ERL designs based on FFAG arcs (eRHIC, LHeC, Cornell)

Dejan Trbojevic

Abstract:

The future Electron Ion Collider (EIC) LHeC 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 and almost completely recovering the energy during deceleration to the initial energy. We present: eRHIC, an ERL for LHeC (an example ***with almost double reduction in size of the linac****, from 2 x 10 GeV to 2 x 5.345 GeV) from the present solution, using two Non-Scaling Fixed Field Alternating Gradient beam lines. This* ***would reduce the three beam lines to two, and*** *raise the luminosity for 34% from the electron current of 6.6 mA to 8.9 mA, for the synchrotron radiation limit of 15 MW.*

OUTLINE

Electron Ion Colliders eRHIC and LHeC

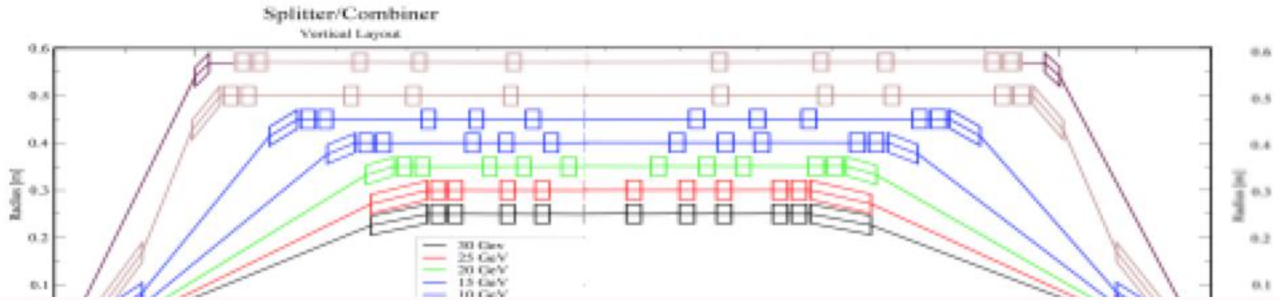
NS-FFAG: Introduction to the concept

Lattice examples of the eRHIC and ERL LHeC

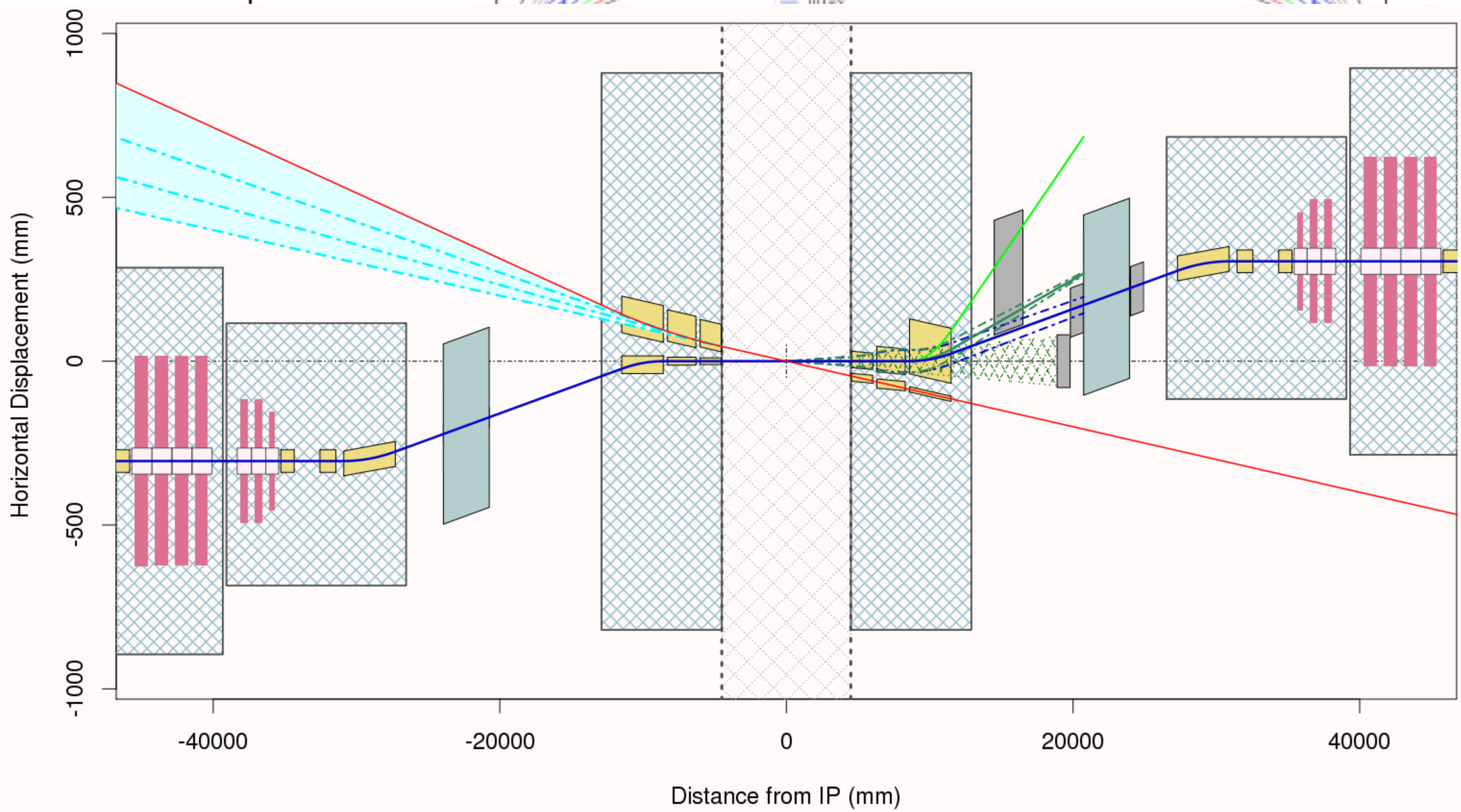
SUMMARY:

Advantages come from multiple passes through the linac bring reduction in the linac size and of three beam circulating lines to two, reducing the synchrotron radiation – raising 42% the luminosity

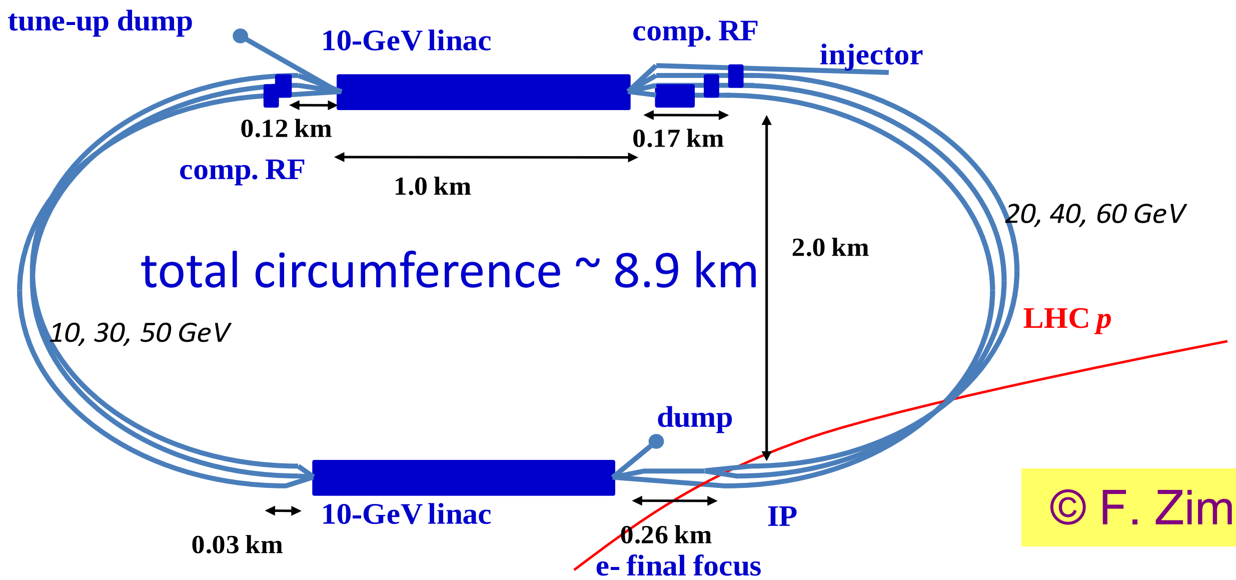
Layout



FFAG Recirculating



Linac-Ring Option – LHeC Recirculator



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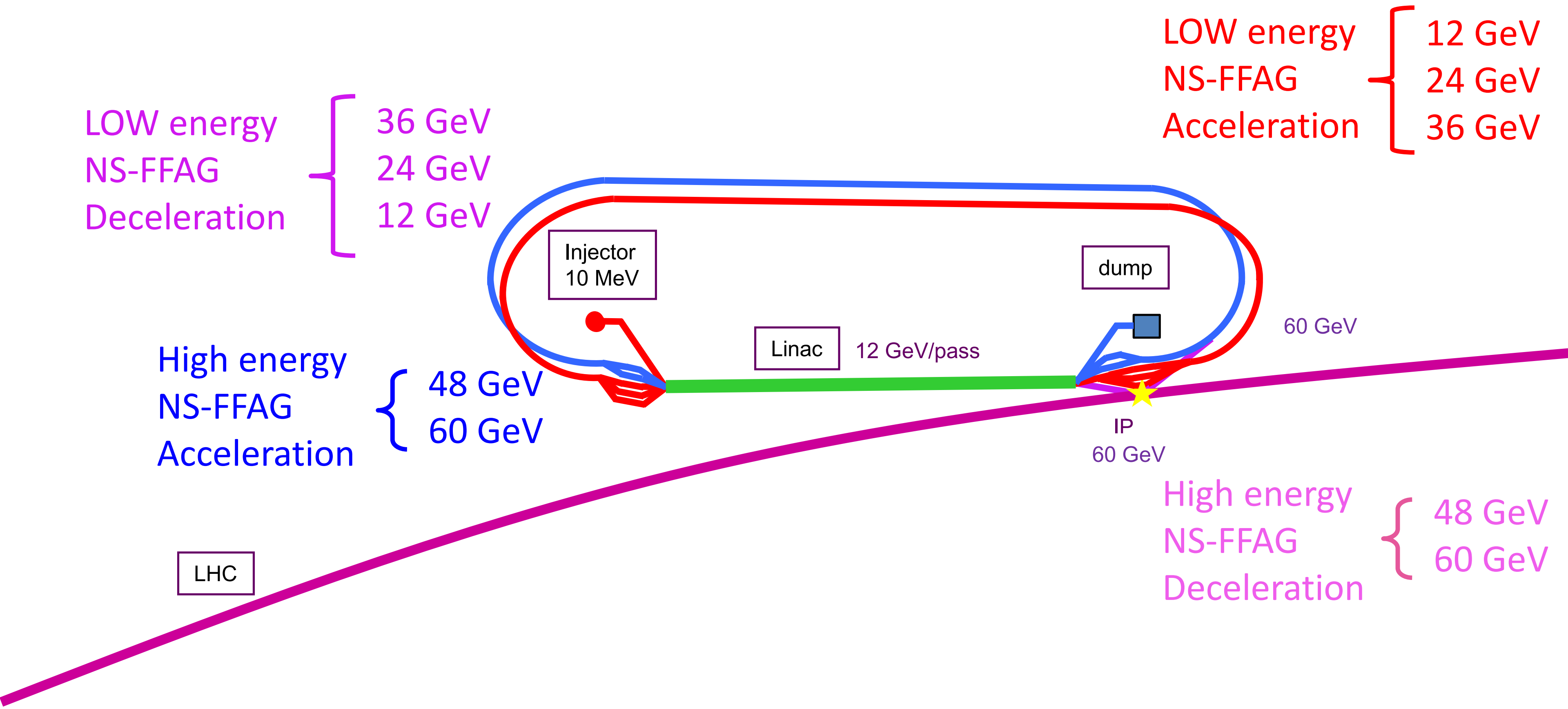
RECIRCULATOR COMPLEX

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

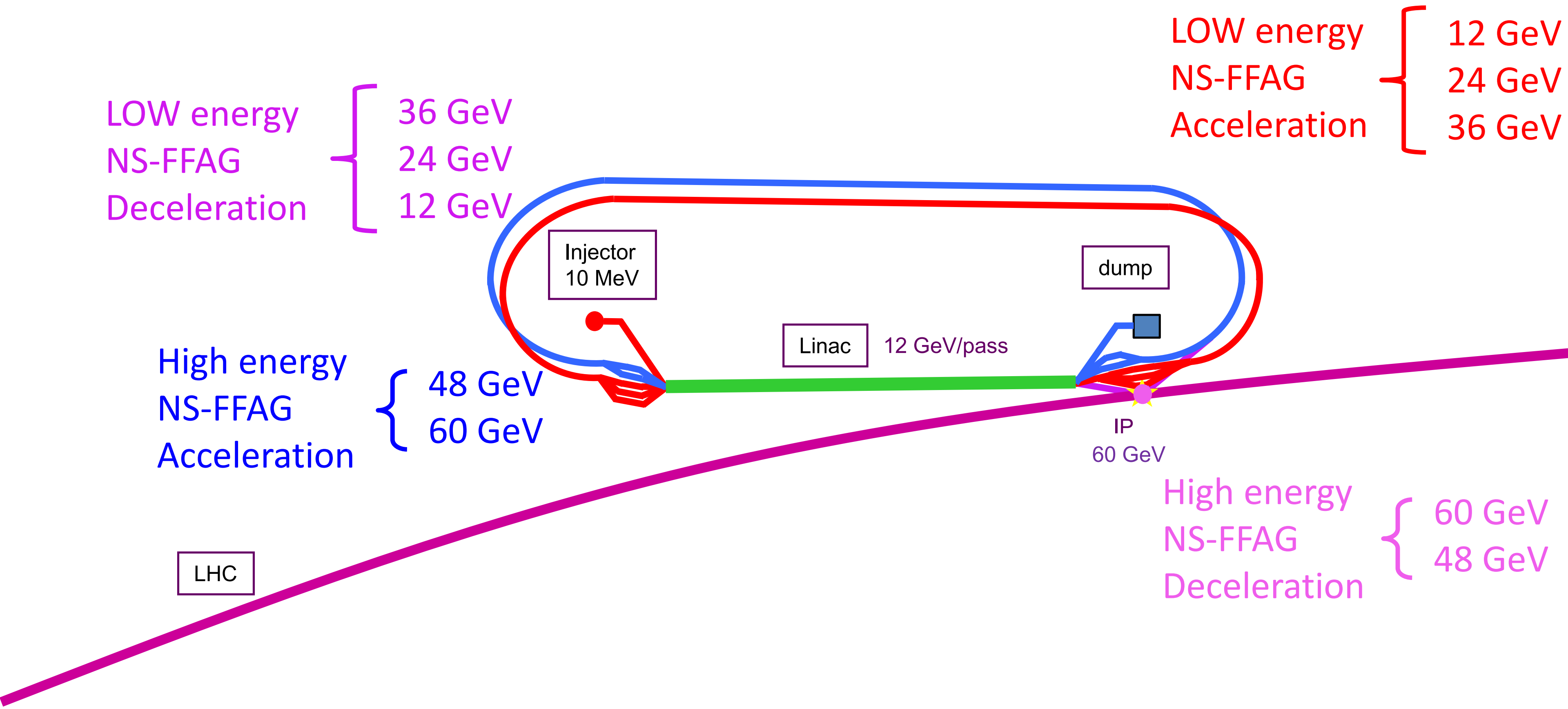
	PROTONS	ELECTRONS
Beam Energy [GeV]	7000	60
Luminosity [$10^{33}cm^{-2}s^{-1}$]	1	1
Normalized emittance $\gamma\varepsilon_{x,y}$ [μm]	3.75	50
Beta Function $\beta^*_{x,y}$ [m]	0.10	0.12
rms Beam size $\sigma^*_{x,y}$ [μm]	7	7
rms Divergence $\sigma'_{x,y}$ [μrad]	70	58
Beam Current [mA]	(860) 430	6.6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

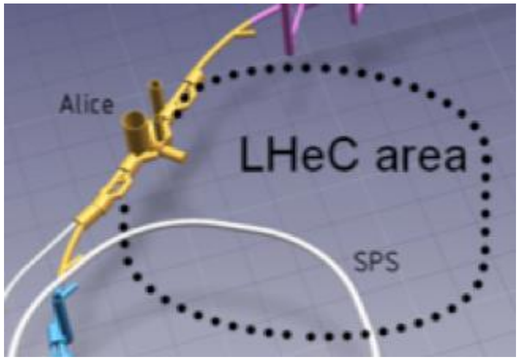
NS-FFAG LHeC Recirculator with 12 GeV ER

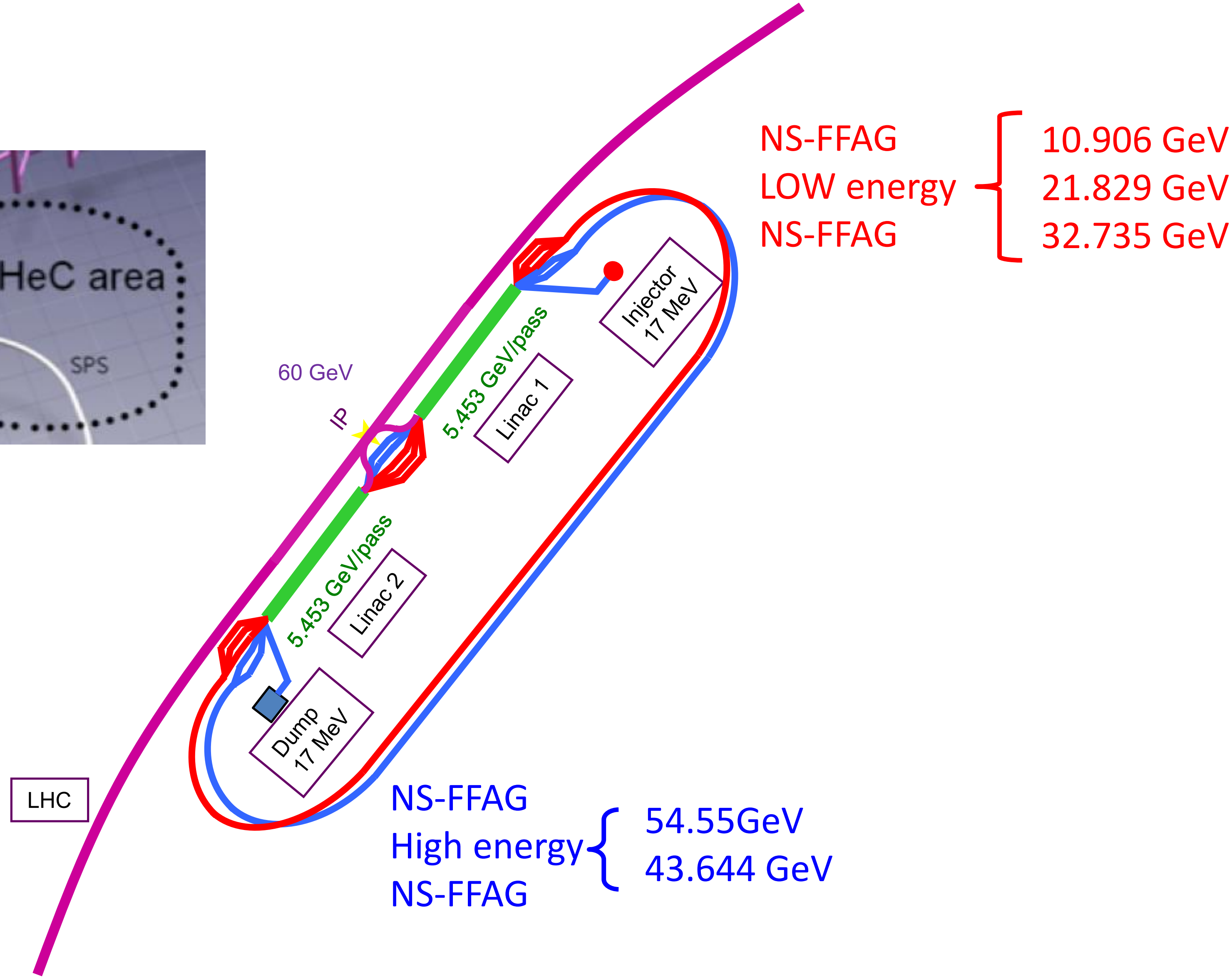


NS-FFAG LHeC Recirculator with 12 GeV ER

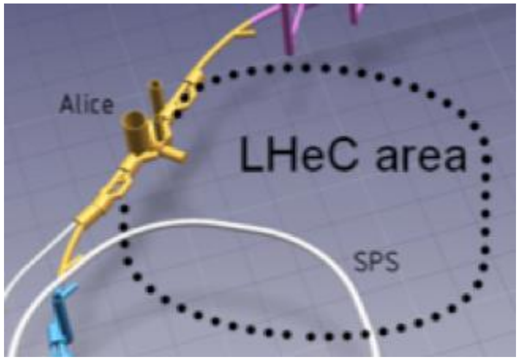


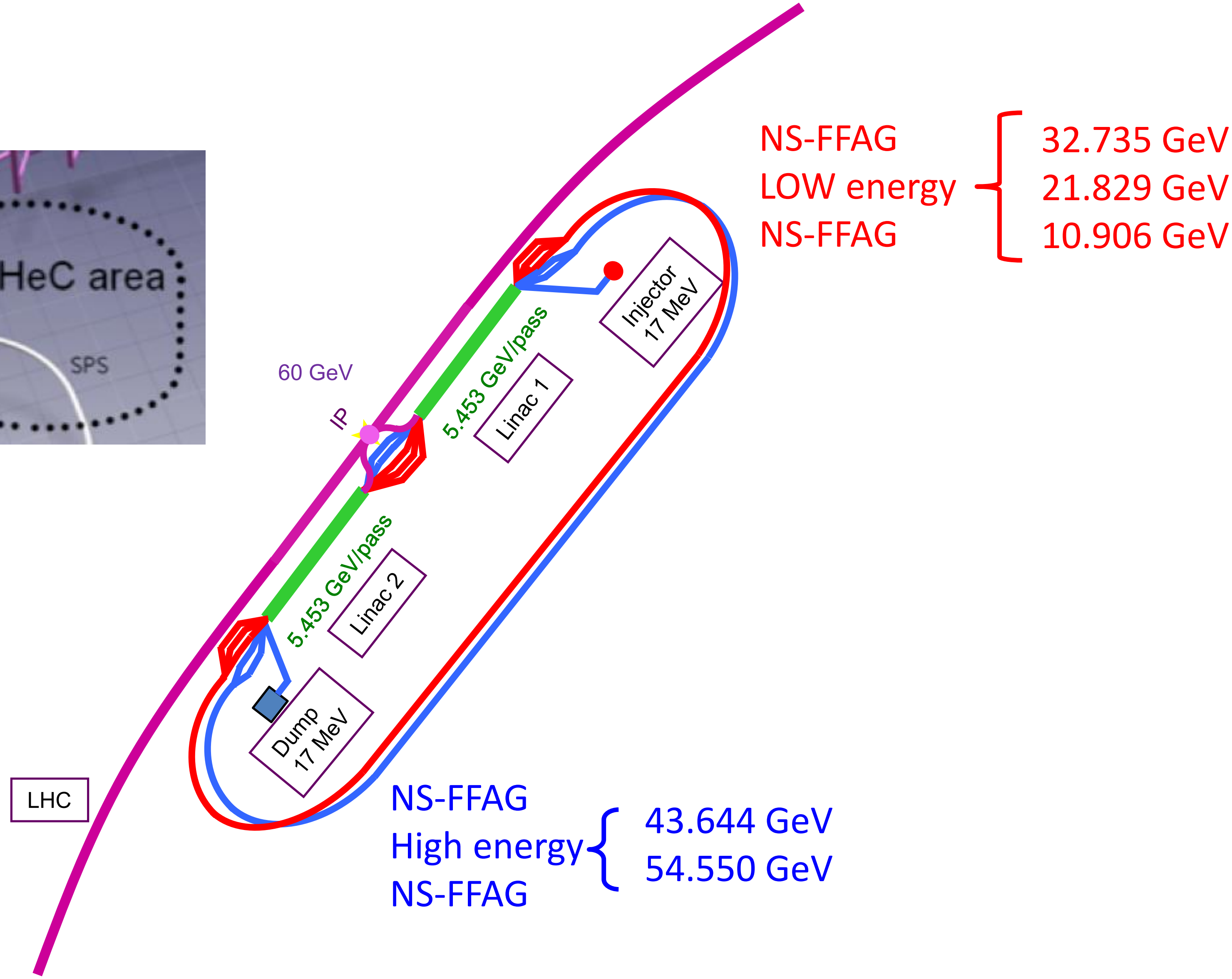
NS-FFAG LHeC Recirculator with ER





NS-FFAG LHeC Recirculator with ER





OUTLINE: NS-FFAG for eRHIC and LHeC

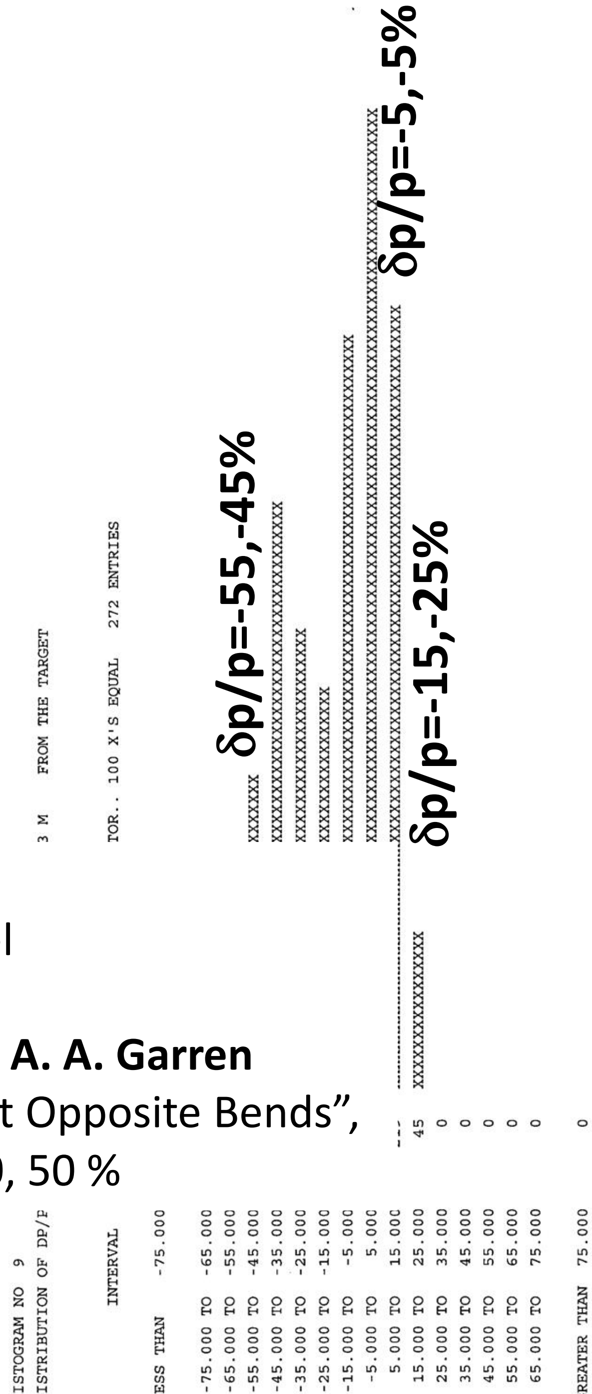
- WHAT IS Non-Scaling FFAG?
- Orbits in NS-FFAG cells
- Tune dependence on momentum
- Path length dependence on energy
- Straight section design
- By pass design

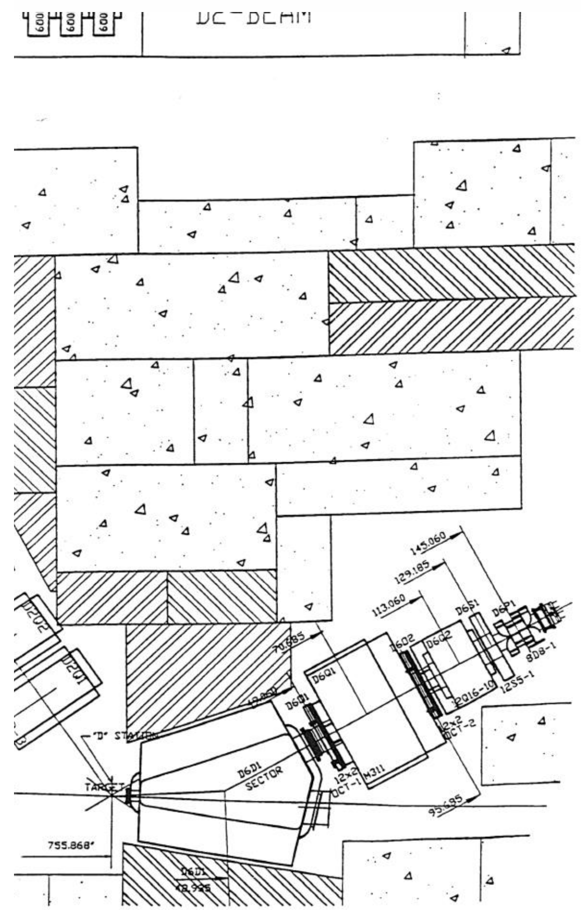
The AGS NS- ... uon Channel

match the degraded ...
alternating A and B ...
the field which, ac...
1 1/2 strong focuss...
reverse the dispers...
ly cancel it.

...annel" set of
...ets was tuned for
...URTLE, would produce
...annel. This will
...D2 will approximate-

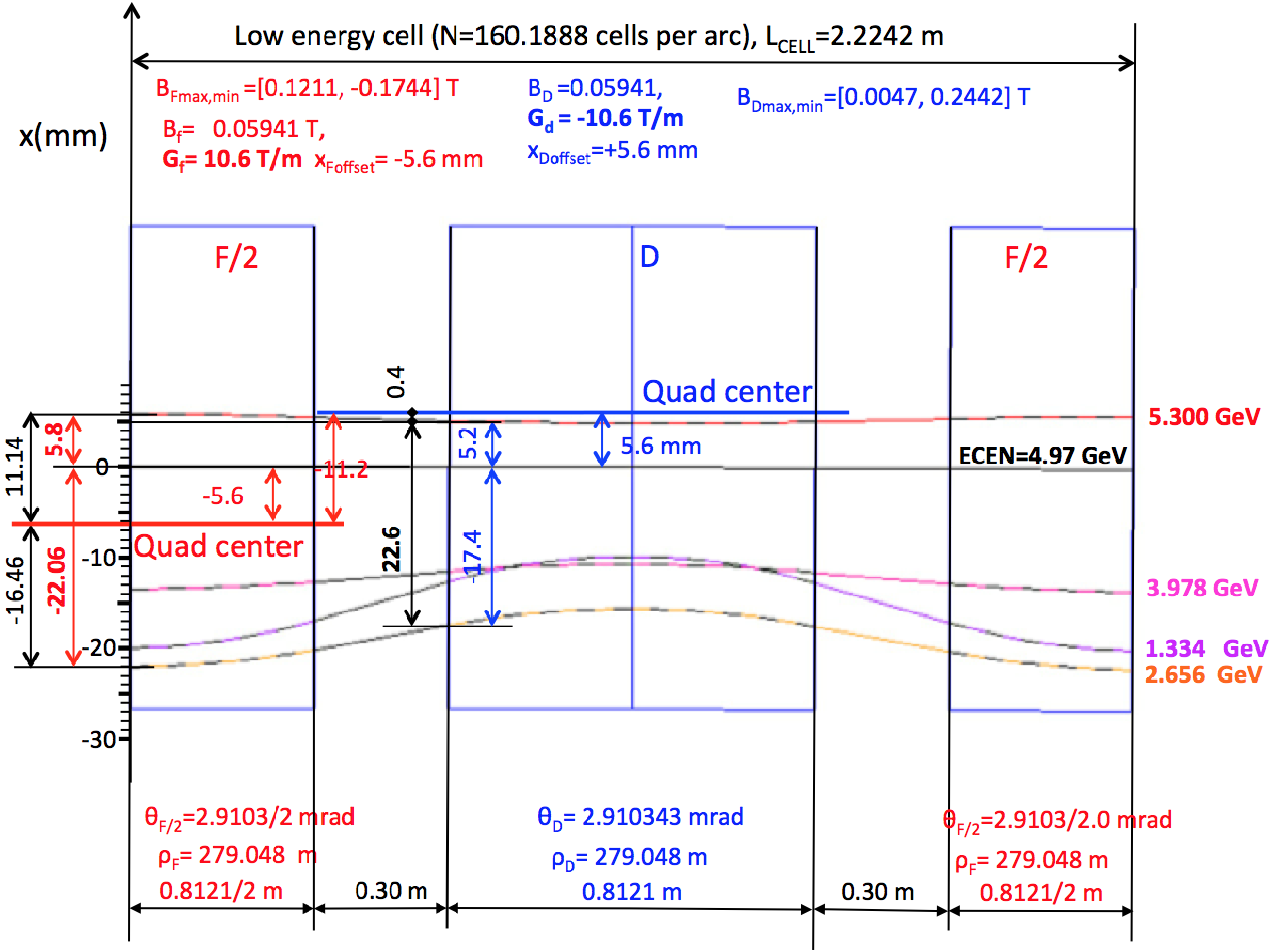
$\delta p/p$= -55, 25 %



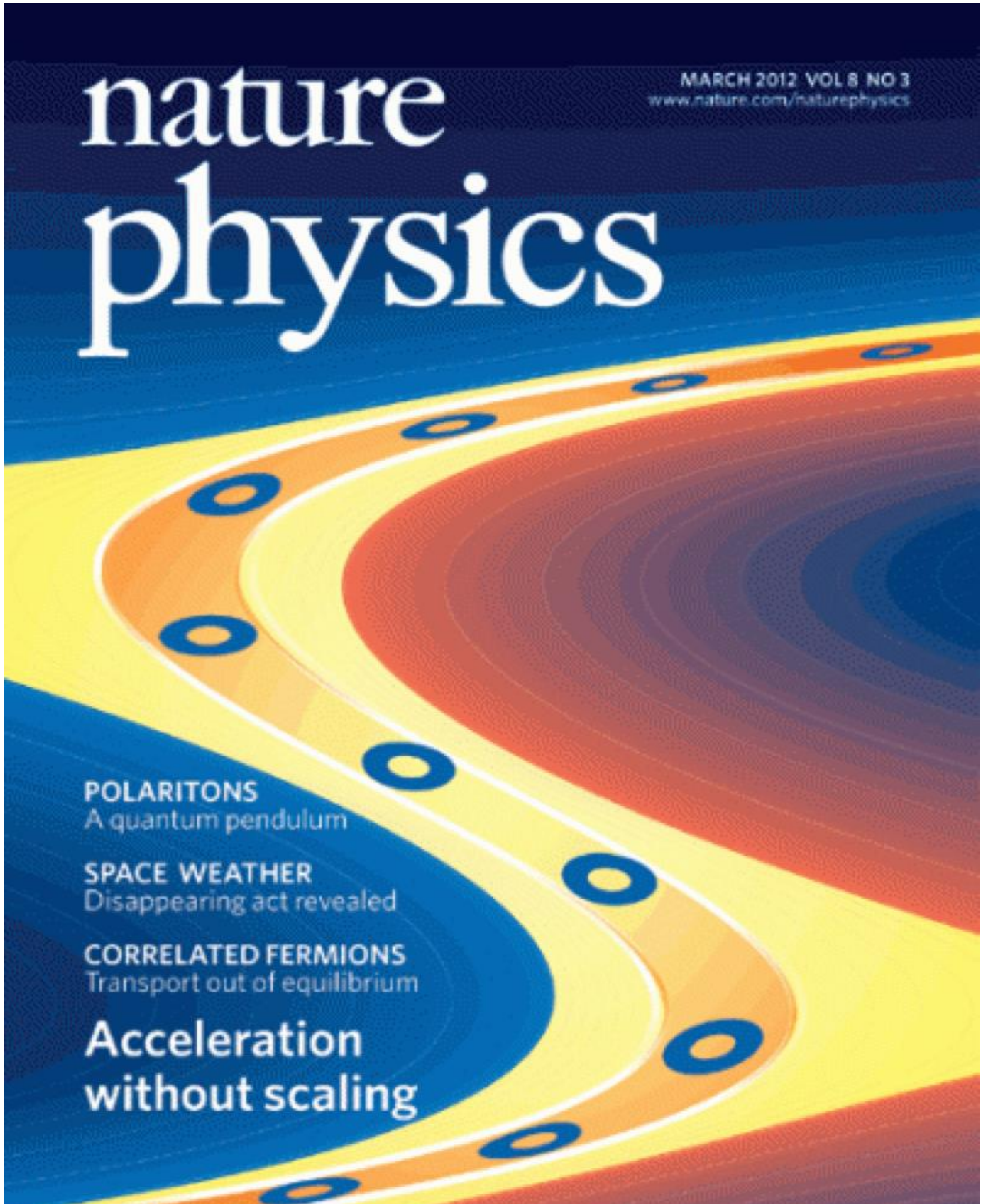


NIM 179**(1981)** 95-103
TRIUMF Vancouver π-μ channel

D. Trbojevic, E.D. Courant, and A. A. Garren
Fall 1999,"FFAG Lattice Without Opposite Bends",
HEMC'99 Workshop, $\delta p/p$= -30, 50 %



Low energy cell (N=160.1888 cells per arc), L_CELL=2.2242 m
B_Fmax,min =[0.1211, -0.1744] T
B_f= 0.05941 T,
G_f= 10.6 T/m x_Foffset= -5.6 mm
B_D =0.05941,
G_d = -10.6 T/m
x_Doffset=+5.6 mm
B_Dmax,min=[0.0047, 0.2442] T
x(mm)
F/2
D
F/2
Quad center
0.4
5.300 GeV
11.14
5.8
0
-11.2
5.2
5.6 mm
ECEN=4.97 GeV
-5.6
Quad center
22.6
-17.4
-16.46
-22.06
-10
3.978 GeV
-20
1.334 GeV
2.656 GeV
-30
θ_F/2=2.9103/2 mrad
ρ_F= 279.048 m
0.8121/2 m
θ_D= 2.910343 mrad
ρ_D= 279.048 m
0.8121 m
θ_F/2=2.9103/2.0 mrad
ρ_F= 279.048 m
0.8121/2 m
0.30 m
0.30 m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MARCH 2012 VOL 8 NO 3
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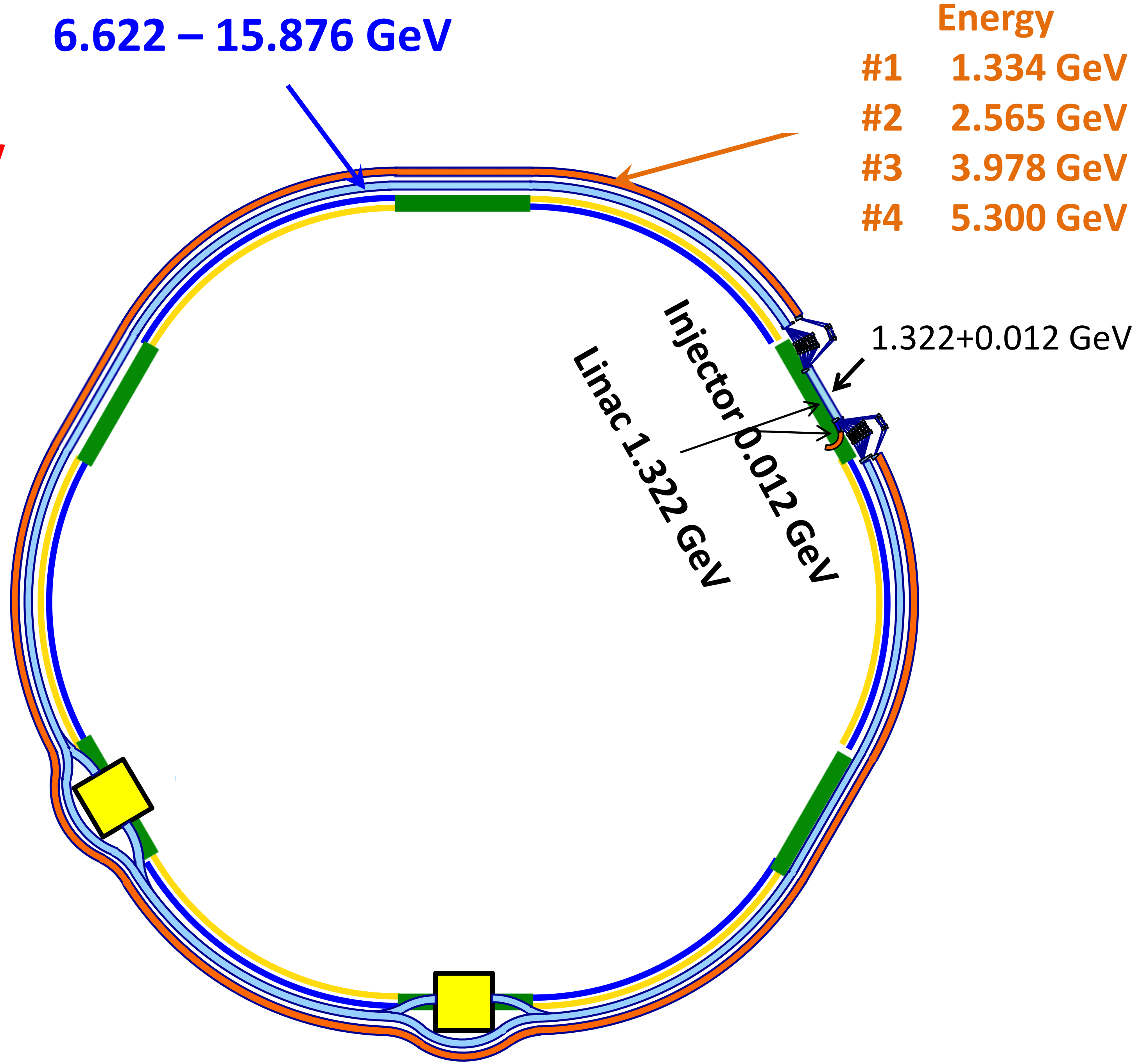
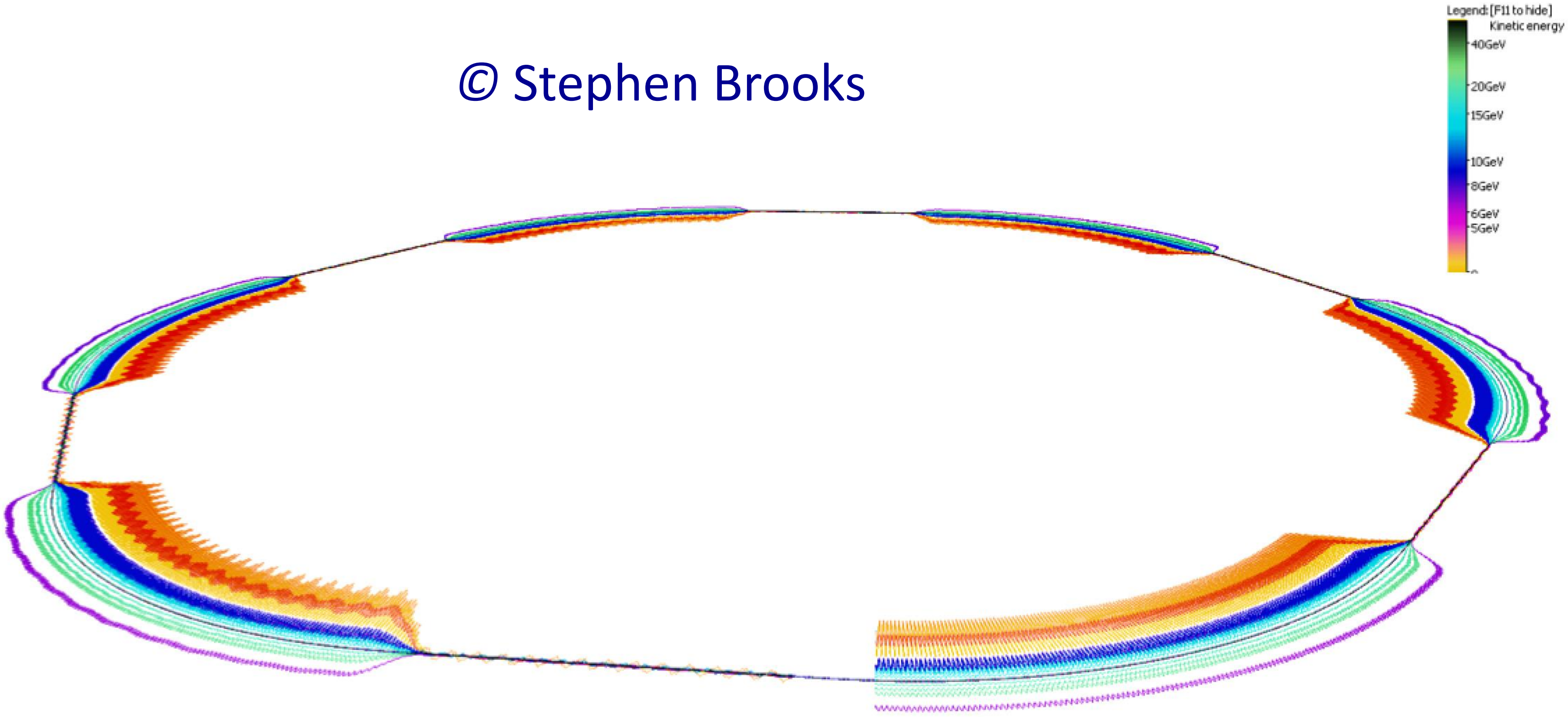
POLARITONS
A quantum pendulum
SPACE WEATHER
Disappearing act revealed
CORRELATED FERMIONS
Transport out of equilibrium
Acceleration without scaling

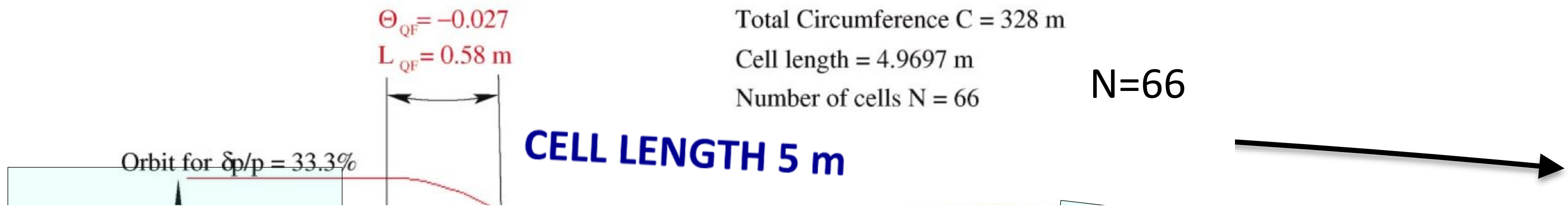
Option #2 Energy
10 mA
Linac 1.322 GeV
#1 6.622 GeV
#2 7.944 GeV
#3 9.266 GeV
#4 10.588 GeV
#5 11.910 GeV
#6 13.232 GeV
#7 14.554 GeV
#8 15.876 GeV
#9 17.198 GeV
#10 18.520 GeV
#11 19.842 GeV
#12 21.164 GeV



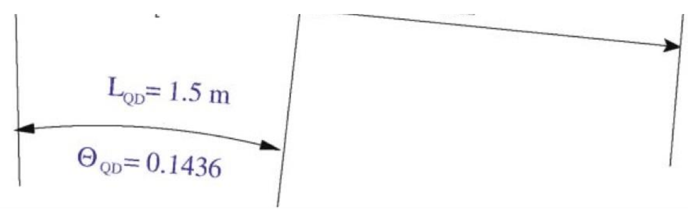
eRHIC FFAG Rings in Perspective



Non-scaling FFAG for Muon Acceleration



- Extremely strong focusing with a small dispersion function
- Tunes vary
- Orbit offsets are small
- Magnets are small
- Large energy acceptance

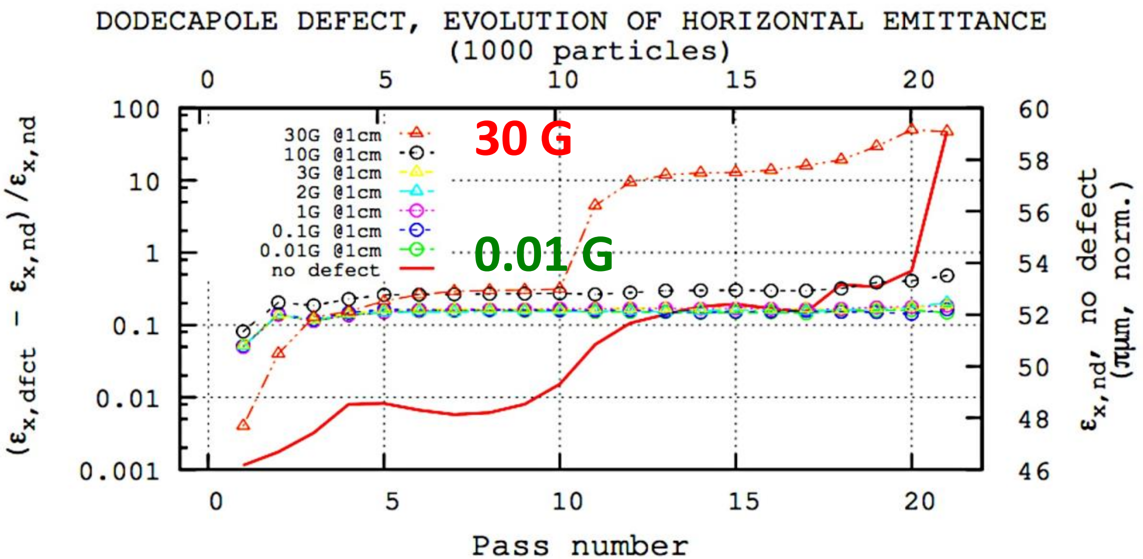


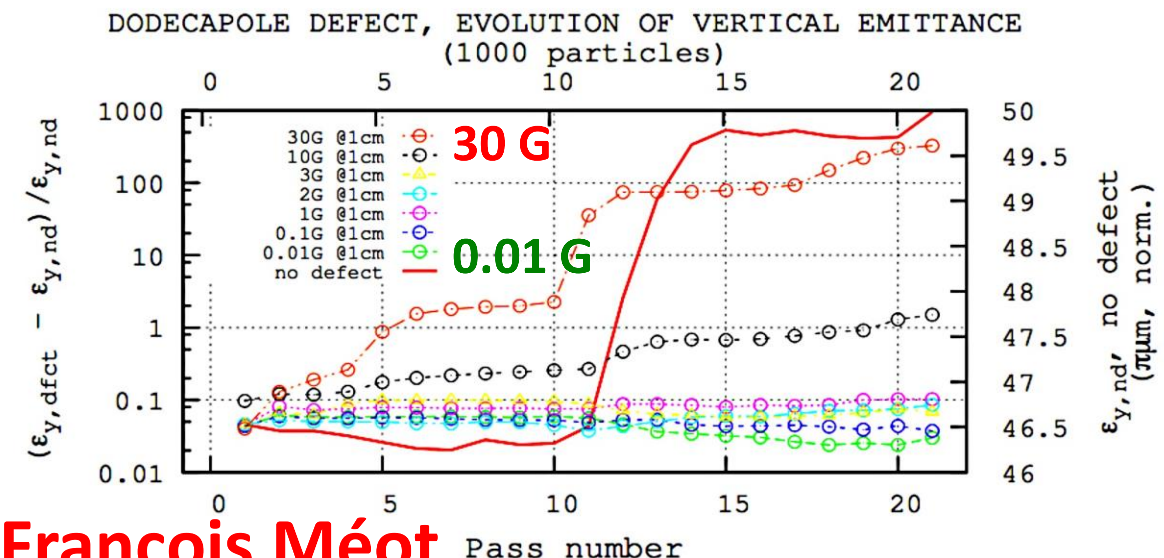
PHYSICAL REVIEW SPECIAL TOPICS - ACCELERATORS AND BEAMS **8**, 050101 (2005)

Design of a nonscaling fixed field alternating gradient accelerator

D. Trbojevic,* E. D. Courant, and M. Blaskiewicz
BNL, Upton, New York 11973, USA

Defect value, following from prior study of emittance growth over single ring turn : ± 3 Gauss at 1 cm





François Méot

The prototype of eRHIC will be built at Cornell

Some of the most important risk items for eRHIC:

1) FFAG loops with a factor of 4 in momentum aperture.
   a) Precision, reproducibility, alignment during magnet and girder production.
   b) Stability of magnetic fields in a radiation environment.
   c) Matching and correction of multiple simultaneous orbits.
   d) Matching and correction of multiple simultaneous optics.
   e) Path length control for all orbits.

2) Multi-turn ERL operation with a large number of turns.
   a) HOM damping.
   b) BBU limits.
   c) LLRF control.
   d) ERL startup from low-power beam.

76 – 286 MeV NS-FFAG Cornell Lattice

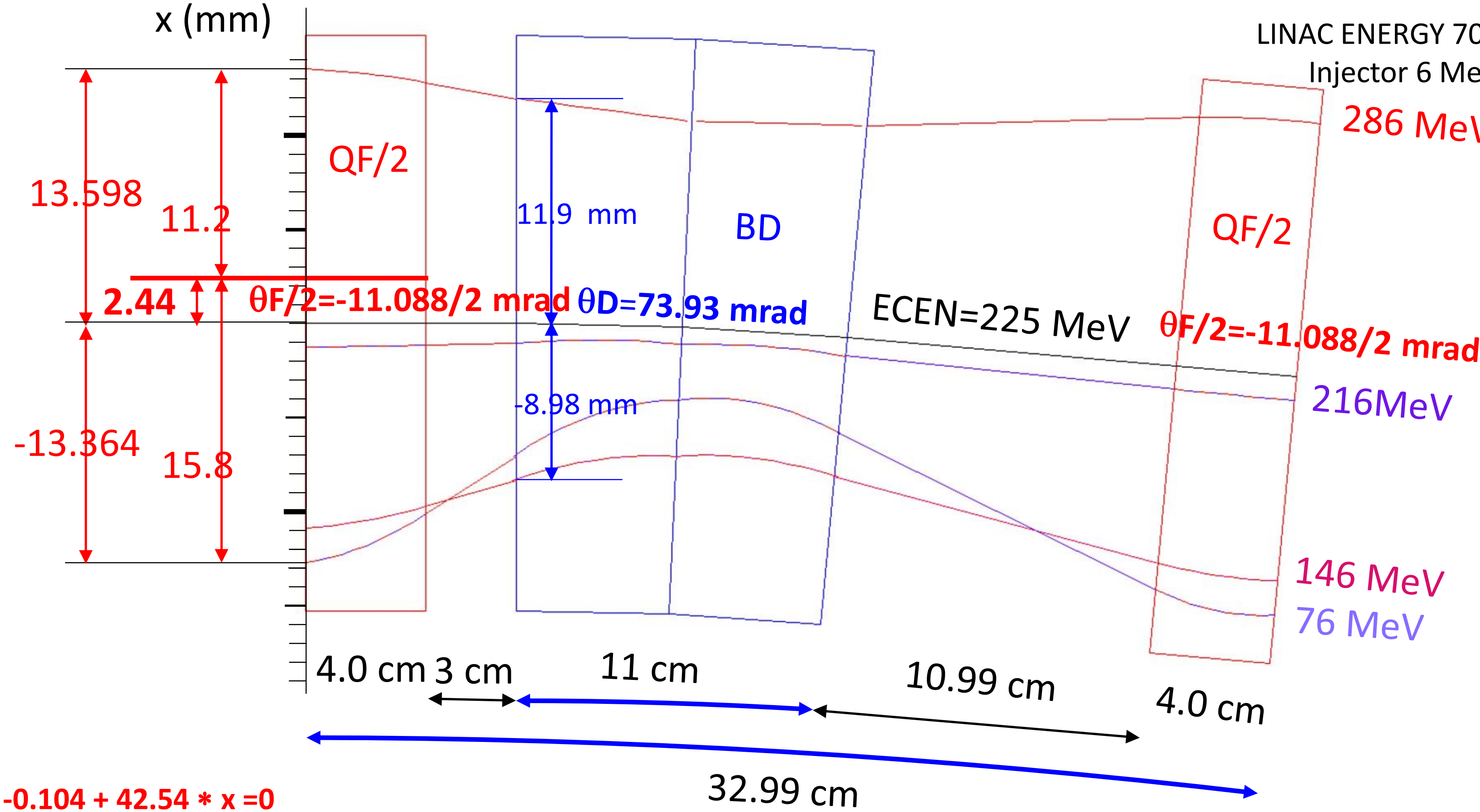
100 cells : Orbits and magnets in the 10.5 m diameter

GF = 42.54 T/m
ByF =-0.104 T

BFmin = -0.104 + 42.54* (-13.364 mm) = -0.673 T
BFmax= -0.104 + 42.54 * (13.598 mm) = 0.4745 T

GD = -27.493 T/m
ByD = 0.5044 T

BDmin= 0.504+(-27.49*11.9 mm)=0.177 T
BDmax= 0.504+(-27.49*-8.98mm) =0.751 T

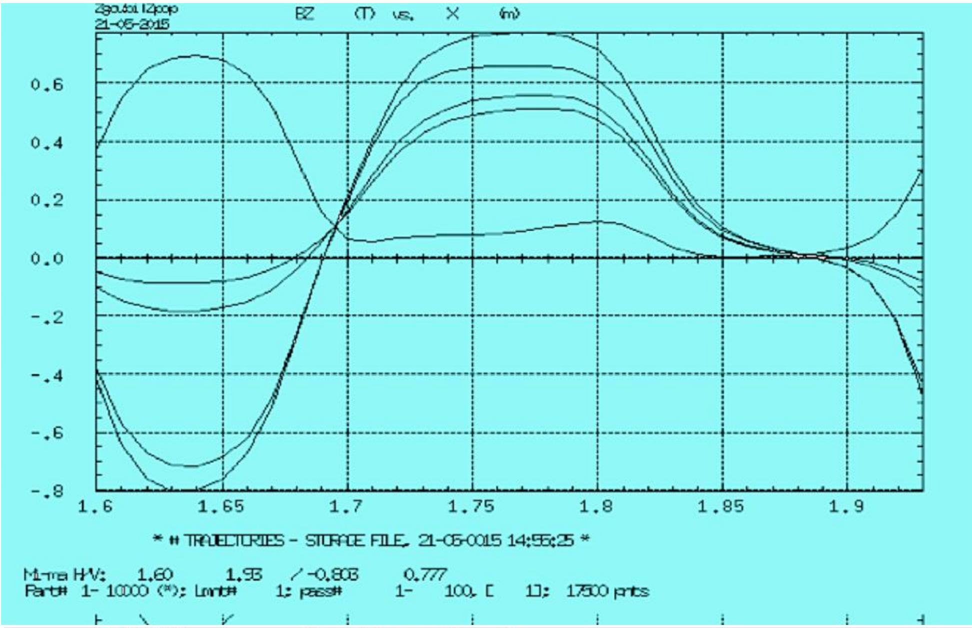


BF= -0.104 + 42.54 * x =0
x = 0.104/42.54 = 2.44 mm

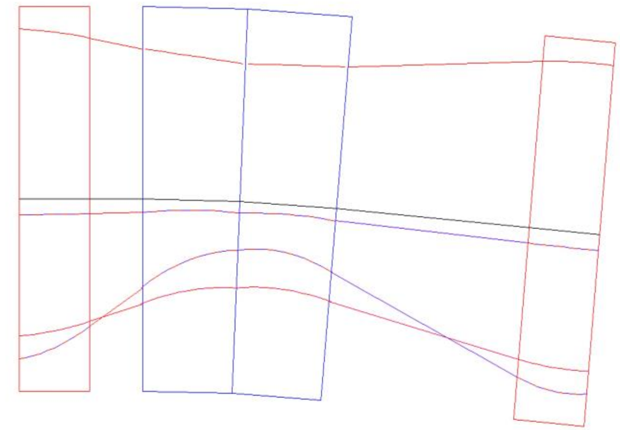
BD=0.504 + (-27.493) x = 0
x = + 18.331 mm

OPERA cell is QF-QD-drift. Axis is straight.

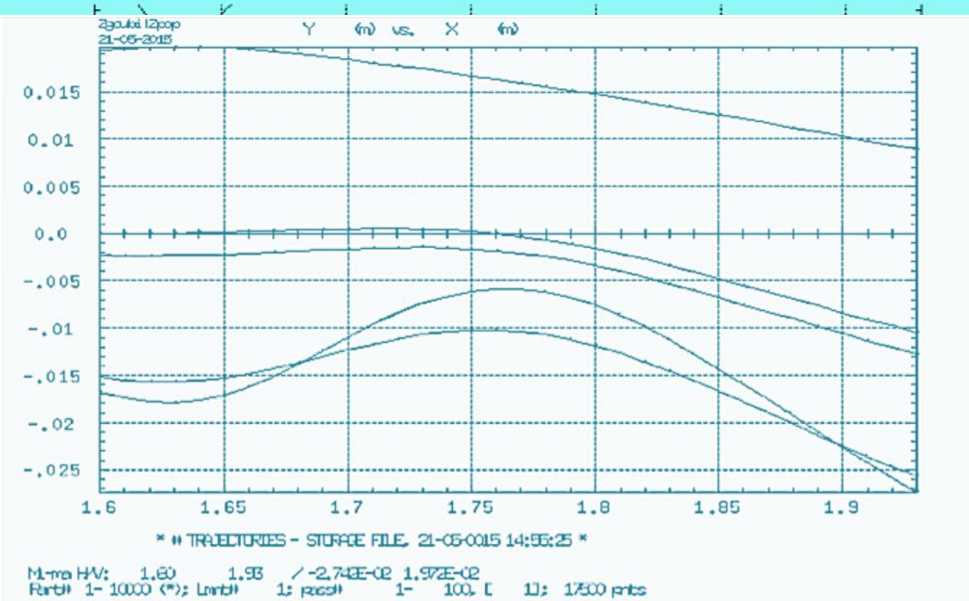
E = 76, 146, 216, 225 (reference) 286 MeV



FIELD

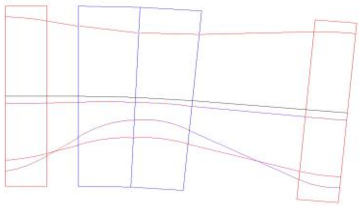


From Francois Meot and Nick Tsoupas

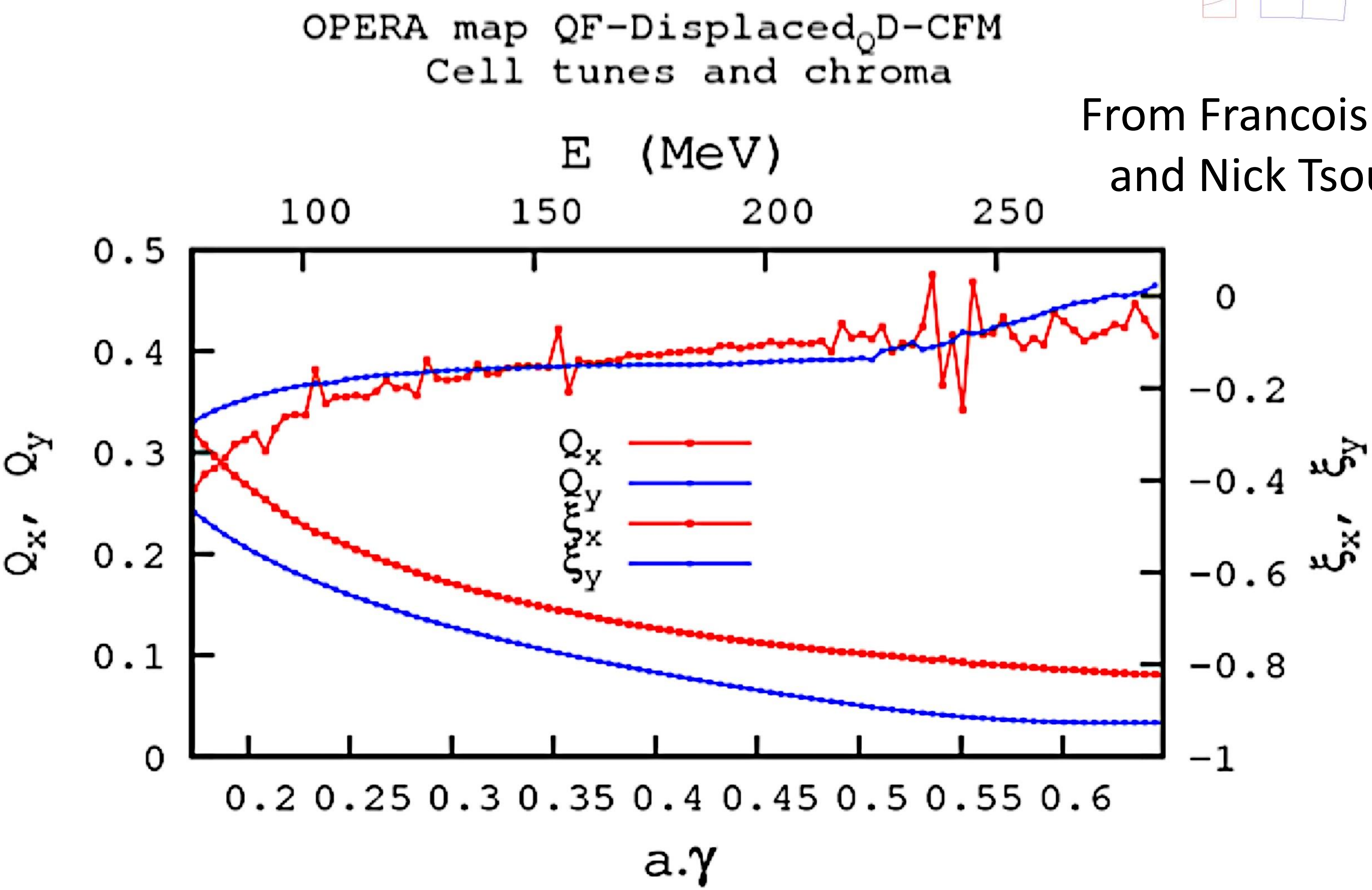


TRAJECTORIES

OPERA cell is QF-QD-drift. Axis is straight.



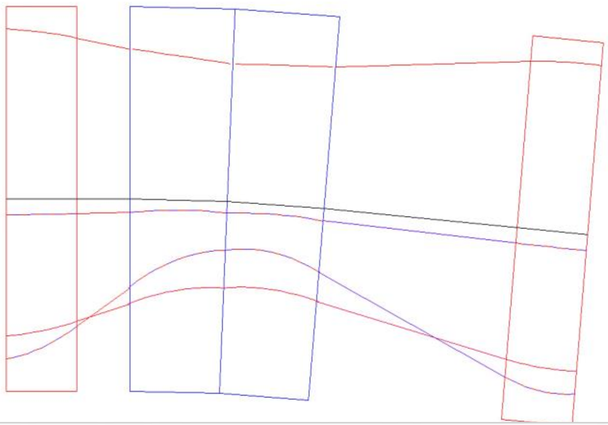
From Francois Meot and Nick Tsoupas

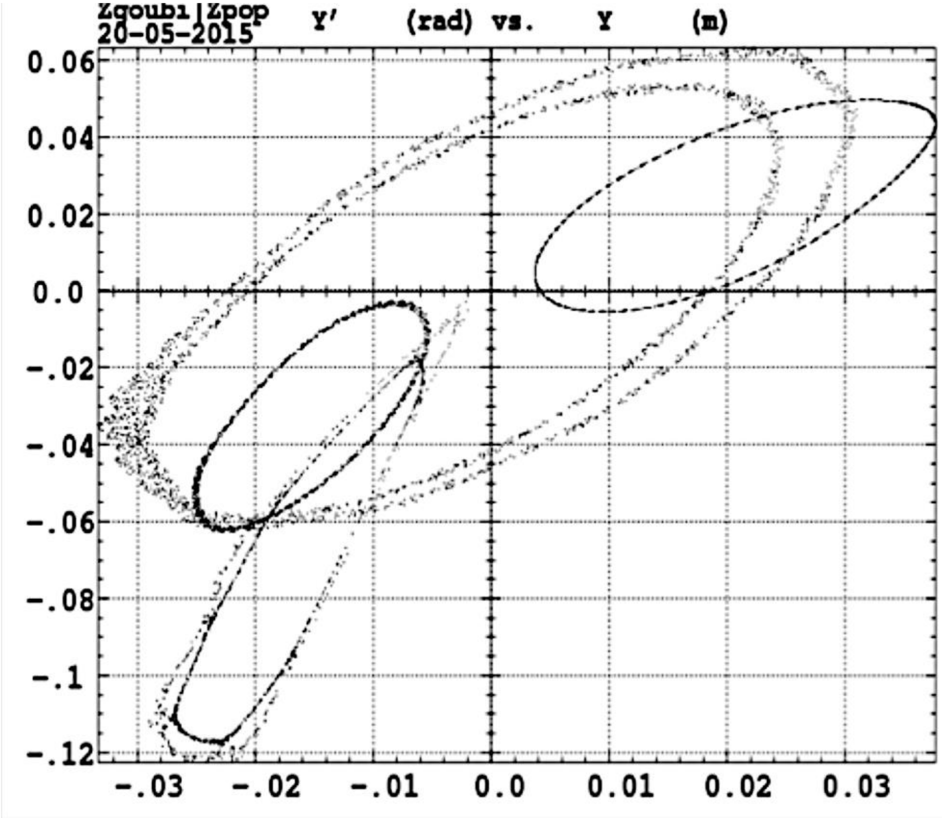


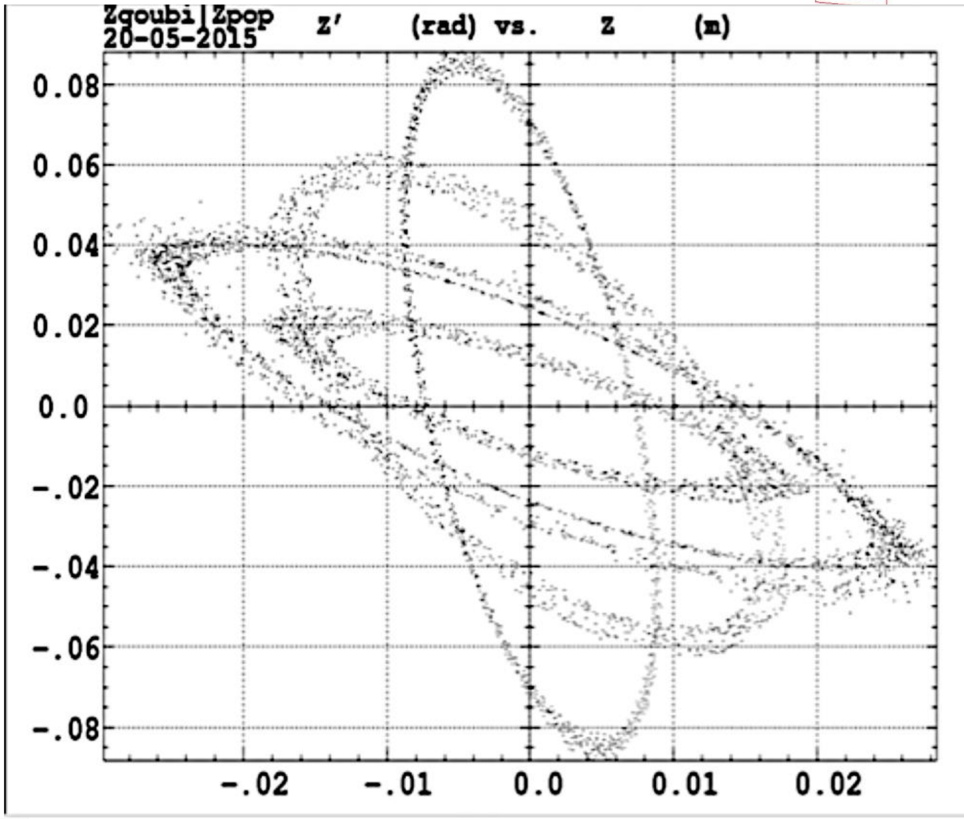
OPERA cell is QF-QD-drift. Axis is straight.

MAXIMAL STABLE AMPLITUDES, H, V :

From Francois Meot
and Nick Tsoupas

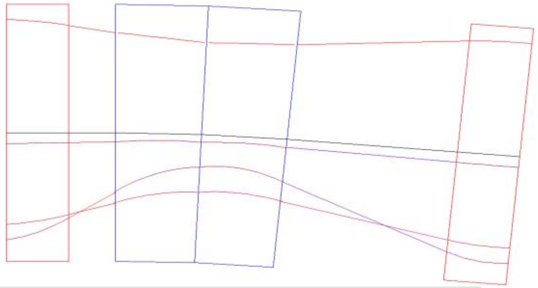




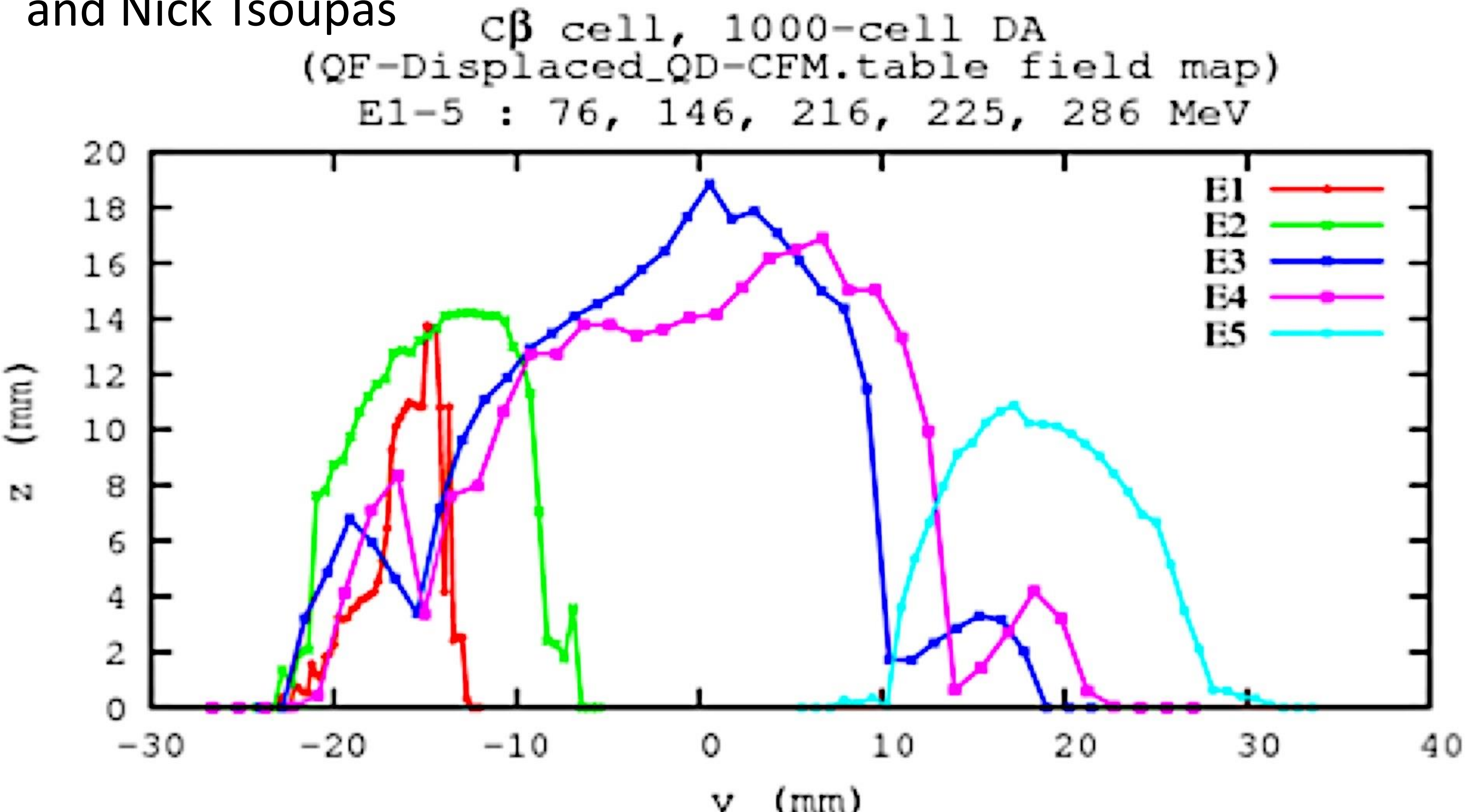


OPERA cell is QF-QD-drift. Axis is straight.

DYNAMICAL ACCEPTANCE

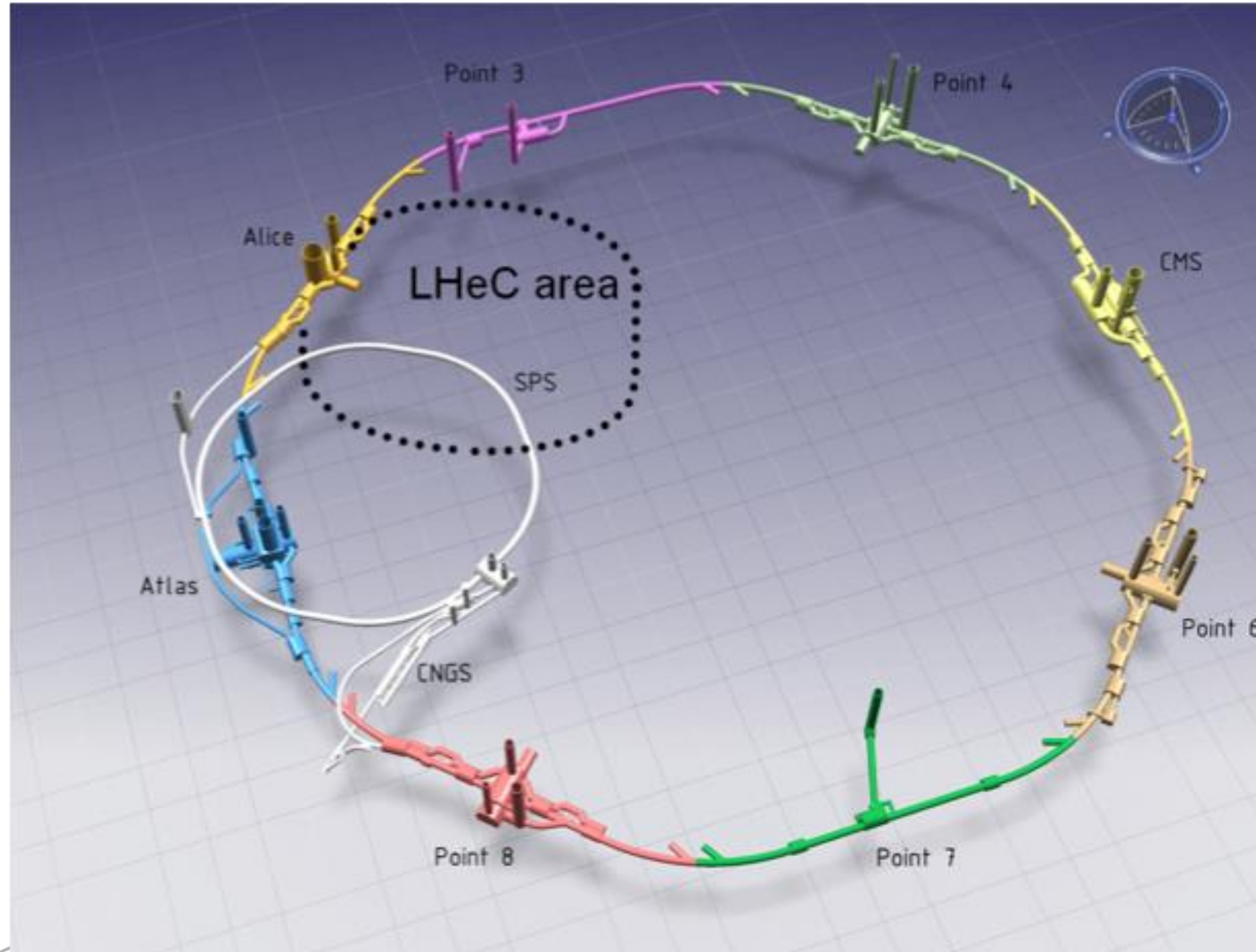


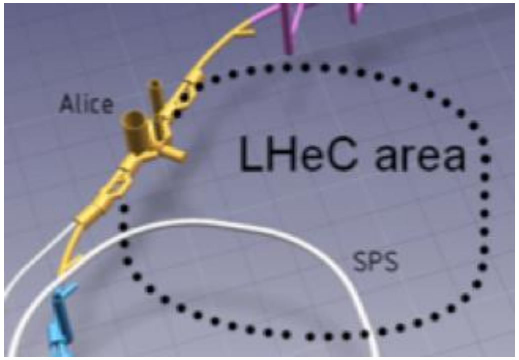
From Francois Meot and Nick Tsoupas

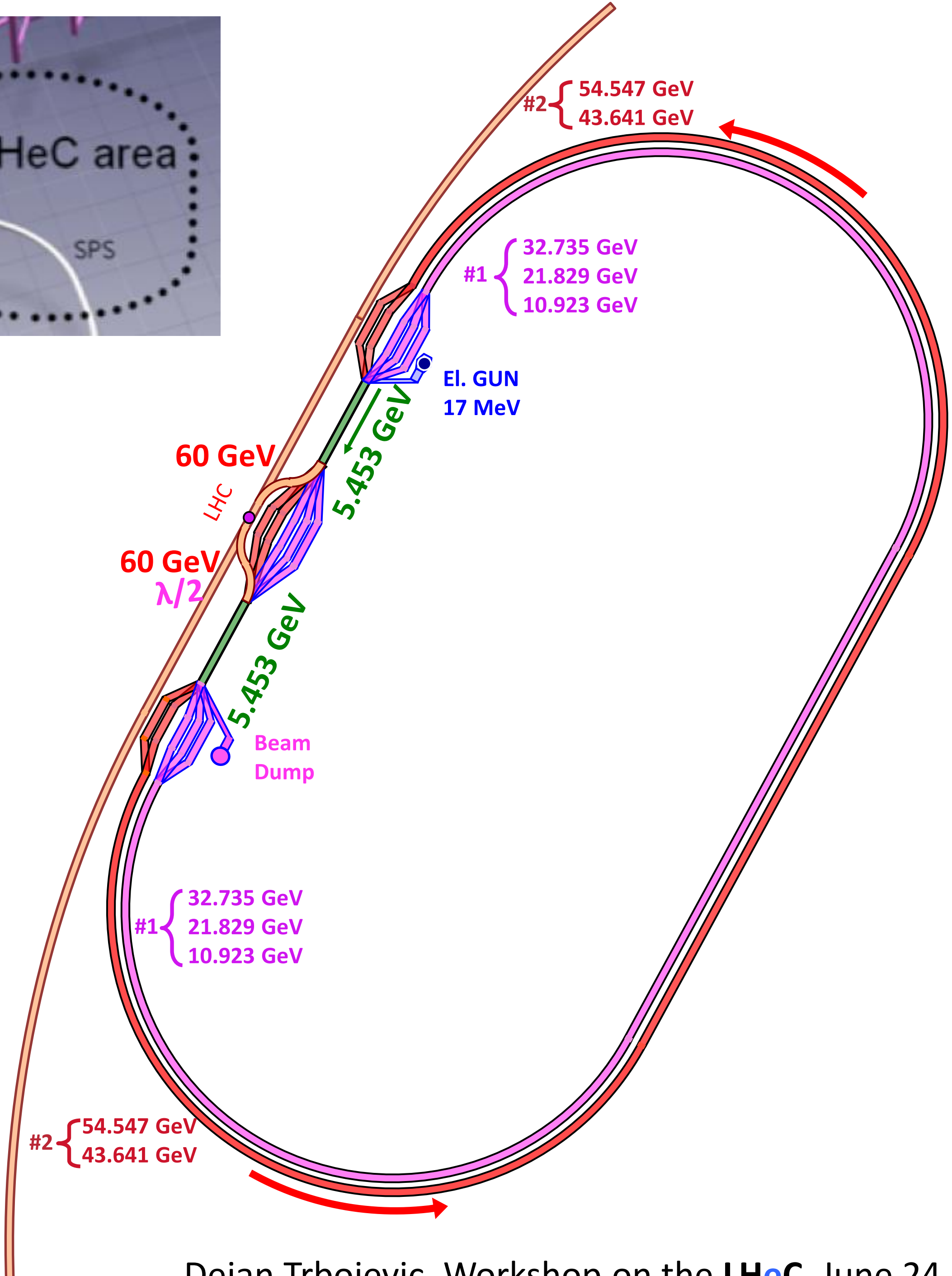


From Oliver Brüning

Layout of the LHeC-LHC-SPS





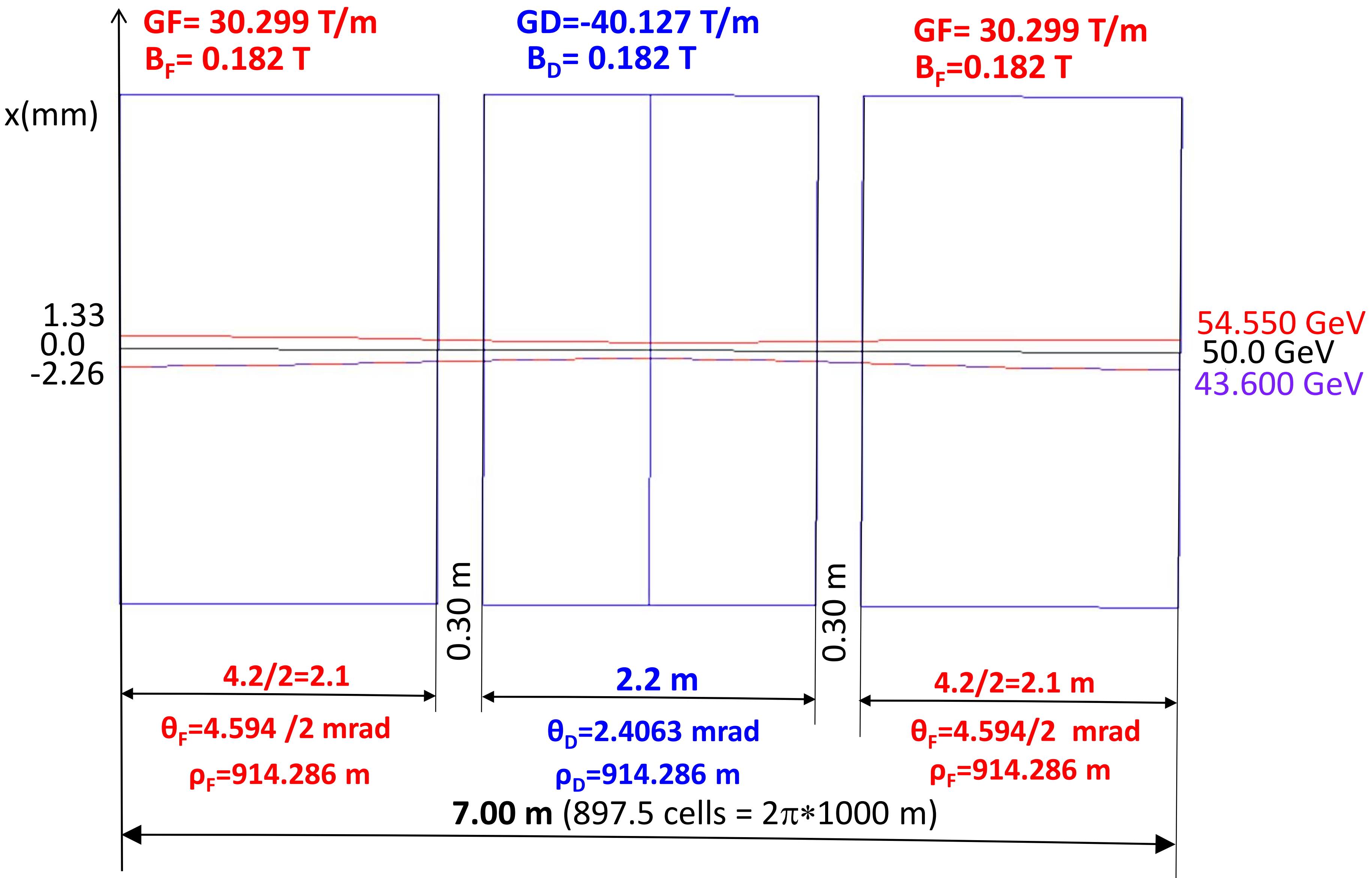


Thomas Roser's idea

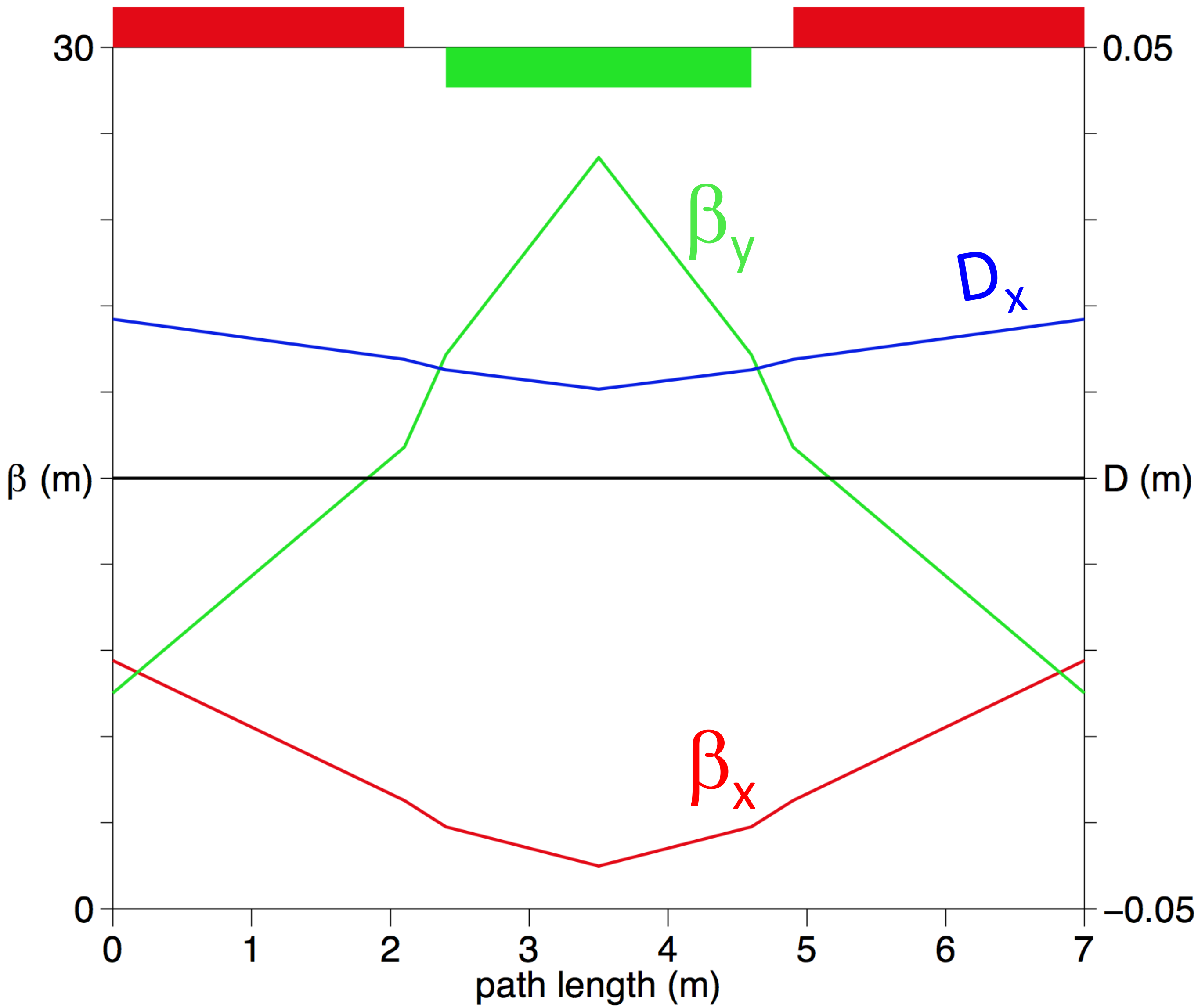
 # 1 NS-FFAG beam line:
3 passes for acceleration
3 passes for recovery

 # 2 NS-FFAG beam line:
2 passes for acceleration
2 passes for recovery

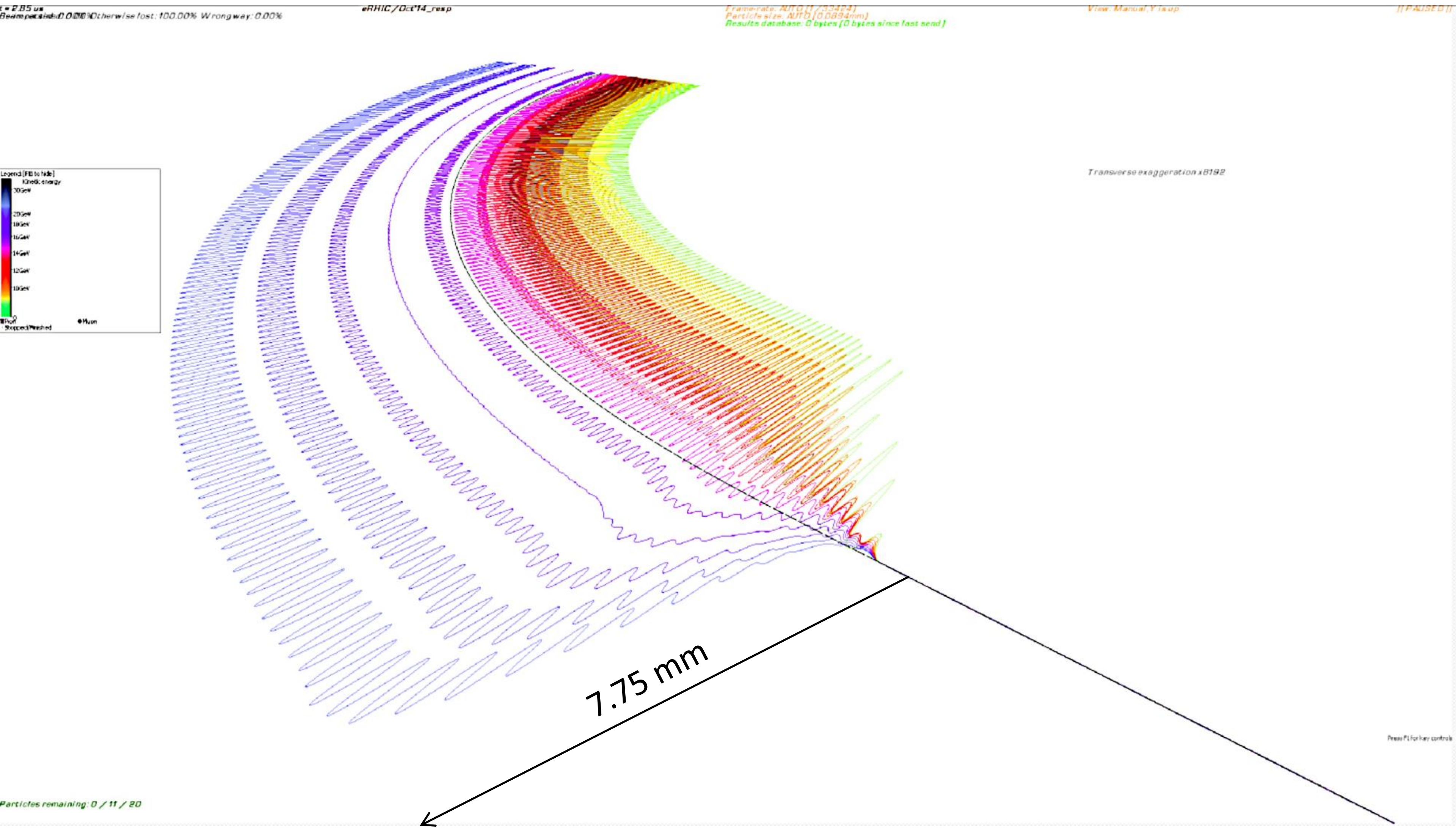
LHeC ARC– 2 x 5.453 GeV linacs:
Orbits in the basic cell of the High energy NS-FFAG **54.55 - 43.644** GeV



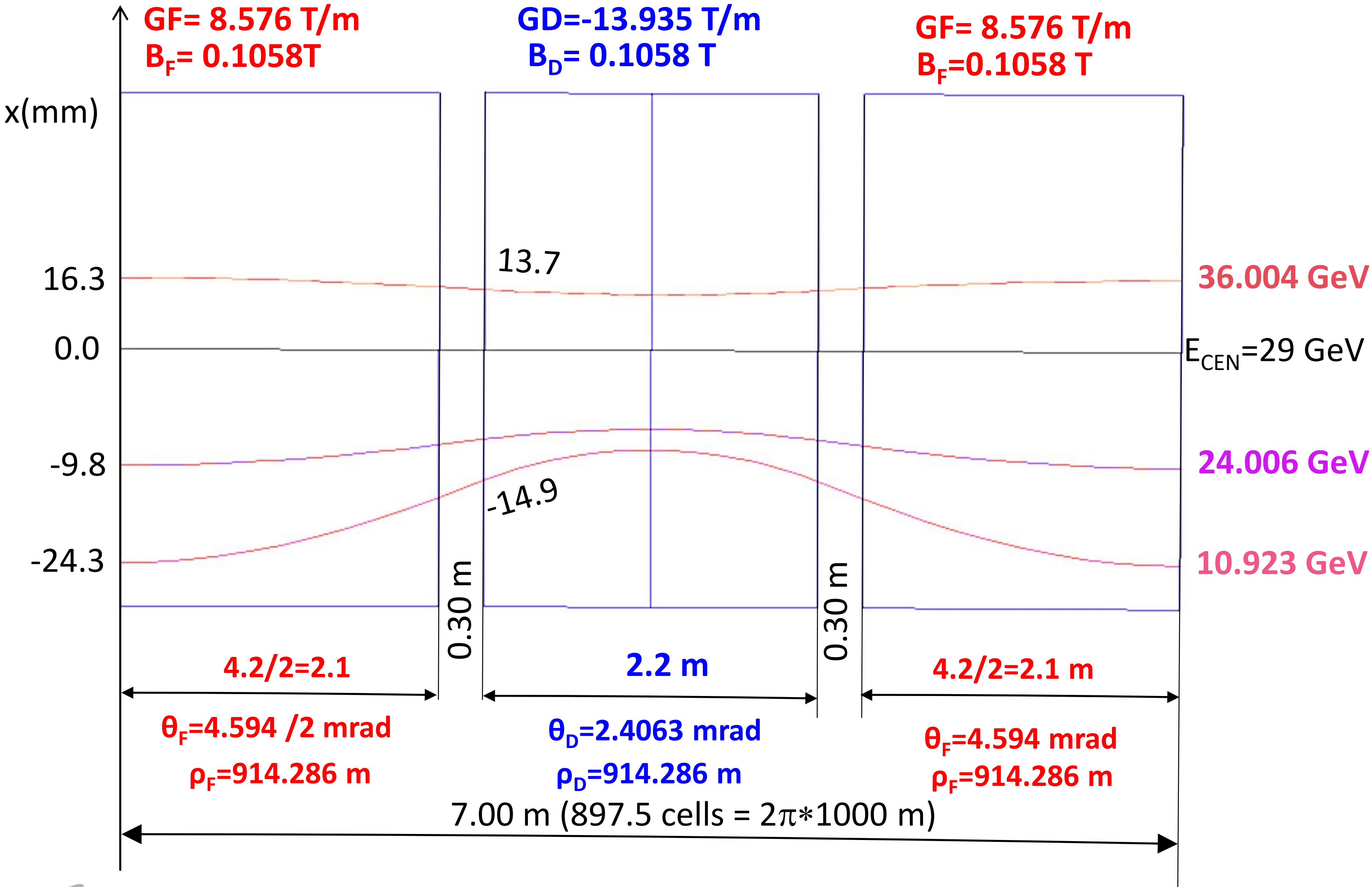
Betatron Functions for E_c=50 GeV, 2 x 5.453 GeV linacs



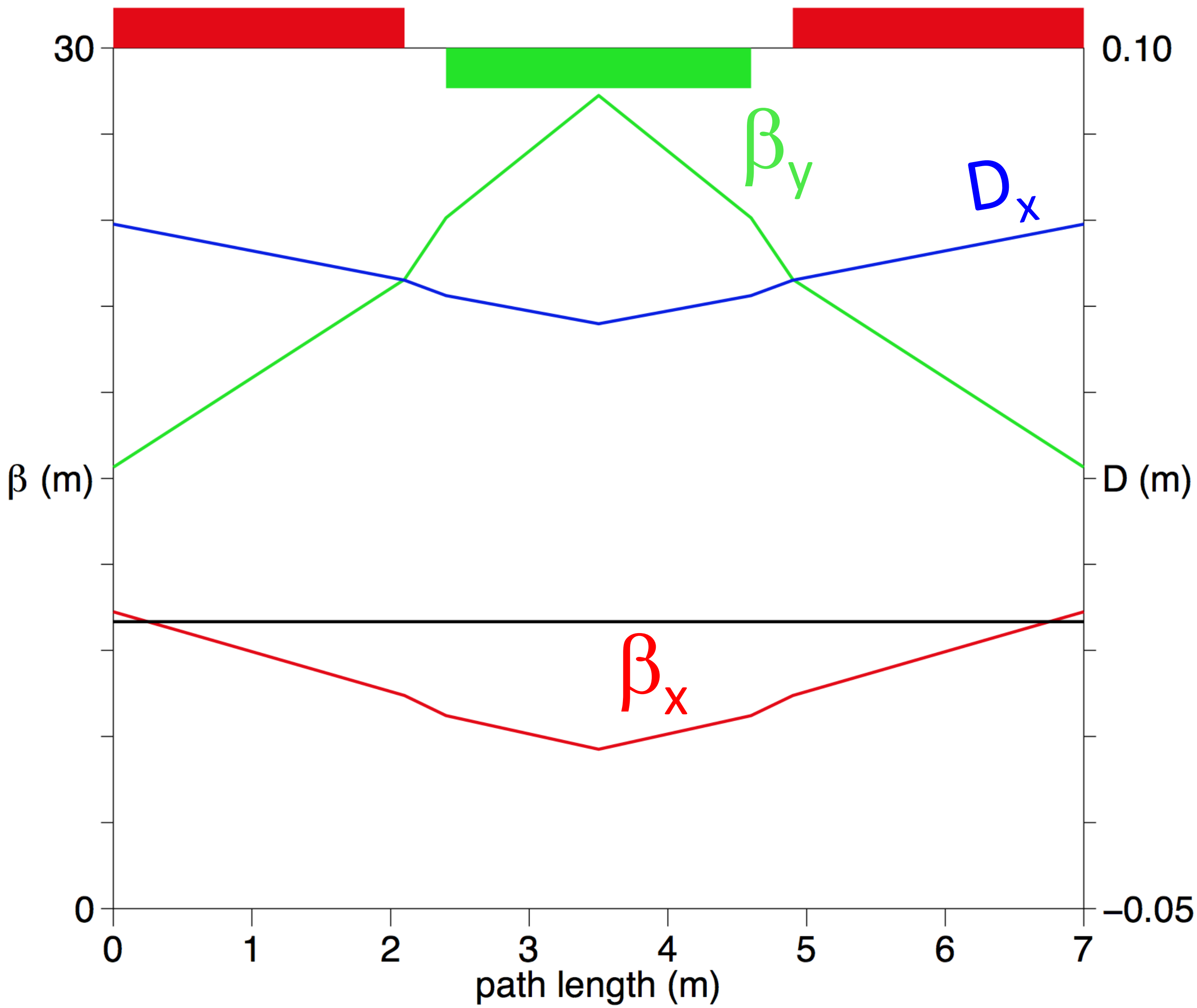
Merging FFAG arcs to the straight section in eRHIC



LHeC-ERL with 2 x 5.453 GeV linacs
Orbits in the basic cell of the Low energy NS-FFAG **10.923 - 32.735** GeV



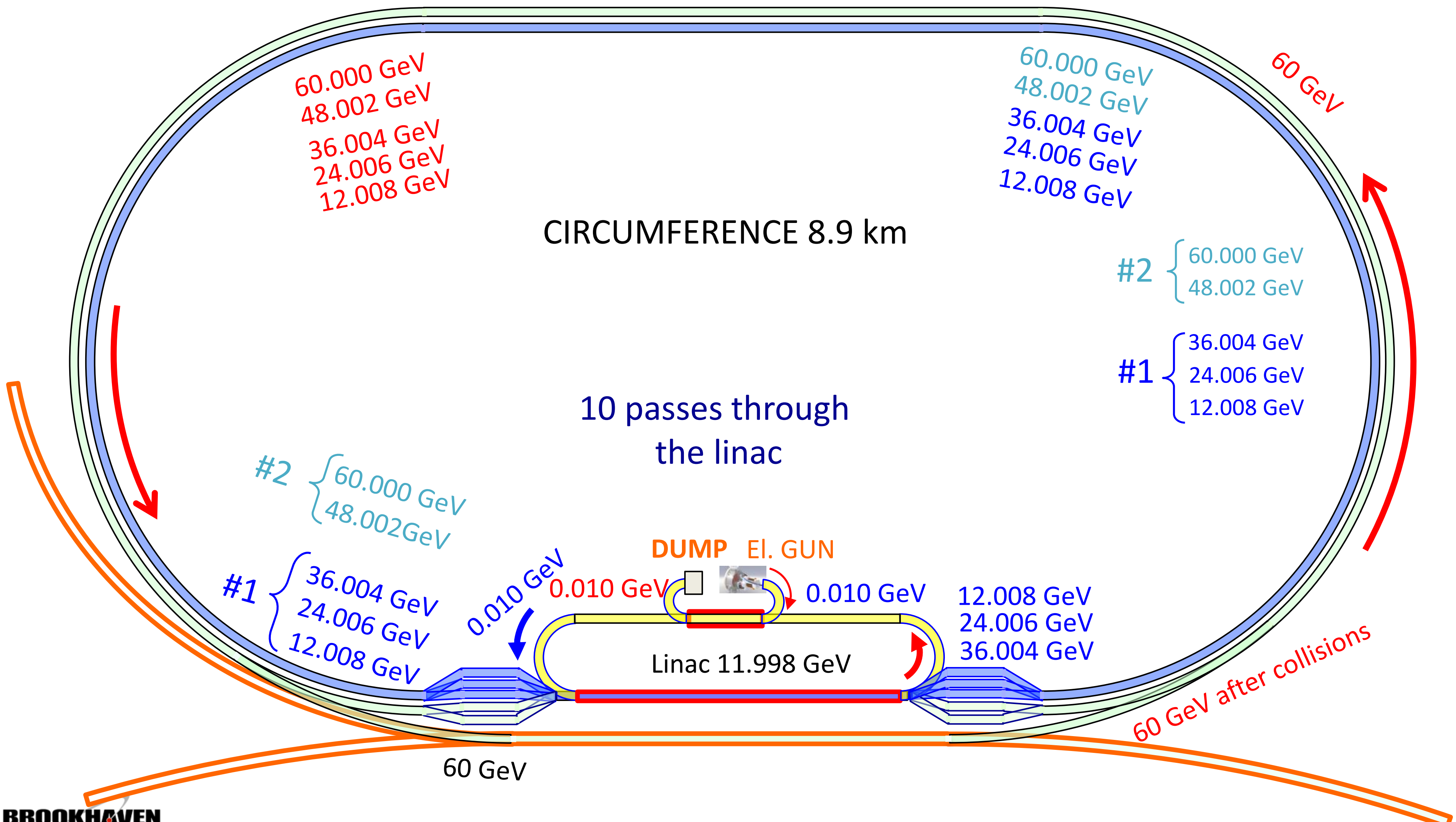
Betatron Functions for E_c=29 GeV, 2 x 5.453 GeV linacs



Synchrotron Radiation in LHeC with 2 x 5.453 GeV linacs
Two NS-FFAG 43.6-54.6 GeV and 10.9-32.7 GeV
Maximum Collision Energy 60 GeV

E(GeV)	Total Power (MW) 8.87035 mA	Total Power (MW) 6.6 mA
54.550	7.5779	5.6383
43.644	4.2080	3.1310
32.735	1.3902	1.0344
21.829	1.2881	0.9584
10.923	0.5359	0.3987
TOTAL	**15.000**	**11.1608**

NS-FFAG for the LHeC ERL-ONE 12 GeV LINAC



Synchrotron Radiation in LHeC with one 12 GeV linac
Two NS-FFAG 48-60 GeV and 12-36 GeV
Maximum Collision Energy 60 GeV

E(GeV)	Total Power (MW) 6.7834 mA	Total Power (MW) 6.6 mA
54.550	**6.4562**	**6.2816**
43.644	4.6537	4.5279
32.735	2.5812	2.5115
21.829	0.8544	0.8313
10.923	0.4546	0.4423
TOTAL	**15.000**	**14.5945**

$G_F = 37.37$ T/m

$B_{yF} = -0.0762$ T

$B_{Fmin} = -0.0762 + 37.37 * (11.82\ mm) = 0.371$ T

$B_{Fmax} = -0.0762 + 37.37 * (-10.79mm) = -0.479$ T

$G_D = -37.37$ T/m

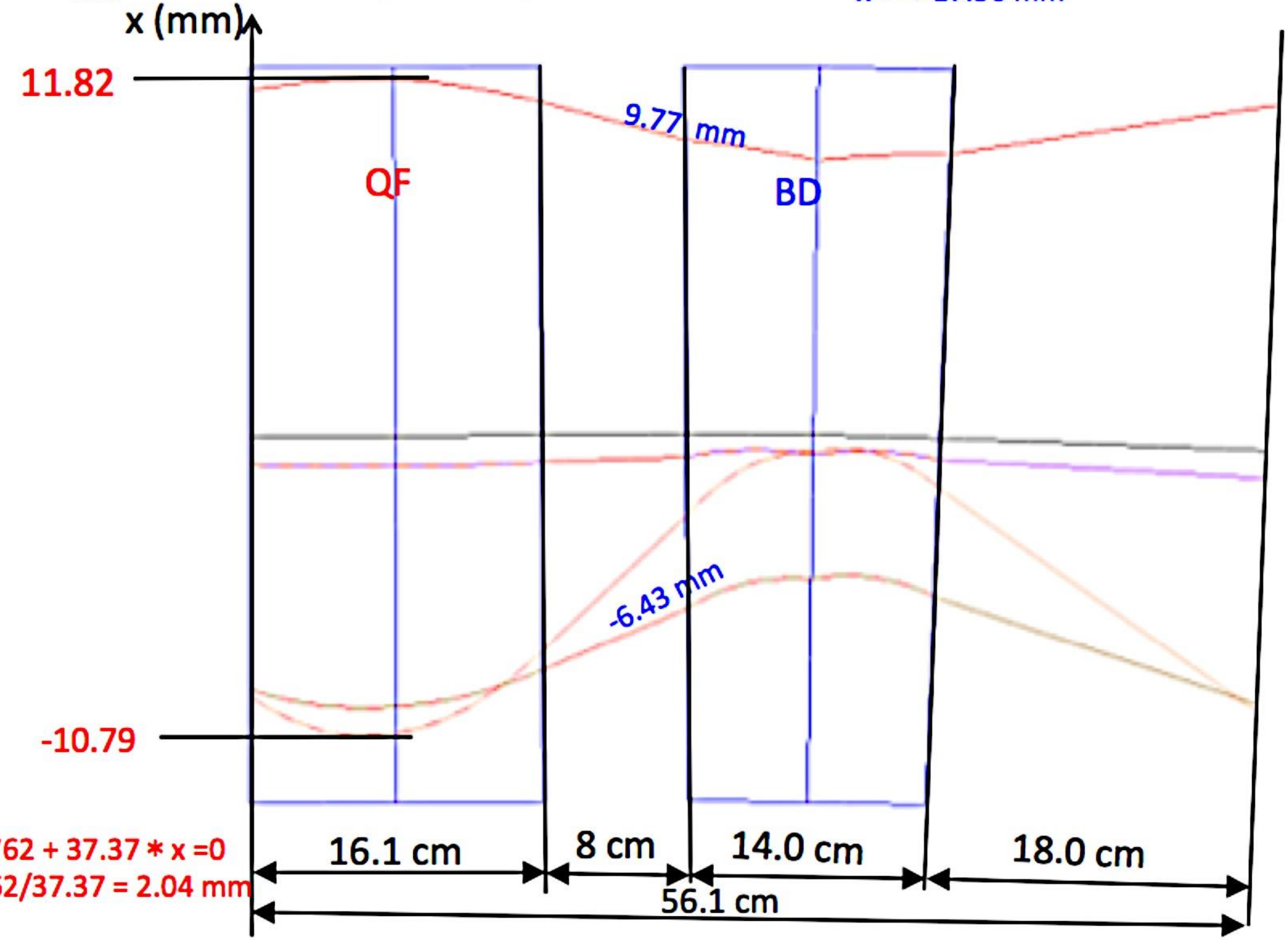
$B_{yD} = 0.649$ T

$B_{Dmin} = 0.649 + (-37.37 * 9.77\ mm) = 0.283$ T

$B_{Dmax} = 0.649 + (-37.37 * -6.43) = 0.889$ T

$BD = 0.649 + (-37.37)\ x = 0$

$x = +17.36$ mm



$B_F = -0.0762 + 37.37 * x = 0$

$x = 0.0762/37.37 = 2.04$ mm

CONCLUSION

- A cost effective eRHIC design with 1.332 GeV linac and maximum energy of 21.2 GeV is shown.
- A proposal for replacement of the 2 x 10 GeV linacs and three arcs, with 2 x 5.453 GeV linacs and two NS-FFAG arcs, respectively.
- A cost-effective solution with lower synchrotron radiation, hence 34 % larger luminosity for the same limit on the value of 15 MW for the total loss from synchrotron radiation.

Scaling down LHeC energies

Circumference of the LHC: C_{LHC} = 26,658.88320 m

① 1/3 C_{LHC} = 8,886.29440 m [60 GeV - Linacs 2x10x3] 10 GeV Linac ~2x 1 km+6.283+4x0.151

② 1/4 C_{LHC} = 6,664.72080 m [45 GeV - Linacs 2x7.5x3]7.5 GeV linac 0.75 km

③ 1/5 C_{LHC} = 5,331.77664 m [36 GeV –Linacs 2x6x3]

FFAG solutions:

① 1/3 C_{LHC} = 8,886.29440 m [60 GeV - Linacs 2x5.453x2]

  ① Or [60 GeV – one linac 12 GeVx2 FFAG lines]

② 1/4 C_{LHC} = 6,664.72080 m [45 GeV –Linacs 2x4.125 GeV]

  ① Or [45 GeV one linac 11.245 GeV[

③ 1/5 C_{LHC} = 5,331.77664 m [36 GeV –one linac 8.99 GeV]