# eRHIC FFAG Lattice Design

Linear-field non-scaling FFAG optimised for synchrotron radiation

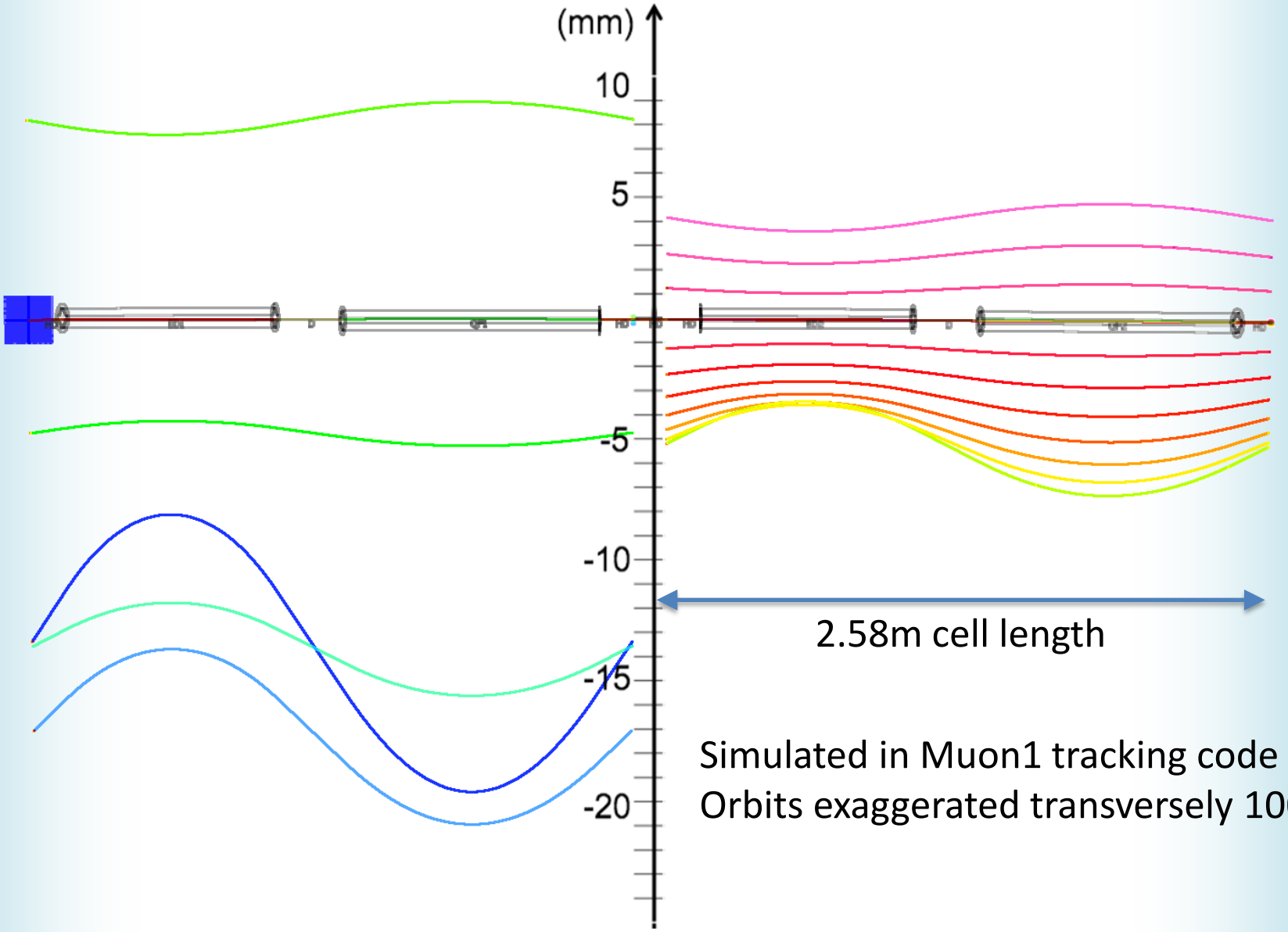
# eRHIC FFAG Arc Cells

| 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<br>10.2MW @ 15.8GeV, 50mA<br>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 |

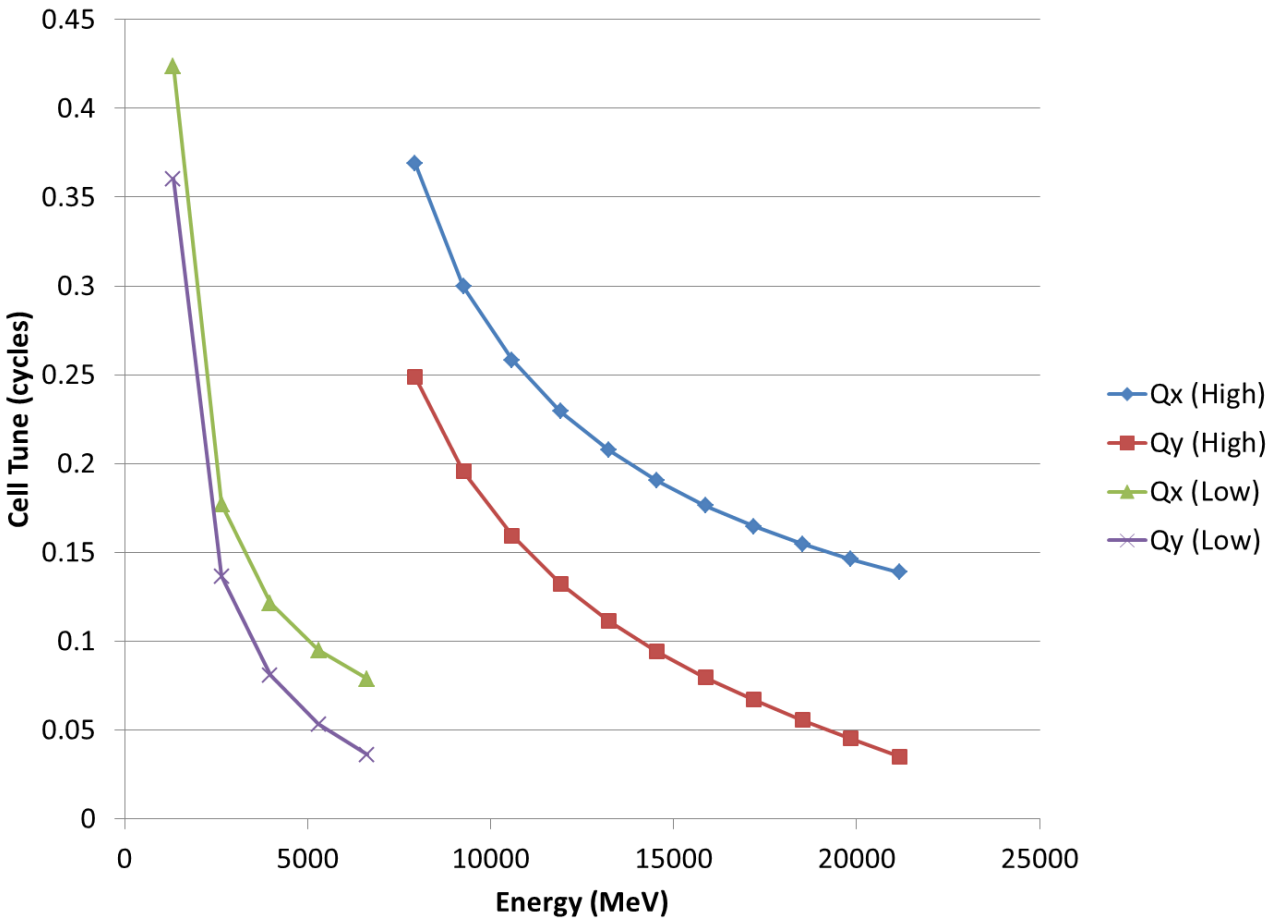
Lattice cell:
½D,BD,D,QF,½D

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

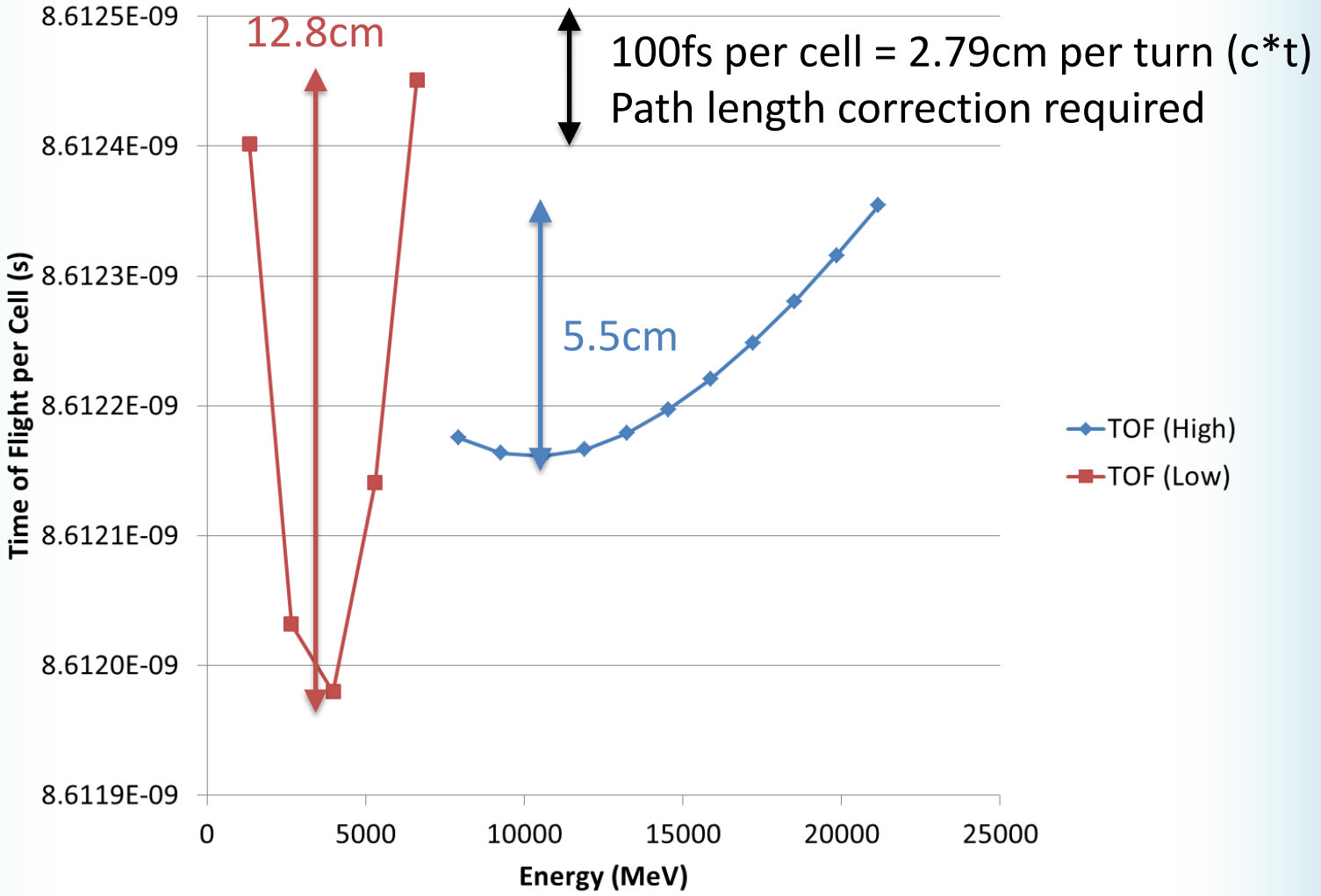



Simulated in Muon1 tracking code
Orbits exaggerated transversely 100x

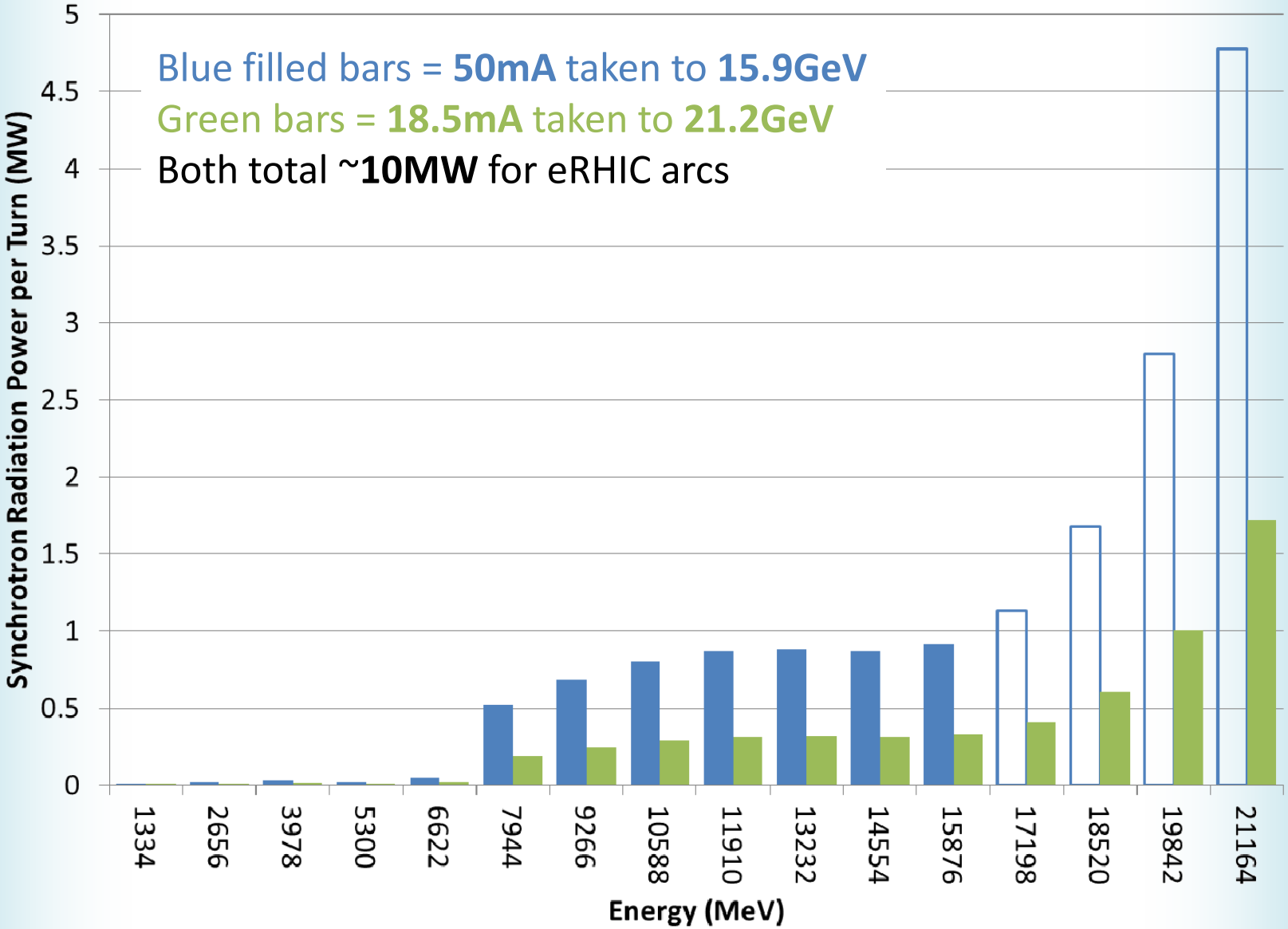
# eRHIC Tune per Cell vs. Energy (both rings)



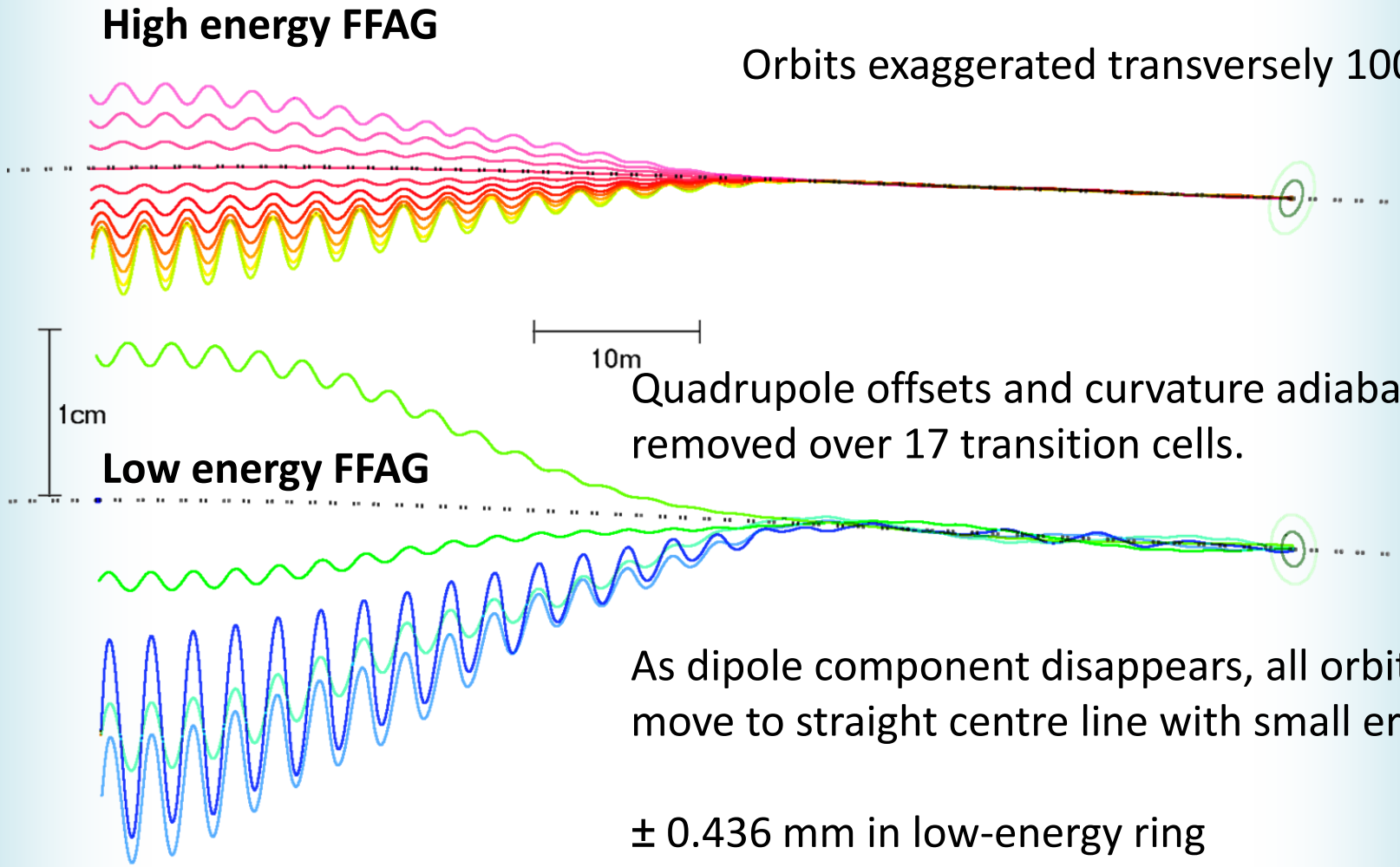
# eRHIC Time-of-Flight Variation with Energy (both rings)



# eRHIC Synchrotron Radiation per Turn (both rings)



# eRHIC FFAG Straight Sections (both rings)



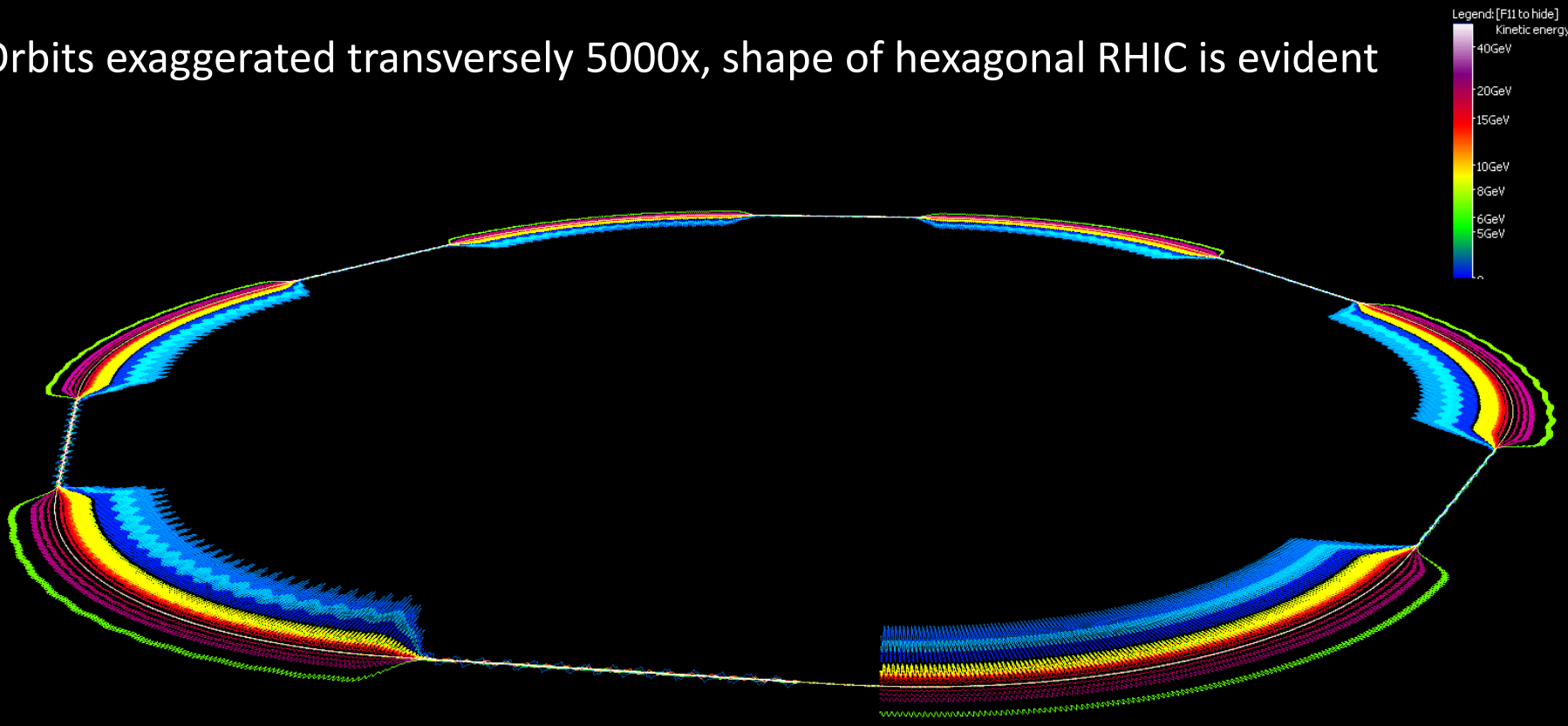

Quadrupole offsets and curvature adiabatically removed over 17 transition cells.

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

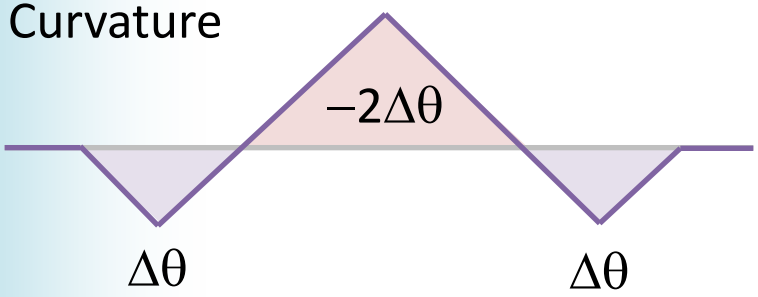
# eRHIC FFAG Rings in Perspective

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

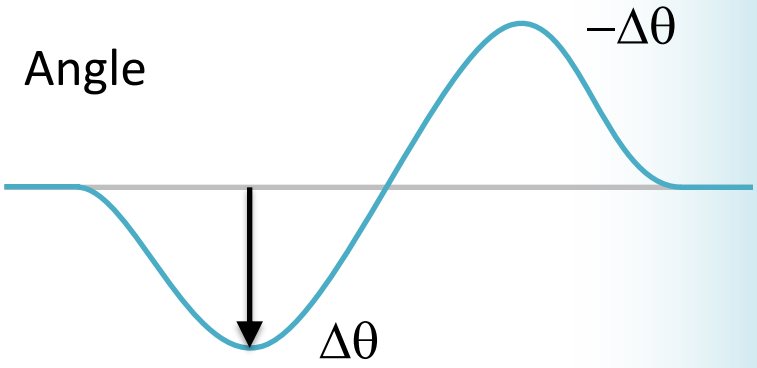


# Detector Bypass Scheme: a Flexible FFAG

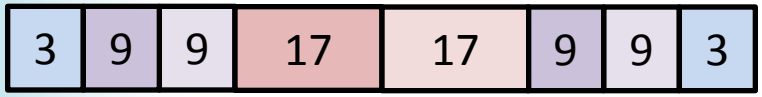
Curvature



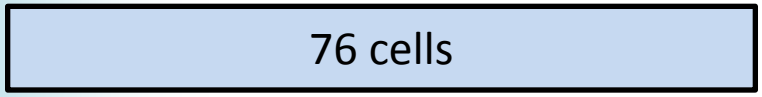

Angle



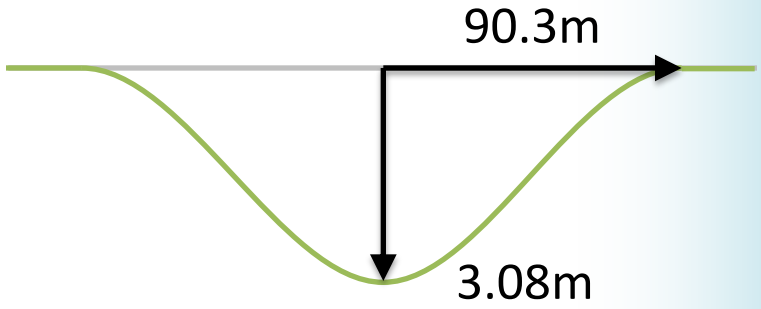

Bypass straight

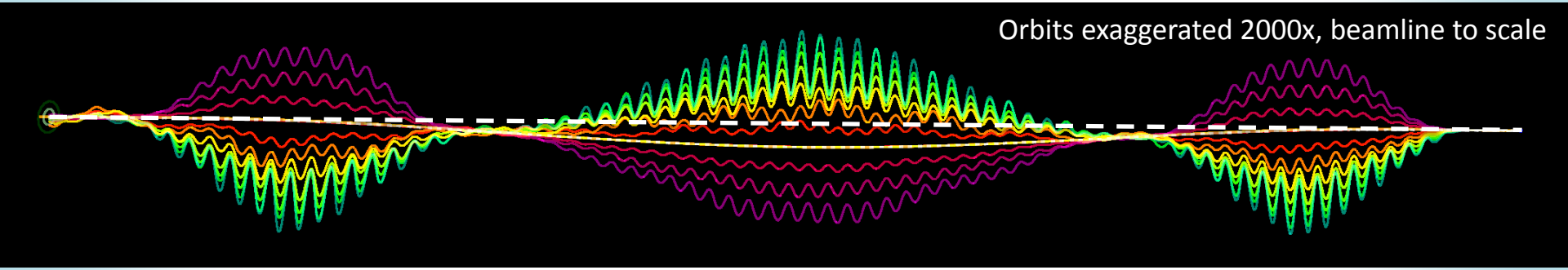



Normal straight

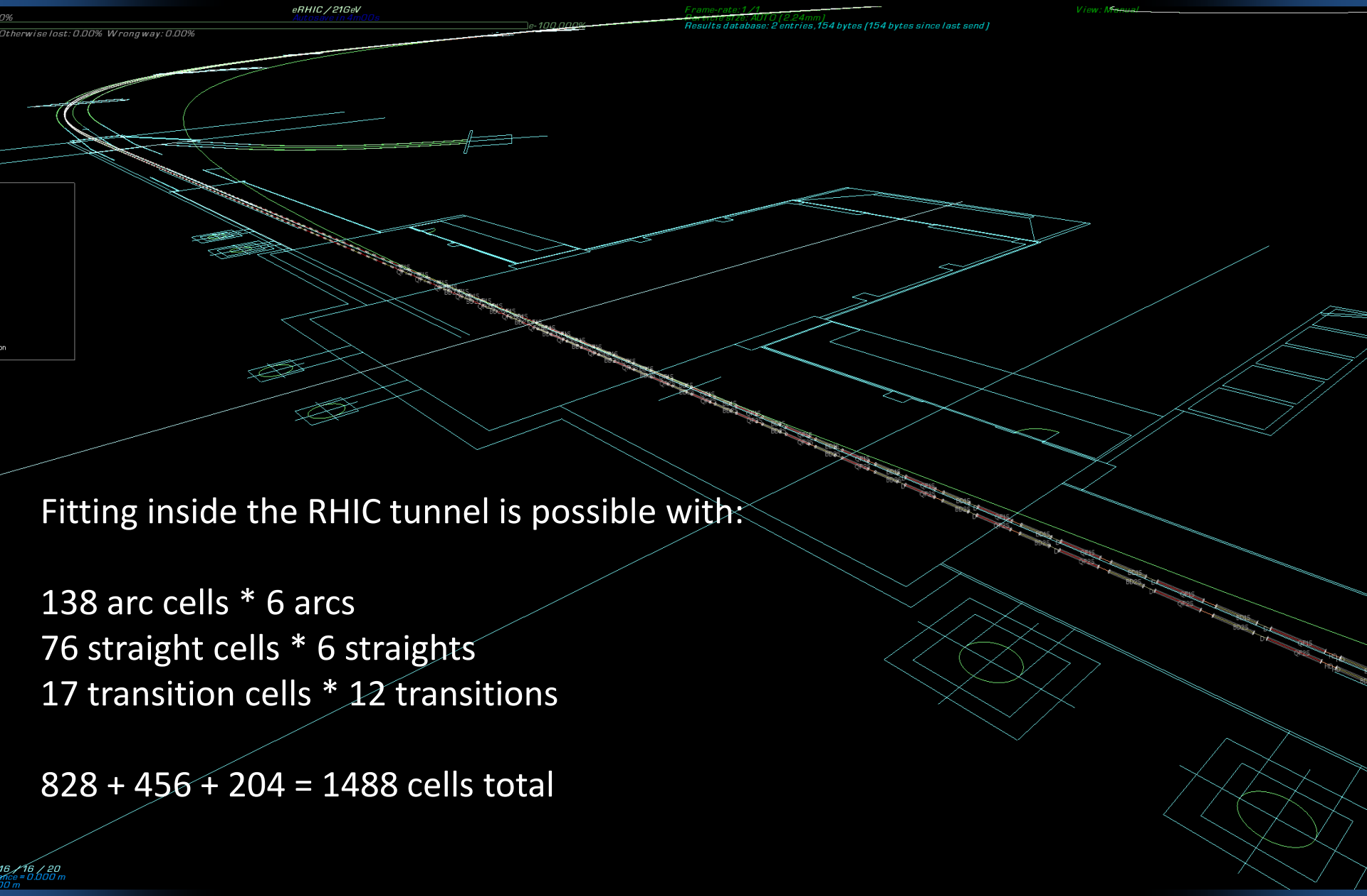



Displacement



# Layout Superimposed on CAD of RHIC Tunnel



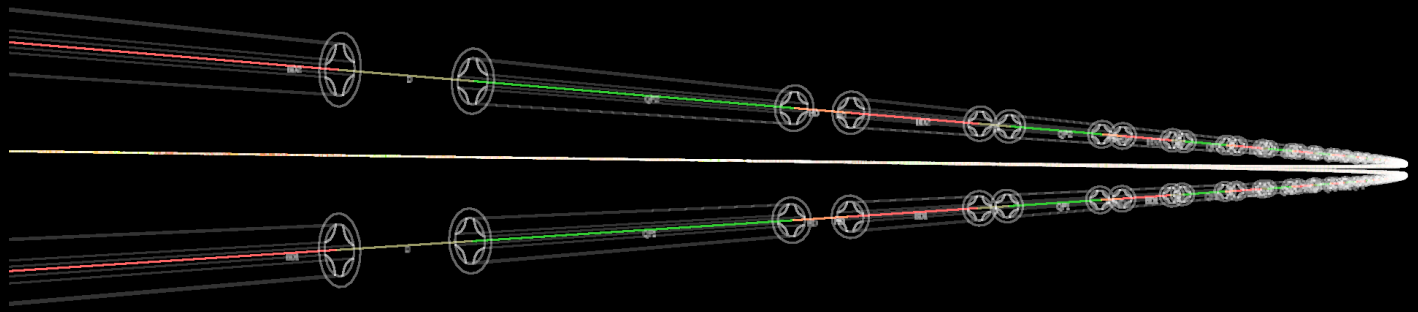

Fitting inside the RHIC tunnel is possible with:

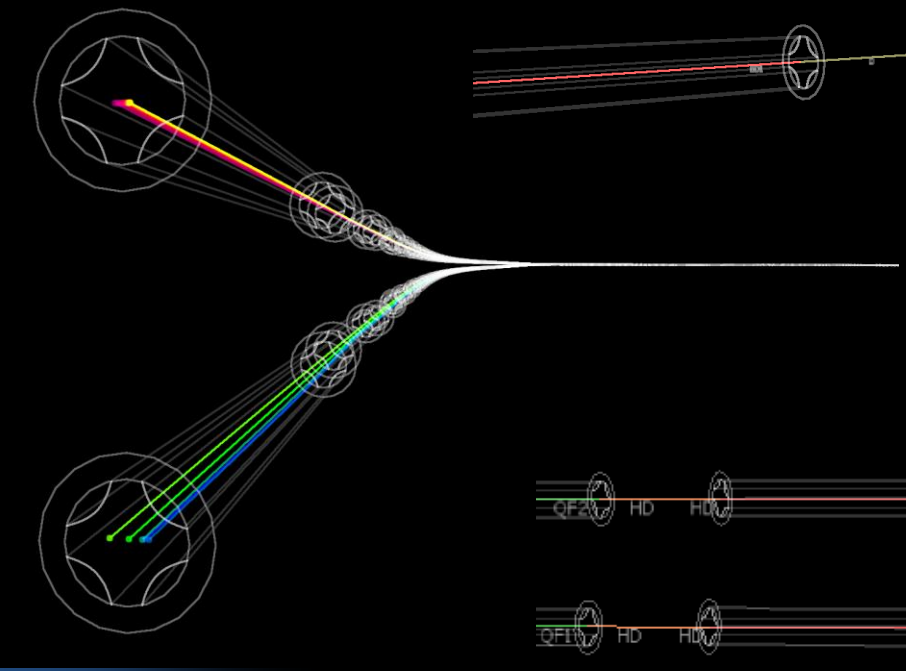
138 arc cells * 6 arcs
76 straight cells * 6 straights
17 transition cells * 12 transitions

828 + 456 + 204 = 1488 cells total

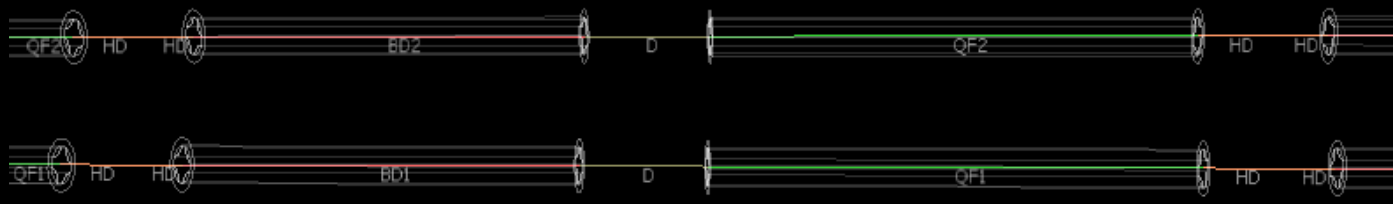
# Girder Stacking

- Both rings have the same element lengths and angles



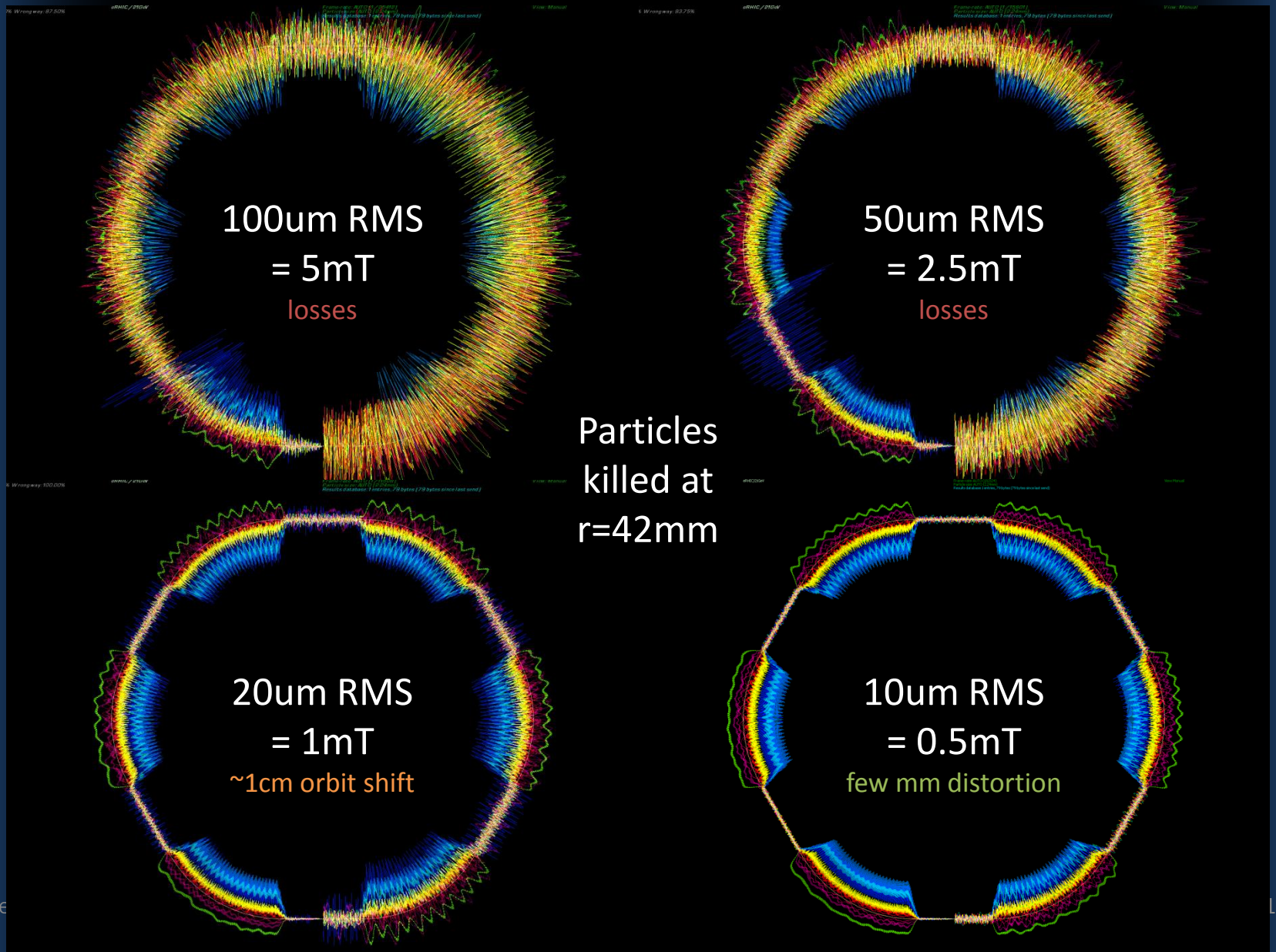


- Common ~2.5m girder can be used for both cells

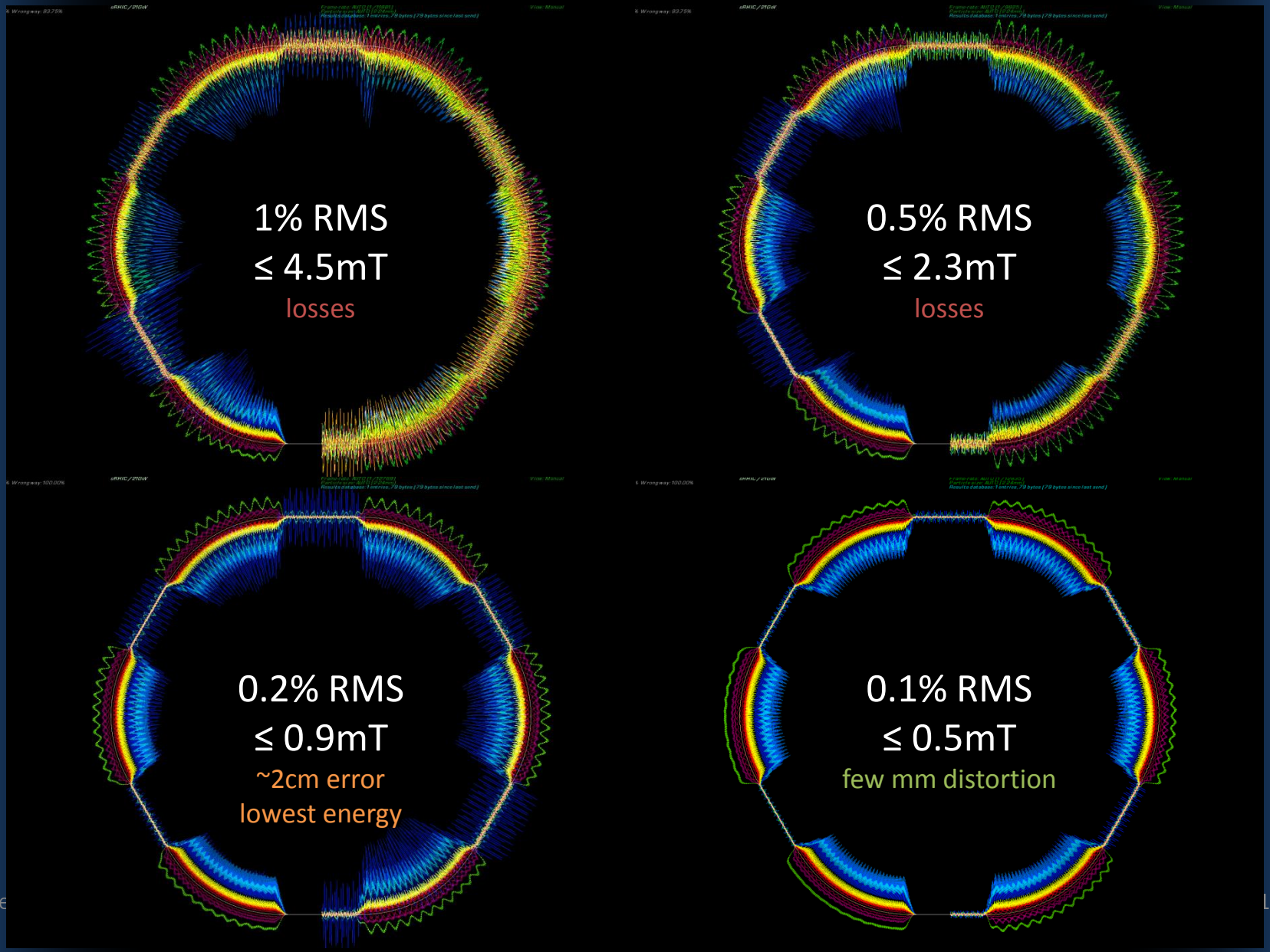


# Quadrupole Displacements = Dipole Errors

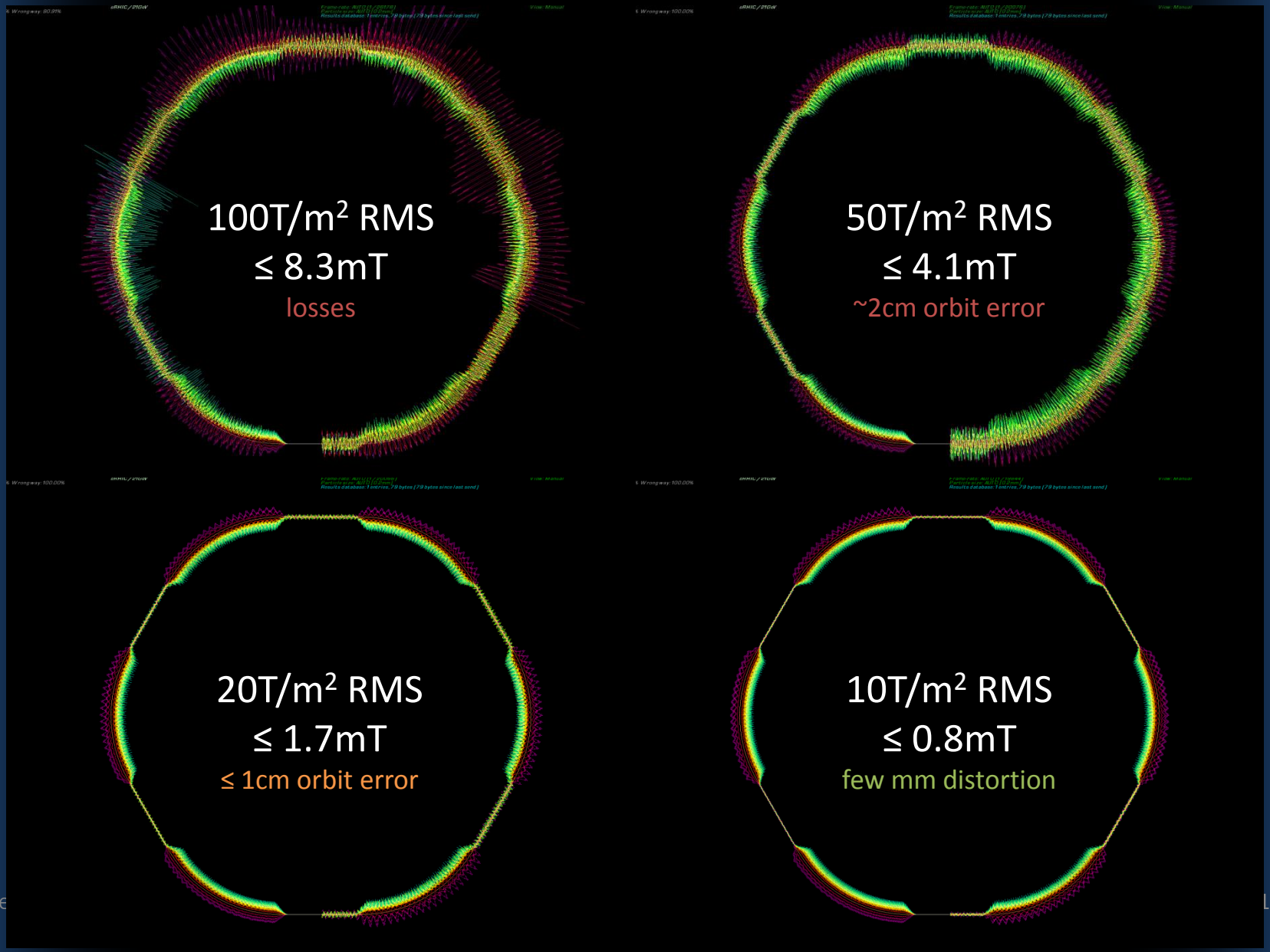
(both rings)



# 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?

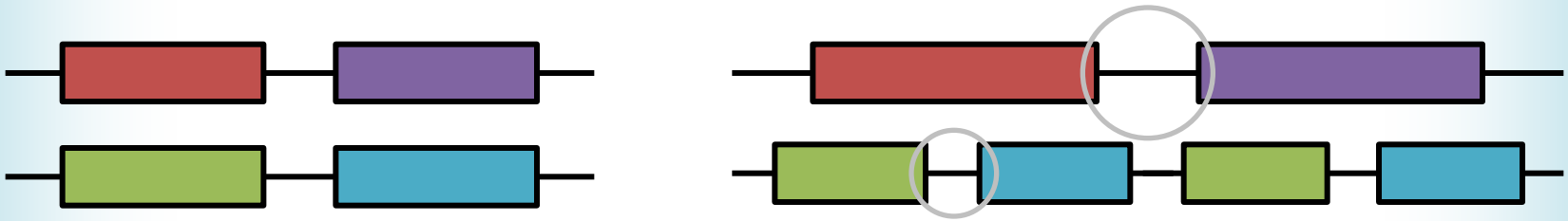
- Magnet vertically at least 8mm away from orbits that are within 9.1mm of quad centre
  - Difficult to produce field “at a distance”
- Vladimir mentioned close-together orbits aren’t very good for extraction
  - Low beta function also not good
- High gradient (small orbit range) increases sensitivity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

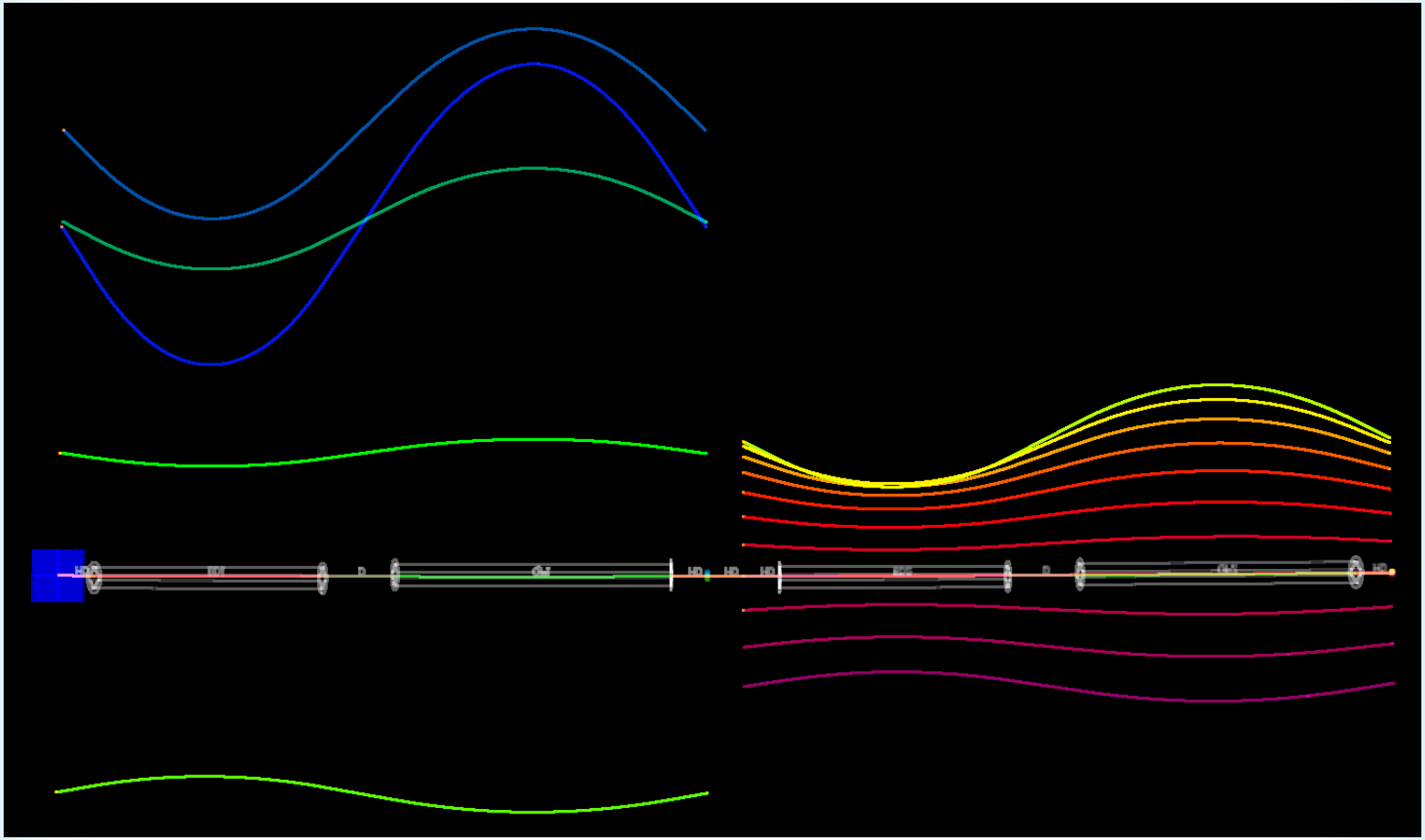
# Current Lattice (Jan'14)

| 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<br>10.2MW @ 15.8GeV, 50mA<br>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 $\|\mathbf{B}\|$ on orbit | 0.227 T | 0.451 T |
| Max quad strength | 9.986 T/m | 49.515 T/m |

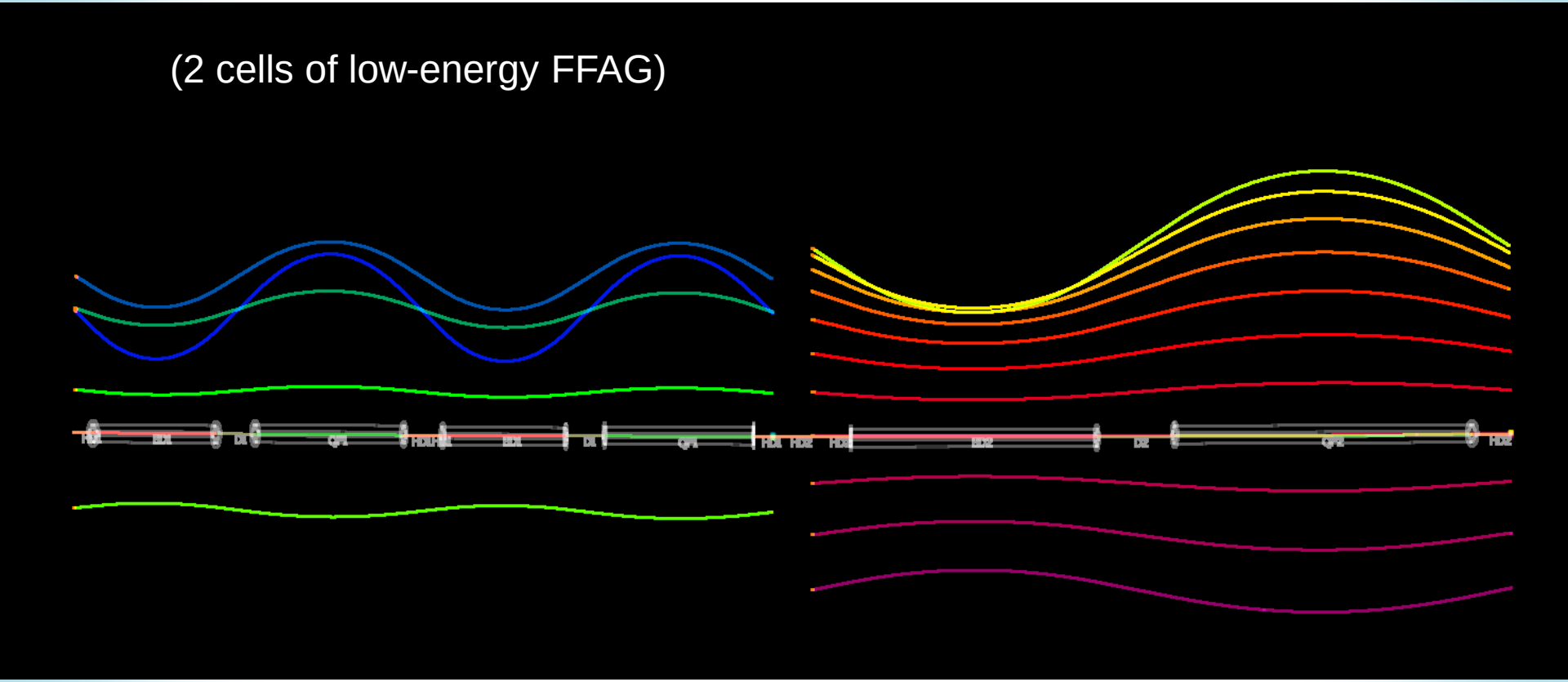
# Scaled and 2:1 Stacked Lattice

| 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<br>10.3MW @ 15.8GeV, 50mA<br>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 \|**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 |

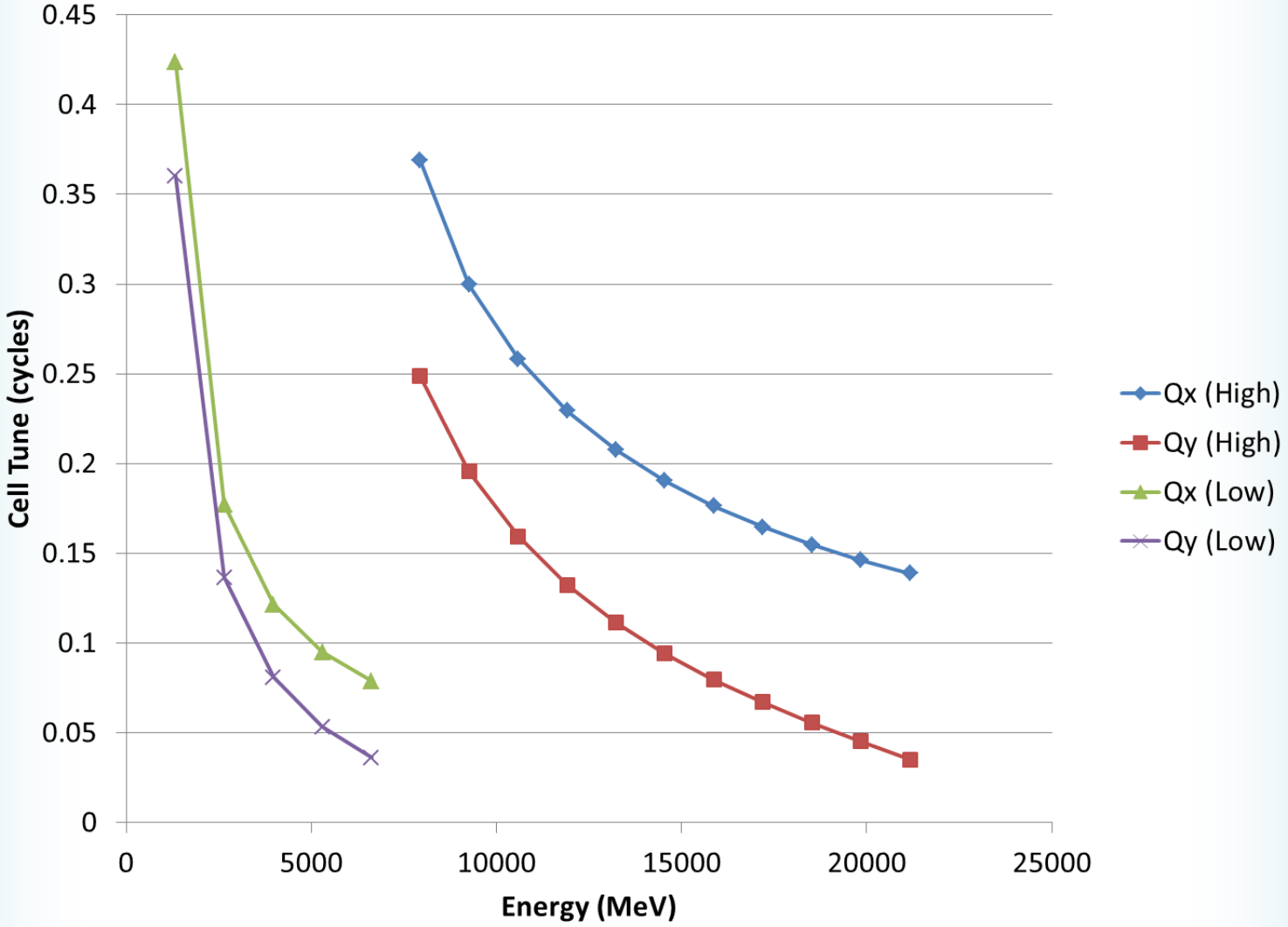
- Cell: ½D,BD,D,QF,½D (length ≈ 2.582m)
- Cells stack exactly, allowing common girder
- Specification on eRHIC Wiki
  - http://www.cadops.bnl.gov/eRHIC/erhicWiki/index.php/FFAG_Design:Electrons:Lattice:Arcs

# 2:1 Lattice Description

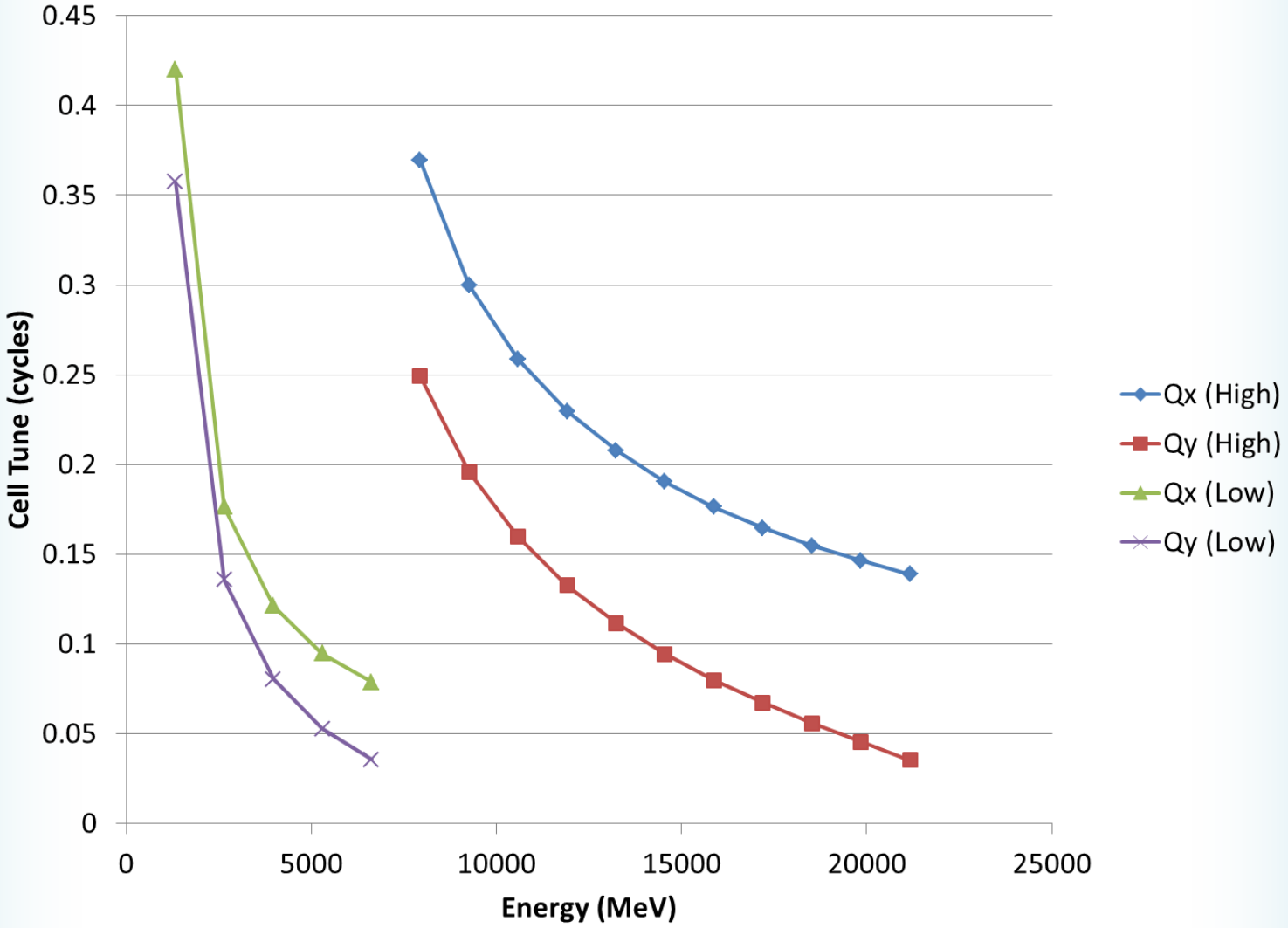
| Element | Length (m) | Angle (mrad) | Gradient (T/m) | Offset (mm) |
|---|---|---|---|---|
| Drift D1 (Low) | 0.185756896 | 0 | | |
| Drift D2 (High) | 0.371513793 | 0 | | |
| BD1 (Low) | 0.586408097 | 1.974541 | 23.945 | -2.897173 |
| QF1 (Low) | 0.709430775 | 2.388782 | -21.595 | 2.897173 |
| BD2 (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

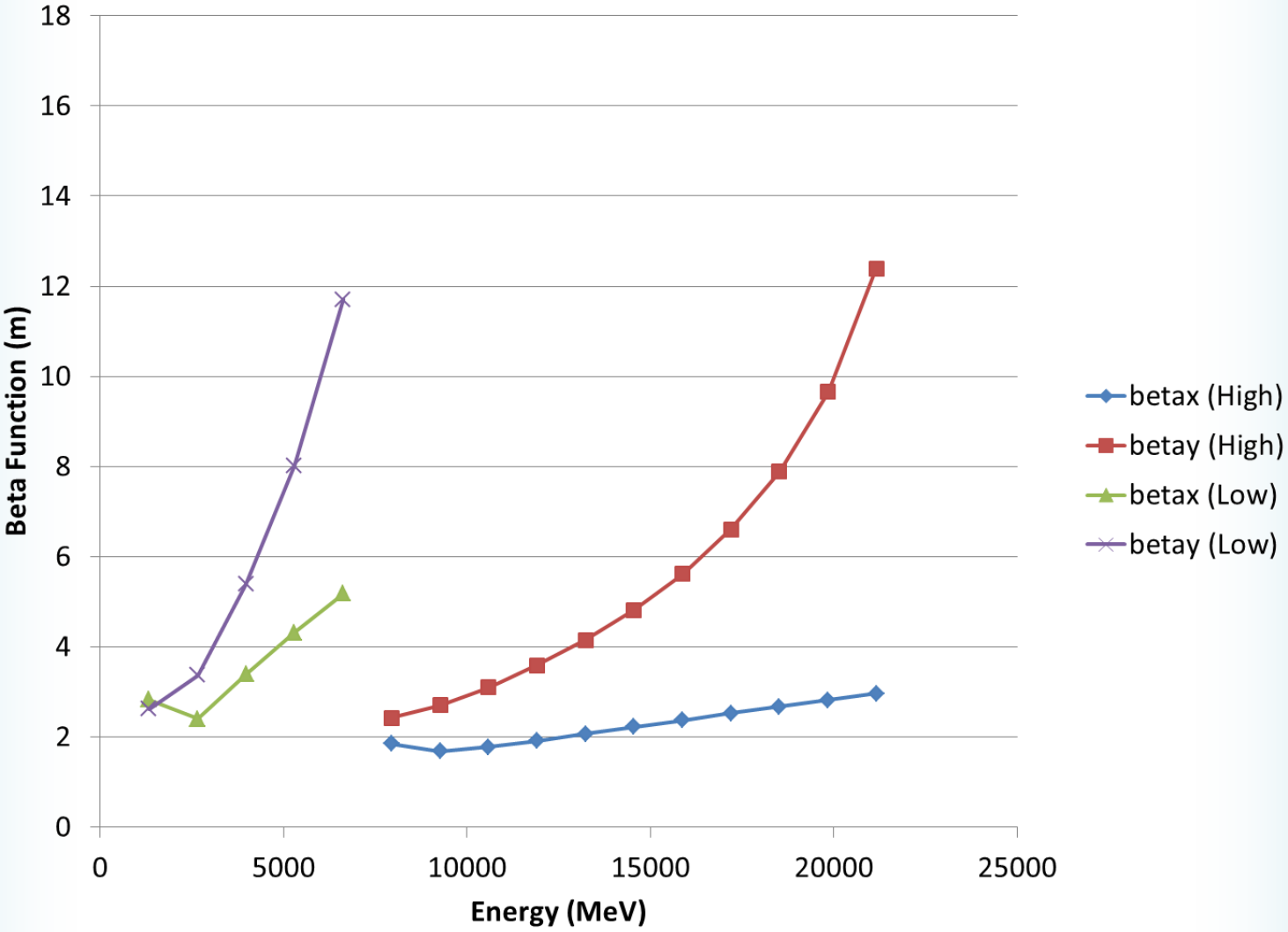
# Jan'14 Tunes


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)

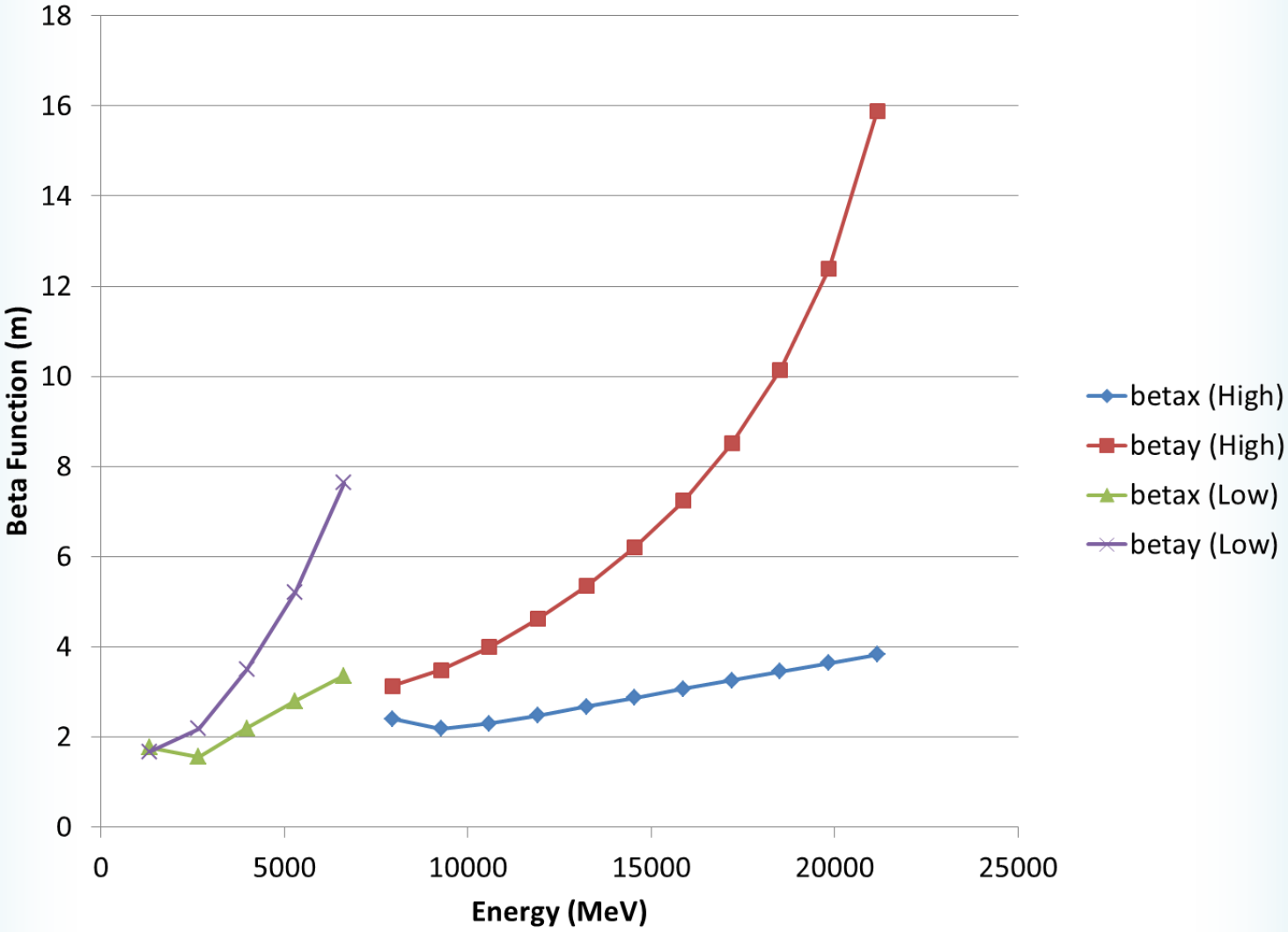
# 2:1 Tunes


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)

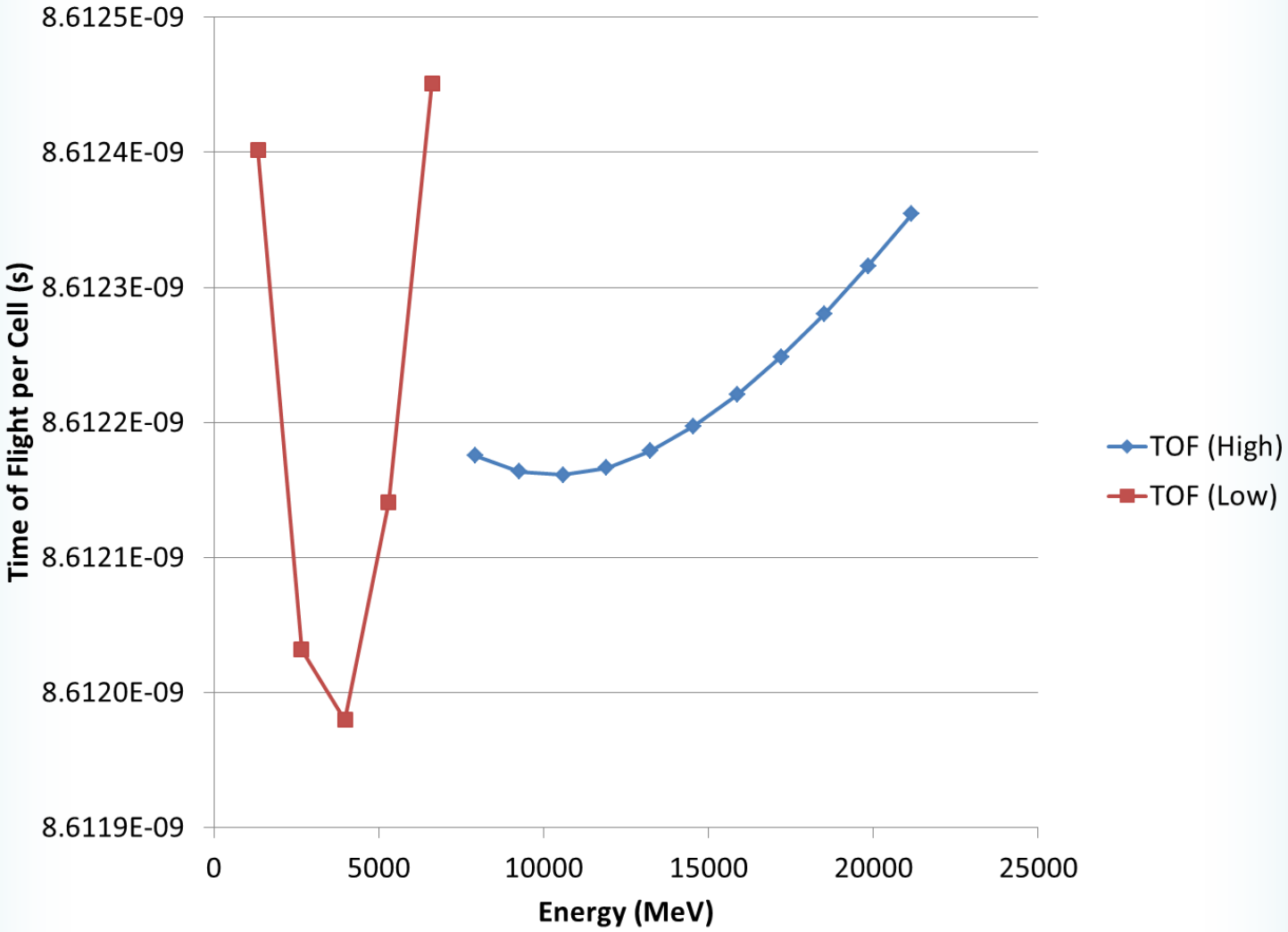
# Jan'14 Betas at Matching Plane



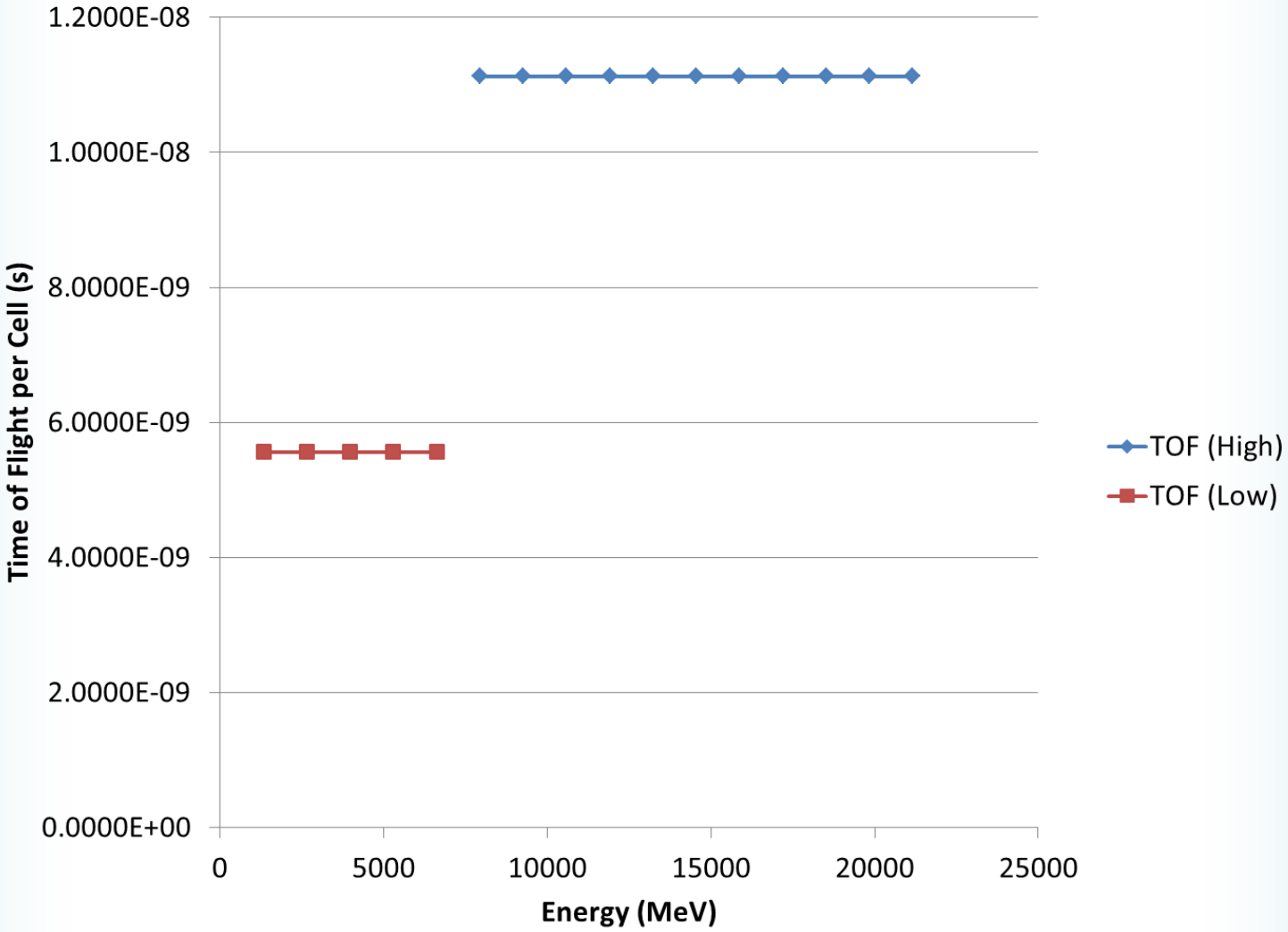
# 2:1 Betas at Matching Plane



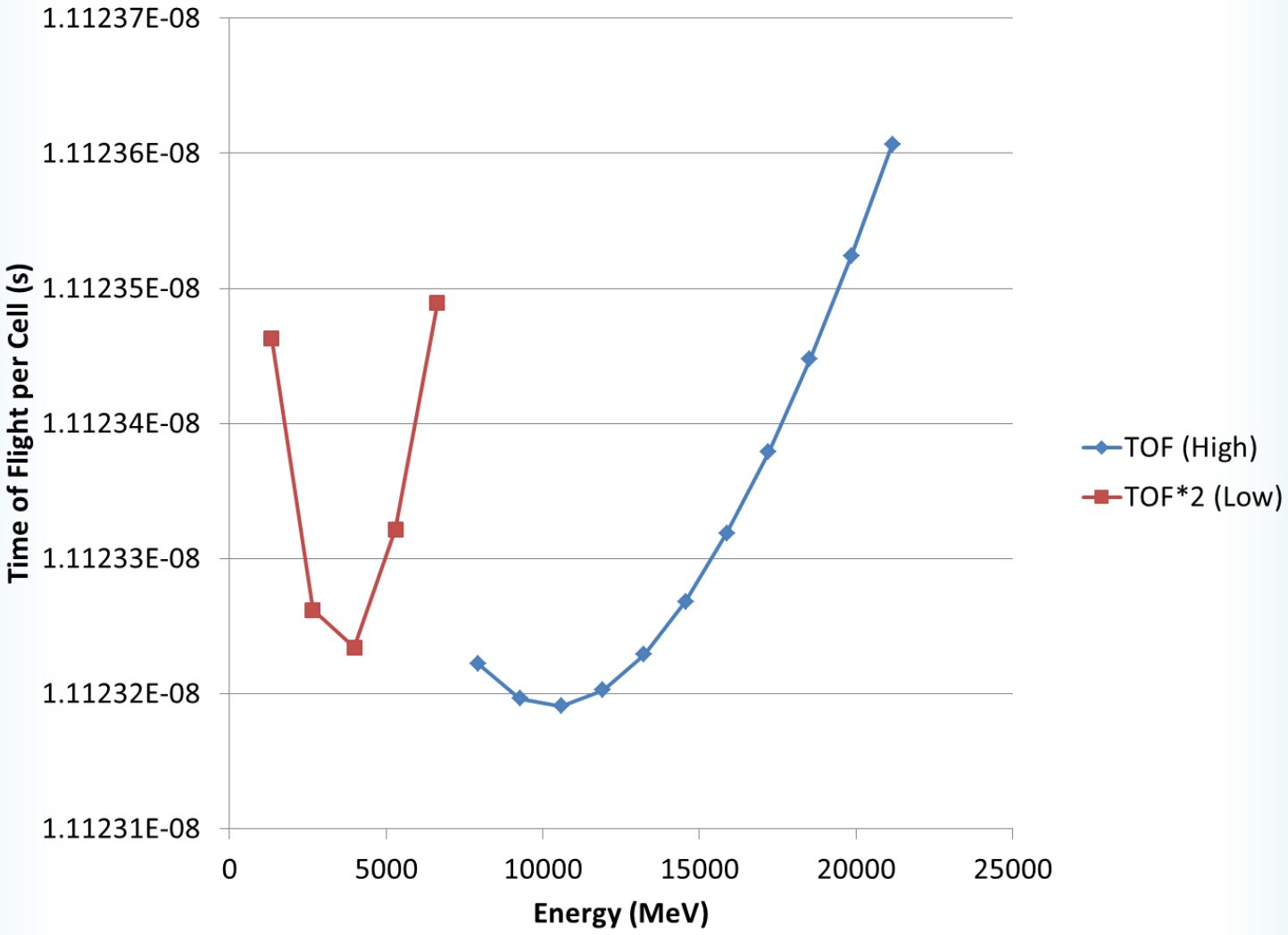
# Jan'14 Time of Flight Variation



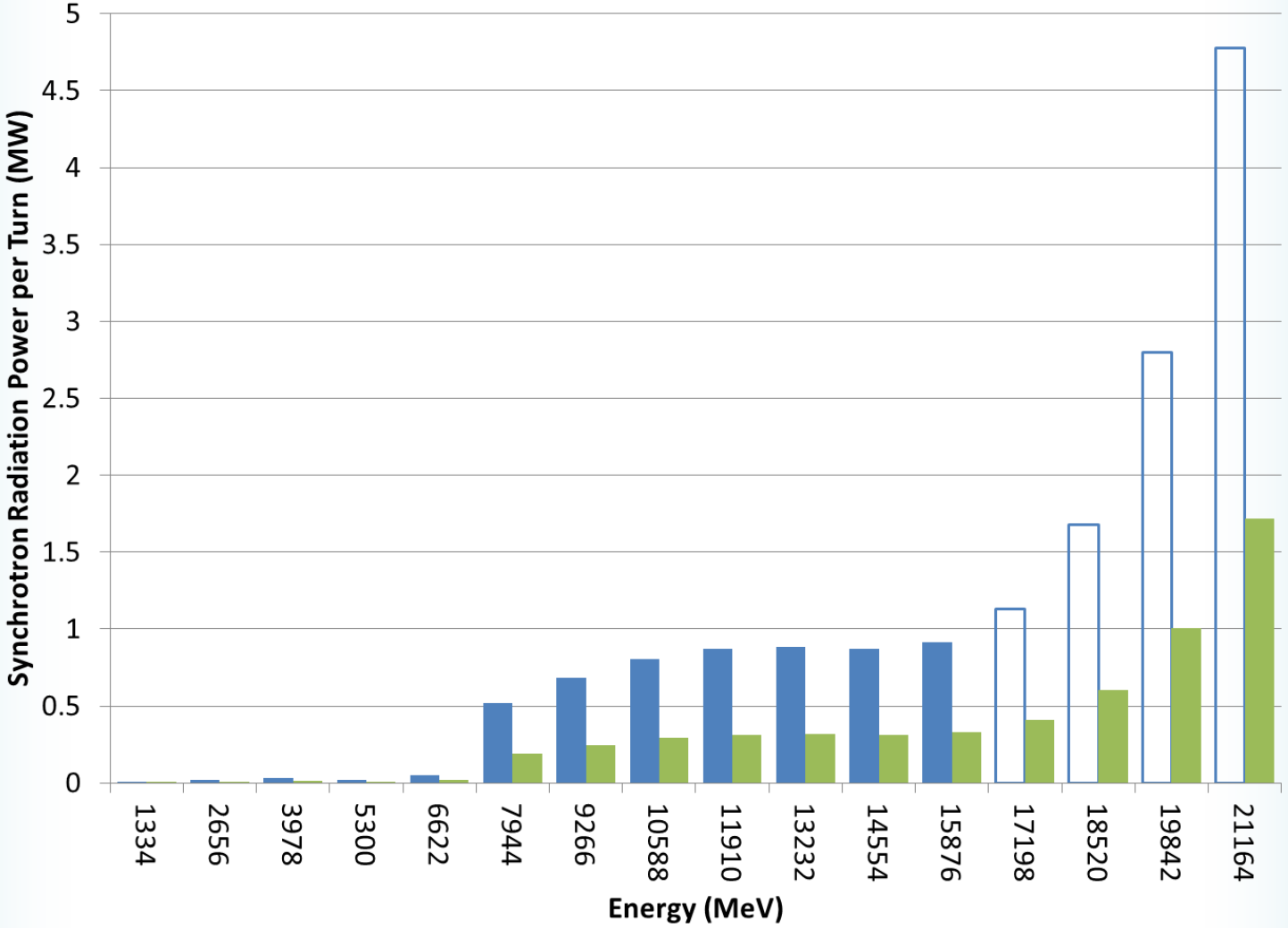
# 2:1 Time of Flight Variation



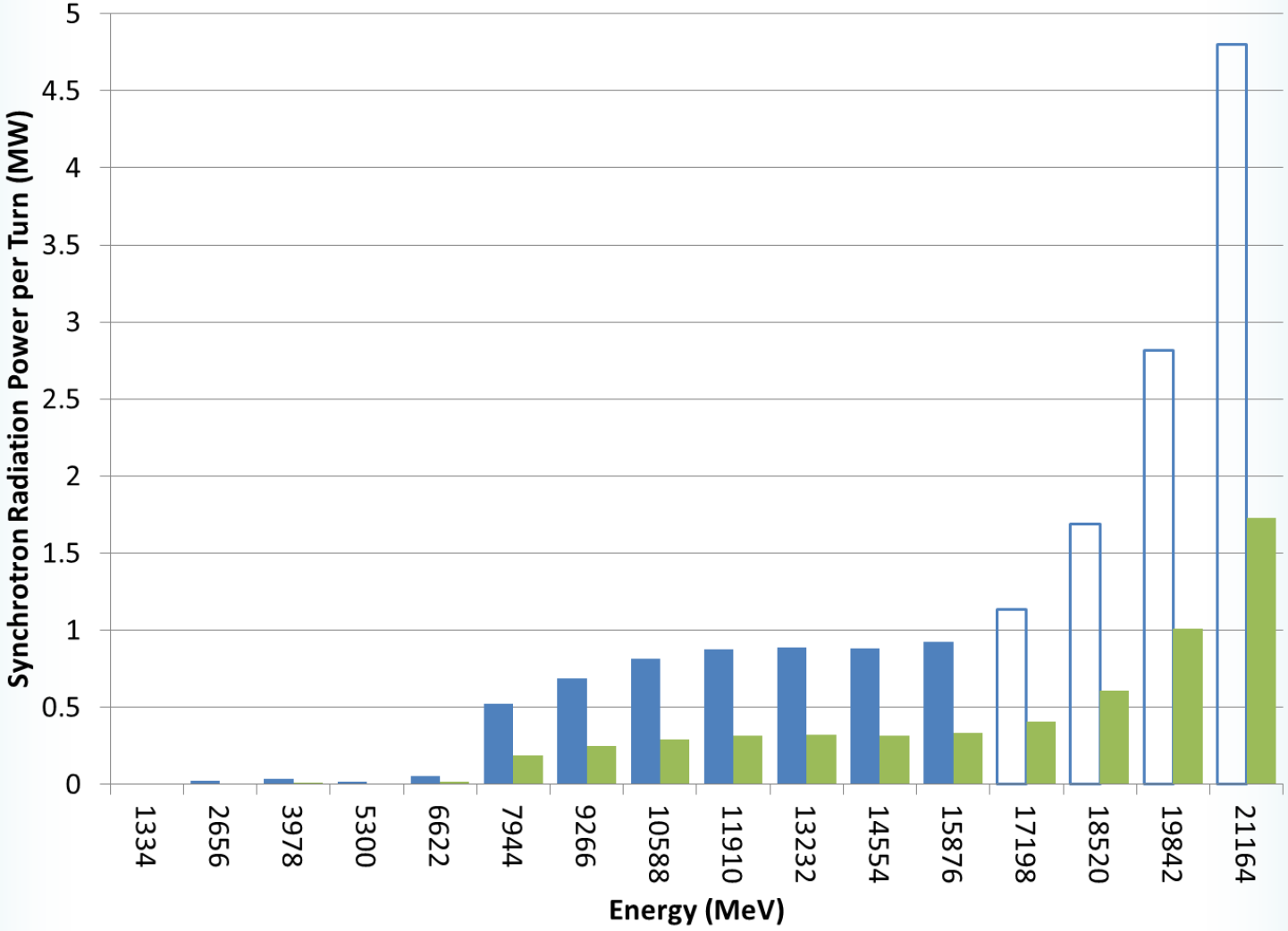
# 2:1 Time of Flight Variation



# Jan'14 SR Loss for Each Turn



# 2:1 SR Loss for Each Turn

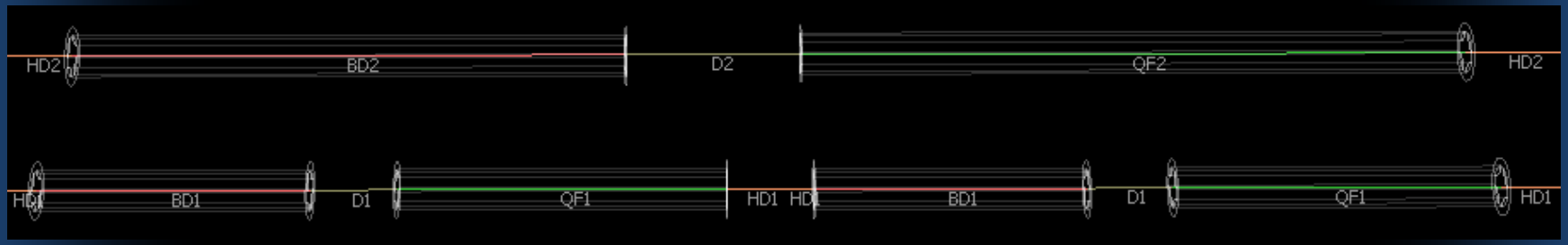


# Adiabatic Matching, Ring Closure

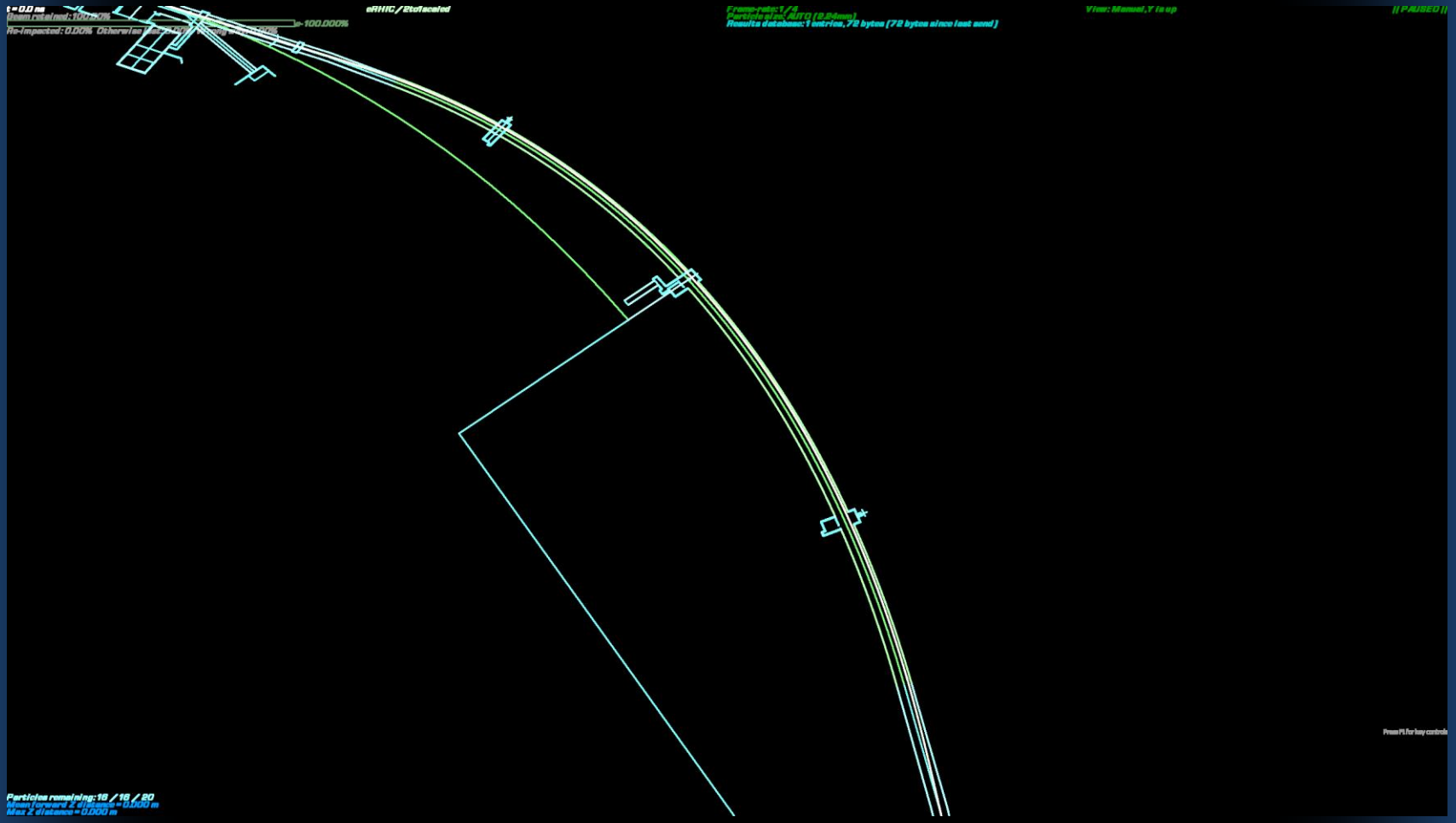
| Cells in… | Jan'14 | 2:1 FFAG1 | 2:1 FFAG2 |
|---|---|---|---|
| Arc | 138 | 212 | 106 |
| Transition | 17 | 28 | 14 |
| Straight | 76 | 116 | 58 |
| Ring (6,10,5) | 1378 | 2132 | 1066 |
| Both rings | 2756 | | 3198 (+16%) |

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

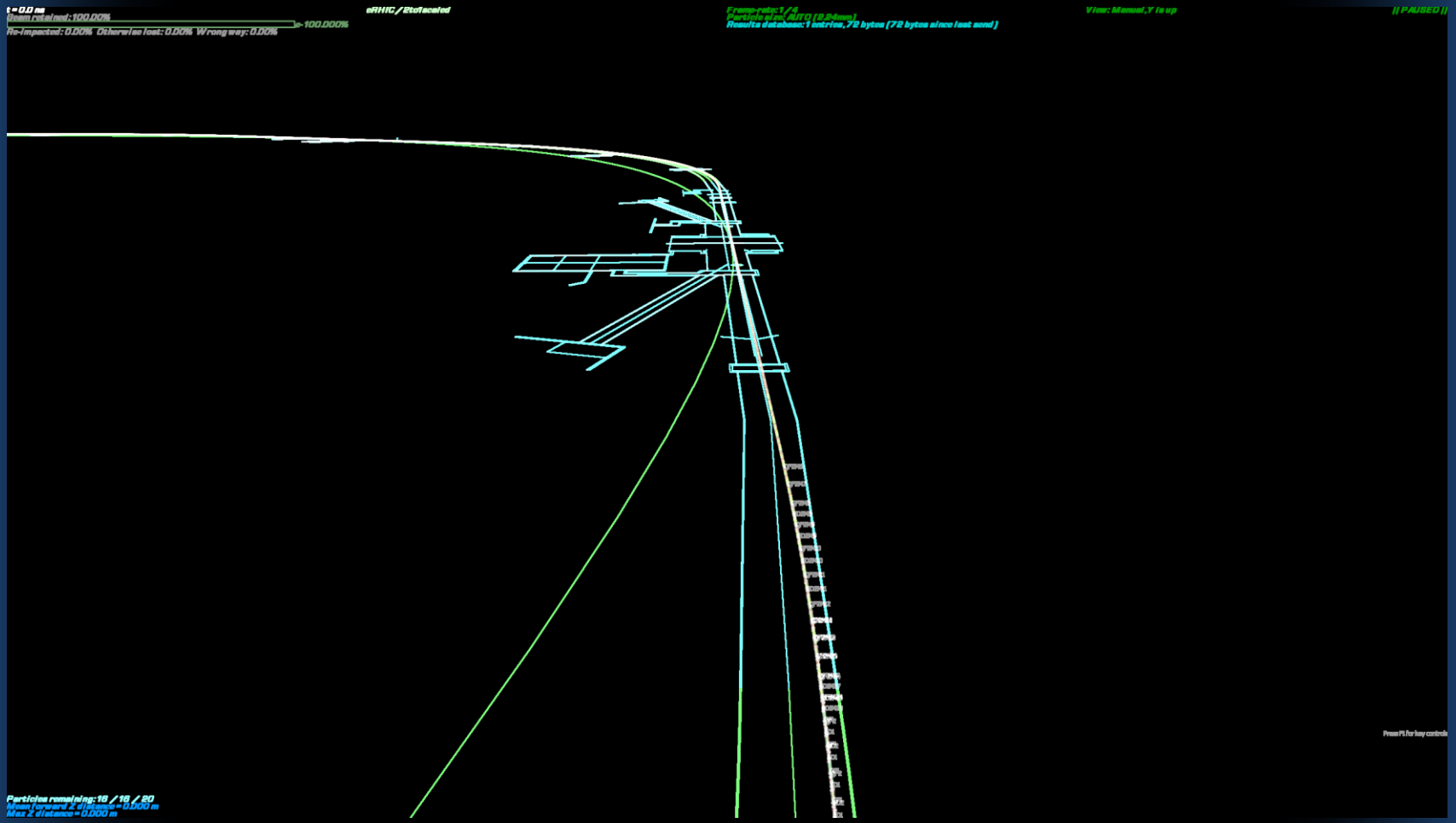
# One Arc Cell of FFAG2
# Two of FFAG1



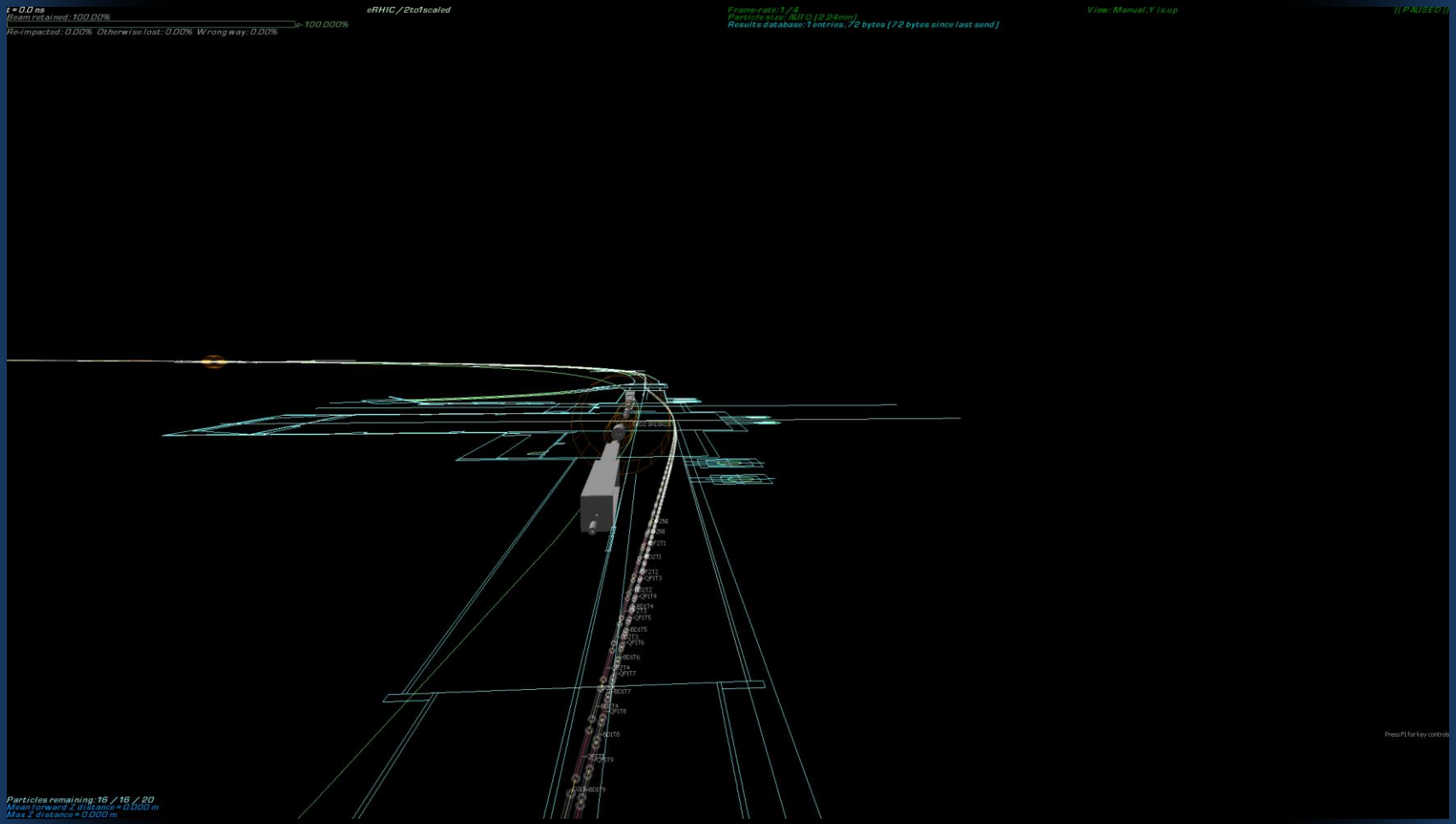
# Lattice in Arc



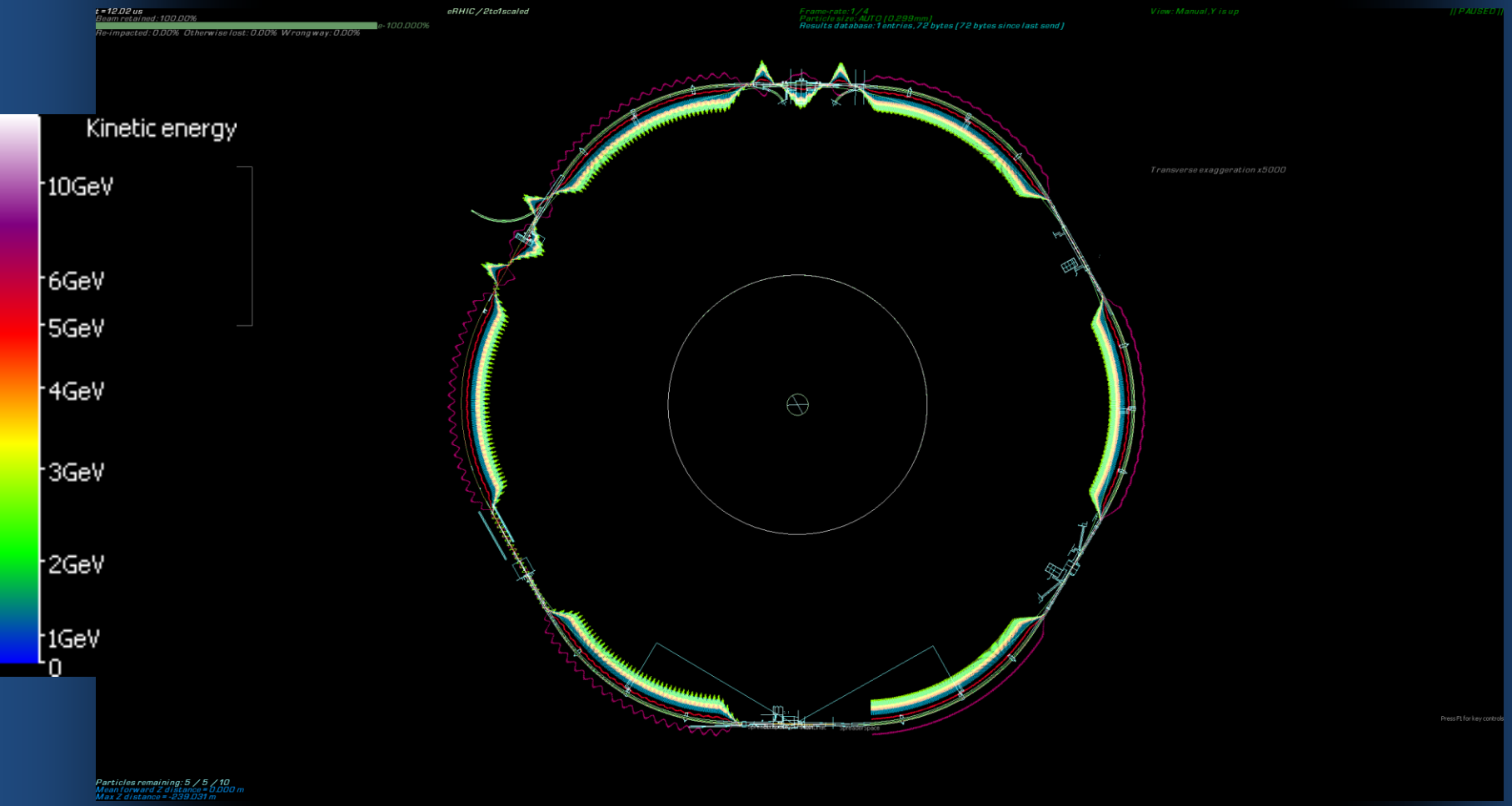
# Transition to Straight Tunnel



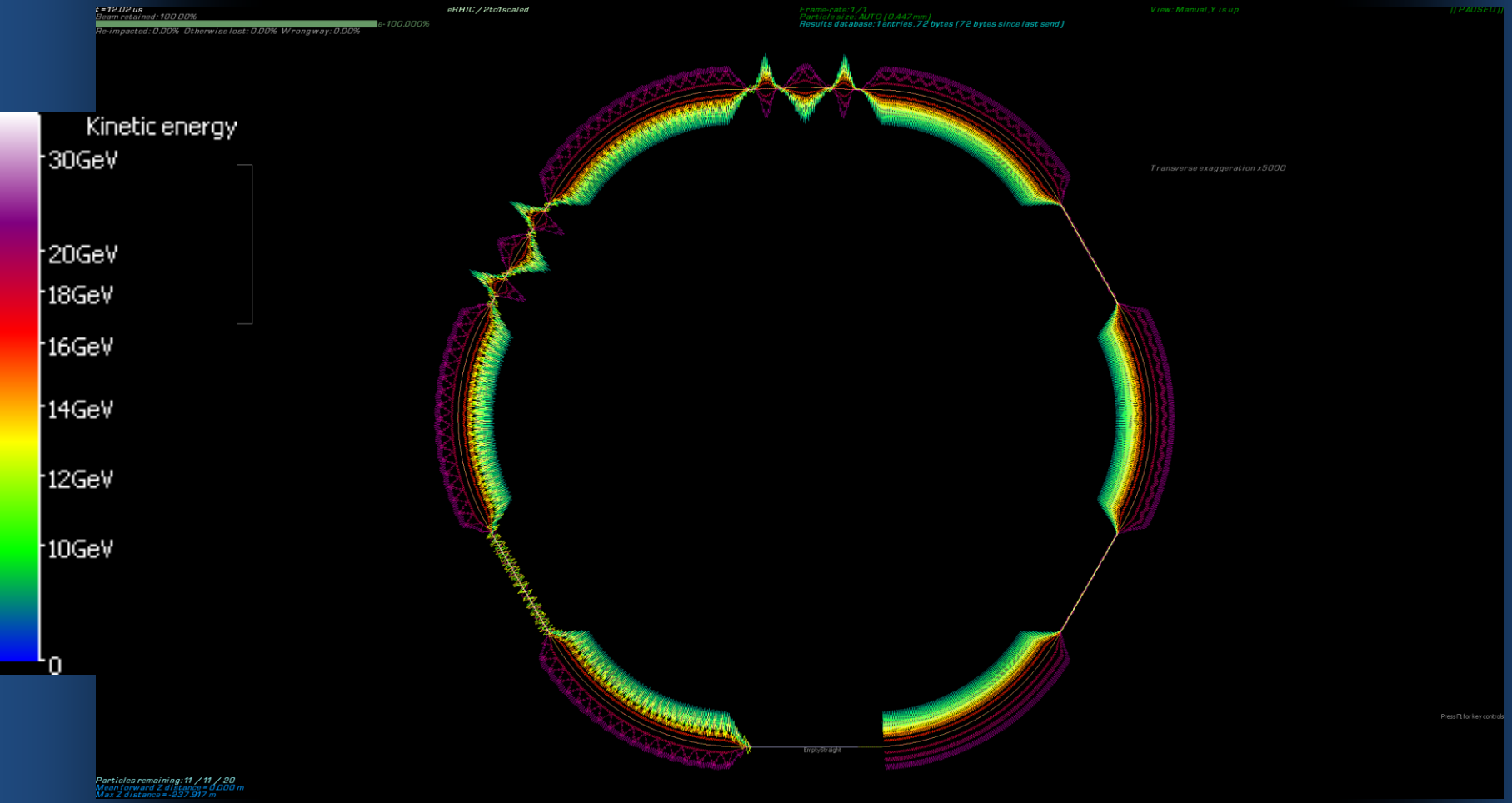
# Detector Bypass (PHENIX)



# Whole Ring Tracking (FFAG1)

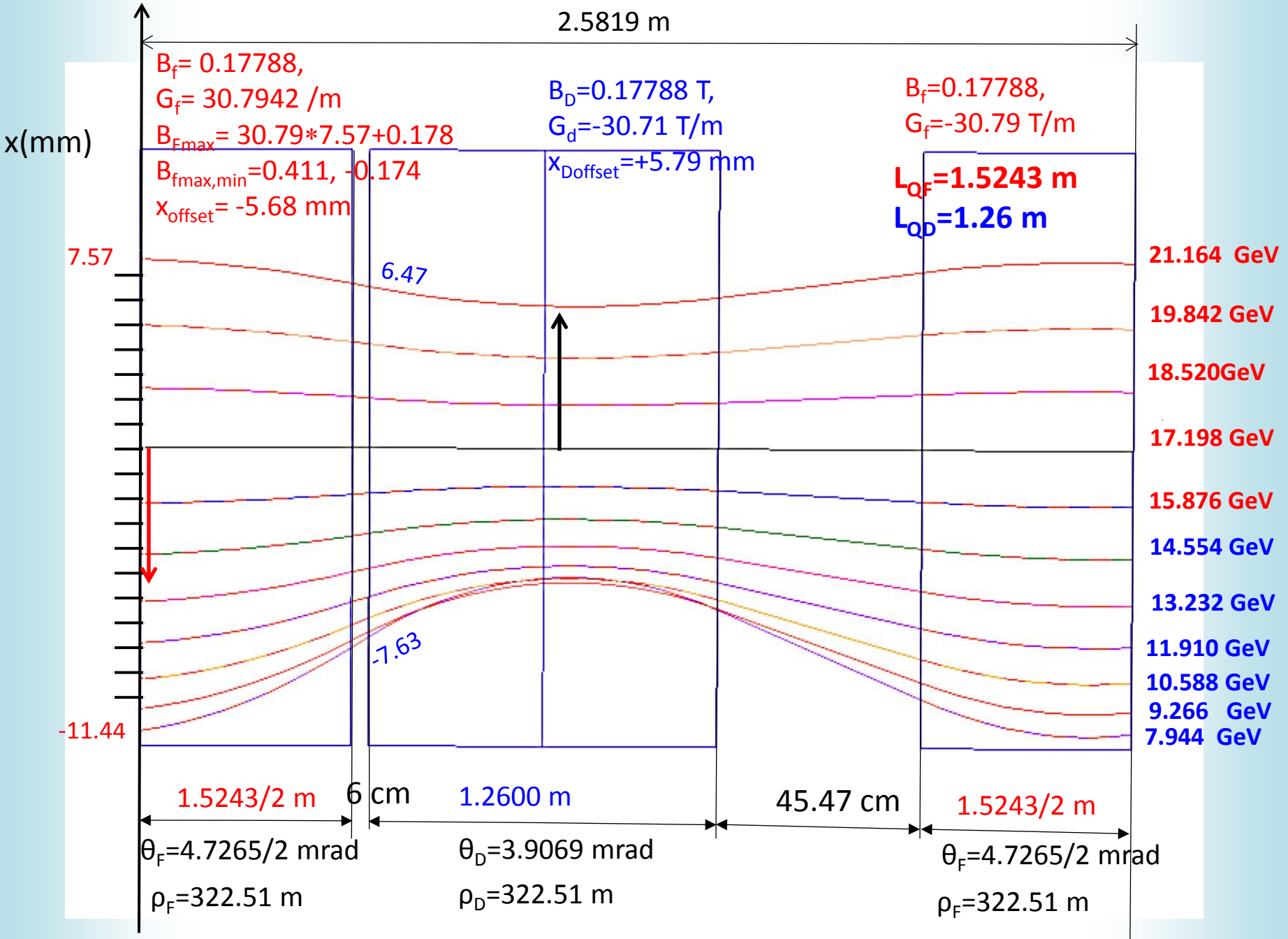


# Whole Ring Tracking (FFAG2)



# 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
$\theta_F$=4.7265/2 mrad
$\rho_F$=322.51 m
$\theta_D$=3.9069 mrad
$\rho_D$=322.51 m
$\theta_F$=4.7265/2 mrad
$\rho_F$=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.