

Beam and polarization dynamics simulations in eRHIC

François Méot, BNL C-AD

With contributions from

S. Brooks, V. Ptitsyn, D. Trbjevic, N. Tsoupas, and others

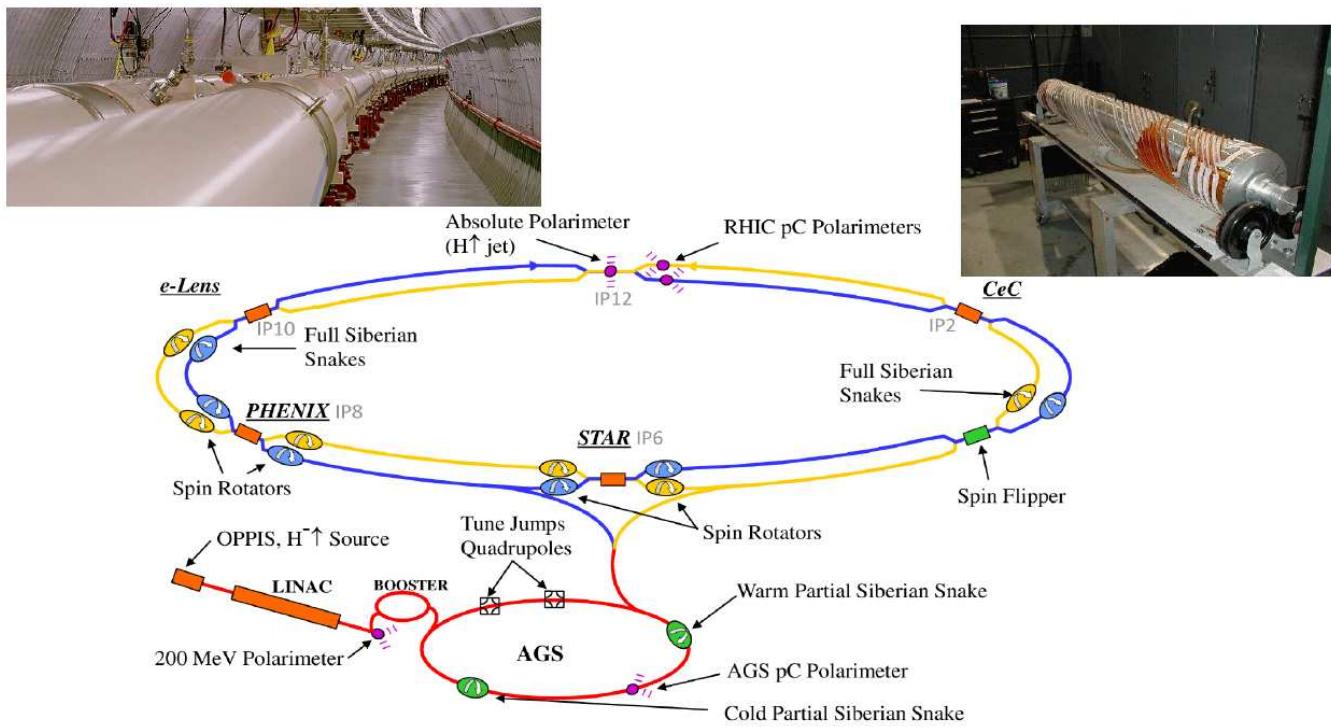
Contents

• Introduction	2
1 eRHIC FFAG2 optics	6
2 Spin diffusion	12
3 Single-turn dynamics	13
4 Multi-turn dynamics in a 6-arc ring	16
5 Magnet studies	17
6 Plans, toward full end-to-end	19

● Introduction

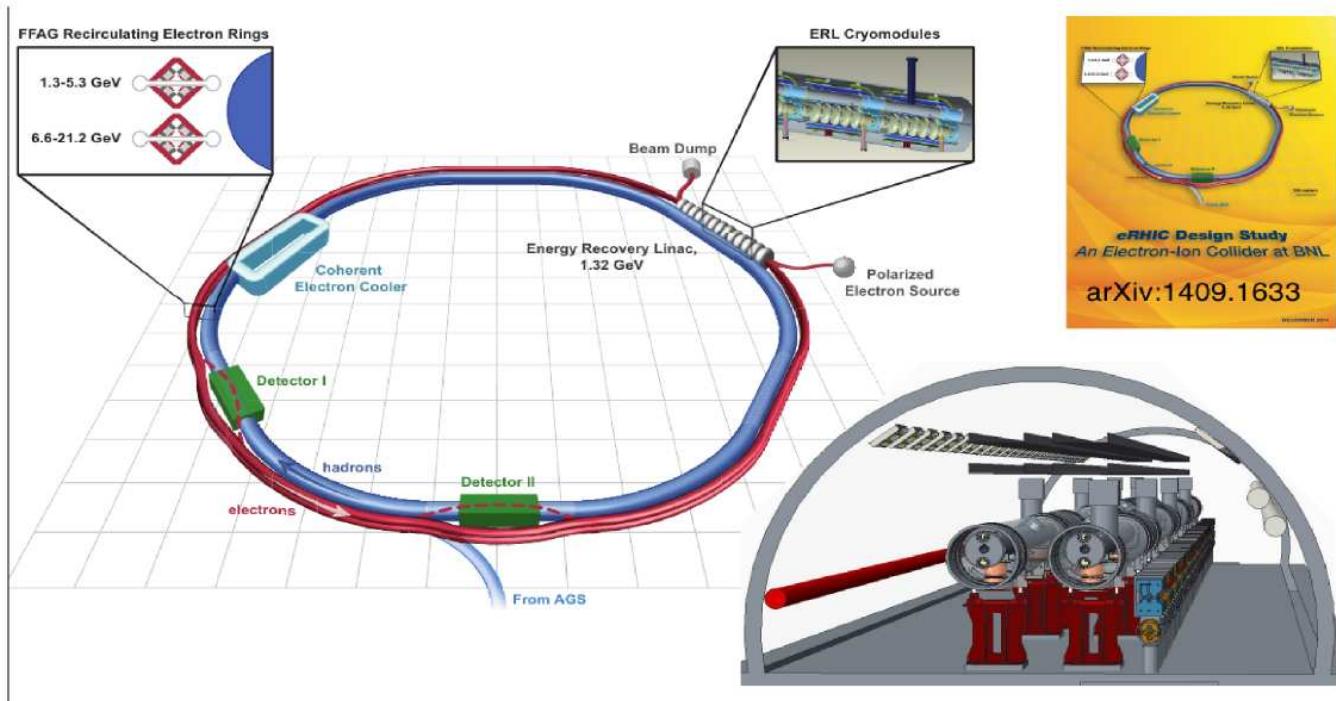
eRHIC at BNL - a linac-ring configuration -

- Based on the existing RHIC hadron facility (a replacement cost of \$2b), using one of the two rings, helical snakes for p and ^3He polarization



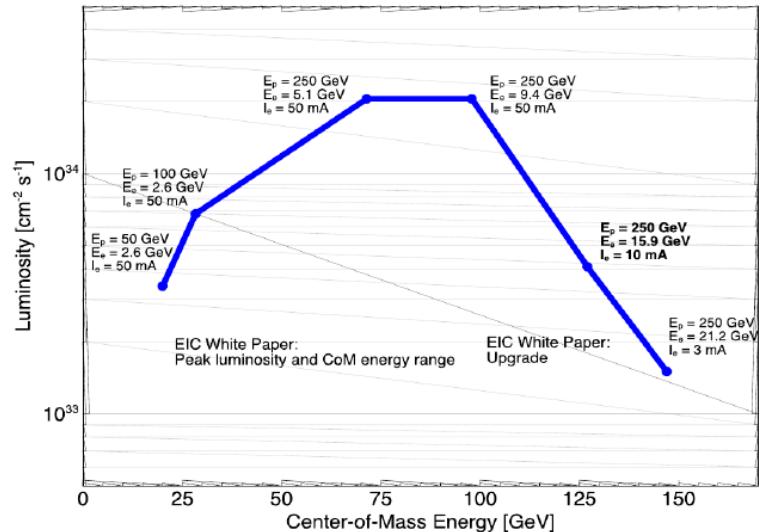
eRHIC EIC

- Based on the existing RHIC hadron facility using one of the two rings, helical snakes for p and 3He polarization
- An ERL as polarized e-bunch accelerator, using a 1.322GeV linac, FFAG arc technology, located alongside RHIC,



eRHIC EIC

- Based on the existing RHIC hadron facility using one of the two rings, helical snakes for p and ^3He polarization
- An ERL as polarized e-bunch accelerator, using a 1.322GeV linac, FFAG arc technology, located alongside RHIC,
- Allowing
 - from 250 GeV polarized proton beams, 30-145 GeV e-p com energy
 - to fully stripped U 100GeV/u beams, 20-90 GeV com energy
 - any polarization direction in electron-hadron collisions
- Possibility of up to 3 interaction regions
- Luminosity in 10^{33} - 10^{34} /cm 2 /s range



eRHIC nominal parameters

	e	p	$^2\text{He}^3$	$^{79}\text{Au}^{197}$
Energy, GeV	15.9	250	167	100
CM energy, GeV		126	103	80
Bunch frequency, MHz	9.4	9.4	9.4	9.4
Bunch intensity (nucleons), 10^{11}	0.07	3.0	3.0	3.0
Bunch charge, nC	1.1	48	32	19.6
Beam current, mA	10	415	275	165
Hadron rms normalized emittance, 10^{-6} m		0.2	0.2	0.2
Electron rms normalized emittance, 10^{-6} m		23	35	58
β^*, cm (both planes)	5	5	5	5
Hadron beam-beam parameter^(a)		0.004	0.003	0.008
Electron beam disruption^(b)		36	16	6
Space charge parameter^(c)		0.08	0.08	0.08
rms bunch length, cm	0.4	5	5	5
Polarization, %	80	70	70	none
Peak luminosity, 10^{33} cm$^{-2}$s$^{-1}$		4.1	2.8	1.7

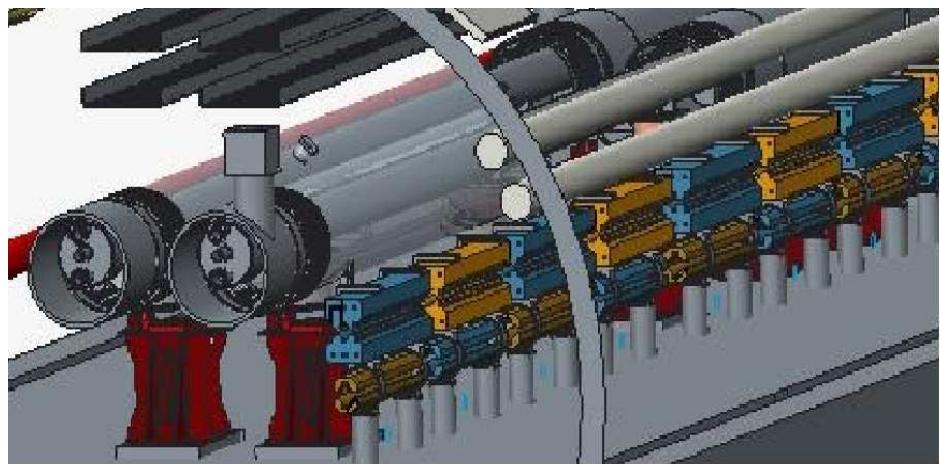
(a) 1/f strength B-B thin lens causes $\cos(\mu) \rightarrow \cos(\mu) - 2\pi\xi\sin(\mu)$, $\xi = \beta^*/4\pi f$. Stability requires $|\cos(\mu) - 2\pi\xi\sin(\mu)| < 1$. One has $dQ \sim \xi$.

(b) d_e =ion bunch length / focal length of linearized beam-beam (kick is $x' = x/f$). Characterizes the deformation of the e-bunch under strong beam-beam interaction, in terms of the number of oscillations of an electron across the ion bunch, $n \sim \sqrt{d_e}/4$.

1 eRHIC FFAG2 optics

- eRHIC optics has been revised recently with a lower gradient, for parameter optimization (compare to presentations at FFAG'14 workshop, BNL).
- There are 12 up passes (and 11 down) in the high energy FFAG (FFAG2) : 6.622 → 21.164 GeV (there were 11 in the previous optics : 7.944 → 21.164 GeV)

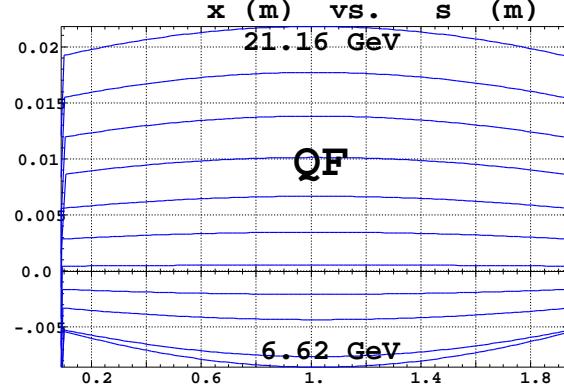
- I focus in this talk on FFAG2, as I'll discuss SR effects on beam and polarization dynamics



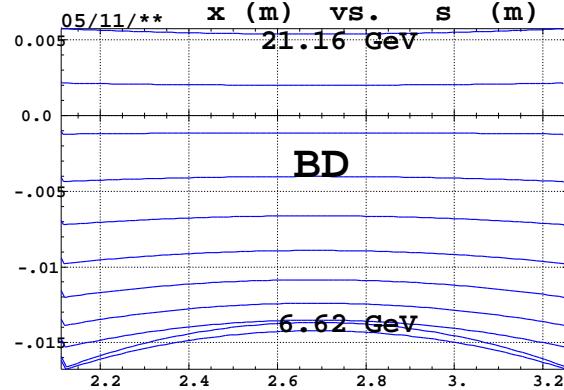
- The earlier and the new gradient values in FFAG2 magnets are as follows :

	previous (T/m)	present (T/m)
QF	49.5	20.6
BD	50	28.9
# cells per arc	138	120

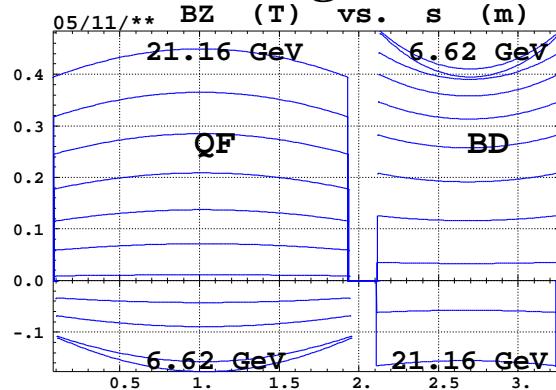
Orbits in QF



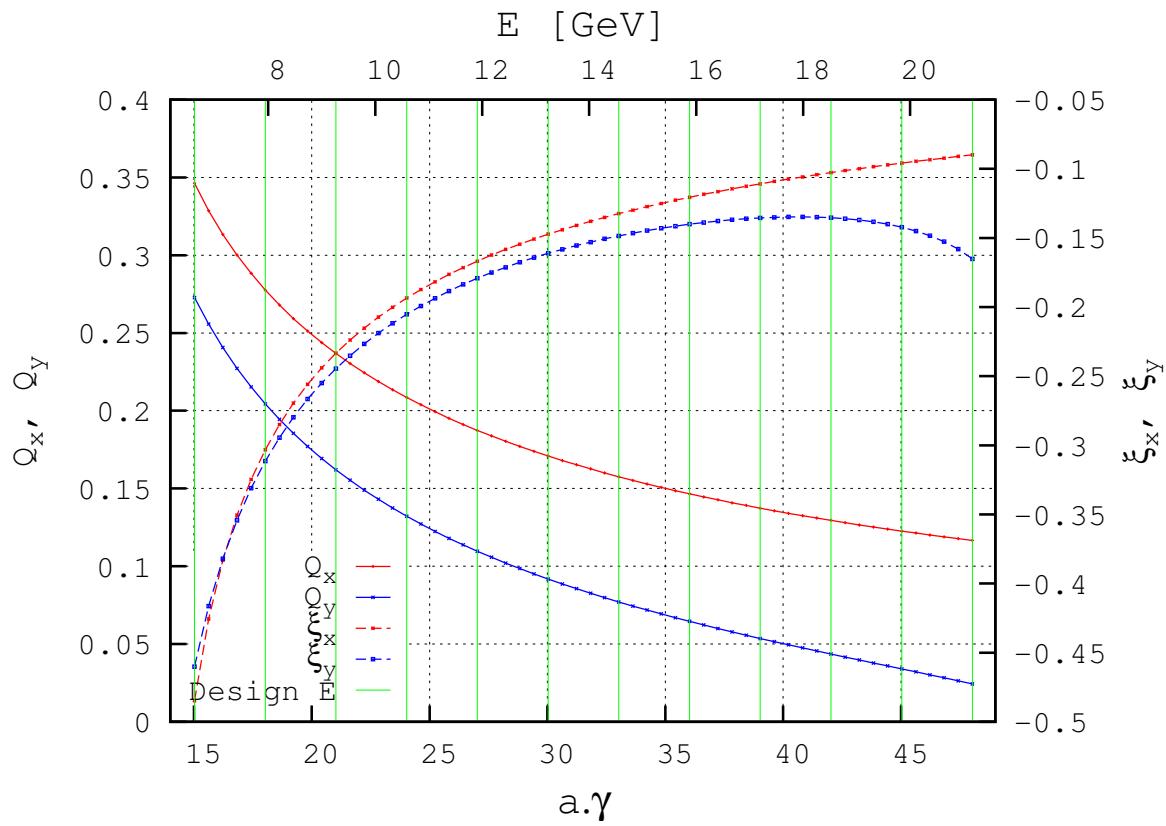
Orbits in BD



Field along orbits

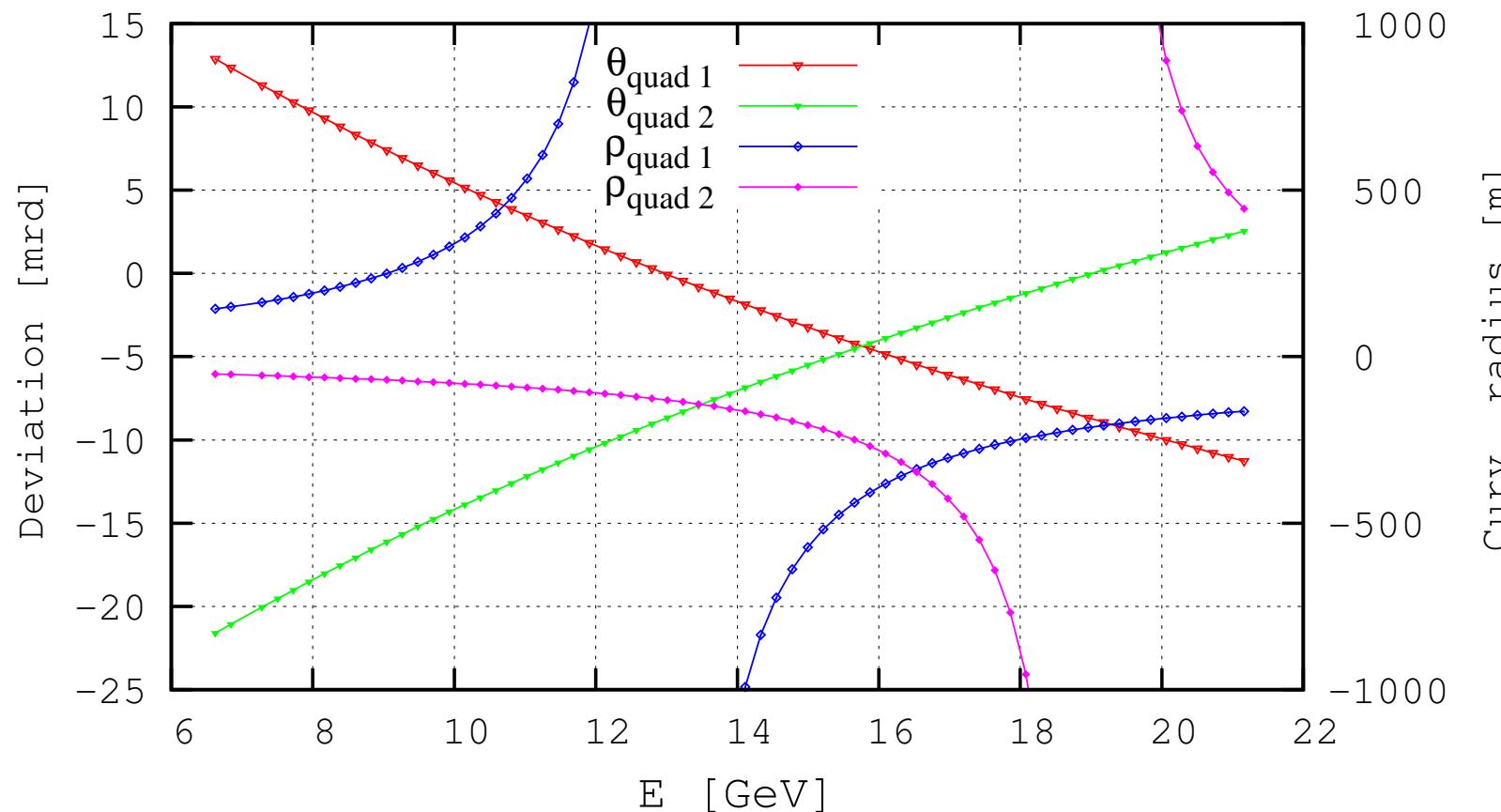


Tunes and chromas from Twiss scan



- A scan of deviation angles θ , curvature radii ρ

DEVIATION AND CURVATURE RADIUS IN CELL'S QUAD 1 AND QUAD 2
(6.622 to 21.164 GeV lattice. Jul 2015)



Deviation angles and curvature radii from tracking (markers), at 67 different energies evenly spread in [6.622,21.164]GeV. The solid lines are to guide the eye.

Hard-edge quadrupole model.

- SR induced ΔE and σ_E , from cell geometry. Comparison with Monte Carlo

SR loss and energy spread induced by the stochasticity of photon emission can be modeled in the following way :

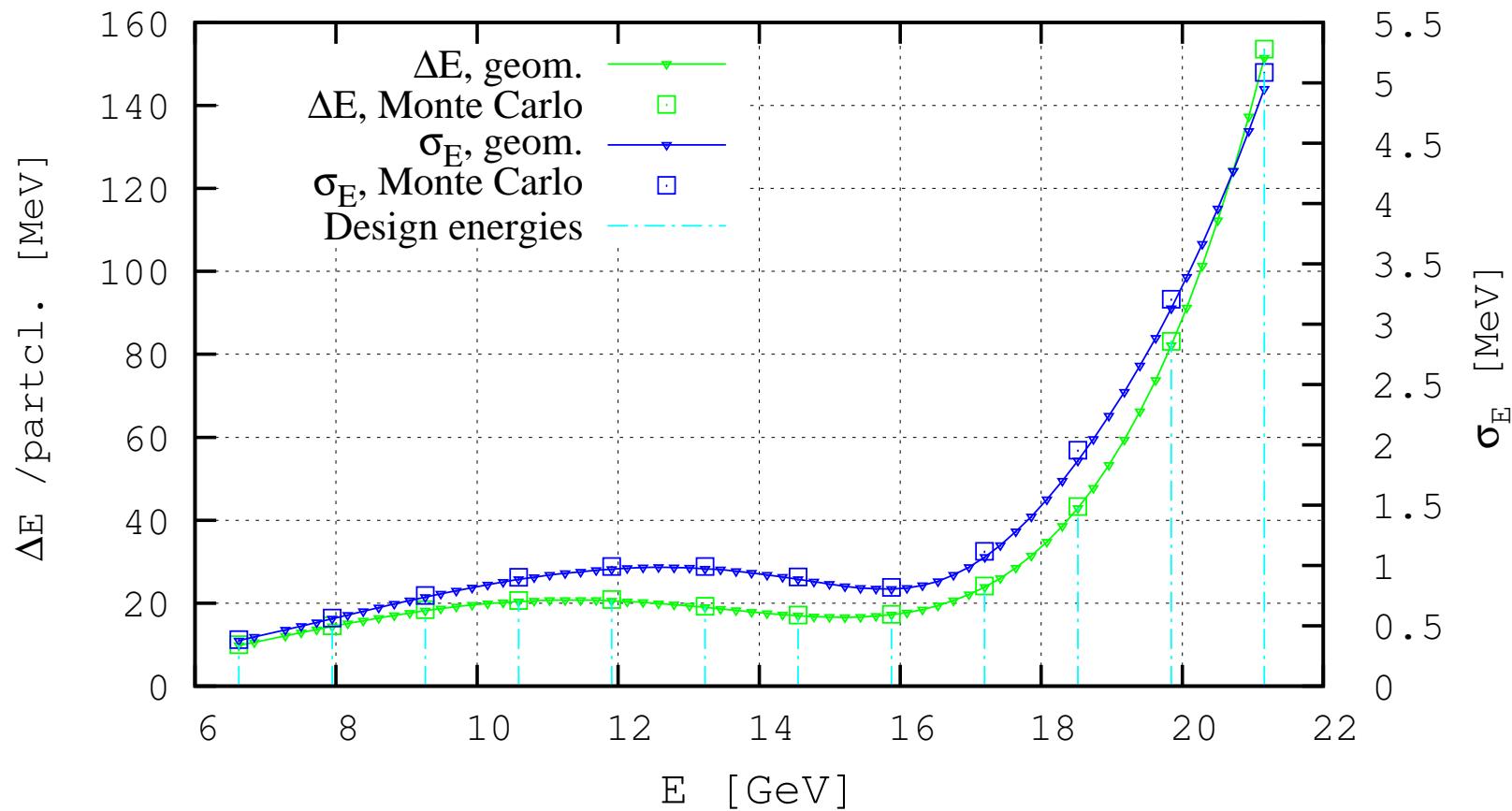
$$\overline{\Delta E}[MeV] = \overline{\Delta E_{QF}} + \overline{\Delta E_{BD}} \approx 0.96 \times 10^{-15} \gamma^4 \left(\frac{\theta_{QF}}{|\rho_{QF}|} + \frac{\theta_{BD}}{|\rho_{BD}|} \right) \quad (1)$$

$\overline{\Delta E}[MeV]$ over cell $\xrightarrow{\times 6\text{arcs} \times 120\text{cells}}$ over ring

$$\sigma_E \approx \sqrt{\sigma_{E,QF}^2 + \sigma_{E,BD}^2} \approx 1.94 \times 10^{-14} \gamma^{7/2} \sqrt{\frac{\theta_{QF}}{\rho_{QF}^2} + \frac{\theta_{BD}}{\rho_{BD}^2}} \quad (2)$$

σ_E over cell $\xrightarrow{\sqrt{\times 6\text{arcs} \times 120\text{cells}}}$ over ring

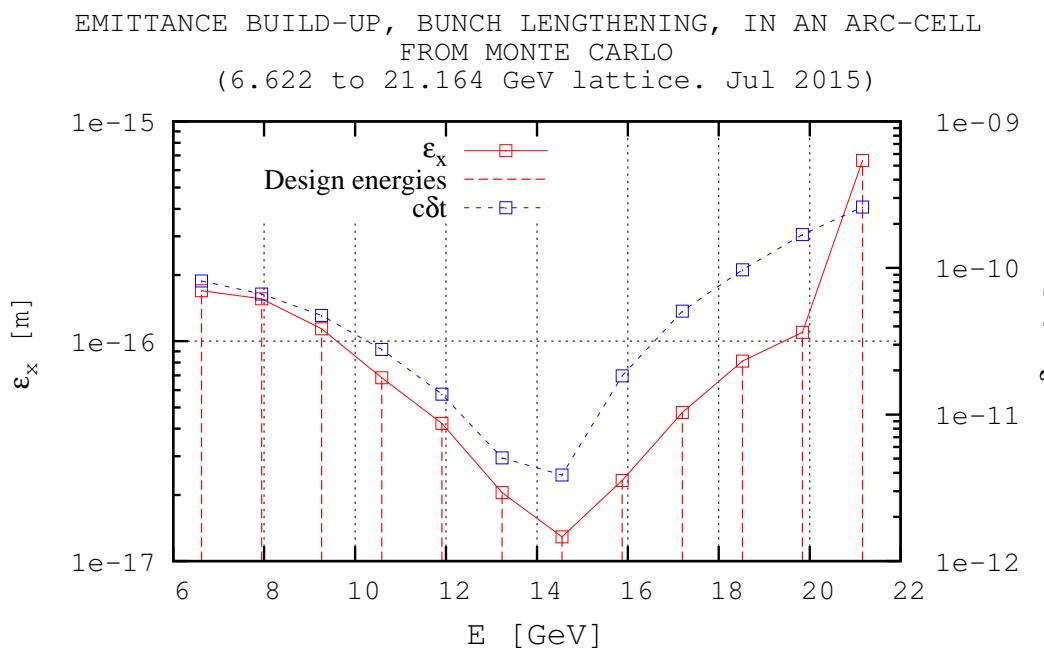
ENERGY LOSS/SPREAD IN A 6*120-CELL RING
 (6.622 to 21.164 GeV lattice. Jul 2015)



The solid lines are from theoretical model, Eq. 1 and Eq. 2, they cover 67 different energies evenly spread in [6.622,21.164]GeV.

“Monte Carlo” data at design energies (square markers) are shown for comparison, taken from 10^4 particle tracking in a single cell, slide #11, and then $\times 6\text{arcs} \times 120\text{cells}$ for energy loss, or $\times \sqrt{6\text{arcs} \times 120\text{cells}}$ for energy spread.

- SR induced emittance and bunch lengthening, in a single arc-cell, from Monte Carlo, 10^4 particle tracked :

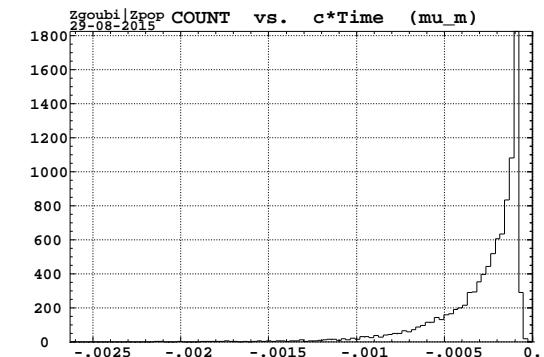
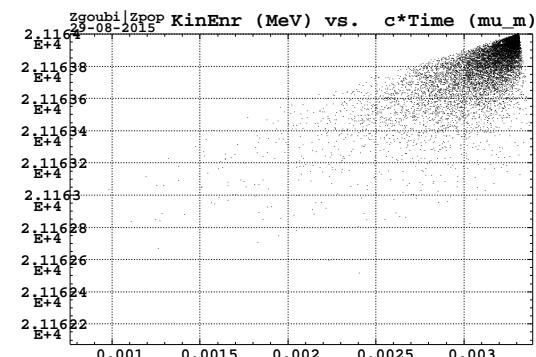
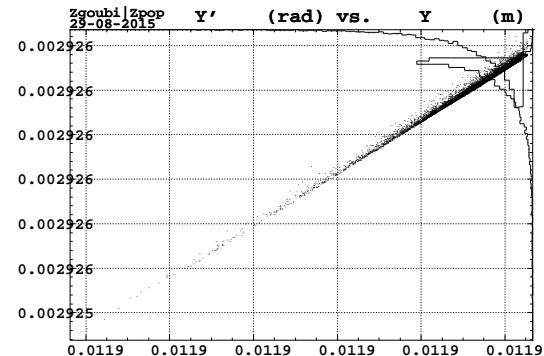


Tracking is only performed at design energies,
the lines are to guide the eye.

Bunch lengthening at 21.16 GeV, extrapolated
from 1 cell to 6 arcs is

$$0.26 \text{ nm} \xrightarrow{\sqrt{6 \text{ arcs} \times 120 \text{ cells}}} 7 \text{ nm over ring}$$

Phase-spaces and densities at
end of arc cell, 21.164 GeV.



2 Spin diffusion

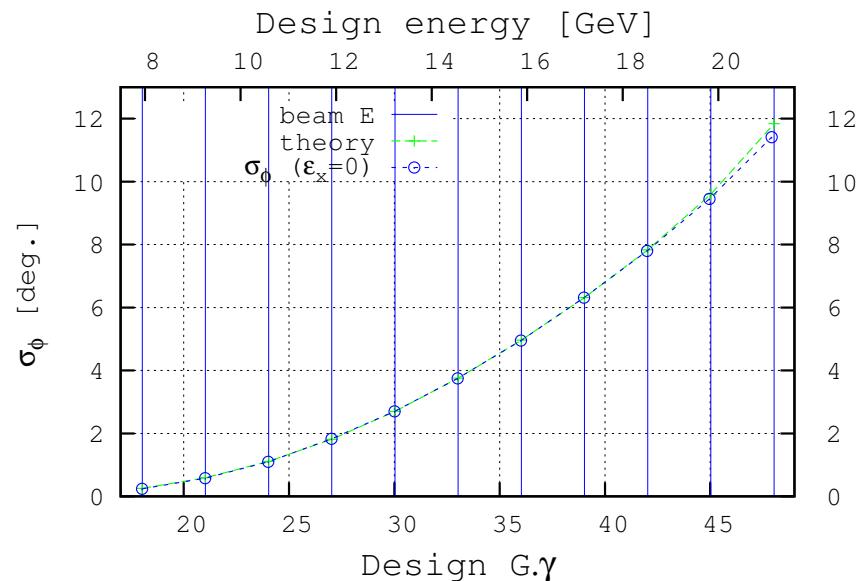
Solution of the diffusion equations [V. Ptitsyn, EIC'14]:

$$V = MV_0 + W, V = \begin{pmatrix} \overline{\Delta E^2} \\ \overline{\Delta E \Delta \phi} \\ \overline{\Delta \phi^2} \end{pmatrix} \xrightarrow{\text{Cst field}} \begin{pmatrix} \overline{\Delta E^2} \\ \overline{\Delta E \Delta \phi} \\ \overline{\Delta \phi^2} \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ \alpha s & 1 & 0 \\ \alpha^2 s^2 & 2\alpha s & 1 \end{pmatrix} \begin{pmatrix} \overline{\Delta E^2} \\ \overline{\Delta E \Delta \phi} \\ \overline{\Delta \phi^2} \end{pmatrix}_{s=0} + \omega \times \begin{pmatrix} s \\ \alpha s^2/2 \\ \alpha^2 s^3/3 \end{pmatrix}$$

where $\omega = \frac{C}{\rho^3} \lambda_c r_e \gamma^5 E^2 \approx 1.44 \times 10^{-27} \frac{\gamma^5}{\rho^3} E^2$ (with $\lambda_c = \hbar/m_e c$ the electron Compton wavelength, $C = 110\sqrt{3}/144$),

$\alpha = \frac{a}{\rho E_0} \approx \frac{1}{0.4406\rho}$ (with $a = 1.16 \times 10^{-3}$ anomalous gyromagnetic factor, electron mass $E_0 = 0.511 \times 10^{-3}$ GeV).

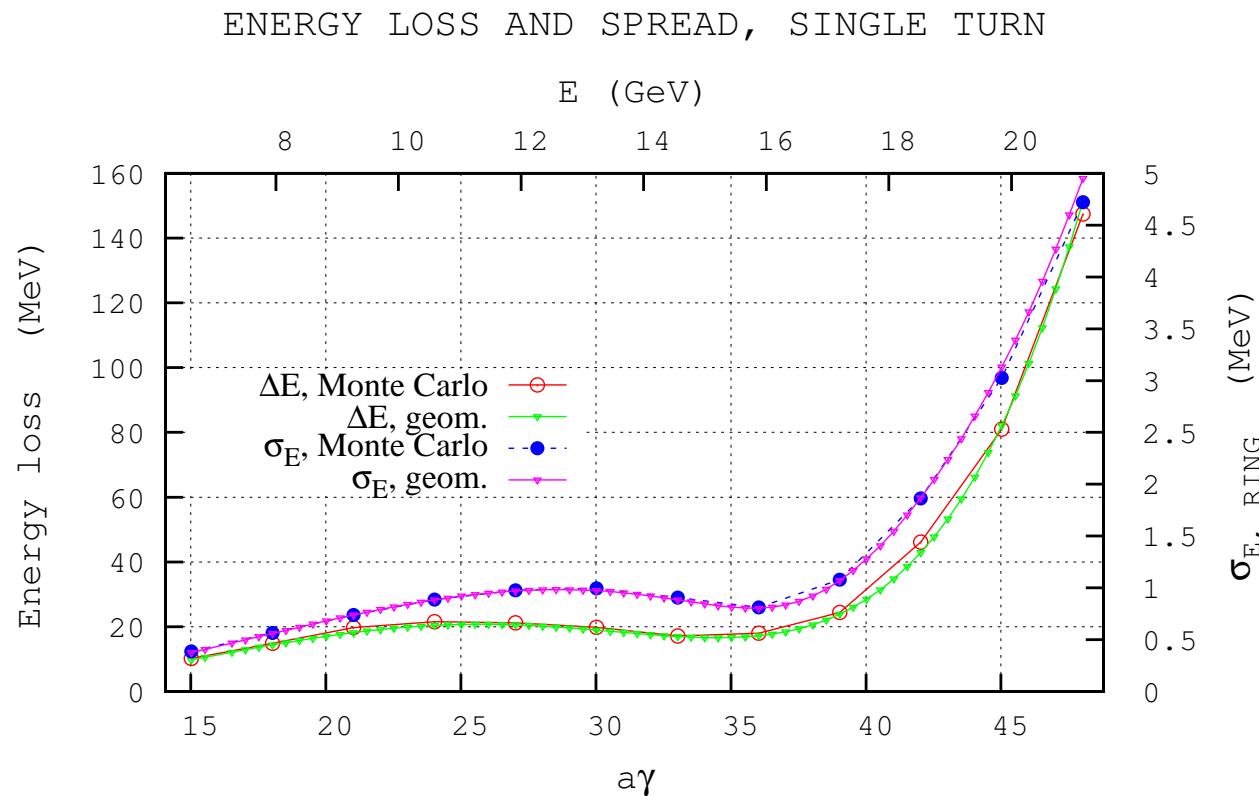
Assuming $\begin{pmatrix} \overline{\Delta E^2} \\ \overline{\Delta E \Delta \phi} \\ \overline{\Delta \phi^2} \end{pmatrix}_{s=0} = 0$ yields in particular $\sigma_E = \overline{\Delta E^2}^{1/2} = (\omega s)^{1/2}$, $\sigma_\phi = \overline{\Delta \phi^2}^{1/2} = \sqrt{\frac{\omega \alpha^2 s^3}{3}}^{1/2} = \frac{\alpha s}{\sqrt{3}} \sigma_E = \frac{\alpha \sigma_E^3}{\sqrt{3} \omega}$.



3 Single-turn dynamics

The game here : a 5000-particle bunch is launched over a 6-arc ring, tracked for a single turn, at each of the 12 different energies.

- SR induced ΔE and σ_E , over one turn. Comparison with geometrical model
- 6-D emittance is zero at start of turn

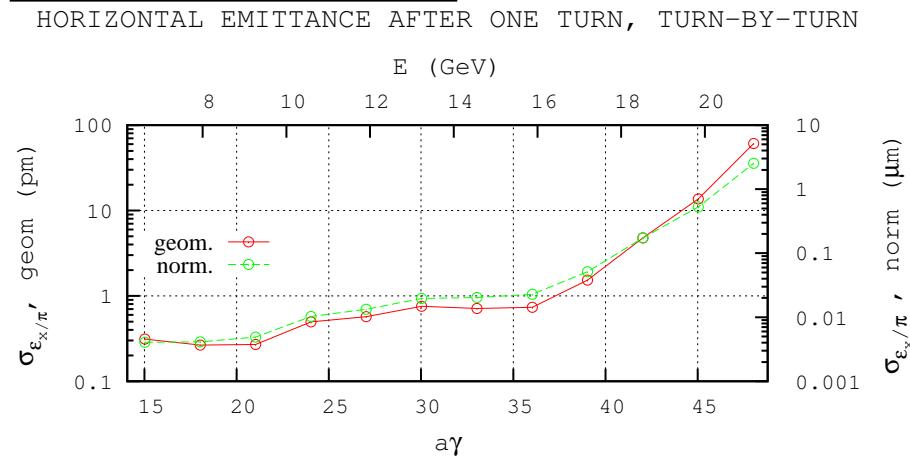


One-turn Monte Carlo simulations (circles) are at design energies only - red (ΔE) and blue (σ_E) lines are to guide the eye.

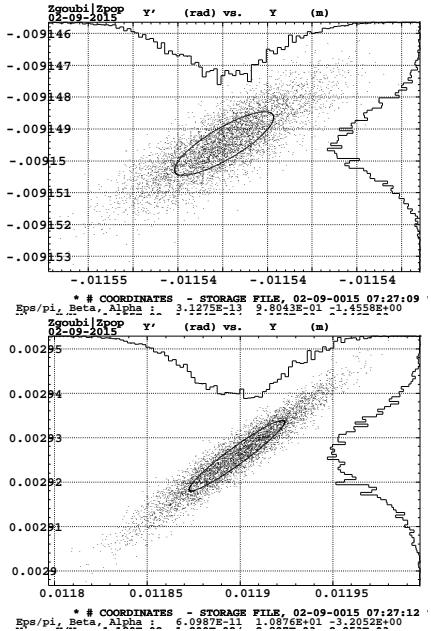
Energy scans in the geometrical model (triangles, from Eqs. 1, 2, figure in slide #9) are superimposed for comparison.

• Emittance growth, re-centering bunch on theoretical FFAG orbit, at each arc

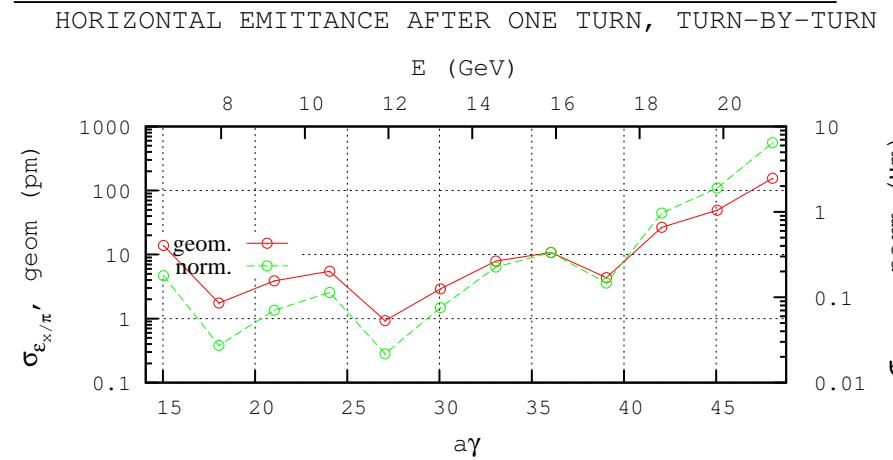
Initial dp/p , ϵ_x , ϵ_y zero.



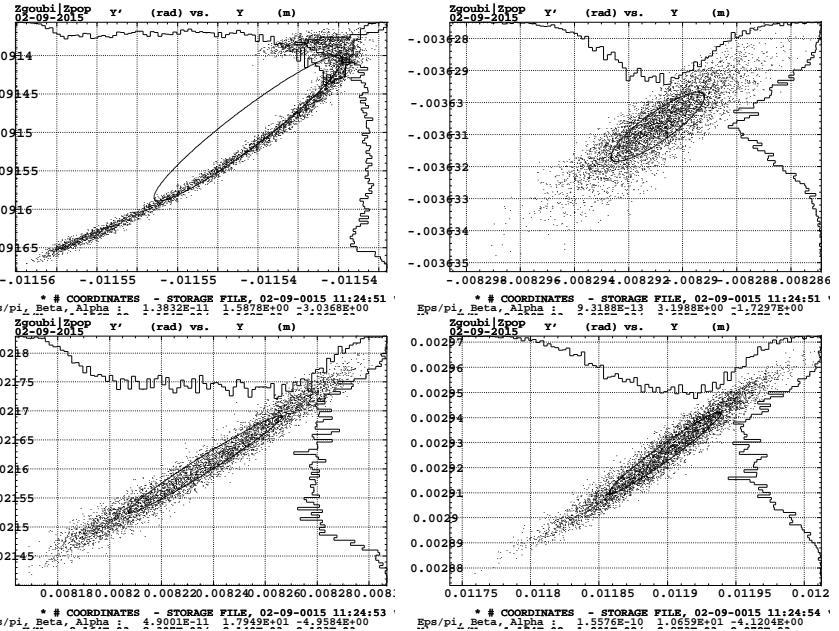
6.6 and 21.2 GeV
(end of pass # 1 and 12)



Initial $dp/p \in \pm 3 \cdot 10^{-4}$ uniform, ϵ_x , ϵ_y zero.

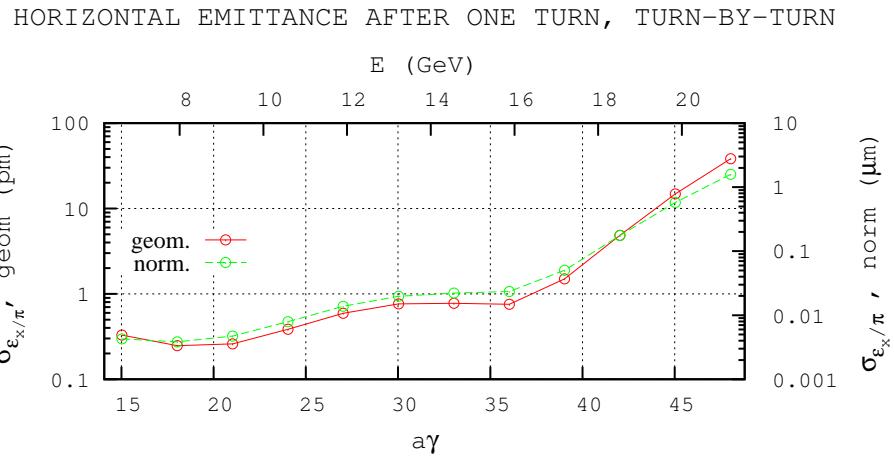


6.6, 11.9, 17.2 and 21.2 GeV
(end of pass # 1, 5, 9, 12)

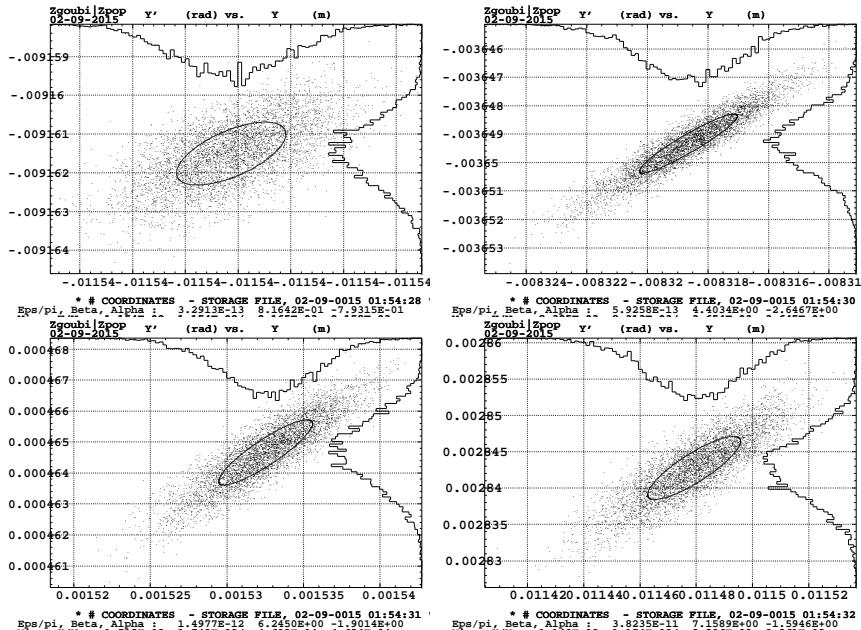


- Emittance growth, no re-centering, for comparison

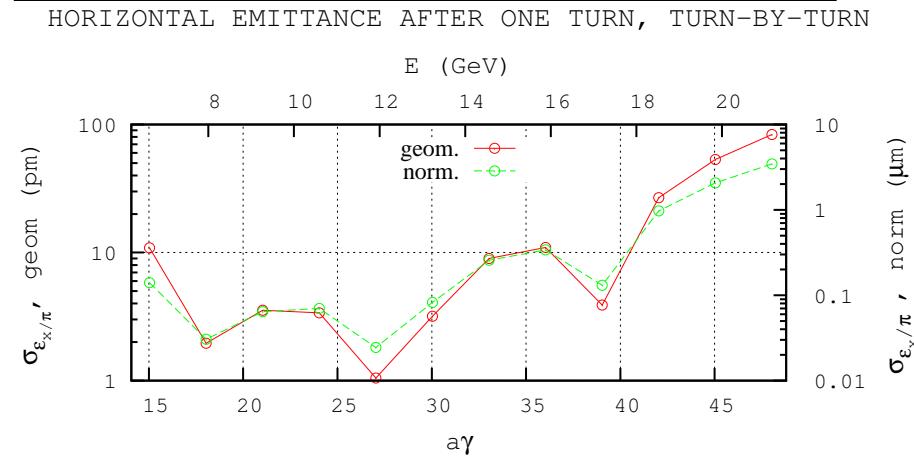
Initial dp/p , ϵ_x , ϵ_y zero.



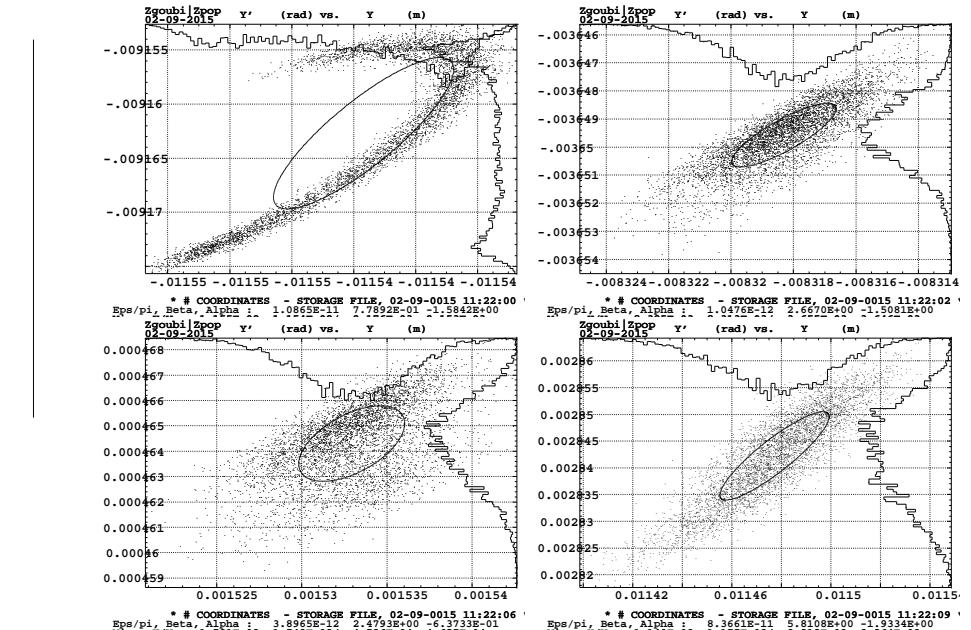
**6.6, 11.9, 17.2 and 21.2 GeV
(end of pass # 1, 5, 9, 12)**



Initial $dp/p \in \pm 3 \cdot 10^{-4}$ uniform, ϵ_x , ϵ_y zero.



**6.6, 11.9, 17.2 and 21.2 GeV
(end of pass # 1, 5, 9, 12)**



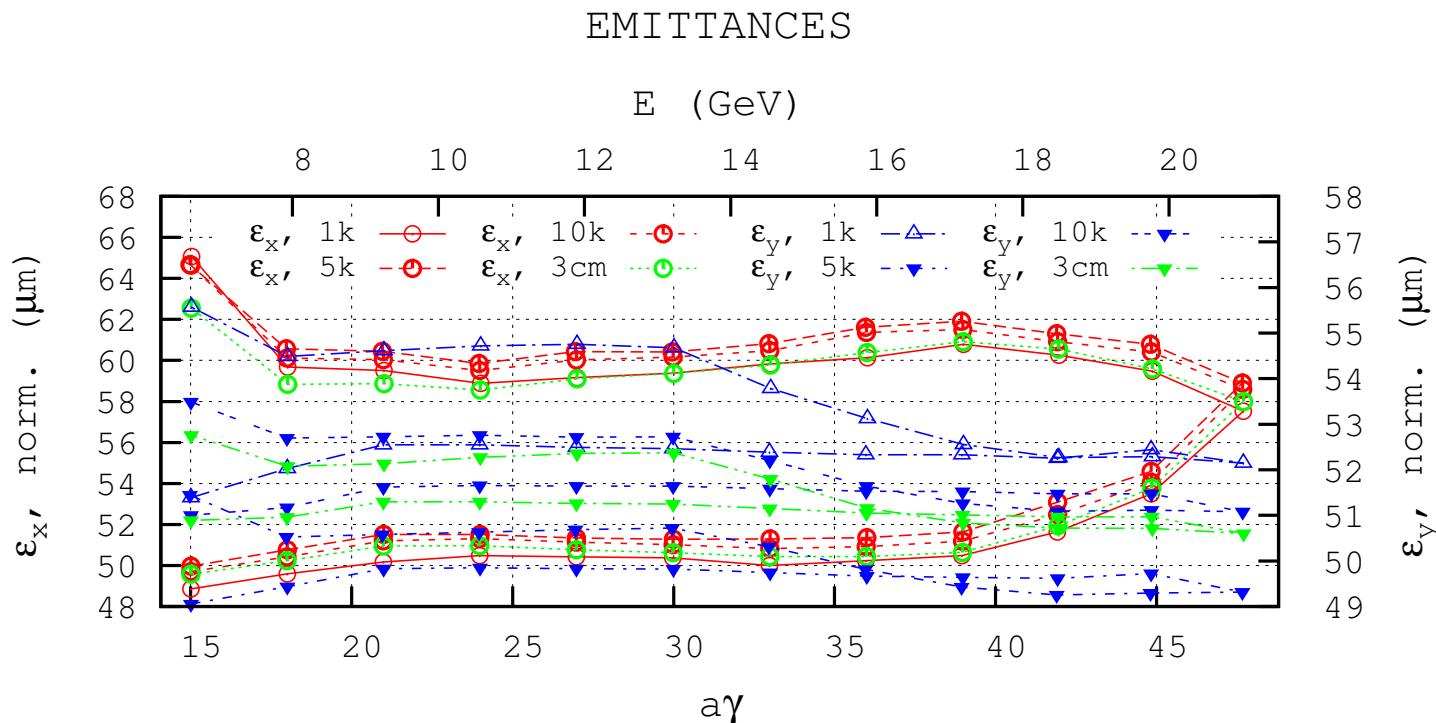
4 Multi-turn dynamics in a 6-arc ring

The game here : a 1000- or 5000-particle bunch is launched for a 23-turn acceleration-deceleration cycle.

- SR is compensated at end of each turn, based on Eq. 1.
- The bunch is re-centered on the theoretical FFAG orbit after each turn.
- In the figure below, the red curves, left V axis : horizontal emittance ; the blue curves, right V axis : vertical.

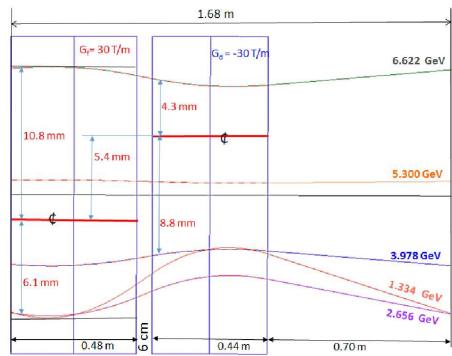
In addition to initial emittances $\approx 50\mu\text{m}$, the beam has dp/p random uniform in $[-3 \times 10^{-4}, +3 \times 10^{-4}]$.

The number of particles is varied, 1cm and 3cm step sizes are assessed. Conclusion : no big difference, the main effect is slight translation of the curves.

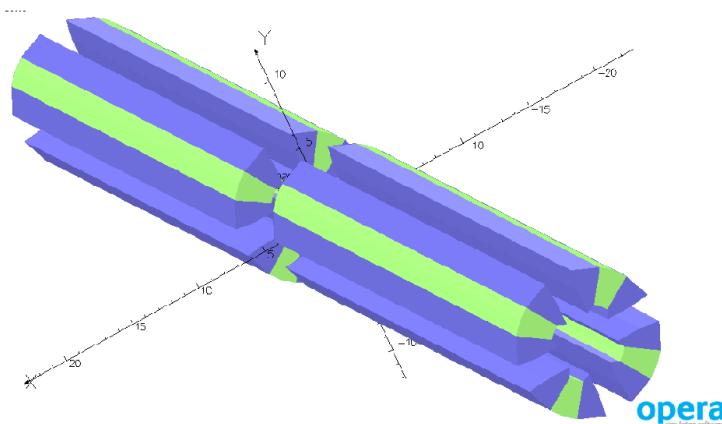


5 Magnet studies

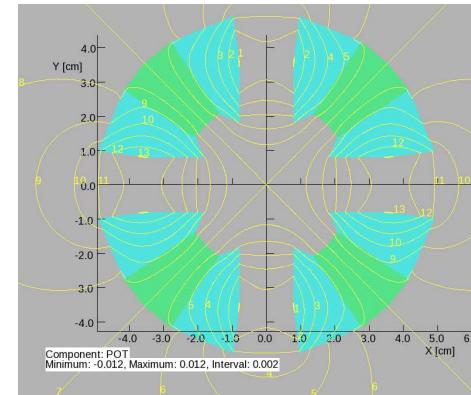
- The optics of the low energy FFAG cell (with the old, 50 T/m gradient optics, 5 passes) has been assessed using realistic fields, in a Halbach style permanent magnet model.
- A 6 cm long permanent magnet prototype has been built and measured, to compare with OPERA outcomes. Difference observed in the 12-pole strength (relative to quadrupole strength), between prototype and OPERA results, is within tolerance of our present optics investigations.



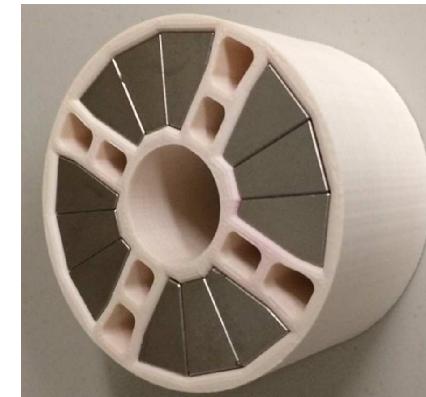
Hard edge model of the low energy FFAG cell (old optics)



The FFAG1 cell in OPERA

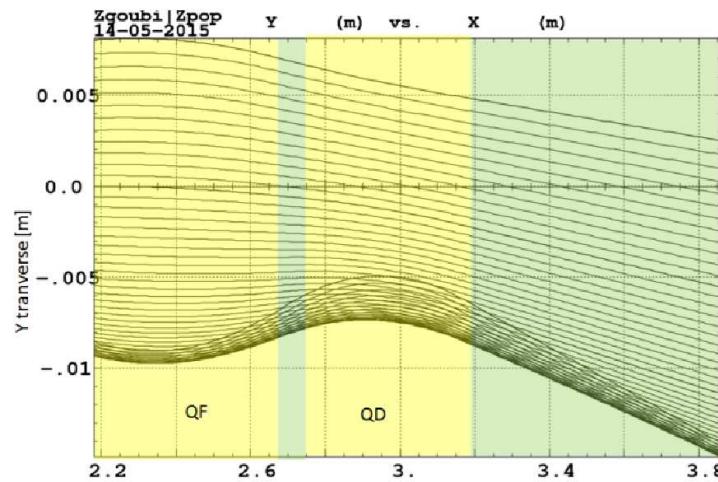


Cross section of the OPERA 3D model.

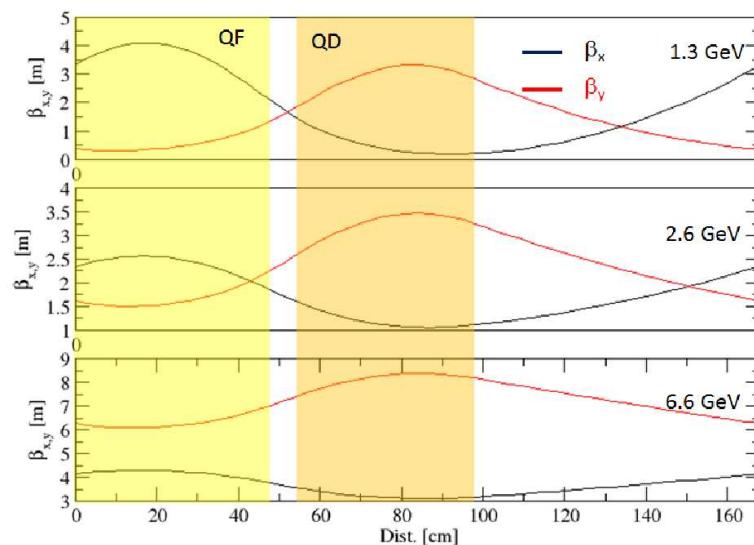


Relative difference in the 12-pole strength, between measurements and OPERA : $\sim 9 \times 10^{-4} \text{ cm}^{-4}$.

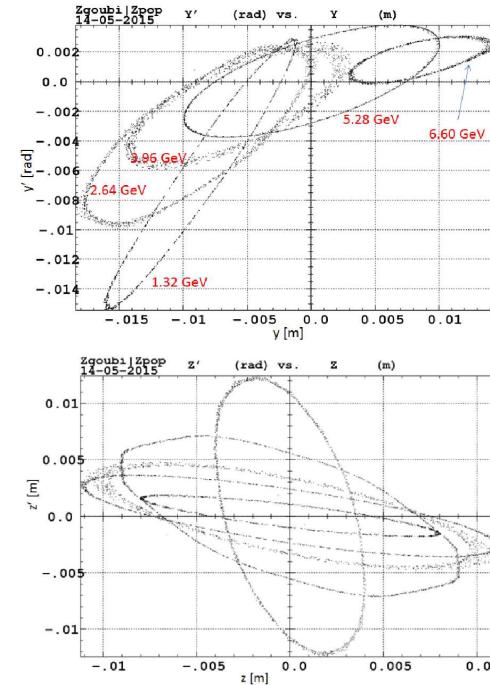
- Tracking in OPERA field map, outcomes :



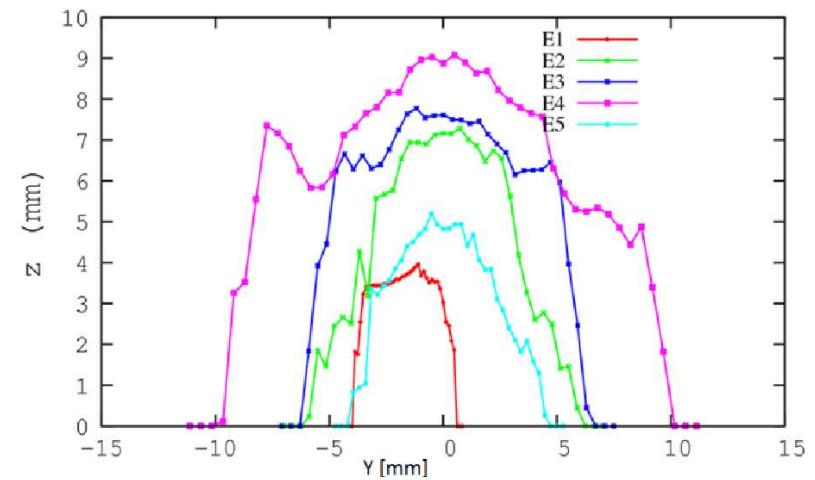
Closed orbits. Differences with the hard edge model are minor.



Betatron functions across the cell at 3 of the 5 design energies



Maximum stable H, V amplitudes in cell



1000-cell dynamic acceptance at the 5 design energies

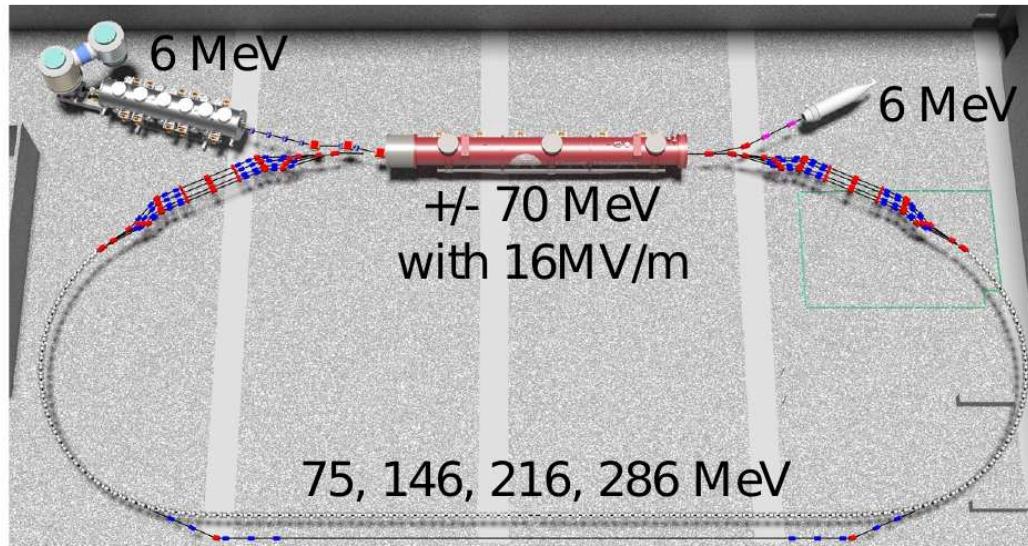
6 Plans, toward full end-to-end

On-going, actually :

- Install a “Chambers matrix” model of the linac, and work on longitudinal matching. The linac model up to now is just a longitudinal boost (including damping)
- **Install spreaders and combiners at linac ends. Work out matching (path length, transverse, R56...)**

- Multi-pass test-ERL at Cornell an eRHIC prototype

- Uses existing 6 MeV low-emittance/high-current injector and 70 MeV CW SRF Linac
- Two recirculation FFAG arcs, four-pass, x4 momentum range
- Arcs use permanent magnets
- Adiabatic transition from curved to straight sections
- Test of spreader/combiner beam lines
- High current will be used to test HOM damping of eRHIC accelerating cavity



THANKS FOR YOUR ATTENTION