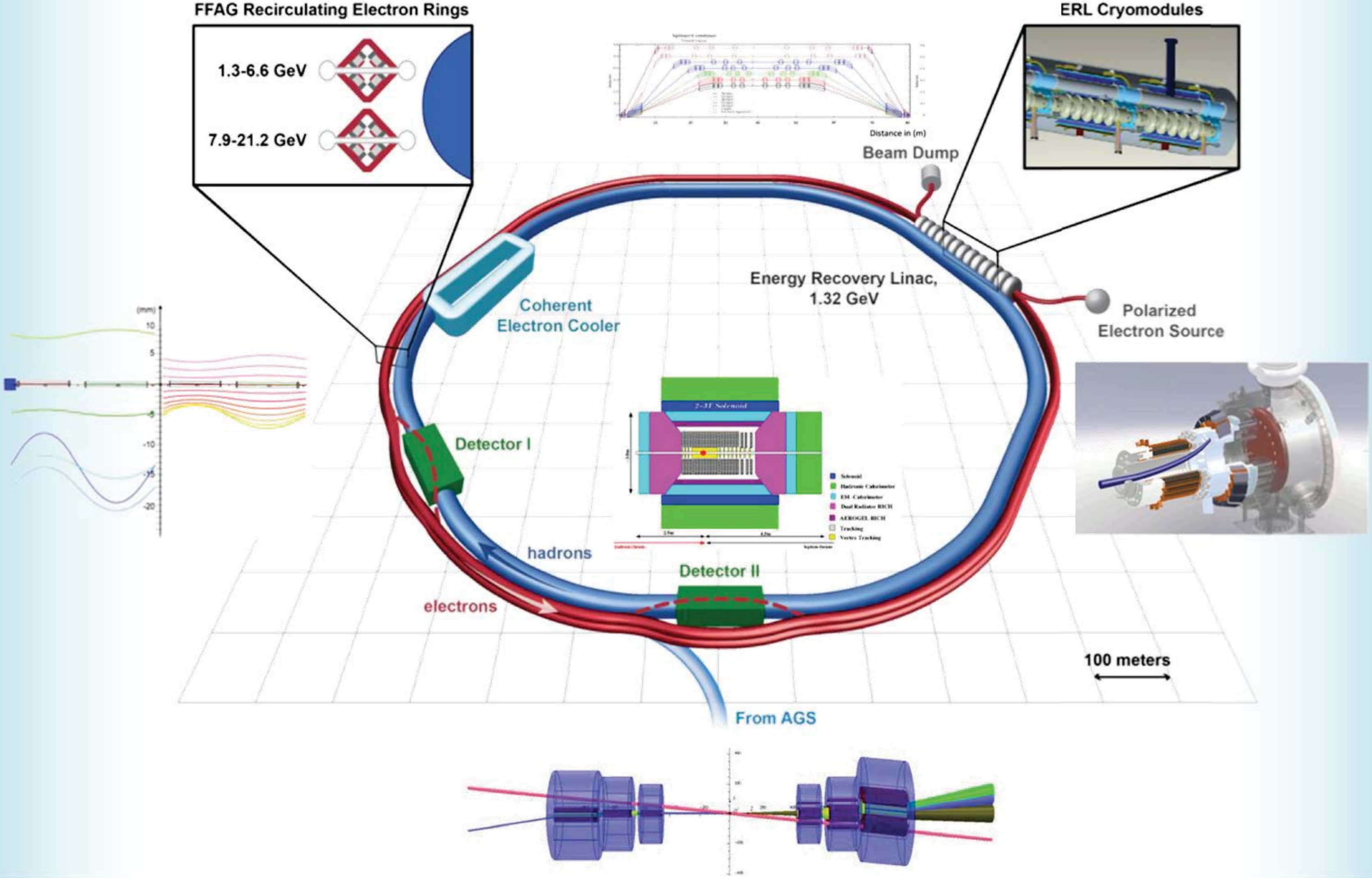
eRHIC: an Efficient Multi-Pass ERL based on FFAG Return Arcs

On behalf of the eRHIC design team

eRHIC Schematic



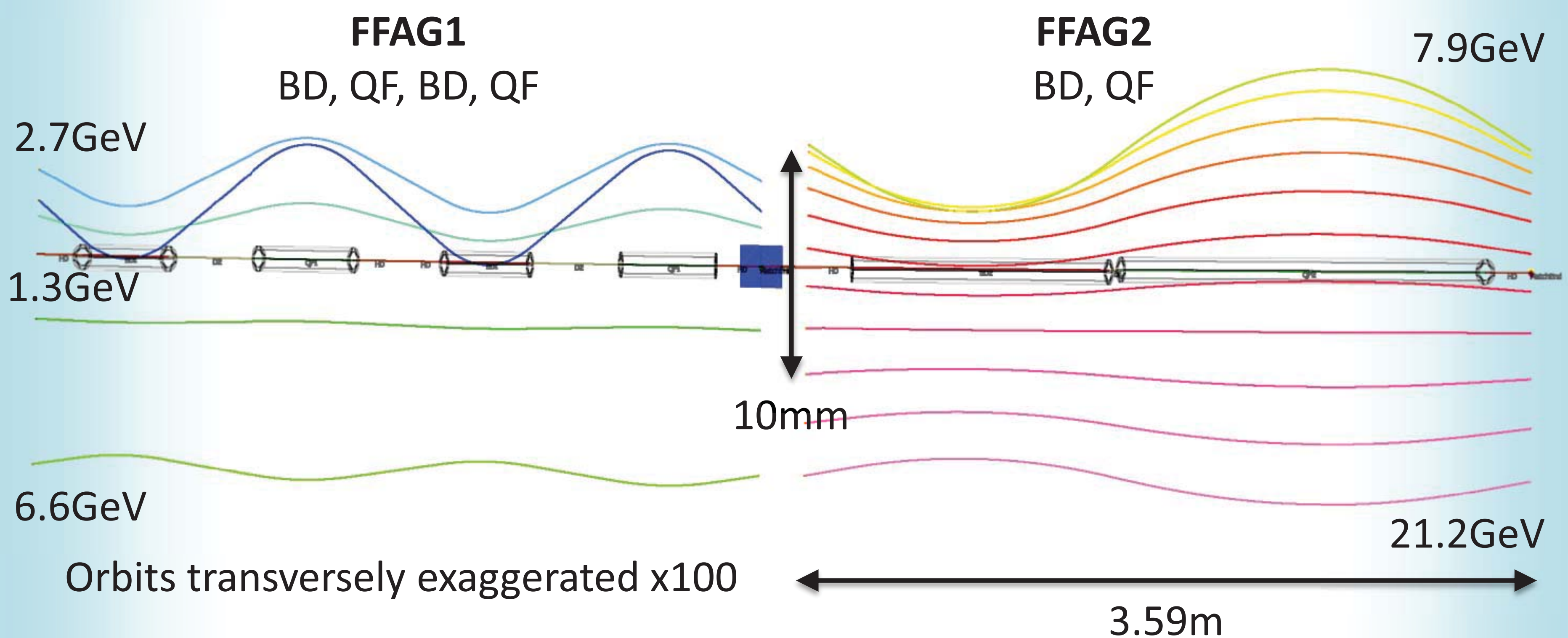
Cost Savings for a ~20GeV ERL EIC

Parameter	Non-FFAG Design	FFAG Design	Reduction
Linac energy per turn	3.33 GeV	1.32 GeV	2.52x
Turns until collision	6	16	(2.67x increase)
Beamline loops built	6	2	3x
Synchrotron power loss for I=20mA	2.18 MW	9.87 MW	4.5x increase

- eRHIC is ERL-based to achieve high luminosity
  - Electron beam only interacts once so can have an extremely high beam-beam tune shift of ~20
  - Would have to be kept stable if in a storage ring

FFAG Cell Orbits

- FFAG1 limited by energy range 4-5x
- FFAG2 optimised for low synchrotron power

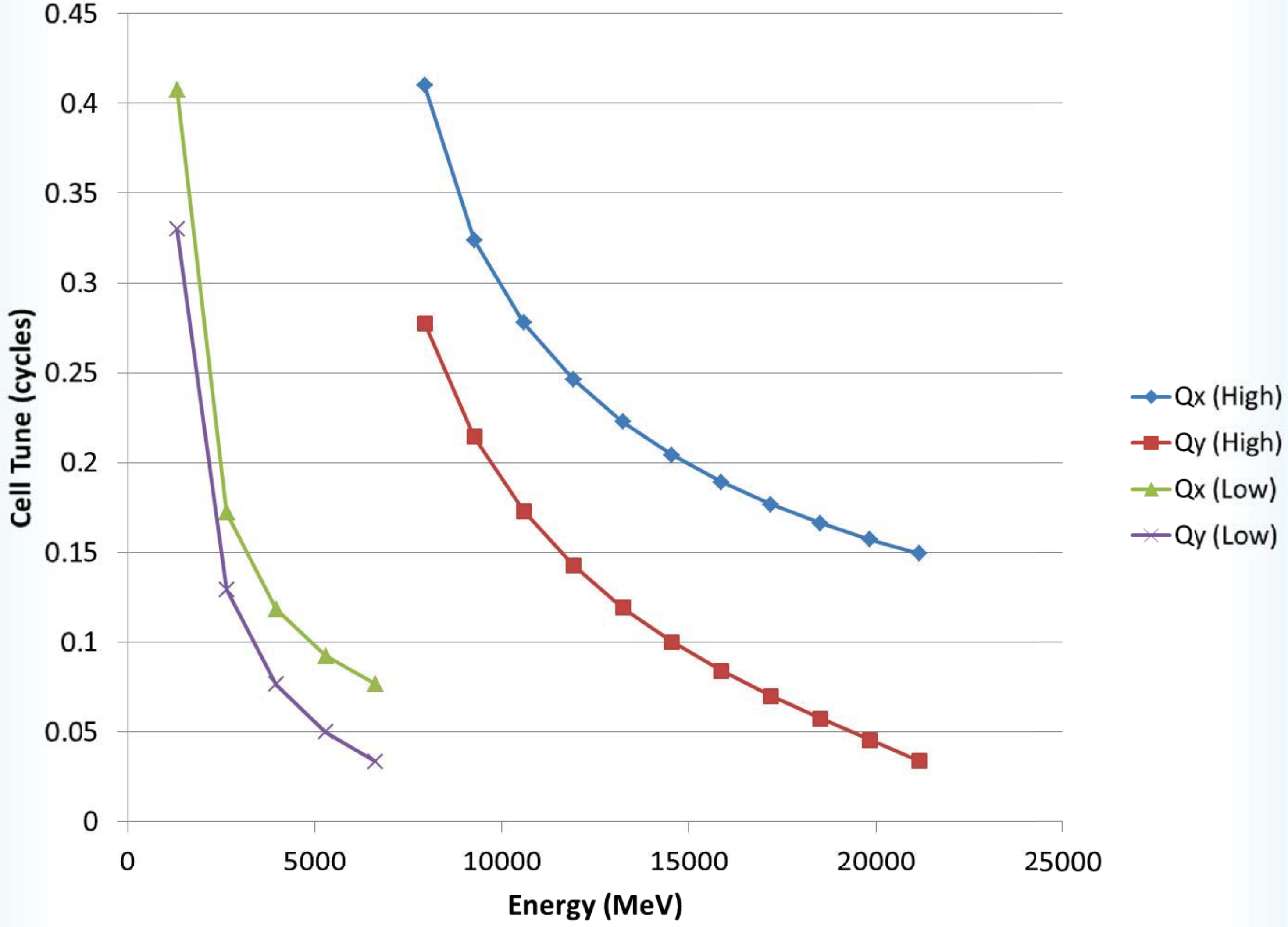


* Just one option, there is also a 4+12 turn scheme

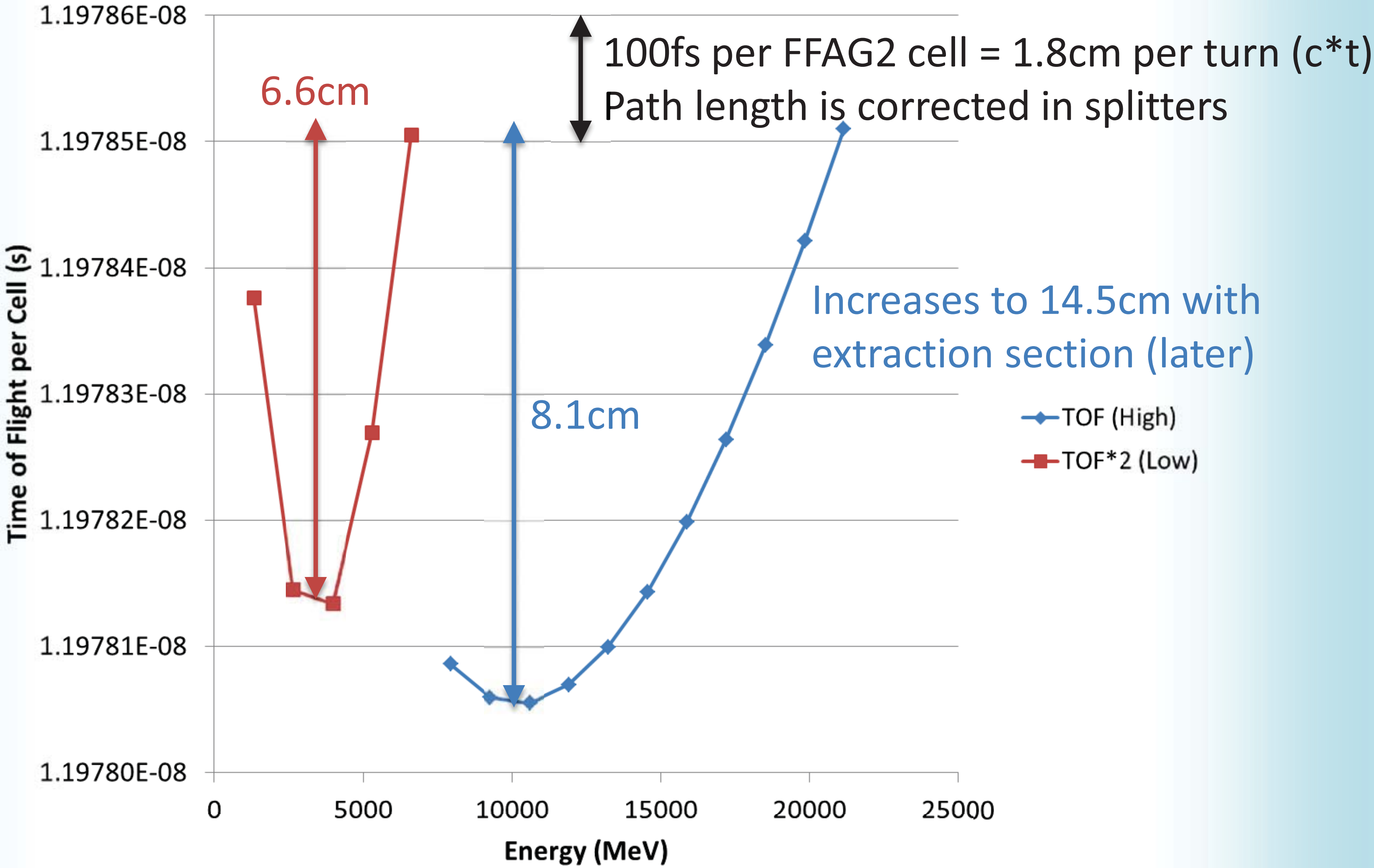
FFAG Cells Parameter Tables

Parameter	FFAG1	FFAG2
Energy range	1.334 – 6.622 GeV	7.944 – 21.164 GeV
Energy ratio	4.96×	2.66×
Number of turns	5	11
Cell length	1.795m	3.591m
BD, QF lengths	0.425m, 0.471m	1.272m, 1.809m
Drift lengths	45cm, 45cm	6cm, 45cm
BD, QF gradients	25 T/m, -25 T/m	29.256 T/m, -25 T/m
Maximum orbit span	16.6mm	21.5mm
Tune per cell range	0.033 – 0.408	0.034 – 0.410
TOF variation	31.0ppm (6.6cm/ring)	38.0ppm (8.1cm/ring)
Maximum field on orbit	0.266 T	0.416 T
Synchrotron power loss	0.34MW, I=50mA	9.87MW, I=20mA, 21.2GeV 9.48MW, I=50mA, 15.9GeV 2.79MW, I=50mA, 10.6GeV

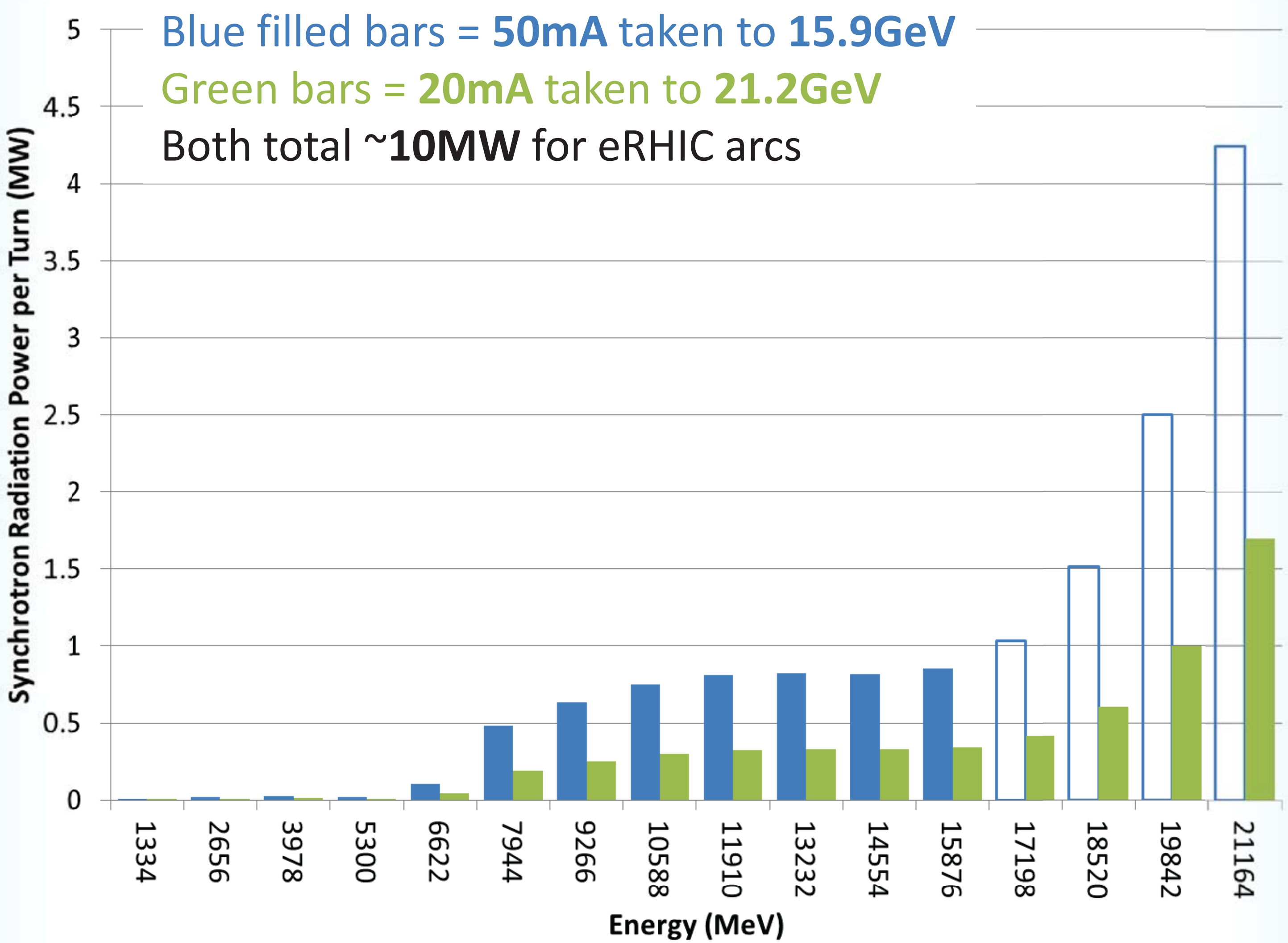
eRHIC Tunes per Cell vs. Energy



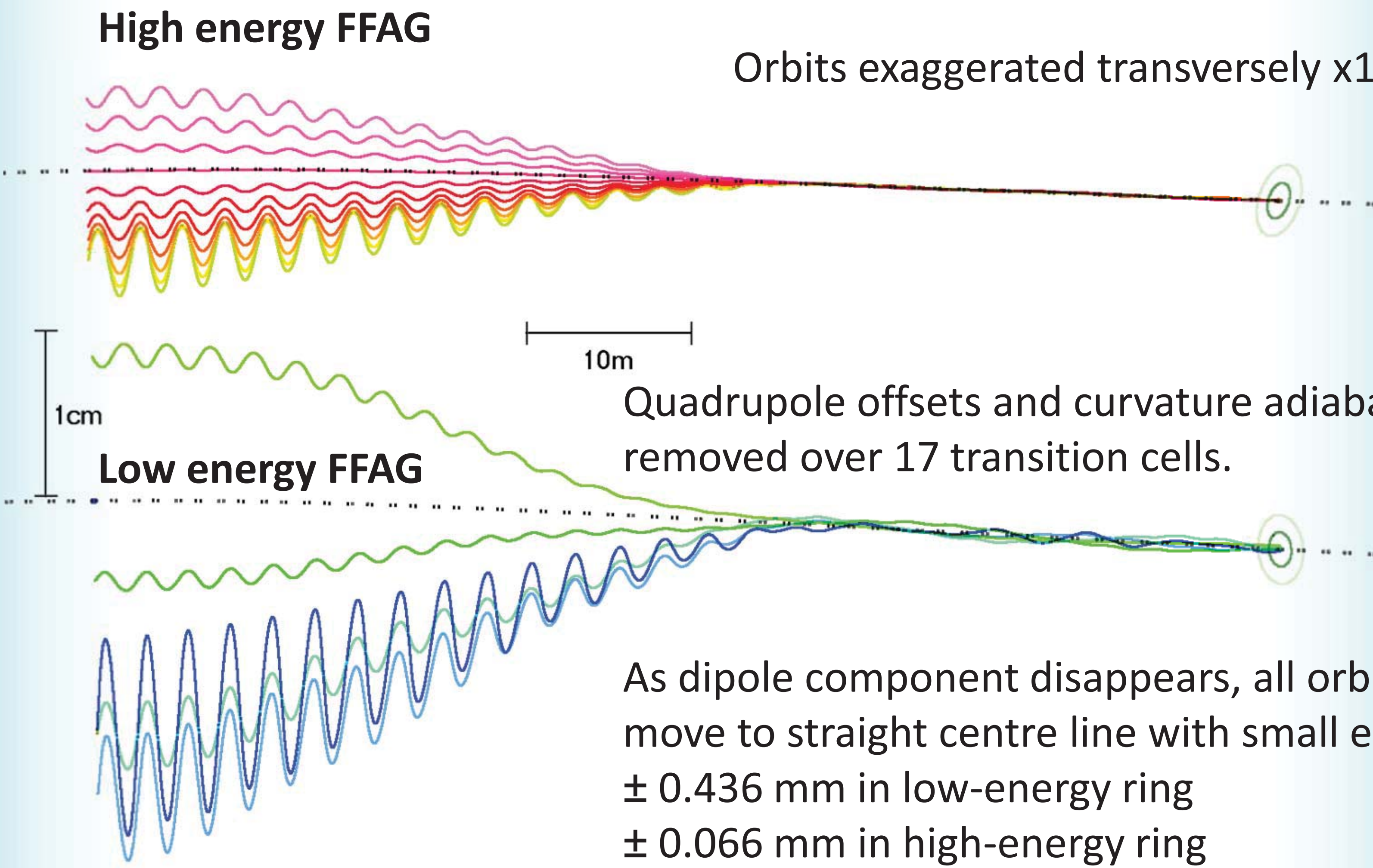
eRHIC TOF Variation with Energy



eRHIC Synchrotron Power per Turn



eRHIC FFAG Straight Sections



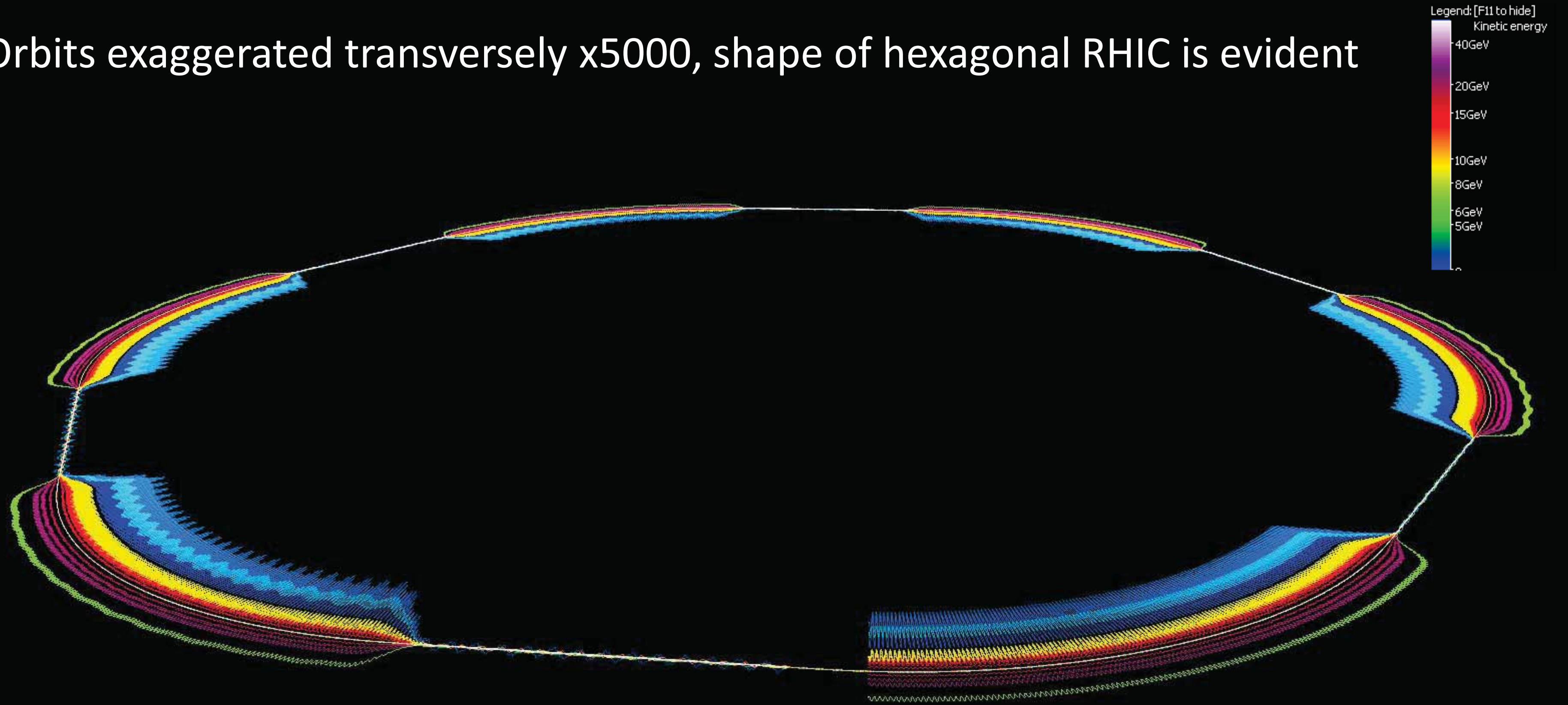
Orbits exaggerated transversely x1000

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
…that can be corrected with fine adjustments

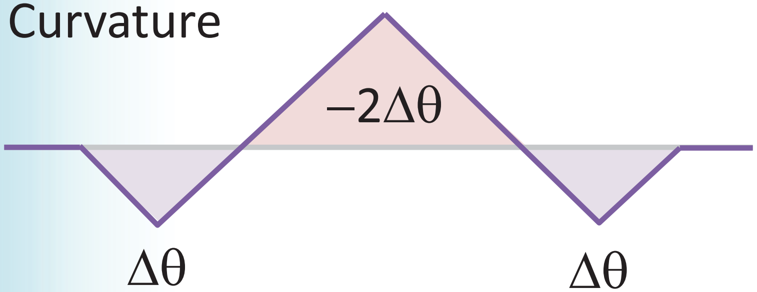
eRHIC FFAG Rings in Perspective

Orbits exaggerated transversely x5000, shape of hexagonal RHIC is evident

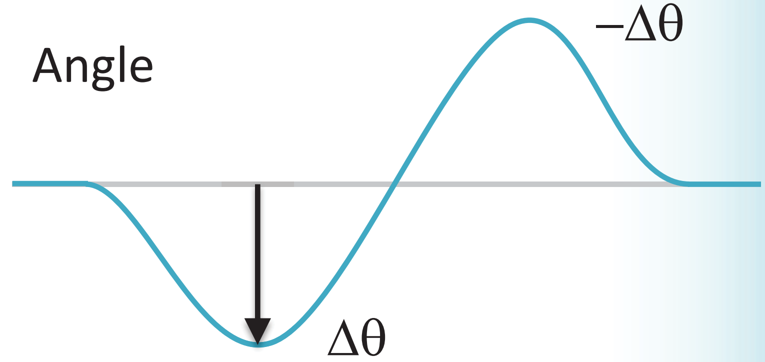


Detector Bypasses: a Flexible FFAG

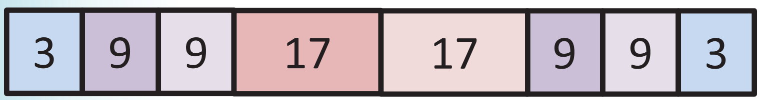
Curvature



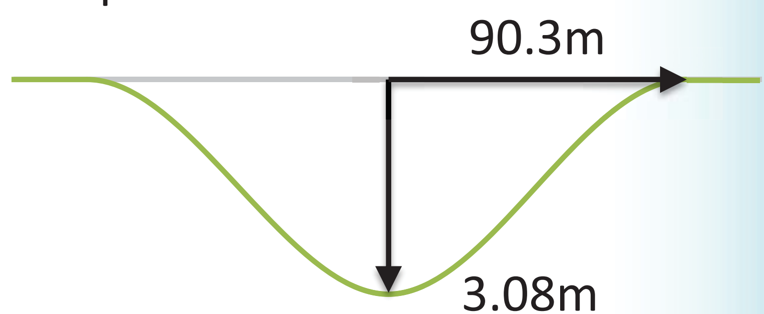
Angle



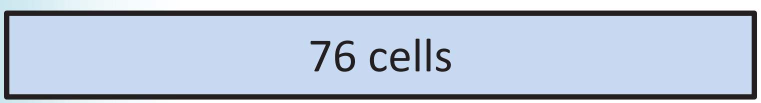
Bypass straight

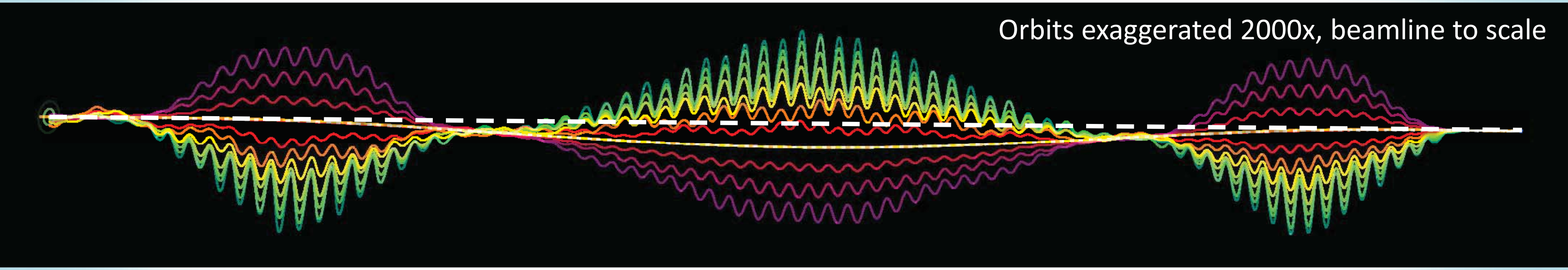


Displacement

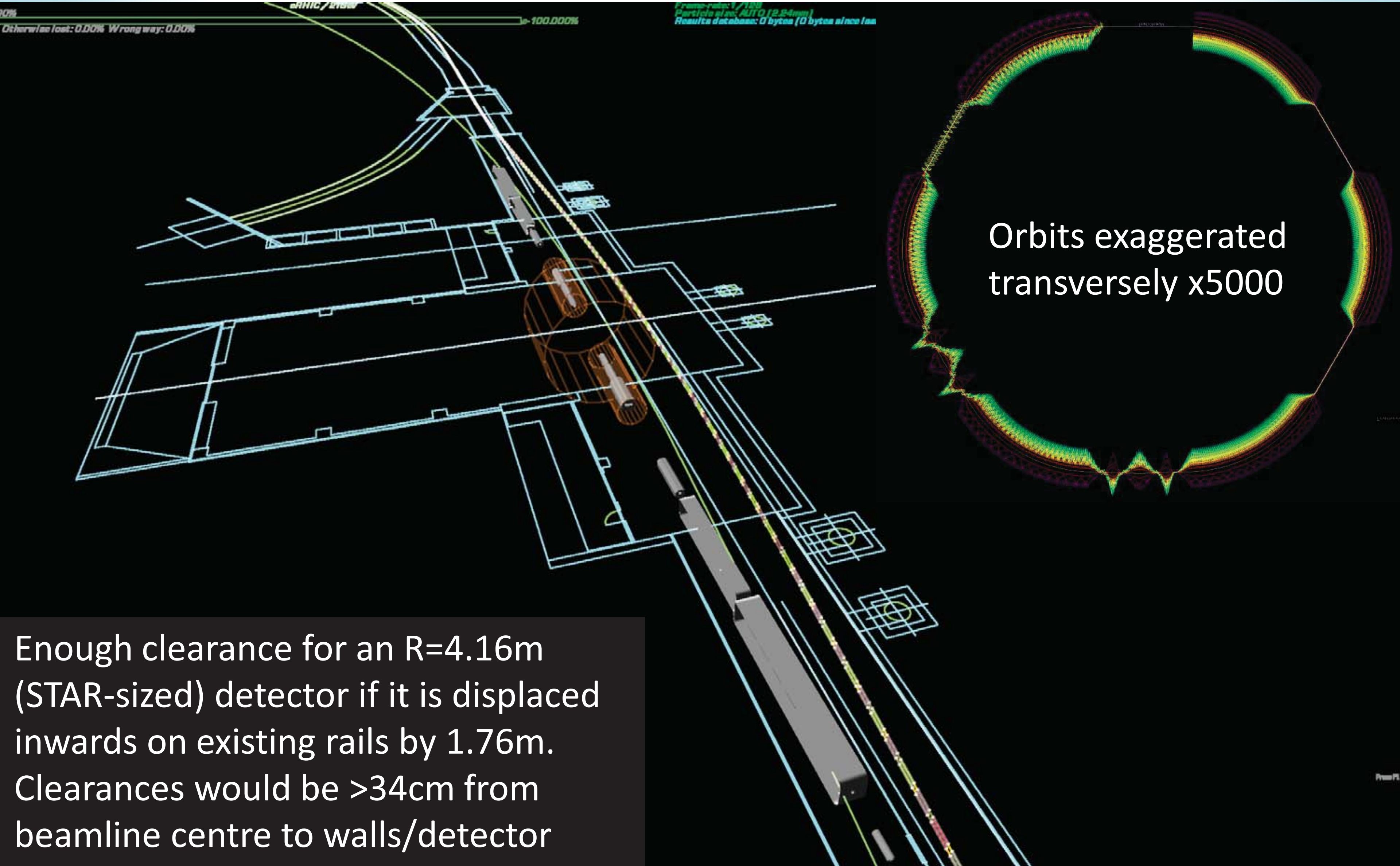


Normal straight





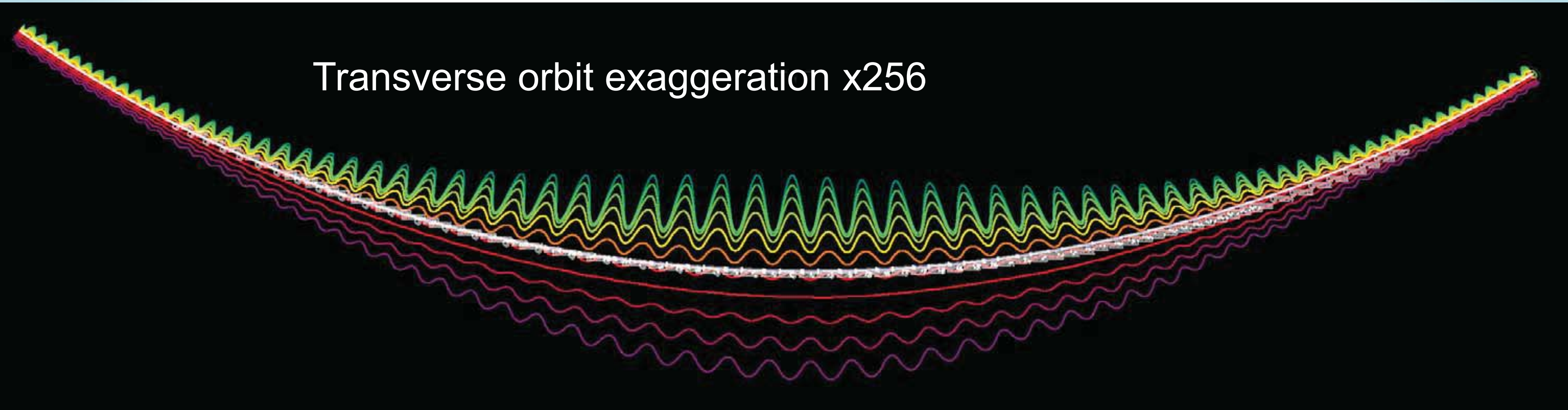
3D Bypass Layout in RHIC Tunnel



Enough clearance for an R=4.16m (STAR-sized) detector if it is displaced inwards on existing rails by 1.76m. Clearances would be >34cm from beamline centre to walls/detector

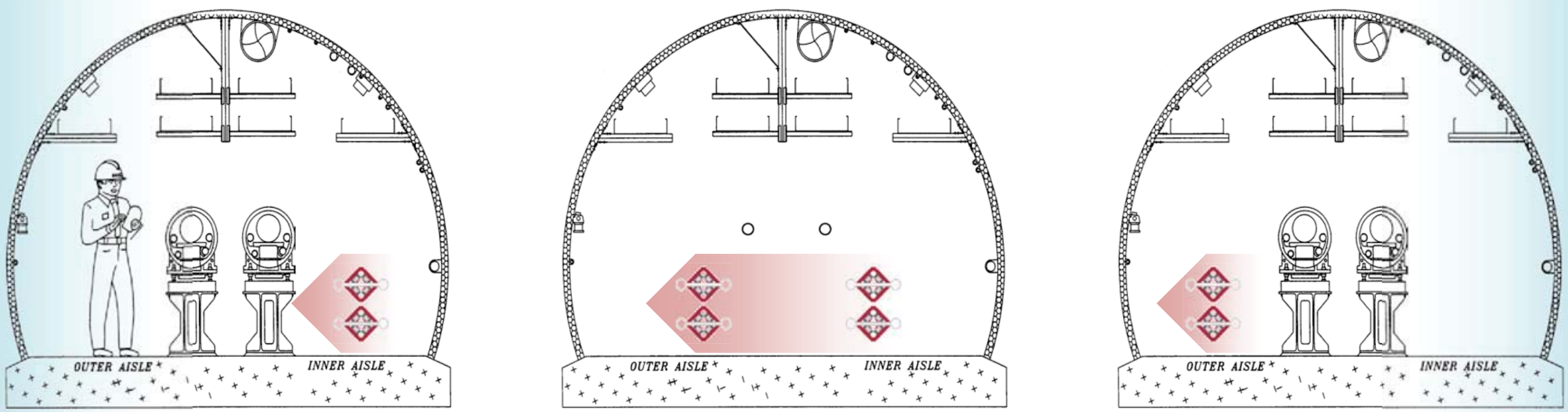
Extraction Scheme

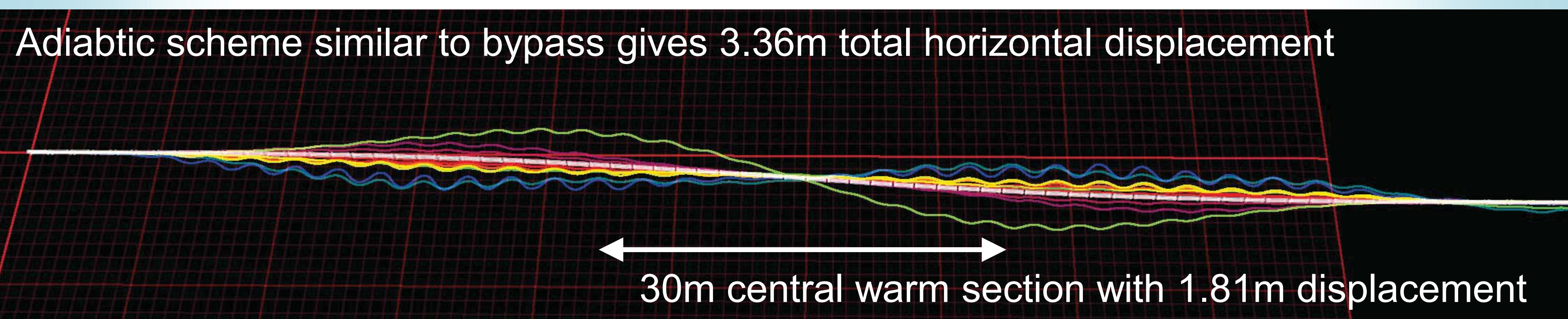
- Adiabatically expand cells in 5 & 9 o'clock arcs
- Cells increase in length by factor e ~= 2.718
  - Orbits separate by factor e^2 ~= 7.389
- In centre, high-energy orbits separated by 2cm
  - Use 0.7T/1.1m massless septum, BD, QF → 8cm



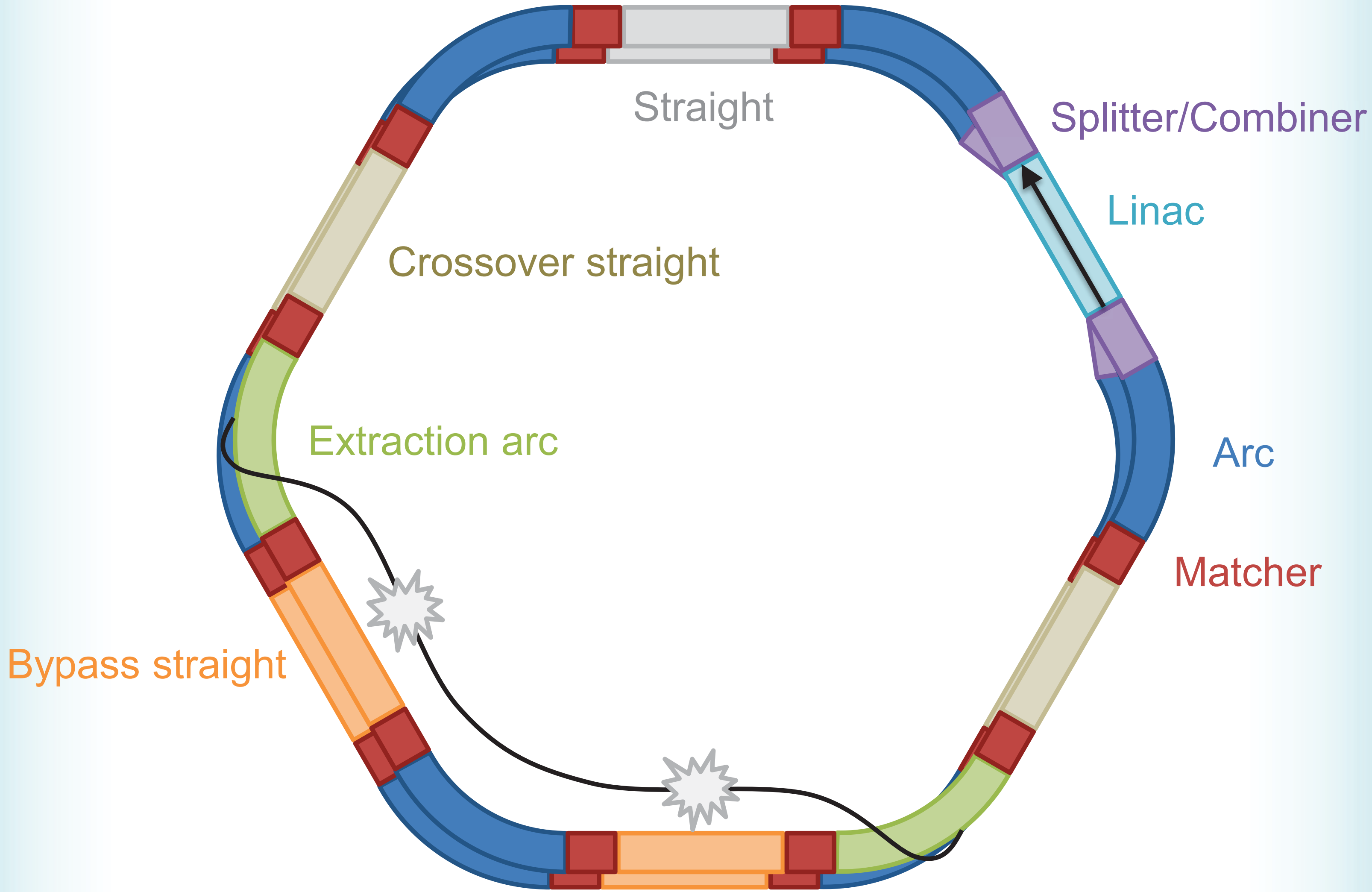
Tunnel Crossover under RHIC Pipe

- eRHIC path length must ~= RHIC hadron ring
  - Can't stay on inside or outside all the way around
- Space under 4 and 10 o'clock no-cryo pipe



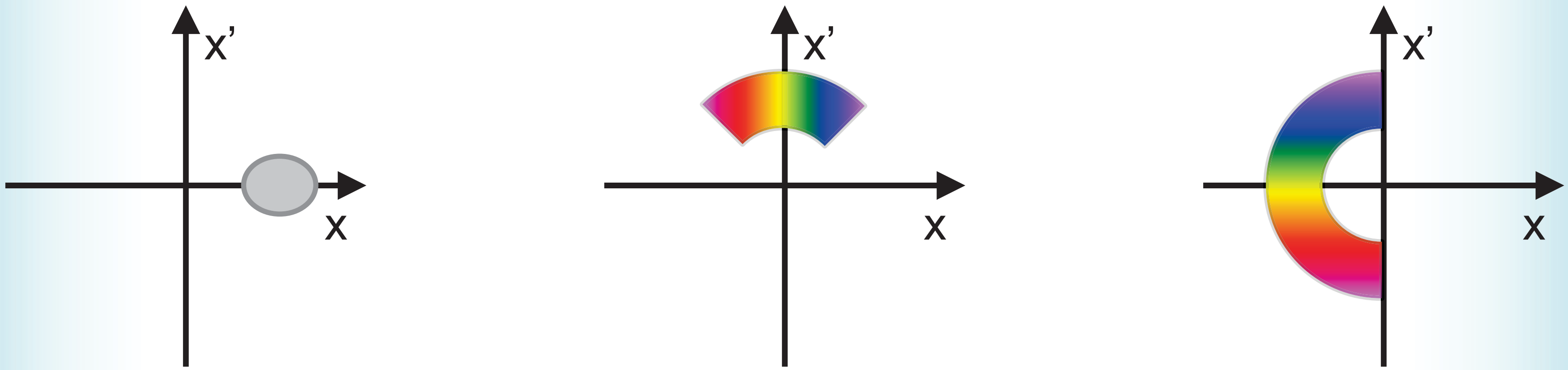


All FFAG Special Sections



Orbit Error Correction is Important

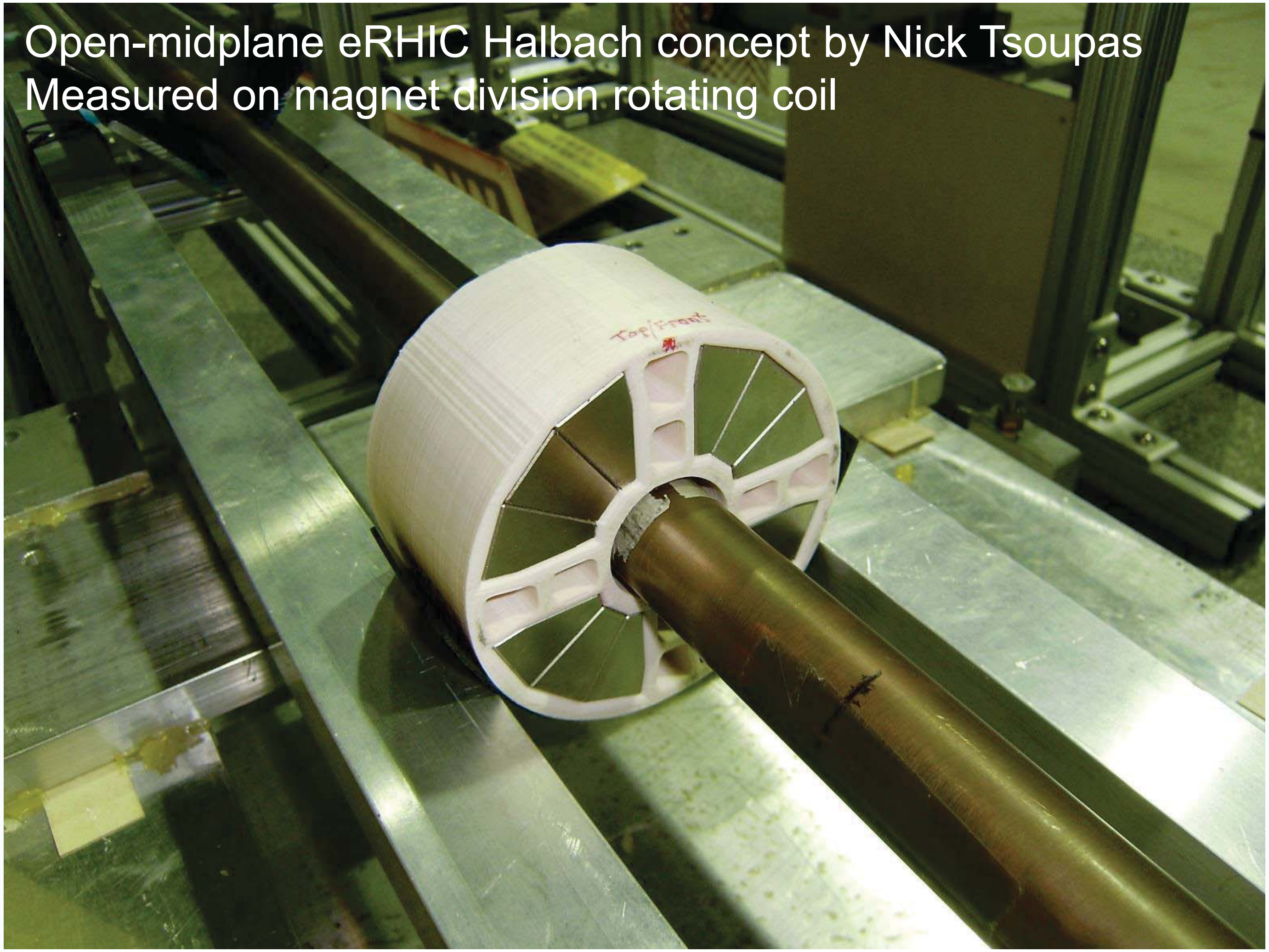
- Even energy spread ~ 10^{-3} in such a long channel can cause phase differences
  - Of the order of 1000 cells around RHIC tunnel
  - Natural chromaticity + errors → emittance growth
  - Must correct orbits to within less than beam size



Field Error Sources and Mitigations

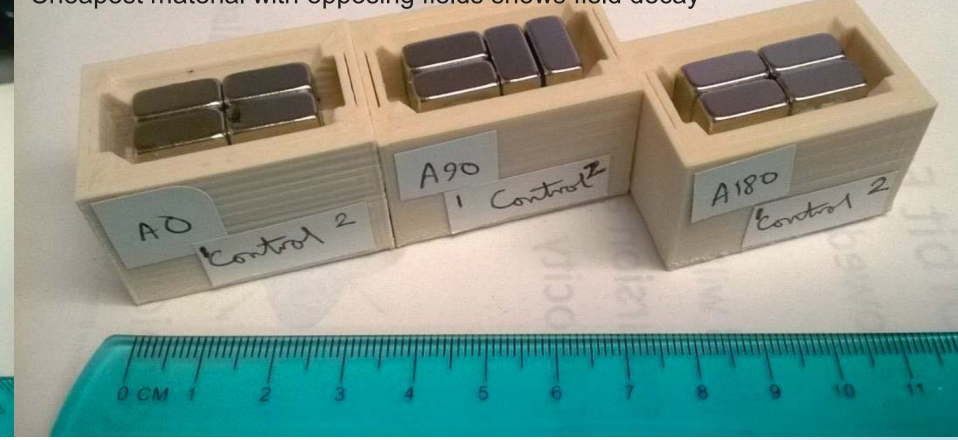
Field error source	Relative size	Equivalent displacement	Time scale	Linear / Nonlinear	Mitigation
Material magnetisation	2e-2	200µm	Constant	Both	Magnet tuning on bench
Magnet assembly	2e-3	20µm	Constant	Both	Magnet tuning on bench
Alignment on girder	1e-2	100µm	Constant	Linear	1% (50G) linear corrector coils
Radiation damage	<1e-3	<10µm	Years	Unknown	1% (50G) linear corrector coils
Temperature coefficient	1e-3/K	10µm/K	Minutes - hours	Linear (?)	Orbit feedback + corrector coils
Slow vibrations	<1e-3	<10µm	< few Hz	Linear	Orbit feedback + corrector coils
Fast vibrations	<1e-5	<0.1µm	> few Hz	Linear	Not corrected (small enough)

Permanent Magnet Prototyping



NdFeB Irradiation Test

Test magnets of 5 material grades placed in hottest parts of RHIC tunnel
~500Gy irradiation so far, eRHIC 20 year estimate 1kGy
No change in 4 of 5 materials
Cheapest material with opposing fields shows field decay



Cβ Prototype Facility at Cornell