Single Fixed Field Return Arcs for PERLE, LHeC, and eRHIC

Dejan Trbojevic

Abstract:

The future Electron Ion Collider (EIC) LHeC, FCCeh and eRHIC will be able to collide electrons with protons/ions. Electron acceleration is based on a concept of Energy Recovery Linacs (ERL) with maximum energies of 60 GeV for LHeC, 905 MeV for PERLE(Powerful Energy Recovery Linac for Experiments), and of 18 GeV for eRHIC. The electron energy will be almost completely recovered during deceleration.

We are presenting a single loop arc design for ***PERLE*** *with two options: one is very similar to the CBETA (Cornell BNL ERL test accelerator) with spreaders and combiners, and one is without the spreaders and combiners. We present two examples of the LHeC design* ***with double reduction in size of the linacs and thus reducing the overall cost of the machine****. The previously proposed two 10 GeV linacs design is reduced to the* ***two 5 GeV linacs*** *(or two 4.425 GeV linacs) using a smaller loop with the maximum energy of* E_{max}*=5 GeV and an additional loop with the fixed field magnets assuming a radius of* R_o*=1000 m. This solution* ***would reduce the previous three large beam lines to a single one with additional 5 (or 4.275) GeV smaller loop.*** *The* ***larger luminosity*** *comes from the larger electron current for the same amount of 15 MW of the synchrotron radiation (previously set limit), as the maximum energy in the arcs is* E_{max}***=55 GeV*** *instead of the previous* E_{max}*=60 GeV. For the LHeC fixed field magnet solution with 2x5 (or 4.275) GeV linacs the total synchrotron radiation loss for 25 mA is 11.1 MW.*

OUTLINES

Introduction: large momentum acceptance fixed field beam lines

A new concept: fixed field beam line adiabatically matched with the linac

From CBETA to PERLE, LHeC and eRHIC

SUMMARY: The present design of the LHeC linacs size is reduced to a half and and the six beam lines are replaced by a single beam line producing larger luminosity.

Introduction

A concept of Fixed Field Large Energy Acceptance Lattice

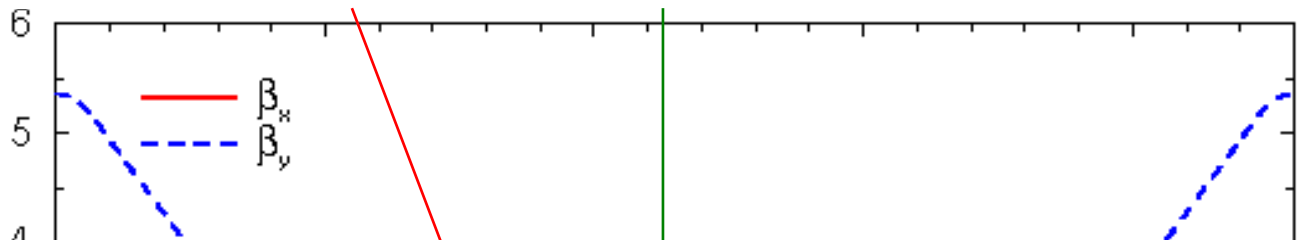
•- Orbits in fixed field cells
•- Tunes vs. energy
•- Path Length vs. energy

Why are we confident of success:

- 3D OPERA fields tracking
- ATF experiment
- High quality Halbach magnets

Adiabatic matching to the ERL Linac

To minimize the dispersion function H the BENDING MAGNET (DEFOCUSING) should be in the centered in the cell with a minimum of $\beta_{xmin}=L_d/2\sqrt{15}$ and $D_{xmin}=\theta^*L_d/24$ @center

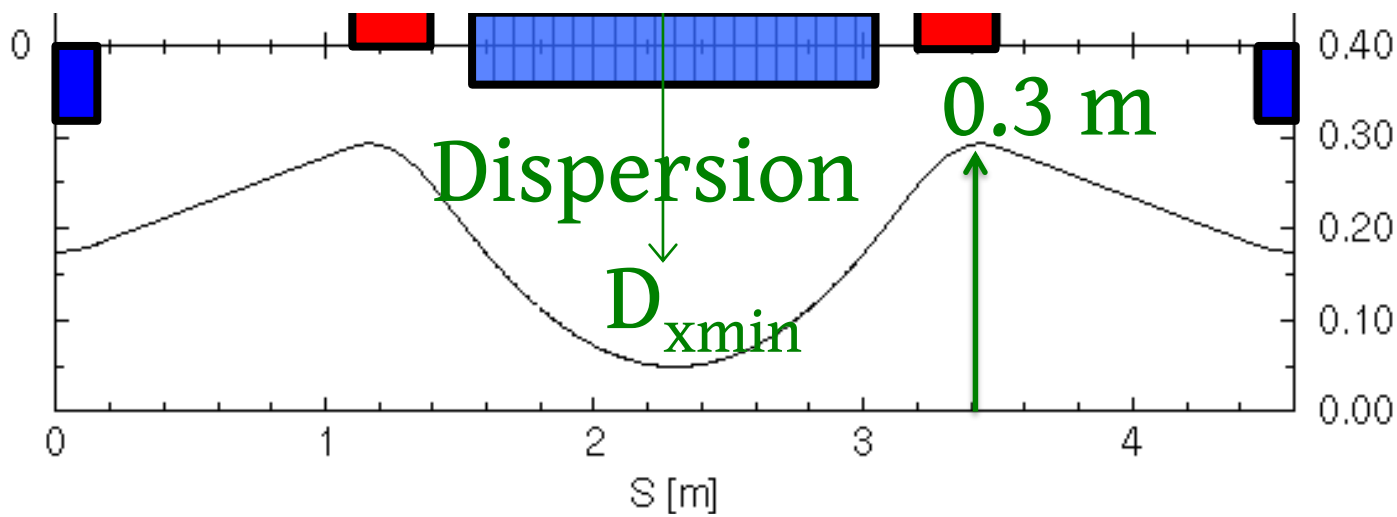


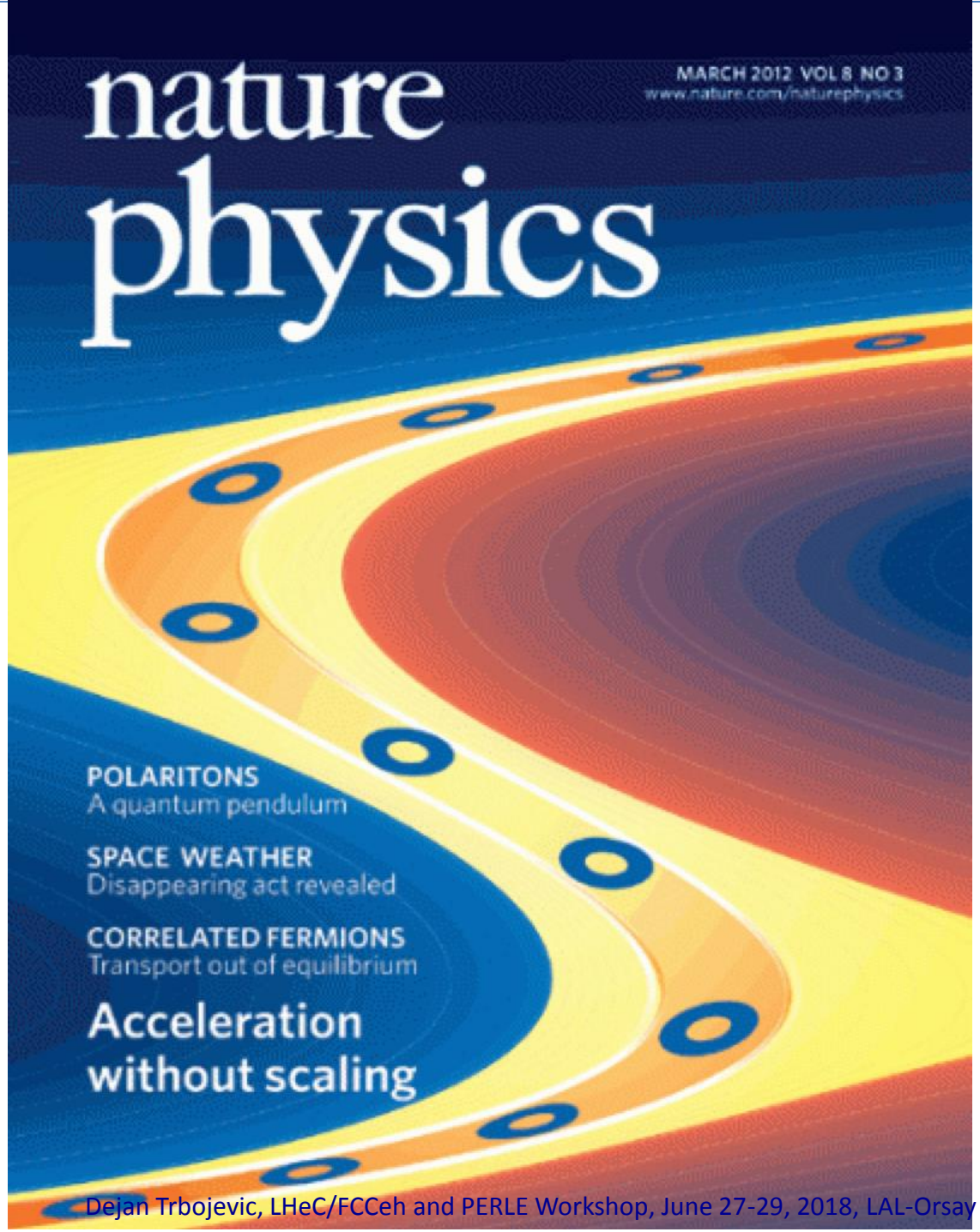
"Fixed Field Alternating Gradient Lattice Without Opposite Bends"

Dejan Trbojevic*, Ernest D. Courant* and Al Garren

Presented in September 1999

CP530, "Colliders and Collider Physics at the Highest Energies: HEMC'99 Workshop", edited by B. J. King

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A quantum pendulum
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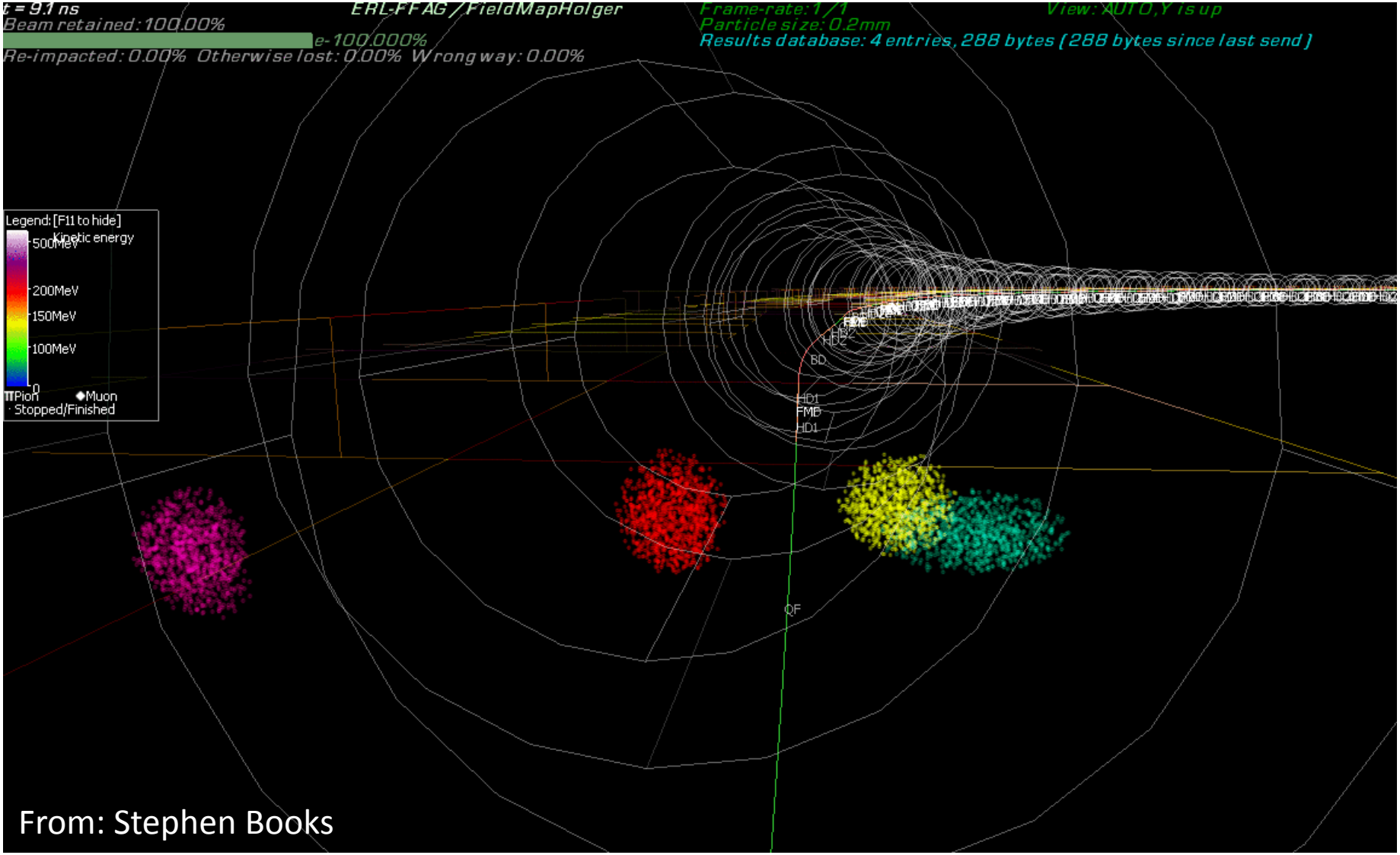
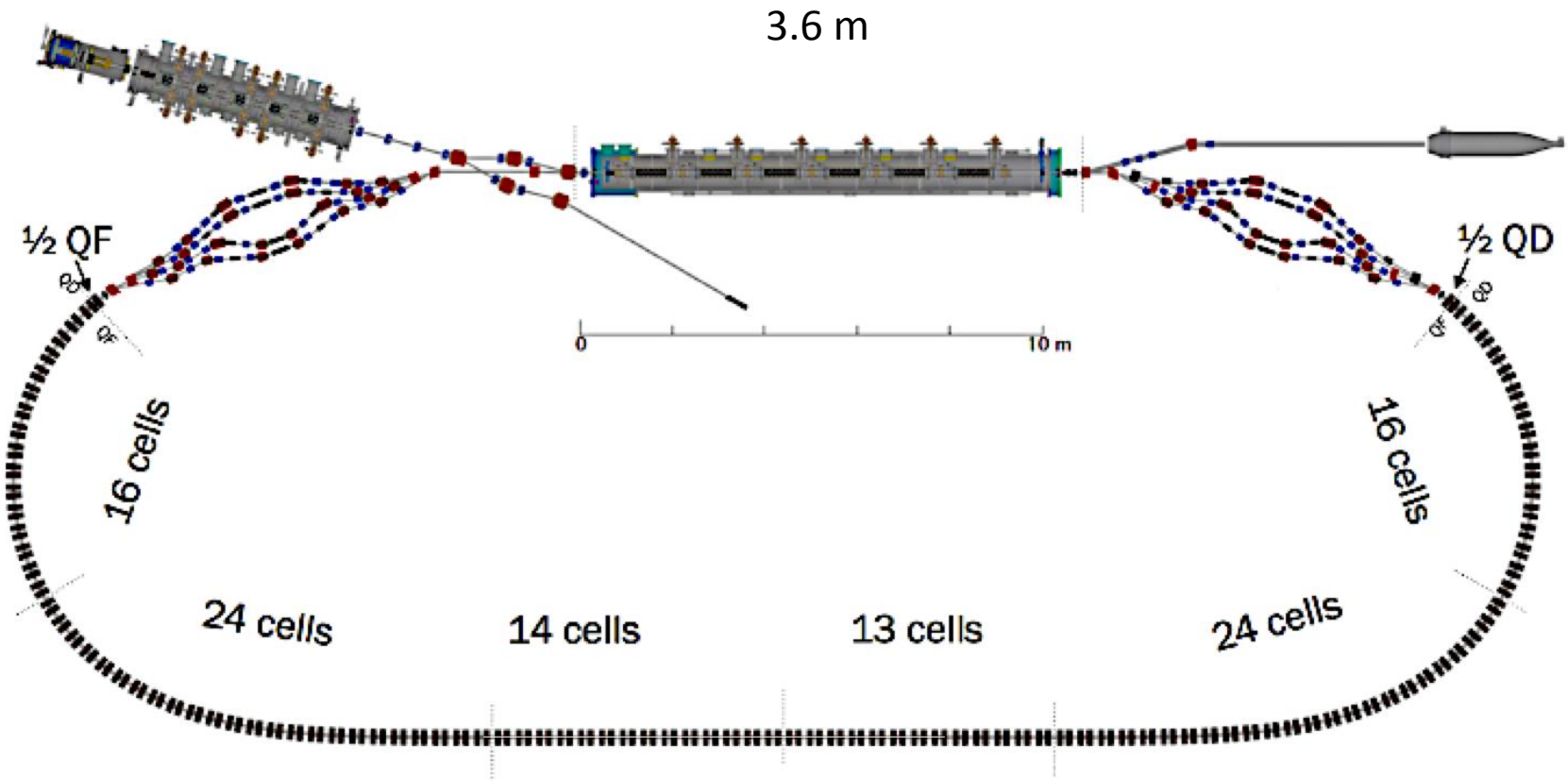
Transport out of equilibrium
Acceleration without scaling

Novelties in CBETA

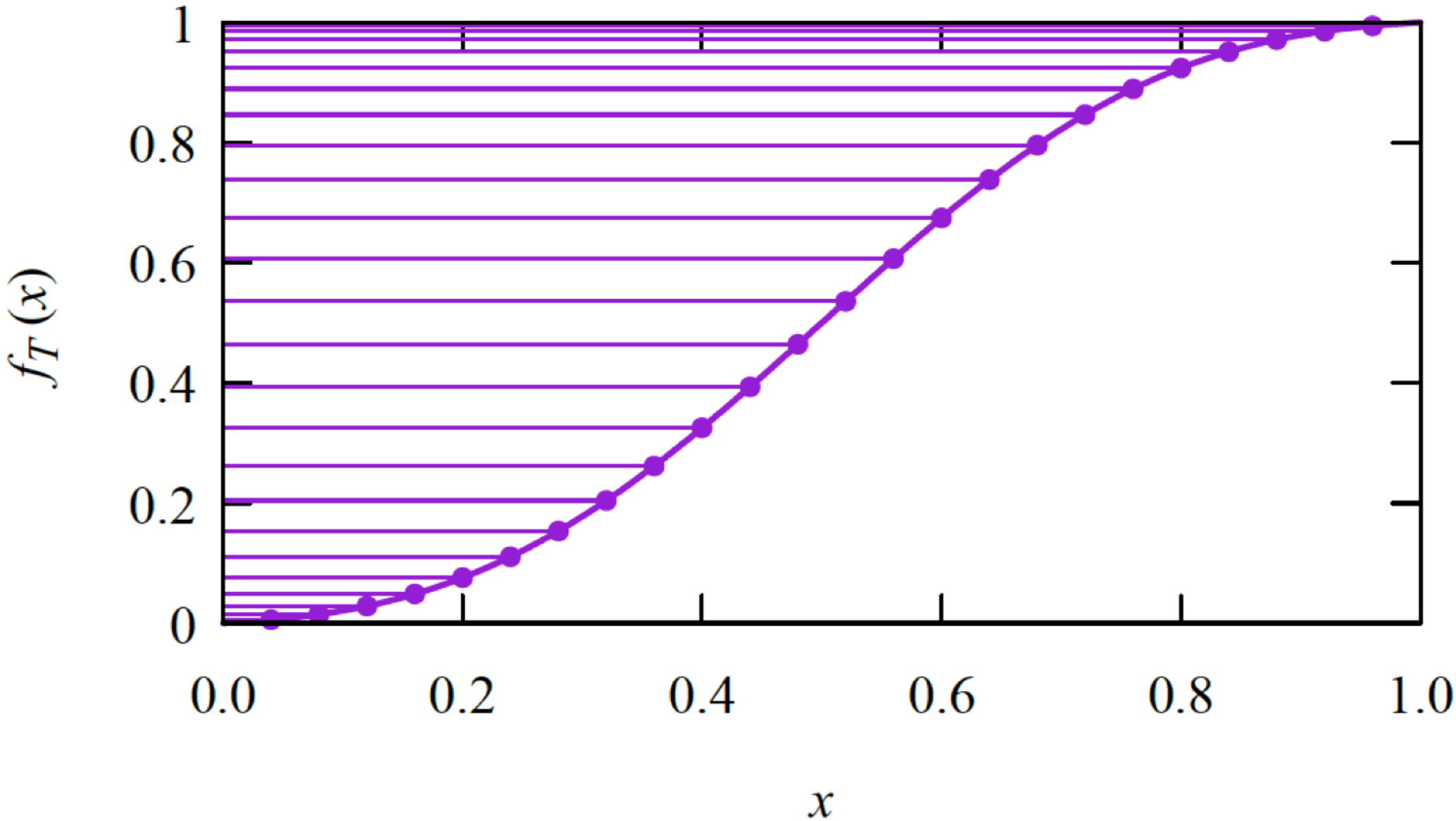


From: Stephen Books

Properties of the linear fixed field large energy acceptance lattice for the CBETA project

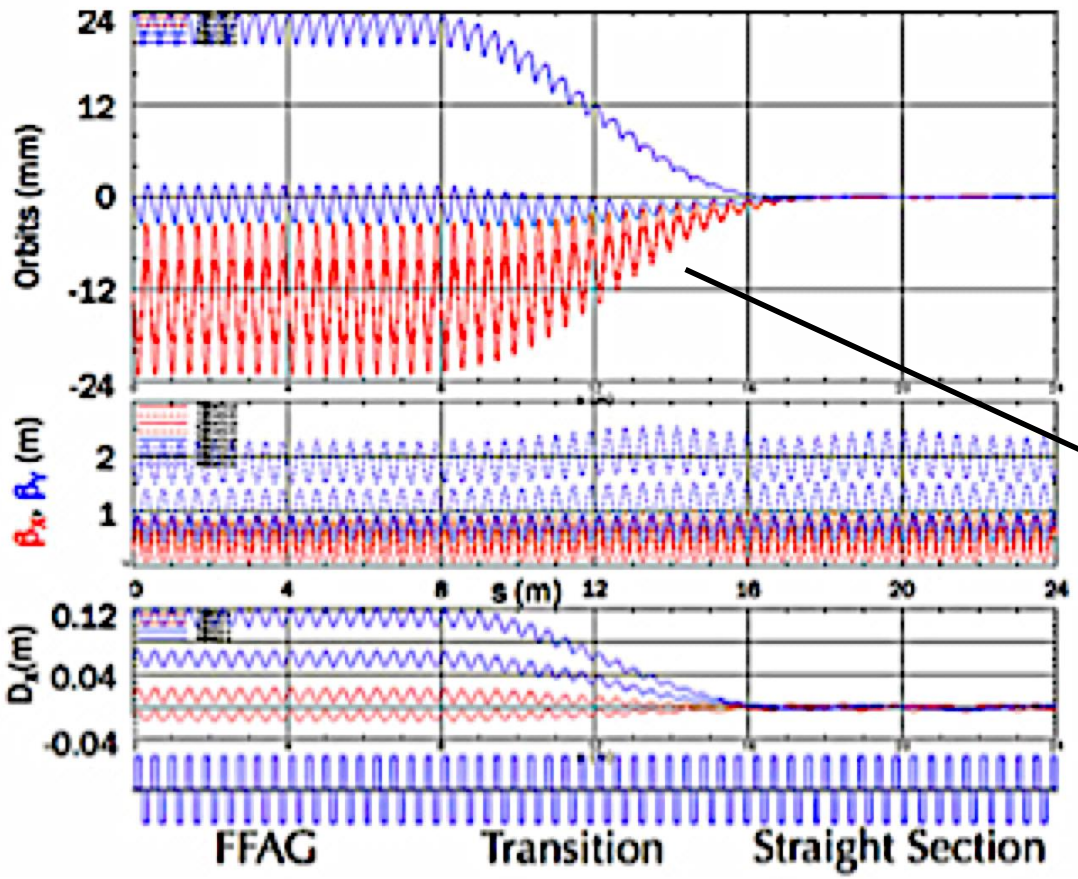


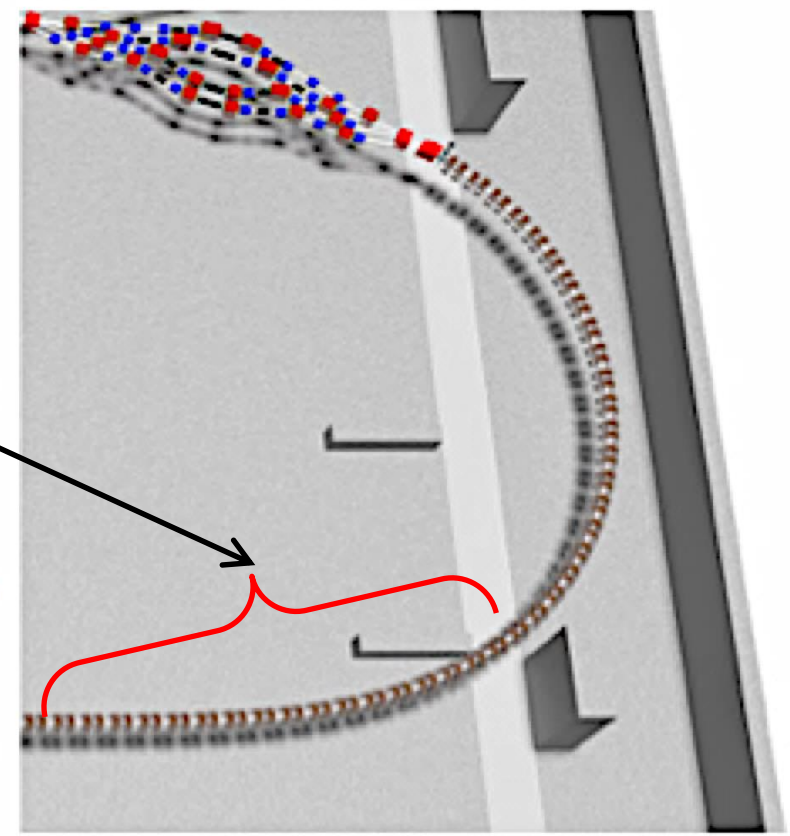
Adiabatic transition from the arc to the straight with expanding the transition cell lengths



The Proton Gantry Design is based on few other examples

Merging of the orbits at the CBETA project

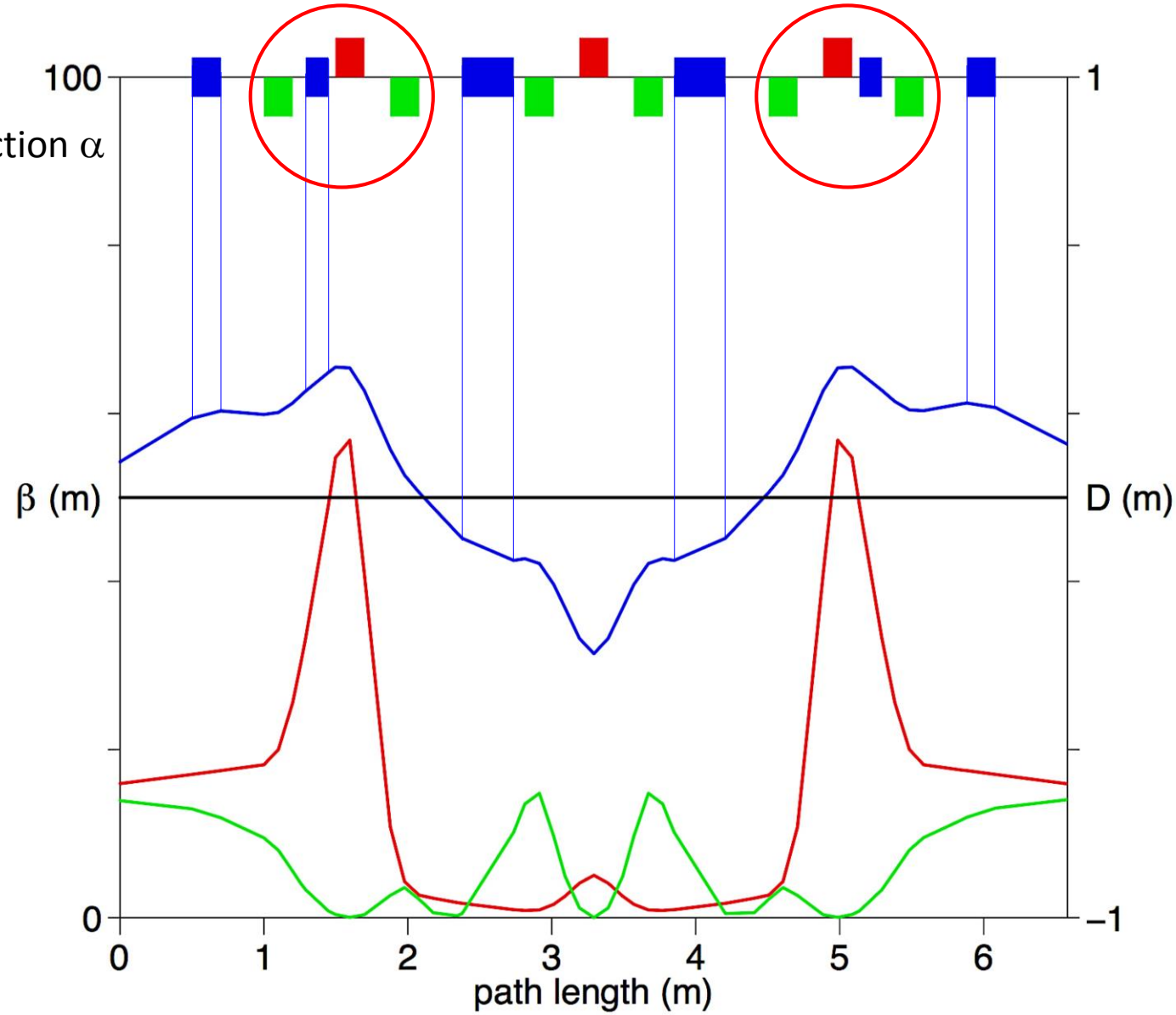




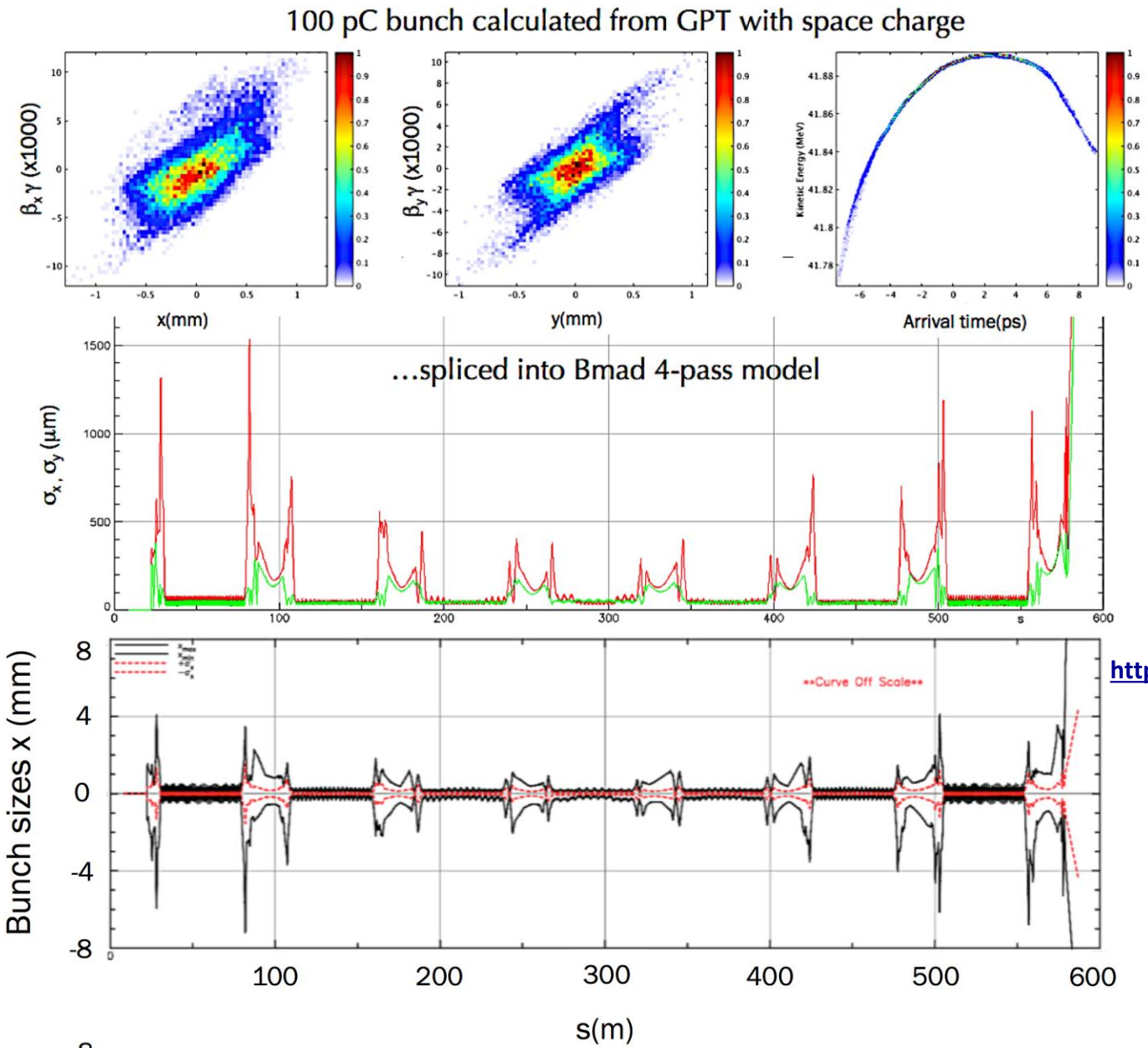
Revisiting the S4 splitter line

The momentum compaction α

$$\alpha = \frac{1}{C_0} \oint \frac{D(s)}{\rho(s)} ds$$



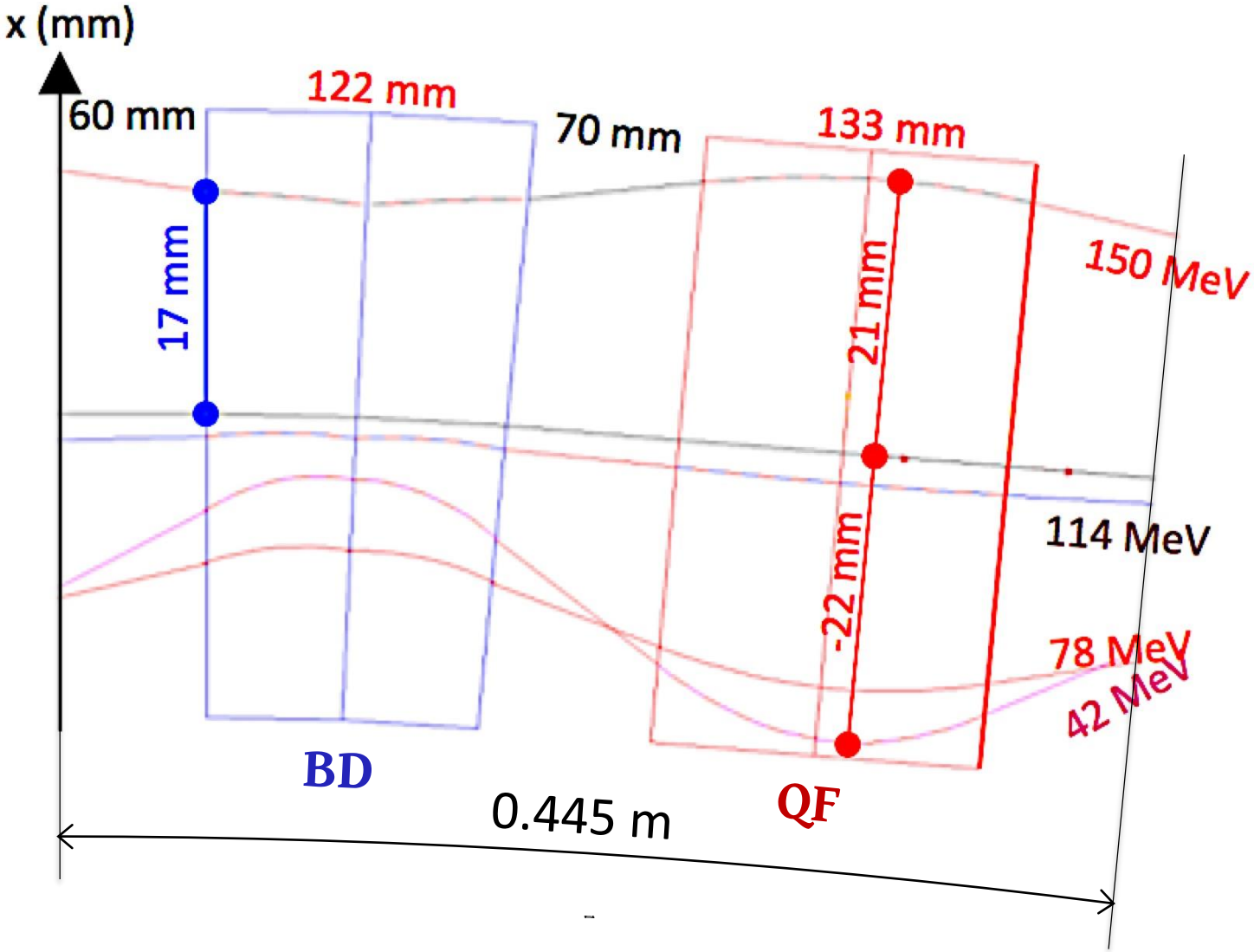
Start-to-End tracking



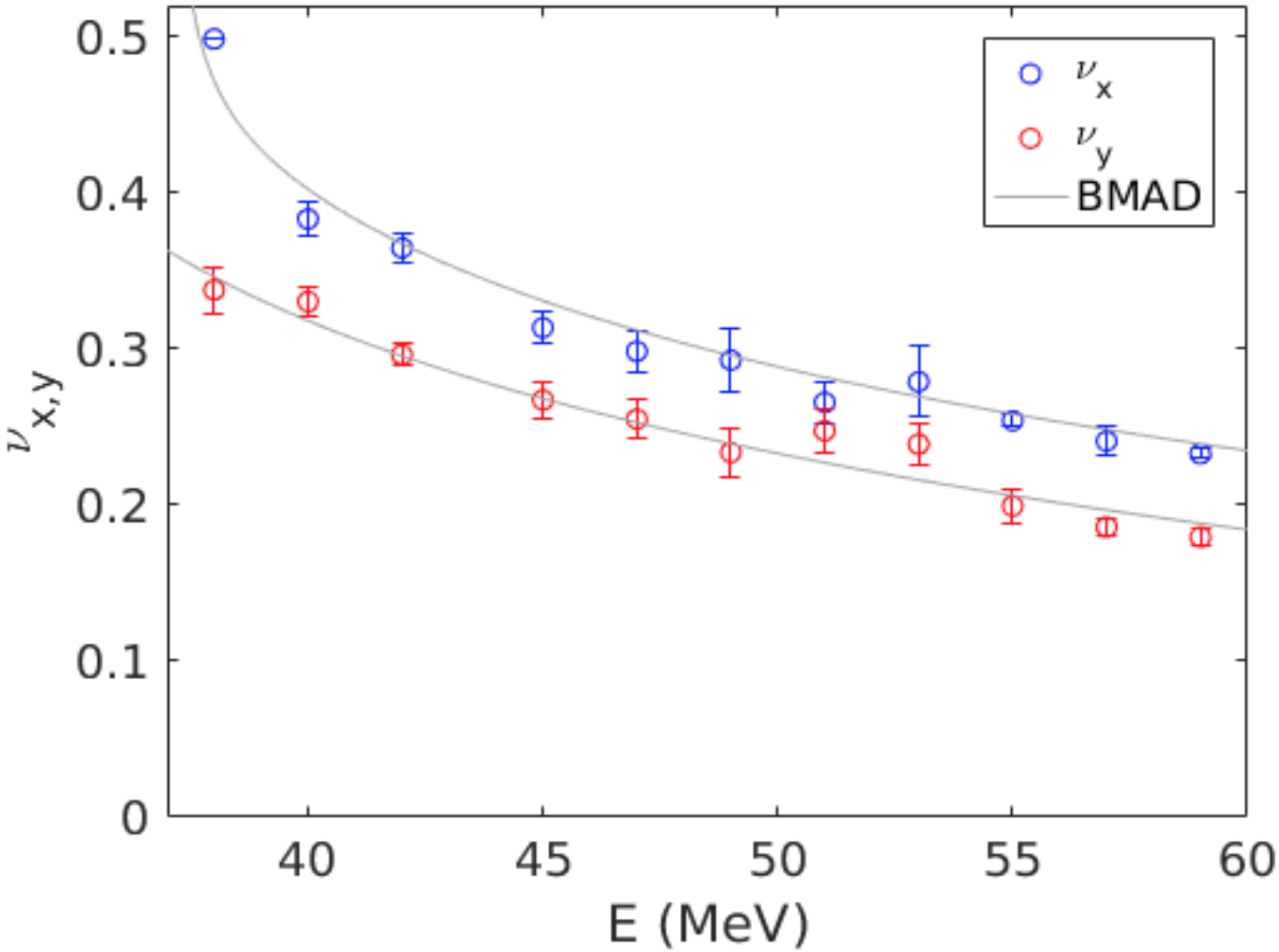
GPT -S.B. van der Geer GENERAL PARTICLE TRACER: A 3D CODE FOR ACCELERATOR AND BEAM LINE DESIGN

***Bmad* – David Sagan**
Chris Mayes results
http://www.lepp.cornell.edu/~dcs/bmad

Orbits in the CBETA Arc Cell (5 degrees)

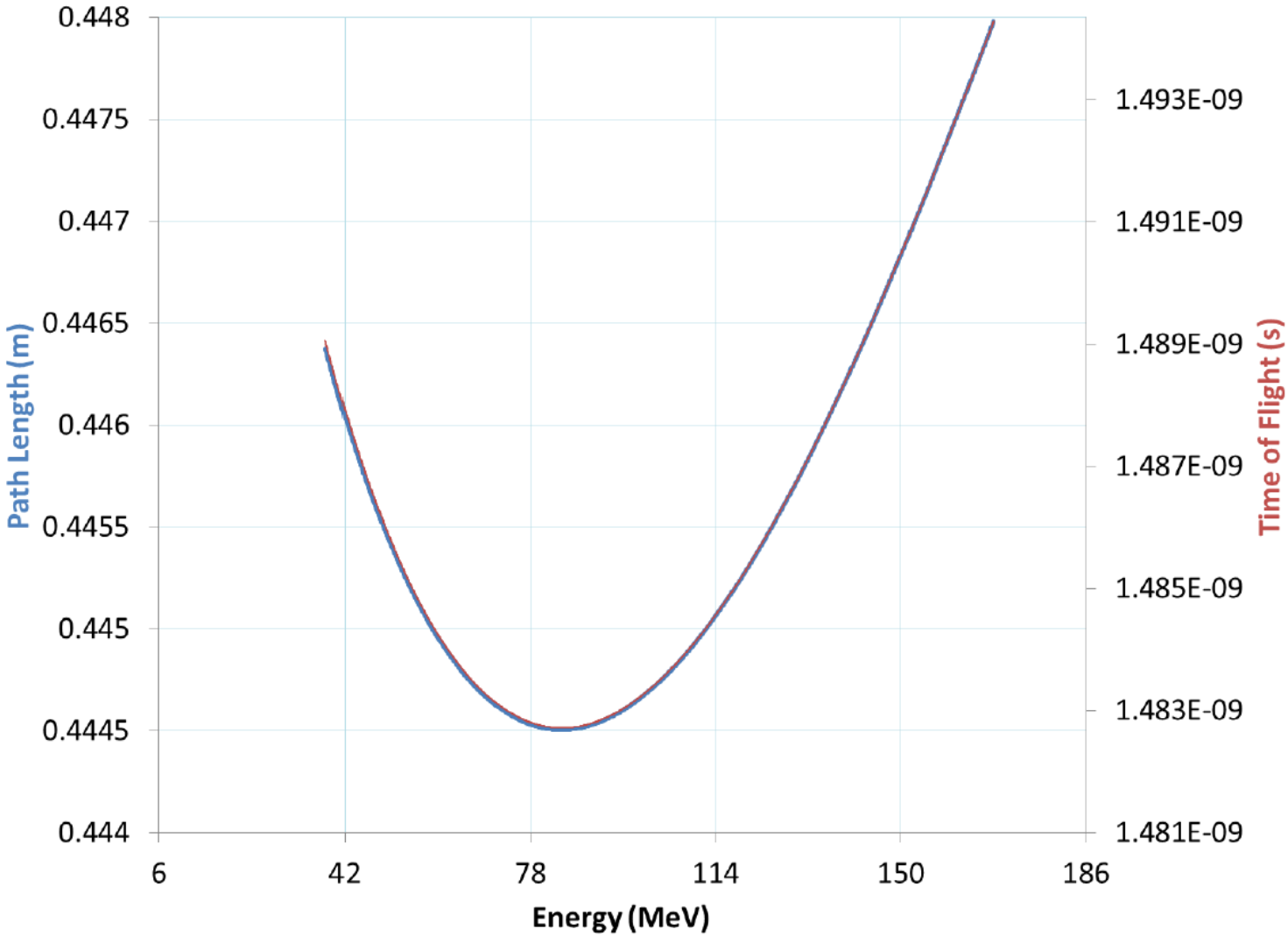


CBETA measured tunes dependence on energy in the partial arc test May 2018



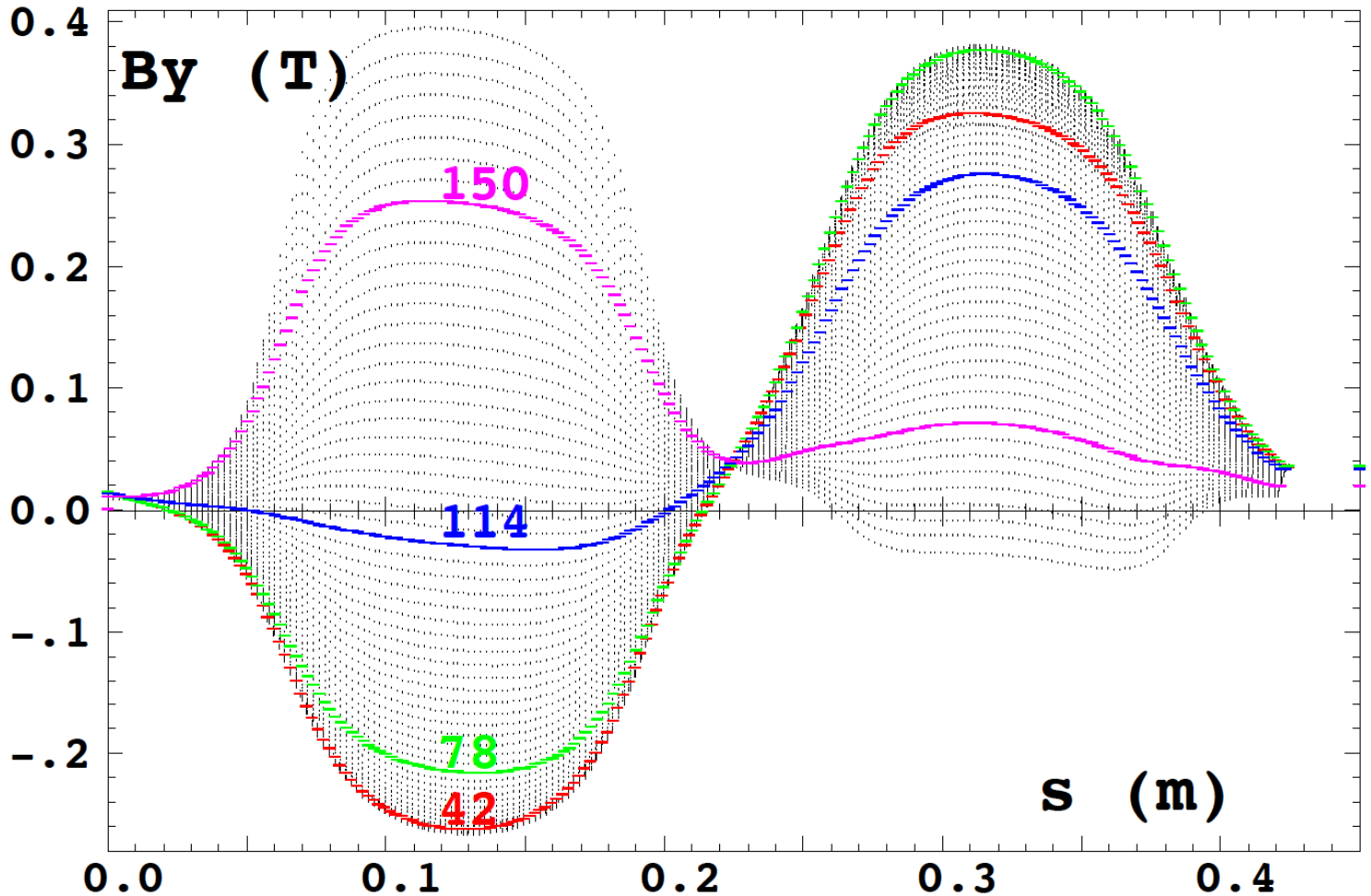
BROOKHAVEN NATIONAL LABORATORY

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

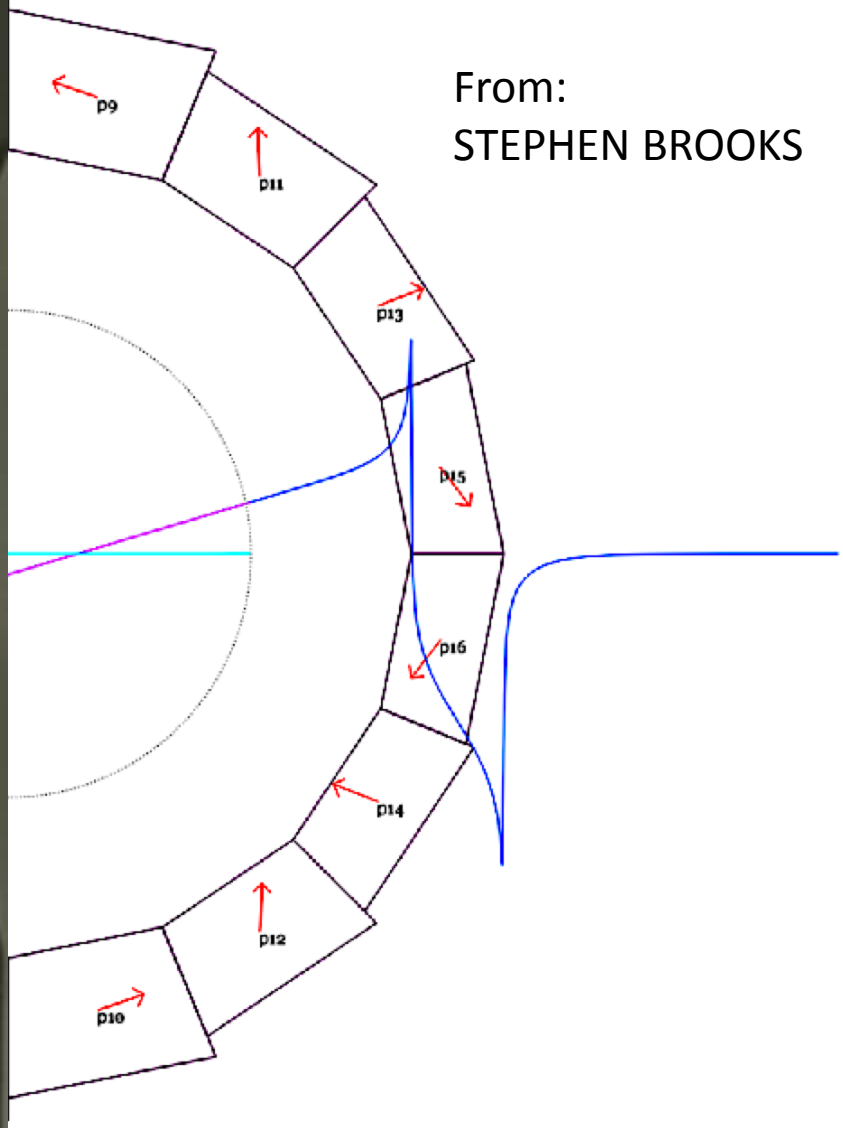


Arc Cells Obtained from the 3D OPERA fields

Francois Meot's results by using the ZGOUBI program with the OPERA 3D fields makes the doublet cell and presents the vertical magnetic field dependence on 's'.
Two effects : The field non-linearities intrinsic to the OPERA model and kinematic non-linearities which are present to high order due to the stepwise ray-tracing method

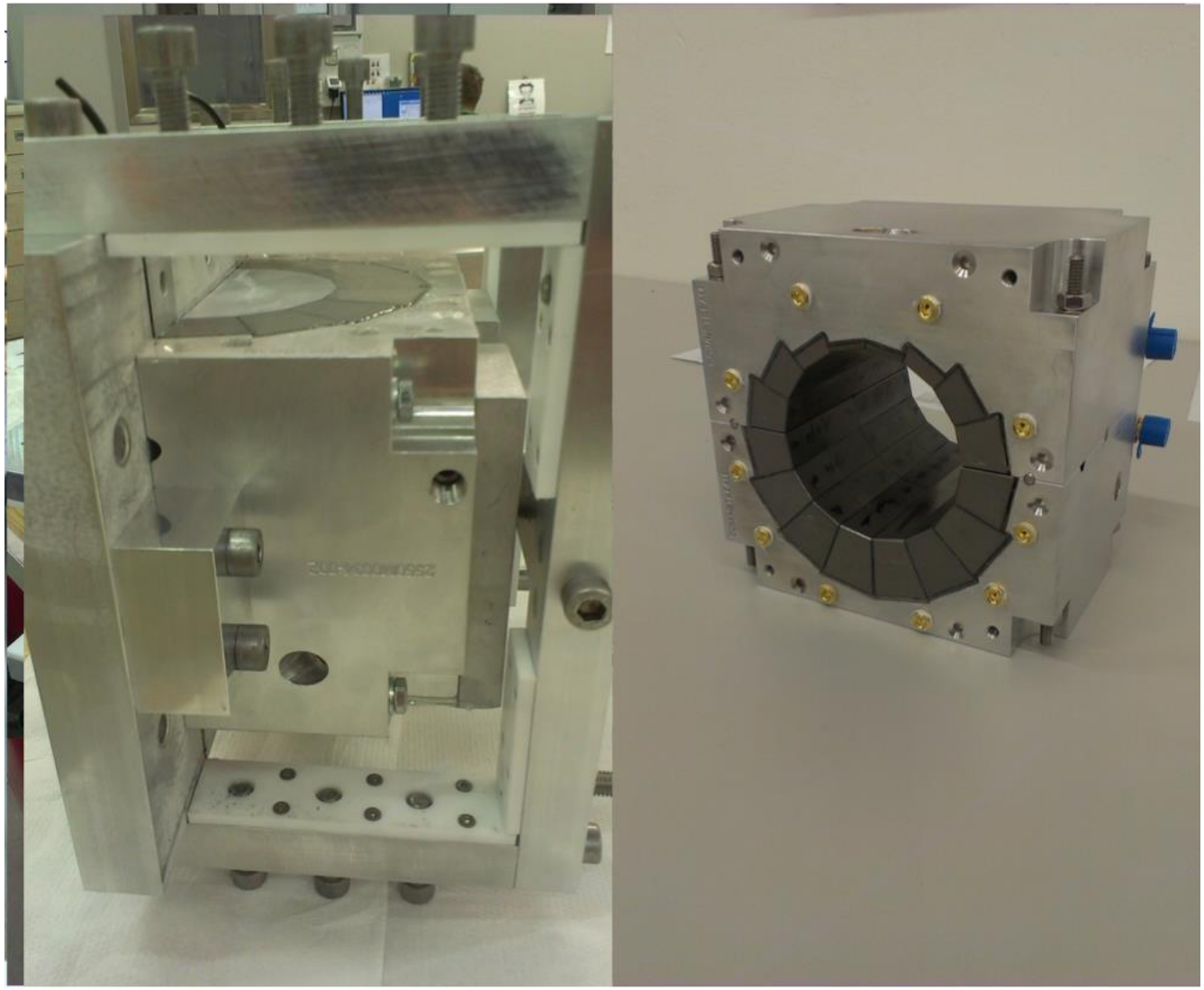


NED FUNCTION MAGNET

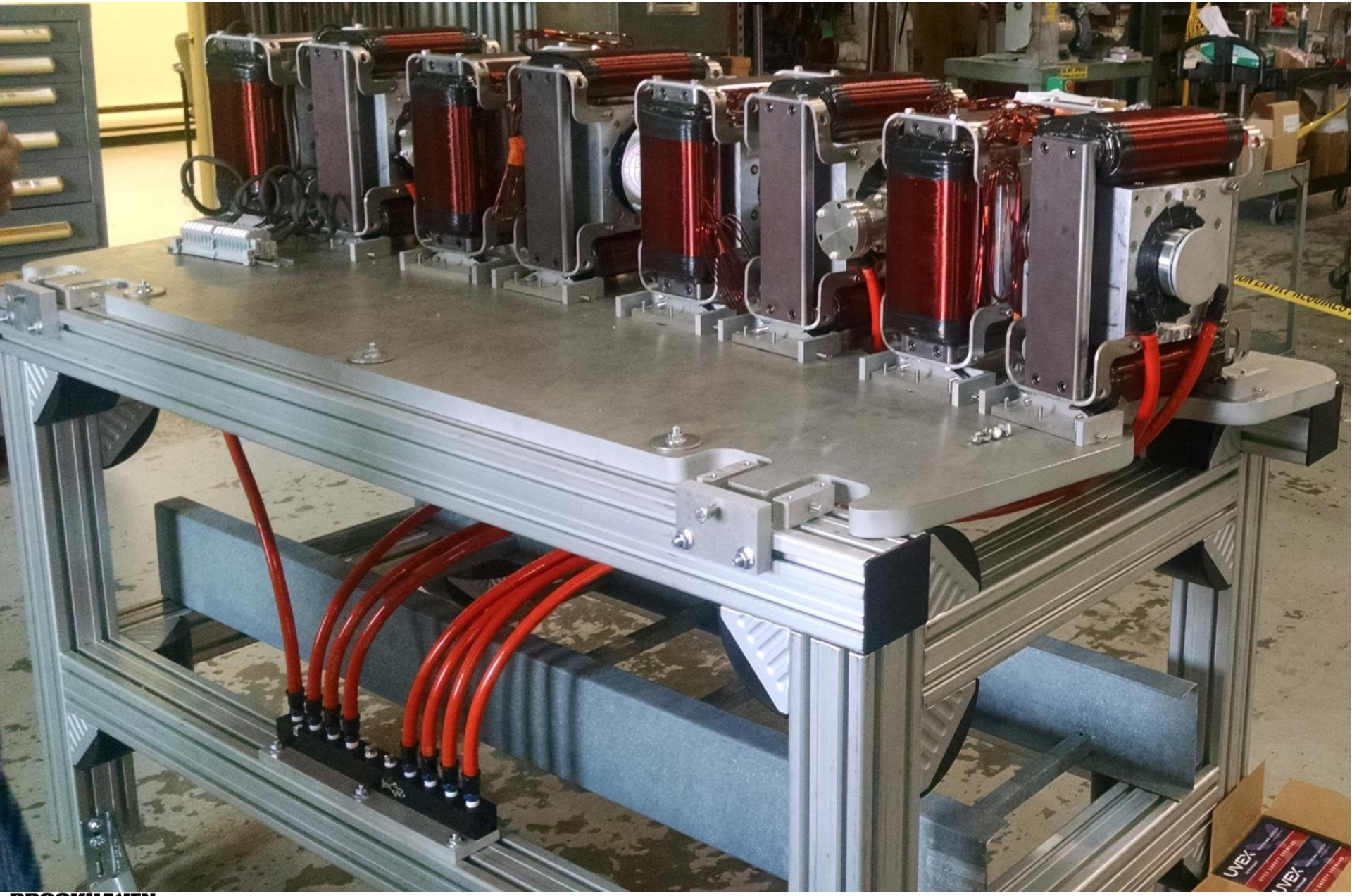


From:
STEPHEN BROOKS

Production of the Halbach magnets



First CBETA Girder with 4 Cells



Quality of the Halbach magnets

Table1.9.9.3: Field harmonics from ERHIC-PMQ_0303_0002_001 at R=10mm. The nominal magnet length is 61.8597mm and the average field corresponds to -19.1007 T/m.

Field harmonic	Normal units	Skew units
Dipole	-19726.36	0.00
Quadrupole	10000.00	-0.00
Sextupole	-1.62	1.35
Octupole	-2.50	0.85
Decapole	1.13	-0.56
Dodecapole	-0.05	0.22
14-pole	0.01	0.00
16-pole	0.03	0.00
18-pole	-0.04	0.02
20-pole	0.00	0.01
22-pole	0.00	-0.01
24-pole	-0.00	-0.00
26-pole	-0.00	0.00
28-pole	0.00	-0.00
30-pole	-0.00	-0.00

The Fixed Field Alternating Gradient Experiment with bending 40° already tested at BNL

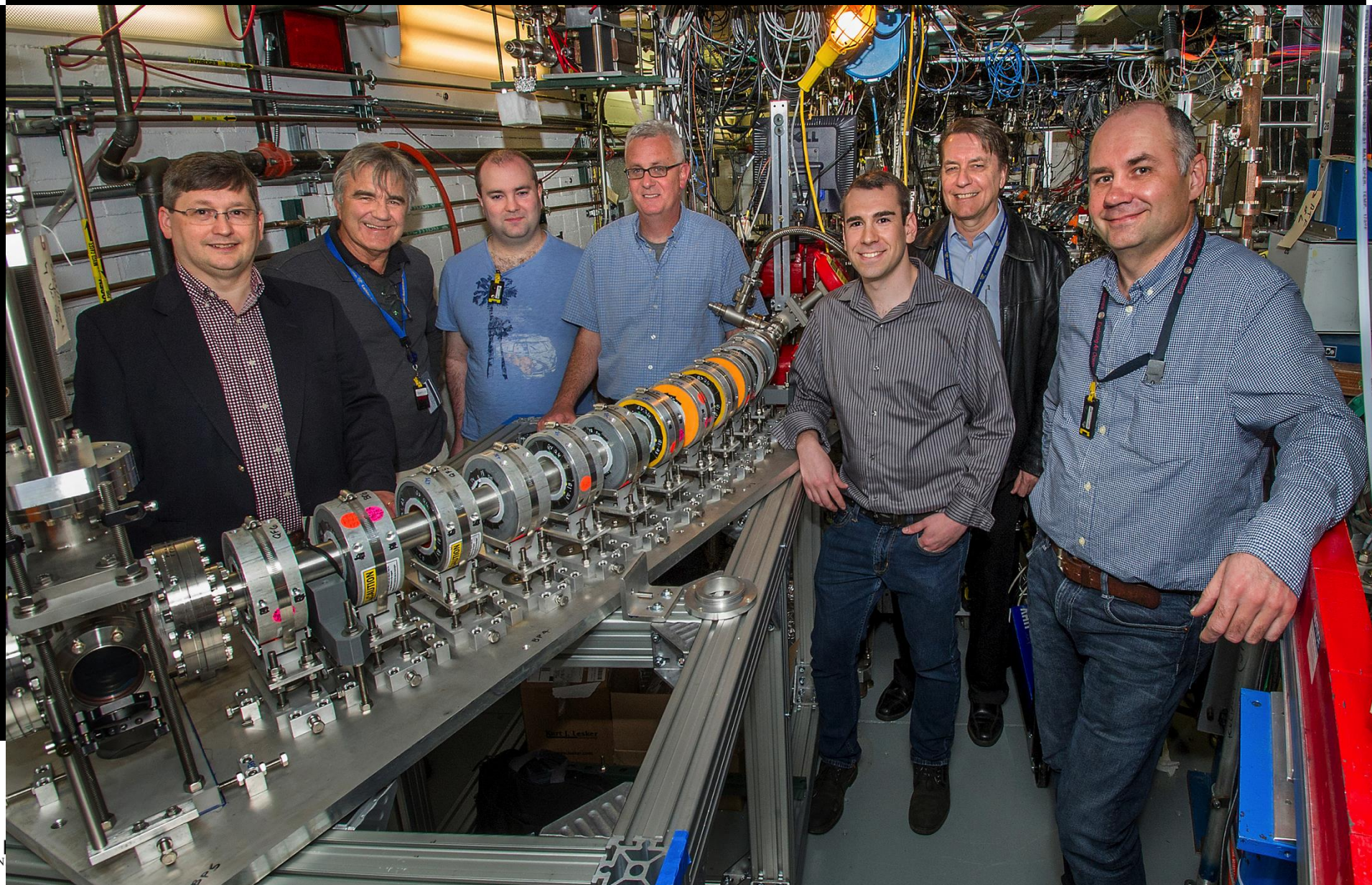
Electron energies in the experiment :18, 24, 36, 54, and 72 MeV

$$Electron\ p_{\max} = 18\ MeV/c \qquad \frac{\Delta p}{p} = -60\%$$

$$Electron\ p_{cent} = 45\ MeV/c$$

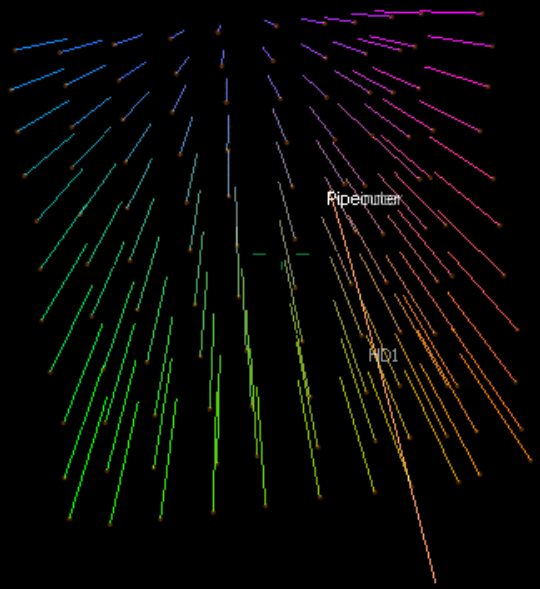
$$Electron\ p_{\min} = 72\ MeV/c \qquad \frac{\Delta p}{p} = +60\%$$

The ATF experiment with 12 CBETA Halbach magnet



t = 0.0 ns
AT F-FF AG / Cell
Beam retained: 100.00%
e-100.000%
Re-impacted: 0.00% Otherwise lost: 0.00% Wrong way: 0.00%

Frame-rate: 1 / 5
View: AUTO, Y is up
Particle size: AUTO (0.0598mm)
Results database: 8 entries, 594 bytes (594 bytes since last send)



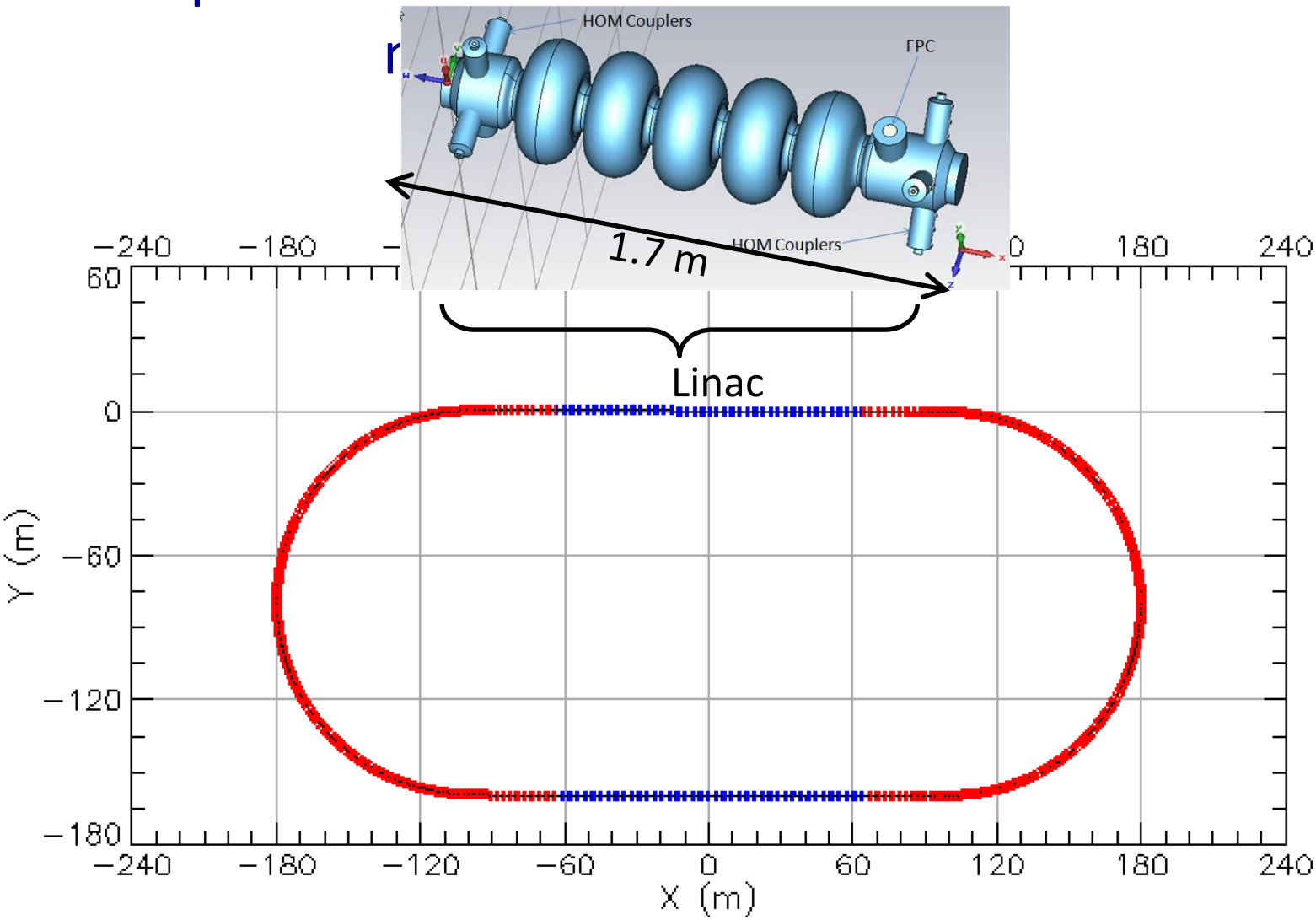
Press F1 for key controls

Particles remaining: 121 / 121 / 146
Mean forward Z distance = 0.007 m
Max Z distance = 0.007 m

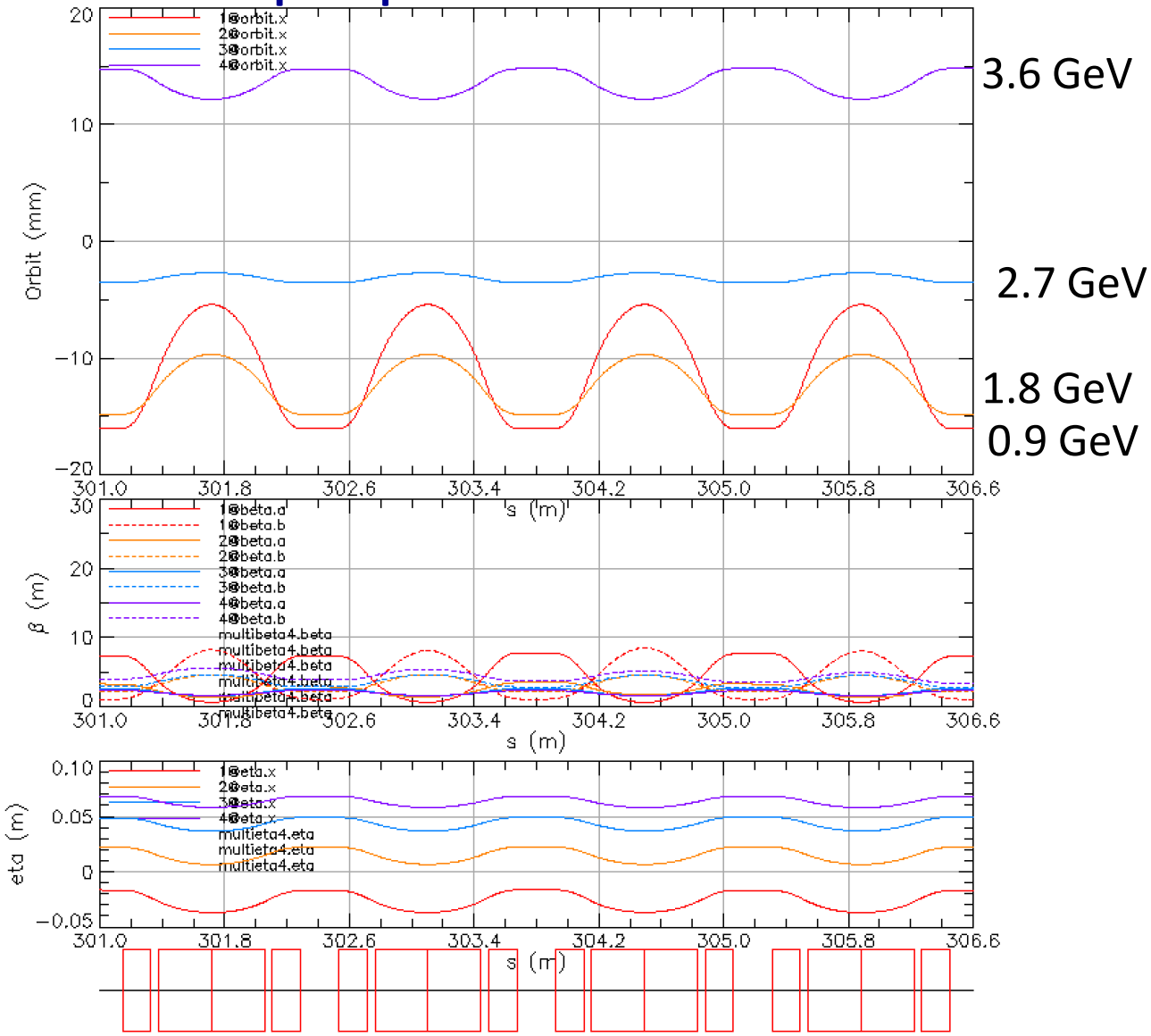
We are presenting for the first time an example of a novel approach in using the Fixed Field single beam line with large energy acceptance connected by an adiabatic transition to the ERL linac:

- This allows additional passes through the linac, this reduces the size of the linac
- Eliminates spreaders and combiners
- Simplifies the operation
- Significantly reduces the overall cost of the whole project

An example of the linear fixed field arcs adiabatically



Lattice properties of the few arc cells



3.6 GeV

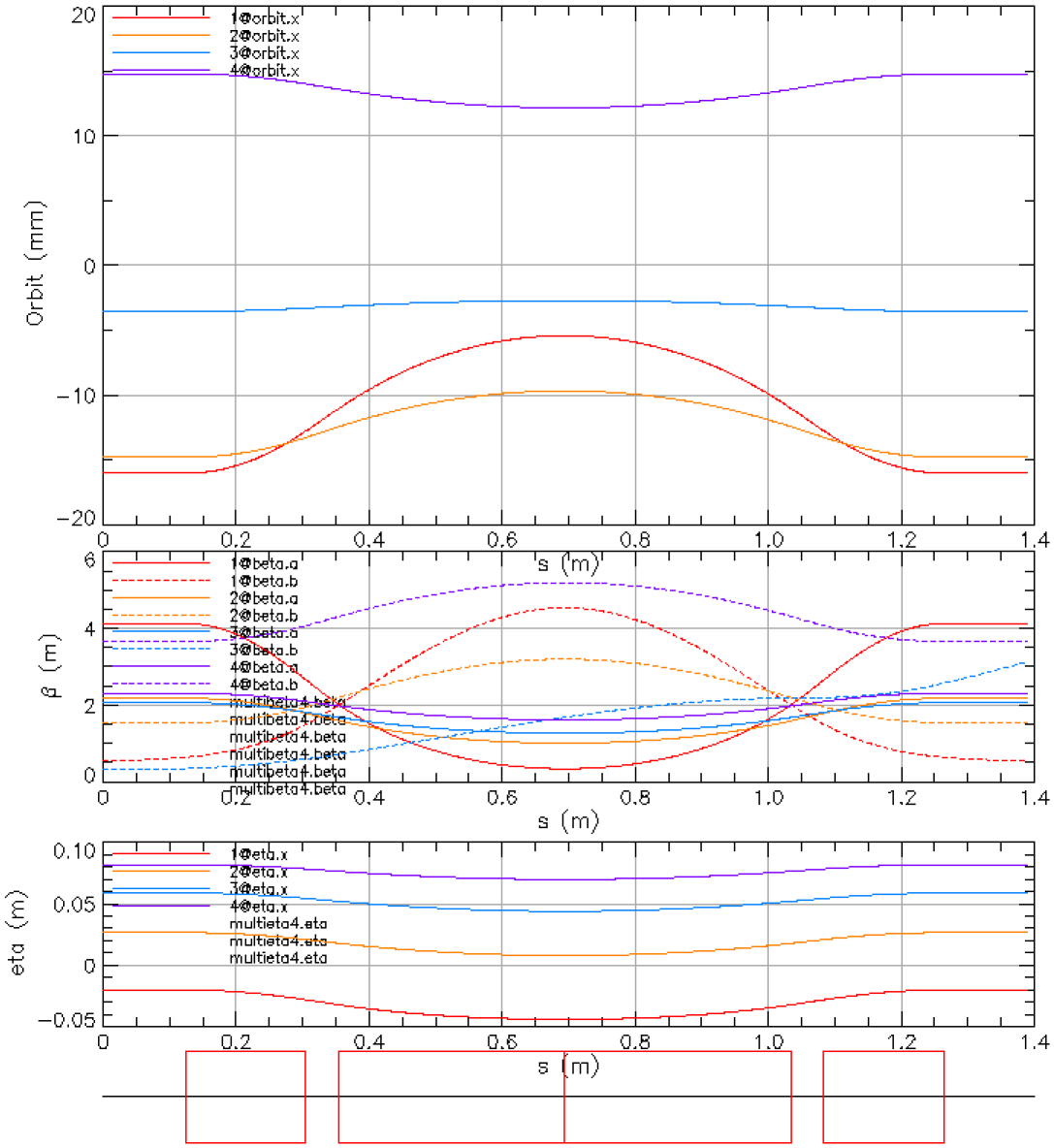
2.7 GeV

1.8 GeV

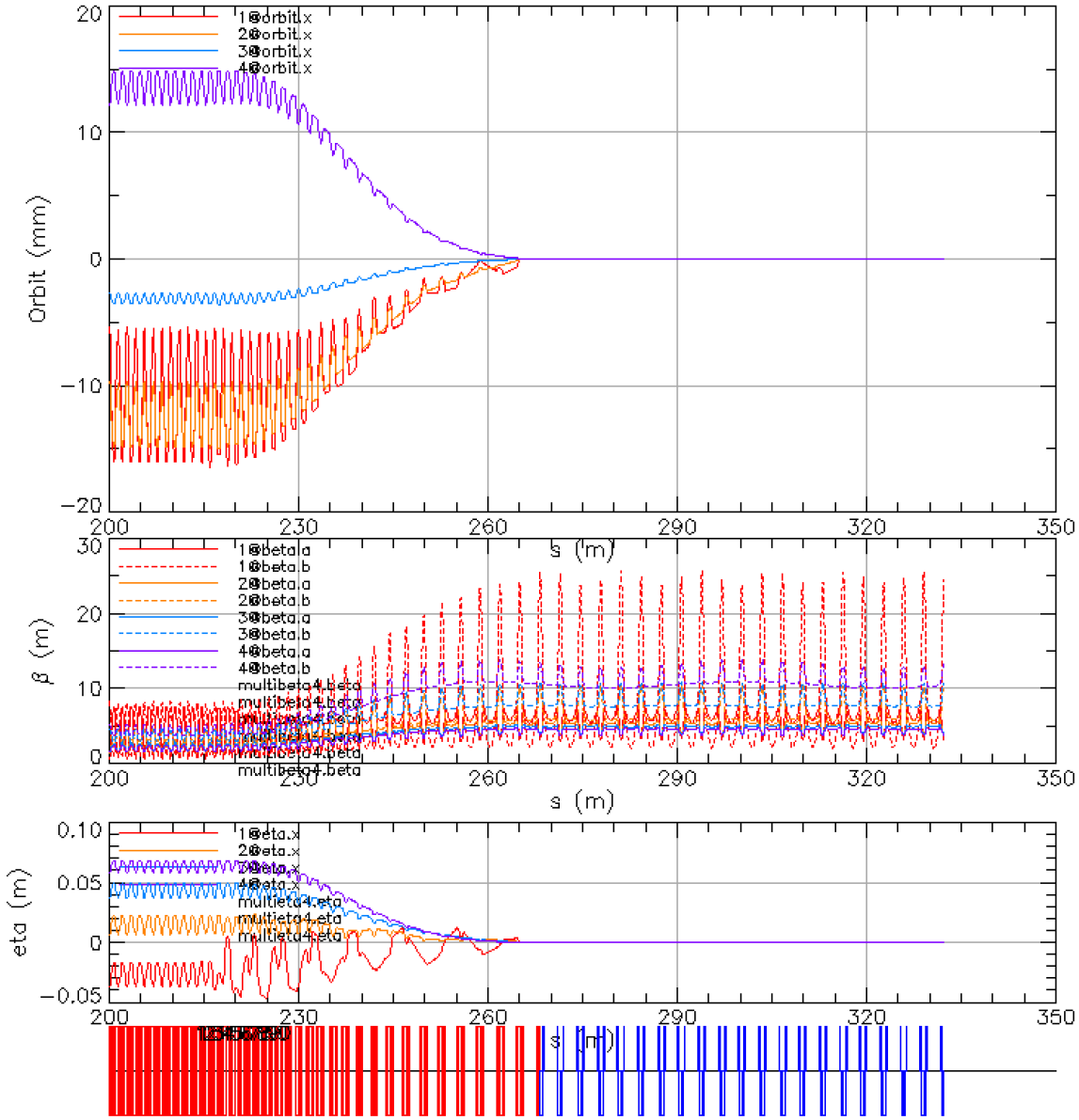
0.9 GeV

Triplet cells

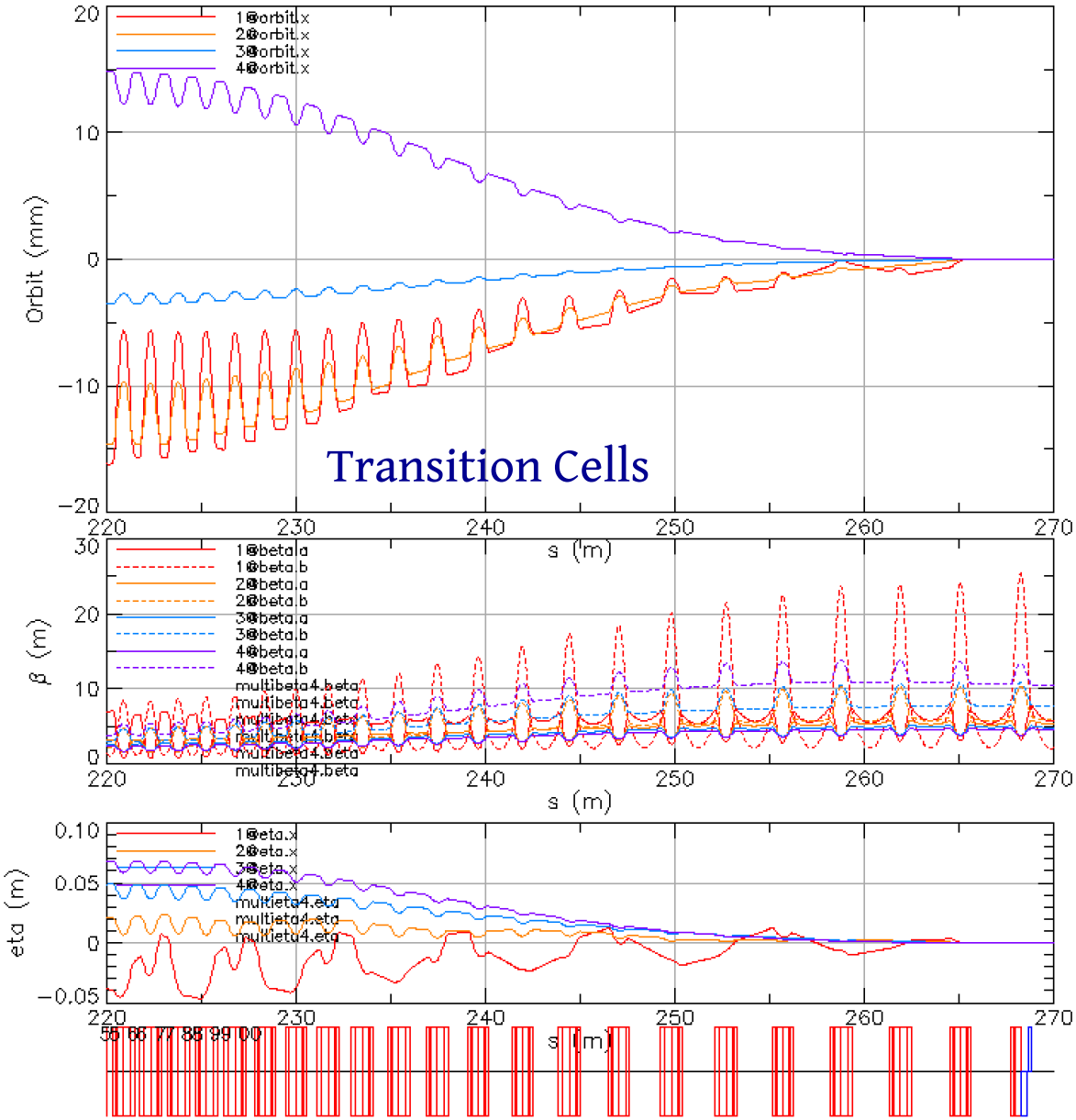
Lattice properties of the single arc cell



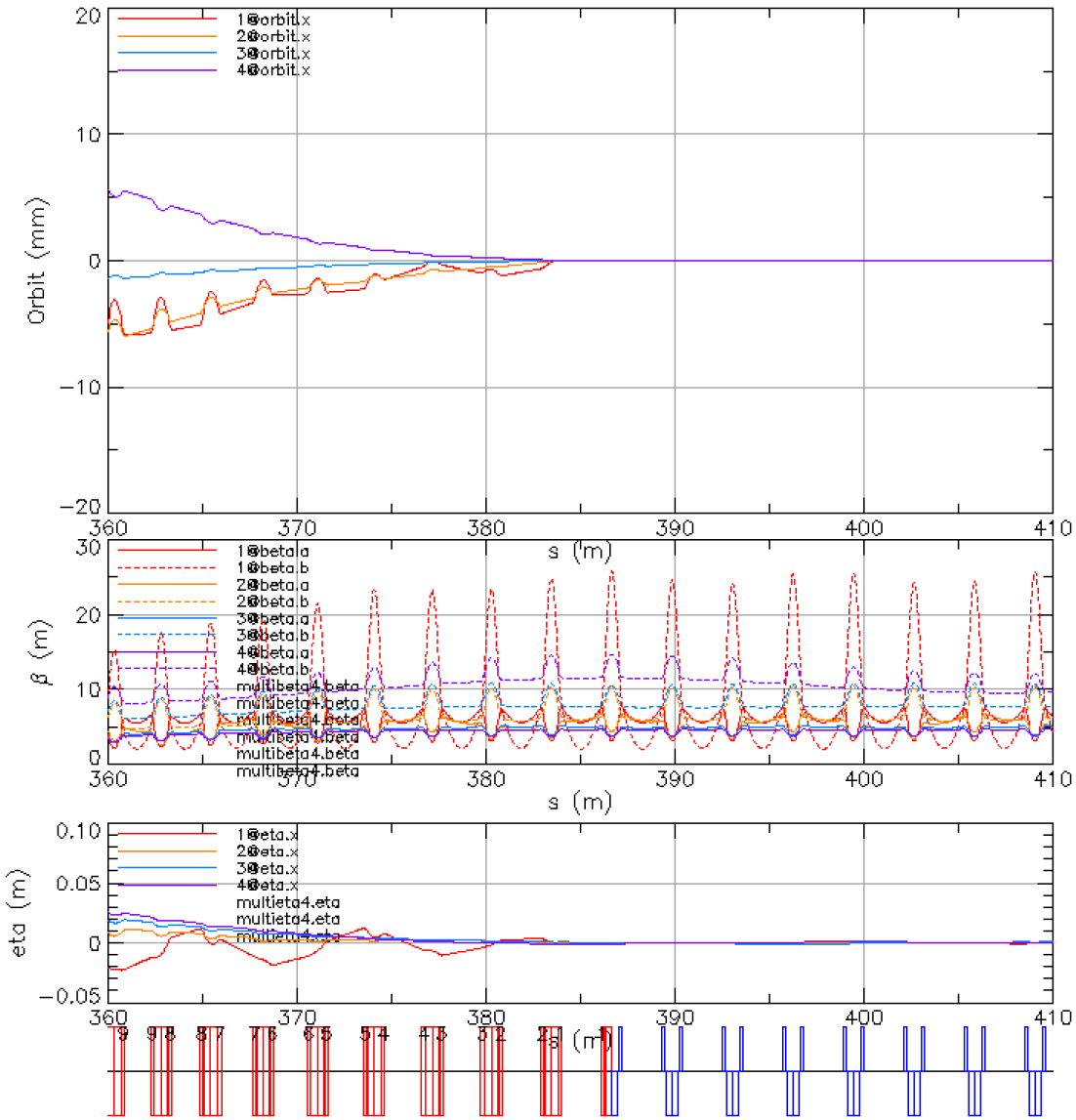
Adiabatic transition of the Fixed Field racetrack



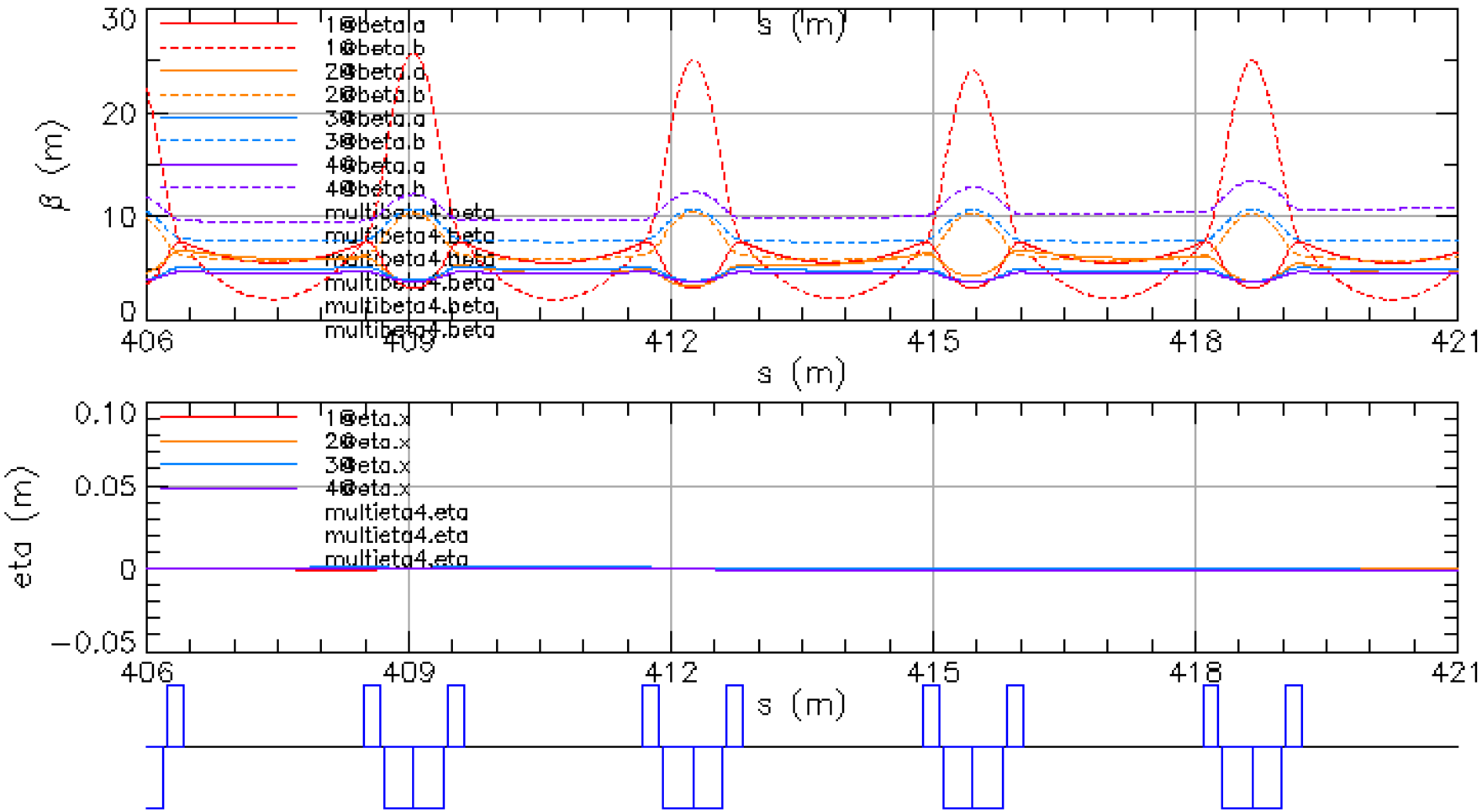
Details of the adiabatic transition



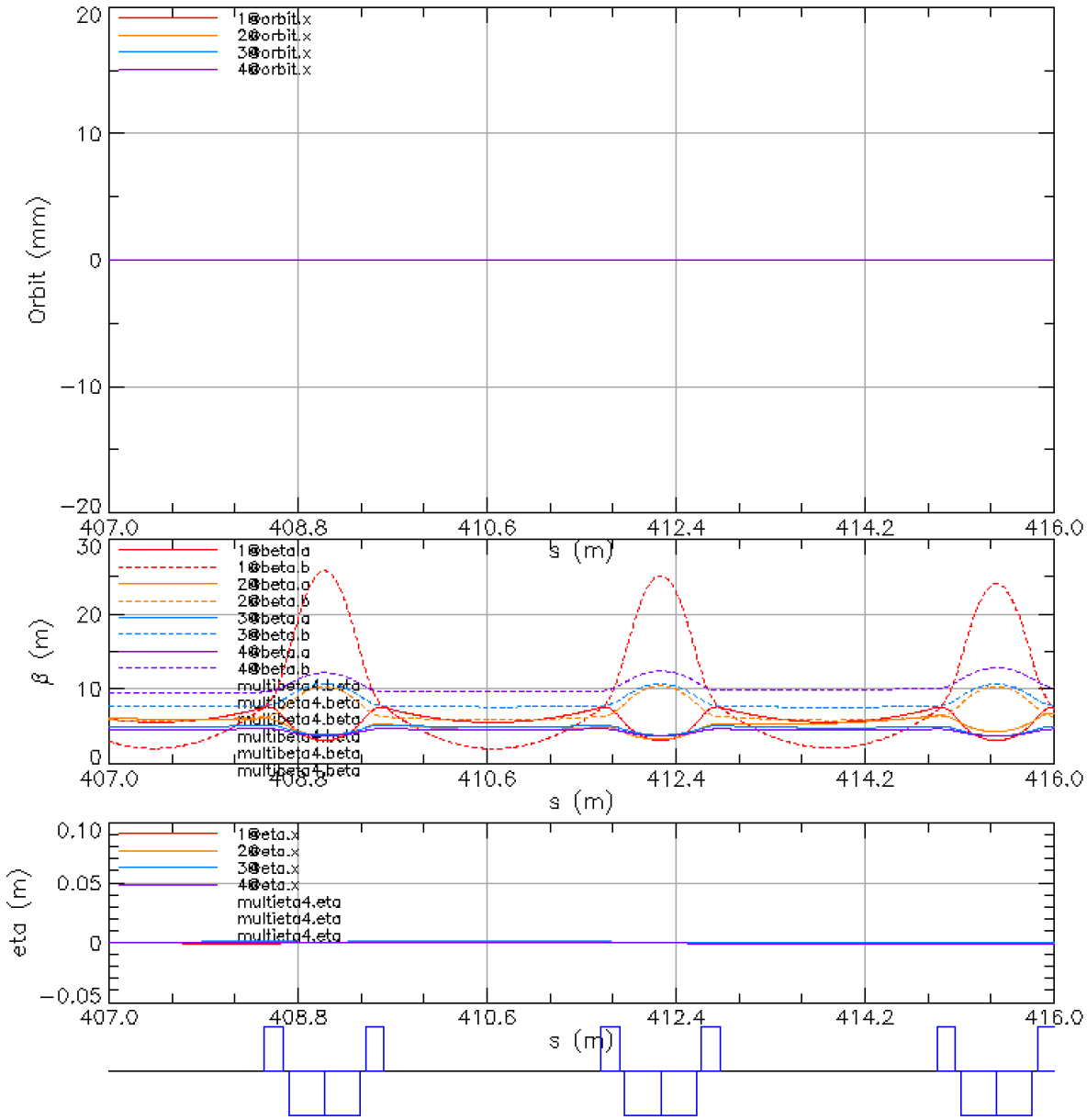
The adiabatic transition towards the straight section



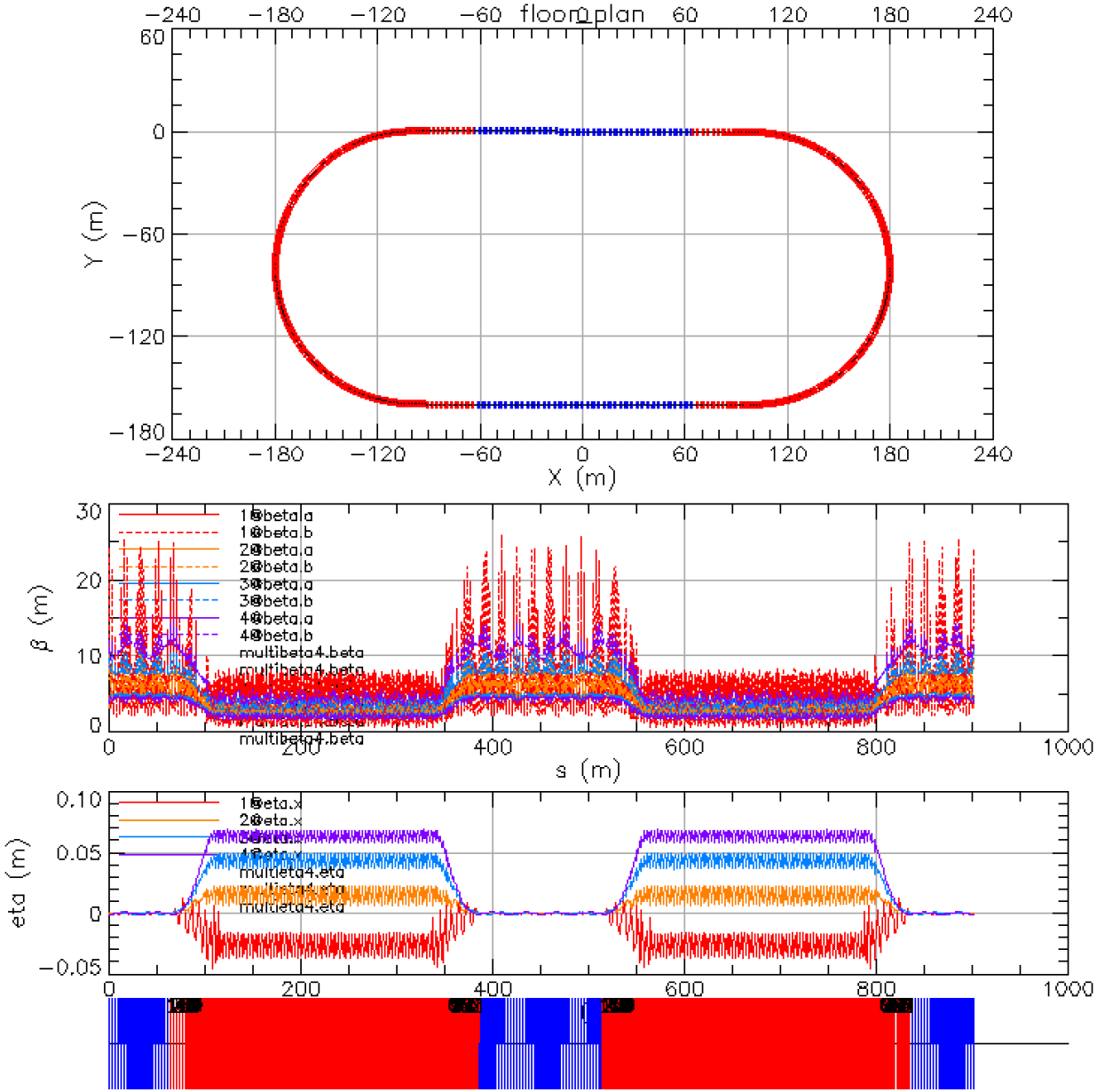
Details of the matched straight section



A detail part of the straight section



Few examples of the Fixed Field racetrack with linac

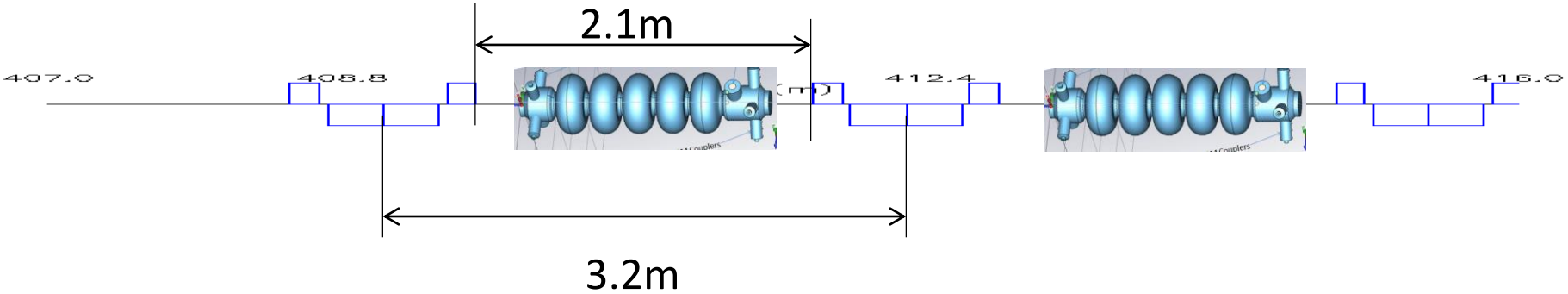


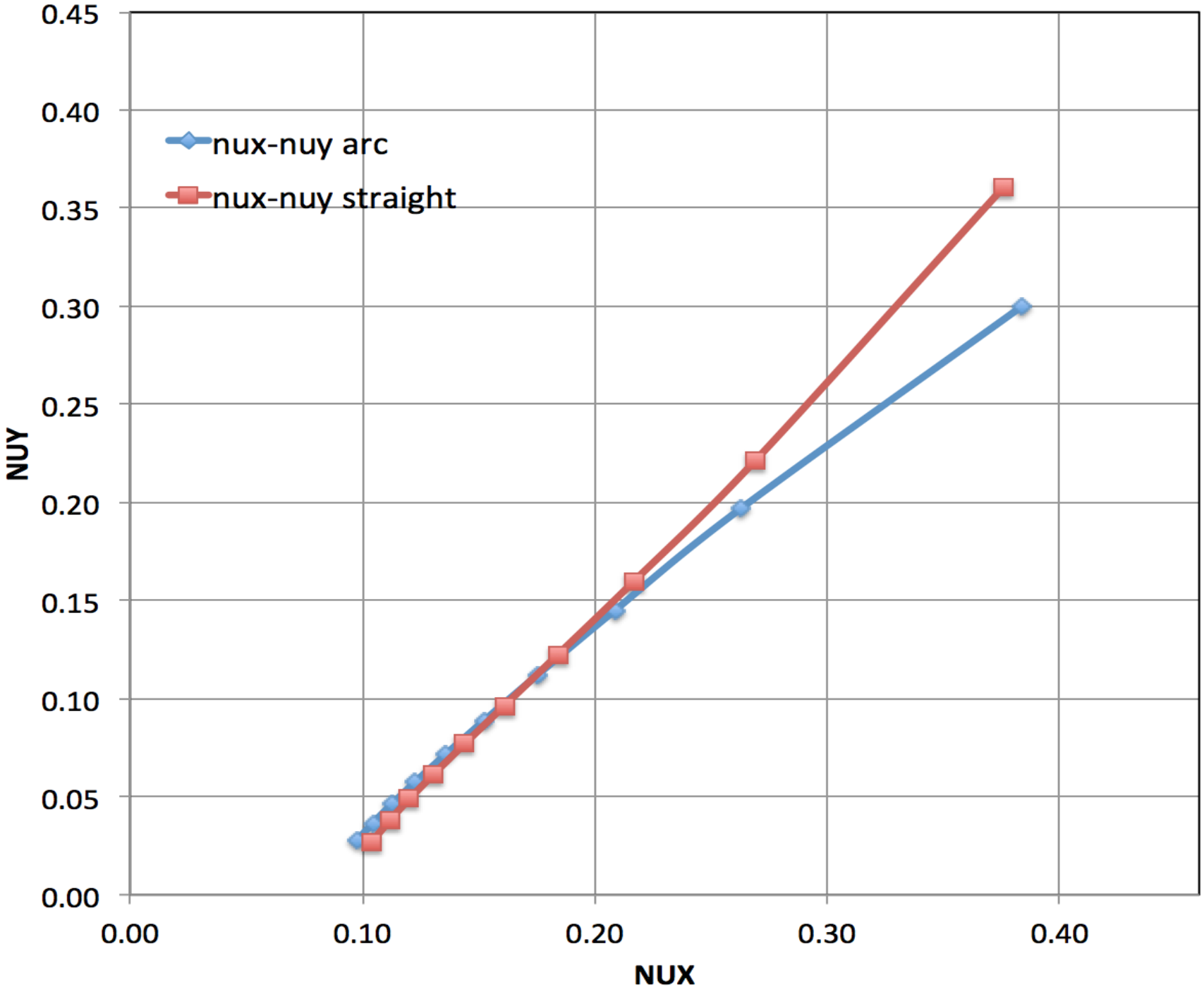
Few examples of the NS-Fixed Field racetrack with linac

Straight Section combined with the linac (small Halbach Magnets with shielding iron around)

A report from RADIABEAM [WEPE077 IPAC 10 Kyoto Japan]

..“Praseodymium - Halbach magnets can operate at lower temperature than Nd-magnets and exhibit greater radiation hardness… Praseodymium cooled to 30 K exhibits a remnant field of 1.7 T and coercivity of 72 kOe.




nux-nuy arc
nux-nuy straight
NUY
NUX
0.45
0.40
0.35
0.30
0.25
0.20
0.15
0.10
0.05
0.00
0.00
0.10
0.20
0.30
0.40

Advantages of the Fixed Field Large momentum lattice:

- For multiturn ERL's there is no other option but to use the fixed field magnets as with the present technologies it is impossible to change the magnetic field in a very short time (ns)

- With the exception of CBETA all ERL's use multiple beam lines with the fixed magnetic field to bring the beam back to linacs.

- The **fixed field large momentum acceptance beam lines** show multiple advantages in the multiple pass ERL's:
  - Multiple beam lines are replaced with a single one
  - Electron beam polarization is preserved
  - Operation is simplified

PERLE proposal with the single fixed field arc

*An Energy Recovery Linac (ERL) named as "**P**owerful **E**nergy **R**ecovery **L**inac for **E**xperiments (PERLE) with a maximum energy of 905 MeV using two 150 MeV superconducting linacs is designed for Orsay.*

The present ERL - PERLE design is a race track with two linacs on the opposite sides, connected by the three beam lines in each arc. Total of six passes through two linacs occur, three during acceleration and three in energy recovery, respectively.
We present an alternative ERL – PERLE design ***where the three separate arc beam lines (total of six arcs) are replace with a single large energy acceptance Fixed Field arcs.***

“PERLE” Present Design

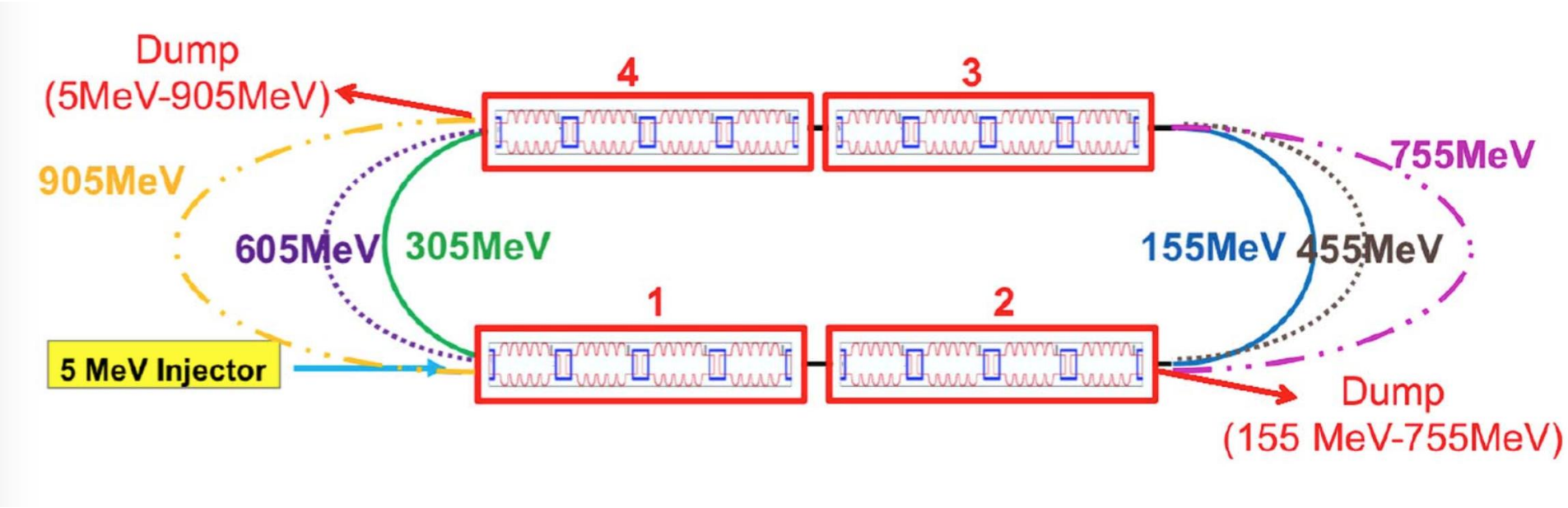
Figure 10. The facility is designed in a modular way. This picture shows a Step 1 layout of two parallel cryomodules to achieve ~75 MeV acceleration per linac and a final beam energy of 155 MeV (or half of it with just one initial cryomodule).

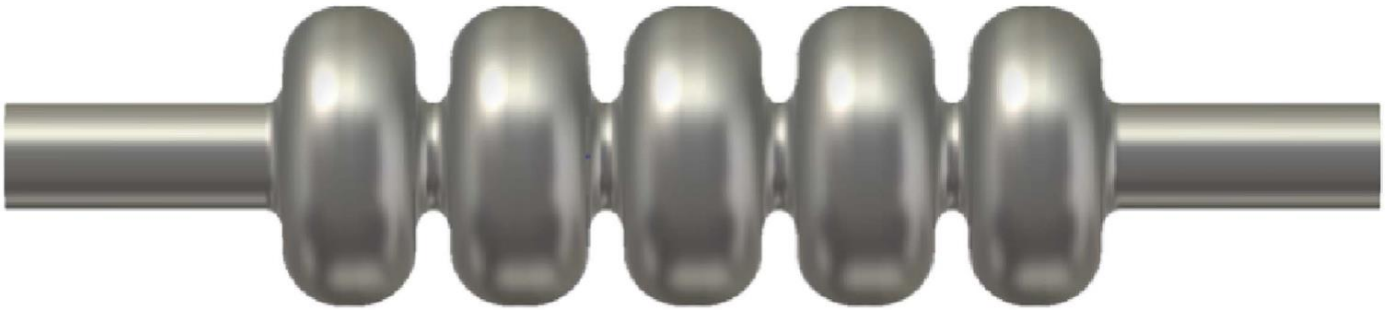
Figure 11. A second phase with recirculation could feature three-pass operation to reach 455 MeV.

Table 2. Basic Parameters of PERLE.

Target parameter	Value
Injection energy (MeV)	5–10
Maximum energy (GeV)	1
Normalised emittance $\gamma\varepsilon_{x,y}$ (mm mrad)	6
Average beam current (mA)	15
Bunch spacing (ns)	25
Bunch length (rms) (mm)	3
RF frequency (MHz)	801.58
Duty factor	CW

PERLE Present Design





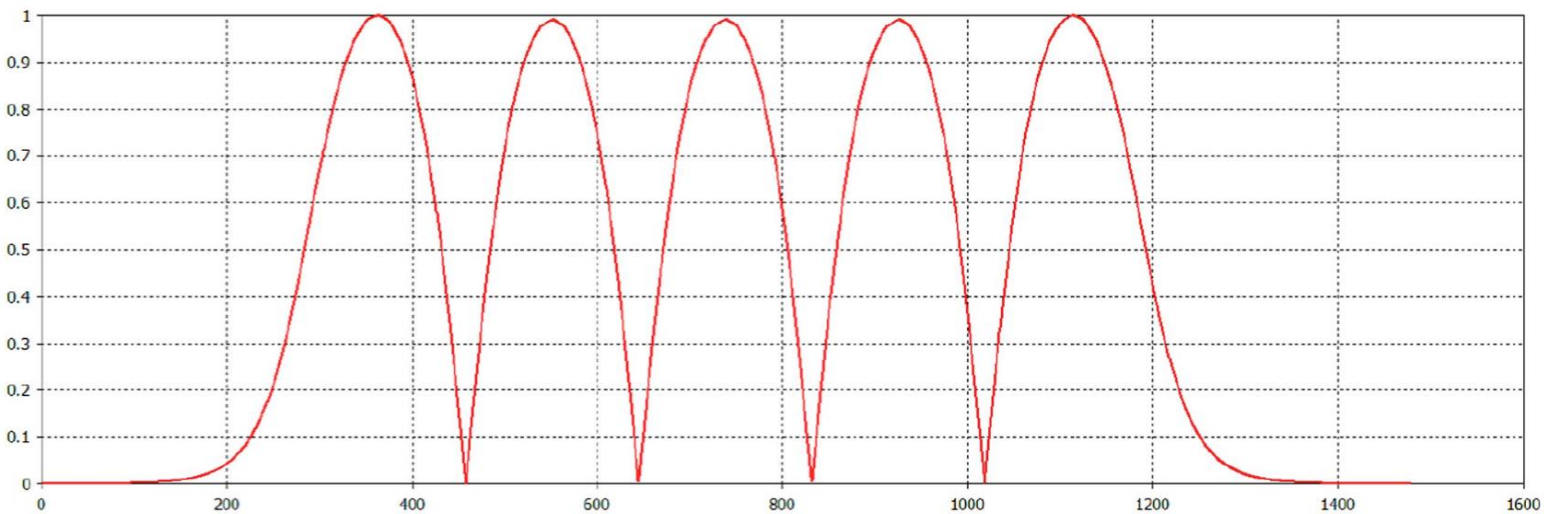


Figure 30. Cavity design (single-die, iris ID = tube ID) 801.58 MHz (top); axial field on axis (bottom).

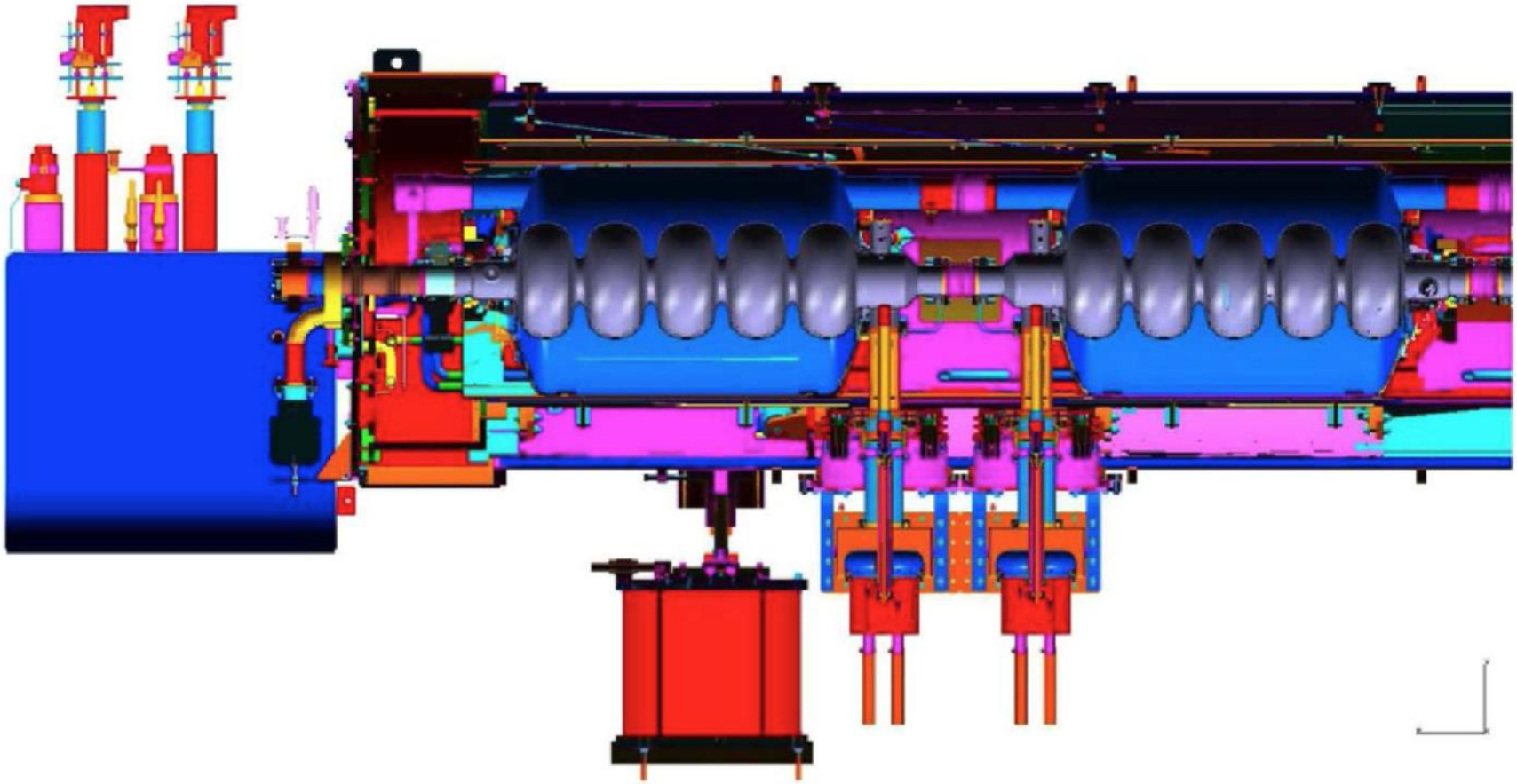
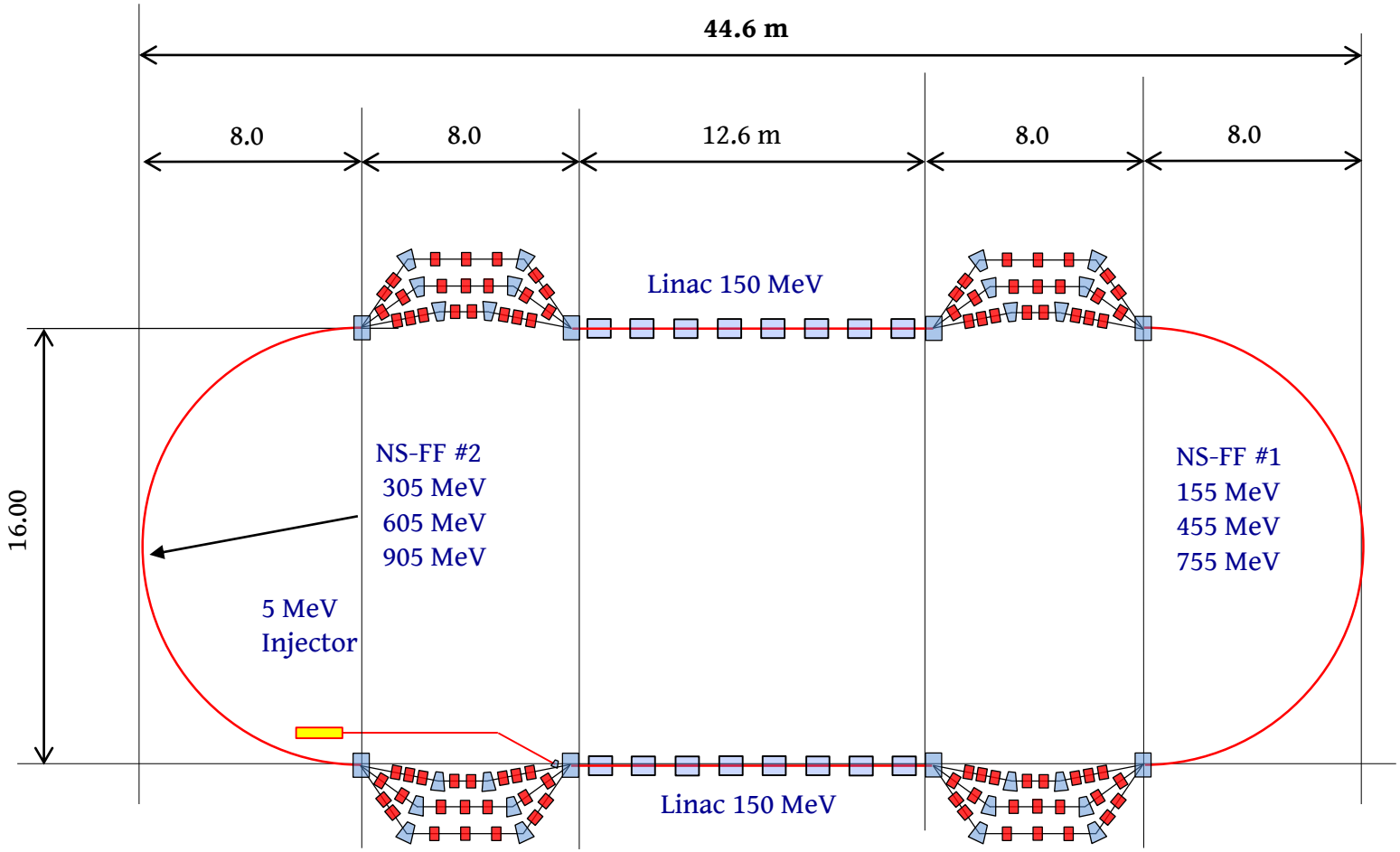
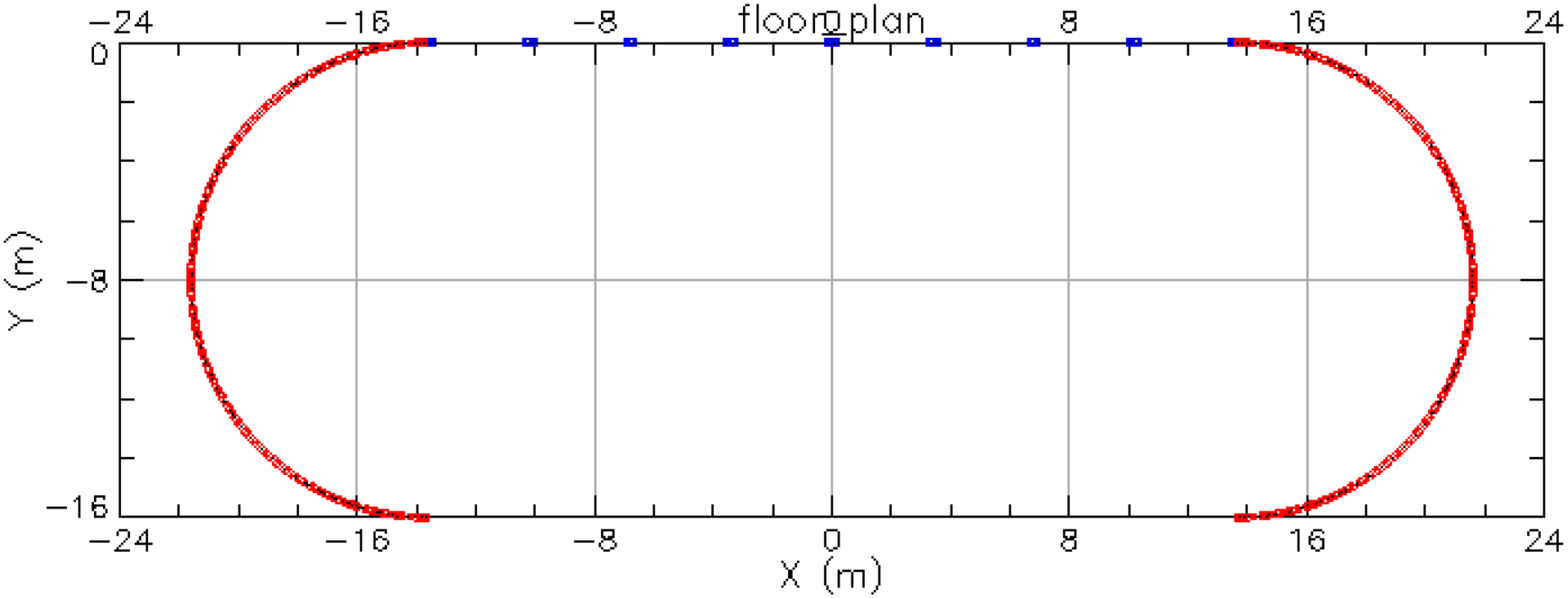


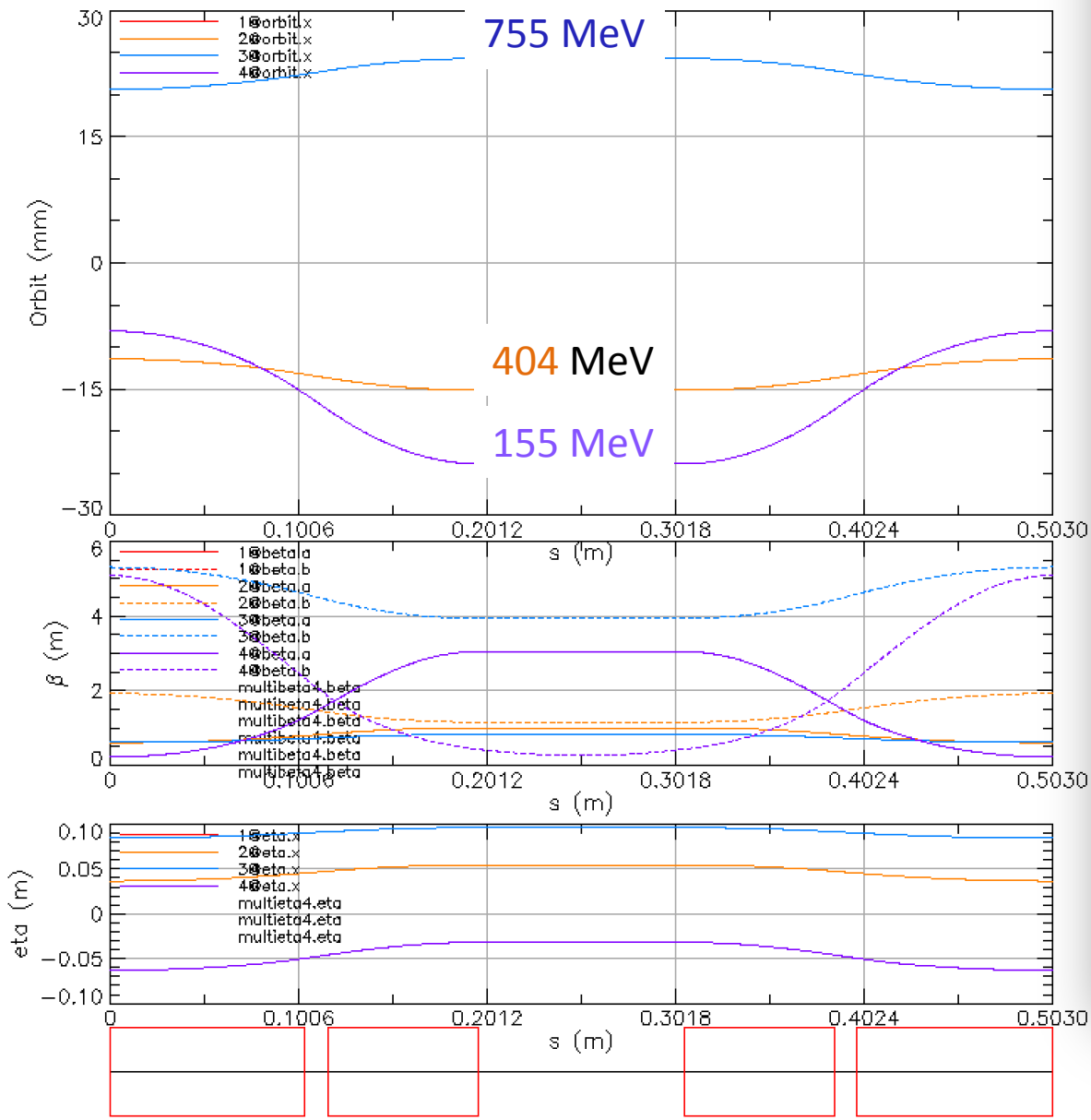
Figure 35. Cavity, coupler and end can detail view.

Fixed Field Arc for PERLE – similar to CBETA



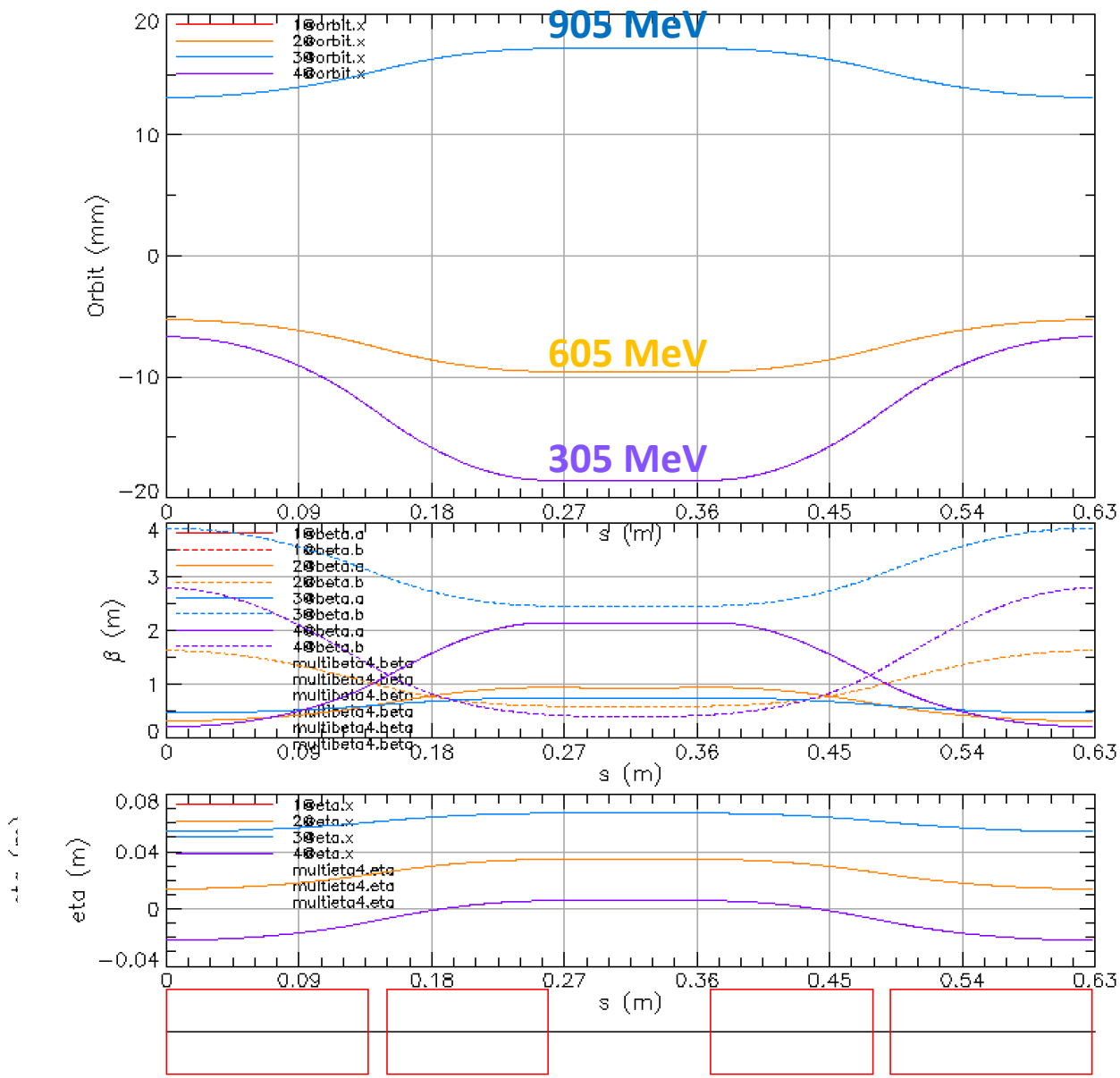
Fixed Field Arc for PERLE – A solution similar to CBETA



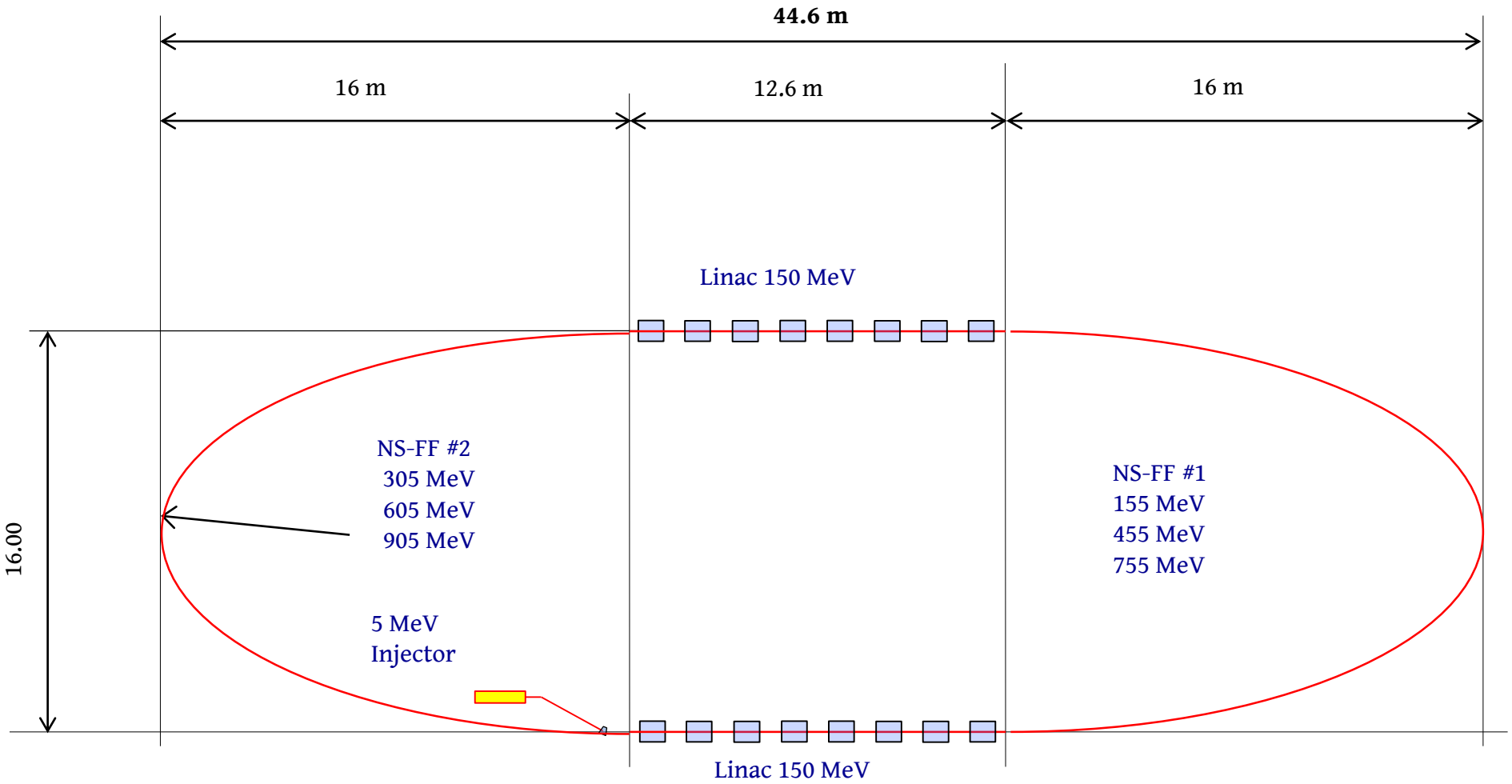


Orbit Offsets and Lattice functions for the single right side arc cell.

Fixed Field Arc for PERLE 305-905 MeV– similar to CBETA

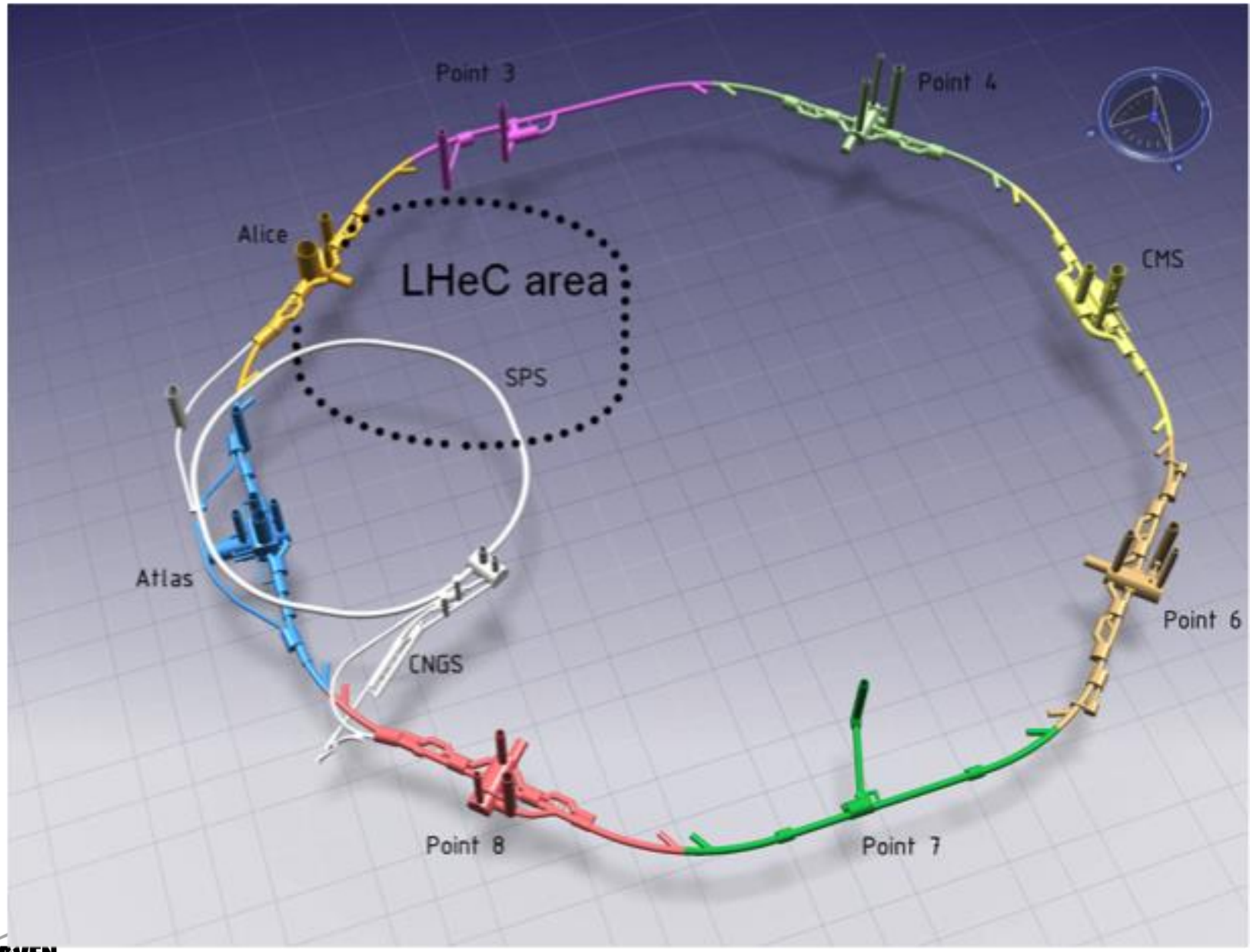


Fixed Field single arcs for PERLE – new proposal as previously described with the triplet magnets between the 5 RF cell units

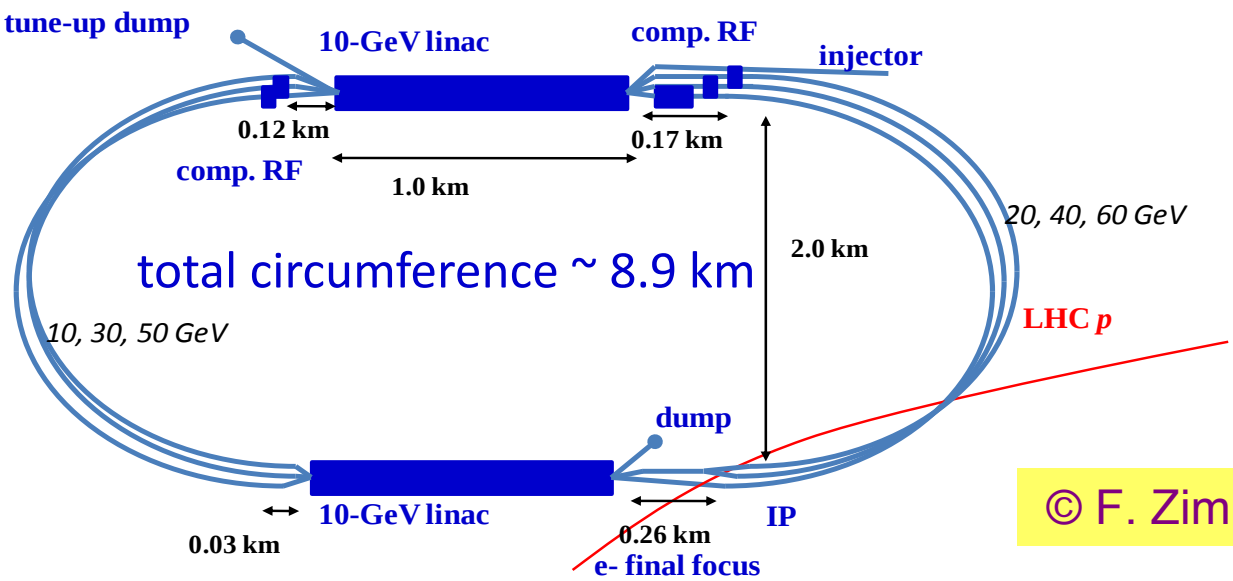


From Oliver Brüning

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

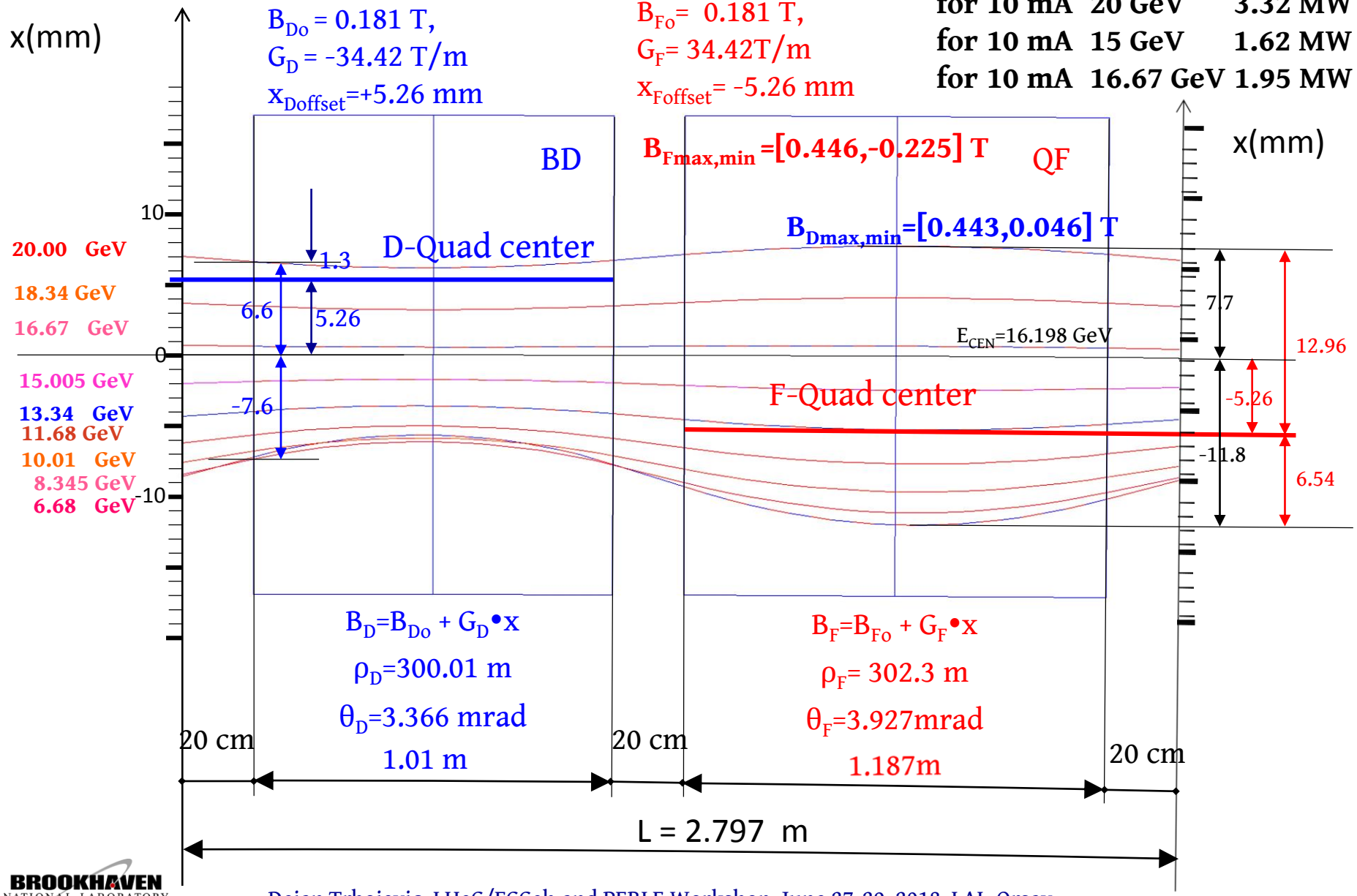
	PROTONS	ELECTRONS
Beam Energy [GeV]	7000	60
Luminosity [10^{33}cm^{-2}s^{-1}]	1	1
Normalized emittance $\gamma\varepsilon_{x,y}$ [μm]	3.75	50
Beta Function $\beta^*_{x,y}$ [m]	0.10	0.12
rms Beam size $\sigma^*_{x,y}$ [μm]	7	7
rms Divergence $\sigma'_{x,y}$ [μrad]	70	58
Beam Current [mA]	(860) 430	6.6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

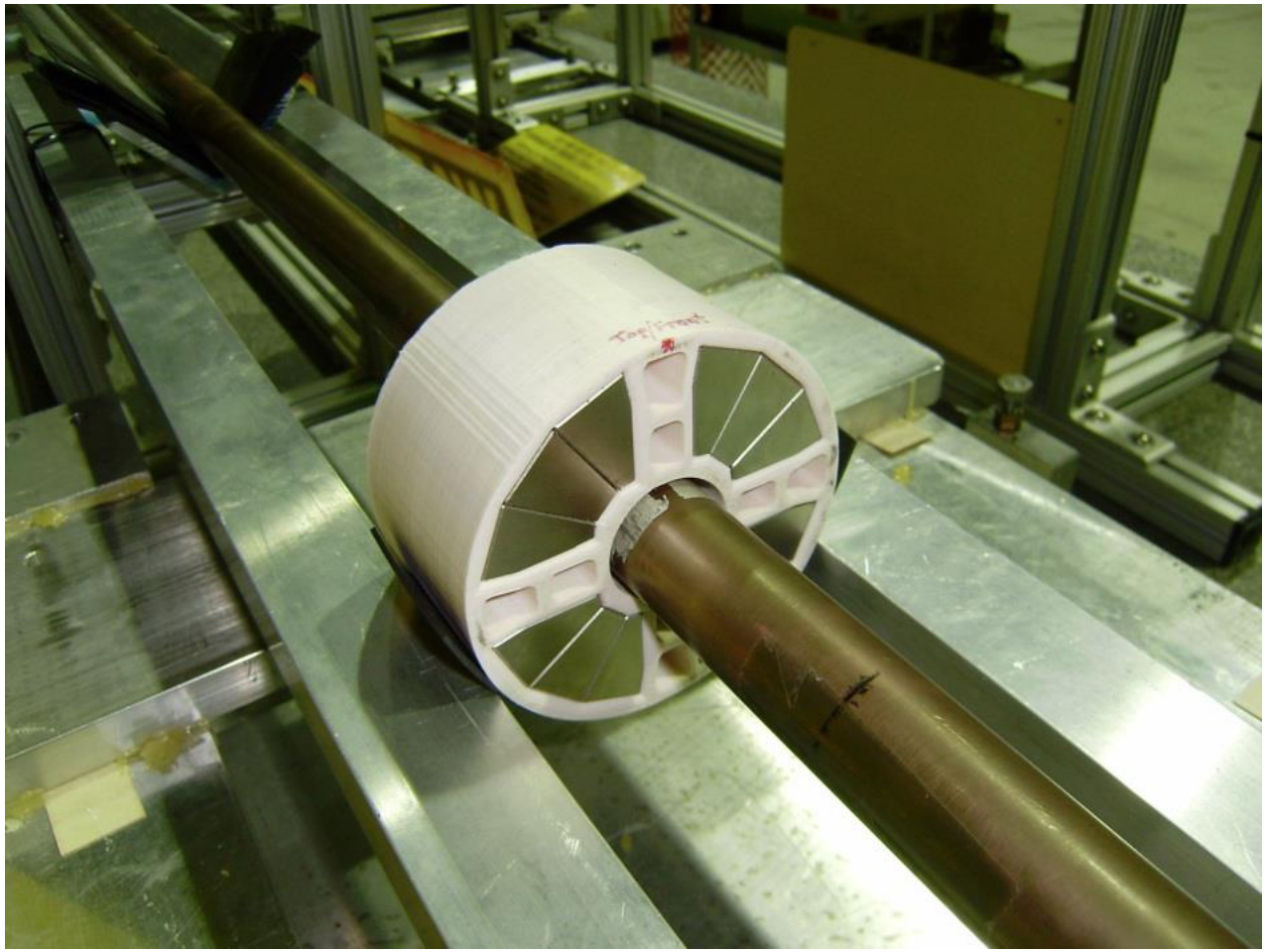
High Energy eRHIC NS-FF Cell

Synchrotron Radiation:

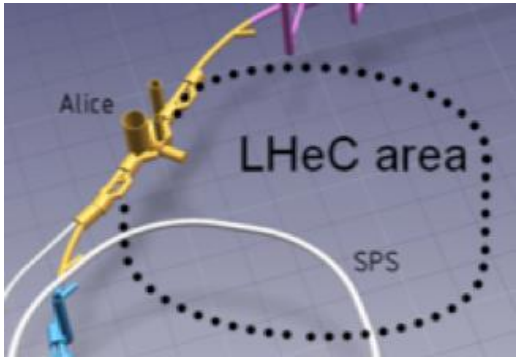
for 10 mA	**20 GeV**	**3.32 MW**
for 10 mA	**15 GeV**	**1.62 MW**
for 10 mA	**16.67 GeV**	**1.95 MW**

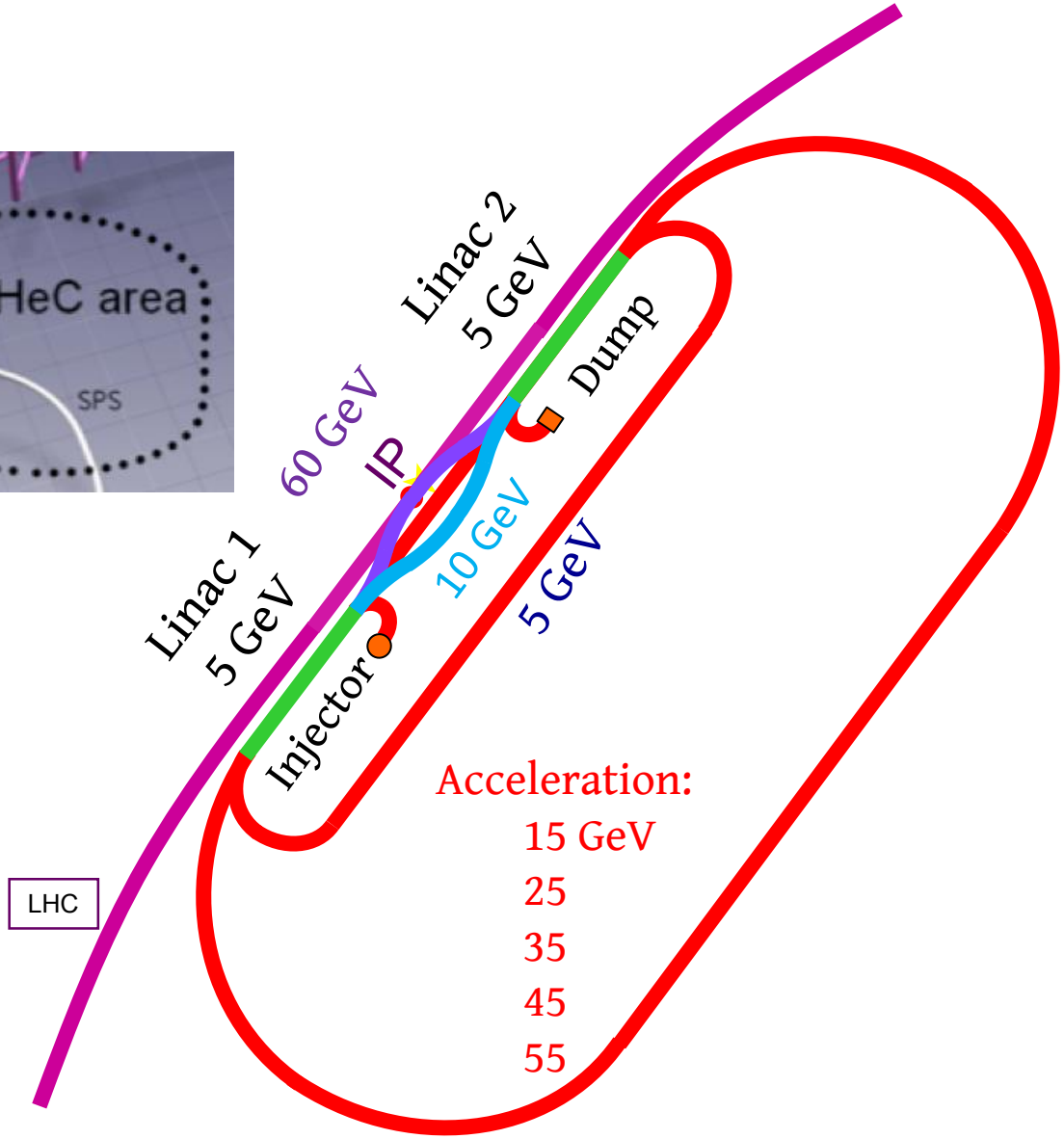


Built and successfully tested Halbach type of magnet with a horizontal gap for the eRHIC ERL type of solution



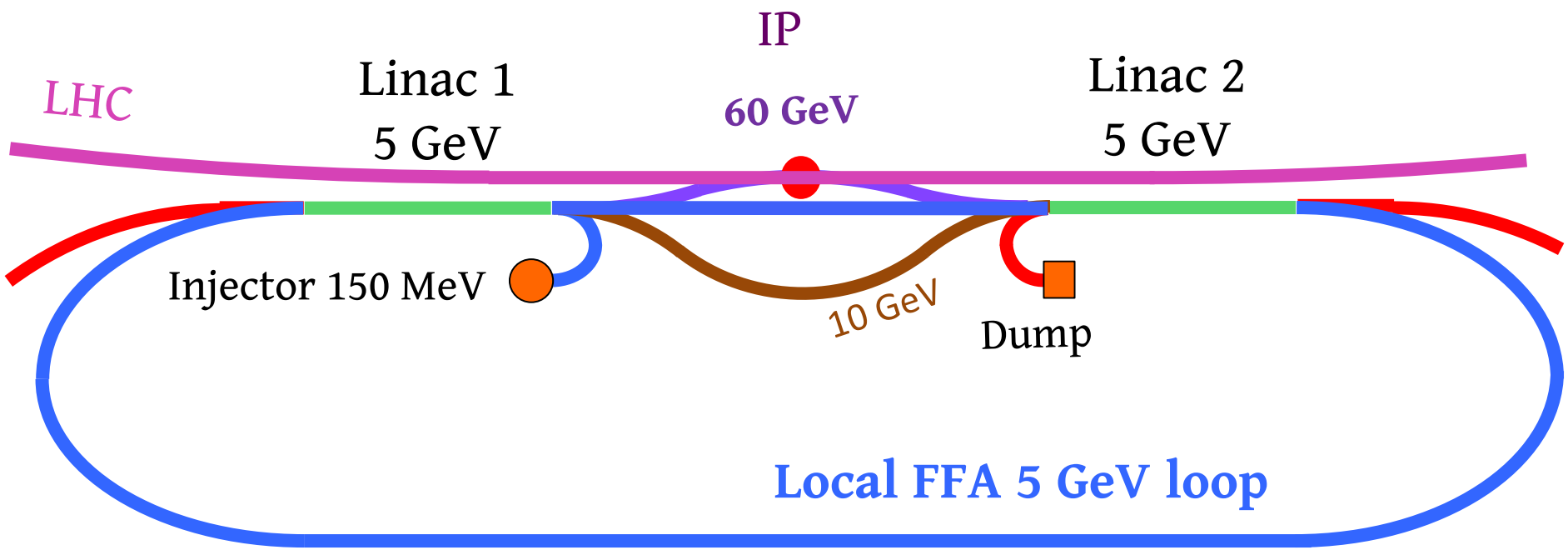
Fixed Field LHeC Recirculator with ER





Recovery:
55 GeV
45
35
25
15

NS-FF LHeC Recirculator with ER

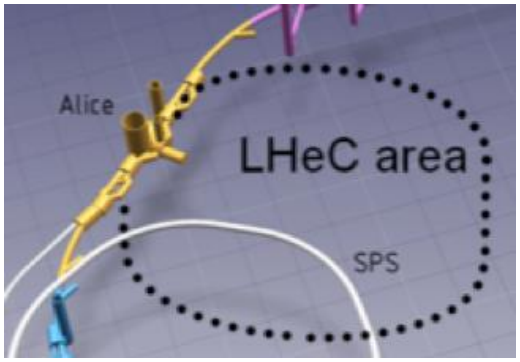


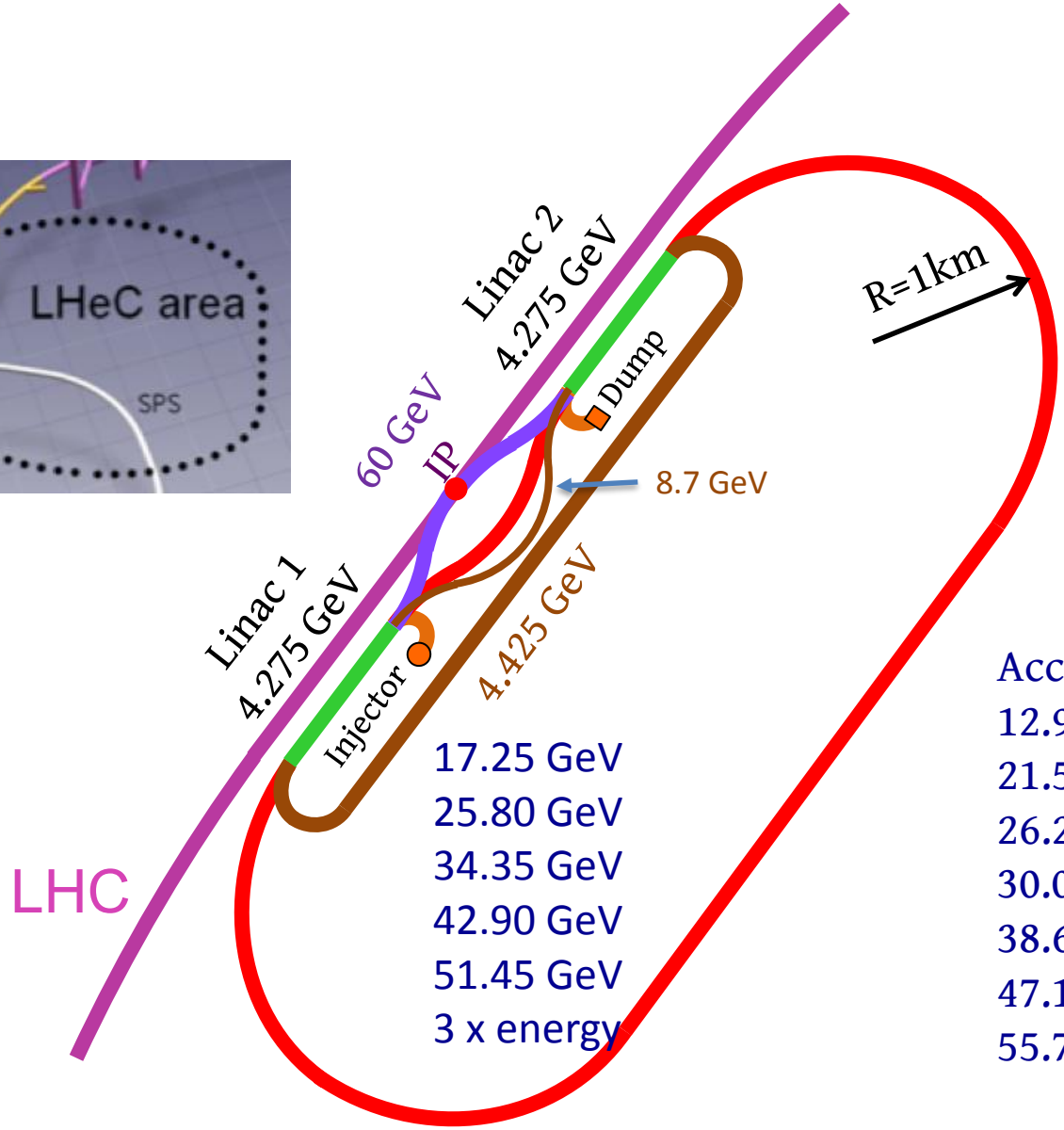
Acceleration
15 GeV
25
35
45
55

3.7 x energy

Recovery
55 GeV
45
35
25
15

NS-FF LHeC/FCCeh Recirculator with ER



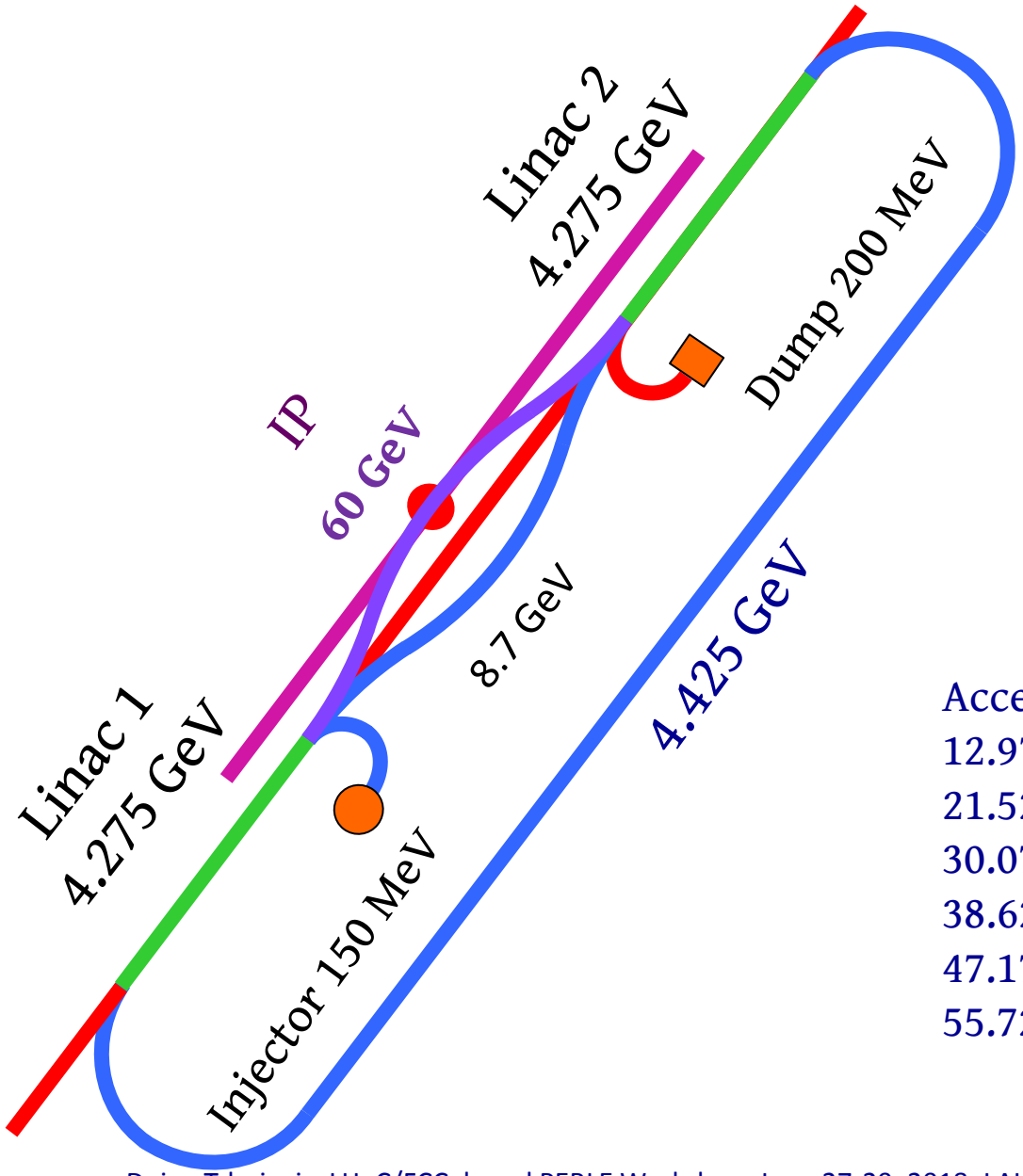


17.25 GeV
25.80 GeV
34.35 GeV
42.90 GeV
51.45 GeV
3 x energy

Acceleration	Energy Recovery
12.975 GeV	55.725
21.525	47.175
26.25	38.625
30.075	30.075
38.625	26.25
47.175	21.525
55.725	12.975

4.3 times in energy

NS-FF LHeC Recirculator with ER



Acceleration	56.25 GeV
12.975 GeV	48.75
21.525	41.25
30.075	33.75
38.625	26.25
47.175	18.75
55.725	11.25

LHC
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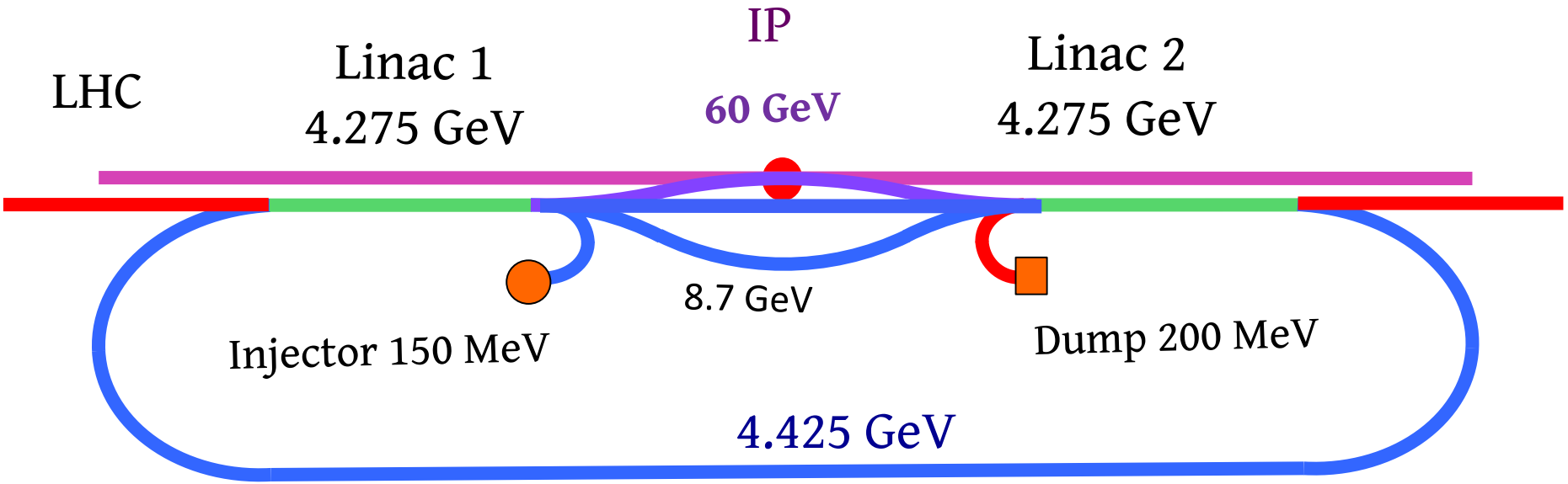
NS-FF LHeC Recirculator with ER



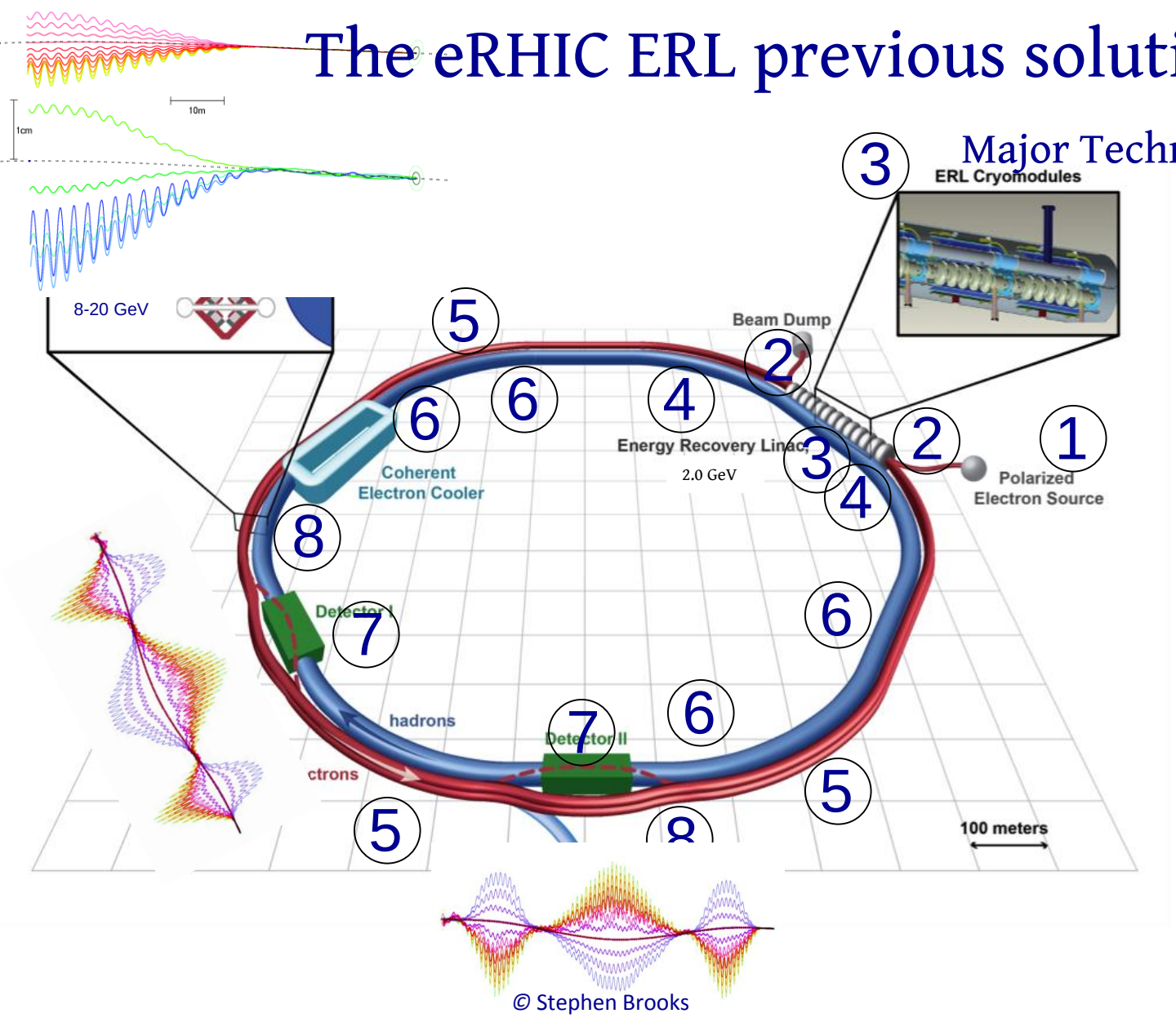
Acceleration
12.975 GeV
21.525
30.075
38.625
47.175
55.725

Recovery
56.25 GeV
48.75
41.25
33.75
26.25
18.75
11.25

Synchrotron Radiation in LHeC with 2 x 5 GeV linacs Maximum Collision Energy 60 GeV

E(GeV)	Total Power (MW) 8.87 mA	Total Power (MW) 6.6 mA
50	7.5779	5.6383
40	4.2080	3.1310
30	1.3902	1.0344
20	1.2881	0.9584
10	0.5359	0.3987
TOTAL	**15.000**	**11.1608**

The eRHIC ERL previous solution



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Major Technical Components:

① Funneling Gun

② ERL mergers

③ Superconducting Linac - ERL

④ Spreaders and Combiners

⑤ NS-FF arcs

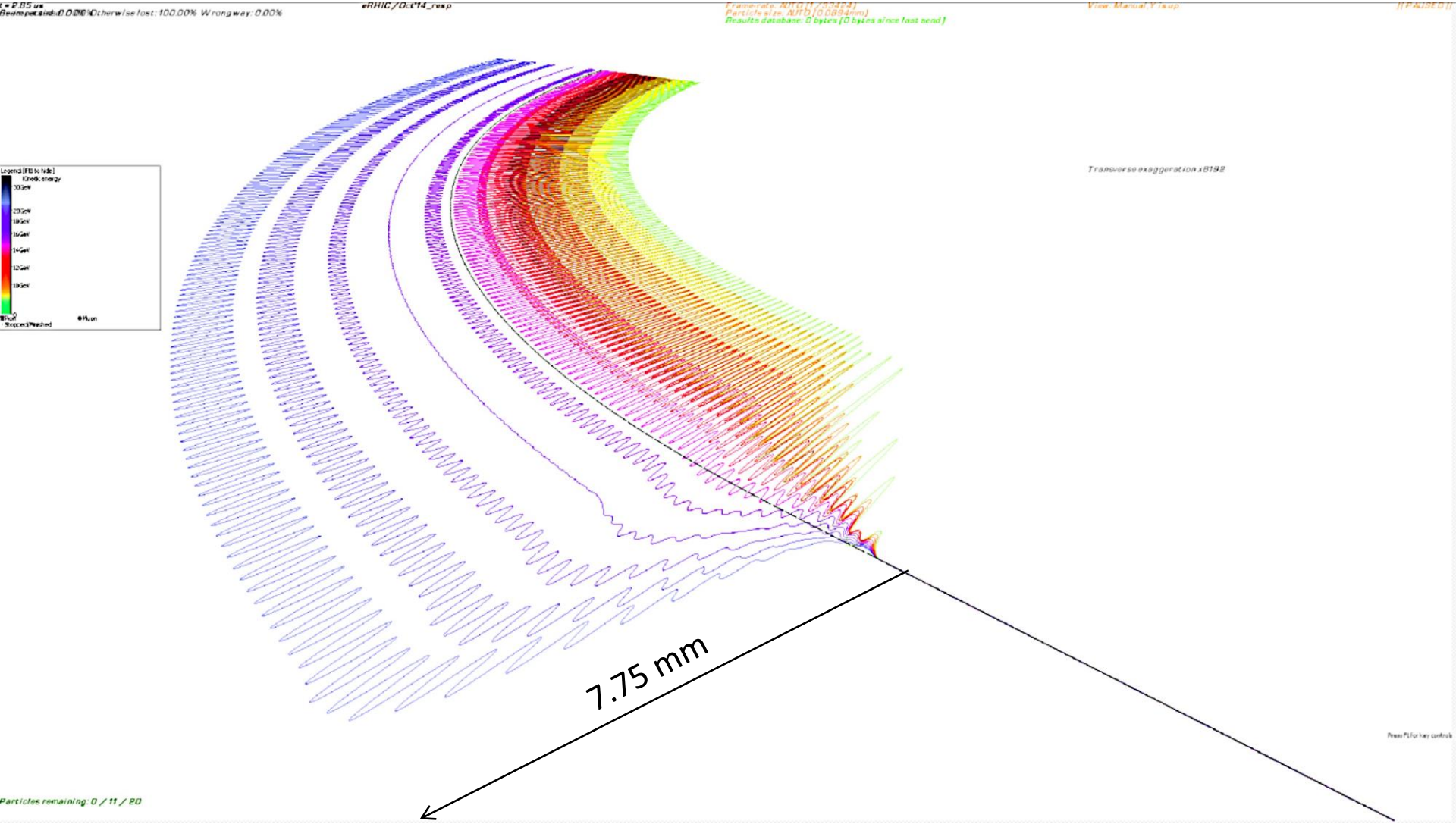
⑥ Merging arcs to straight section

⑦ Straight section

⑧ Extracted high energy beam

⑨ Detector By Passes

Merging Fixed Field linear arcs to the straight section in eRHIC



eRHIC Fixed Field Orbits Magnified x1000

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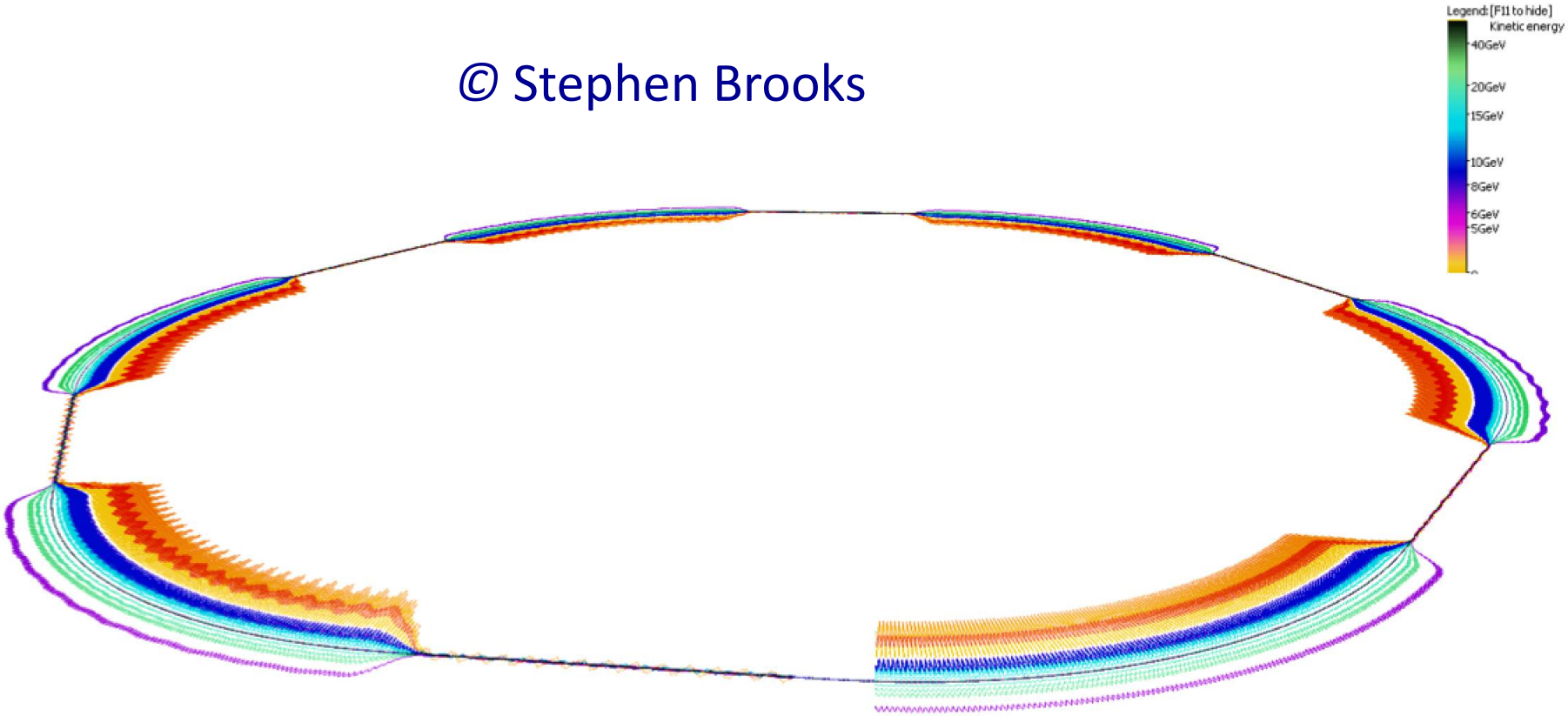
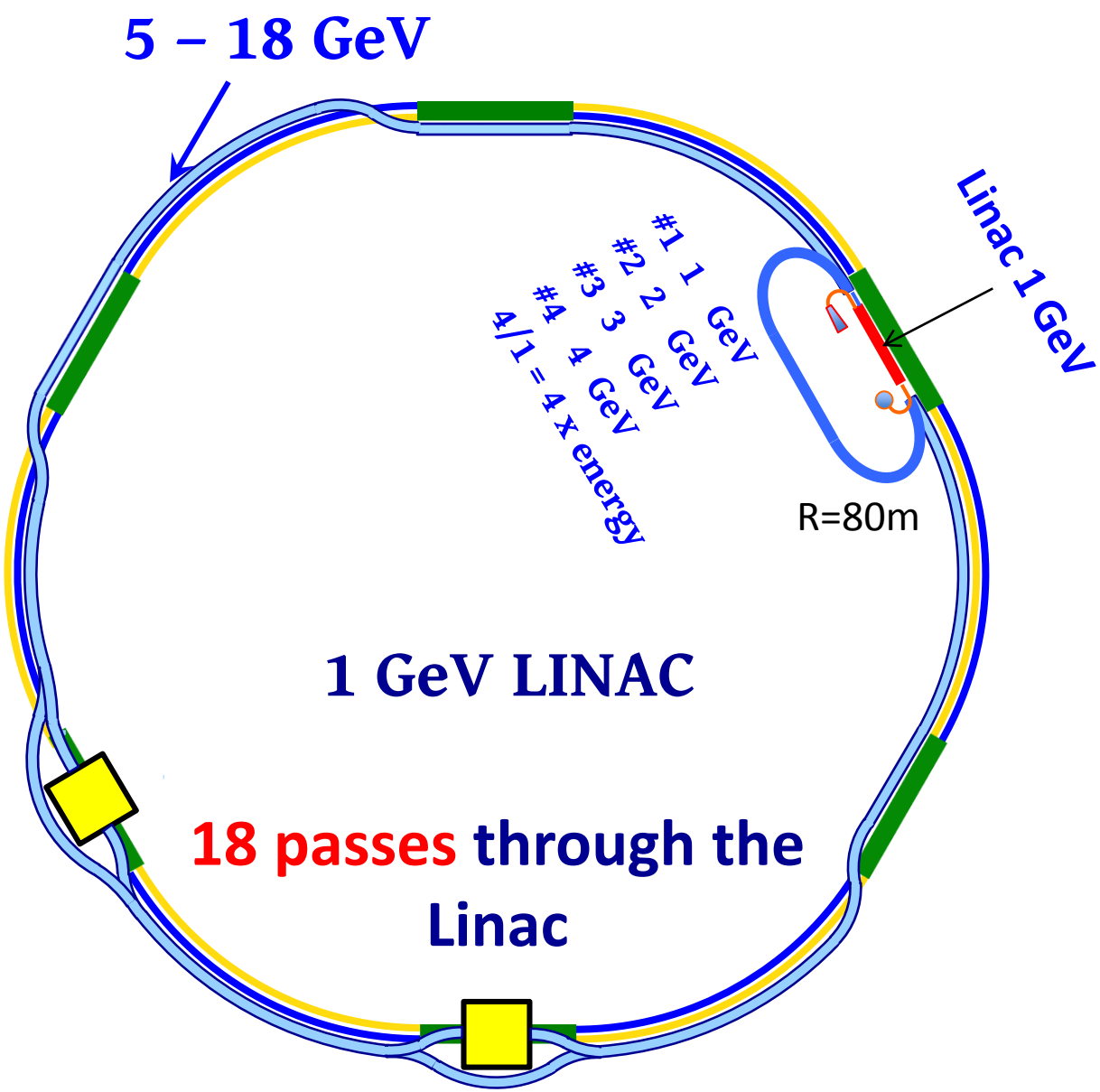


eRHIC Layout

Linac 1.0	GeV
#1	5 GeV
#2	6 GeV
#3	7 GeV
#4	8 GeV
#5	9 GeV
#6	10 GeV
#7	11 GeV
#8	12 GeV
#9	13 GeV
#10	14 GeV
#11	15 GeV
#12	16 GeV
#13	17 GeV
#14	18 GeV



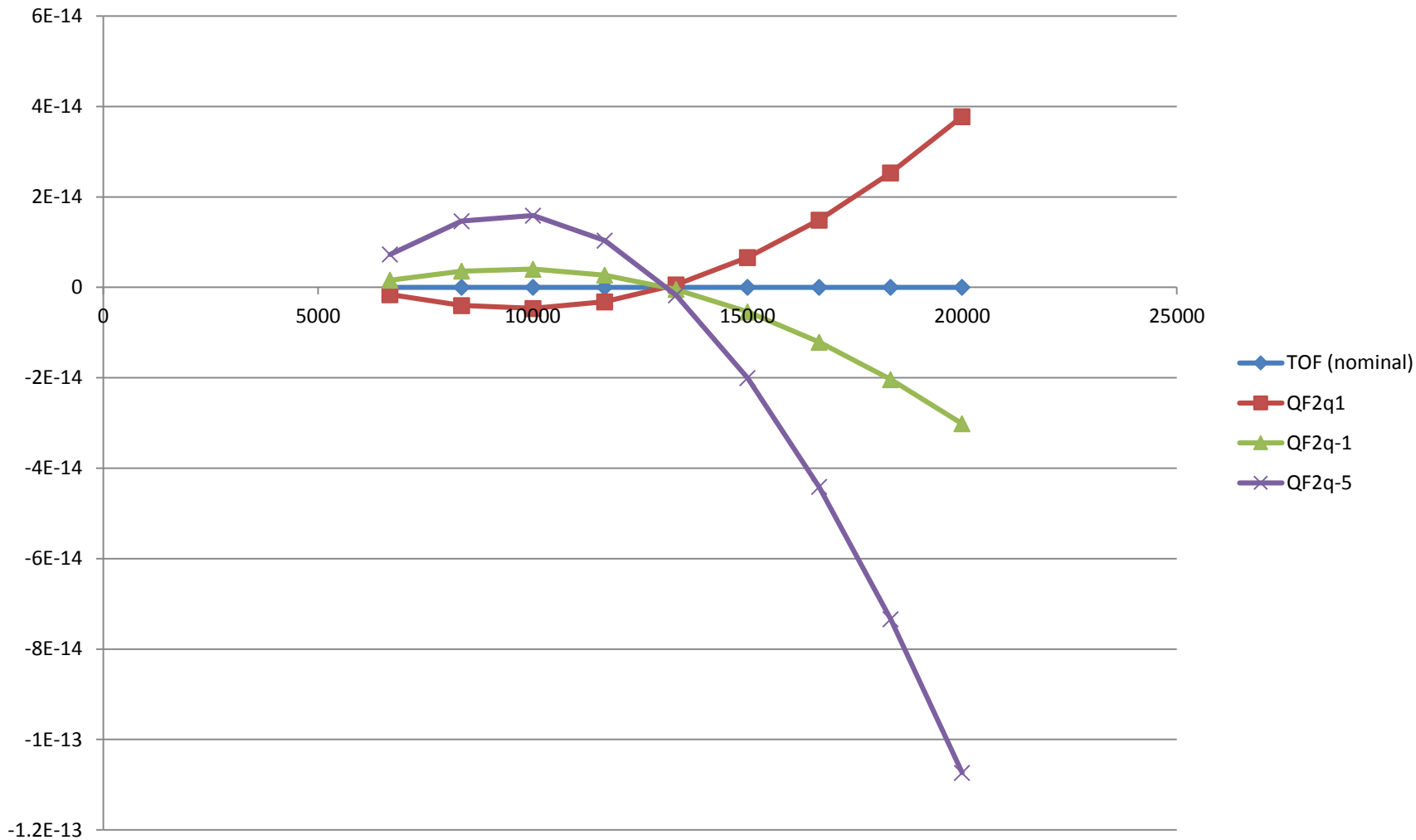
X 3.7

CONCLUSION

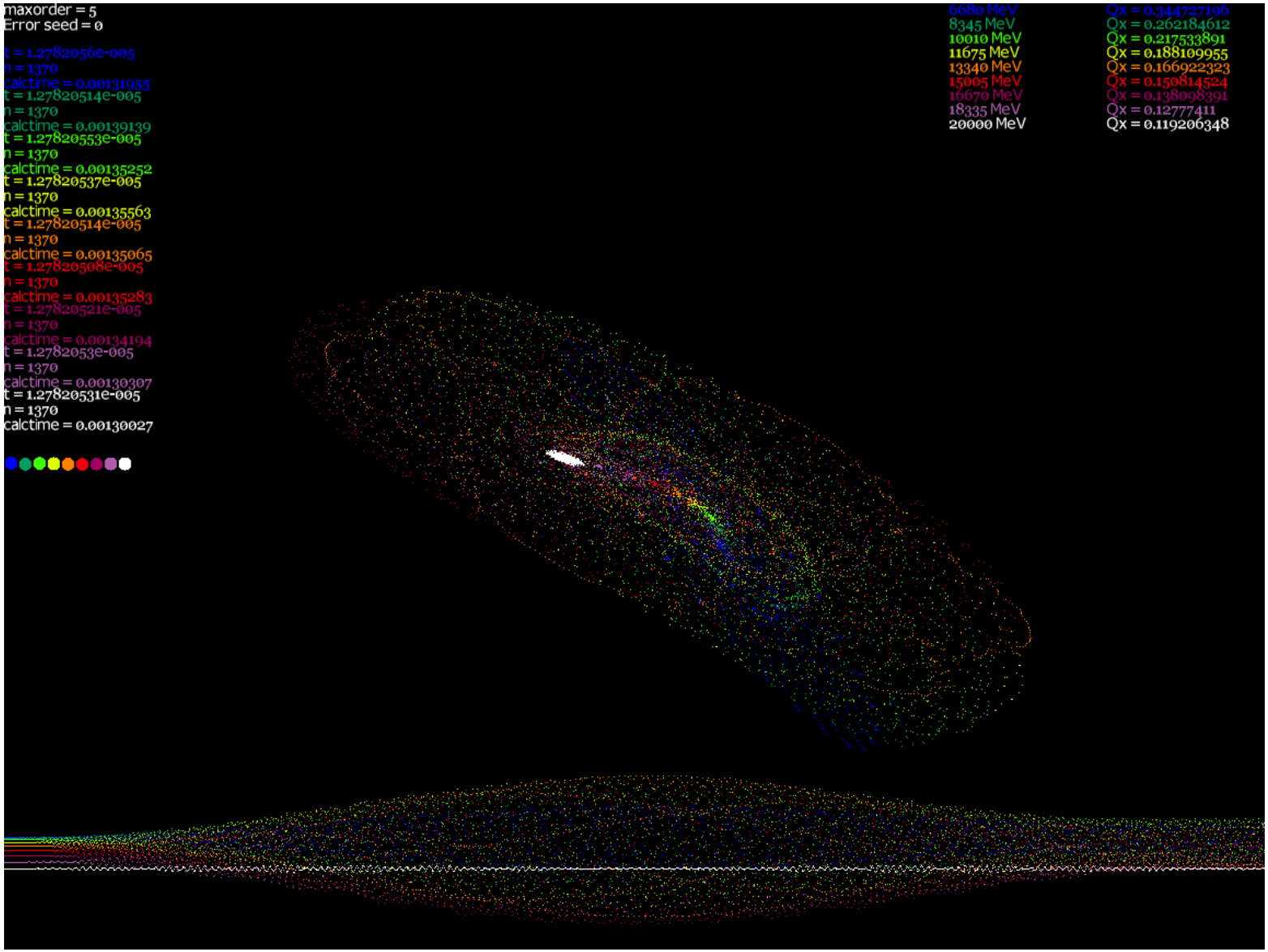
- Two lattice solutions are proposed for the PERLE design with a single arc line
- A new LHeC proposal replaces the 2 x 10 GeV linacs and three arcs, with 2 x 5 GeV linacs and two fixed field 3.7 times energy acceptance arcre. This is a cost-effective solution. It reduces the synchrotron radiation in arcs, hence provides 35 % larger luminosity for the same limit on the value of 15 MW for the total loss from synchrotron radiation.

Back up slides

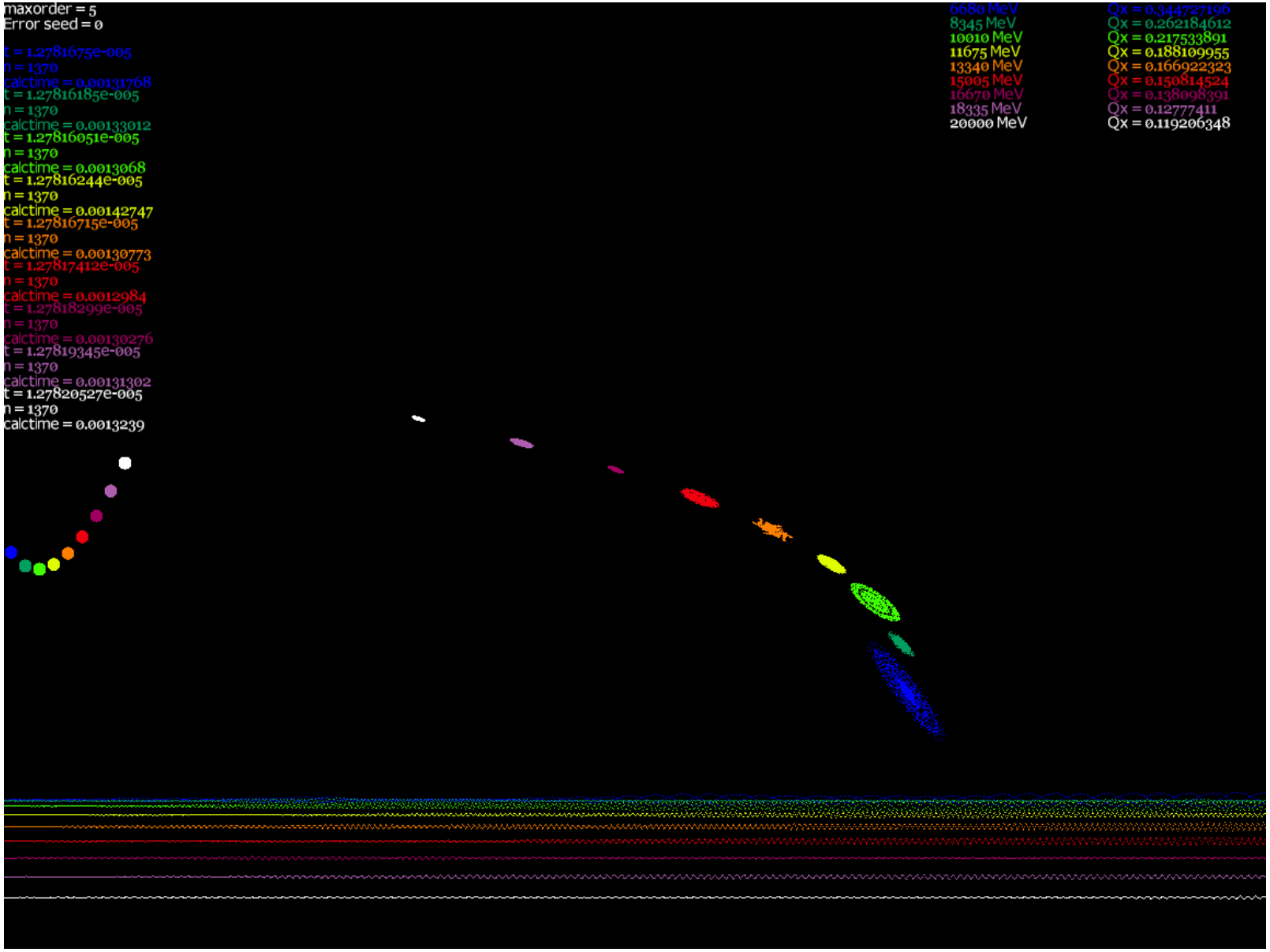
Time of flight adjustments



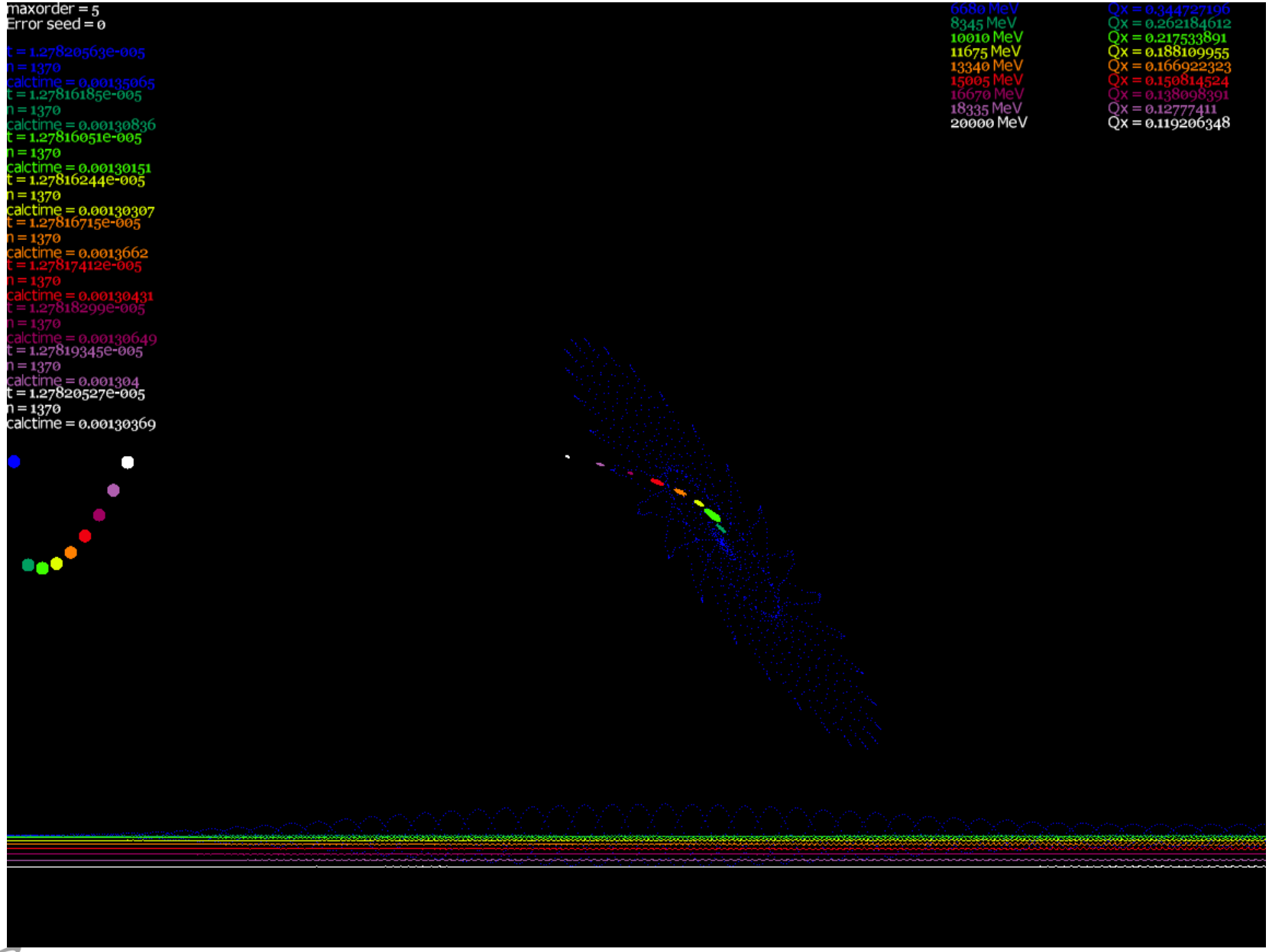
Time of flight adjustments



Time of flight adjustments



Time of flight adjustments



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