eRHIC FFAG Lattice Design

Linear-field non-scaling FFAG optimised for synchrotron radiation

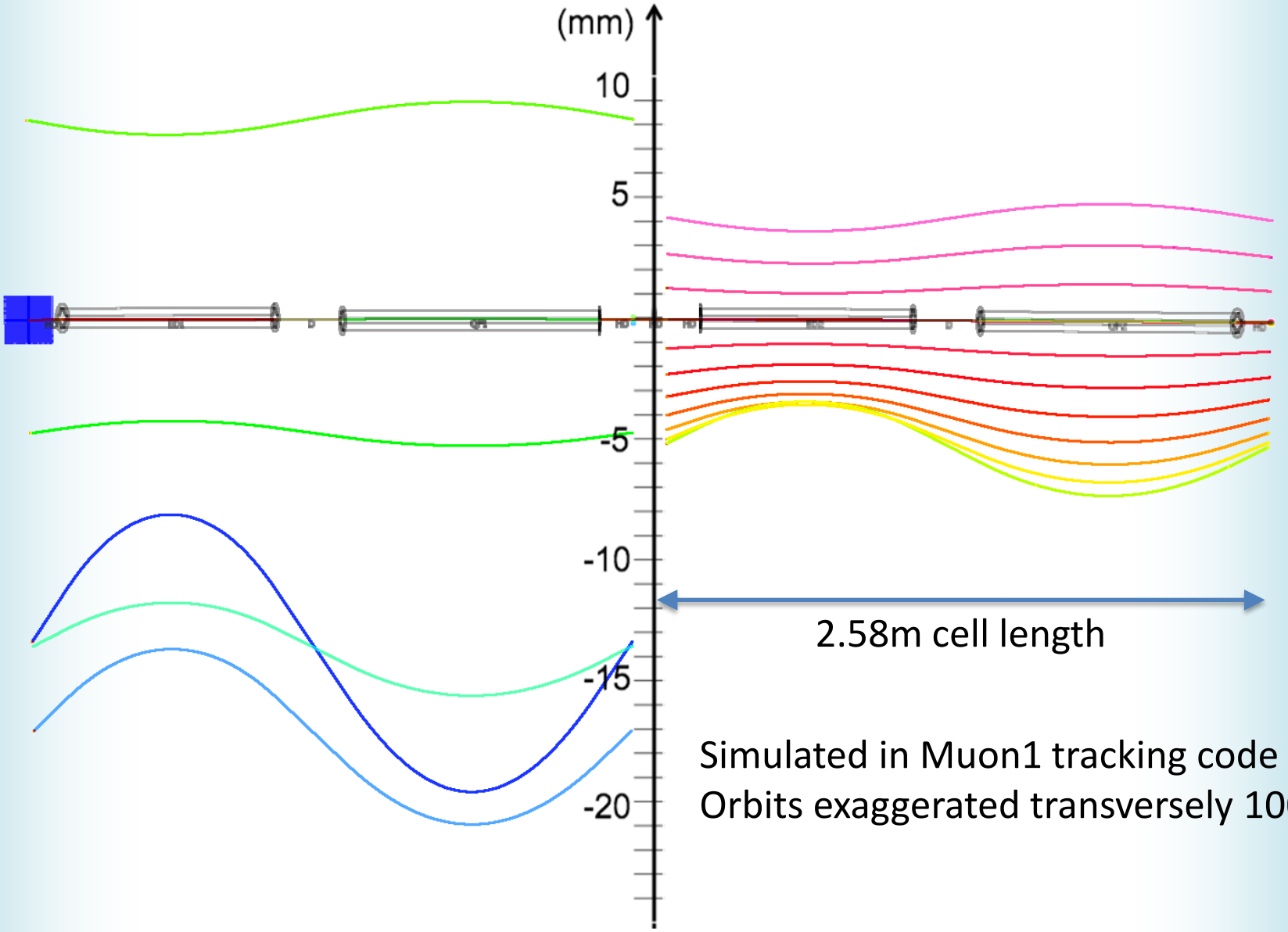
eRHIC FFAG Arc Cells

Parameter	Low-Energy FFAG	High-Energy FFAG
Energy range	1.334 – 6.622 GeV	7.944 – 21.164 GeV
Energy ratio	4.96×	2.66×
Turns (1.322GeV linac)	5	11
Synchrotron power	0.26MW @ 50mA	9.8MW @ 21.1GeV, 18mA 10.2MW @ 15.8GeV, 50mA 3.2MW @ 10.5GeV, 50mA
TOF range	54.7ppm (12cm)	22.4ppm (5cm)
Drift space	28.8cm	28.8cm
Tune range	0.036 – 0.424	0.035 – 0.369
Orbit range (quads)	31.3mm (r_{max} = 23.6mm)	12.6mm (r_{max} = 9.1mm)
Max |**B**| on orbit	0.227 T	0.451 T
Max quad strength	9.986 T/m	49.515 T/m

Element	Length (m)	Angle (mrad)	Gradient (T/m)	Offset (mm)
All Drifts	0.287643623	0		
BD (Low)	0.90805 = 35¾”	3.057567	9.986	-6.946947
QF (Low)	1.09855 = 43¼”	3.699017	-9.006	6.946947
BD (High)	0.90805	3.057567	49.515	-3.901098
QF (High)	1.09855	3.699017	-49.515	3.901098

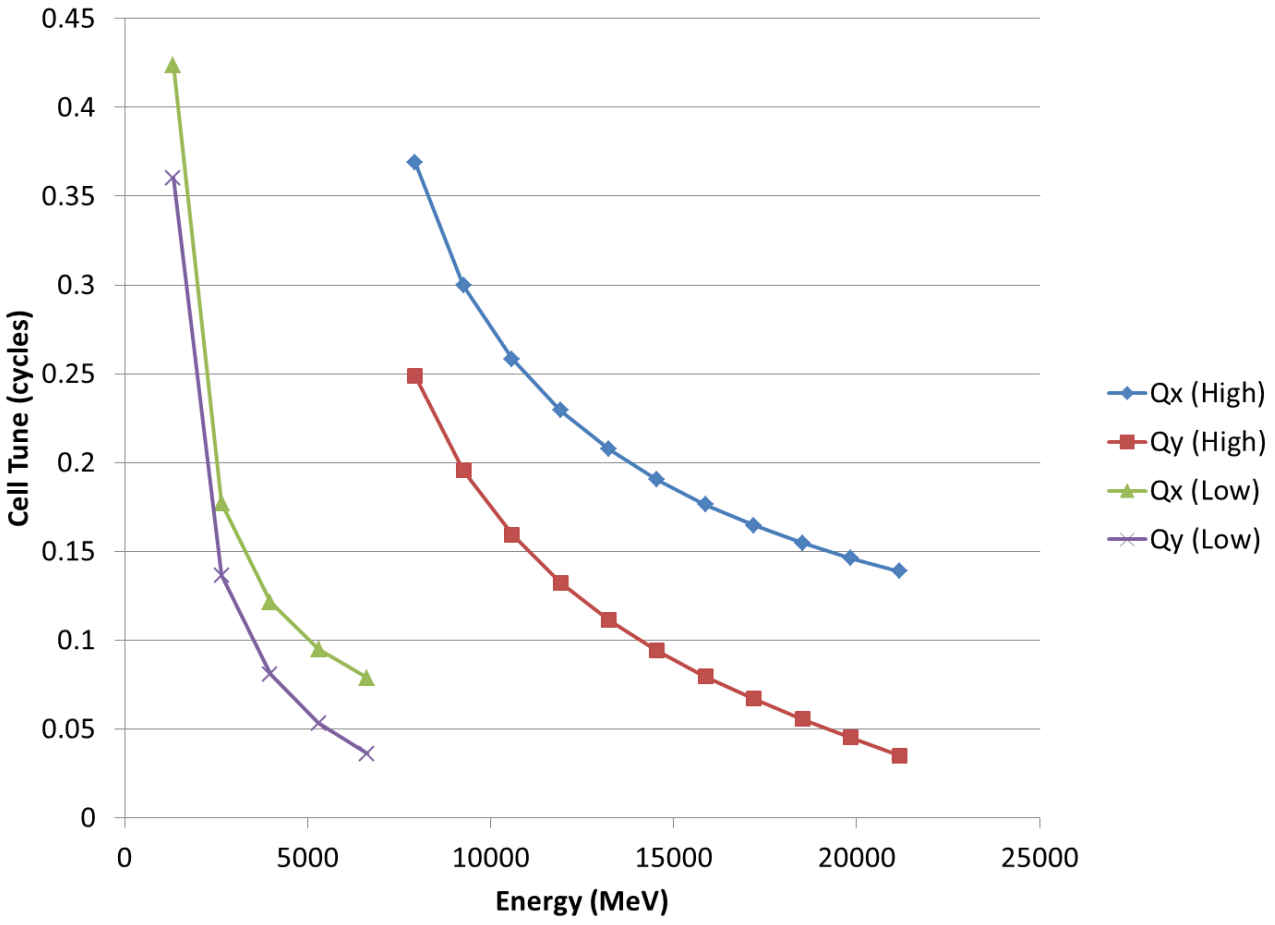
Lattice cell:
½D,BD,D,QF,½D

eRHIC: Low (left) and High (right) Energy FFAG Orbits

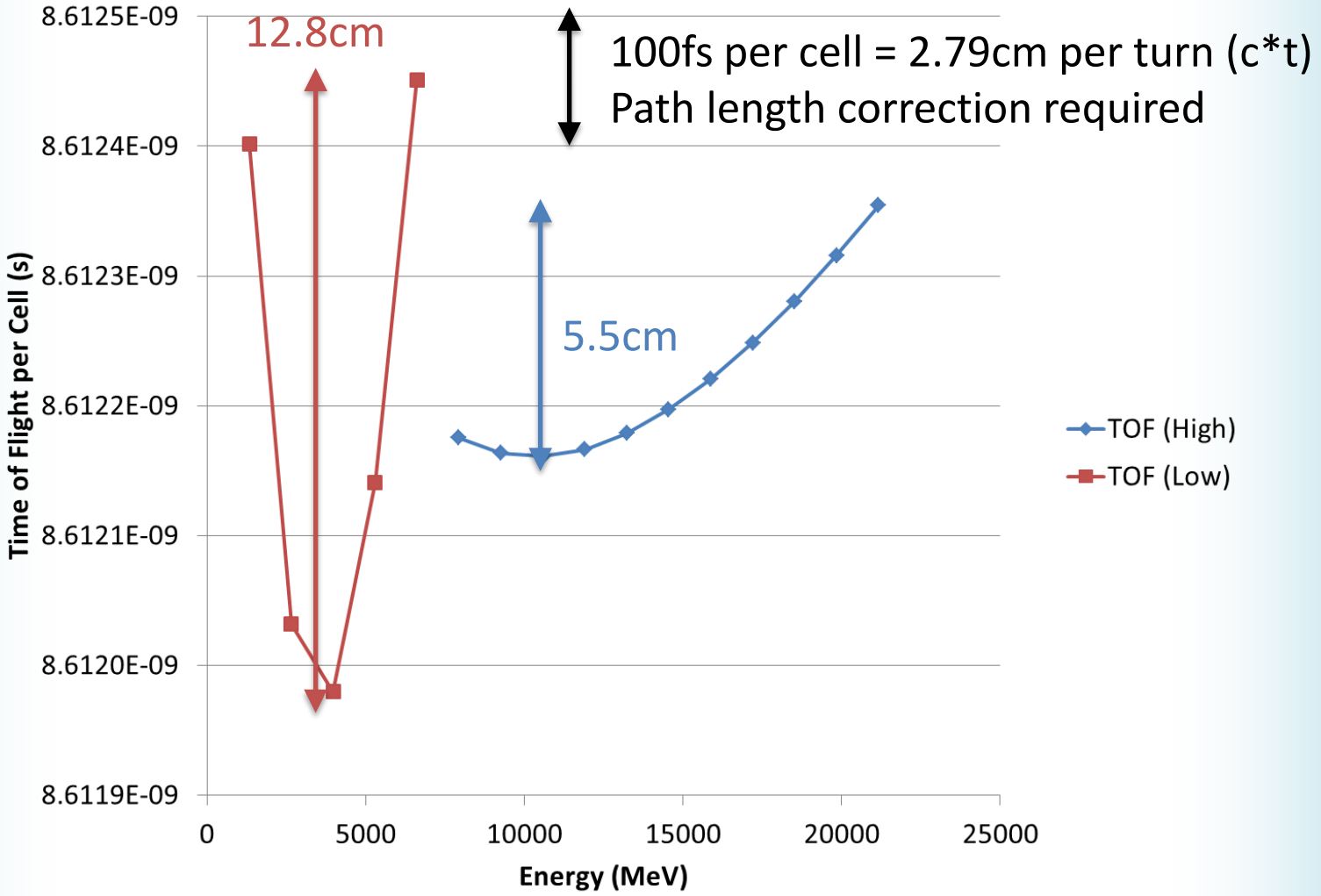


Simulated in Muon1 tracking code
Orbits exaggerated transversely 100x

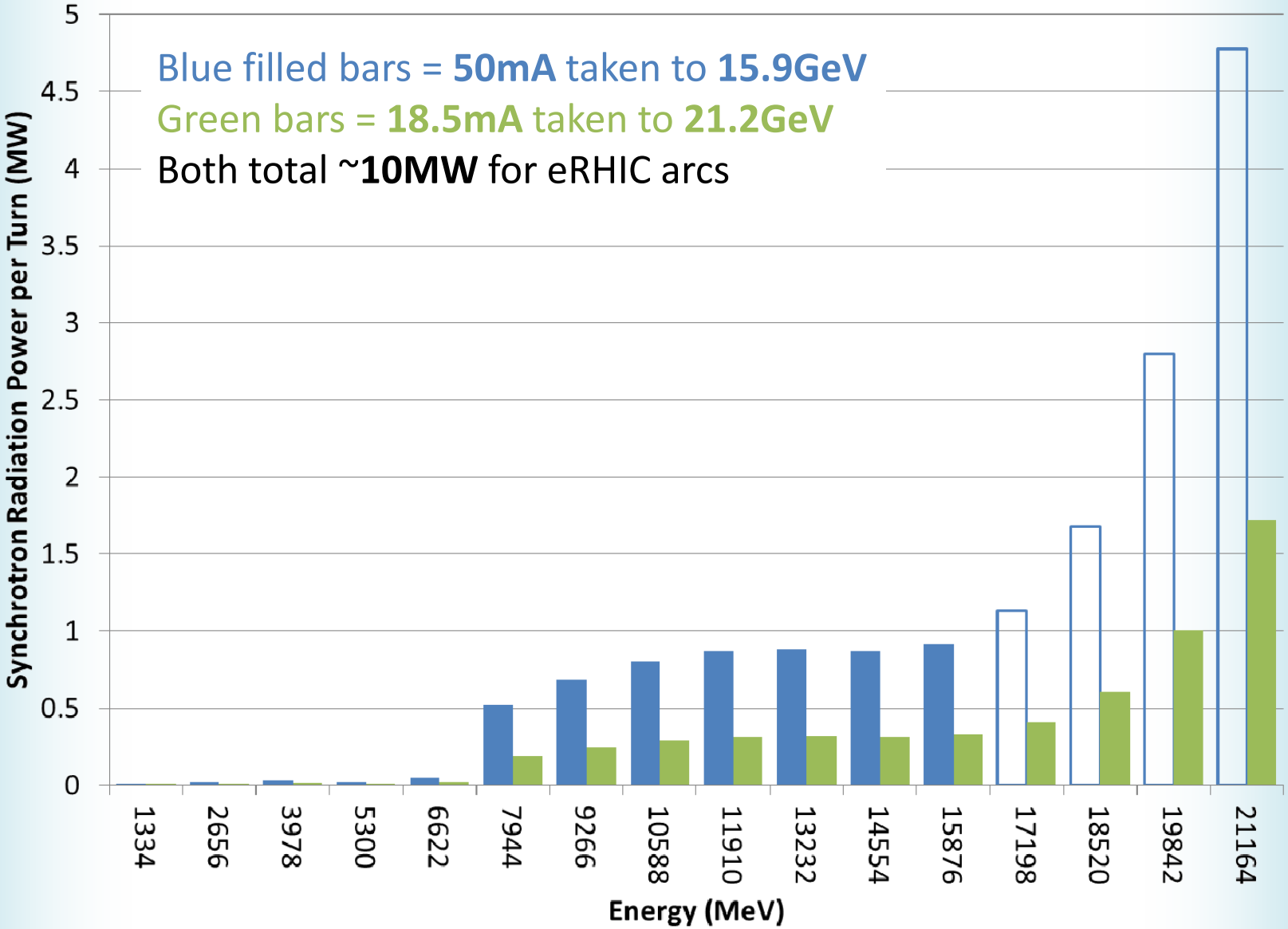
eRHIC Tune per Cell vs. Energy (both rings)



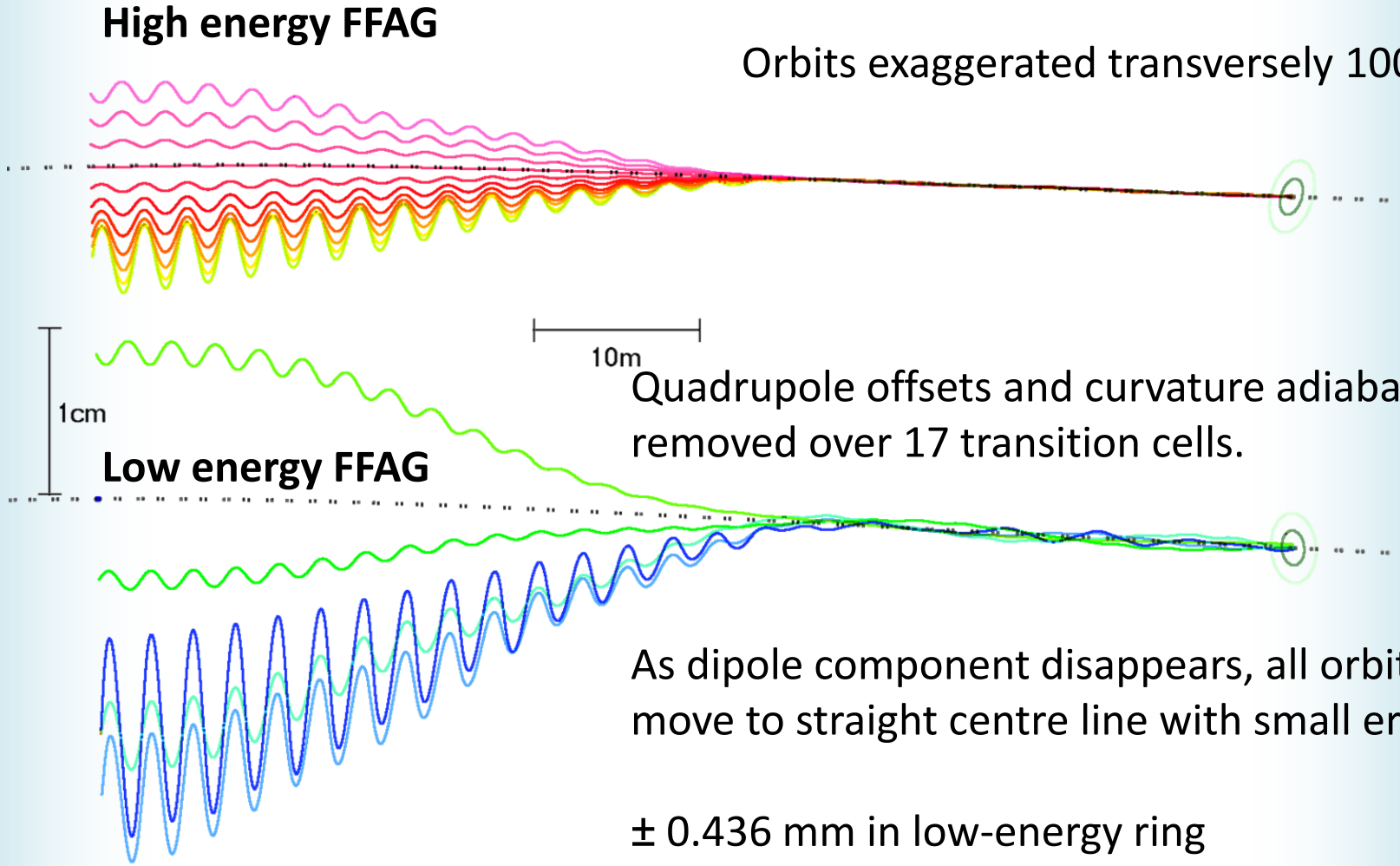
eRHIC Time-of-Flight Variation with Energy (both rings)



eRHIC Synchrotron Radiation per Turn (both rings)



eRHIC FFAG Straight Sections (both rings)



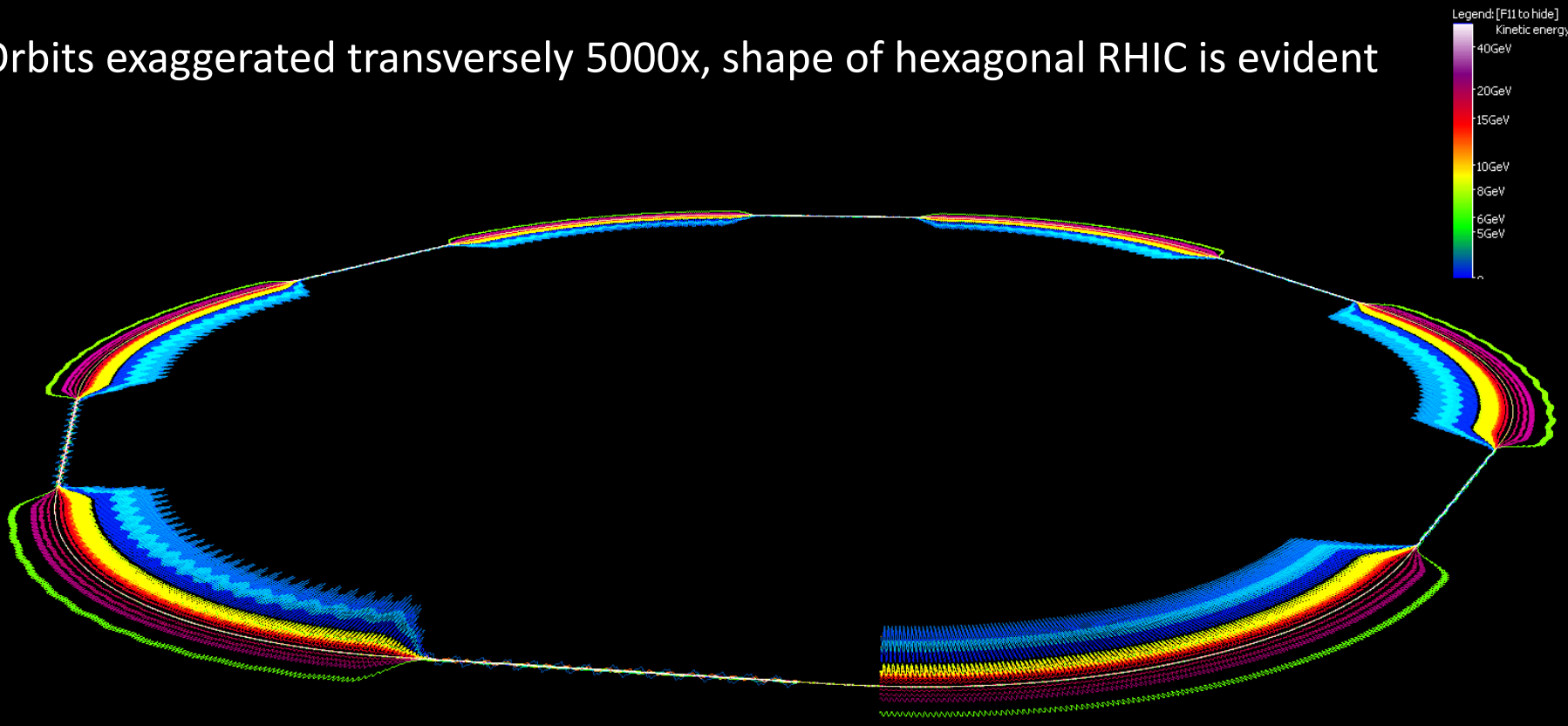
Quadrupole offsets and curvature adiabatically removed over 17 transition cells.

As dipole component disappears, all orbits move to straight centre line with small errors:

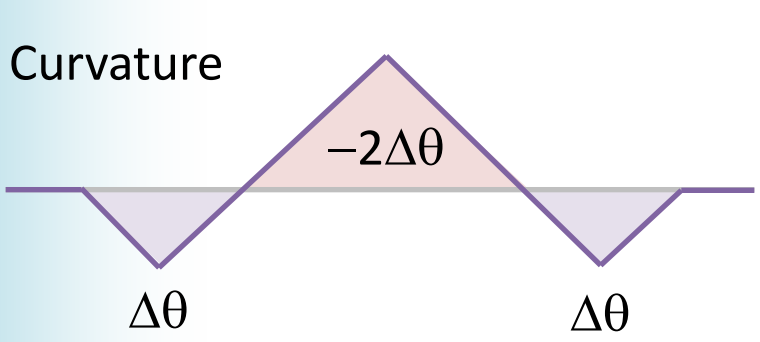
± 0.436 mm in low-energy ring
± 0.066 mm in high-energy ring

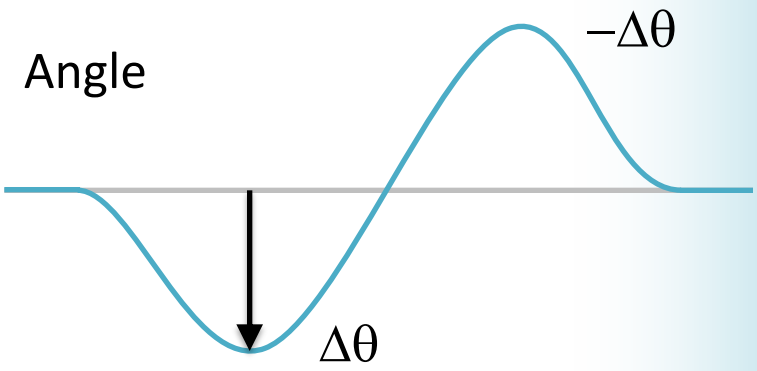
eRHIC FFAG Rings in Perspective

Orbits exaggerated transversely 5000x, shape of hexagonal RHIC is evident



Detector Bypass Scheme: a Flexible FFAG



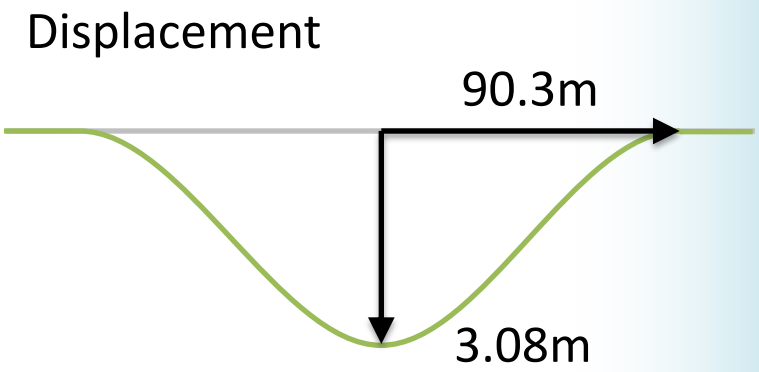


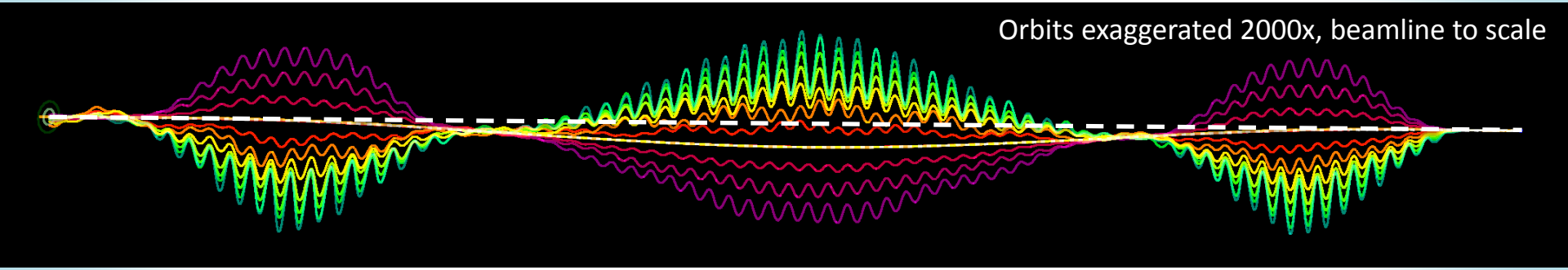
Bypass straight

3	9	9	17	17	9	9	3

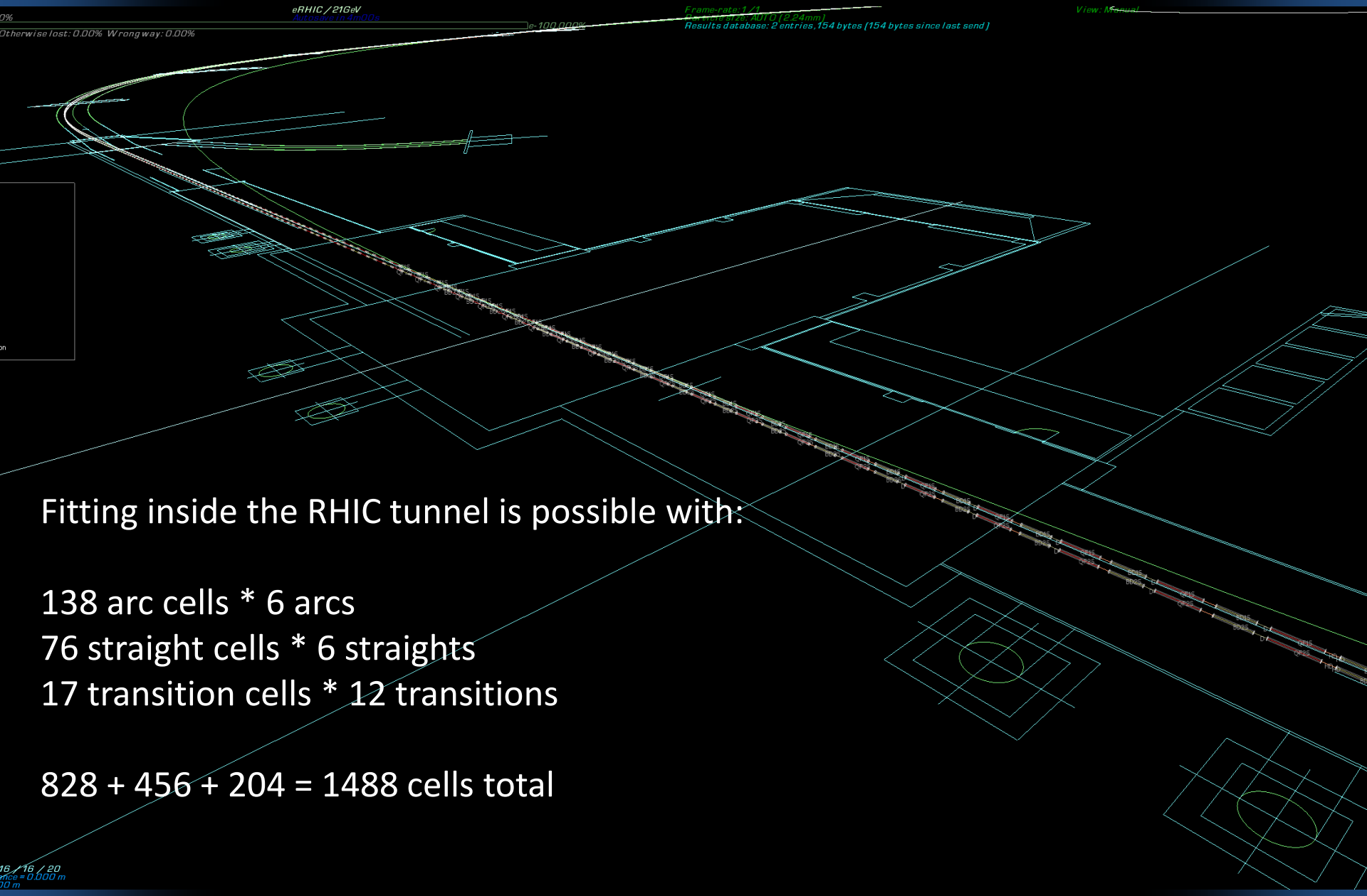
Normal straight

76 cells





Layout Superimposed on CAD of RHIC Tunnel



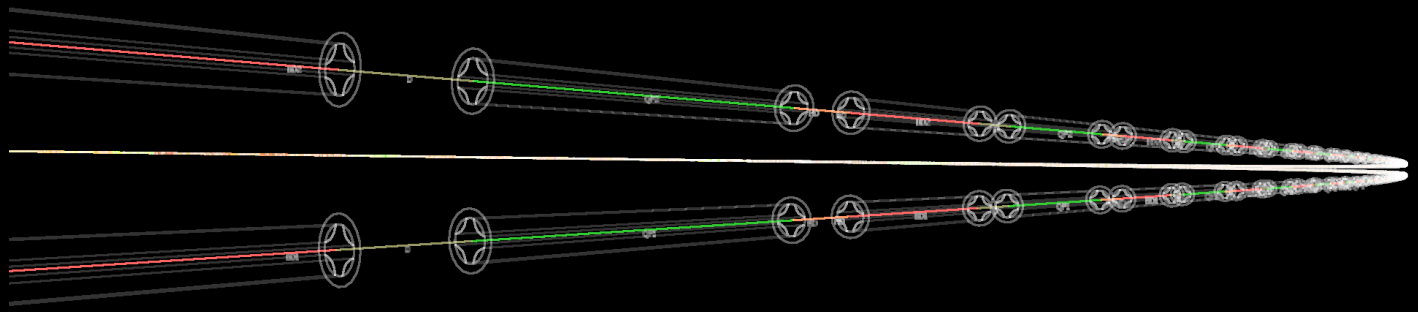
Fitting inside the RHIC tunnel is possible with:

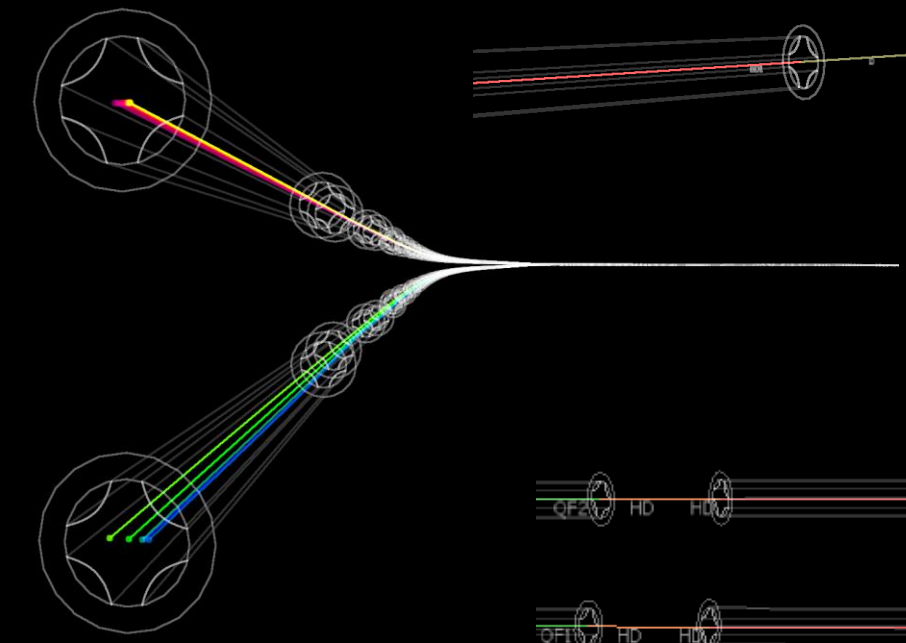
138 arc cells * 6 arcs
76 straight cells * 6 straights
17 transition cells * 12 transitions

828 + 456 + 204 = 1488 cells total

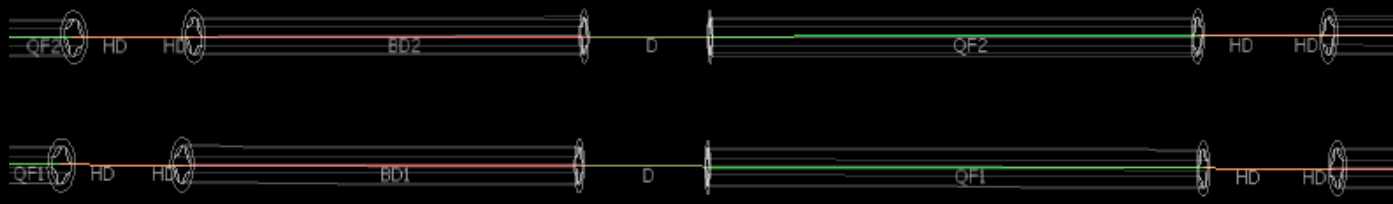
Girder Stacking

- Both rings have the same element lengths and angles



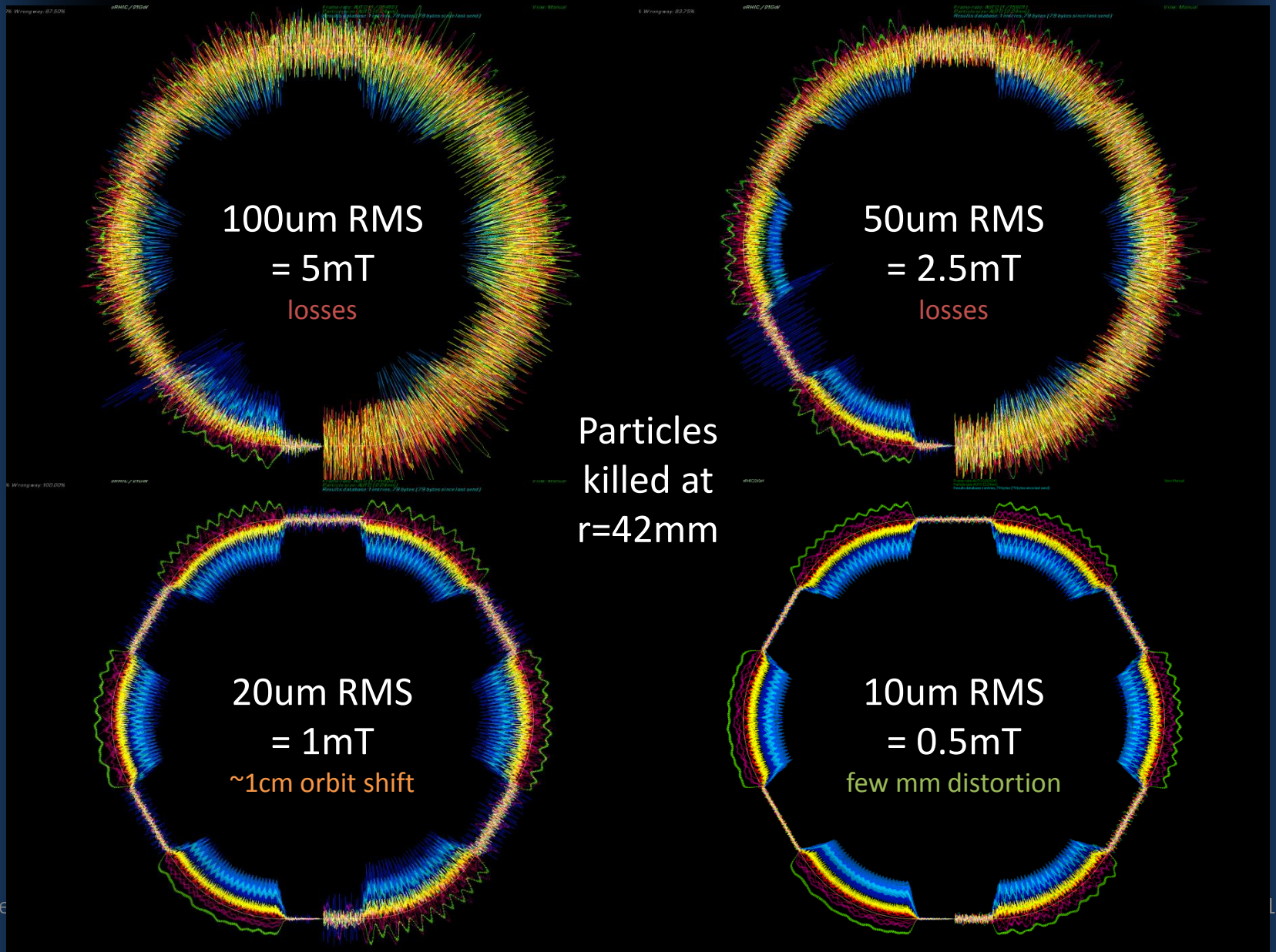


- Common ~2.5m girder can be used for both cells

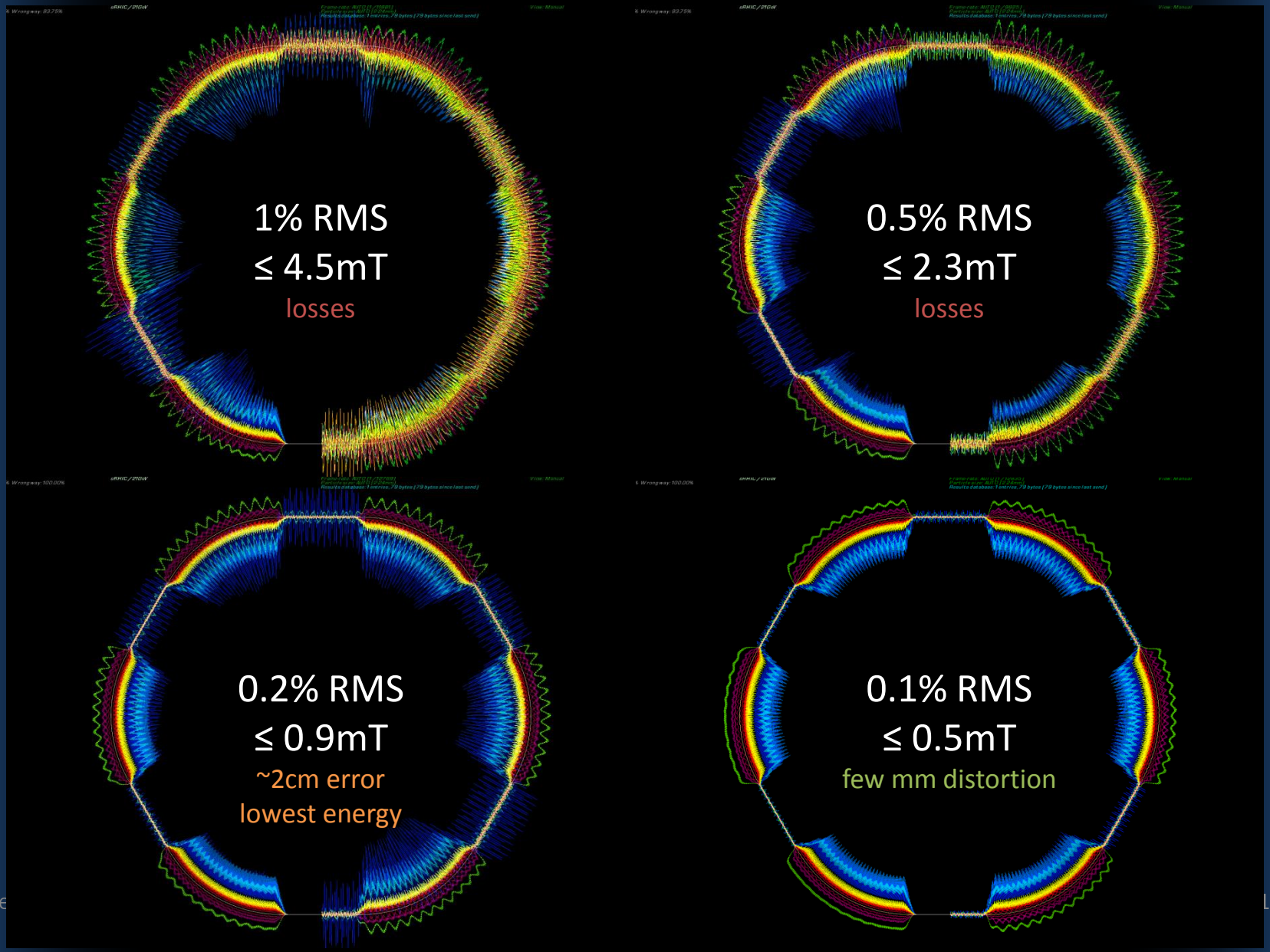


Quadrupole Displacements = Dipole Errors

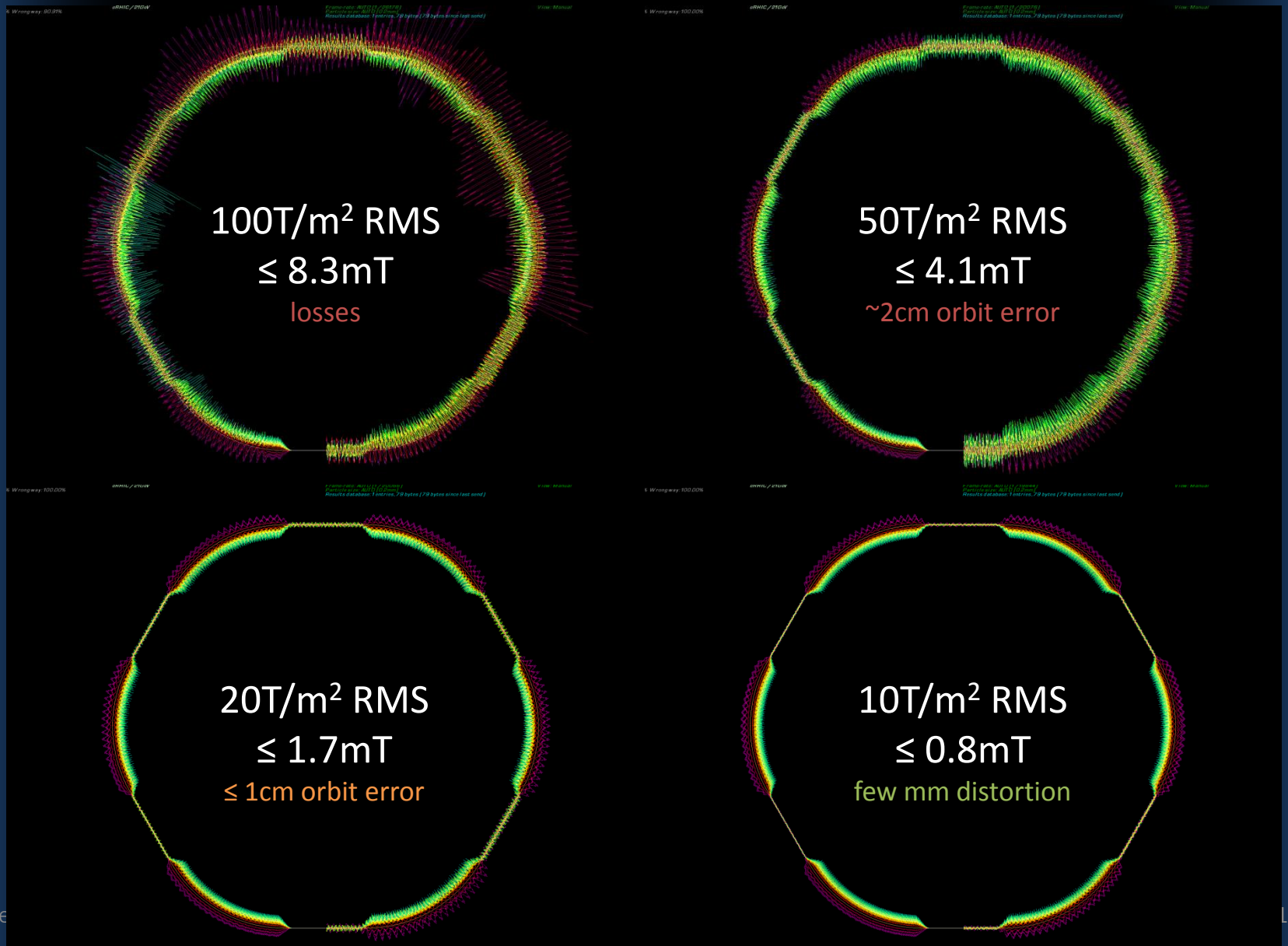
(both rings)



Quadrupole Errors (both rings)



Sextupole Errors (high-energy ring only)



“2:1” Scaled eRHIC FFAG Design

Featuring ≤30T/m quadrupoles

FFAG2 Orbits Too Close Together?

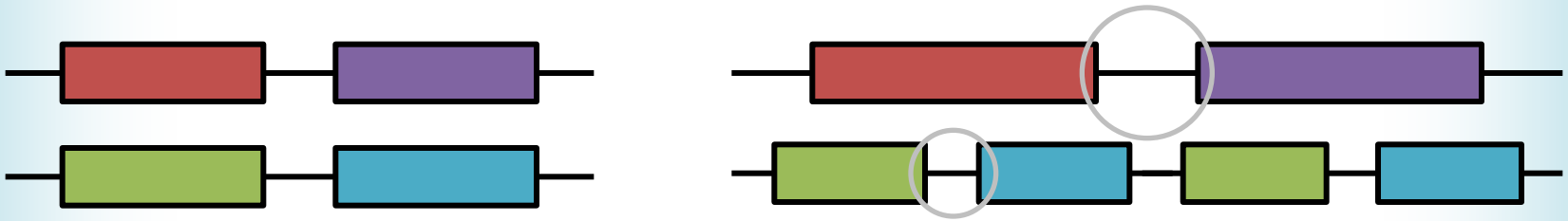
- Magnet vertically at least 8mm away from orbits that are within 9.1mm of quad centre
  - Difficult to produce field “at a distance”
- Vladimir mentioned close-together orbits aren’t very good for extraction
  - Low beta function also not good
- High gradient (small orbit range) increases sensitivity to alignment errors

Optics-Preserving FFAG Cell Scaling

- Multiply element lengths by factor A
  - And beta functions
- Multiply orbit excursion by A^2
- Divide gradients by A^2
- Keep dipole field the same
  - Equivalently, multiply quad offsets by A^2
- Tunes per cell stay the same
- Synchrotron radiation per turn stays the same

2:1 Cell and Girder Stacking

- Make FFAG1 have a shorter cell (closer orbits) and FFAG2 a longer cell (lower gradient)
- Tried making the FFAG2 cell twice the length of the FFAG1 cell (roughly as shown below)
  - Enables two-beamline repeating module if needed
  - Free parameter: choice of FFAG1 cell length



Parameter Scaling (simplified)

Parameter	FFAG1	FFAG2
Old gradient (T/m)	9.986	49.515
Old orbit range (mm)	31.3	12.5
Old angle per cell (rad)	0.006757	0.006757
Cell length scaling	**0.645788**	1.291577
Angle per cell (rad)	0.004363	0.008727
Cells per 60deg	240	120
Orbit range scaling	0.417043	1.66817
Gradient (T/m)	23.9448	29.68222
Orbit range (mm)	13.05343	20.85213
Old packing factor	0.774627	
Corrected packing factor	0.651011	0.825506
Corrected gradient (T/m)	28.4915	27.85281

What Has Not Been Done

- Tracking study in this section didn't correct drift lengths back to 30cm, just scaled
  - Might get improvement in radiation for FFAG2
- Overall scale of cells can still be varied
- Maybe use magnet design to find optimum
  - High gradients run into problems but low gradients also ought to require increasing amounts of material at some point, so there should be an optimum

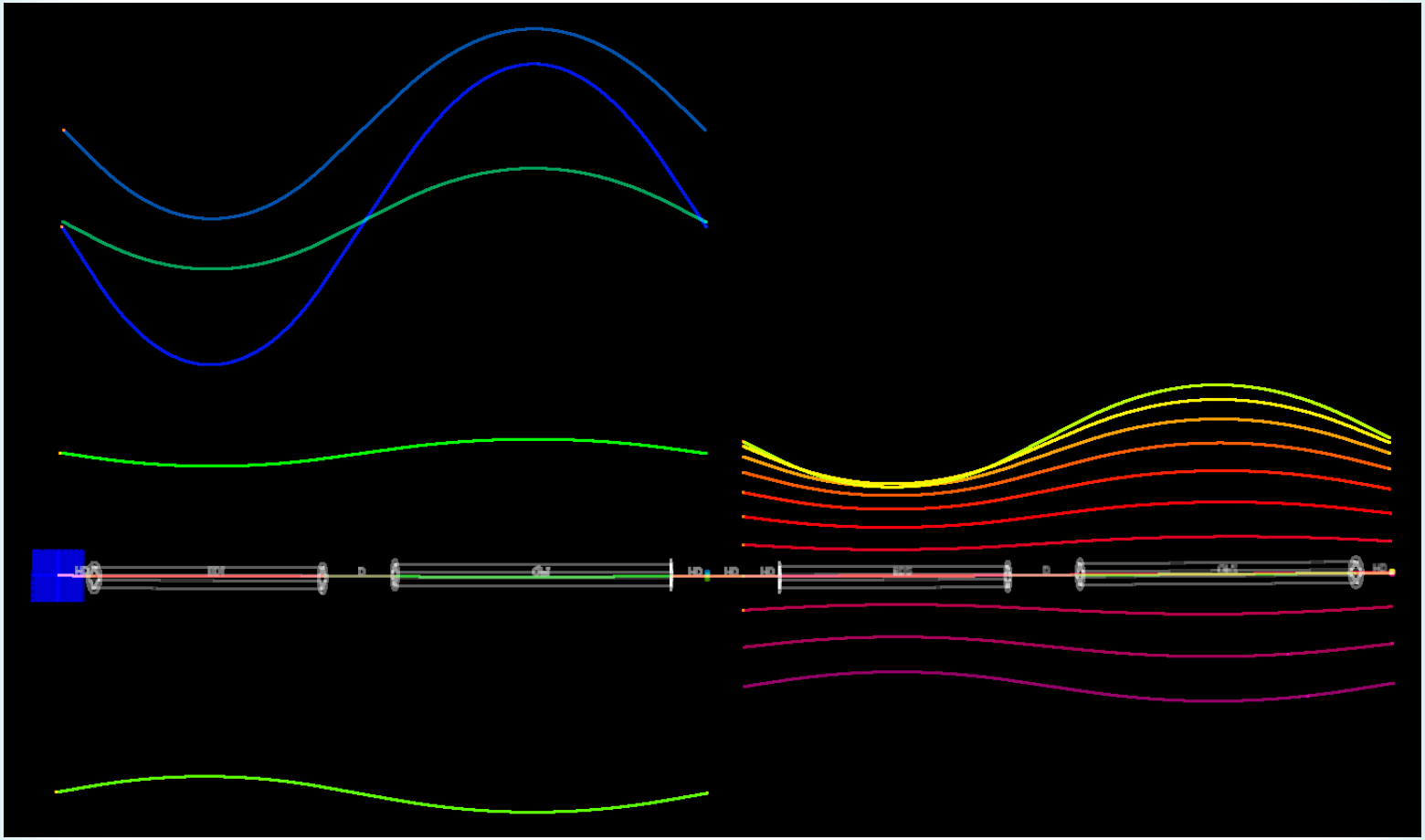
Current Lattice (Jan'14)

Parameter	Low-Energy FFAG	High-Energy FFAG
Energy range	1.334 – 6.622 GeV	7.944 – 21.164 GeV
Energy ratio	4.96×	2.66×
Turns (1.322GeV linac)	5	11
Synchrotron power	0.26MW @ 50mA	9.8MW @ 21.1GeV, 18mA 10.2MW @ 15.8GeV, 50mA 3.2MW @ 10.5GeV, 50mA
TOF range	54.7ppm (12cm)	22.4ppm (5cm)
Drift space	28.8cm	28.8cm
Tune range	0.036 – 0.424	0.035 – 0.369
Orbit range (quads)	31.3mm (r_{max} = 23.6mm)	12.6mm (r_{max} = 9.1mm)
Max |**B**| on orbit	0.227 T	0.451 T
Max quad strength	9.986 T/m	49.515 T/m

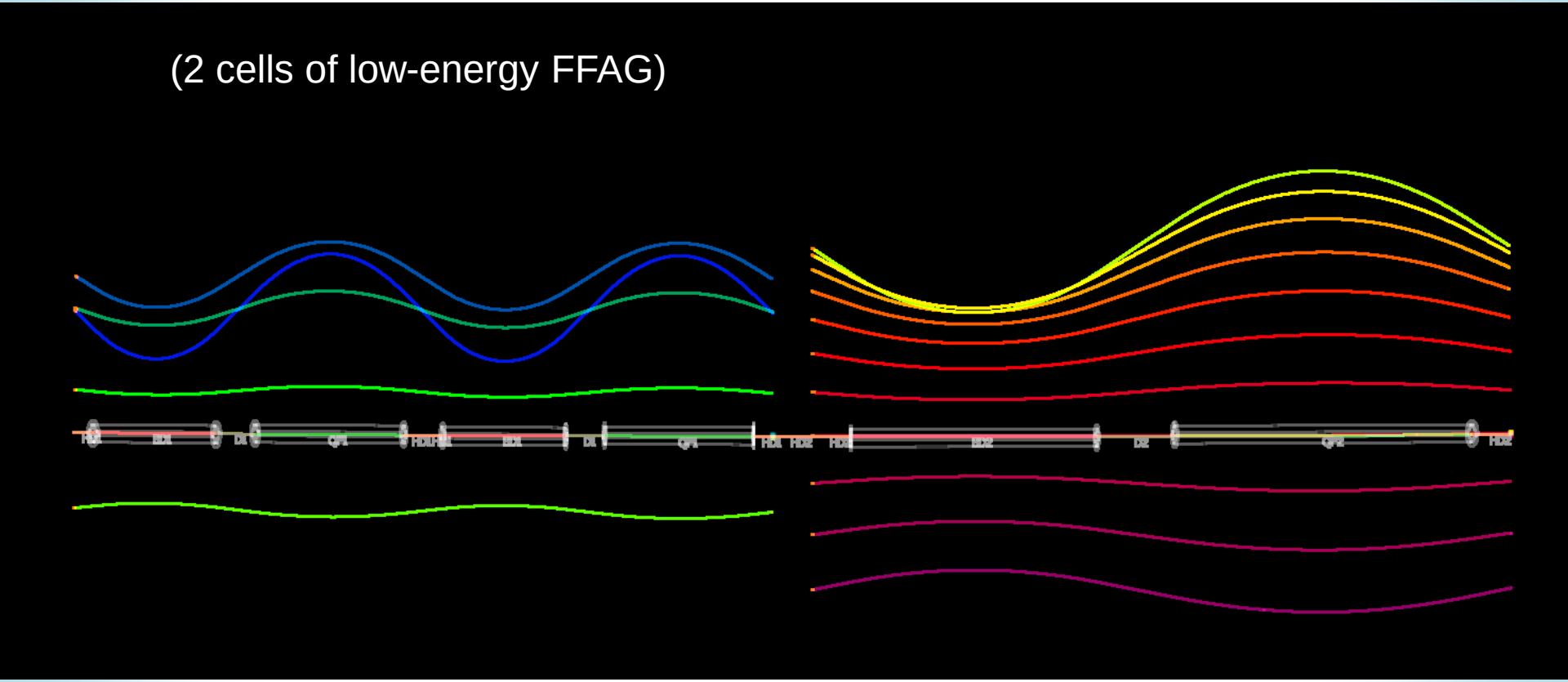
Scaled and 2:1 Stacked Lattice

Parameter	Low-Energy FFAG	High-Energy FFAG
Energy range	1.334 – 6.622 GeV	7.944 – 21.164 GeV
Energy ratio	4.96×	2.66×
Turns (1.322GeV linac)	5	11
Synchrotron power	0.25MW @ 50mA	9.8MW @ 21.1GeV, 18mA 10.3MW @ 15.8GeV, 50mA 3.2MW @ 10.5GeV, 50mA
TOF range	22.9ppm (5cm)	37.4ppm (8cm)
Drift space	18.6cm	37.2cm
Tune range	0.036 – 0.420	0.035 – 0.369
Orbit range (quads)	13.1mm (r_{max} = 9.9mm)	21.0mm (r_{max} = 15.2mm)
Max $\|\mathbf{B}\|$ on orbit	0.224 T	0.451 T
Max quad strength	23.945 T/m	29.682 T/m

Jan’14 Orbits Exaggerated 100x



2:1 Orbits Exaggerated 100x



Jan'14 Lattice Description

Element	Length (m)	Angle (mrad)	Gradient (T/m)	Offset (mm)
All Drifts	0.287643623	0		
BD1 (Low)	0.90805 = 35¾"	3.057567	9.986	-6.946947
QF1 (Low)	1.09855 = 43¼"	3.699017	-9.006	6.946947
BD2 (High)	0.90805	3.057567	49.515	-3.901098
QF2 (High)	1.09855	3.699017	-49.515	3.901098

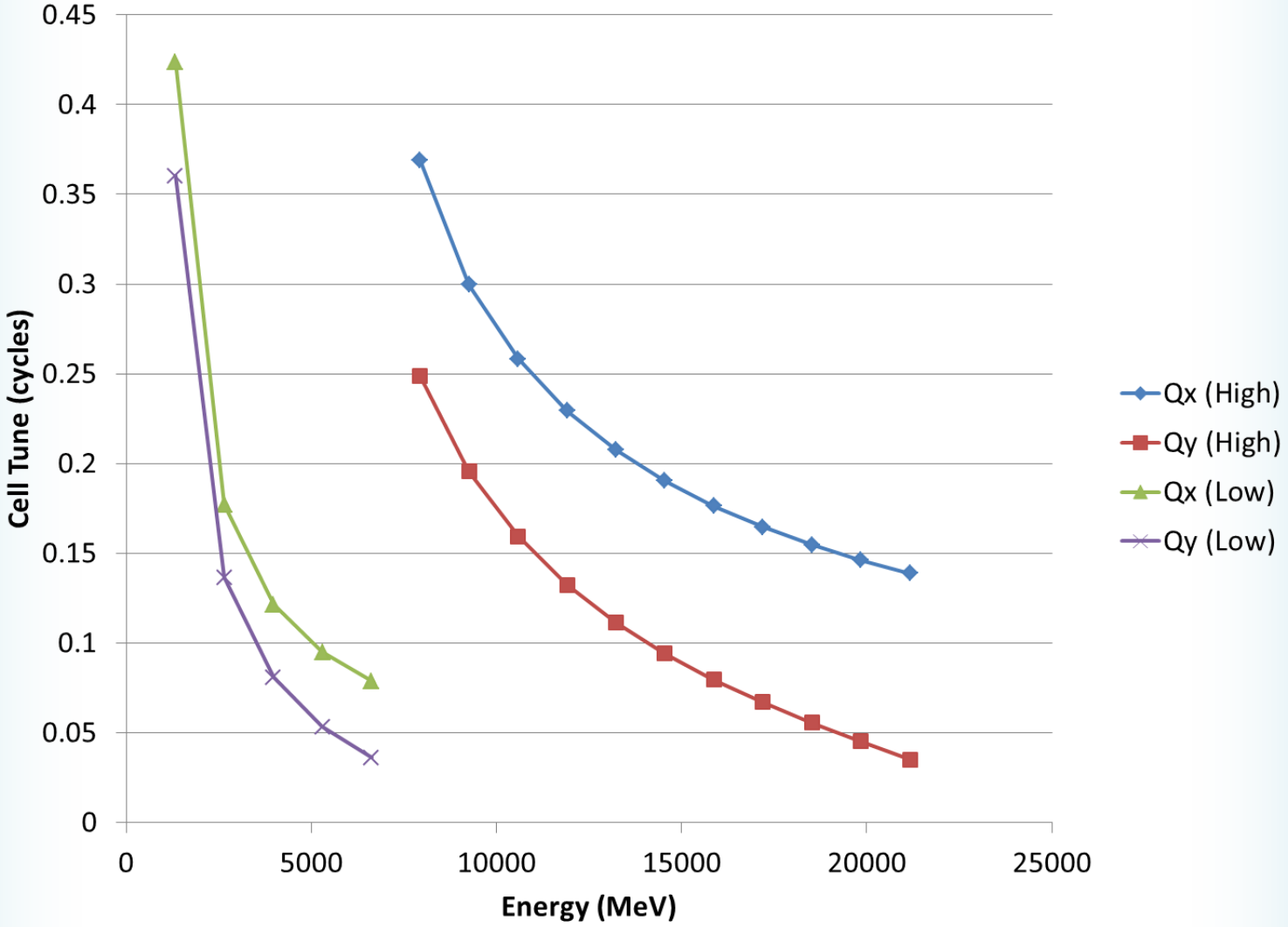
- Cell: ½D,BD,D,QF,½D (length ≈ 2.582m)
- Cells stack exactly, allowing common girder
- Specification on eRHIC Wiki
  - http://www.cadops.bnl.gov/eRHIC/erhicWiki/index.php/FFAG_Design:Electrons:Lattice:Arcs

2:1 Lattice Description

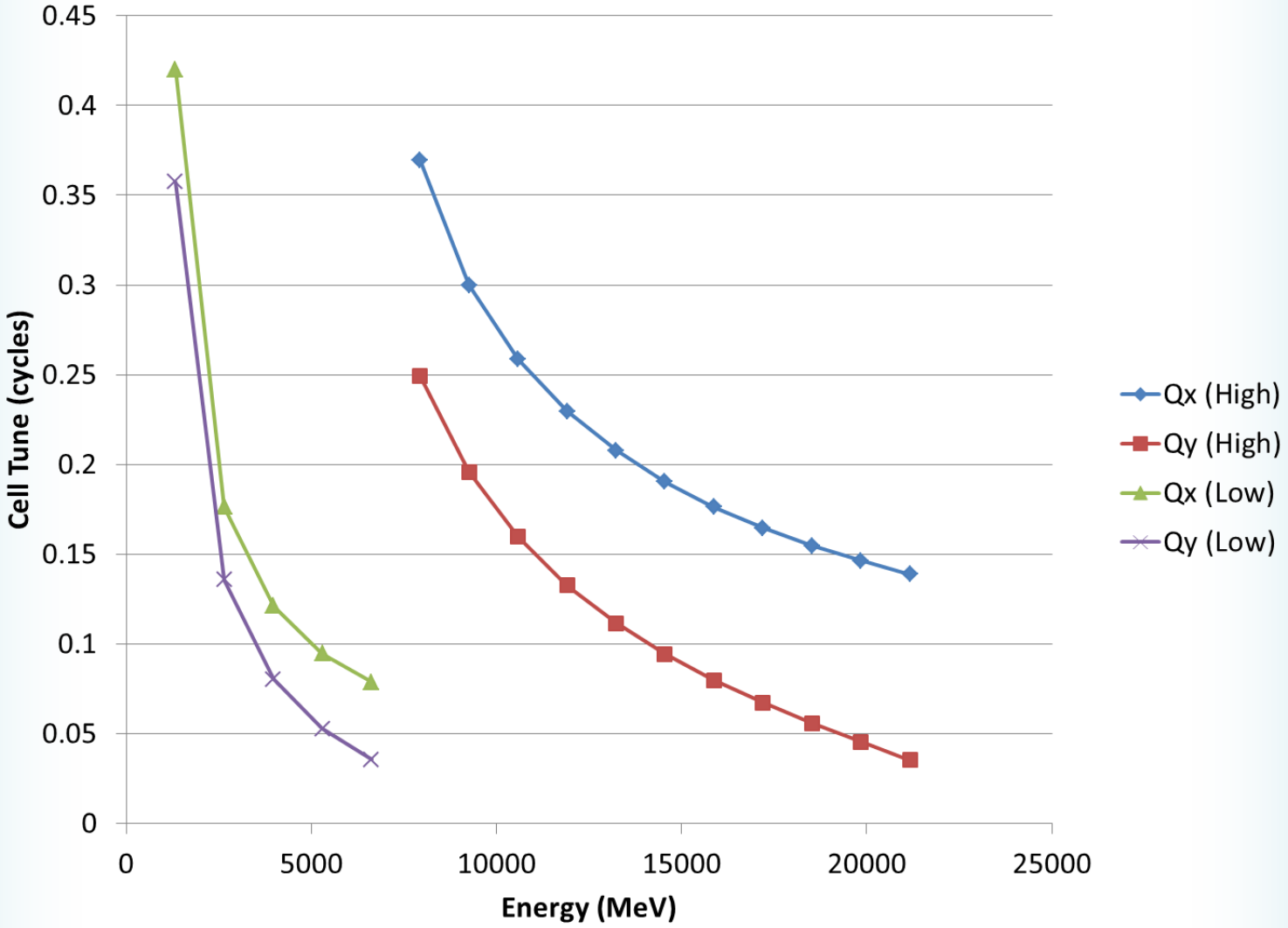
Element	Length (m)	Angle (mrad)	Gradient (T/m)	Offset (mm)
Drift D1 (Low)	0.185756896	0		
Drift D2 (High)	0.371513793	0		
BD1 (Low)	0.586408097	1.974541	23.945	-2.897173
QF1 (Low)	0.709430775	2.388782	-21.595	2.897173
BD2 (High)	1.172816195	3.949082	29.682	-6.507696
QF2 (High)	1.418861550	4.777564	-29.682	6.507696

- Cell: ½D,BD,D,QF,½D
- One FFAG2 cell (length ≈ 3.335m) stacks on top of two FFAG1 (length ≈ 1.667m) cells

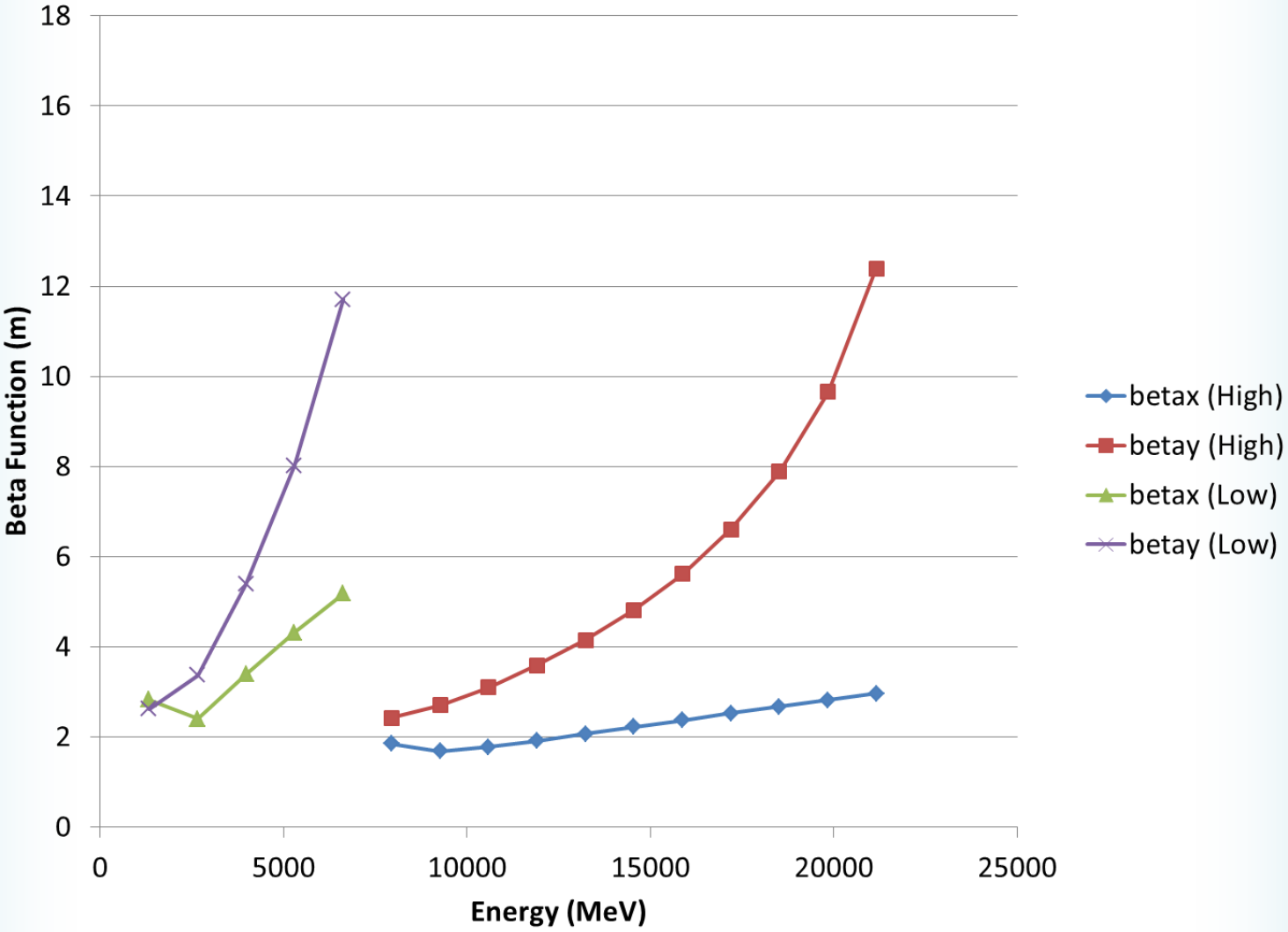
Jan'14 Tunes


0.45
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
Cell Tune (cycles)
0
5000
10000
15000
20000
25000
Energy (MeV)
Qx (High)
Qy (High)
Qx (Low)
Qy (Low)

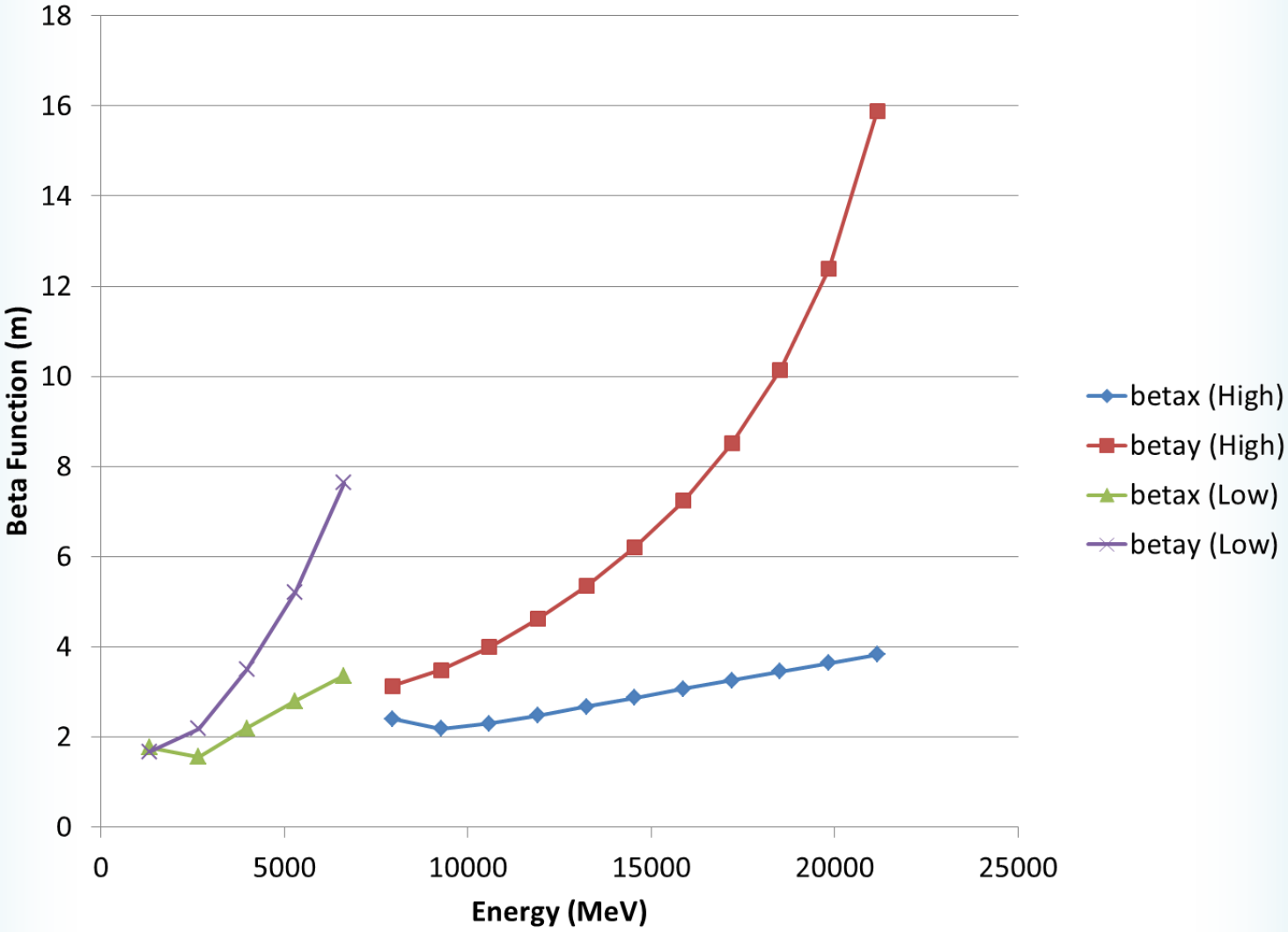
2:1 Tunes


0.45
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
Cell Tune (cycles)
0
5000
10000
15000
20000
25000
Energy (MeV)
Qx (High)
Qy (High)
Qx (Low)
Qy (Low)

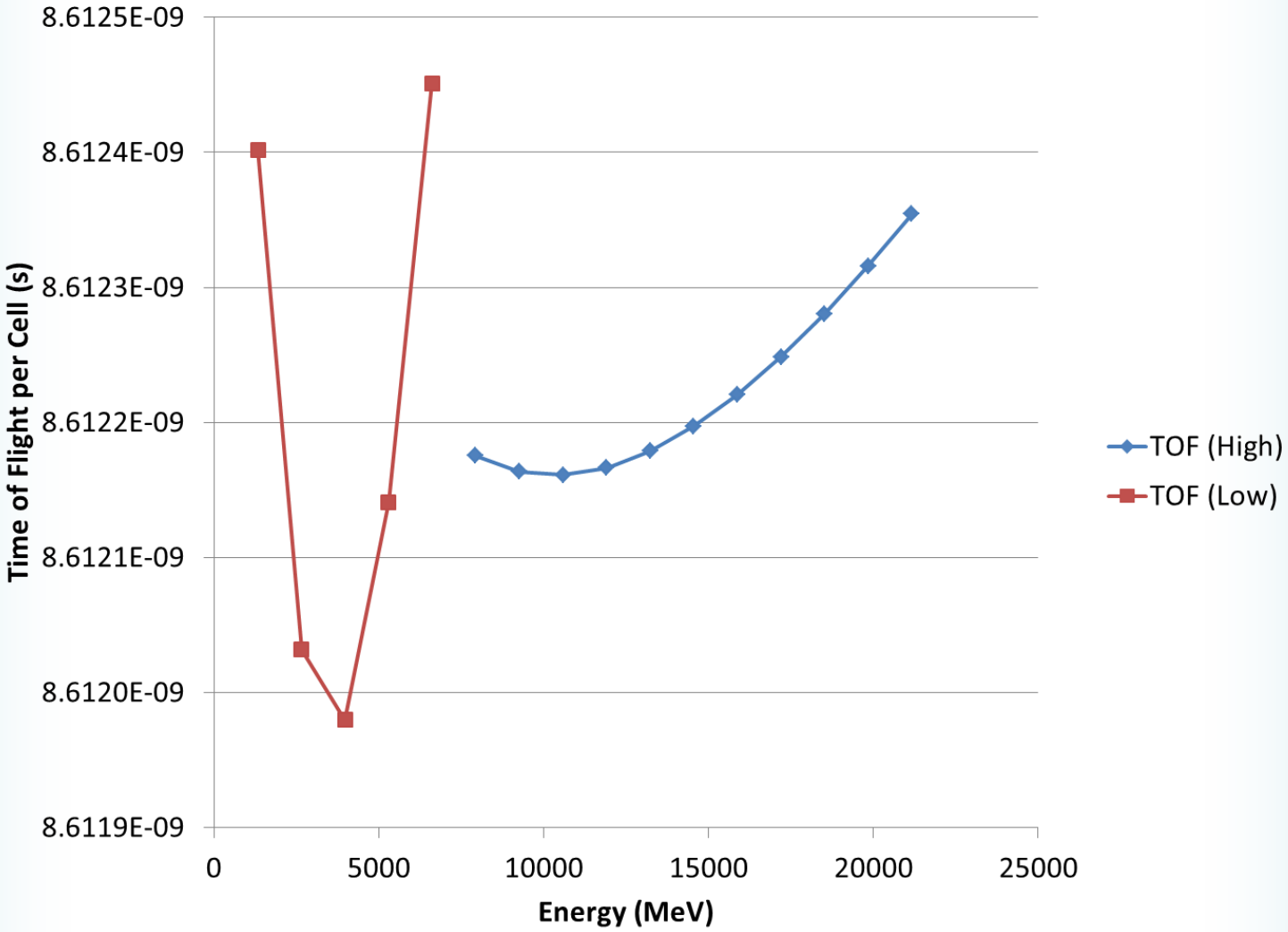
Jan'14 Betas at Matching Plane



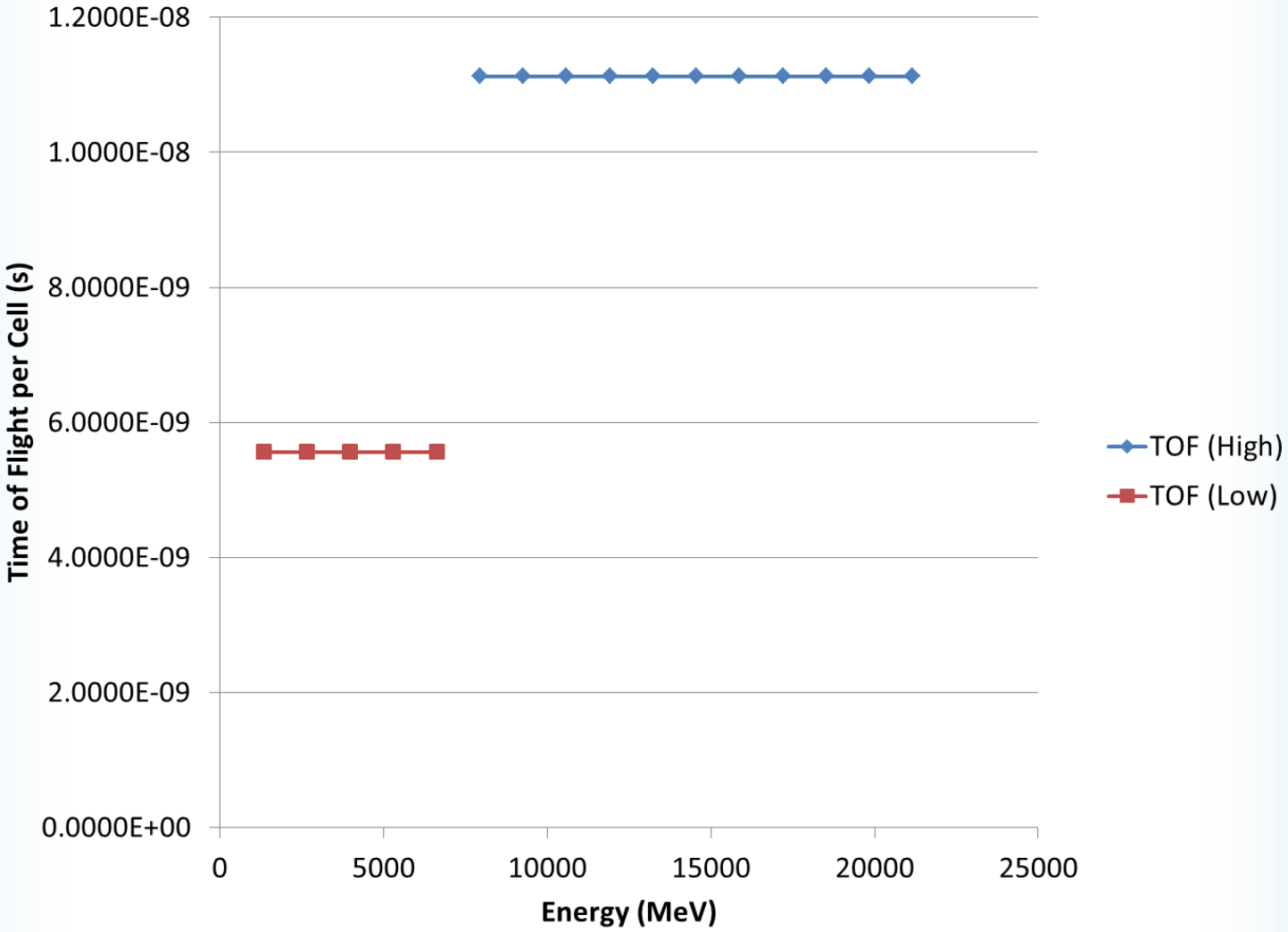
2:1 Betas at Matching Plane



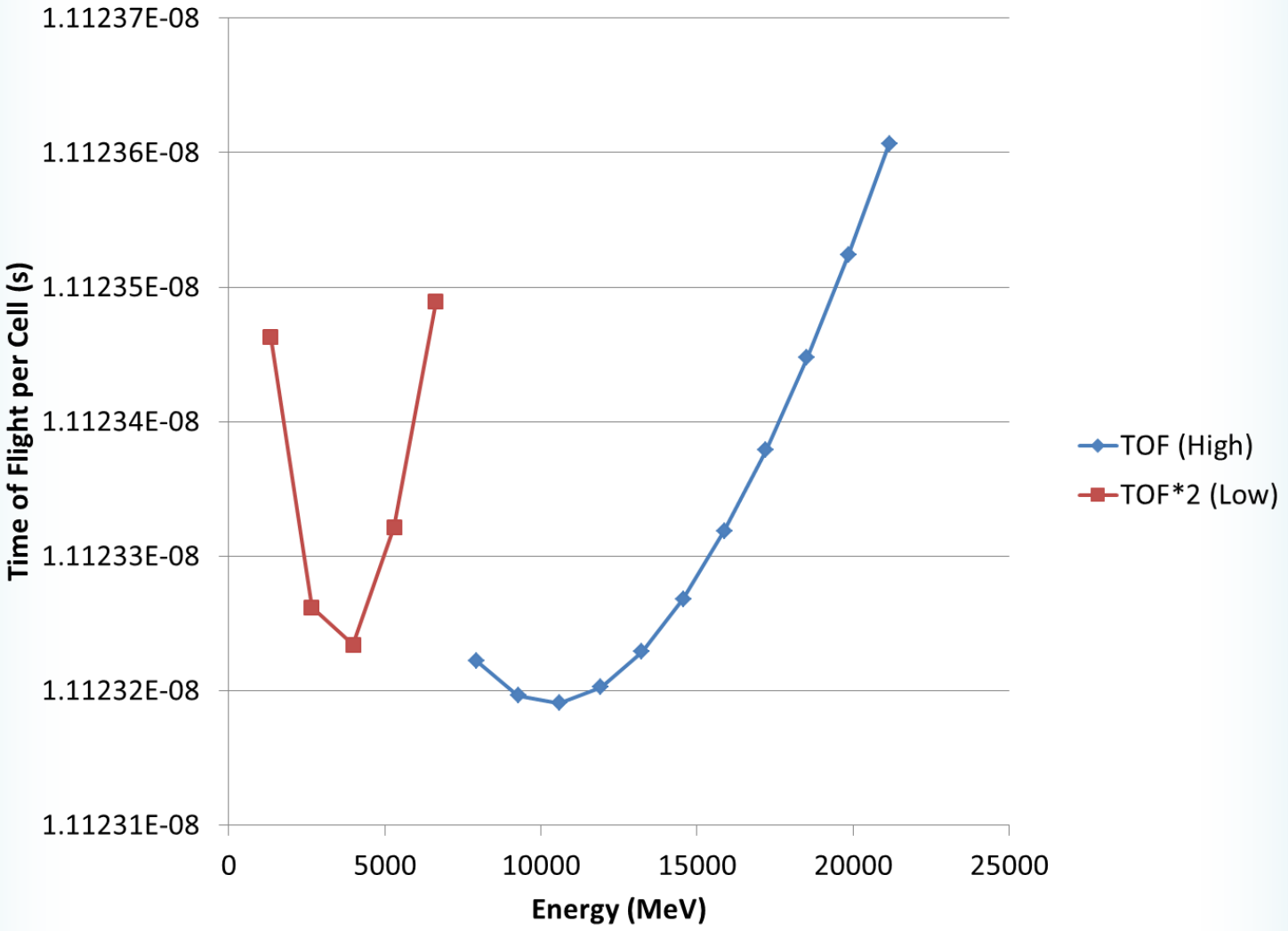
Jan'14 Time of Flight Variation



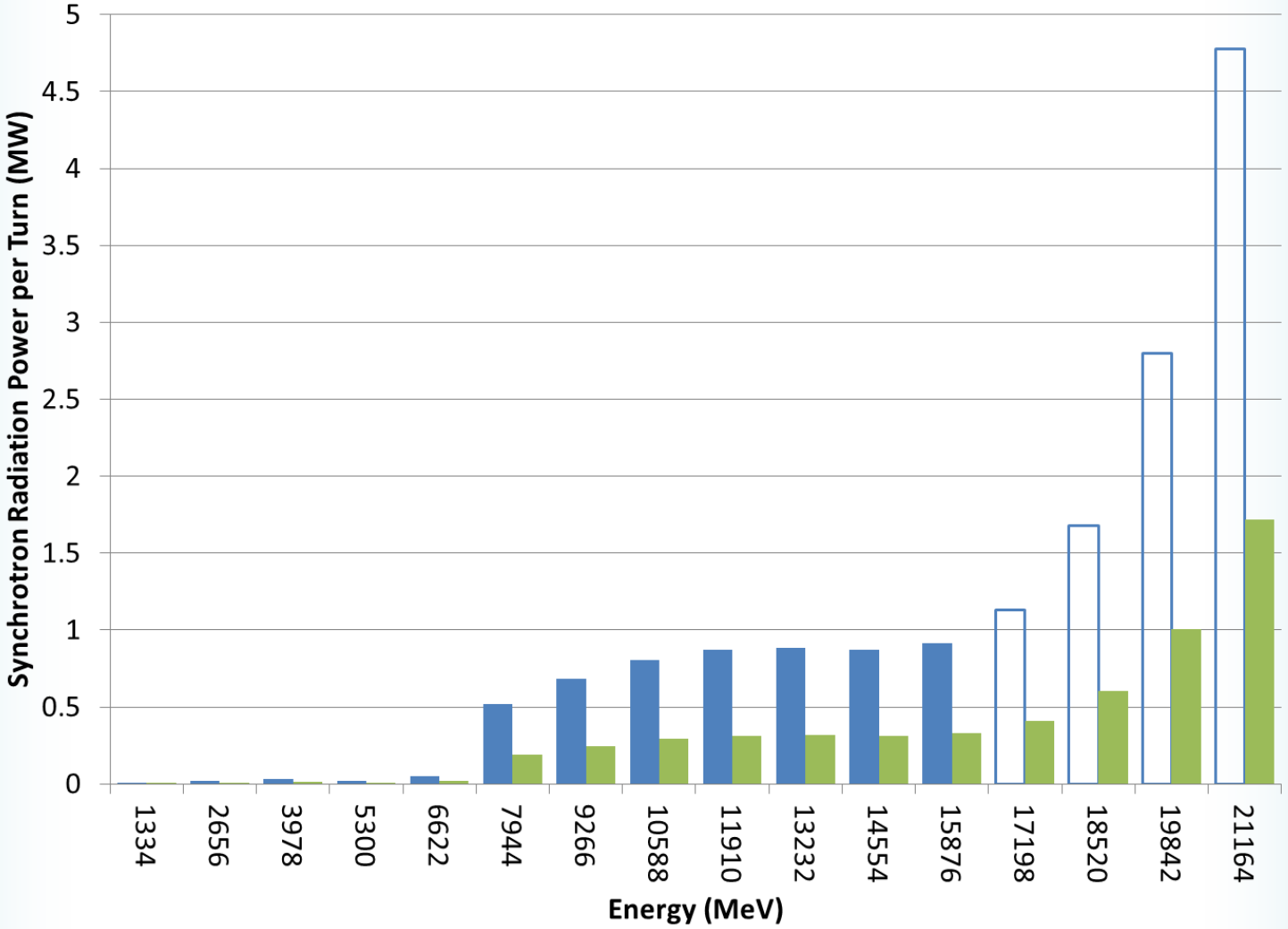
2:1 Time of Flight Variation



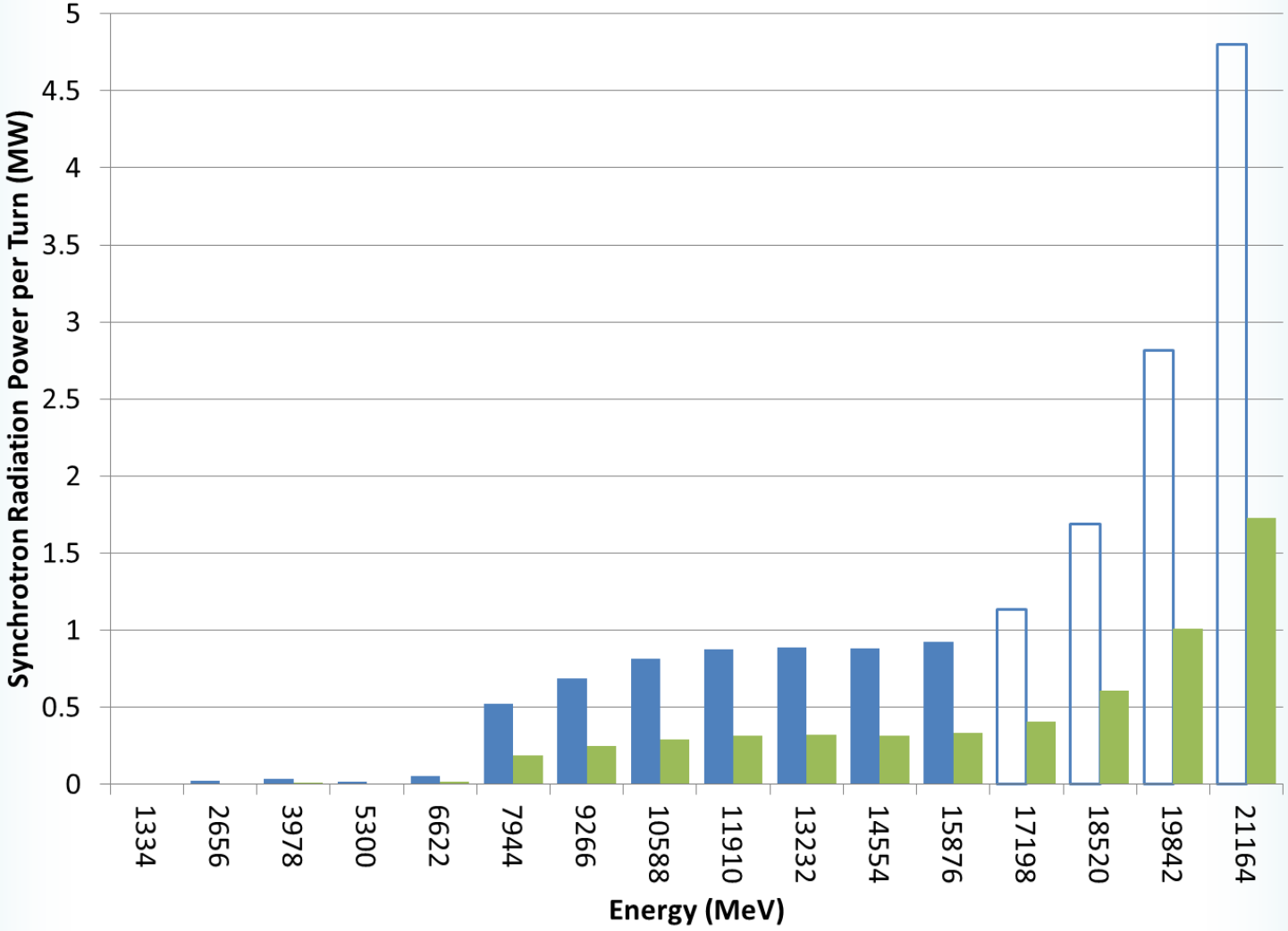
2:1 Time of Flight Variation



Jan'14 SR Loss for Each Turn



2:1 SR Loss for Each Turn

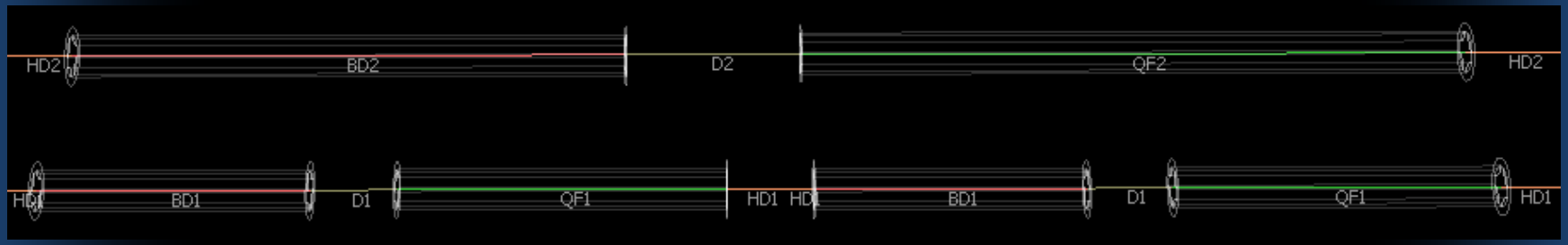


Adiabatic Matching, Ring Closure

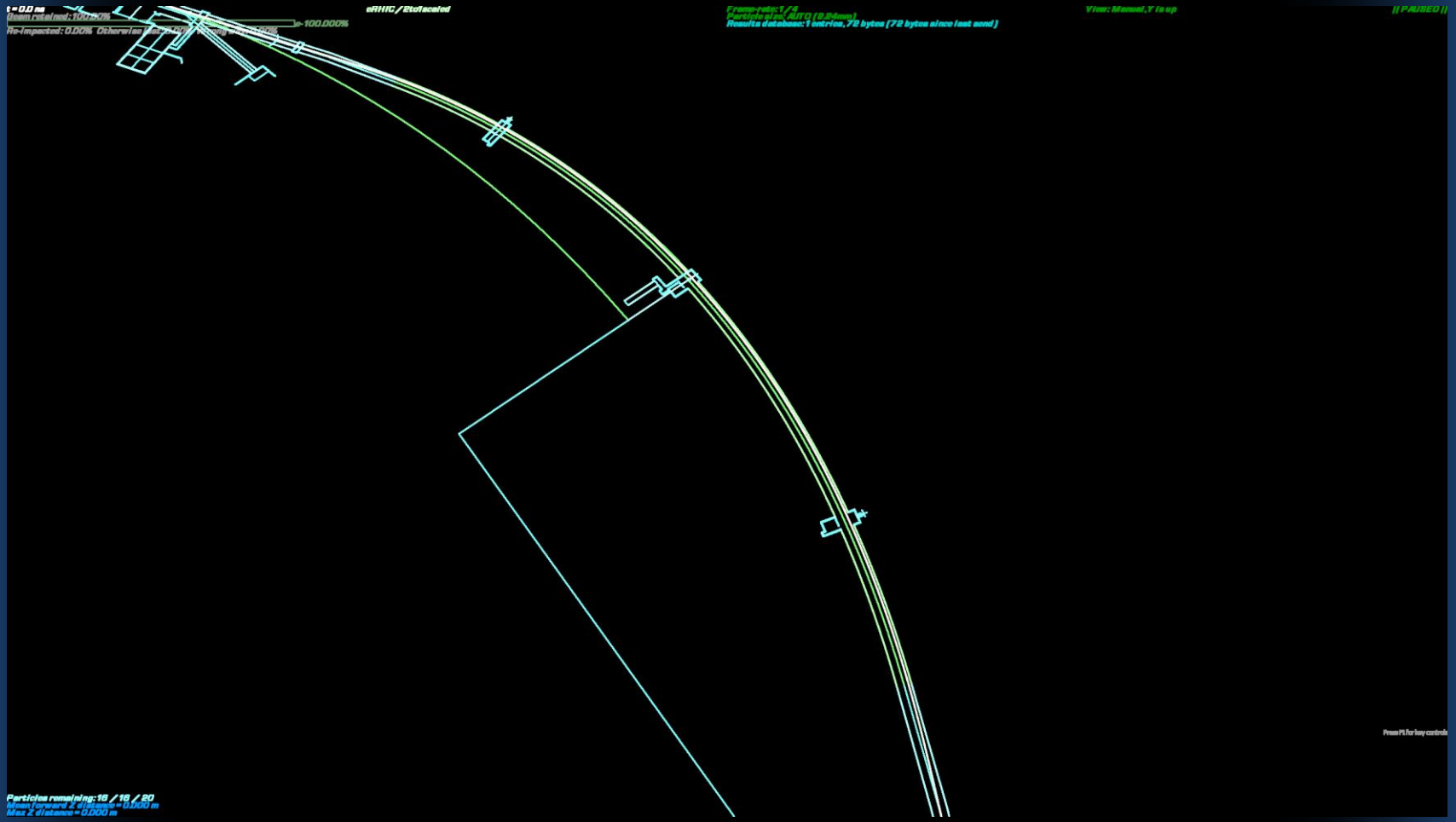
Cells in…	Jan'14	2:1 FFAG1	2:1 FFAG2
Arc	138	212	106
Transition	17	28	14
Straight	76	116	58
Ring (6,10,5)	1378	2132	1066
Both rings	2756		3198 (+16%)

- The numbers of cells above keep the ring in the tunnel and provide adequate matching

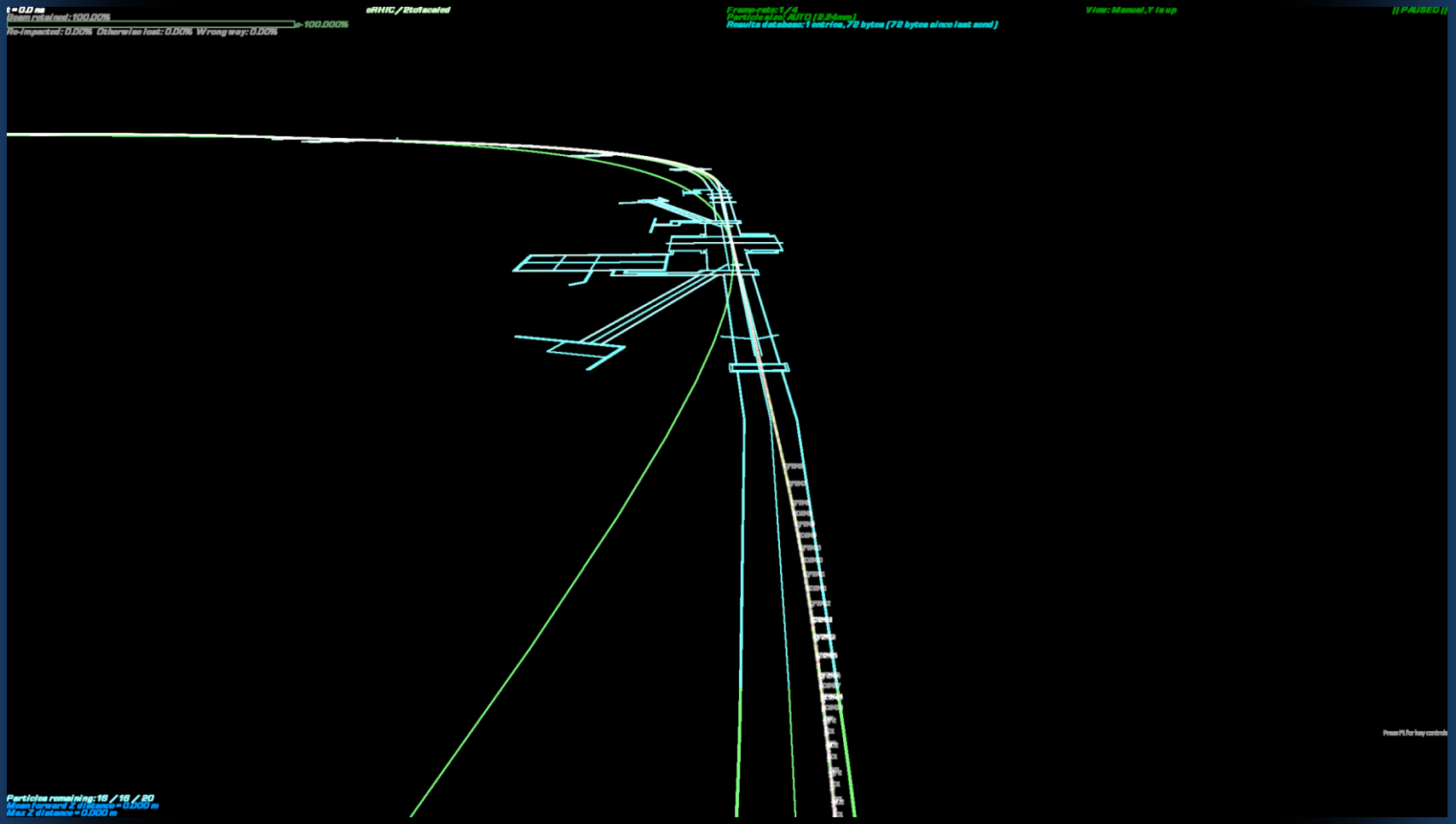
One Arc Cell of FFAG2
Two of FFAG1



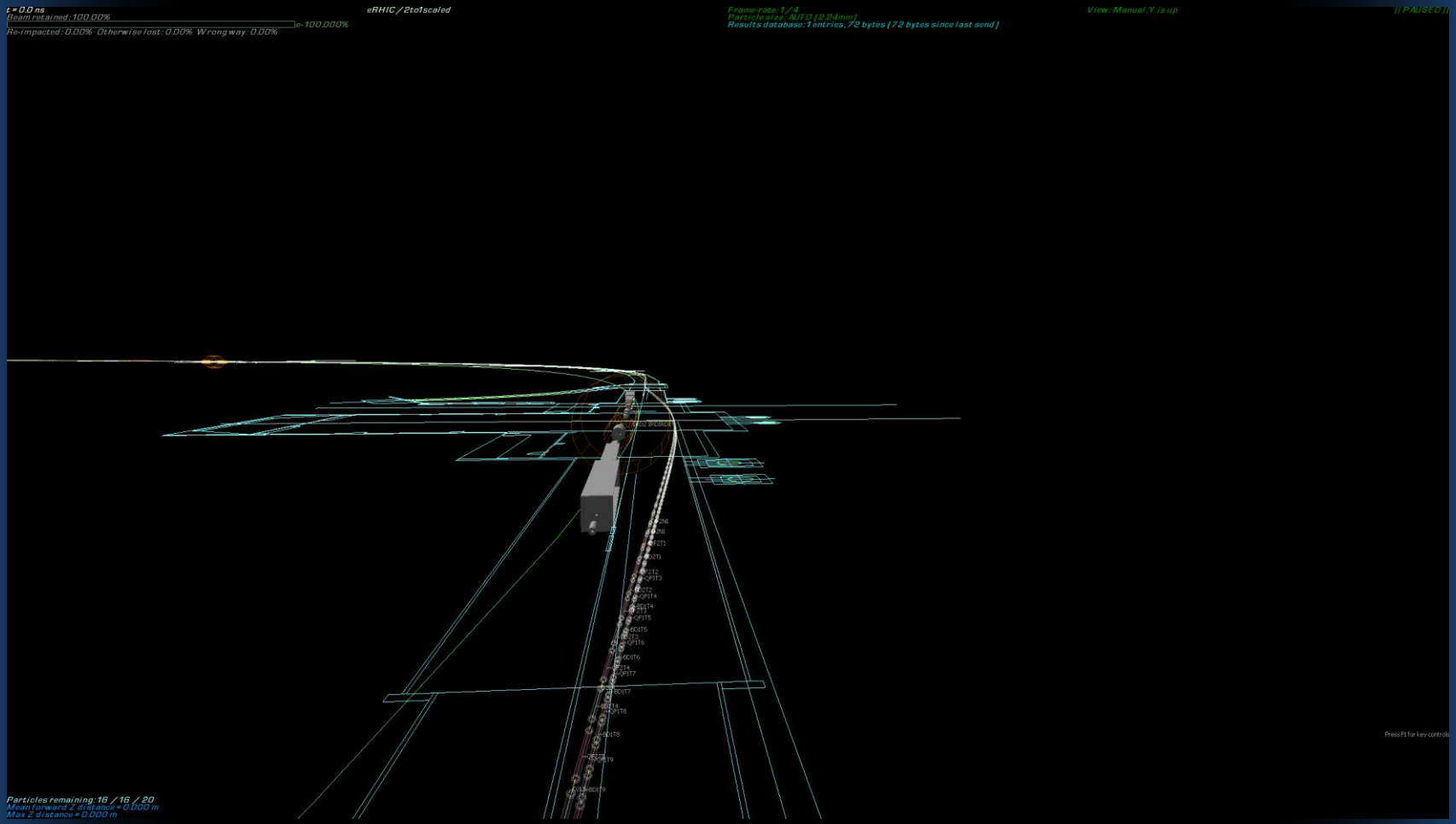
Lattice in Arc



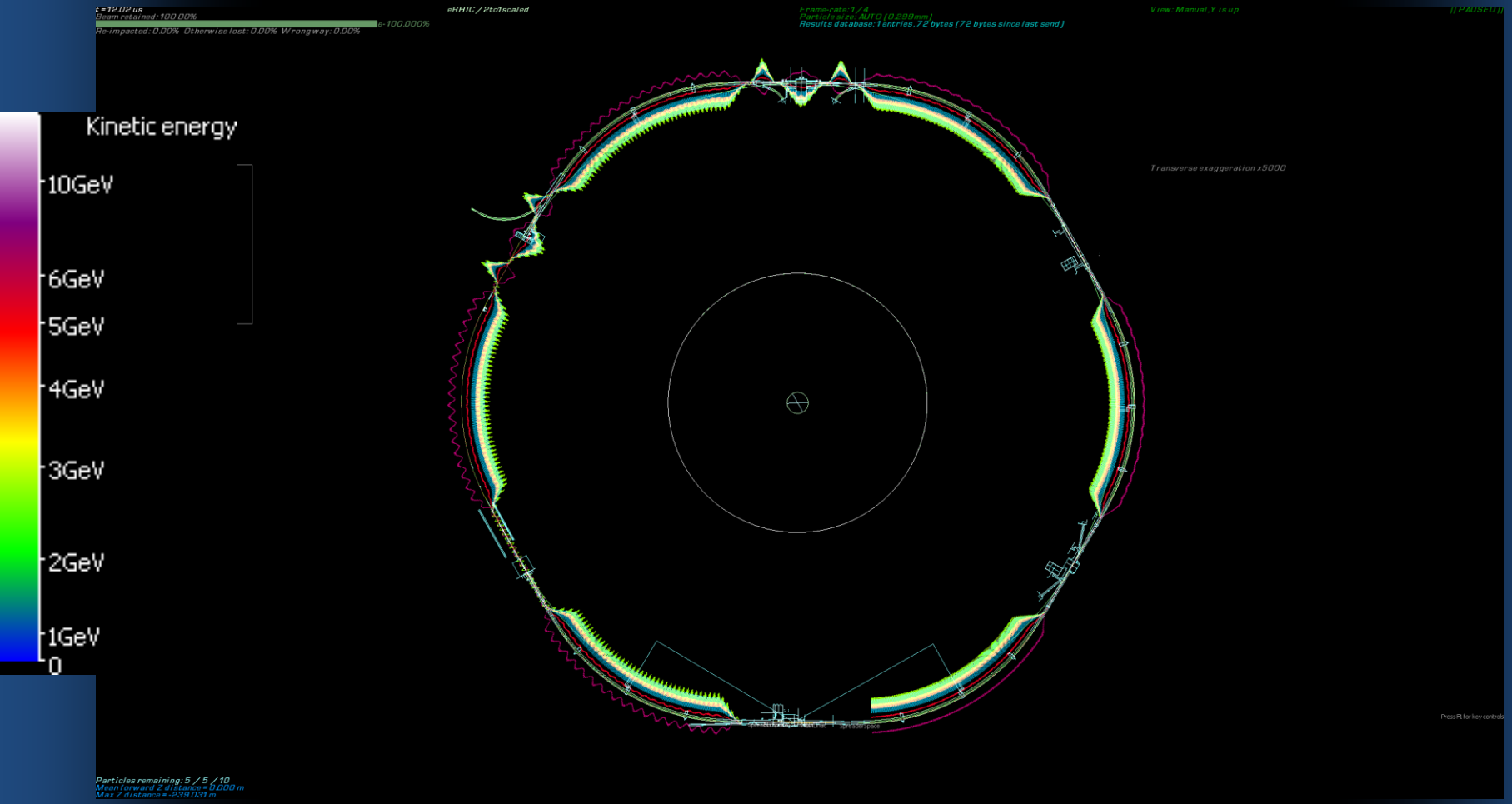
Transition to Straight Tunnel



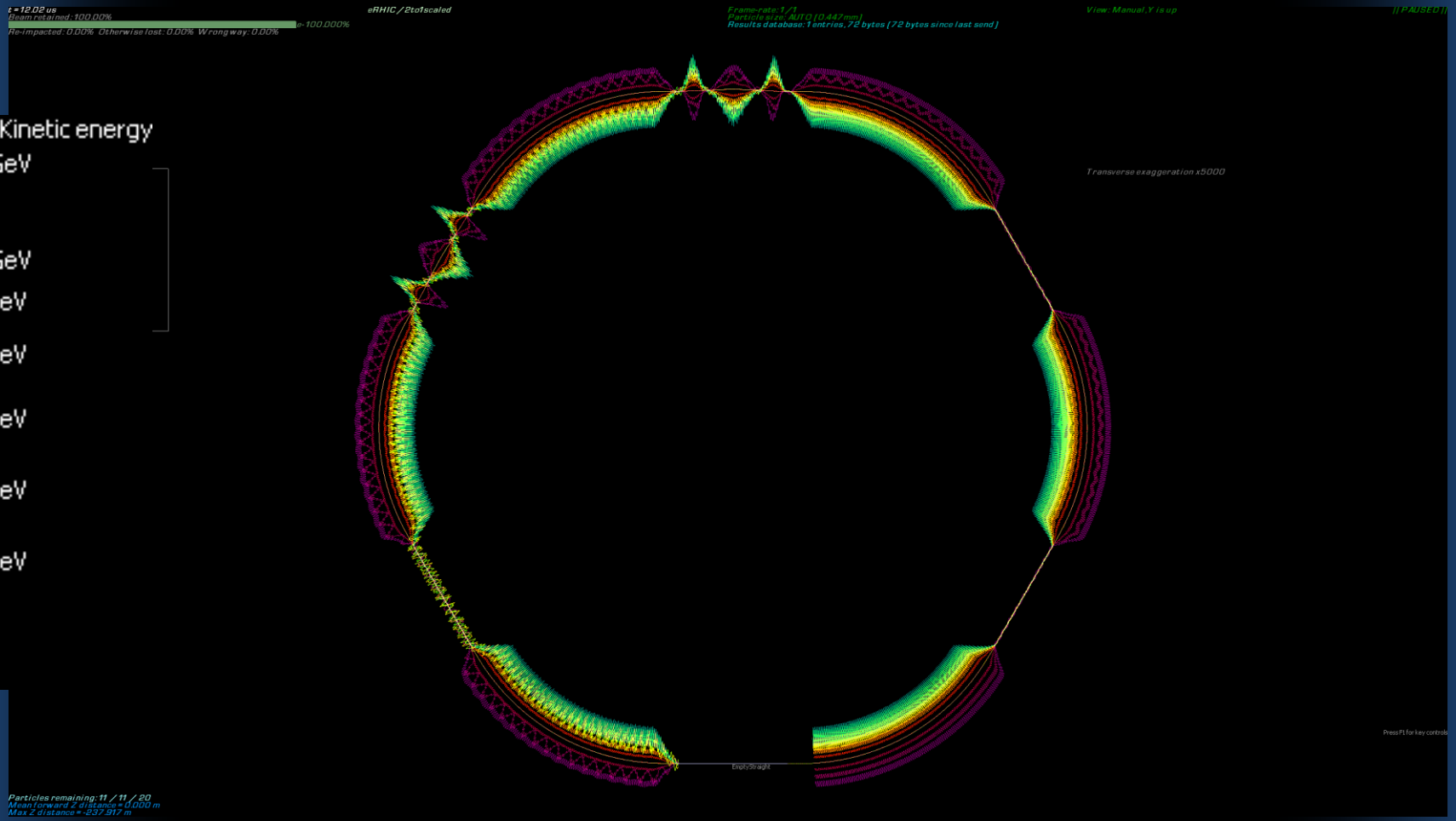
Detector Bypass (PHENIX)



Whole Ring Tracking (FFAG1)

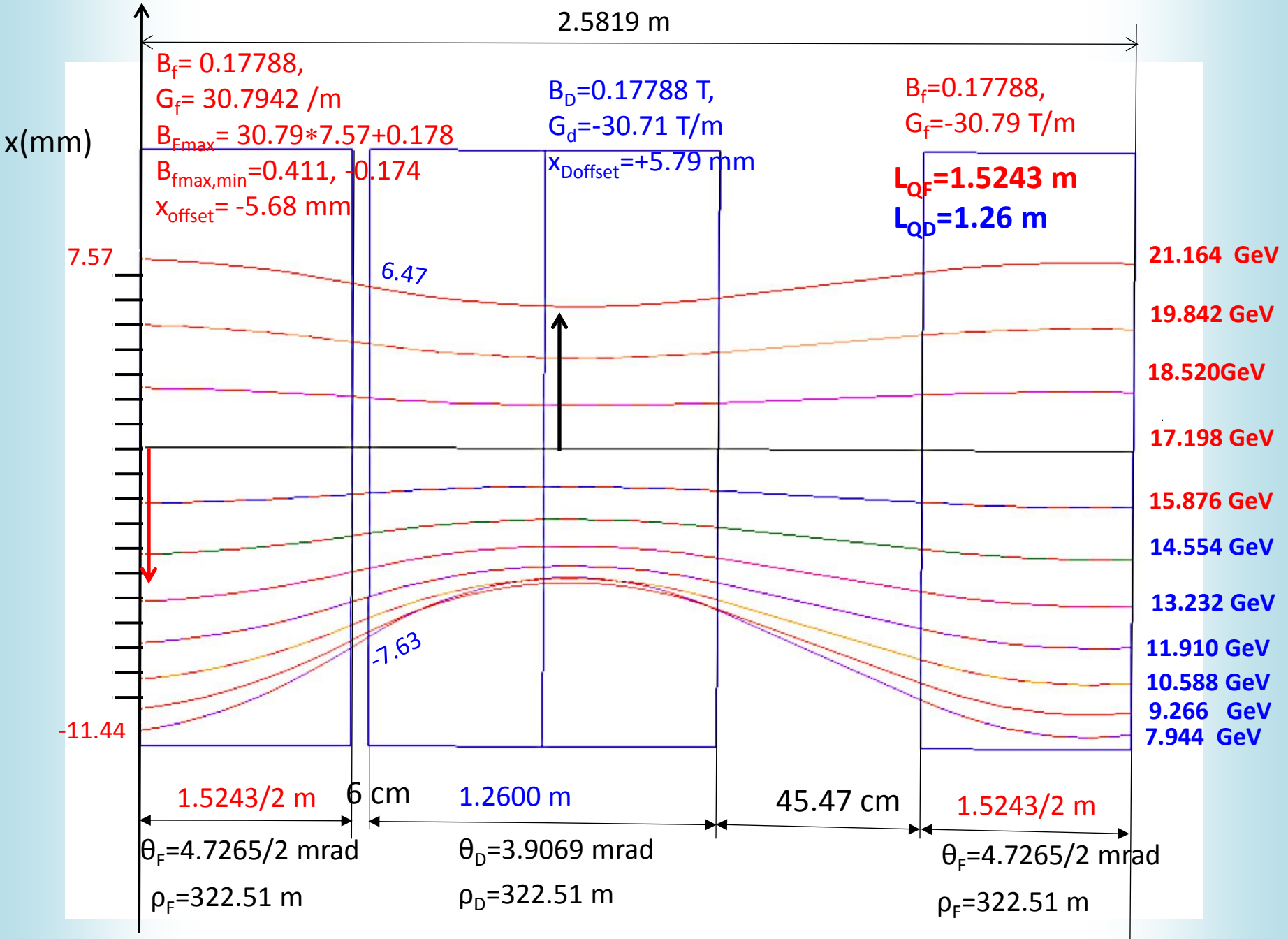


Whole Ring Tracking (FFAG2)



Doublet Design with 45cm Drift

Lattice by Dejan Trbojevic


2.5819 m
x(mm)
B_f= 0.17788,
G_f= 30.7942 /m
B_{Fmax}= 30.79*7.57+0.178
$B_{fmax,min}$=0.411, -0.174
x_{offset}= -5.68 mm
B_D=0.17788 T,
G_d=-30.71 T/m
$x_{Doffset}$=+5.79 mm
B_f=0.17788,
G_f=-30.79 T/m
L_{QF}=1.5243 m
L_{QD}=1.26 m
7.57
6.47
-7.63
-11.44
21.164 GeV
19.842 GeV
18.520GeV
17.198 GeV
15.876 GeV
14.554 GeV
13.232 GeV
11.910 GeV
10.588 GeV
9.266 GeV
7.944 GeV
1.5243/2 m
6 cm
1.2600 m
45.47 cm
1.5243/2 m
θ_F=4.7265/2 mrad
ρ_F=322.51 m
θ_D=3.9069 mrad
ρ_D=322.51 m
θ_F=4.7265/2 mrad
ρ_F=322.51 m

Lattice Performance Comparison

Lattice (for FFAG2)	FODO-Jan'14 (50T/m)	Triplet (40T/m)	Doublet (30T/m)
SR loss at 15.9GeV	10.3MW	10.9MW	9.7MW
Max B field on orbit	0.451T	0.449T	0.420T
TOF variation	22.4ppm	29.3ppm	33.7ppm
Max current at 21GeV (for 10MW SR in arcs)	18.4mA	18.0mA	19.6mA

- This is likely to form the basis of the next major eRHIC lattice revision, I think only minor optimisations are now needed.