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Polarization Transport in the ERL-ERL FCC e+e- Collider

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Polarization Transport in the ERL-ERL FCC e+ e- Collider*

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Abstract

An alternative approach for the Future Circular electron-positron Collider uses energy recovery linac recirculators to mitigate the otherwise enormous power consumption needed to compensate 100 MW of beam energy losses by synchrotron radiation in a ring-ring design. This approach would also allow to extend CM energy to 500 GeV (or above) for double Higgs production. An additional advantage of the ERL-ERL scheme is its allowing polarized e+ e- beam collision. A 100 km, 6250cell, 220 GeV loop is subjected to polarized bunch transport simulations. A linear Fixed Field Alternating gradient (FFA) design is also assessed as to spin transport.

1 FCC ERL-ERL

The FCC $e^+ - e^-$ is a proposal for a next HEP collider, a ring-ring design, 100 km footprint. The total radiated power is 100 MW SR at 365 MeV CM. An e^+erl - e^-erl version has been developed at BNL, an evolution of a former eRHIC Linac-Ring Electron Ion Collider concept [1]. It allows up to $\times 10$ reduction of SR energy loss while maintaining high luminosity at high energy, it allows to extend CM energy to 500 GeV or above, for double-Higgs production, and allows polarized e- and e+ beams.

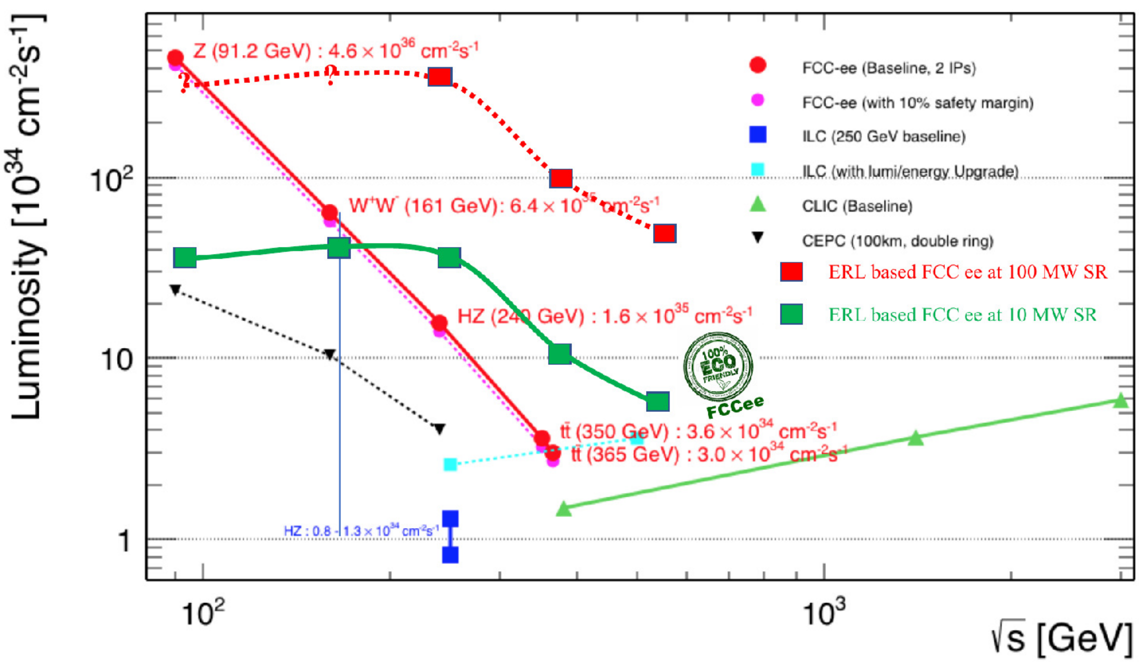

Figure 1: Luminosity at the FCC-ee collider.

1.1 Polarization: What to Expect

Highest energy is considered here, 219 GeV) as it corresponds to greatest SR energy loss. Besides, it is not necessary to strictly stick to the detailed design of the return arc in Ref. [1] to investigate polarization transport, a simplified combined function FODO lattice is considered instead, with bend field 0.05 T, 16 meter cell length, phase advance 90 deg/cell. A 100 km loop is comprised of 6250 cells.

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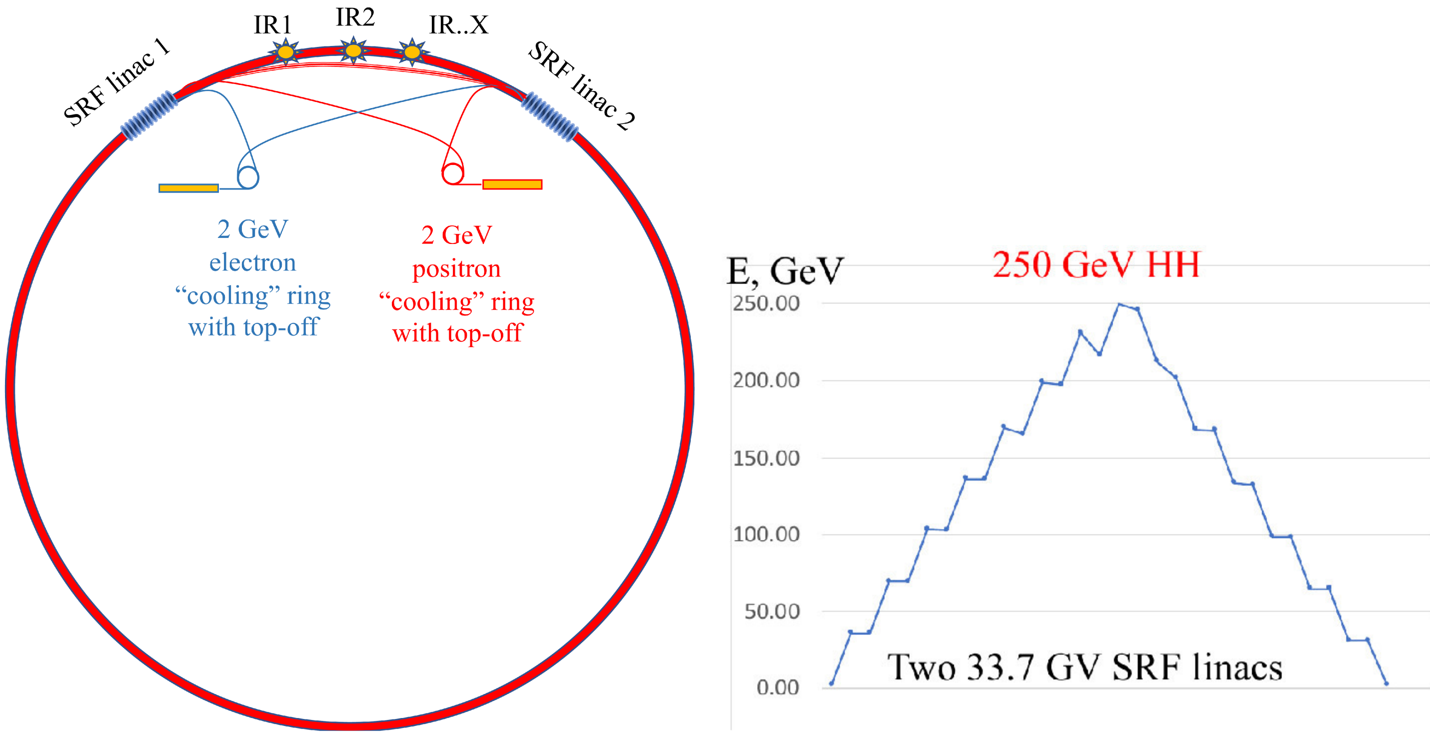


Figure 2: Left: A sketch of an ERL-ERL FCC [1]. Right: Staged energy gain, and energy recovery, in the ERL-ERL FCC.

Ingredients in relation with the transport of polarized particles include introducing a distorted vertical orbit, looking for the resulting 1-pass periodic orbit, and launching particles centered on that periodic orbit. The reason for using a periodic orbit as the beam centroid path is to obtain bounded vertical bunch excursion, to mimic a corrected path along a beam line. Add betatron oscillation: a few 10s of particles launched on a $8\,\mu$m (nominal emittance) horizontal invariant, whereas a 20×8 nm (20 times the nominal emittance) vertical invariant is considered in order to exaggerate resonance strengths.

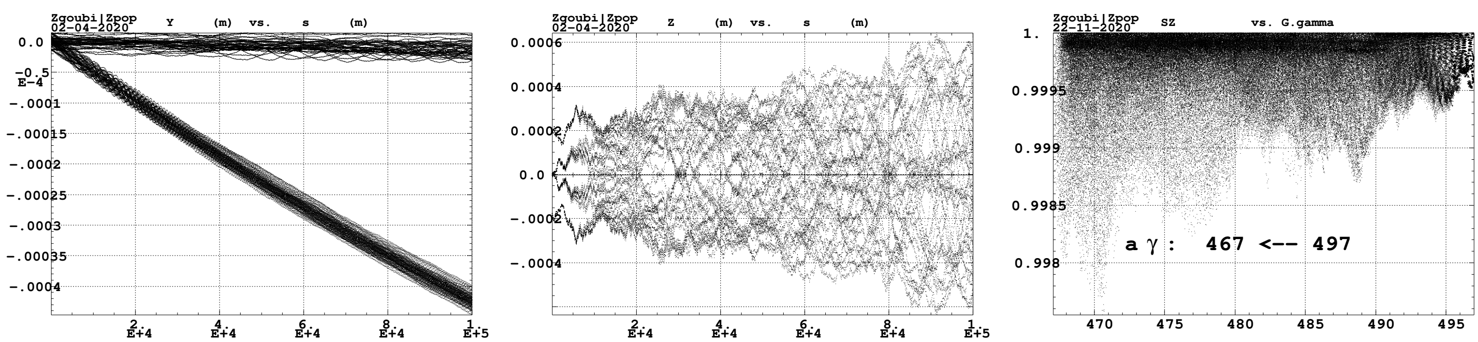


Figure 3: A few 10s of particles launched on $\epsilon_x = 8\,\pi\mu m$, $\epsilon_y = 20 \times 8\,\pi nm$ invariant (nominal rms bunchsize). Left: horizontal, either w/o or w/ fields scaling (fields scaled for energy loss, a theoretical scaling factor is applied); center: vertical; right: S_y component of spins (launched vertical).

The conclusion out of this simulation is: no polarization loss, over 100 km, at 220 GeV, in presence of substantial orbit error and bunch size.

1.2 Polarization: case of periodic distorted orbit

As a preliminary check of lattice parameters, SR and polarization transport simulations, create resonant depolarization conditions and check consistency: the spin precession is $a\gamma\alpha$, with $a = 1.15965 \times 10^{-3}$; $a\gamma = 497$ at 219 GeV, α=orbital angle. Completing one precession requires $a\gamma\alpha = 2\pi$, hence an orbital angle $\alpha = 2\pi/497 = 12.64$ mrad, or $6250[cells]/\,2\pi \times 0.01264 = 12.6$ cells. Adjust the energy to get one spin precession over an integer number of cells, say 13 cells: this requires 211.85 GeV. Finally: expect to excite the integer resonance, and so create a resonant condition, by introducing a 13-cell periodic distorted vertical orbit.

No SR, first: bunch particles are in the vicinity of the resonant, as expected their spins are observed to be flipping as the bunch proceeds along the line.

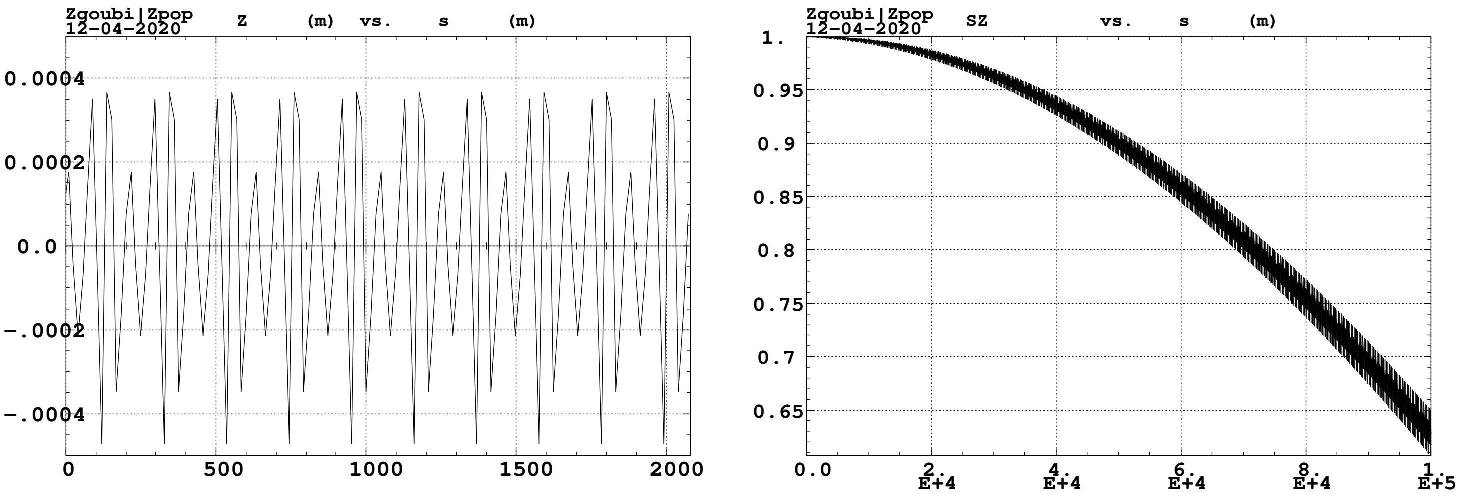


Figure 4: Left: Vertical orbit over first 2 km (13-cell pattern repeats itself over the 100 km). Right: Spin motion (S_y) over 100 km: fixed energy, spins stay on resonance $a\gamma = 1$ (or near, depending on $\delta E/E$) thus polarization begins a flipping motion: spins precess around precession axis which lies in the bend plane.

Add SR next: spin tune $a\gamma$ moves away from the resonant condition $a\gamma$=integer as beam proceeds, due to SR. Spins precess around the stable precession direction which oscillates around the vertical axis. Note: in the absence of vertical orbit excursion ($\epsilon_y \equiv 0$) spins would just

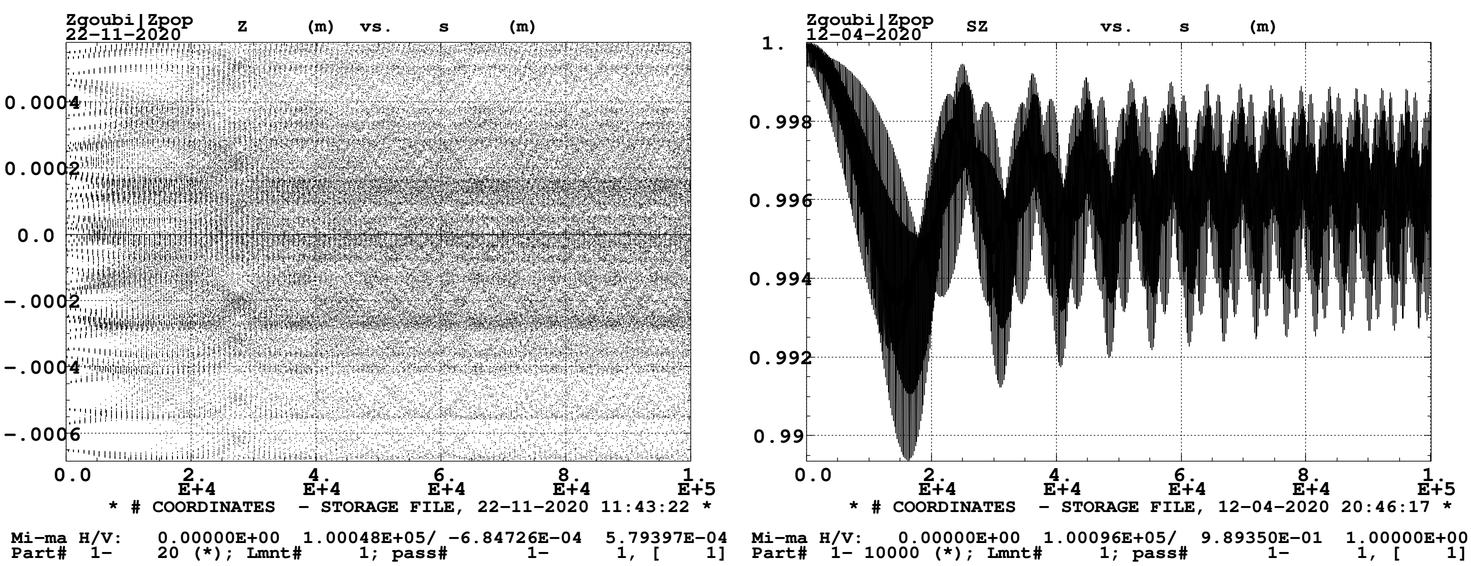


Figure 5: Left: Vertical excursion (rather large on purpose, to excite spin resonance) of a few tens of particles launched on $\epsilon_y = 20 \times 8\,\pi nm$ invariant, over 100 km. Right: Spins over 100 km, $a\gamma$: 497 at start; by contrast with SR free case, they quickly cross repeating resonant conditions $G\gamma$ =integer; polarization loss $\approx 1\%$.

remain vertical.

2 LINEAR FFA RETURN LOOP

This attempt is based on eRHIC 21 GeV ERL design comprised of two recirculation loops alongside RHIC (details in [2, 3]): FFA1 (low energy) and FFA2 (high energy), a 1.322 GeV linac located in RHIC IR2, connected to the FFA loops by a merger and a spreader section. The return loop is a 3.8 km ring: 6 arcs × 120 cells/arc, 12 periodic orbits across FFA2 cell. In the latter, a radial shift of the two quads of 13.48 mm ensures 8.73 mrad orbit bending. This essentially constitutes a long beam line, comprised of 4 first passes in FFA1 to 5.2 GeV: 4×3.8 km (not concerned here), 12 passes in FFA2 from 6.6 to 21.1 GeV.

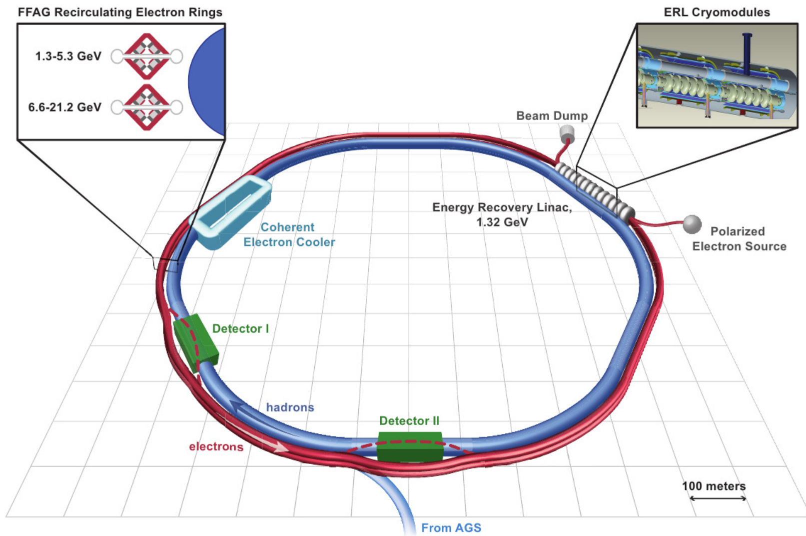


Figure 6: eRHIC linac-ring collisioner, with 2 FFA return loops ensuring 16 passes to top energy.

Spins are launched longitudinal for 12 passes (47 km) in FFA2, an overall $12 \times 3.8 \approx$ km path, including 12 combiner lines from FFA2 to linac, 12 splitter lines from linac to FFA2; they precess in the bend plane.

Assess without SR, first (2000 spins, all launched longitudinal):

Then add SR:

2.1 Back to FCC-erl-erl Simulations (219 GeV)

The linear-FFA cell in this ERL-ERL FCC simulation: A 100 km ring, 6250 × 16-meter cells, use similar QF, BD cell to eRHIC-LL.

Synchrotron radiation in the 219 GeV loop: The field experienced along the (*initially*) 219 GeV orbits is in 0.06∼0.16 T (decreasing with distance due to energy loss): along QF: about 2.5 times the value in the combine function FODO cell (0.06 T). For the record: the loss per cell amounts to $\overline{\Delta E}[MeV] \approx 0.96 \times 10^{-15}\gamma^4 \left(\frac{l_{BD}}{\rho_{BD}^2} + \frac{l_{QF}}{\rho_{QF}^2}\right)$. (and, in passing, per cell, $\sigma_E \approx \sqrt{\sigma_{E,BD}^2 + \sigma_{E,QF}^2} \approx 1.94 \times 10^{-14}\gamma^{7/2}\sqrt{\frac{l_{BD}}{|\rho_{BD}^3|} + \frac{l_{QF}}{|\rho_{QF}^3|}}$).

The energy loss in the present cell design is about 5 times the combined function FODO cell.

TRACKING A BUNCH ALONG THE "219 GeV" LINE Introduce a distorted vertical orbit (taken 100 km-periodic in the absence of SR), add betatron oscillation. Track a 2,000-particle bunch with Gaussian density, and rms horizontal emittance 8 μm norm., rms vertical emittance 8 nm norm., initial dp/p=0.

Bunch depolarization at end of "219 GeV" line is a few 0.1%.

3 POLARIZATION: CONCLUSION

Only negligible polarization loss is to be expected along the high energy loop of the FCC-erl-erl, in a regular design as well as if using an linear FFA lattice.

References

[1] High-energy high-luminosity e+e- collider using energy-recovery linacs, Vladimir N. Litvinenko, Thomas Roser, Maria Chamizo-Llatas, Phys. Lett. B Volume 804, 135394 (2020)

[2] F. Méot et al., eRHIC ERL modeling in Zgoubi, https://technotes.bnl.gov/PDF?publicationId=38865

[3] F. Méot et al., Tracking studies in eRHIC energy-recovery recirculator, eRHIC Tech. Note 45 (July 2015)

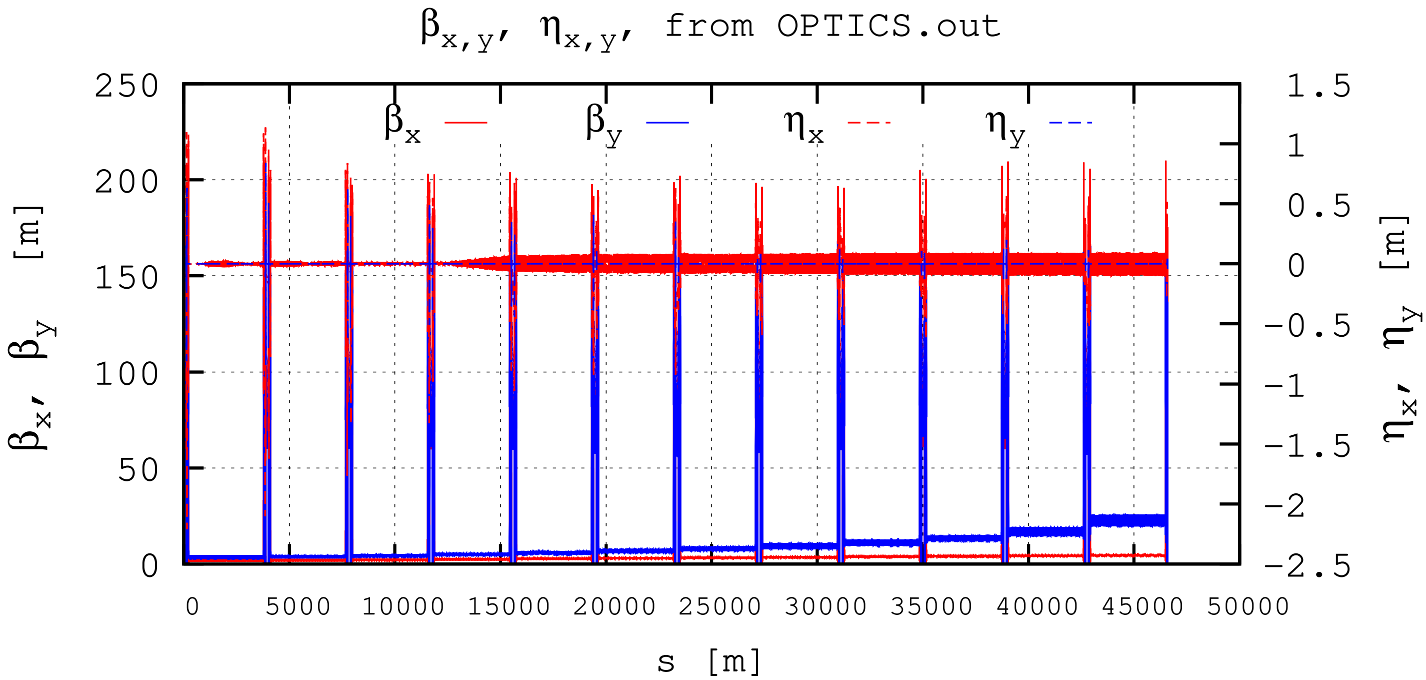
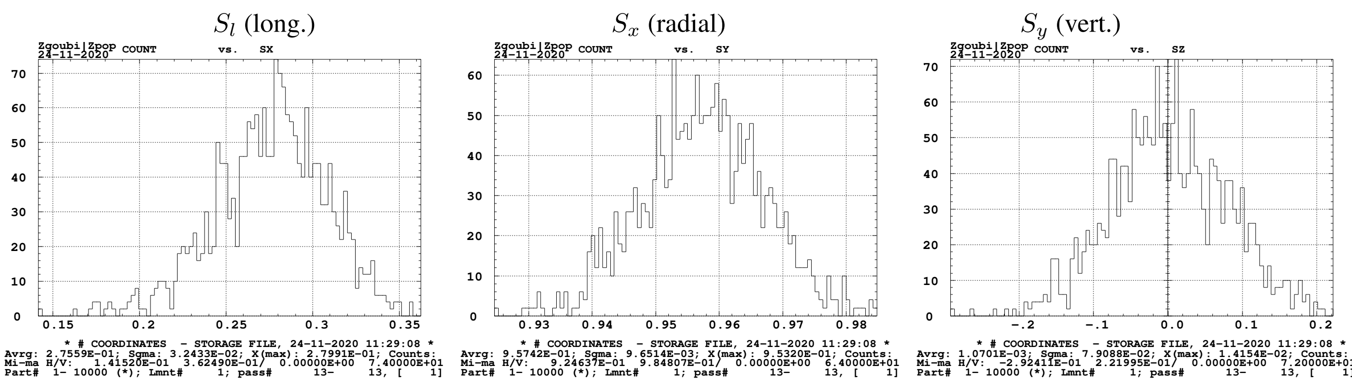


Figure 7: Optical functions along the 12 recirculation loops in eRHIC FFA2 line



Bunch polarization at collision energy, 21.164 GeV, without SR.

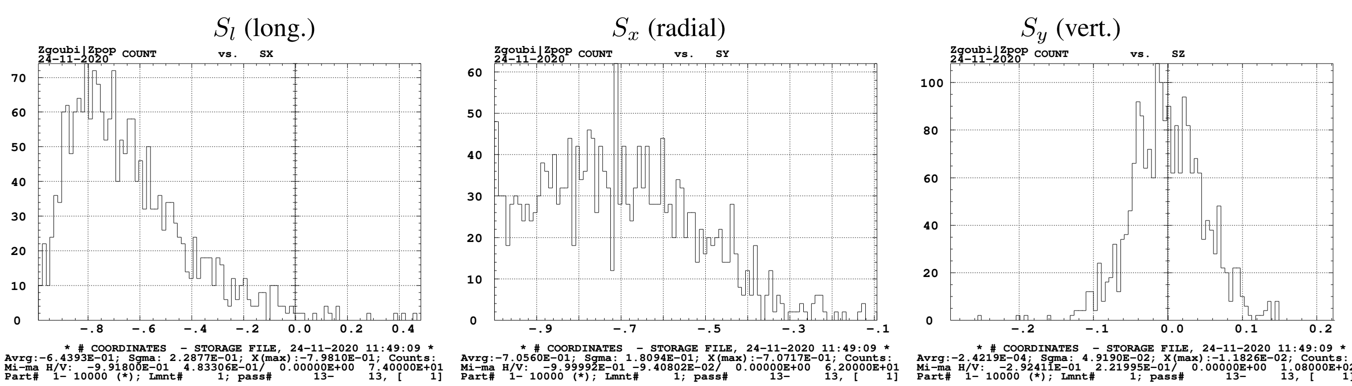


Figure 8: Bunch polarization at collision energy, 21.164 GeV, in eRHIC style (linac-ring) Electron Ion Collider. SR included, here.

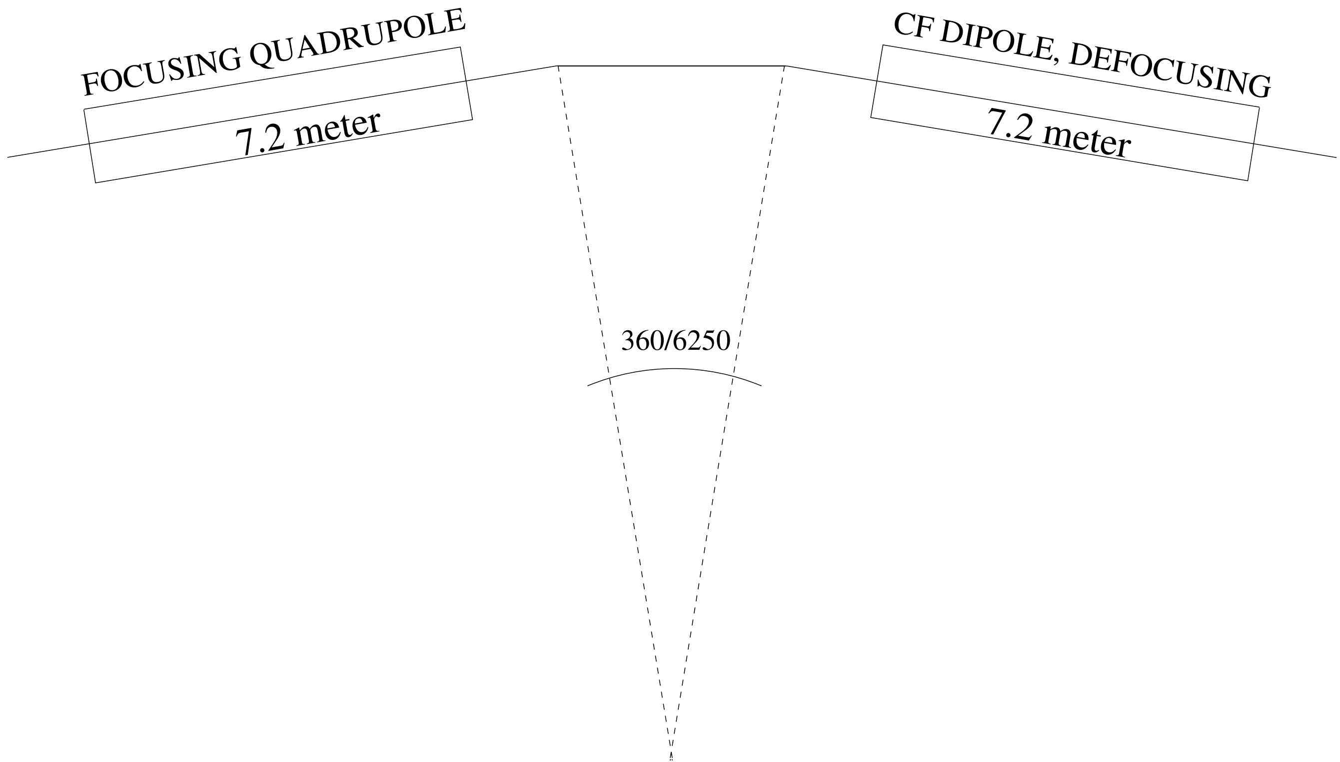
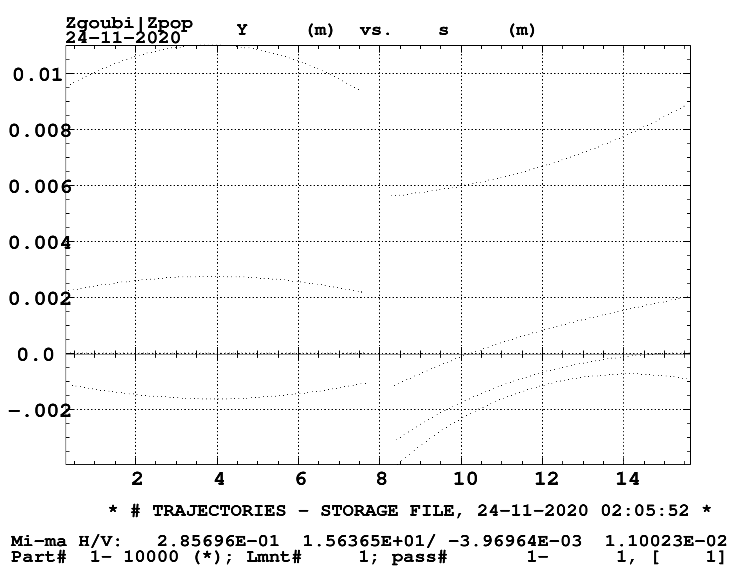


Figure 9: $360/6250 = 0.0576$ deg optical axis break between QF and BD, tunes comprised in $0.13 \sim 0.37$ from 95 to 219 GeV.



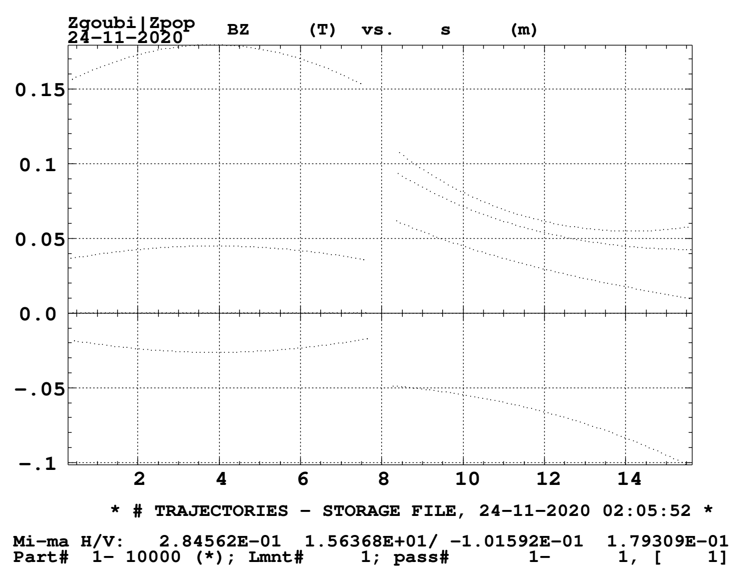


Figure 10: Left: 95, 157, 125 GeV (not a real trajectory: optical reference) and 219 GeV orbits across QF and BD Right: Magnetic field along 95, 157 and 219 GeV orbits across QF and BD

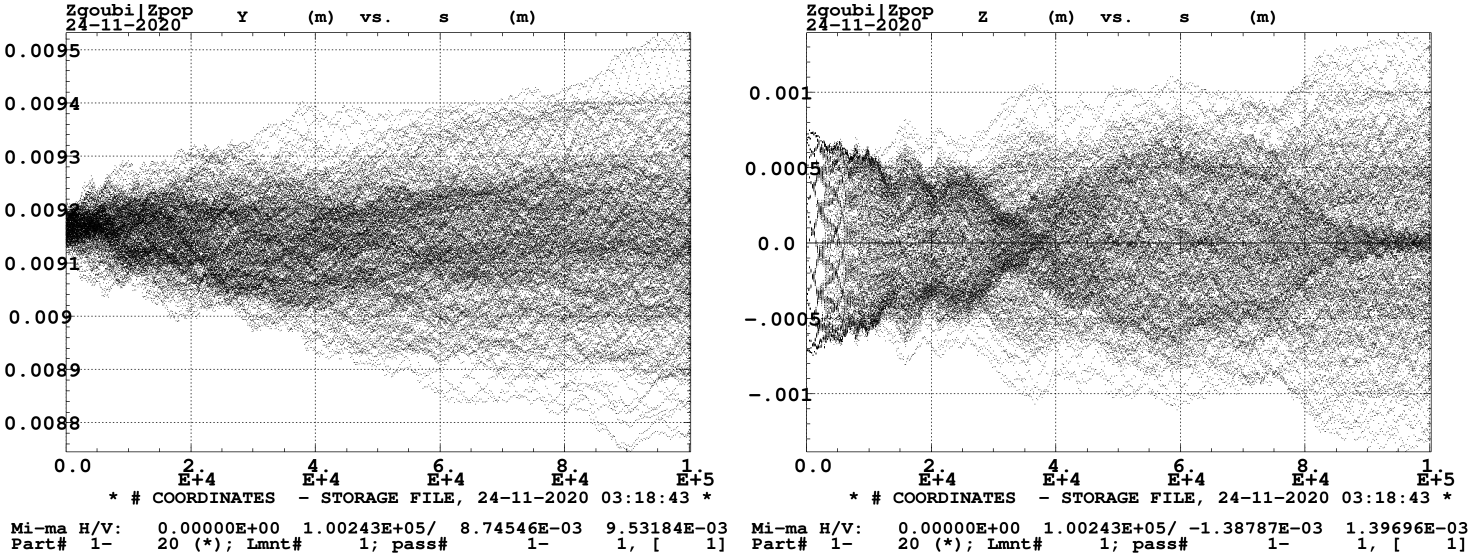


Figure 11: Left:Y(s). Right: Z(s). Right graph: spins: S_y(s)

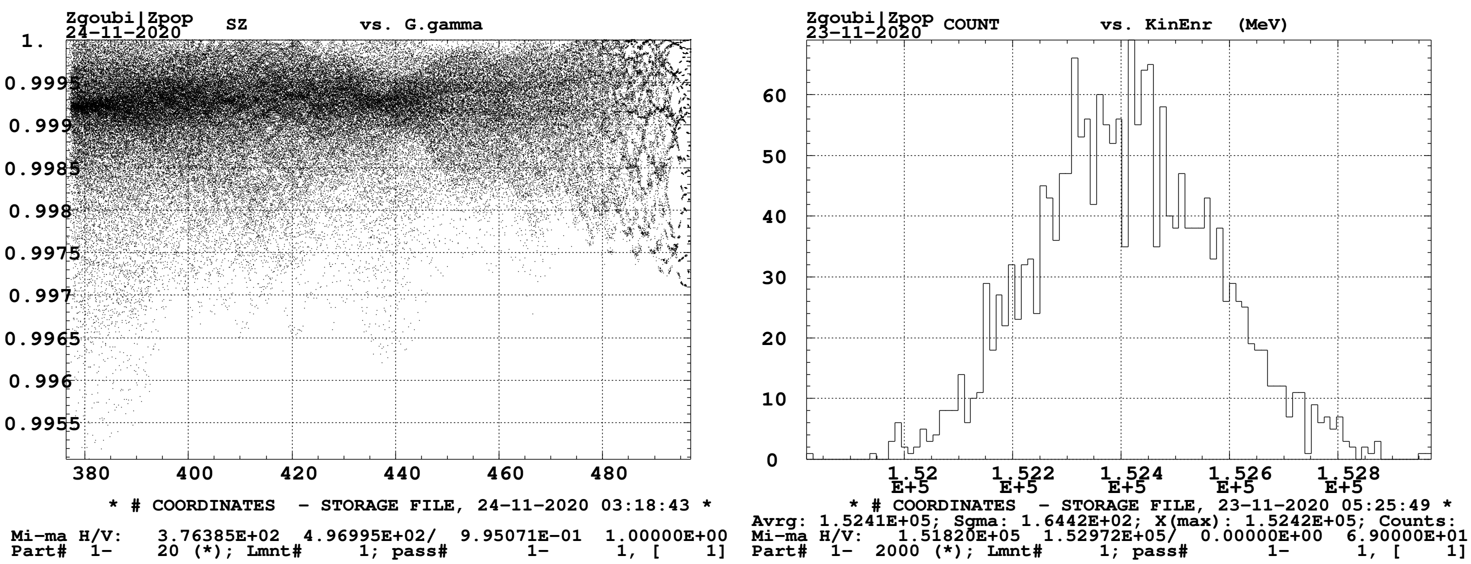


Figure 12: Left: Spins along the line S_y(s). Right: Energy density.

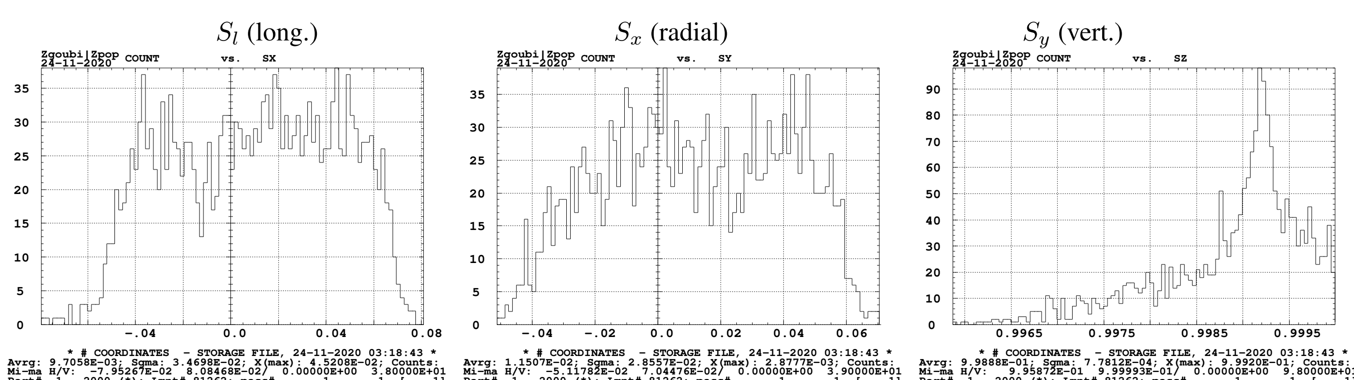


Figure 13: Densities of spin components after 100km path