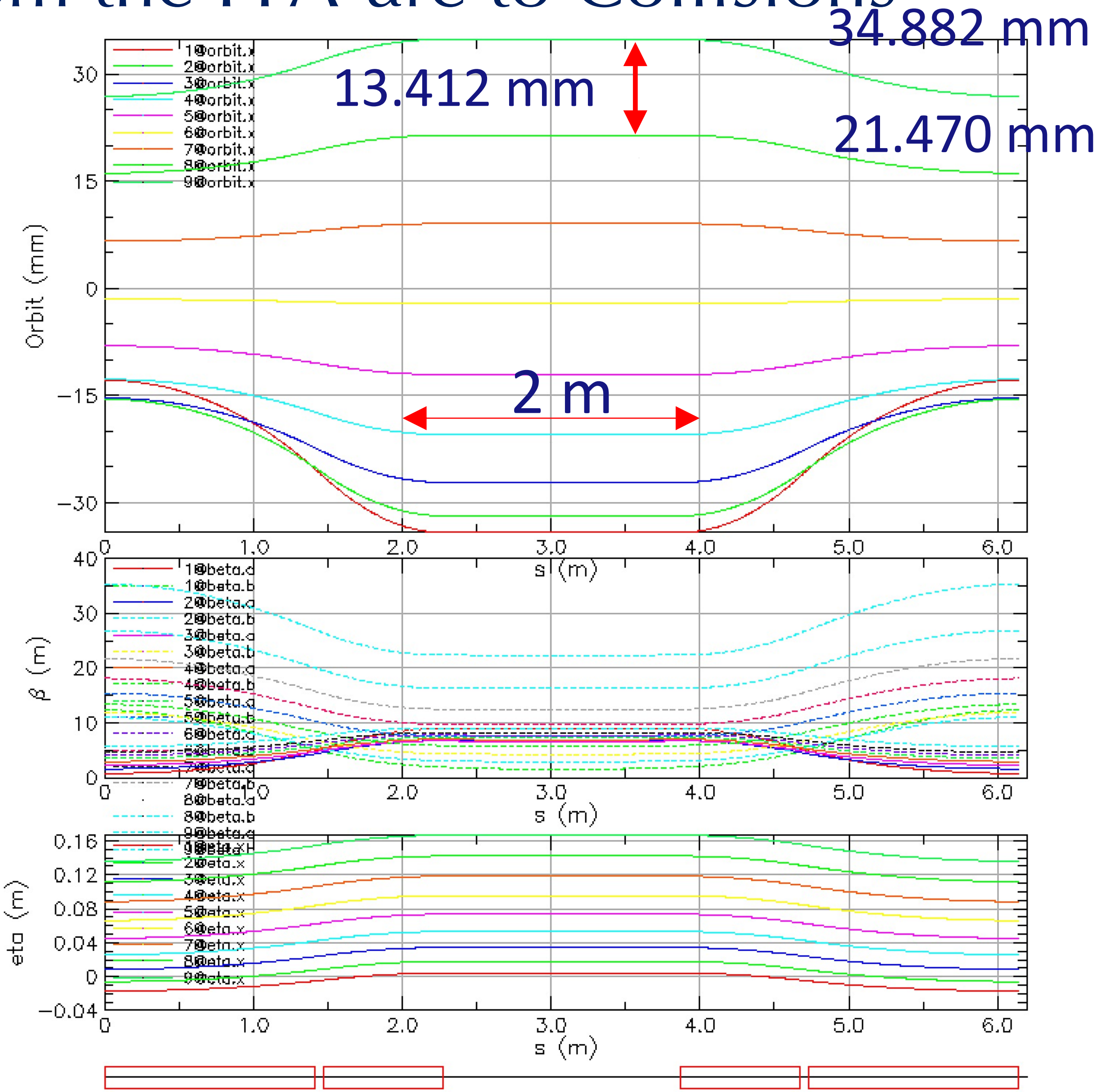
Focusing magnet

L_{QF} = 1.6 m

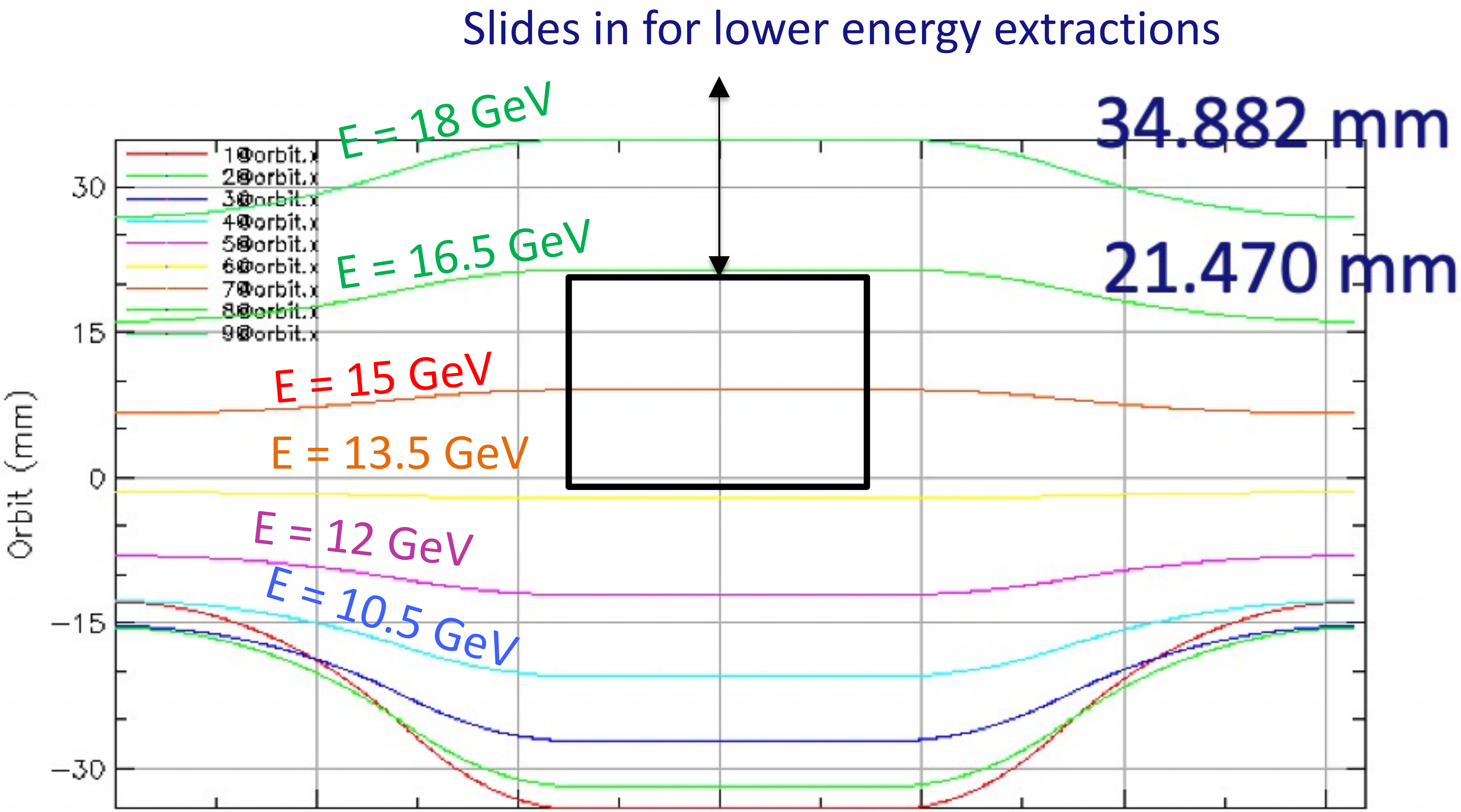
G_F = -15.586 T/m

B_F = 0.0420 T

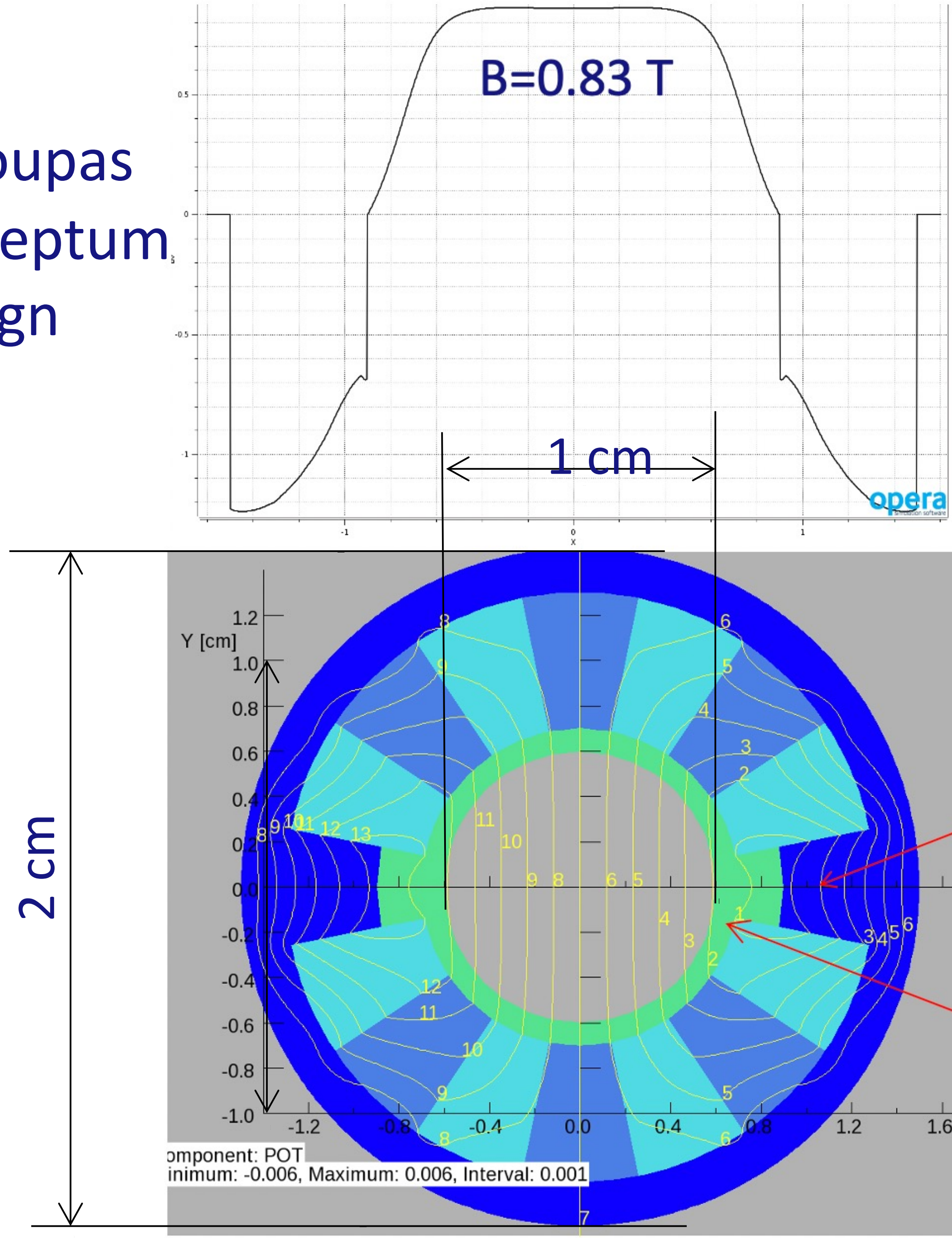
B_{Fmax} = 0.586 T



Extraction from the FFA-arc to Collisions



Nick Tsoupas OPERA Septum Design



B<0.5 Gauss

Iron with cooling channel

Inconel or Al

Reduced from Nick's design of 3cm to 2 cm