“2:1” Scaled eRHIC FFAG Design

Featuring ≤30T/m quadrupoles

FFAG2 Orbits Too Close Together?

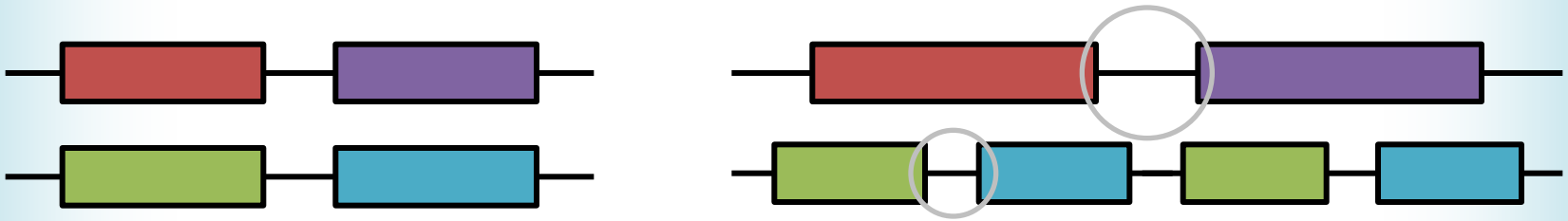
- Magnet vertically at least 8mm away from orbits that are within 9.1mm of quad centre
  - Difficult to produce field “at a distance”
- Vladimir mentioned close-together orbits aren’t very good for extraction
  - Low beta function also not good
- High gradient (small orbit range) increases sensitivity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

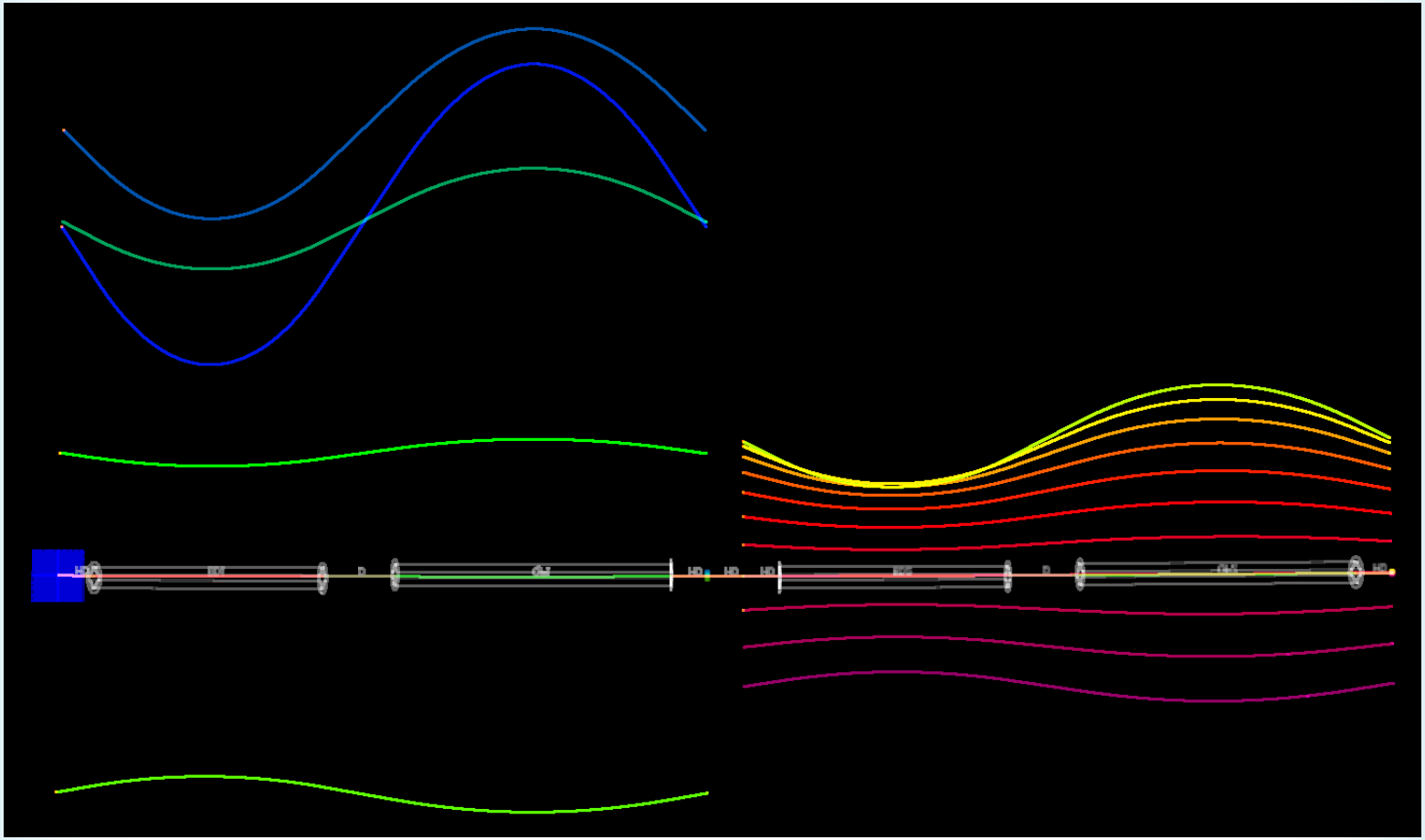
Current Lattice (Jan'14)

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

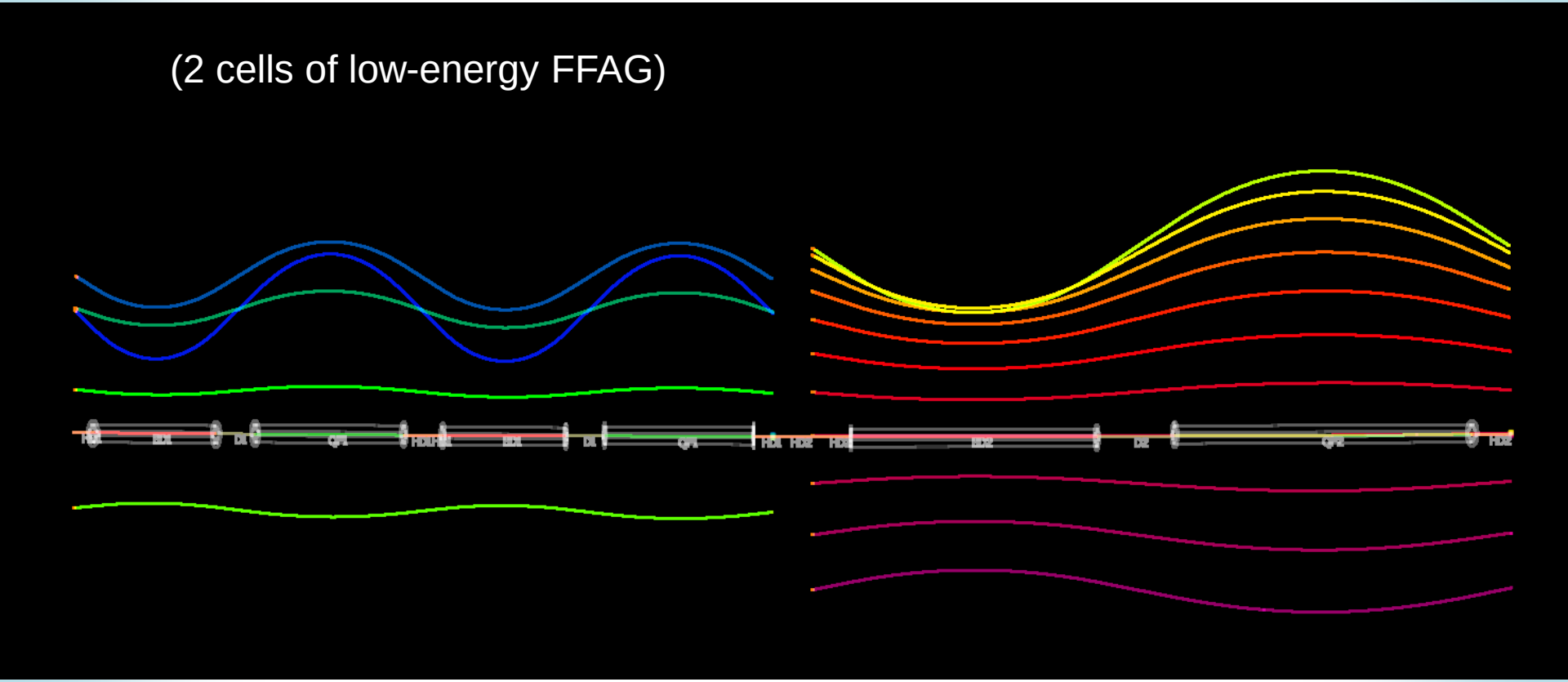
Scaled and 2:1 Stacked Lattice

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

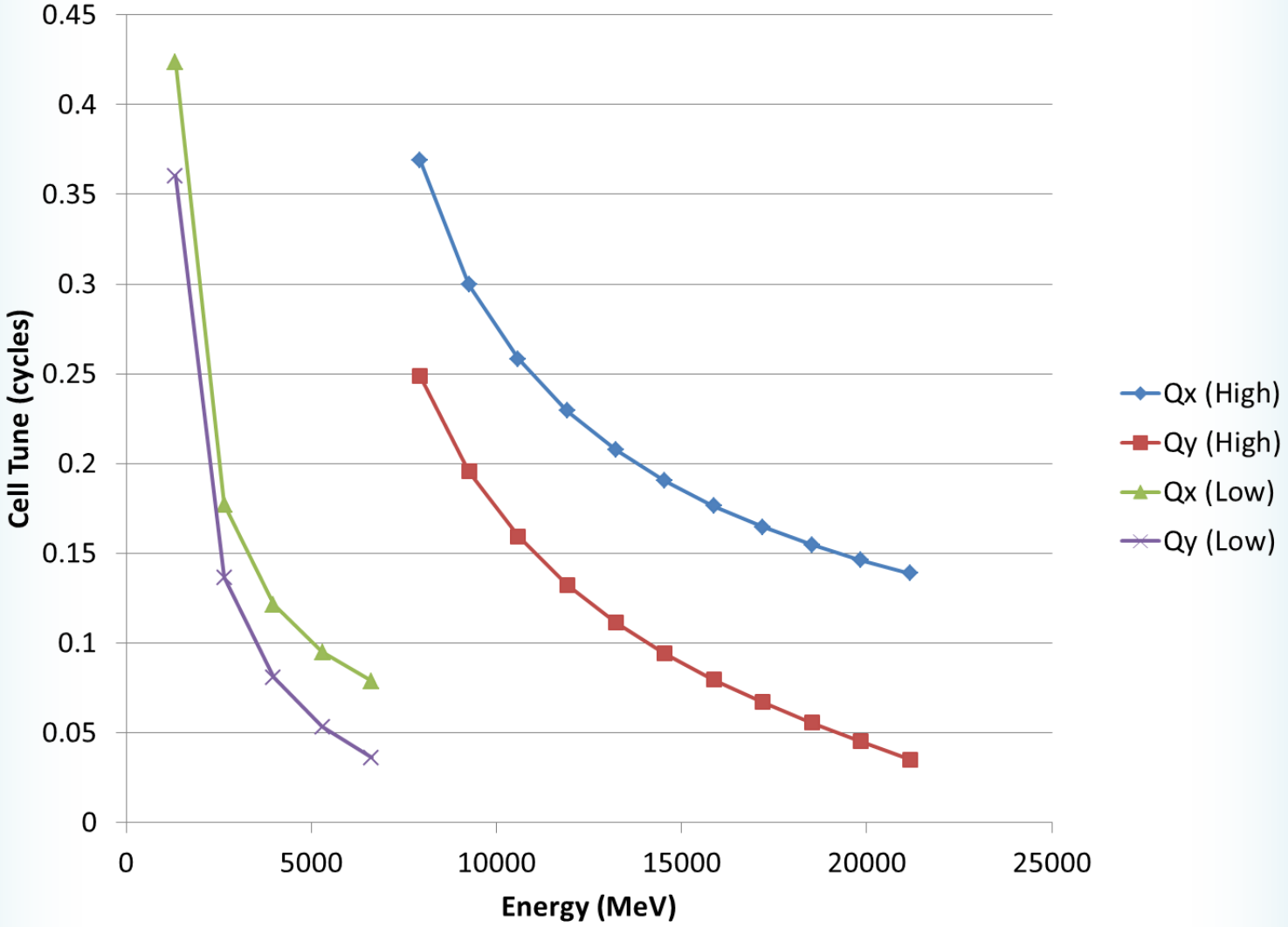
- Cell: ½D,BD,D,QF,½D (length ≈ 2.582m)
- Cells stack exactly, allowing common girder
- Specification on eRHIC Wiki
  - http://www.cadops.bnl.gov/eRHIC/erhicWiki/index.php/FFAG_Design:Electrons:Lattice:Arcs

2:1 Lattice Description

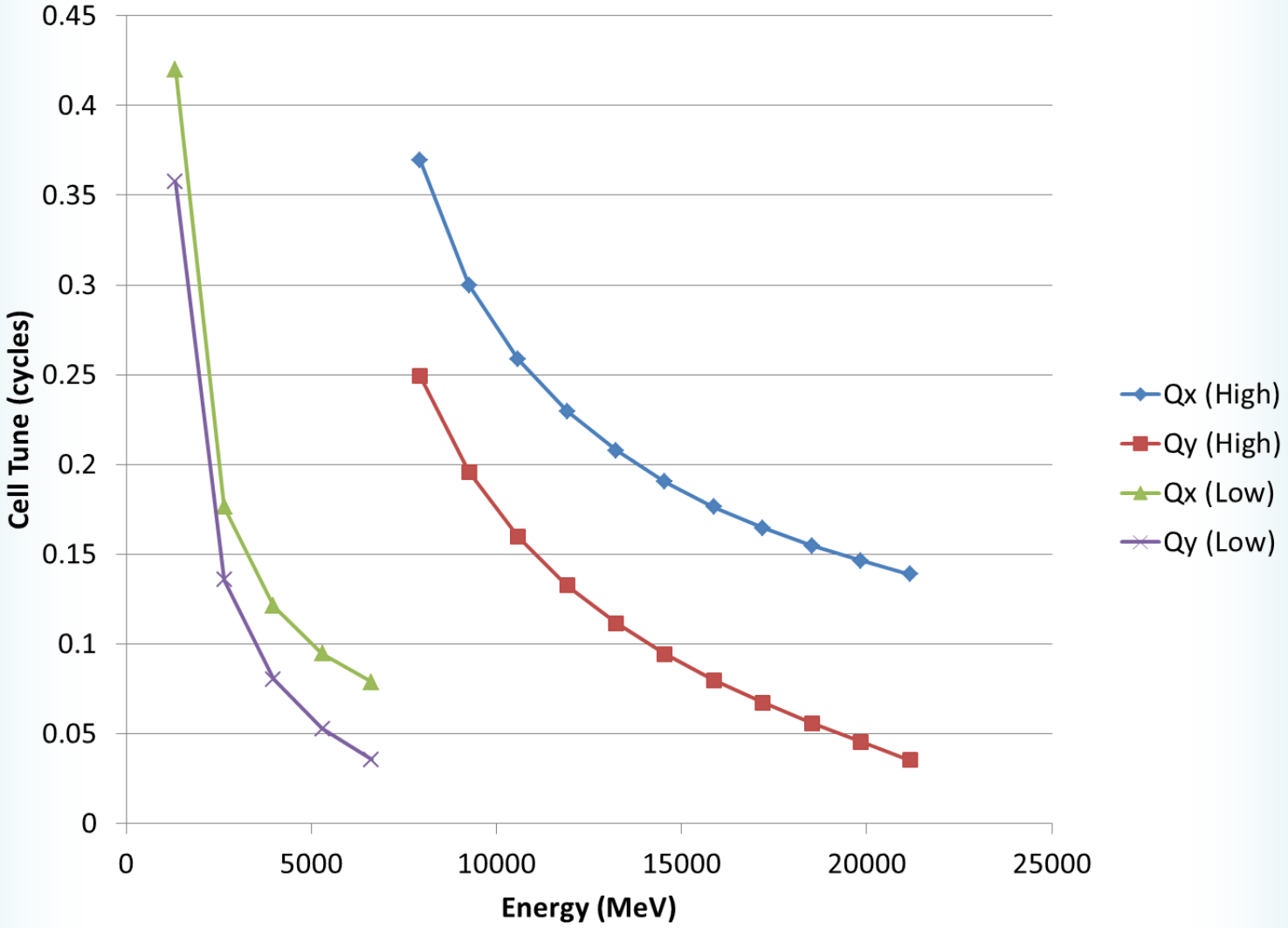
Element	Length (m)	Angle (mrad)	Gradient (T/m)	Offset (mm)
Drift D1 (Low)	0.185756896	0		
Drift D2 (High)	0.371513793	0		
BD1 (Low)	0.586408097	1.974541	23.945	-2.897173
QF1 (Low)	0.709430775	2.388782	-21.595	2.897173
BD2 (High)	1.172816195	3.949082	29.682	-6.507696
QF2 (High)	1.418861550	4.777564	-29.682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

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

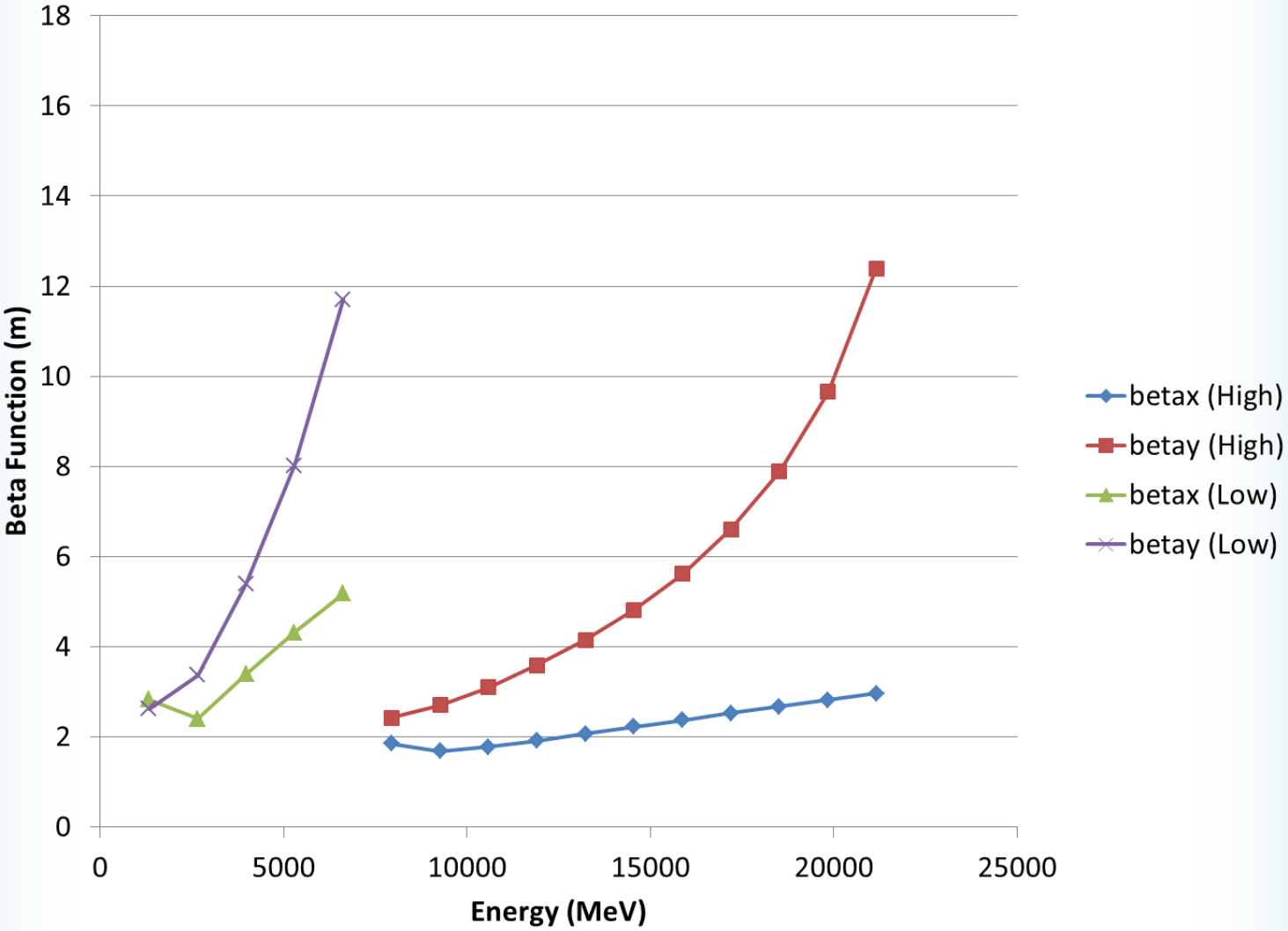
Jan'14 Tunes


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)

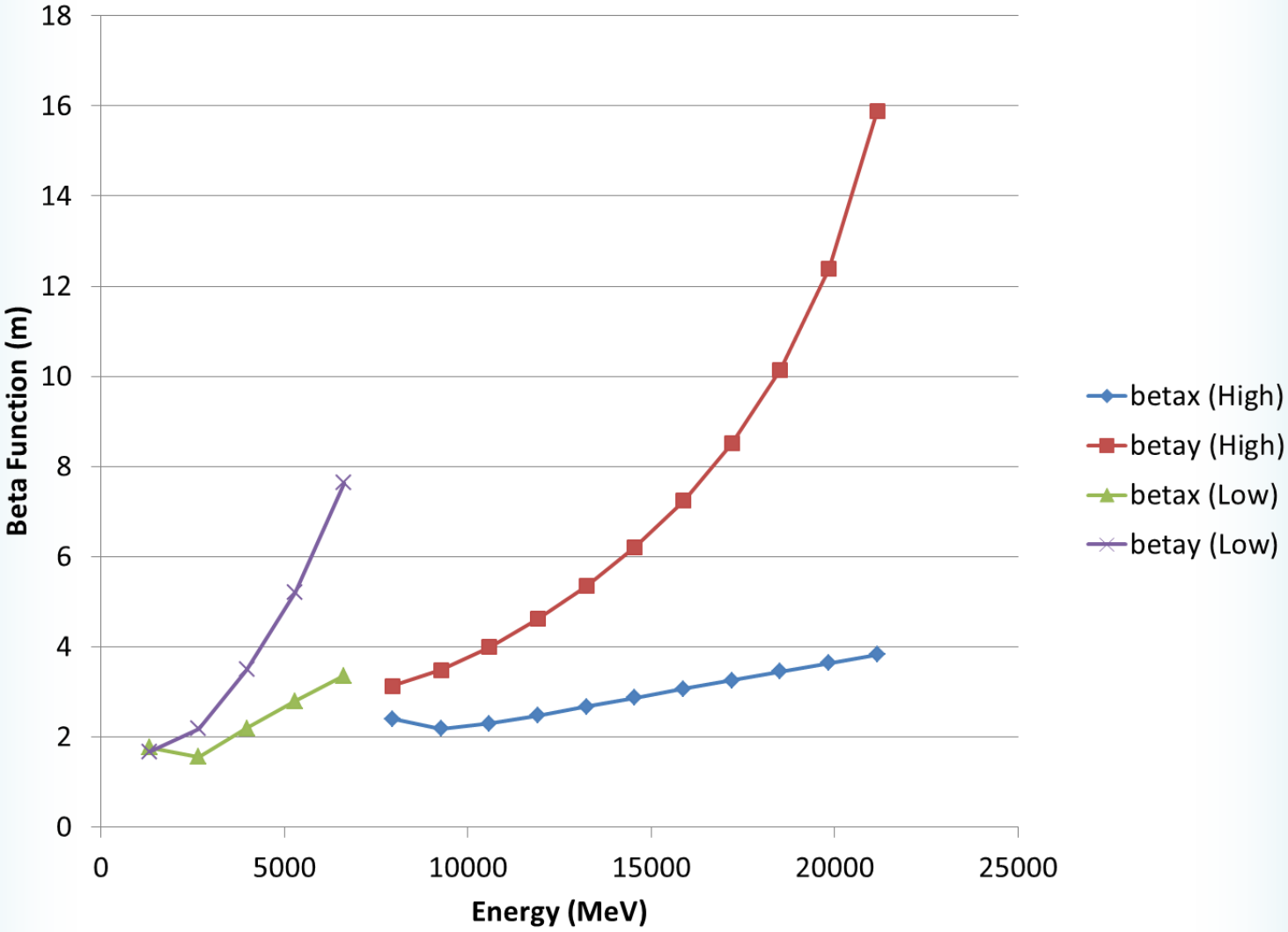
2:1 Tunes


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)

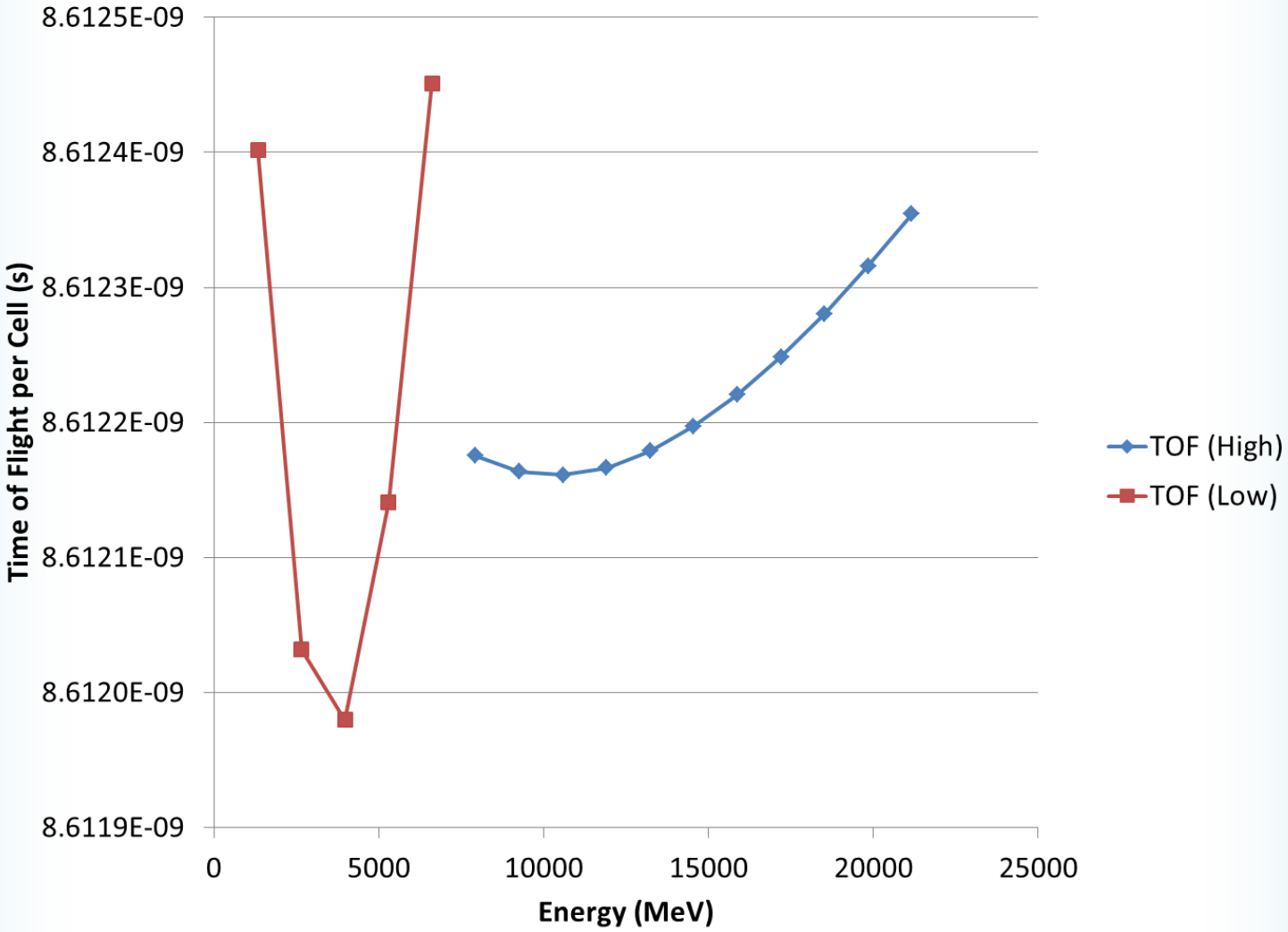
Jan'14 Betas at Matching Plane



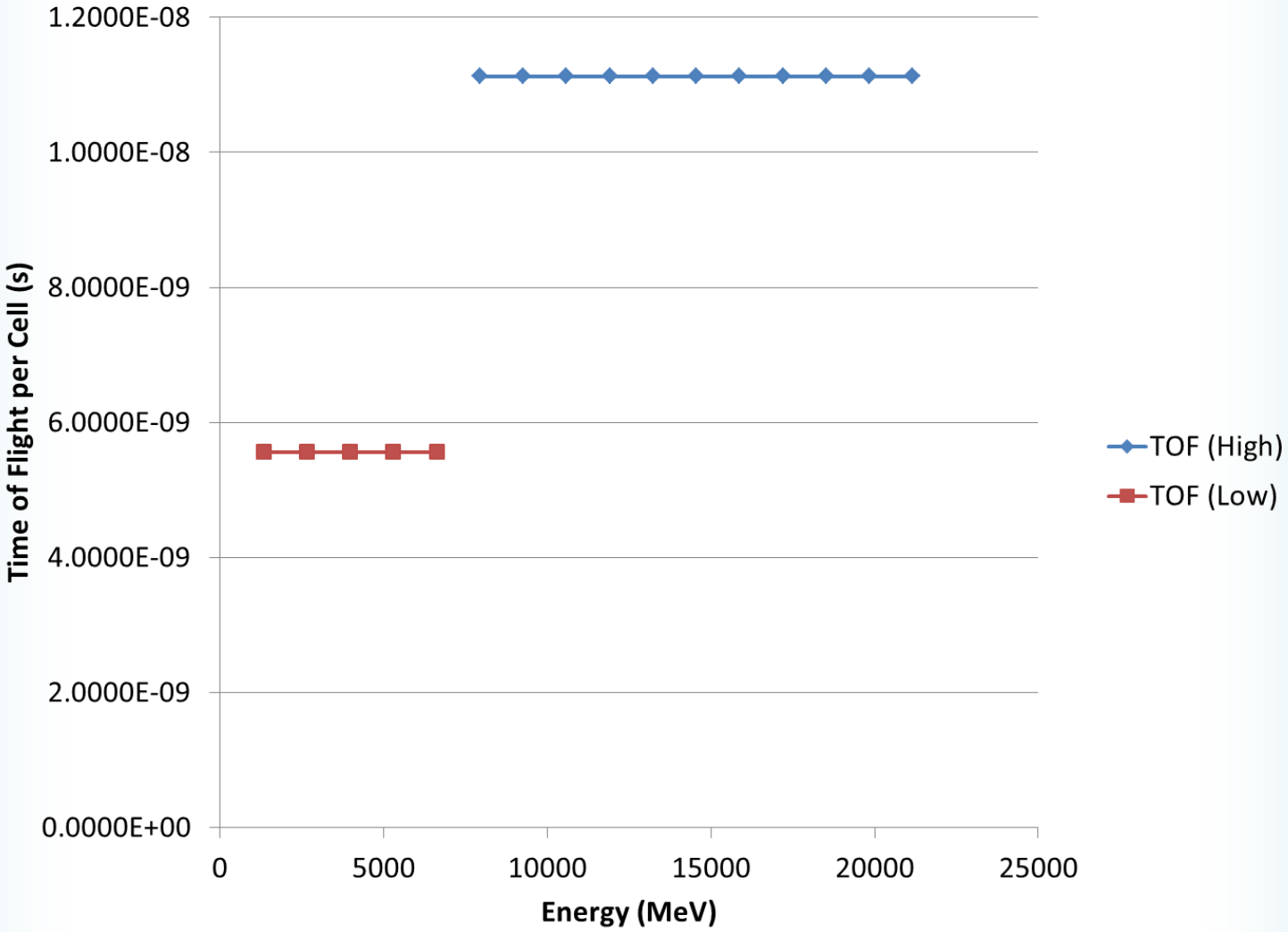
2:1 Betas at Matching Plane



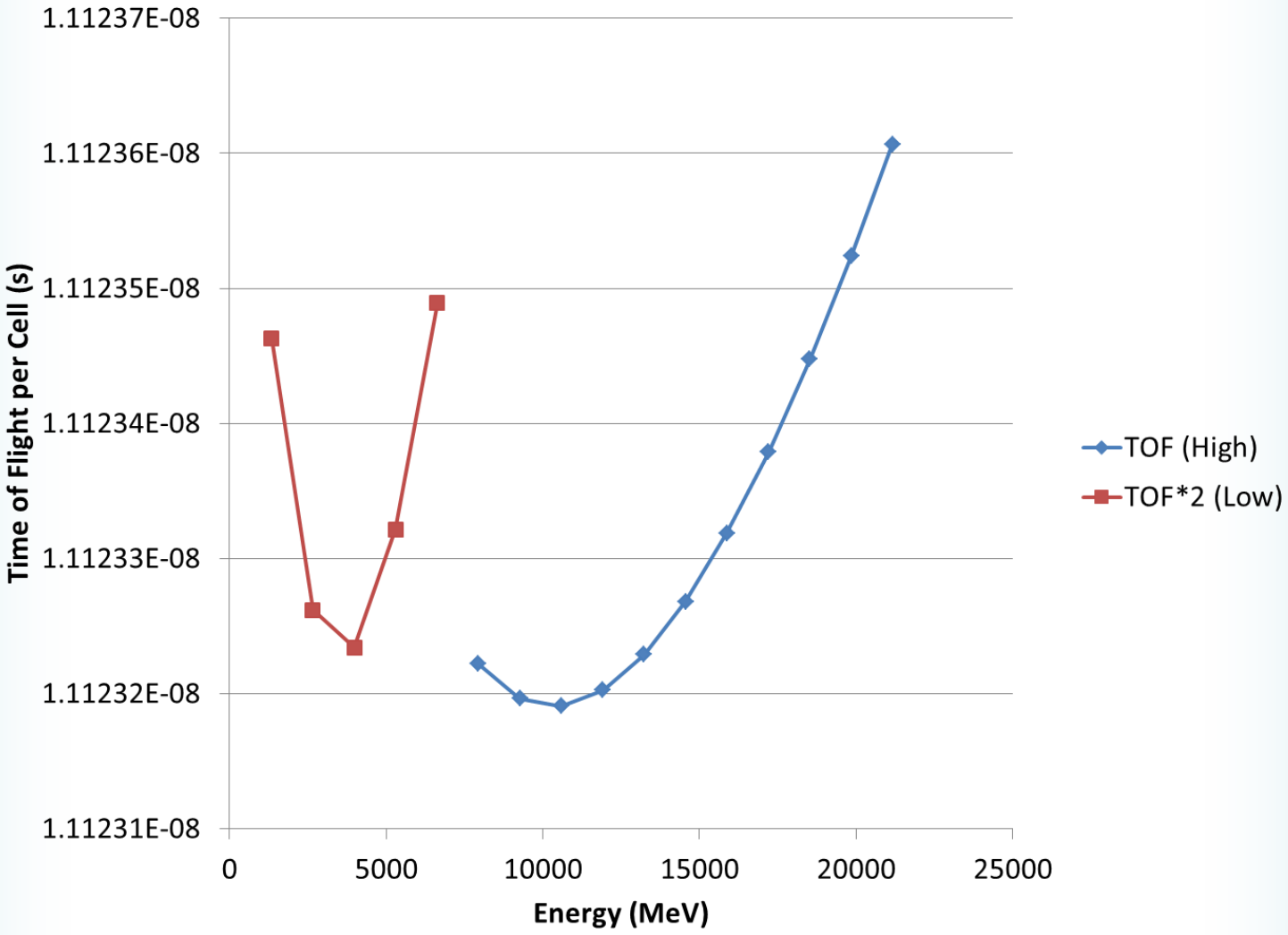
Jan'14 Time of Flight Variation



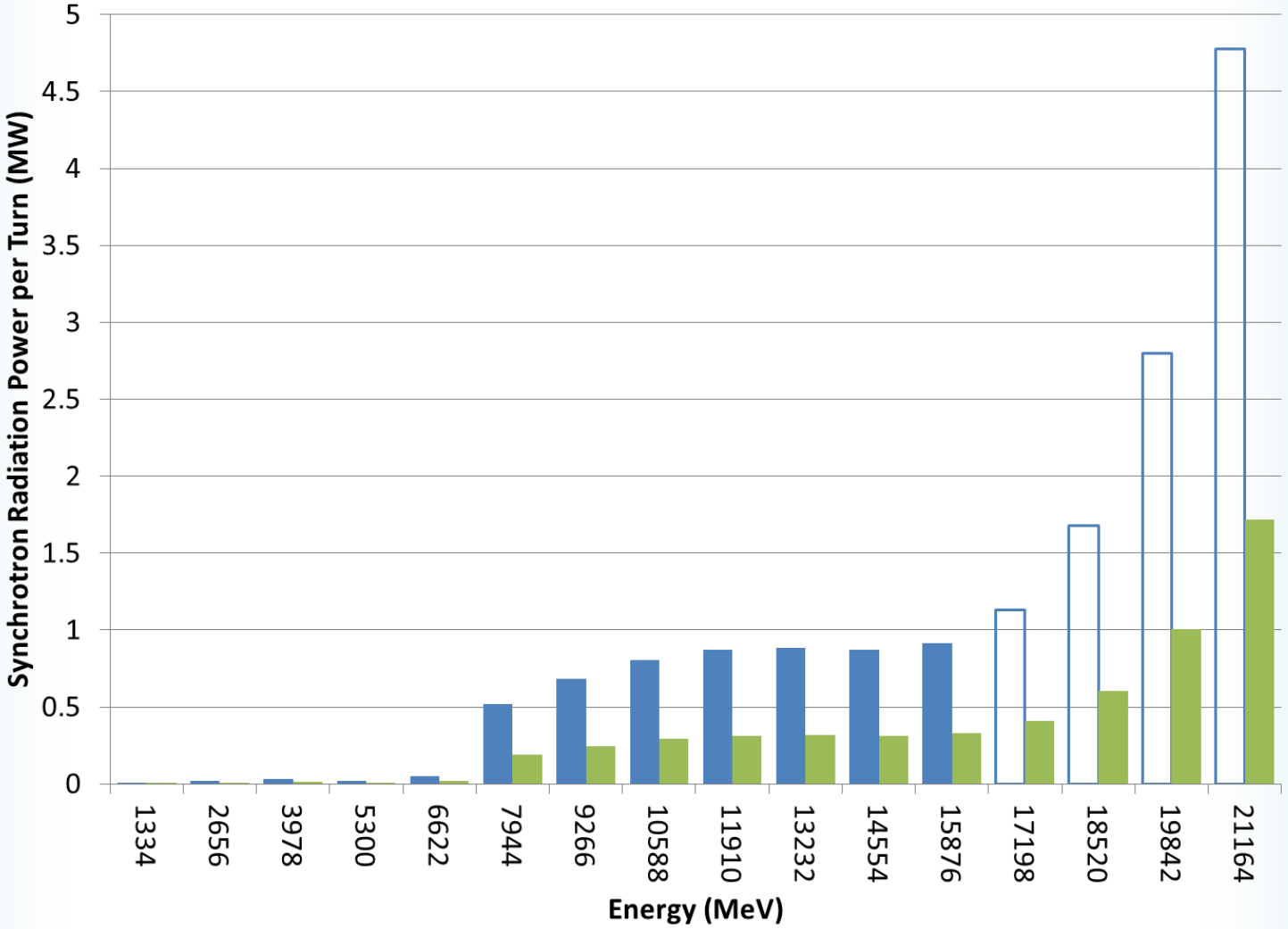
2:1 Time of Flight Variation



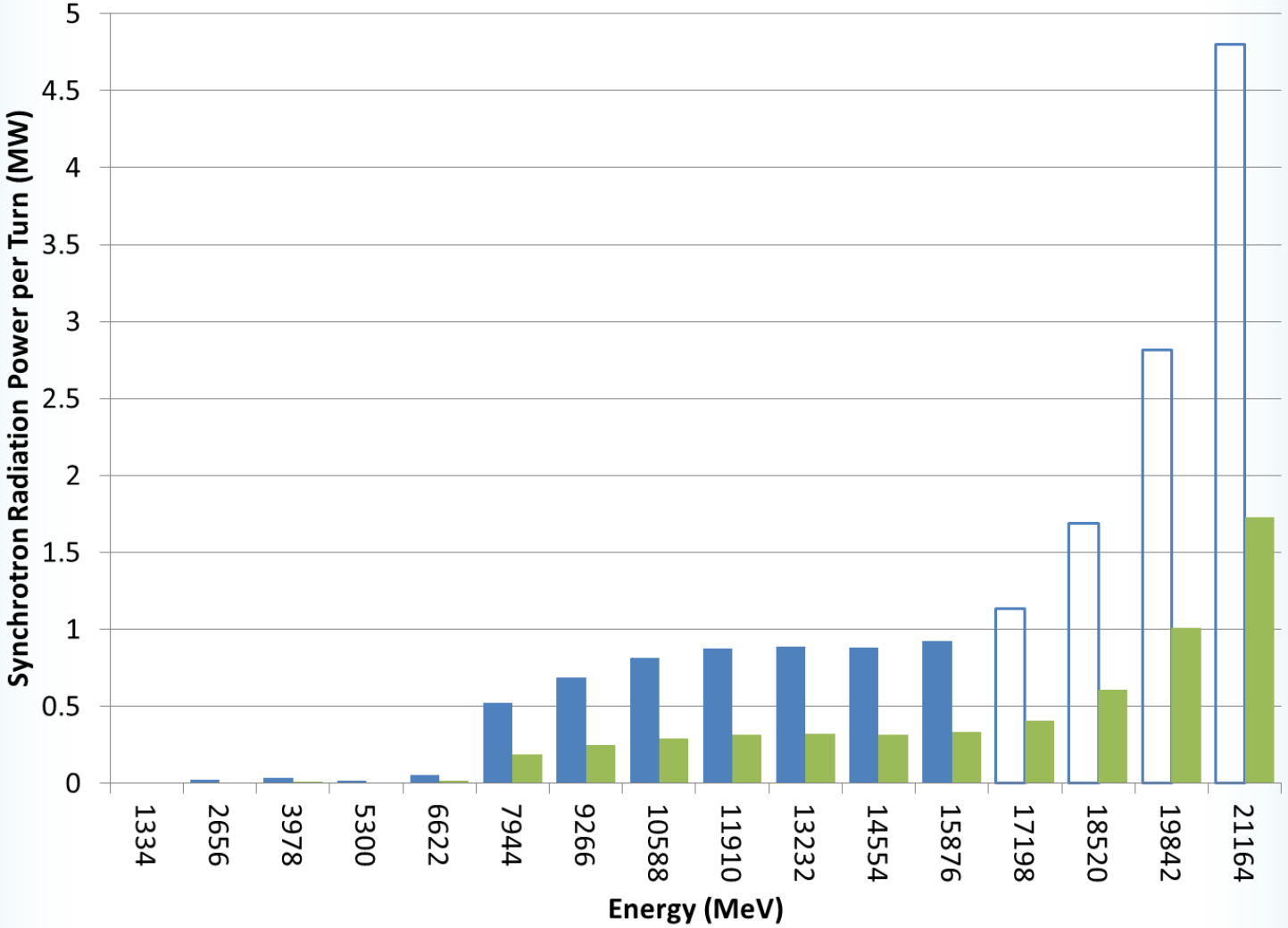
2:1 Time of Flight Variation



Jan'14 SR Loss for Each Turn



2:1 SR Loss for Each Turn

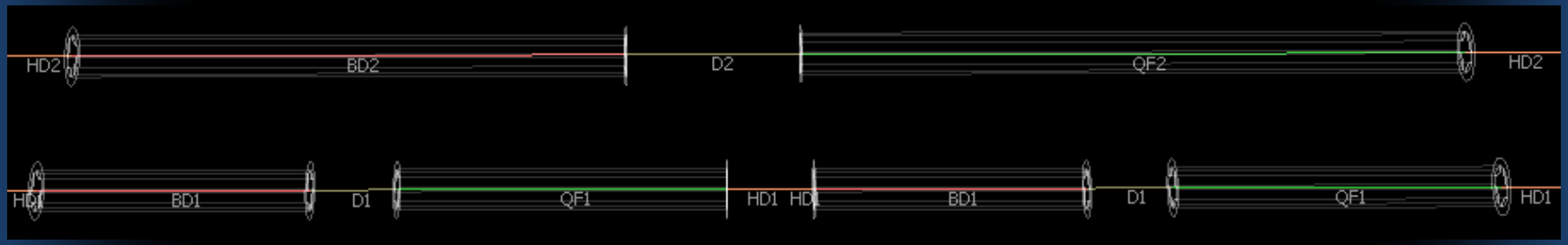


Adiabatic Matching, Ring Closure

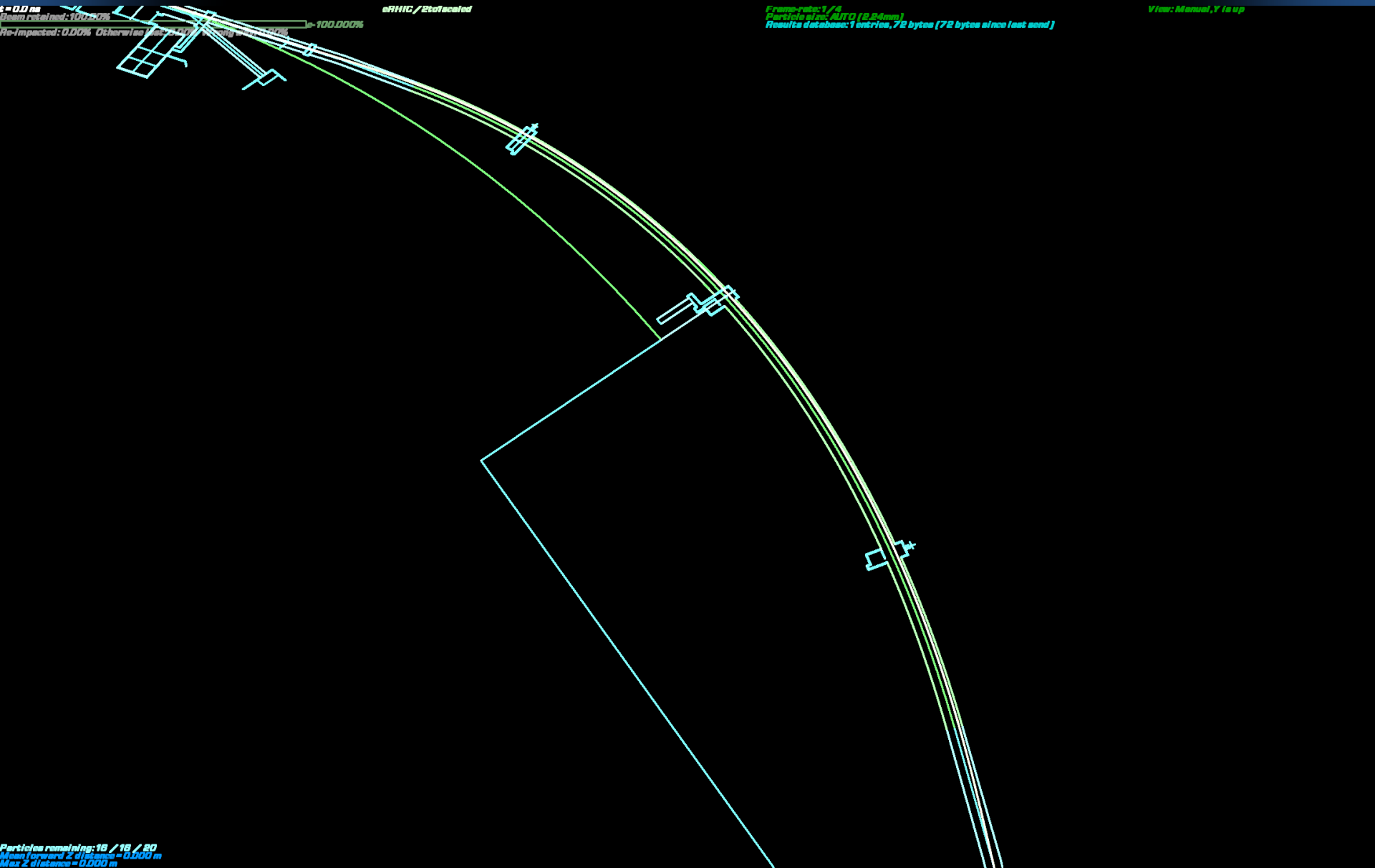
Cells in…	Jan'14	2:1 FFAG1	2:1 FFAG2
Arc	138	212	106
Transition	17	28	14
Straight	76	116	58
Ring (6,10,5)	1378	2132	1066
Both rings	2756		3198 (+16%)

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

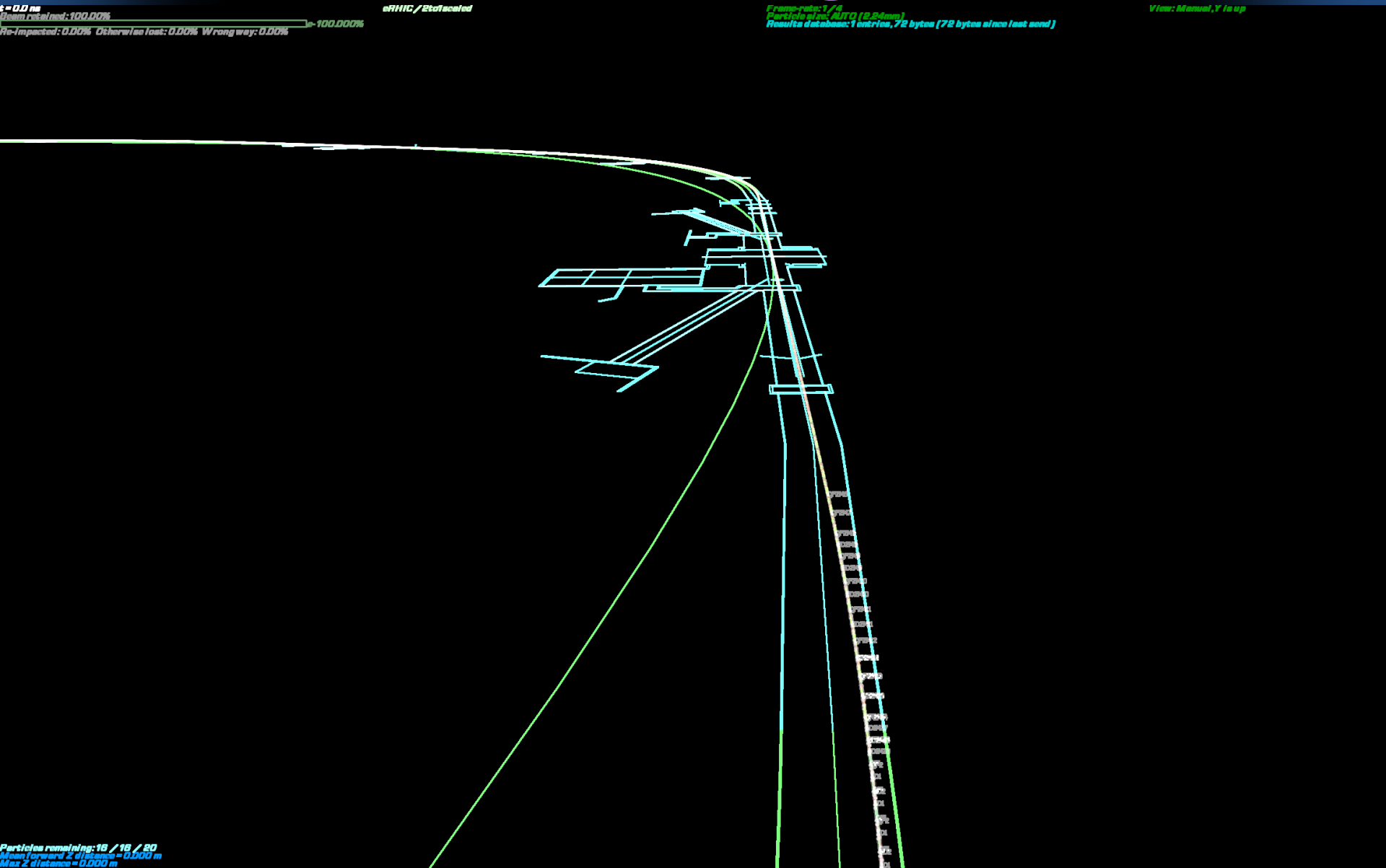
One Arc Cell of FFAG2
Two of FFAG1



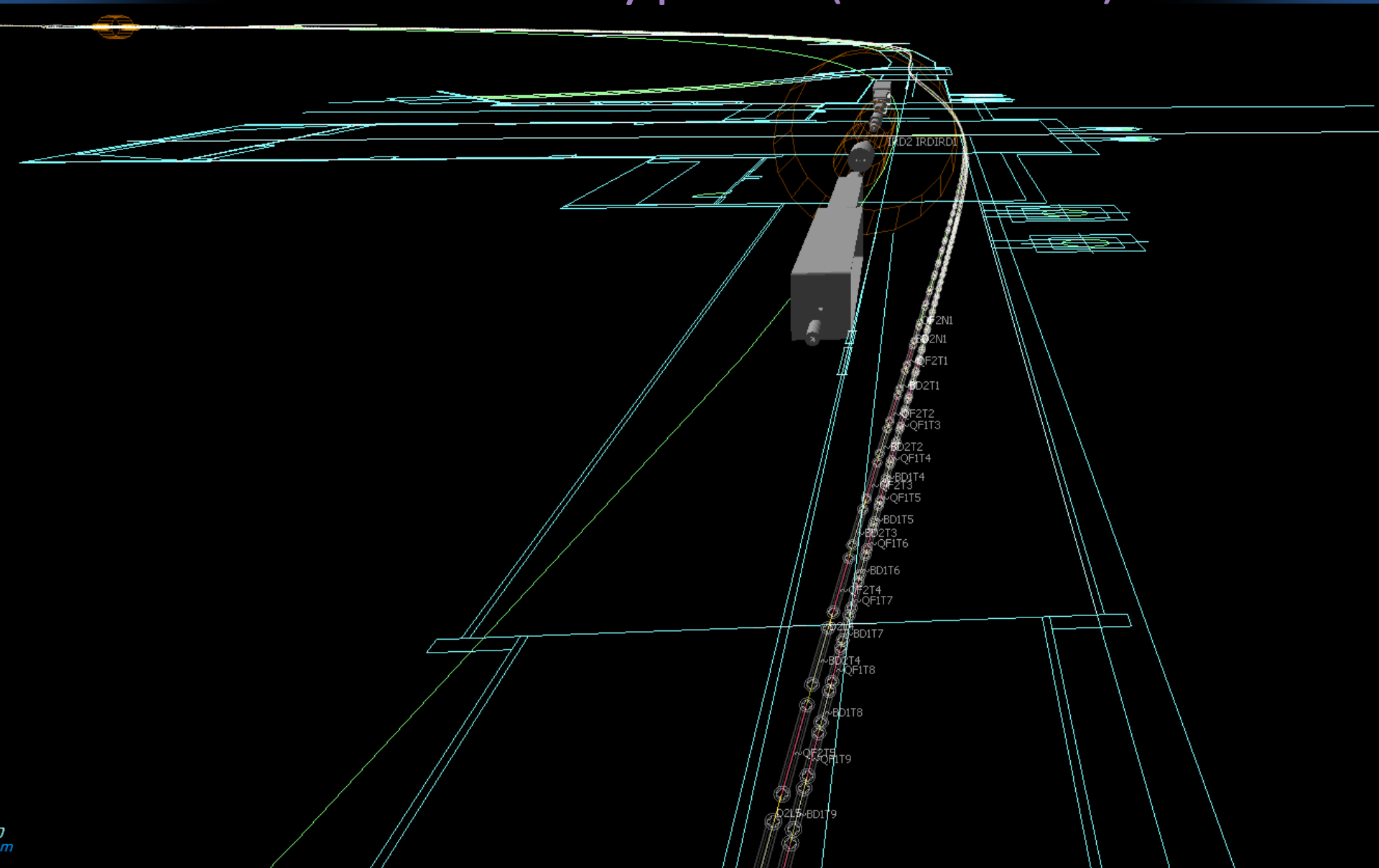
Lattice in Arc



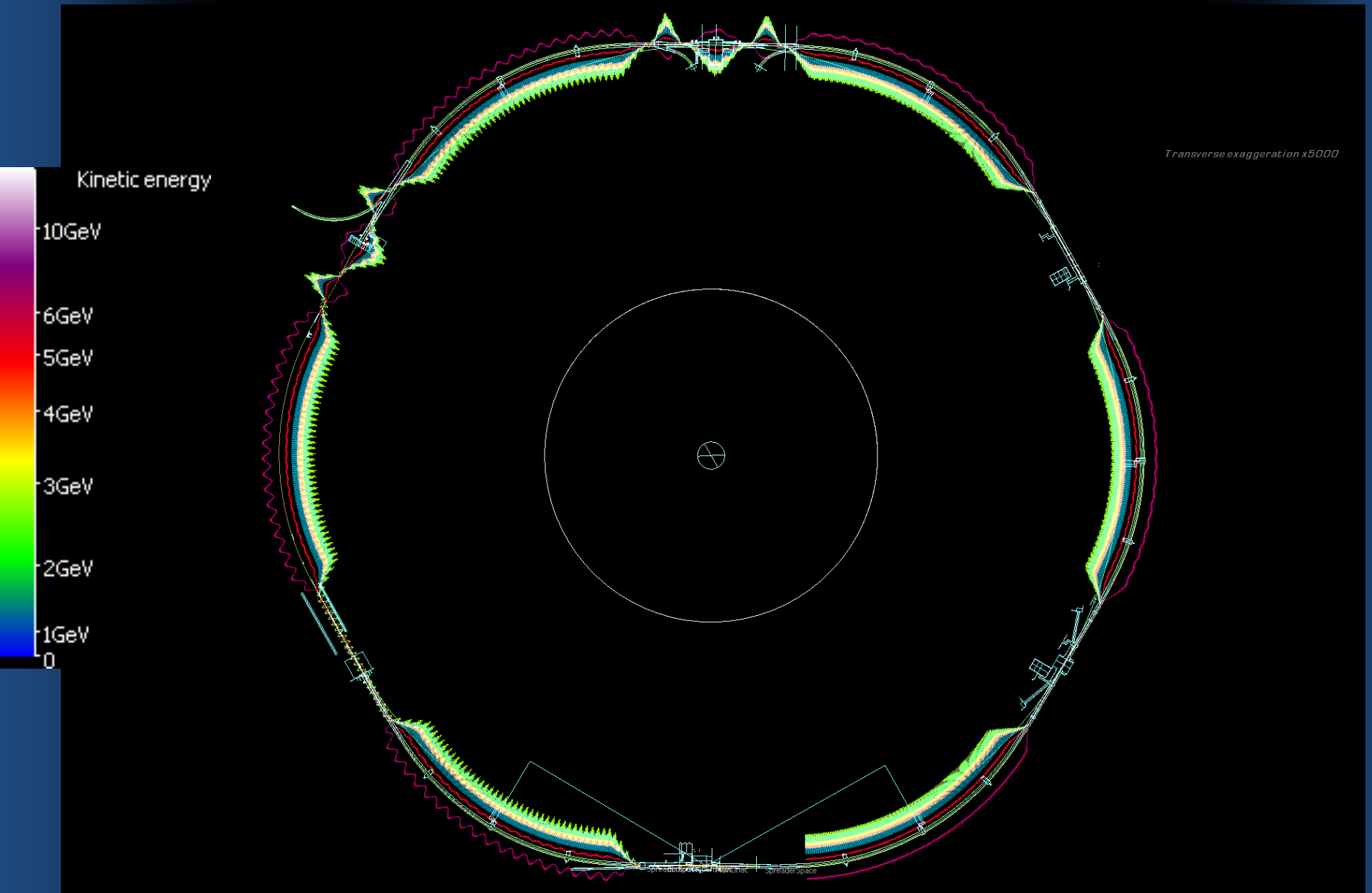
Transition to Straight Tunnel



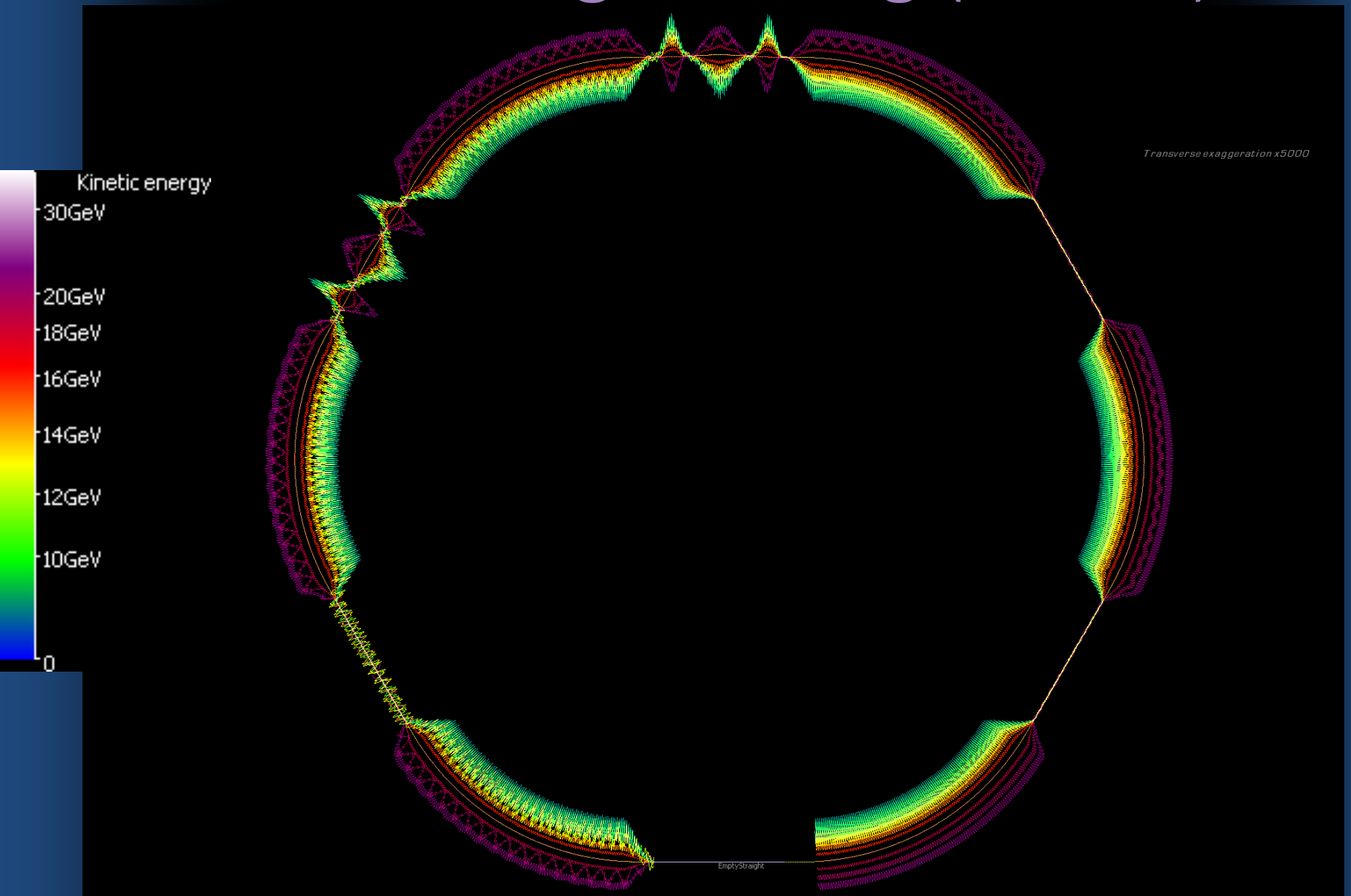
Detector Bypass (PHENIX)



Whole Ring Tracking (FFAG1)



Whole Ring Tracking (FFAG2)



“Late’14” eRHIC Lattice: Process

- Need to agree on cell length/gradient choice
  - Make sure it satisfies all our criteria
- Benchmark and implement in 2-3+ codes
- Optimise transitions, bypasses for new cells
- Critical feature: ensure new ring can be placed without hitting RHIC
  - Blue ring survey data file will help
- Publish to eRHIC Wiki

Future Improvements

- Can be included in further monthly iterations:
  - Correct circumference relative to RHIC blue ring
    - Requires all splitters, transfer lines and bypasses
  - Splitter design in 3D, trackable, joins with FFAGs
    - Requires Muon1 magnet field model for long bent dipoles, already underway
  - Extraction design (trackable)
- Don’t do all this in one version or it’ll never happen (also be sure of lattice cells first)