

FFAG 2020 Workshop, Nov 30 - Dec 4, 2020
TRIUMF UBC Canada

FCC ERL-ERL :

**Polarization transport
through a 220 GeV, 100 km, 6250 cell,
linear FFAG return loop**

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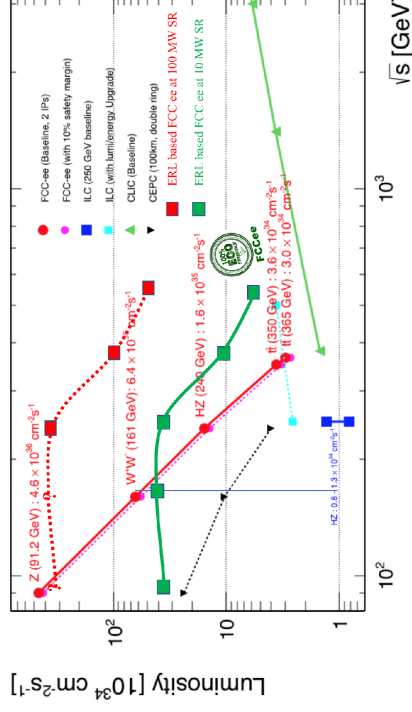
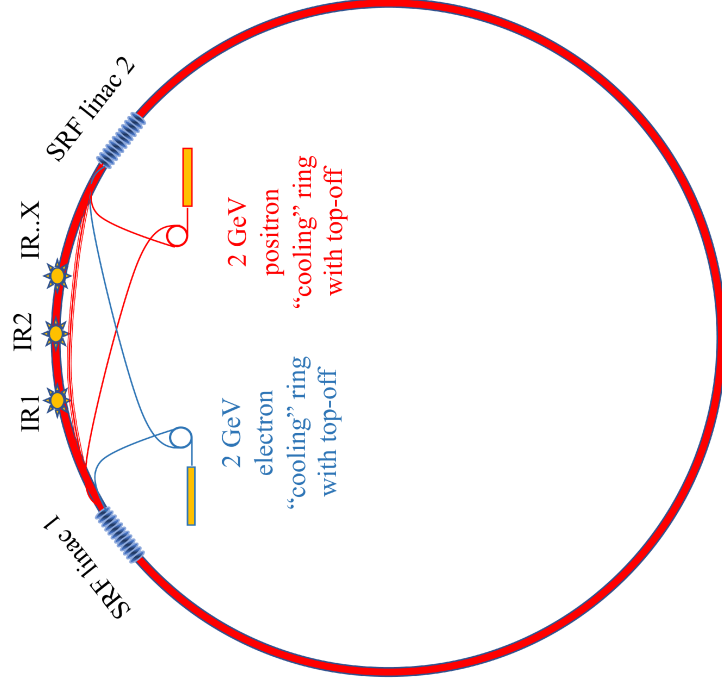
1 FCC ERL-ERL

<https://arxiv.org/pdf/1909.04437.pdf>

Future High Energy Circular e⁺e-Collider using Energy-Recovery Linacs
 Vladimir N Litvinenko, Thomas Roser, Maria Chamizo Llatas

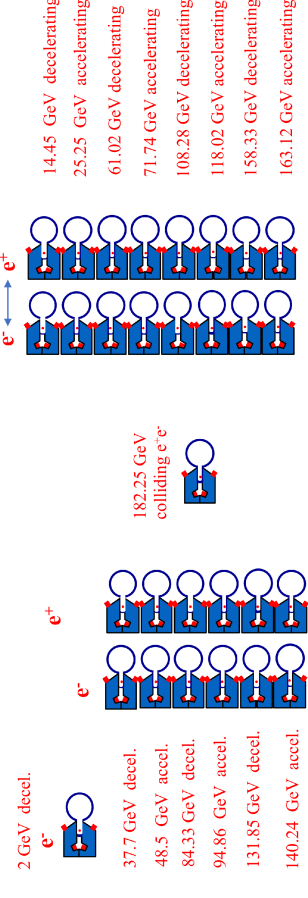
- FCC e-e : next HEP collider, ring-ring design, 100 km footprint. 100 MW SR at 365 MeV CM.

- BNL parties have developed an e⁺erl - e⁻erl version, an evolution of former eRHIC-LL EIC concept, (slide 10).



- ◇ up to $\times 10$ reduction of SR energy loss while maintaining high luminosity at high energies,
- ◇ allows to extend CM energy to 500 GeV or above, for double-Higgs production.
- ◇ allows polarized e⁻ and e⁺ beams.

Possible layout of the return loops



Polarization: What to Expect

- I do not strictly stick to <https://arxiv.org/pdf/1909.04437.pdf>
- **Focus on highest energy (here, 219 GeV)**
- Combined function FODO cell, bend field 0.05 T
- 16 meter long
- phase advance 90 deg
- **Make the loop 100 km \Rightarrow 6250 cells.**

• Cell simulation data:

```
'DRIFT'
40.
0
'MULTIPOL' QF
720.000000 10.00 6.98131701E-04 3.90869163E-02 0. 0.0 0.0 0.0 0.0 0.0 0.0 0.0
0.0000 0.0000 8.00 8.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00
6 1.12200E-01 6.26710E+00 -1.49820E+00 3.58820E+00 -2.12090E+00 1.72300E+00
0.0000 0.0000 8.00 8.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00
6 1.12200E-01 6.26710E+00 -1.49820E+00 3.58820E+00 -2.12090E+00 1.72300E+00
0 0 0 0 0 0 0 0
2.
3. 0. 3.12295633E-02 -2.51327415E-04
'DRIFT'
75.
0
'MULTIPOL' WKICK
0
5.000000 10.00 2.13906229E-05 0. 0. 0.0 0.0 0.0 0.0 0.0 0.0
0.0000 0.0000 8.00 8.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00
6 1.12200E-01 6.26710E+00 -1.49820E+00 3.58820E+00 -2.12090E+00 1.72300E+00
0.0000 0.0000 8.00 8.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00
6 1.12200E-01 6.26710E+00 -1.49820E+00 3.58820E+00 -2.12090E+00 1.72300E+00
1.57079632679 0 0 0 0 0 0 0
2.
1. 0. 0.00000000E+00 0.00000000E+00
'MULTIPOL' QD
0
720.000000 10.00 6.98131701E-04 -3.90869124E-02 0. 0.0 0.0 0.0 0.0 0.0 0.0
0.0000 0.0000 8.00 8.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00
6 1.12200E-01 6.26710E+00 -1.49820E+00 3.58820E+00 -2.12090E+00 1.72300E+00
0.0000 0.0000 8.00 8.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00
6 1.12200E-01 6.26710E+00 -1.49820E+00 3.58820E+00 -2.12090E+00 1.72300E+00
0 0 0 0 0 0 0 0
2.
3. 0. 2.91875475E-02 -2.51327415E-04
'DRIFT'
40.
```

Beam matrix, tunes:

```
Beam matrix (beta/-alpha/-alpha/gamma) and periodic dispersion (MKSAs units)
12.766516 2.128813 0.000000 0.000000 0.000000 0.000000 0.007923
2.128813 0.433309 0.000000 0.000000 0.000000 0.000000 0.001121
0.000000 0.000000 12.766515 -2.128813 0.000000 -0.000000 -0.000000
0.000000 0.000000 -2.128813 0.433309 0.000000 0.000000 0.000000
0.000000 0.000000 0.000000 0.000000 0.000000 0.000000 0.000000
0.000000 0.000000 0.000000 0.000000 0.000000 0.000000 0.000000

NU_Y = 0.25003140      Betatron tunes (Q1 Q2 modes)      NU_Z = 0.25003139
                                Momentum compaction :
dL/L / dp/p = 5.03453630E-07
                                Transition gamma = 1.40935455E+03
                                Chromaticities :
dNu_y / dp/p = -3.13996351E-01
dNu_z / dp/p = -3.13996822E-01
```

• Now, some ingredients in relation with the transport polarized particles:

◇ Introduce a defect vertical orbit, make it 100 km-periodic:

Launch particles centered on that 1-pass **periodic** vertical orbit.

Only reason for launching bunch on periodic orbit: bounded vertical excursion, “mimic corrected orbit”.

2×33.7 GeV linacs,
4 passes up, 4 passes down,
in [linac1 & linac2]

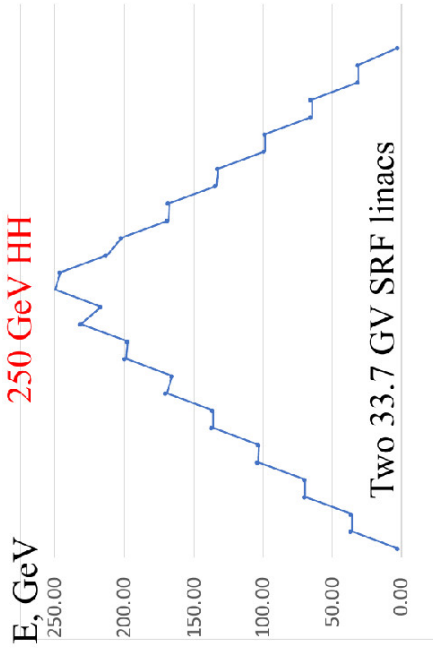
◇ Add betatron oscillation:

- a few 10s of particles launched on nominal emittance

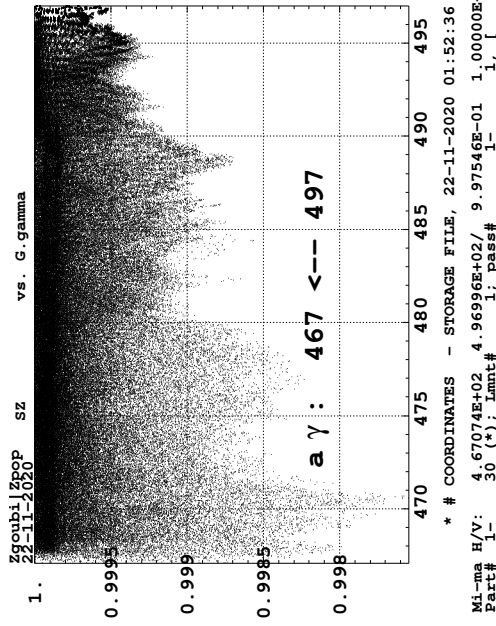
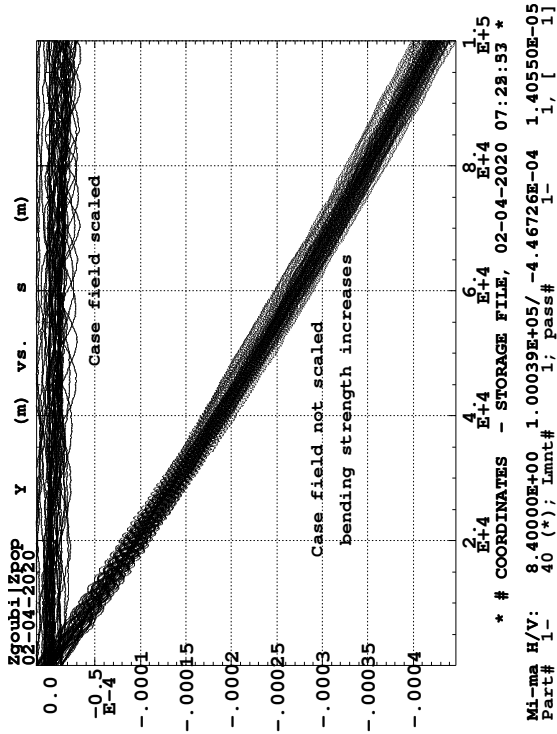
$8 \mu\text{m}$ H invariant, and 20×8 nm V invariant

$20 \times$ nominal emittance
enhanced resonance strengths

◇ Add Monte Carlo SR:

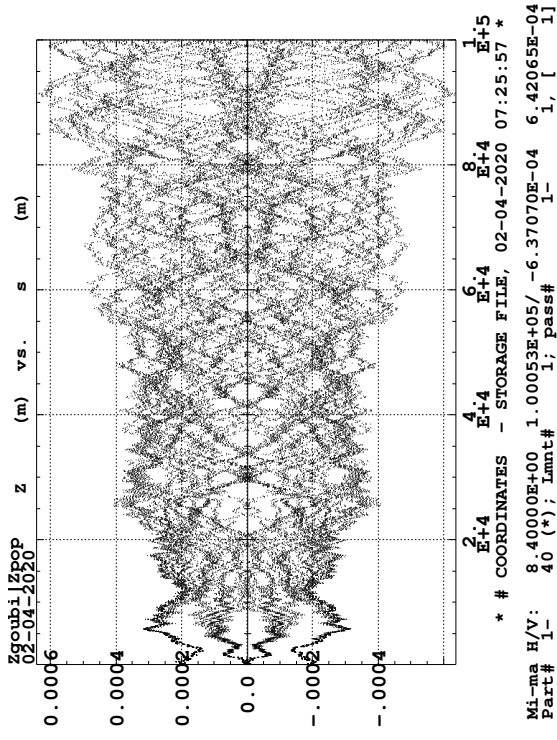


```
*****
50999 Keyword, label(s) : SRPRINT
pass #,      particle #      -> total # of photons,      total energy loss (MeV) (over 100 km)
1           1                27270.00              11673.23
* Monte Carlo S.R. statistics, from beginning of structure, on a total of 4533425 integration steps :
Average energy loss per particle per pass : 1.1673226E+07 keV.      Relative to initial energy : 5.5101318E-02
Critical energy of photons (average) : 1370.569 keV
Average energy of radiated photon : 428.0611 keV
rms energy of radiated photons : 806.7605 keV
Smallest, BIGEST photon : 3.9808E-13 7.1949E+03 keV
Number of photons radiated - Total : 27270.00
*****
```



- A few 10s of particles lunched on $\epsilon_x = 8\pi\mu\text{m}$, $\epsilon_y = 20 \times 8\pi\text{nm}$ invariant;
- top left: horizontal, either w/o or w/ fields scaled for energy loss, a theoretical scaling factor is applied;
 - top right: vertical.
 - bottom: S_y component of spins (launched vertical).

CONCLUSION: no polarization loss, over 100 km, 220 GeV, in presence of substantial orbit error + bunch size



```

'MCOBJET'
730.507072990975e3 ! 219 GeV beta*gamma=428573.33435914869
3
200
1 1 1 1 1 1
0. 0. 1.52615322E-04 -3.06497046E-05 0.00 1.00000000E+00 'o'
-2.128625 12.767156 1.86665836594e-11 1 ! H invariant = 8 mu*m
2.128625 12.767157 1.86665836594e-14 -20 20.0001 ! V invariant = 20 x 8 nm
0. 1. 0. 1

'SRLOSS'
1 ! srLoss
MULTIPOL scale
1 123456
    
```

nominal
rmsbunch
size

Polarization: make sure we're not missing something...

Let's create resonant depolarization conditions:

- Spin precession $a\gamma\alpha$:

- $a = 1.15965 \times 10^{-3}$; $a\gamma = 497$ at 219 GeV

$\alpha = \text{orbital angle}$ } $\Leftrightarrow a\gamma\alpha = 2\pi$
one spin precession completed

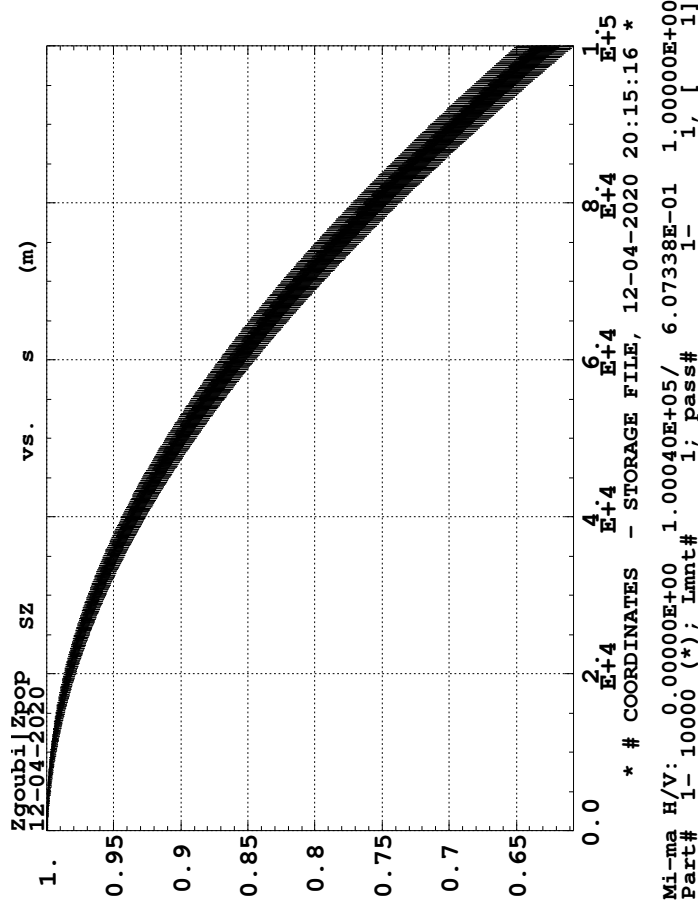
- it takes an orbital angle $\alpha = 2\pi/497 = 12.64$ mrad

→ $6250[\text{cells}]/2\pi \times 0.01264 = 12.6$ cells.

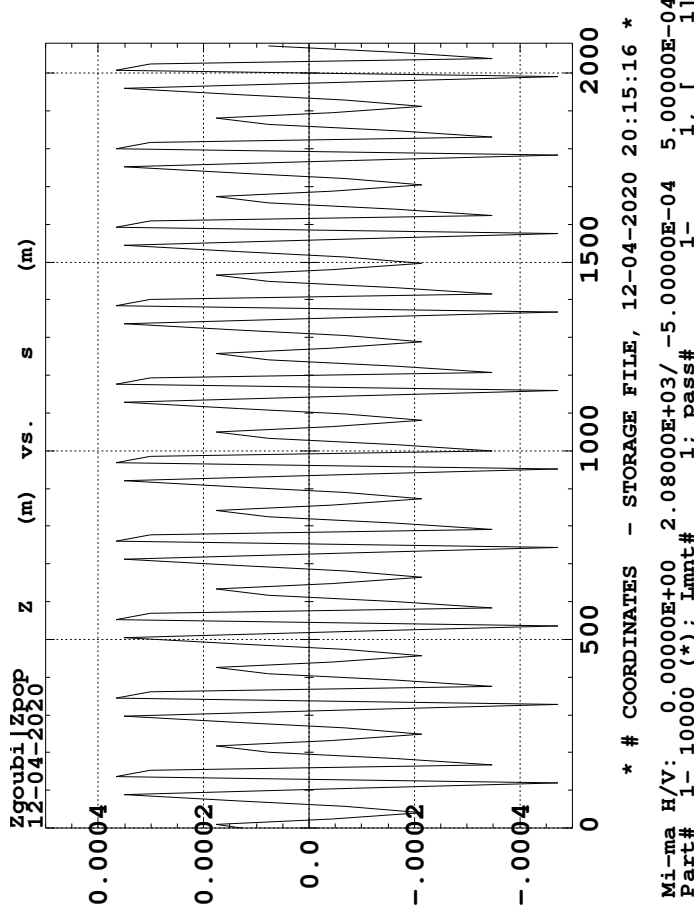
- Adjust energy to get 1 spin precession over an integer number of cells:
13 cells → 211.85 GeV.

- Finally: expect to excite the integer resonance, and so, create a resonant condition, by introducing a 13-cell periodic defect vertical orbit.

- And, yes, we get what's expected:
- No SR, first:

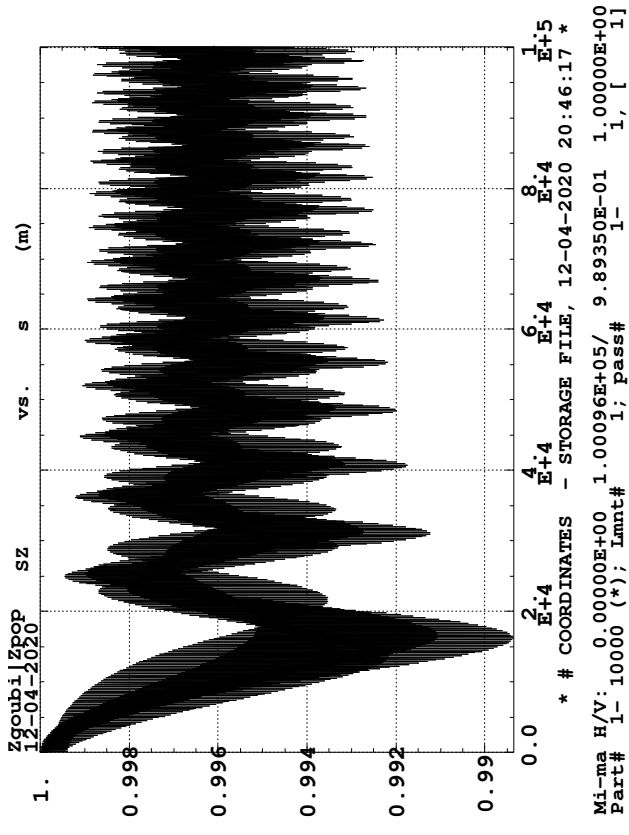


Spin motion (S_y) over 100 km:
 fixed energy, spin stays on
 resonance $a\gamma = 1 \rightarrow$ spins are
 flipping: precess around precession
 axis which lies in the bend plane.

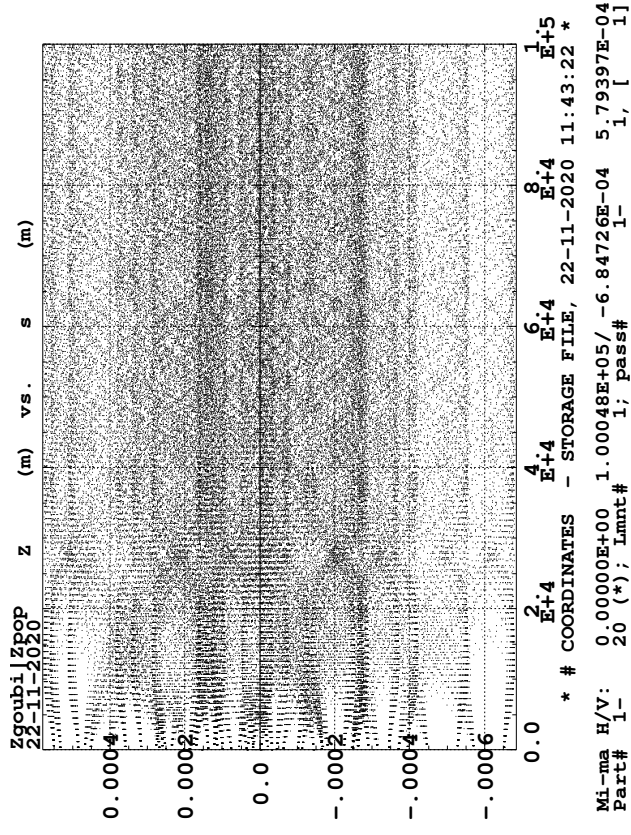


Vertical orbit over first 2 km
 (13-cell pattern repeats itself over
 the 100 km).

- Now add SR:



Spins over 100 km, $a\gamma : 497 \rightarrow$: by contrast with no SR, they quickly cross repeating resonant conditions $G\gamma = \text{integer}$; polarization loss $\approx 1\%$.



Vertical excursion of a few 10s of particles launched on $\epsilon_y = 20 \times 8 \pi \text{nm}$ invariant, over 100 km.

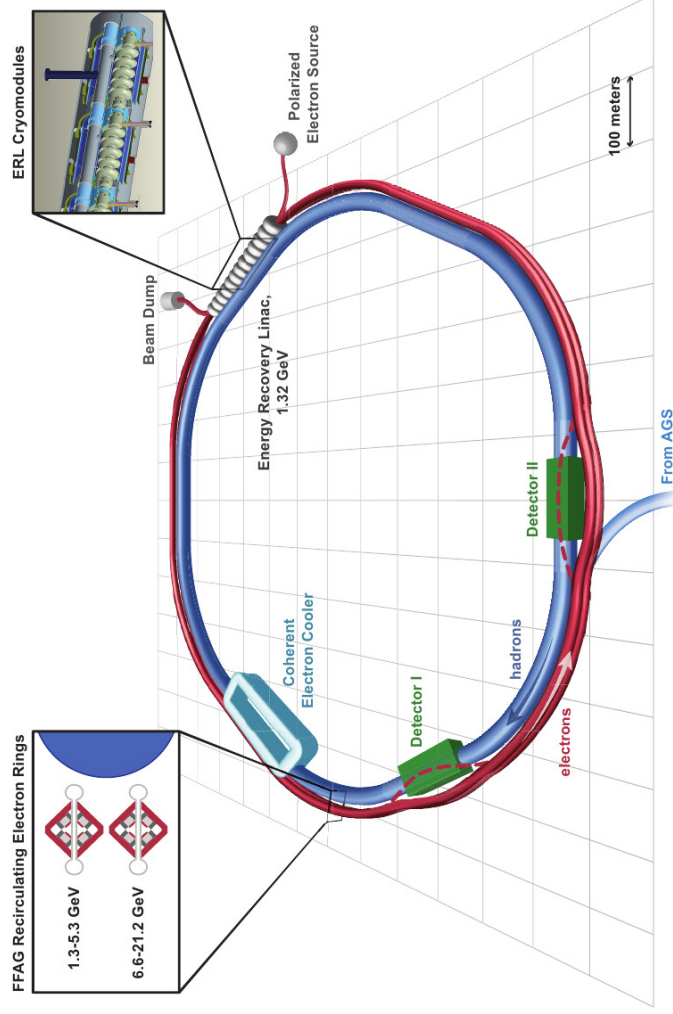
- Note: if there were no vertical orbit excursion ($\epsilon_y \equiv 0$), then spins would just stay vertical.

2 LINEAR FFAG RETURN LOOP

2.1 We're Not in Totally Unknown Grounds

eRHIC-LL: $\bar{e}20\text{ GeV} \times \bar{p}275\text{ GeV}$

[Details in BNL/C-AD Tech Notes C-A/eRHIC/45 and 49]



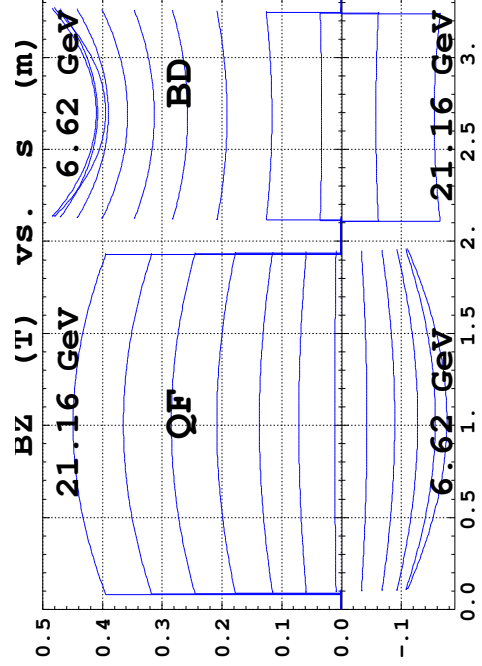
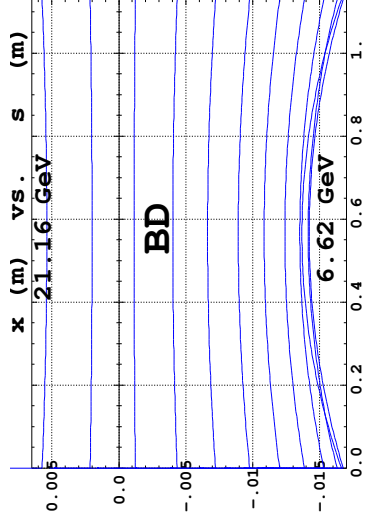
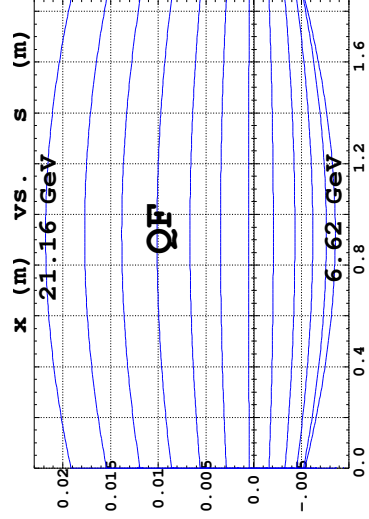
- The 21 GeV ERL at eRHIC:
- two recirculation loops alongside RHIC: FFAG1 (low energy) and FFAG2 (high energy),
- 1.322 GeV linac located in RHIC IR2, connected to the FFAG loops by a merger and a spreader section.

- the return loop is a 3.8 km ring: 6 arcs \times 120 cells/arc.

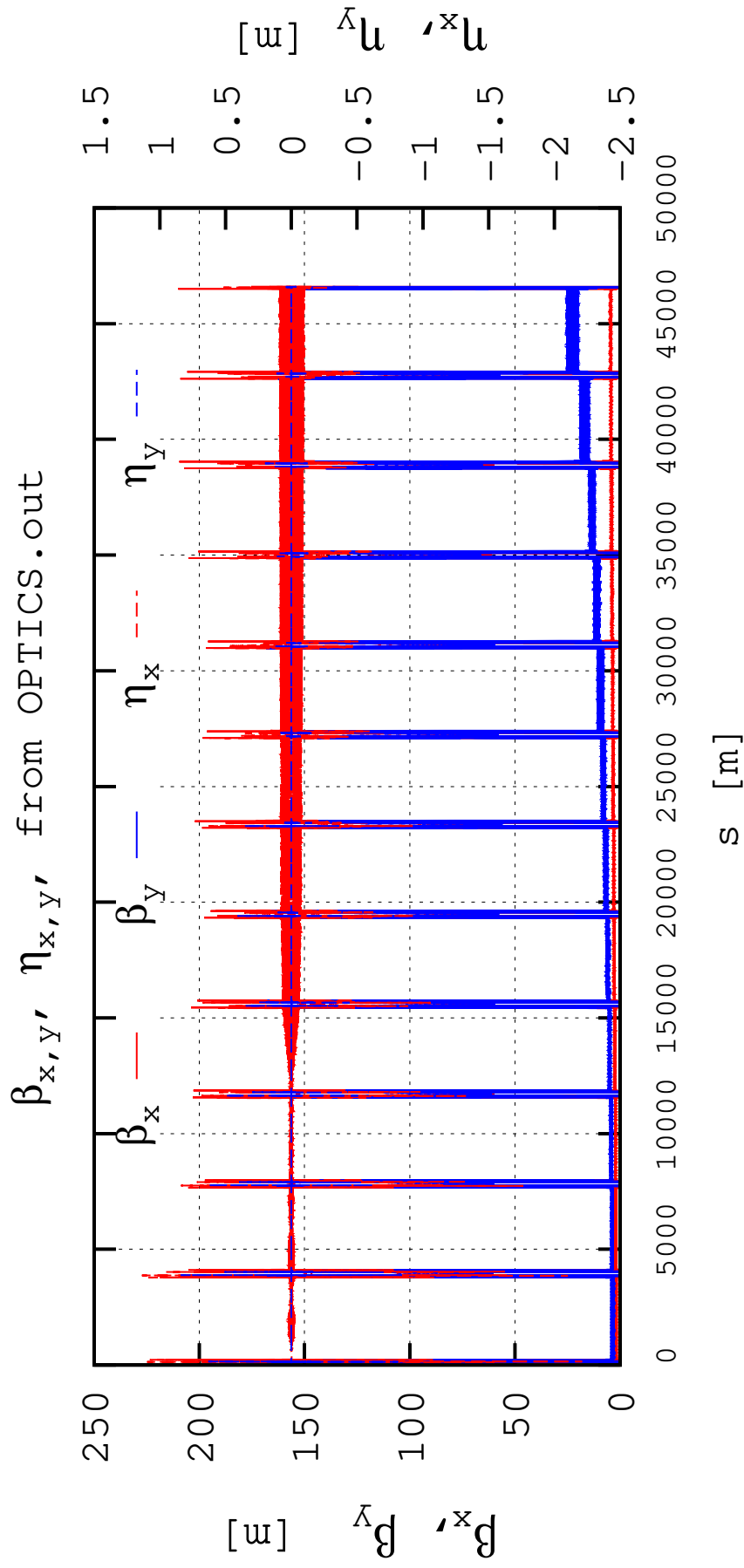
12 periodic orbits across FFAG_2 cell:

Radial shift of the two quads: 13.48 mm, ensures 8.73 mrad orbit bending.

Magnetic field experienced along the 12 orbits:



- A long beam line: 47 km, comprised of
 - 4 first loops in FFAG1 to 5.2 GeV: 4×3.8 km (not concerned here),
 - 12 loops in FFAG2 from 6.6 to 21.1 GeV, 12×3.8 = 46 km,
 (I am not counting the 11 loops down: I am interested in spin transport to collision)
- including 12 combiner lines from FFAG2 to linac, 12 splitter lines from linac to FFAG2.

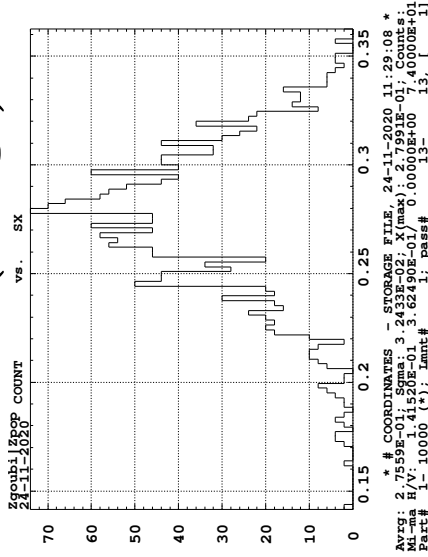


● Bunch polarization at collision energy, 21.164 GeV

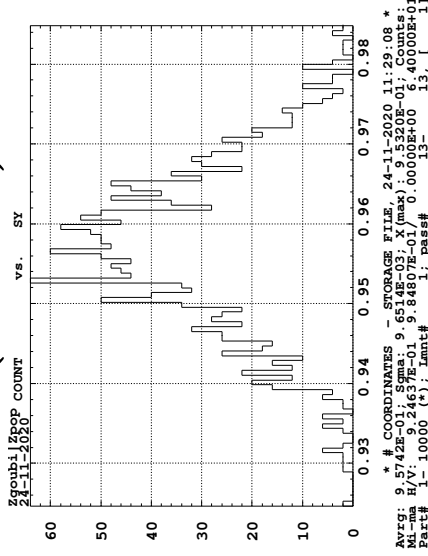
Spins are launched longitudinal, they precess in the bend plane

◇ Try w/o SR, first (2000 spins, all launched longitudinal):

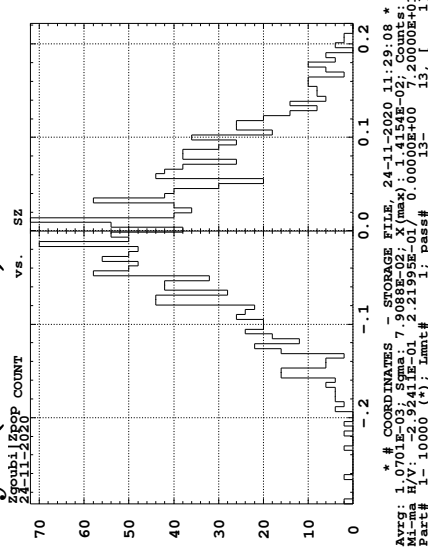
S₁ (long.)



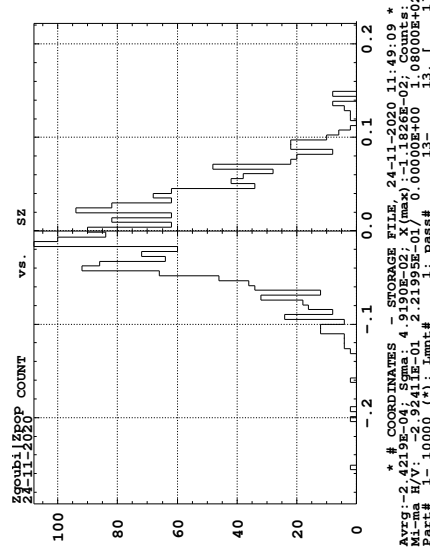
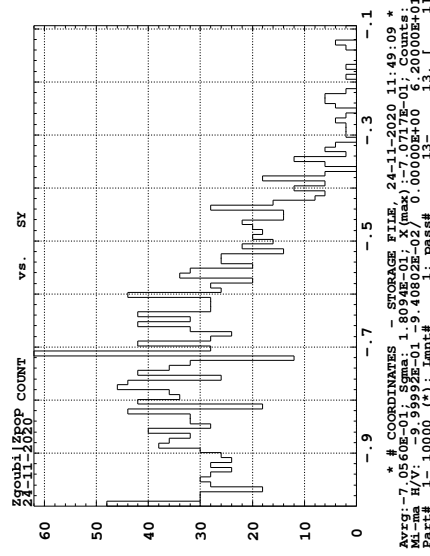
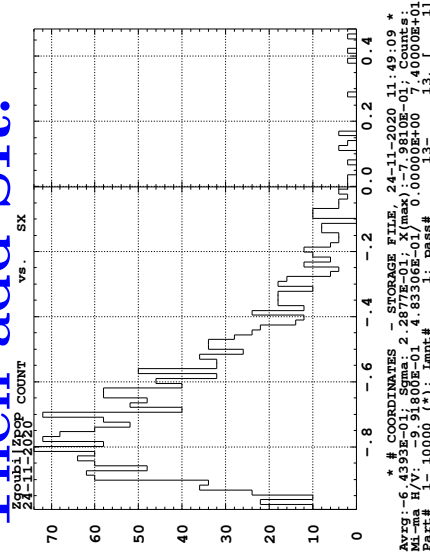
S_x (radial)



S_y (vert.)



◇ Then add SR:



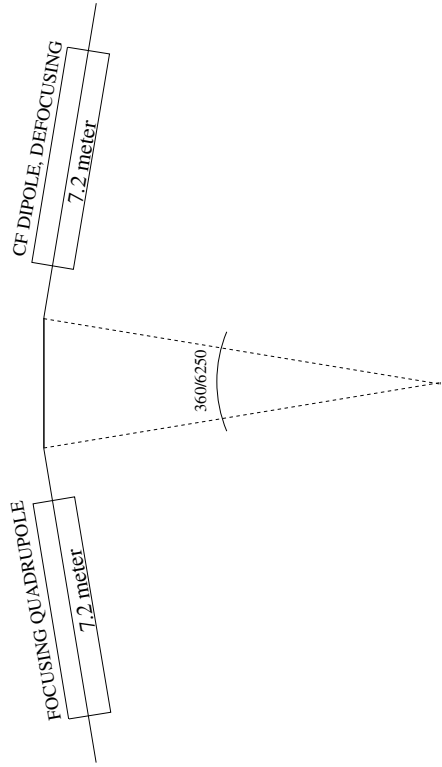
COORDINATES - STORAGE FILE, 24-11-2020 11:49:09 * Avrg: 6.4393E-01; Sgma: 2.2830E-01; X(max): 4.8330E-01; Counts: MI-ma H/V: 9.91800E-01 4.8330E-01/ 0.00000E+00 4.0000E+01 Part# 1- 10000 (*); Lmt# 1; pass# 13, [13, [1]]

COORDINATES - STORAGE FILE, 24-11-2020 11:49:09 * Avrg: 7.0560E-01; Sgma: 1.8074E-01; X(max): 1.8074E-01; Counts: MI-ma H/V: 5.6999E-01 1.8074E-01/ 0.00000E+00 13, [13, [1]]

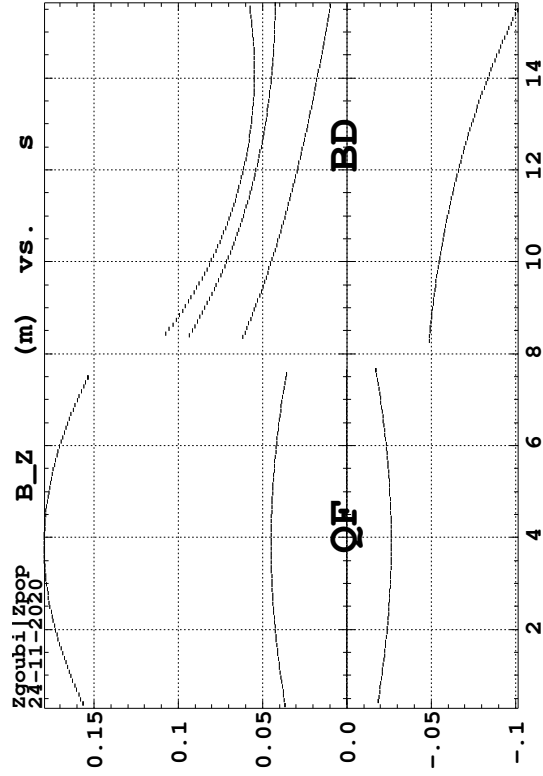
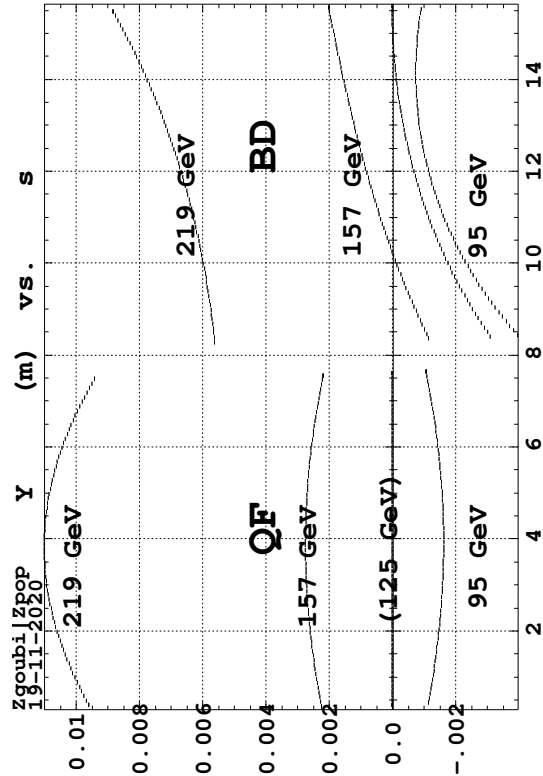
COORDINATES - STORAGE FILE, 24-11-2020 11:49:09 * Avrg: 2.4219E-01; Sgma: 2.524E-01; X(max): 4.2095E-01; Counts: MI-ma H/V: 2.92411E-01 2.2199E-07/ 0.00000E+00 7.20000E+01 Part# 1- 10000 (*); Lmt# 1; pass# 13, [13, [1]]

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

Linear-FFAG Cell



- A 100 km ring, 6250 × 16-meter cells,
- use similar QF, BD cell to eRHIC-LL,
- 360/6250 = 0.0576 deg optical axis break between QF and BD,
- tunes comprised in 0.13 ~ 0.37 from 95 to 219 GeV.



95, 157, 125 GeV (not real: reference) and 219 GeV orbits across QF and BD

Magnetic field along 95, 157 and 219 GeV orbits across QF and BD

Linear-FFAG Cell (CONT'D)

```

'DRIFT'
40.      ! spilt 10 2
'MULTIPOL' QF
720.000000 10.00 0.    3.908669163E-02 0. 0. 0. 0. 0. 0. 0. 0.
'DRIFT'
10.      ! spilt 10 2
'CHANGREF'
ZR -0.05760000
'DRIFT'
25.      ! spilt 10 2
'MULTIPOL' VKICK
10.000000 10.00 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0.
'FAISCEAU'
'DRIFT'
25.      ! spilt 10 2
'CHANGREF'
ZR -0.05760000
'DRIFT'
10.      ! spilt 10 2
'FAISCEAU'
'MULTIPOL' BD
720. 10. 1.01648144E-03 -3.90869124E-02 0 0 0 0 0 0 0 0
1 0 0.35128927 0.  ! posit.
'DRIFT'
40.      ! spilt 10 2
'MARKER' #E_cell

```

95 GeV

```

Beam matrix (beta/-alpha/-alpha/gamma) and periodic dispersion (MKS units)
14.902550  3.832302  0.000000  0.000000  0.000000  0.001881
 3.832302  1.052608  0.000000  0.000000  0.000000  0.000824
 0.000000  0.000000  14.902550  -3.832319  0.000000  0.000000
 0.000000  0.000000  -3.832319  1.052614  0.000000  -0.000000

```

Betatron tunes

NU_Y = 0.37654250 NU_Z = 0.37654333

157 GeV

```

Beam matrix (beta/-alpha/-alpha/gamma) and periodic dispersion (MKS units)
14.965063  1.857074  0.000000  0.000000  0.000000  0.012922
 1.857074  0.297274  0.000000  0.000000  0.000000  0.001384
 0.000000  0.000000  14.965064  -1.857074  0.000000  0.000000
 0.000000  0.000000  -1.857074  0.297274  0.000000  -0.000000

```

Betatron tunes

NU_Y = 0.19089182 NU_Z = 0.19089190

125 GeV (reference, cell phase advance 90 deg)

```

Beam matrix (beta/-alpha/-alpha/gamma) and periodic dispersion (MKS units)
12.767164  2.128625  0.000000  0.000000  0.000000  0.006246
 2.128625  0.433224  0.000000  0.000000  0.000000  0.001095
 0.000000  0.000000  12.767146  -2.128624  0.000000  0.000000
 0.000000  0.000000  -2.128624  0.433225  0.000000  -0.000000

```

Betatron tunes

NU_Y = 0.24999991 NU_Z = 0.25000021

219 GeV

```

Beam matrix (beta/-alpha/-alpha/gamma) and periodic dispersion (MKS units)
20.155847  1.702669  0.000000  0.000000  0.000000  0.031783
 1.702669  0.193447  0.000000  0.000000  0.000000  0.001942
 0.000000  0.000000  20.155853  -1.702669  0.000000  0.000000
 0.000000  0.000000  -1.702669  0.193447  0.000000  -0.000000

```

Betatron tunes

NU_Y = 0.13289146 NU_Z = 0.13289149

SR in 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, see slide 4),

- For the record: the loss per cell amounts to

$$\overline{\Delta E}[\text{MeV}] \approx 0.96 \times 10^{-15} \gamma^4 \left(\frac{I_{\text{BD}}}{\rho_{\text{BD}}^2} + \frac{I_{\text{QF}}}{\rho_{\text{QF}}^2} \right)$$

(and, in passing, per cell, $\sigma_E \approx \sqrt{\sigma_{E,\text{BD}}^2 + \sigma_{E,\text{QF}}^2} \approx 1.94 \times 10^{-14} \gamma^{7/2} \sqrt{\frac{I_{\text{BD}}}{|\rho_{\text{BD}}^3|} + \frac{I_{\text{QF}}}{|\rho_{\text{QF}}^3|}}$).

- ◇ Energy loss 5 times the combined function FODO cell:

* Monte Carlo S.R. statistics, from beginning of structure,

2000 particles, a total of 186250000 integration steps :

Average energy loss per particle per pass : 52.727840E+06 keV.

Relative to initial energy : 0.2407664

Critical energy of photons (average) :	2407.627	keV
Average energy of radiated photon :	924.1118	keV
rms energy of radiated photons :	1893.438	keV
Smallest, BIGEST photon :	0.0000E+00	9.9915E+03 keV
Number of photons radiated - Total :	1.1411572E+08	
- per particle per pass :	57057.86	
- per particle, per step :	6.1270184E-02	

LET'S TRACK A POLARIZED BUNCH IN THE "219 GeV" LINE

- ◇ Introduce a defect vertical orbit (taken 100 km-periodic in the absence of SR)
- ◇ Add betatron oscillation:
 - 2,000-particle bunch Gaussian density,
 - with rms H 8 μm norm., rms V 8 nm norm., initial $dp/p=0$.

```

FCCerl-erl
'MCOBJET'
730.505368478e3 ! 219 GeV
3
2000
1 1 2 2 2 2
0.91659952e-2 0.82956328e-3 7.21481481E-04 -6.04444444E-05 0.00 1. 'd'
-1.702670 20.155765 1.86665836594e-11 3 ! rms width H = 8 mu_m
1.702668 20.155767 1.86665836594e-14 3 ! rms width V = 8 nm
0. 1. 0. 1
123456 234567 345678

'PARTICUL'
POSITRON
'SPNTRK'
4.1
0. 0. 1.

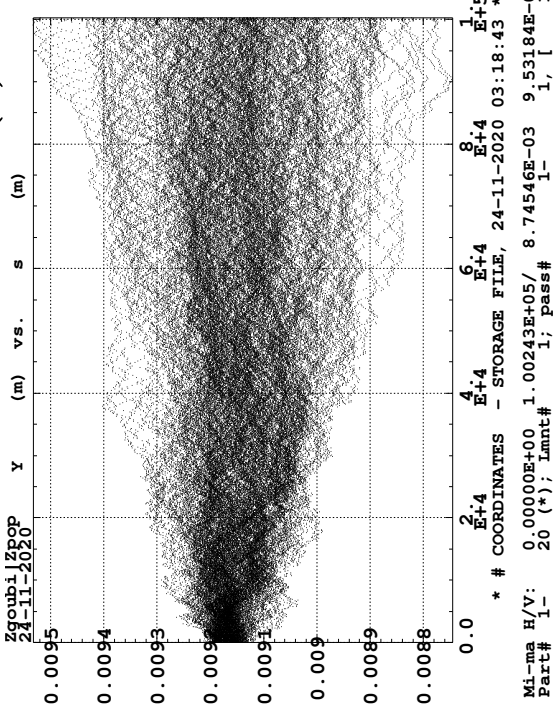
'SRLOSS'
1 ! srLoss
MULTIPOL scale[19d0]
1 123456

!'ERRORS'
!1 1 123466 ! dB(kG)
!MULTIPOL{VKICK} 1 BP A U 0. 0.1 9999

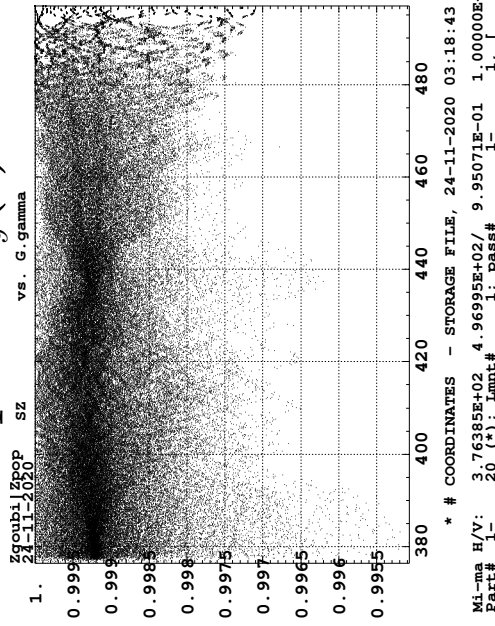
'SCALING'
1 2
MULTIPOL
-1
730.505368478
1
MULTIPOL VKICK
-1
416.95511899420603
1

```

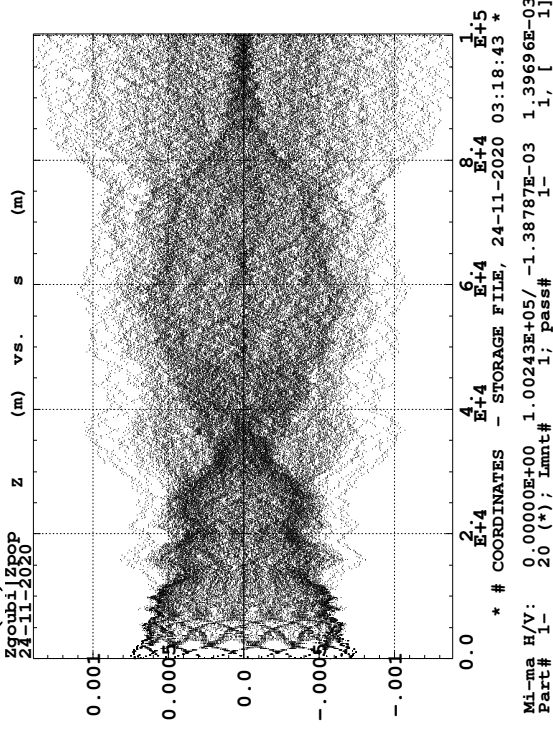
Y(s)



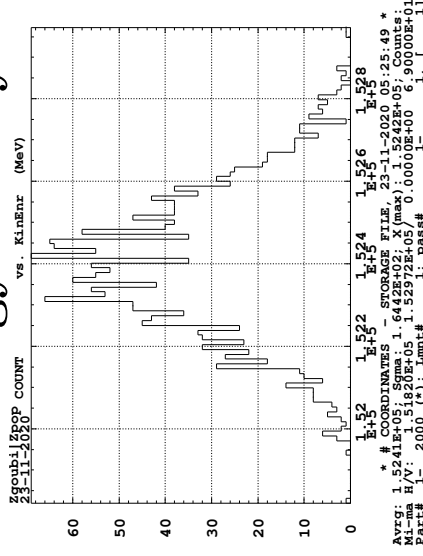
spins: $S_y(s)$



Z(s)



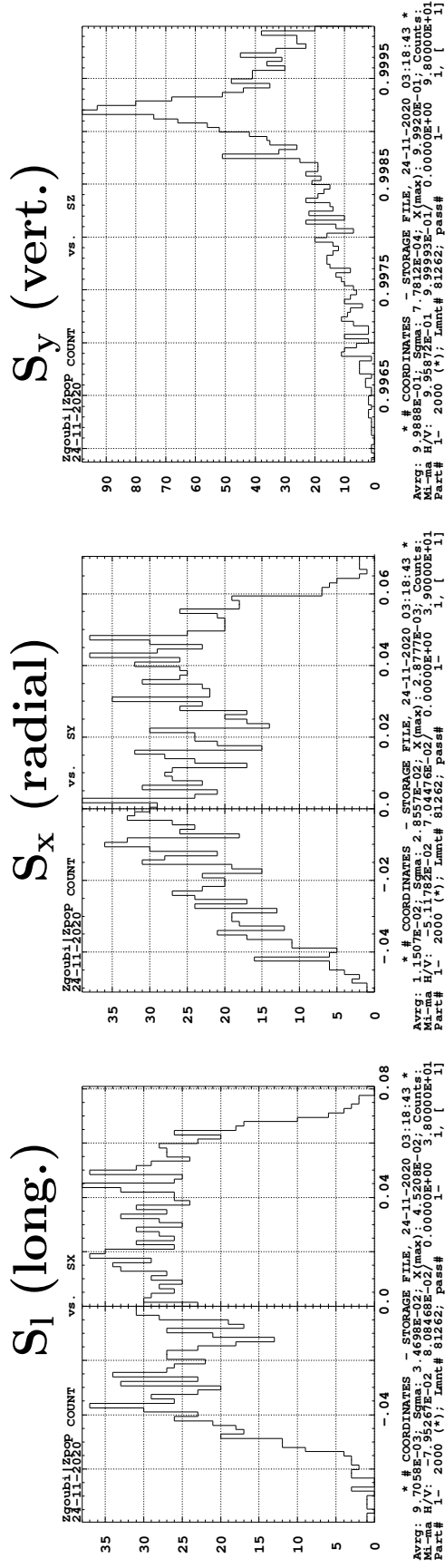
◇ Energy density



A few particles, from a 2,000 bunch launched with rms $\epsilon_x = 8 \pi \mu\text{m}$, $\epsilon_y = 8 \pi \text{nm}$;

- top left: horizontal, w/ field scaled for energy loss - a theoretical scaling factor;
- top right: vertical excursion (large, presumably prone to excite any strong integer resonance);
- bottom: S_y (spins are launched vertical), vs. $G\gamma$ decreasing from right to left.

- Bunch polarization at end of “219 GeV” line
- ◇ Spins:



● Polarization after 100 km:

81264 Keyword, label(s) : SPNPRT IPASS= 1

Momentum group #1 ; average over 2000 particles at this pass :

AVERAGES OVER 2000 PARTICLES:

	INITIAL	FINAL			
SX	SY	SZ	SX	SY	SZ
0.000000	0.000000	1.000000	0.009706	0.011507	0.998876
			377.335167	2.551352	0.933987
			(deg)	(deg)	(deg)
			G.gma	sigma'	
			(SI,SF)	(SI,SF)	

3 POLARIZATION: CONCLUSION

- SR-wise:

Need to minimized energy loss through alternate bend cell,

- Spin-wise:

No obvious indication of polarization loss over the high energy

FFAG loop, for nominal rms bunch size, in spite of large vertical

orbit excursion.