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Zgoubi vs. the machines

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Topical meeting of Spin tracking for Precision Measurements
IPAC 15, 5-6 May 2015

Zgoubi vs. The Machines

François Méot, BNL C-AD

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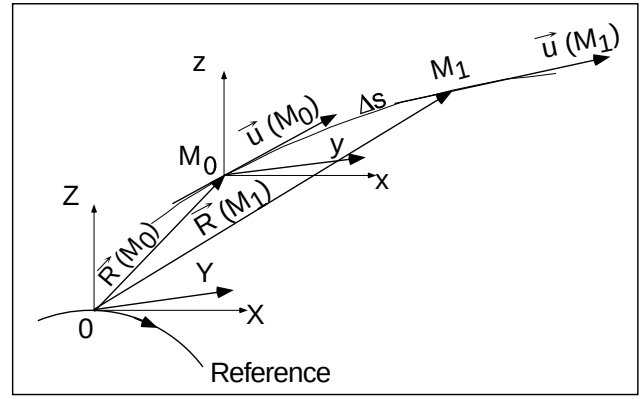
1 Stepwise tracking numerical machinery

1.1 Particle and spin motion

- $\dfrac{d(m\vec{v})}{dt} = q\,(\vec{e} + \vec{v} \times \vec{b})$
- $\dfrac{d\vec{S}}{dt} = \dfrac{q}{m}\,\vec{S} \times \vec{\omega},$

$$\vec{\omega} = (1+\gamma G)\vec{b} + G(1-\gamma)\vec{b}_{//} + \gamma(G + \frac{1}{1+\gamma})\frac{\vec{e} \times \vec{v}}{c^2}$$

G : gyromagnetic factor, γ : Lorentz relativistic factor, c : velocity of light, q : charge, m :mass.



Position and velocity of a particle, pushed from location M_0 to location M_1 in Zgoubi frame.

• Both equations are solved using a truncated Taylor series in the step size Δs, of the form

$$\vec{a}(M_1) \approx \vec{a}(M_0) + \frac{d\vec{a}}{ds}(M_0)\,\Delta s + ... + \frac{d^n\vec{a}}{ds^n}(M_0)\,\frac{\Delta s^n}{n!} \tag{1}$$

- Solving particle motion : $\vec{a}$ **stands for position** $\vec{R}$ **or normalized velocity** $\vec{u} = \vec{v}/v$**.**

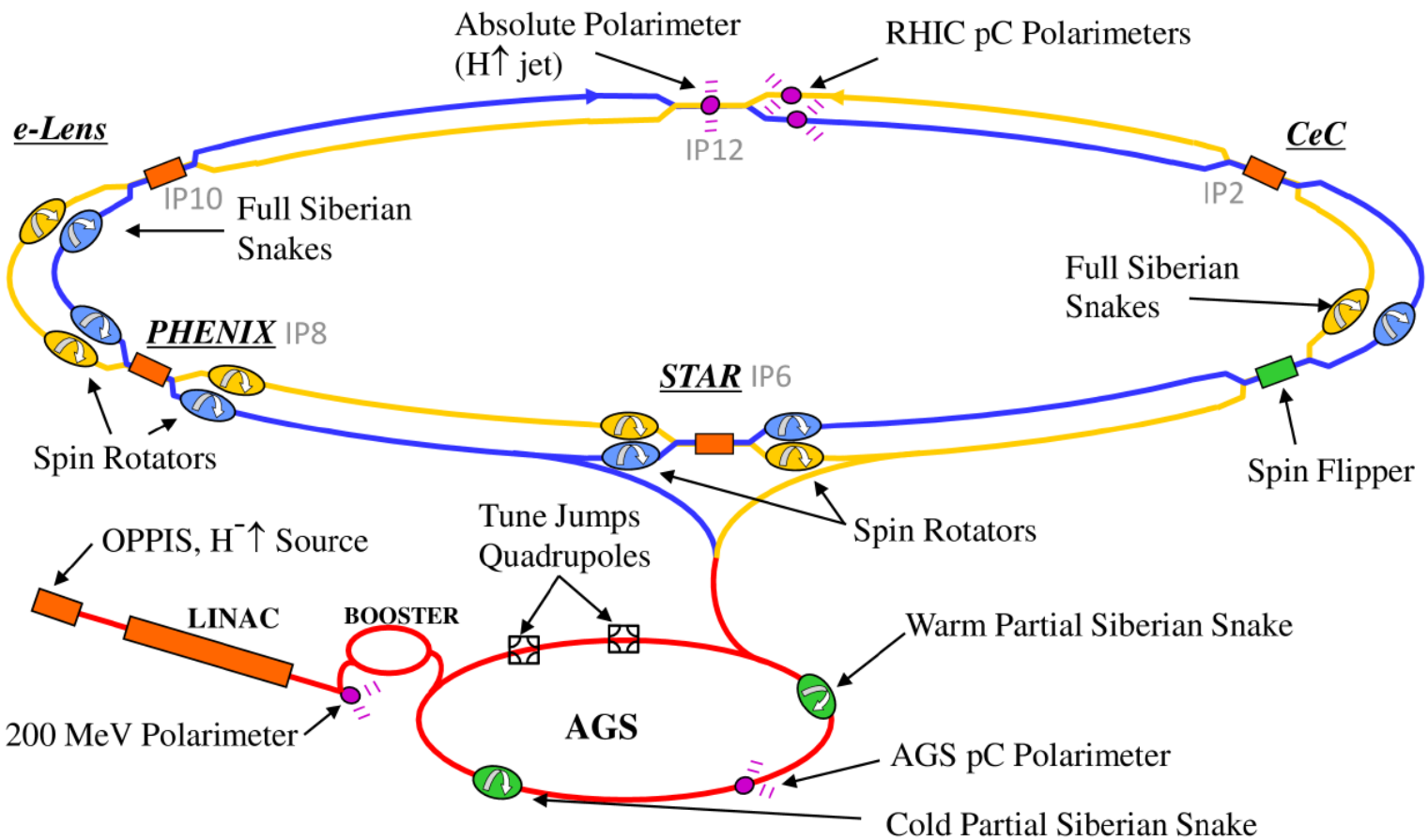
In the presence $\vec{e} \neq 0$ **: rigidity** $B\rho$ **and time of flight** T **are pushed in the same manner.**

- Solving spin motion : $\vec{a}$ **stands for the spin** $\vec{S}$**.**

• The local $\vec{e}$ **and** $\vec{b}$ **fields and their derivatives fully determine the coefficients** $a^{(n)} = d^n a/ds^n$ **in these Taylor series.**

2 Polarization at RHIC complex

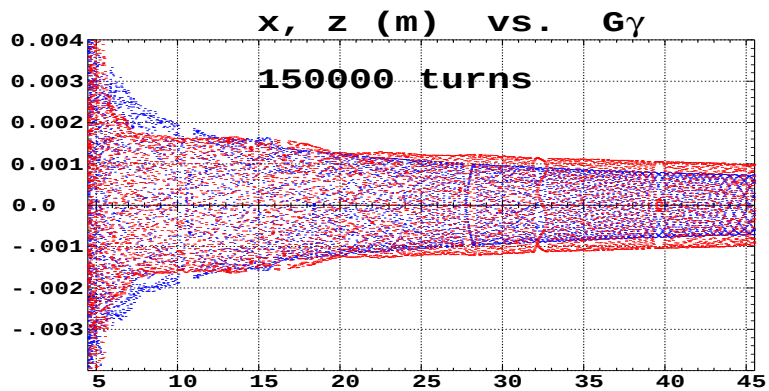
- **Polarized beam simulations in RHIC complex using Zgoubi**
  - **include p, He3**
  - **start at the booster, and include AGS, AtR, RHIC**



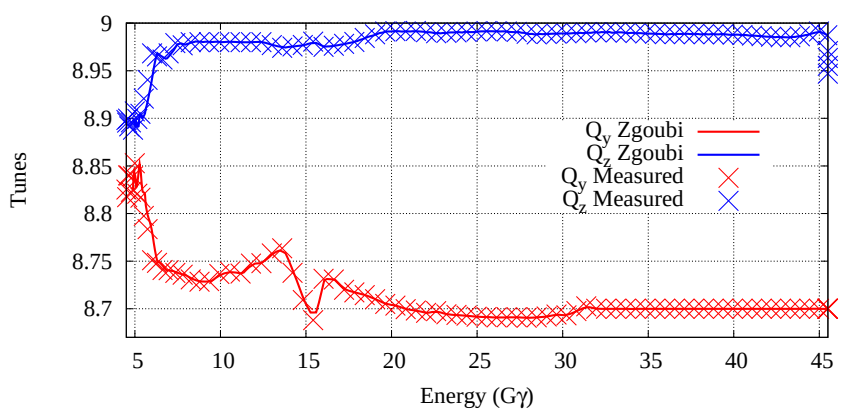
2.1 AGS on-line and off-line model

- **Zgoubi is one of the two engines of the on-line model of the AGS (other is MADX).**
  It uses the 3-D OPERA field maps of the helical snakes
  The 240 main dipoles in the AGS may also be represented by their *measured* field maps.

- **Full polarized proton bunch acceleration cycles in the AGS are routinely simulated : thousands of particles, 150000 turns. (on NERSC at the moment, plans for GPU platforms [V. Ranjbar])**

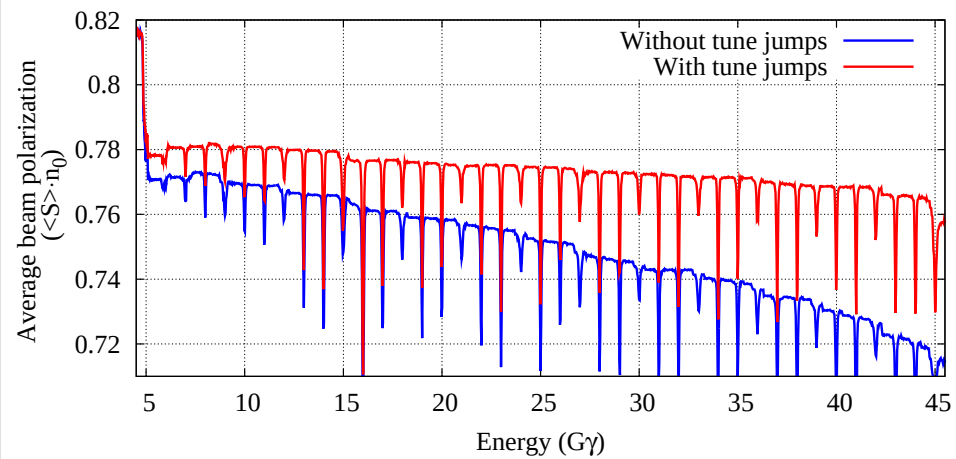


Particle excursion over full AGS cycle.



Tunes, measured and modelled.

- **Optimization of AGS parameter settings routinely based on Zgoubi simulations.**
  [Y. Dutheil, BNL C-AD, PhD dissertation, April 2015].



Evolution of the polarization along AGS acceleration cycle, 10^3 particles, 6-D bunch.
Loss at $G\gamma \sim 5$ (a pair of weak vertical intrinsic resonances) and at $G\gamma = 36 + Q_y$ in the present hypotheses.

More in the AGS [Y. Dutheil, PhD Diss.]

Comparing measured and simulated polarization profiles ($R = \sigma_p/\sigma_I)^2$)
This is on-going R/D and spin tool developments.

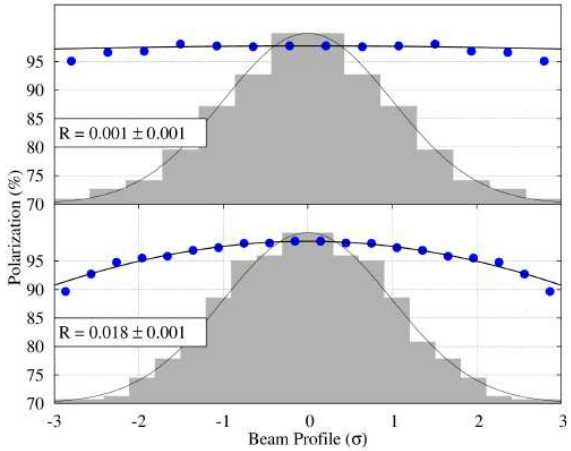


Figure 5.13 Polarization profile obtained from the Zgoubi tracking at $G\gamma = 7.5$ for the horizontal (top plot) and vertical plane (bottom plot).

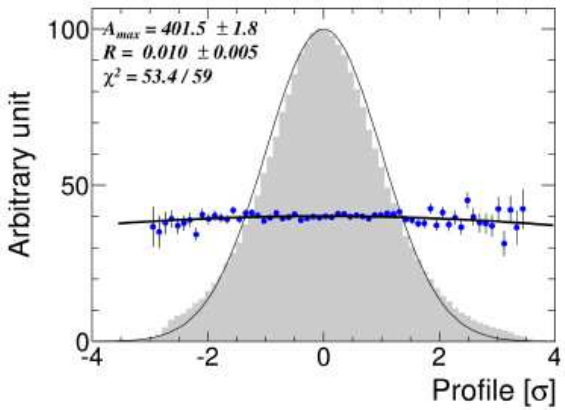
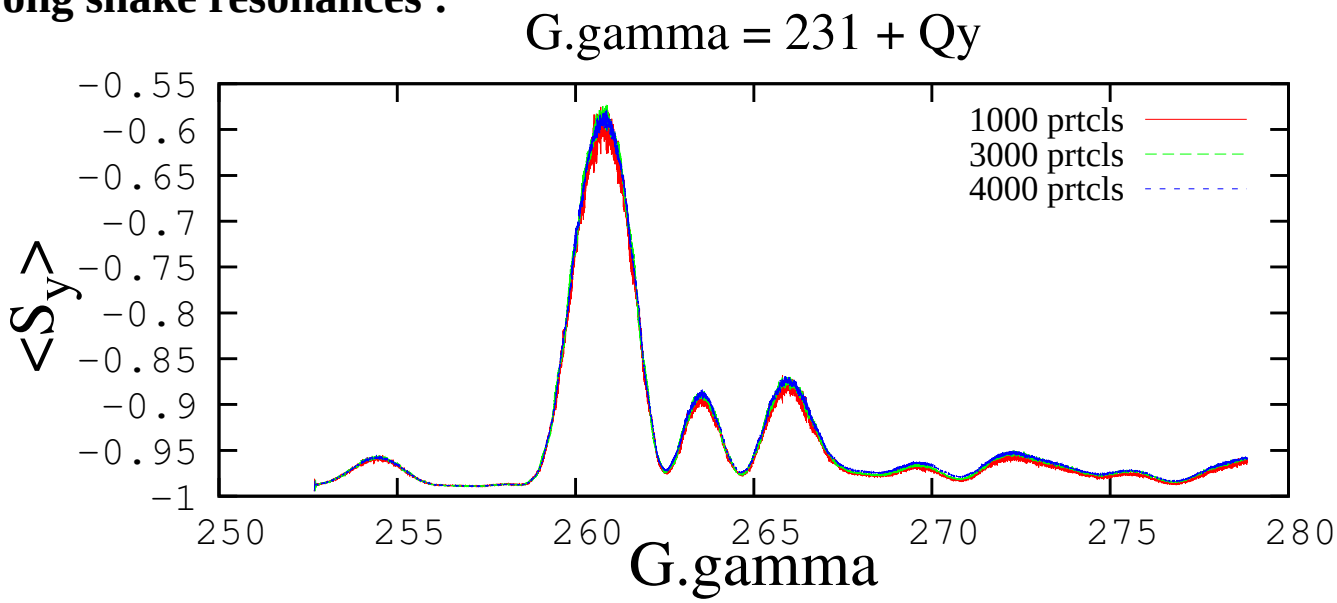


Figure 5.14 Measured vertical polarization profile at $G\gamma = 7.5$ with vertical tune jumps.

2.2 RHIC ring

• **Zgoubi is used since 2010 to study polarization transport in RHIC, for instance, spin dynamics across strong snake resonances :**



Evolution of the polarization upon crossing of $G\gamma = 231 + Q_y$ snake resonance. 4000 particles in a realistic 6-D ellipsoid, 100,000 turns.

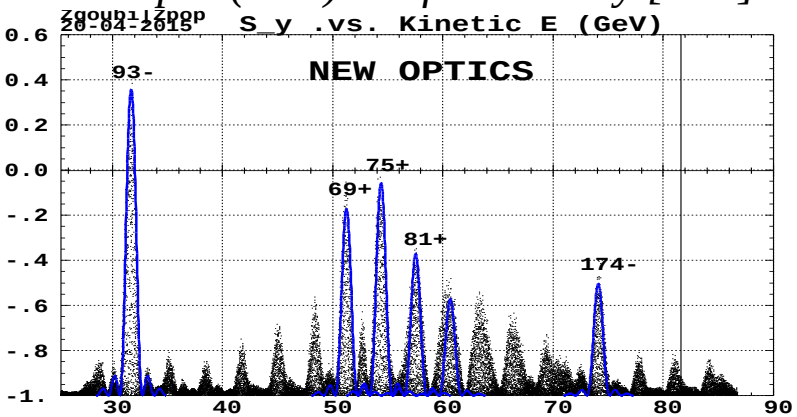
• **Routine studies include sensitivity to defects (*e.g.*, spin rotation angle in snakes or in rotators), studies accompanying RHIC runs, optimization of the AtR beam line, etc.**

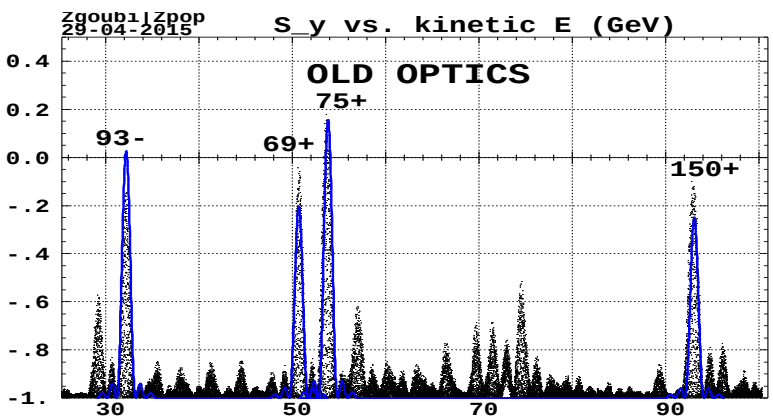
• **Zgoubi is used for polarized Helion program at RHIC, to investigate spin dynamics in all 3 rings : Booster, AGS, RHIC, including plans for AC dipole in Booster, 4+ snake schemes at RHIC, etc.**

More at RHIC

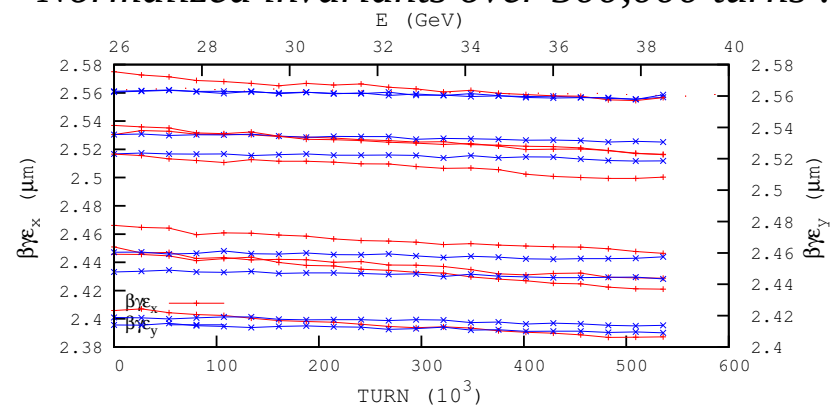
- **A recent example [TUPWI053, this conference] : comparison of polarization transport over a full acceleration cycle in the 100 GeV$\times$100 GeV pp runs, 3 million turns at a rate of $\dot{\gamma} = 2$:**
  - **new, Run 15 optics**
  - **Run 13 and earlier optics**

8 particles on 10 rms invariants are plotted. Envelopes (blue) are from theory [SYL].

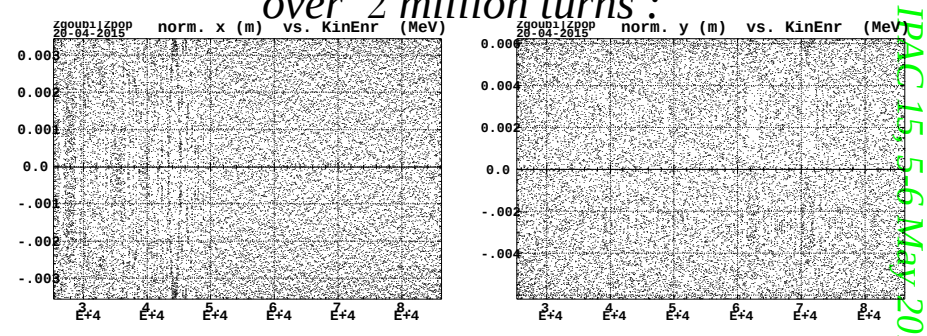




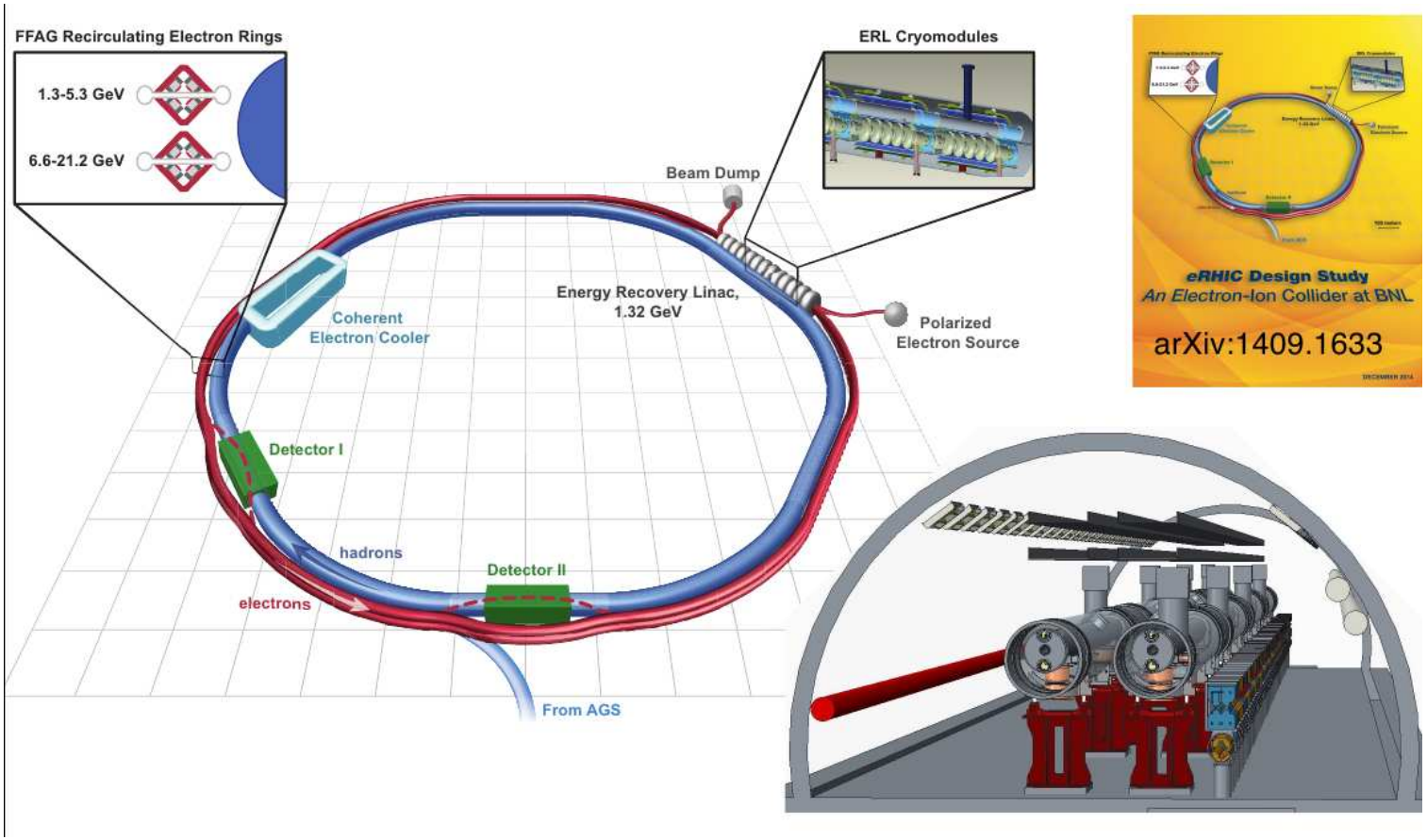
Normalized invariants over 500,000 turns :



$x \times \sqrt{(p/p_0)}$ and $y \times \sqrt{(p/p_0)}$ over 2 million turns :



3 Polarization in eRHIC

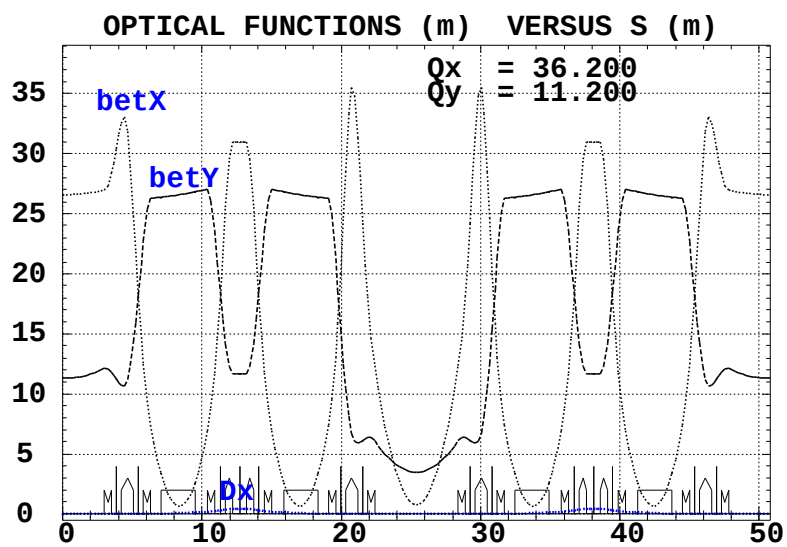


Studies in eRHIC include SR induced spin diffusion :

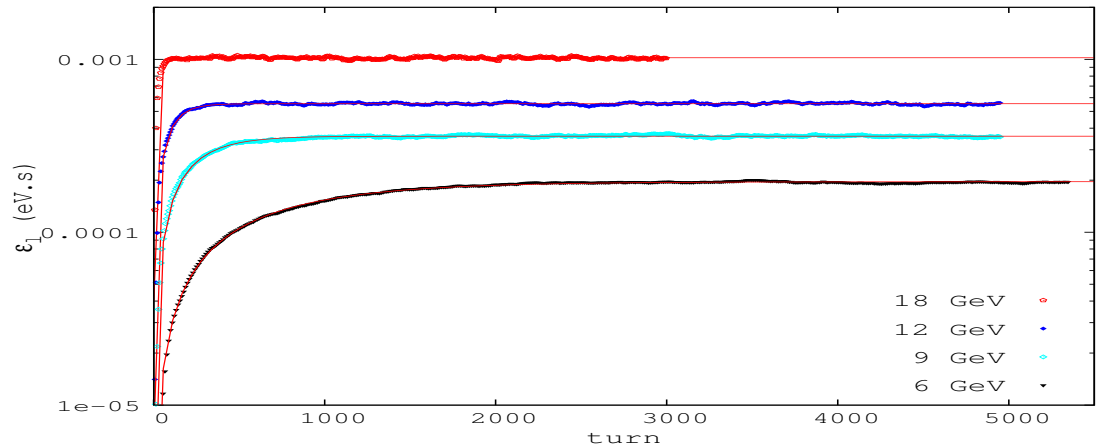
$$\left.\begin{array}{r}\textbf{SPIN DYNAMICS}\\ +\\ \textbf{STOCHASTIC ENERGY LOSS BY SR}\end{array}\right\} \Longrightarrow \textbf{SPIN DIFFUSION}$$

3.1 Monte Carlo SR in Zgoubi was benchmarked in storage ring :

- **Thousands of particles, tracked over tens of thousands of turns**
- **Used in the recent past for polarization studies in Frascati's superB project, resurrected for eRHIC**



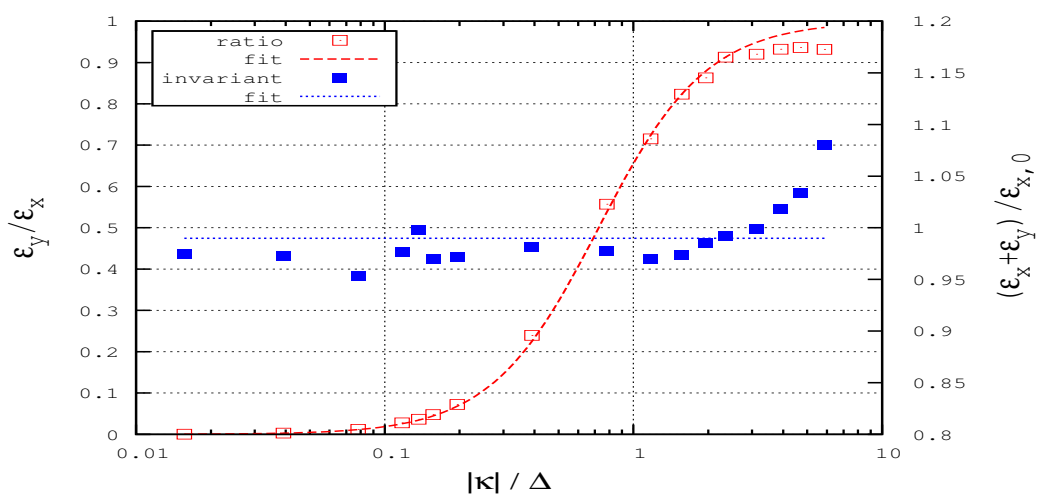
Chasman-Green cell.
Benchmarking virtue : provides analytical formulas for damping times, emittance damping, etc.



Longitudinal damping, 6, 9, 12 and 18 GeV. $2\,10^3$ **particles ray-traced. Excellent match with e.g., here.** $\epsilon_{l,eq} = \frac{\alpha E_s}{\Omega_s}\frac{\mathcal{C}_q\gamma^2}{J_l\,\rho}$.

Good agreement with

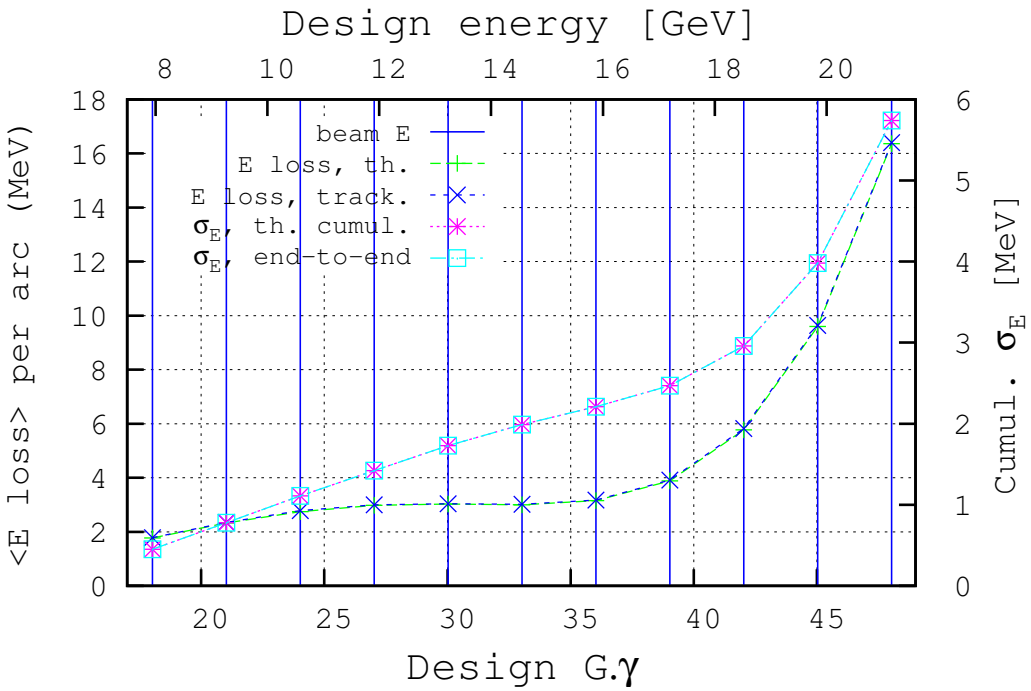
$$\frac{\epsilon_y}{\epsilon_x} = \frac{|\kappa|^2}{|\kappa|^2 + \Delta^2/2}$$



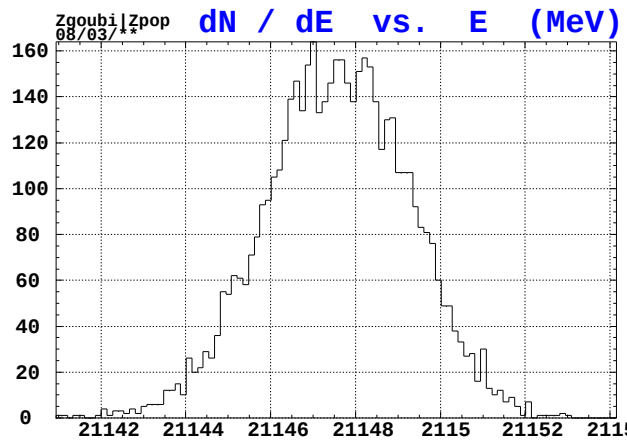
Coupled lattice. 6 GeV. 2000 particles, 20,000 turns.

3.2 SR loss in eRHIC

- **A 6 arc ring, FFAG style of arcs**



- **Here we monitor the energy density. Example, 5000 particles at end of pass #11 (21 GeV) :**



- **A quick estimate, approximation to** $\Delta E \propto E^2\, B^2 \Delta t$**, taking** $\overline{\rho_{\rm QF}} = l_{\rm QF}/\theta_{\rm QF}$**,** $\overline{\rho_{\rm BD}} = l_{\rm BD}/\theta_{\rm BD}$ **:**

$$\overline{\Delta E}[MeV] = \overline{\Delta E_{QF}} + \overline{\Delta E_{BD}} \approx 0.96 \times 10^{-15} \gamma^4 \left(\frac{\theta_{\rm QF}}{|\overline{\rho_{\rm QF}}|} + \frac{\theta_{\rm BD}}{|\overline{\rho_{\rm BD}}|}\right) \quad \textbf{per cell} \qquad (2)$$

- **Assuming** $< (1/\rho)^2 > \approx 1/\overline{\rho}^2$**, then :**

$$\sigma_E \approx \sqrt{\sigma^2_{E,\rm QF} + \sigma^2_{E,\rm BD}} \approx 1.94 \times 10^{-14} \gamma^{7/2} \sqrt{\frac{\theta_{\rm QF}}{\overline{\rho_{\rm QF}}^2} + \frac{\theta_{\rm BD}}{\overline{\rho_{\rm BD}}^2}} \quad \textbf{per cell} \qquad (3)$$

3.3 Spin diffusion

• **Expected spin precession :**

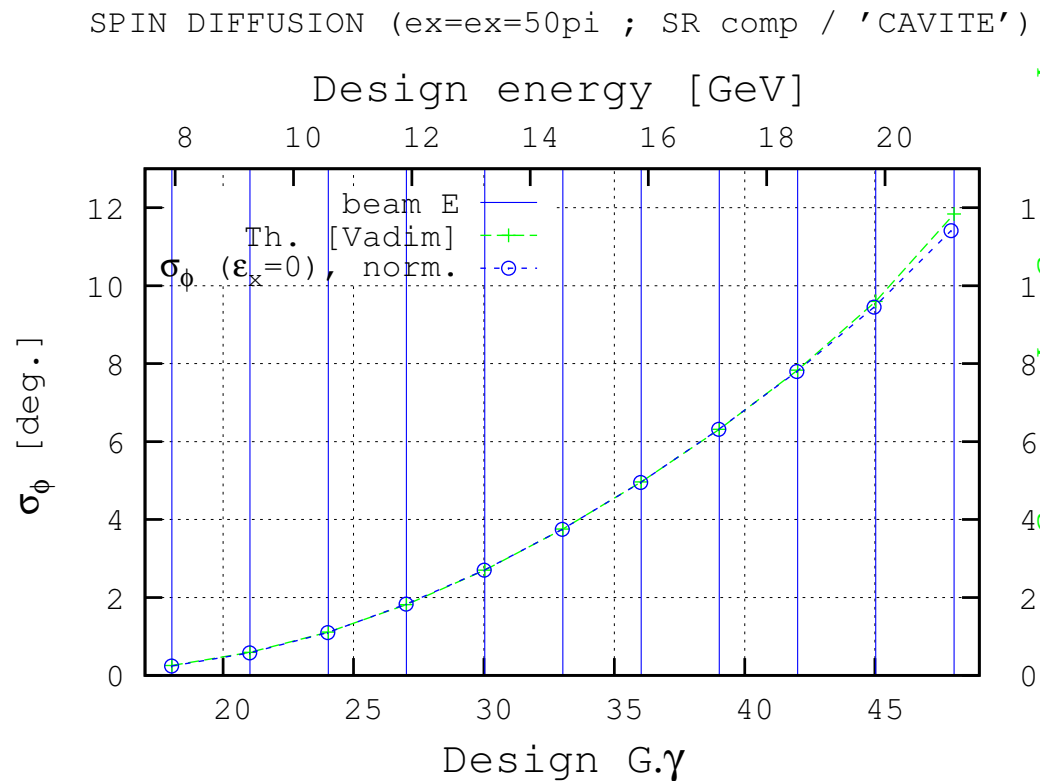
$$\phi = G\gamma\theta = G\gamma(\theta_{\rm QF} + \theta_{\rm BD})$$

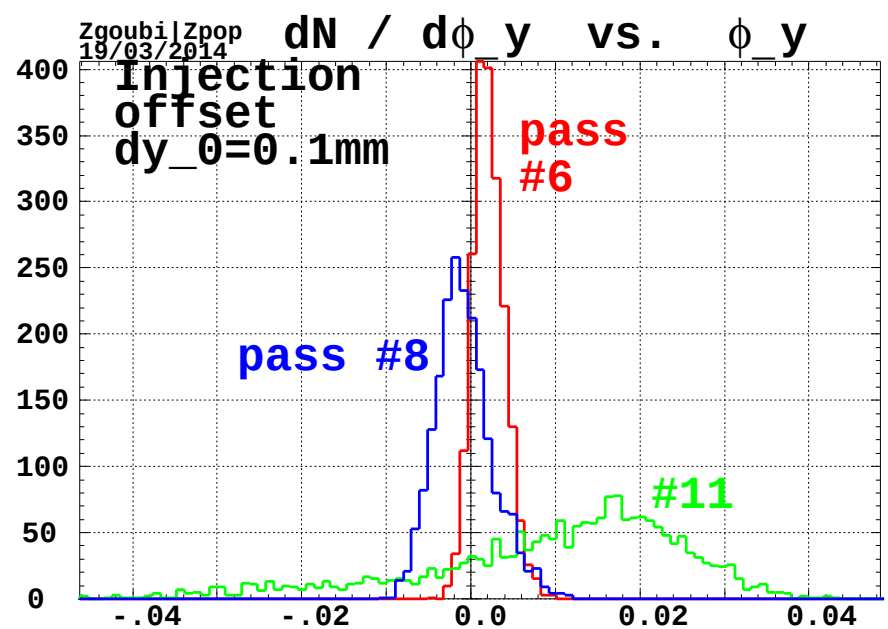
per cell $\xrightarrow{\times 138}$ per arc

• **Change of energy upon stochastic SR causes spin diffusion [V. Ptitsyn] :**

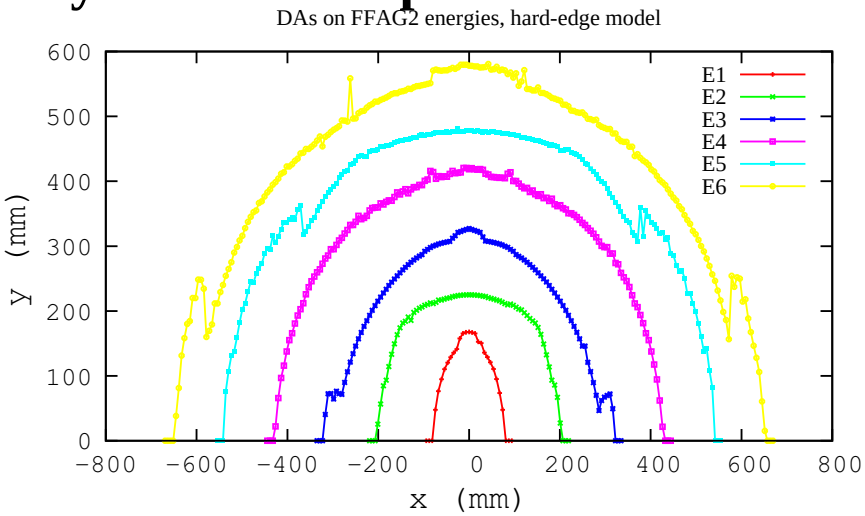
• **Vertical orbit and betatron motion add diffusion vertical spin component**

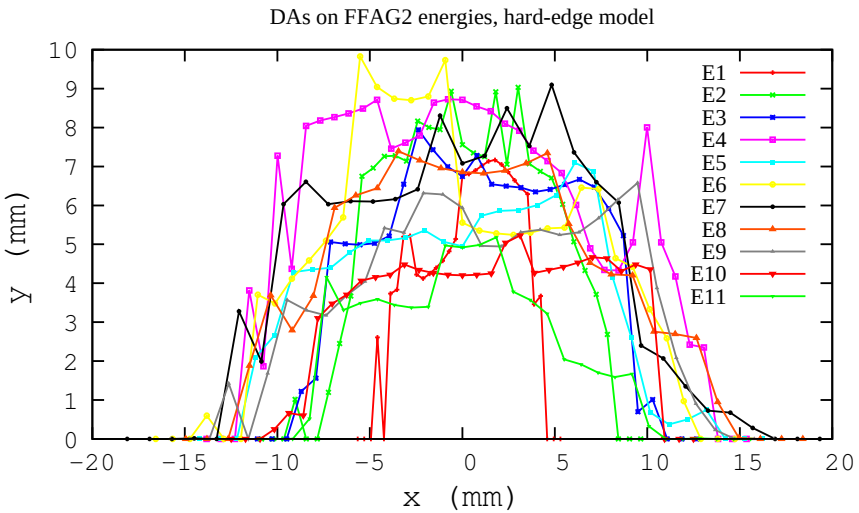
• **Benchmarking efforts using available analytical formalism are on-going.**





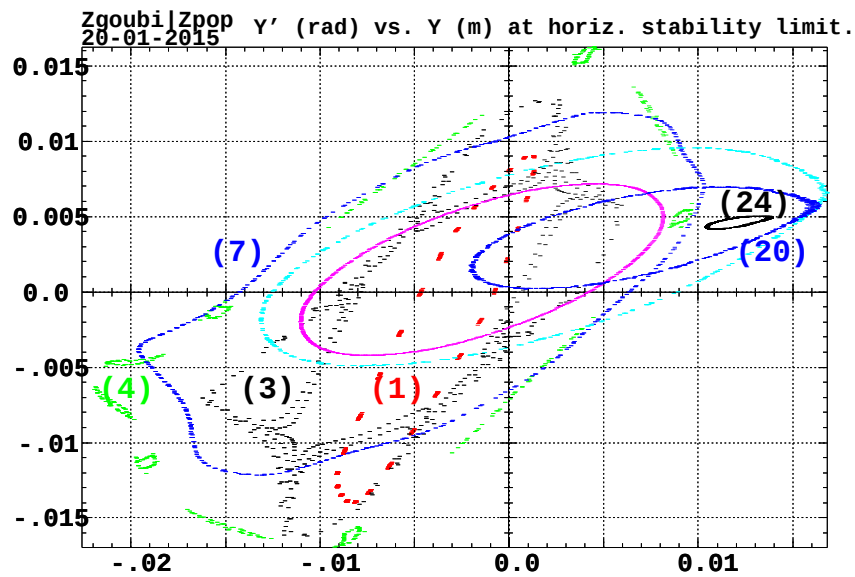
4 Dynamical acceptance of eRHIC FFAG ring





Available injection window into the ring at mid-LSS, for each of the 11 beams, observed at the center of an LSS.
Top : defect-free lattice.
Bottom : in the presence of dodecapole defect, ± 3 Gauss at 1 cm, random uniform.

[TUPWI052, IPAC 15]

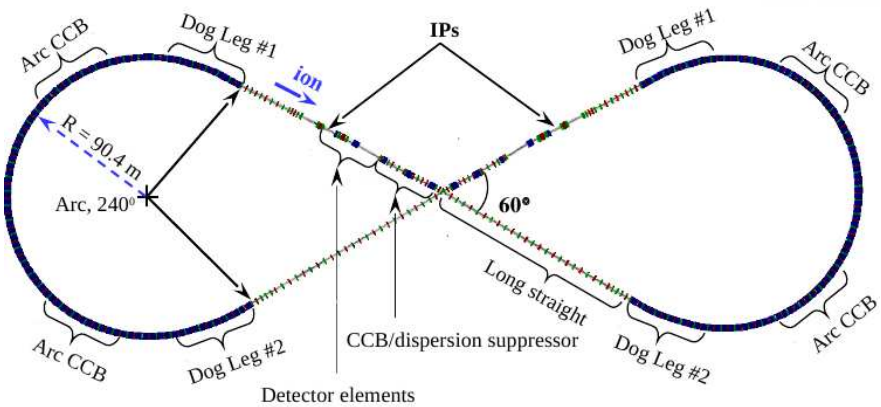


Using OPERA 3-D field maps :

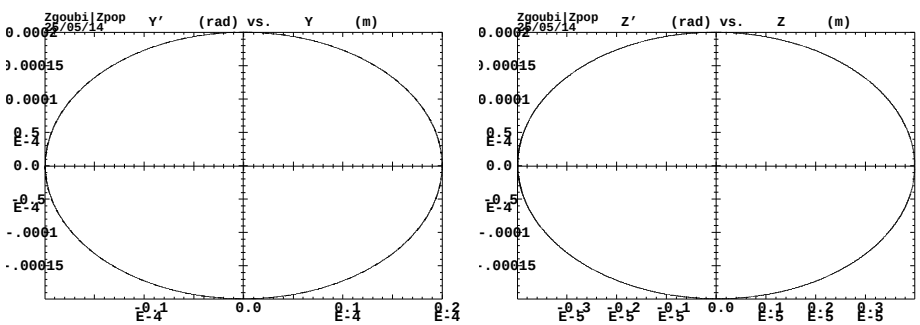
Vertical amplitude at H stability limit, for initial vertical invariant $\epsilon_y(t=0) \equiv 0$:

5 Polarization in the “MEIC” Figure-8 Collider Ring

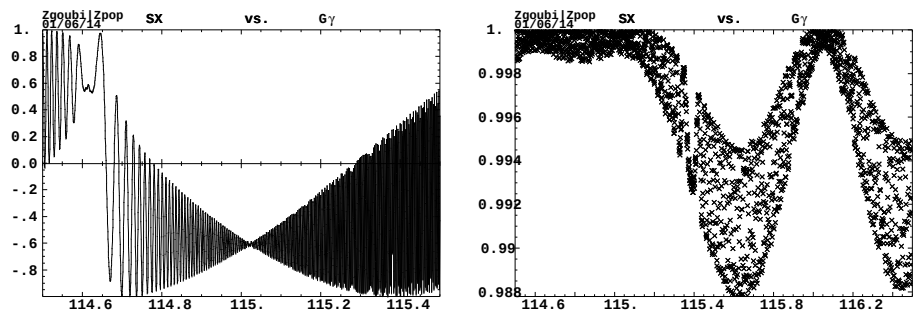
[TUPWI054]



Based on thousands of turns tracking, effects of various causes of loss of polarization have been assessed, such as
- betatron oscillations
- dipole roll error
- quadrupole vertical misalignment



Horizontal (left) and vertical (right) 200,000 turn phase-space, for the particle launched with initial horizontal and vertical angles both 0.2 mrad in an ideal ring.

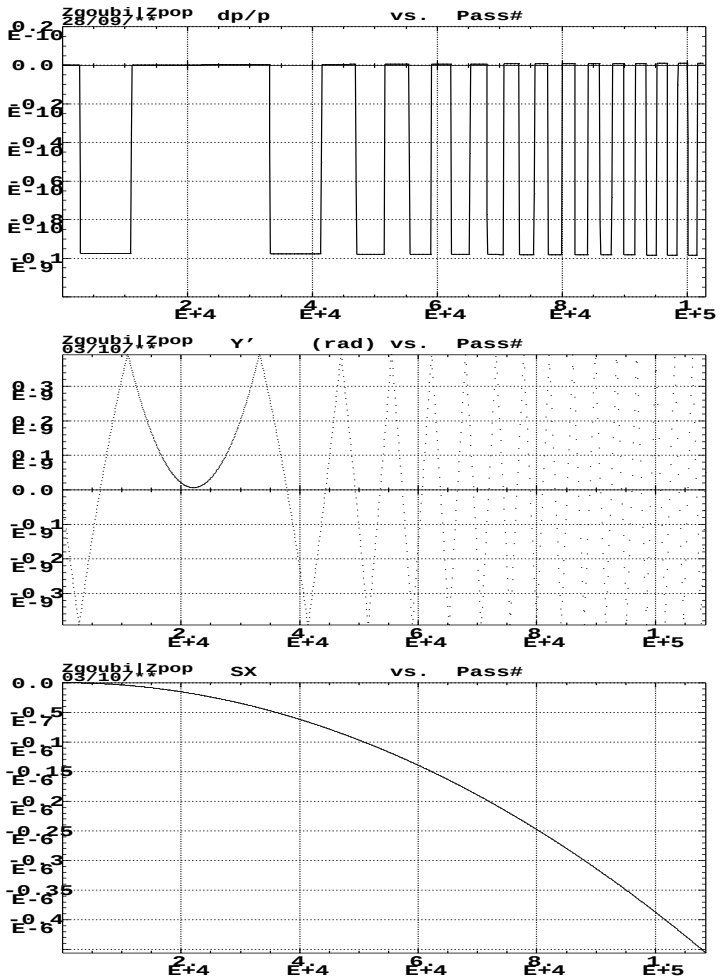


Longitudinal spin component S_x of a particle with $S_x^i = 1$, vs. $G\gamma$, over 200,000 turns (left) and 400,000 turns (right). The particle is initially launched along the reference orbit in a ring with one of the arc dipoles rolled by 0.2 mrad. In the right plot case, the ring contains a spin rotator placed at the launch point, which rotates the spin by 5° about the longitudinal axis.

6 p-EDM ring, prospects

- **Tracking of spin motion in electric field had been installed for the Trento p-EDM workshop**
- **Tracking in cylindrical deflectors ($E \propto (r_0/r)^n$), hard edge, was investigated**
- **Conservation of energy and transverse invariants had been investigated, over thousands of turns**
- **These investigations need be carried on**

Typical results, about 100,000 turns :



$dp/p < 2\,10^{-11}$

$x' \in \pm 4\,10^{-10}$

$|1 - S_l| < 4.5\,10^{-6}$

p-EDM plans

- **Investigate AGS option**

- **Work on questions as accuracy, long-term tracking, CPU speed, thousands of particles per batch, in performing stepwise integration in electrostatic ring.**