BNL-219926-2020-TECH

EIC-ADD-TN-007

Simulation of Polarized Electron Bunch Acceleration in EIC RCS Bunch and Spin Densities at Extraction

F. Méot

September 2020

Electron-Ion Collider

Brookhaven National Laboratory

U.S. Department of Energy

USDOE Office of Science (SC), Nuclear Physics (NP) (SC-26)

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EIC TECHNICAL NOTE	NUMBER EIC-ADD-TN-007
AUTHORS **François Méot** **Vahid Ranjbar**	DATE Sept. 15, 2020

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Abstract

This Tech. Note reports numerical methods and outcomes regarding the simulation of polarized bunch acceleration in the EIC RCS [1], from injection (or bunch merge) energy to ESR store energy, including bunch densities and polarization at the end of the acceleration ramp, ready for transfer to the ESR. This work is based on earlier code developments and similar studies regarding CESR RCS injector [2].

Contents

1 Introduction

The EIC electron-hadron collider project, currently in its conceptual design stage, includes an electron rapid cycling synchrotron (RCS), as the full energy injector to the electron storage ring (ESR).

This Tech Note summarizes simulations of full acceleration cycles in the RCS, their outcomes include final bunch densities and polarization at the end of the acceleration ramp, ready for transfer to the ESR. Tracking simulation hypotheses are detailed, including some of the input data to the tracking code. Some developments specific to EIC RCS simulations, including RF management, are outlined, for clarity.

Specimen of the simulation input data files resorted to here, are available at

$$https://sourceforge.net/p/zgoubi/code/HEAD/tree/trunk/exemples/EIC/RCS/$$

Similar studies have been performed in the past for a similar energy (greater repetition rate) RCS, namely, CESR injector at Cornell. Reference [2] can be referred to for comparison of both the methods and results, including polarization preservation. Simulation data files can be found at

$$https://sourceforge.net/p/zgoubi/code/HEAD/tree/trunk/exemples/Cornell\_rings/RCS\_injector/$$

2 EIC RCS Parameters

Table 1 lists RCS parameters considered for the setup of the polarization transport simulation files. Figure 1 shows the orbit hypotheses (zero orbit), Figure 2 shows the optical functions, lattice parameters (MADX style "Twiss file" header) are given in Tab. 2.

Detailed statistics from Monte Carlo synchrotron radiation at 0.4, 1, 5, 10 and 18 GeV are given in page 5, they are summarized in Tab. 4. The latter also gives the SR integrals in ESR and RCS.

Table 1: RCS parameters in the tracking simulations.

Initial energy	GeV	1
Top energy	GeV	5, 10, 18
Circumference $\mathcal{C}$	m	3841.35
Bend radius	m	235.000
Lattice		
Arc β_x, β_y, max.	m	≈ 80
$\mathrm{Q_x}$, $\mathrm{Q_y}$ (frac.)		0.8329, 0.7543
ξ_x, ξ_y		few units
Bunch parameters, at injection		
$\beta\gamma\varepsilon_\mathrm{x,y}$	$(\pi\mu\mathrm{m})$	26
Length, total	ps	180
dE/E, rms		$2.5\,10^{-3}$
Longitudinal, RF		
$\mathrm{f_{rev}}$	kHz	78.1
h		7560
voltage	MV	up to 60
SR partition numbers		
$J_x = 1 - \mathcal{D}$		≈ 1
J_y		1
$J_l = 2 + \mathcal{D}$		≈ 2

Optical functions

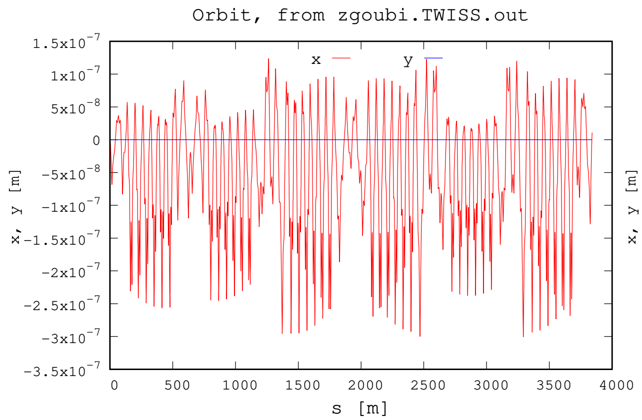


Figure 1: In the defect free lattice simulated here, the design orbit is zero around the ring.

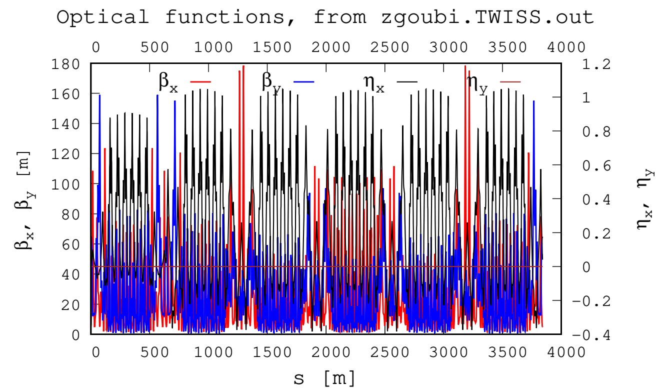


Figure 2: Betatron functions and dispersion.

Table 2: "Twiss file" header, from raytracing

@ LENGTH	3841.351355		
@ ALFA	0.4688745367E-03		
@ ORBIT5	-0		
@ GAMMATR	46.18188718		
@ Q1	0.8328968821		
@ Q2	0.7543490456		
@ DQ1	0.8333740361		
@ DQ2	-0.3950533812		
@ DXMAX	1.04806880E+00	@ DXMIN	-3.83664534E-01
@ DYMAX	0.00000000E+00	@ DYMIN	0.00000000E+00
@ XCOMAX	1.23786225E-05	@ XCOMIN	-3.00842877E-07
@ YCOMAX	0.00000000E+00	@ YCOMIN	0.00000000E+00
@ BETXMAX	1.78264978E+02	@ BETXMIN	1.15867478E+00
@ BETYMAX	1.59288020E+02	@ BETYMIN	7.66285809E-01
@ XCORMS	9.23721890E-08		
@ DXRMS	3.39655418E-01		
@ TITLE	"Zgoubi model"		

Table 3: SR statistics, from Monte Carlo tracking, 10,000 particles, one pass around the RCS

- 400 MeV:

```
 * Monte Carlo S.R. statistics, from beginning of structure,
10000 particles,  a total of      1009740000 integration steps
  Average energy loss per particle per pass :       9.7434685E-03 keV.       Relative to initial energy :  2.4358671E-08
  Critical energy of photons (average) :           4.4571211E-04 keV
  Average energy of radiated photon :              1.8806917E-04 keV
  rms energy of radiated photons :                 3.4444217E-04 keV
  Smallest, BIGEST photon :                        7.2548E-18      9.9407E+03     keV
  Number of photons radiated - Total :                         518079.0
                             - per particle per pass :         51.80790
                             - per particle, per step :       5.1308159E-04
```

- 1 GeV:

```
 * Monte Carlo S.R. statistics, from beginning of structure,
10000 particles,  a total of      1009740000 integration steps :
  Average energy loss per particle per pass :       0.3791386     keV.       Relative to initial energy :  3.7913857E-07
  Critical energy of photons (average) :           6.9642578E-03 keV
  Average energy of radiated photon :              2.9287155E-03 keV
  rms energy of radiated photons :                 5.3711990E-03 keV
  Smallest, BIGEST photon :                        5.8038E-17      9.9746E+03     keV
  Number of photons radiated - Total :                         1294556.
                             - per particle per pass :         129.4556
                             - per particle, per step :       1.2820687E-03
```

- 5 GeV:

```
 * Monte Carlo S.R. statistics, from beginning of structure,
10000 particles,  a total of      1009740000 integration steps :
  Average energy loss per particle per pass :        236.7804     keV.       Relative to initial energy :  4.7356087E-05
  Critical energy of photons (average) :           0.8706135     keV
  Average energy of radiated photon :              0.3656743     keV
  rms energy of radiated photons :                 0.6709560     keV
  Smallest, BIGEST photon :                        0.0000E+00      9.9915E+03     keV
  Number of photons radiated - Total :                         6475173.
                             - per particle per pass :         647.5173
                             - per particle, per step :       6.4127132E-03
```

- 10 GeV:

```
 * Monte Carlo S.R. statistics, from beginning of structure,
10000 particles,  a total of      1009740000 integration steps :
  Average energy loss per particle per pass :        3790.037     keV.       Relative to initial energy :  3.7900375E-04
  Critical energy of photons (average) :            6.969458     keV
  Average energy of radiated photon :               2.923548     keV
  rms energy of radiated photons :                  5.376011     keV
  Smallest, BIGEST photon :                        0.0000E+00      9.9915E+03     keV
  Number of photons radiated - Total :                        1.2963827E+07
                             - per particle per pass :         1296.383
                             - per particle, per step :       1.2838777E-02
```

- 18 GeV:

```
 * Monte Carlo S.R. statistics, from beginning of structure,
10000 particles,  a total of      1009740000 integration steps
  Average energy loss per particle per pass :        39725.17     keV.       Relative to initial energy :  2.2069537E-03
  Critical energy of photons (average) :            40.79130     keV
  Average energy of radiated photon :               16.93466     keV
  rms energy of radiated photons :                  31.27895     keV
  Smallest, BIGEST photon :                        0.0000E+00      9.9915E+03     keV
  Number of photons radiated - Total :                        2.3457908E+07
                             - per particle per pass :         2345.791
                             - per particle, per step :       2.3231632E-02
```

A summary of SR statistics data

Table 4 summarizes some of the statistics outcome detailed in page 5, as resulting from Monte Carlo SR simulation. Theoretical data are included for comparison.

Table 4: Summary of SR statistic data, from Monte Carlo tracking, 10,000 particles, one pass around the RCS. Curvature radius in tracking trials is $\rho = 235\,\mathrm{m}$ (Tab 1). Theoretical values are given for comparison.

Energy (E_s)	(GeV)	0.4	1	5	10	18
SR loss (U_s)	(MeV/turn)	9.74×10^{-6}	3.79×10^{-4}	0.2368	3.790	39.725
theory$^{(a)}$		9.63×10^{-6}	3.74×10^{-4}	0.2352	3.764	39.517
damping time (E_s/U_s)	(turn)	41×10^6	2.64×10^6	21116	2642	453
rms energy loss	(keV)	3.44×10^{-4}	5.37×10^{-3}	0.671	5.376	31.28
theory$^{(b)}$		3.38×10^{-4}	5.28×10^{-3}	0.660	5.278	30.78

(a) *Theor.* $U_s = C_\gamma E_s^4/\rho = 88.46276 \times E^4_{s[GeV]}/\rho_{[m]}$.
(b) *Theor. rms energy loss*$= \frac{\sqrt{211}}{15\sqrt{3}}\epsilon_c$, ϵ_c =*energy of critical photon* $= \frac{3}{2}\frac{\hbar\gamma^3 c}{\rho e}$.

Equilibrium quantities at 18 GeV

Values of equilibrium quantities in the "theory" columns, Table below, are derived from SR integrals. Values in the "tracking" column are from Monte Carlo SR, 2,000 particles tracked over 2700 turns (about 6 damping times). ESR data are included for comparison.

The difference in the theoretical horizontal equilibrium emittances, between ESR and RCS, results from the difference in I_5/I_2.

		ESR	RCS	
		theory	theory	tracking
		SR integrals		
I1		1.82434	1.82434	
I2		0.02489	0.026737	
I3		1.0150e-4	1.137743e-4	
I4		≈ 0	3.3e-5	
I5		4.23E-06	7.38e-6	
		Equilibrium quantities		
τ_{ϵ_x}	ms	6.27	5.842	5.8
τ_{ϵ_y}	ms	6.27	5.834	5.8
τ_l	ms	3.133	2.915	3.0
$\gamma\epsilon_x/\pi$	mm	2.85	4.61	4.2
ϵ_x/π	nm	81	131	120
ϵ_l/π	μeV.s		$\approx$400	363

3 Simulation Hypotheses: RF, Phase Space, Spin

RF Ramp

• All the RF is located at RFCA1 (s=1204 m), rather than split over the 4 RFCA stations. It has been checked that this makes no difference on beam and spin dynamics over the acceleration cycle. It makes no difference either, to locate the RF at an end of the ring sequence instead.

Voltage and phase ramps are pre-calculated (Fig. 3). During tracking they are read from a dedicated log file.

This RF ramp is undergoing optimization, essentially in order to reduce losses (which are small anyway, here), results derived here are preliminary, however they produce the bulk of the behavior.

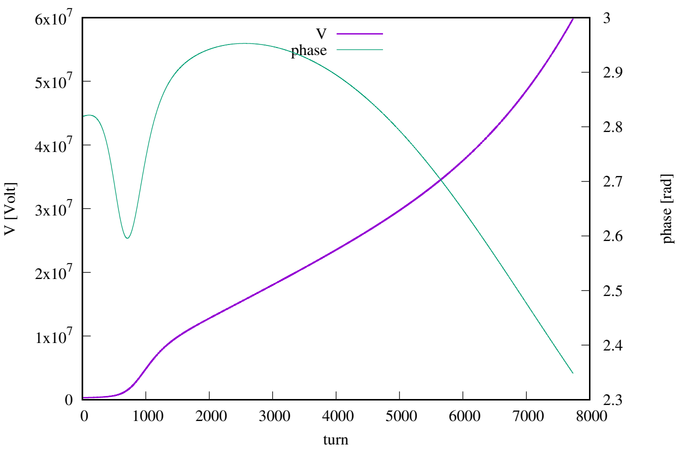


Figure 3: RF voltage and synchronous phase ramps.

"CAVITE" input data: the RF is concatenated at station RFCA1 (located at s=1240 m).
RF program is read from a pre-computed ancillary file.

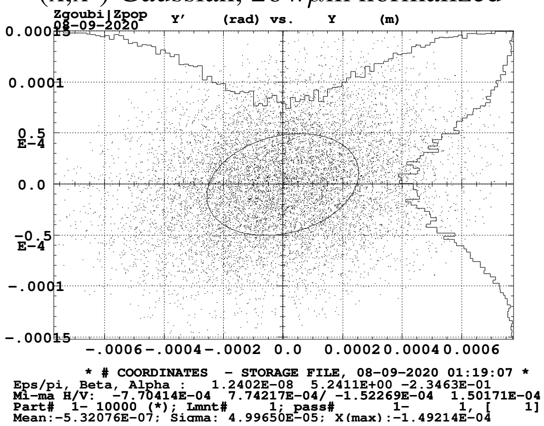
```
'CAVITE' accelCav_1
11   EICRCS_File        ! Cavity option 11(allows double-frequency, SR compensation).
3841.351268  7560       ! Circumference; harmonic number.
7.5E6 3.08 0. 1204.80   ! Voltage and RF phase not used, due to above EICRCS_File,
                        ! indicating that they are read from zgoubi.RFLaw.In.
```

• For the record: head and tail of the ancillary RF program file used in the present simulations:

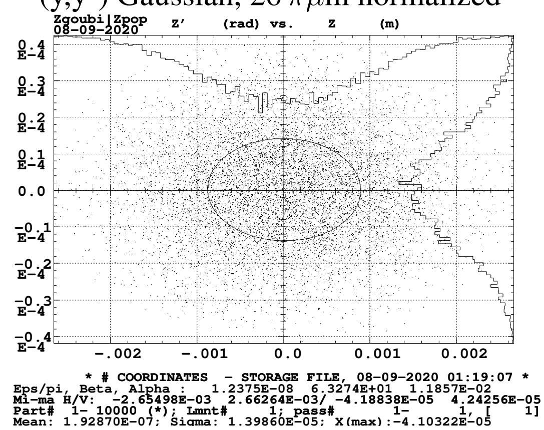
```
Turn   Energy (GeV)   Bunch Length (s)   Voltage (V)   Phase (rad)   1/Qs   time (s)   Qs
1   1.0001035203394717e9   1.8028926548975248e-10   327539.3324794361   0.3227807532258099   75.66945204877118   0.000012813368603822 58   0.013215372556886902
2   1.0002070971351715e9   1.802620090722254e-10   327667.9795979095   0.32274077460969236   75.65800346777236   0.000025626737207645 16   0.013217372309143272
3   1.0003107310649942e9   1.802346291266711e-10   327797.1788409724   0.3227009919749387   75.64650304121196   0.000038440105811467 74   0.013219381726809016
4   1.0004144228140453e9   1.802071251560068e-10   327926.93333388347   0.32266140789 70054   75.63495056042323   0.000051253474415290 32   0.013221400854901337
5   1.0005181730747123e9   1.8017949666175083e-10   328057.2462205613   0.3226220249736046   75.6233458161519   0.0000640668430191129   0.013223429738629952
..........................................................
7733   1.808993e10   6.600000000000004e-11   5.974381116086878e7   0.7923880890938422   27.685530783648293   0.09908577941336001   0.03611995044684579
7734   1.809214e10   6.600000000000004e-11   5.976144556333635e7   0.7925586218453715   27.685530772106933   0.09909859278196384   0.036119950461903236
7735   1.809435e10   6.600000000000004e-11   5.977908684868751 5e7   0.7927291388101053   27.68553076056979   0.09911140615056765   0.036119950476955175
7736   1.809656e10   6.600000000000004e-11   5.979673501923519 4e7   0.7928996399687998   27.685530749036875   0.09912421951917148   0.036119950492001 60
7737   1.809877e10   6.600000000000004e-11   5.981439007729240 5e7   0.7930701253022269   27.6855307375082   0.09913703288777531   0.0361199505070425
7738   1.810098e10   6.600000000000004e-11   5.983205202517209e7   0.7932405947911686   27.685530725983725   0.09914984625637913   0.036119950522077914
```

Initial Phase Space, 1 GeV

(x,x') Gaussian, 26 $\pi\mu$m normalized



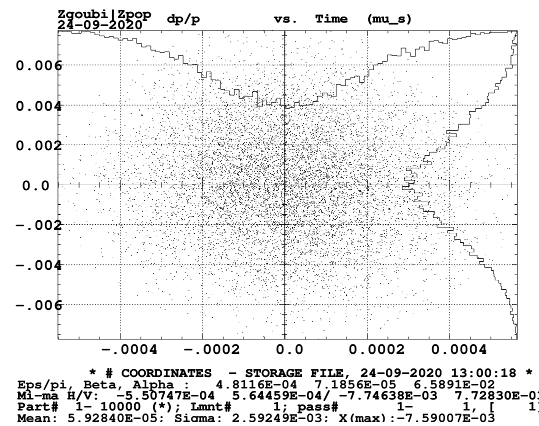
(y,y') Gaussian, 26 $\pi\mu$m normalized



• Initial Gaussian 6D phase space, input data:

```
'MCOBJET'
3.3366646935164153E+03    ! 1GeV, beta*gamma   1957.551806
3
10000                              ! 10,000 particles.
2 2 2 2 2 2                        ! Gaussian densities.
0. 0. 0. 0. 0. 1.                  ! Reference trajectory.
-0.232183    5.276444  1.3e-8  3.  ! H beam parameters here. epsilon/pi=1.3e-8.
 0.018529   64.157433  1.3e-8  3.  ! V beam parameters here. epsilon/pi=1.3e-8.
0.  21.6  150e-6  3.               ! long. beam parameters here.
123456 234567 345678
```

Longitudinal (time-dp/p)
rms $\sigma_{\delta E/E} = 2.592 \times 10^{-3}$,
rms $\sigma_{\delta t} = 185.941$ ps



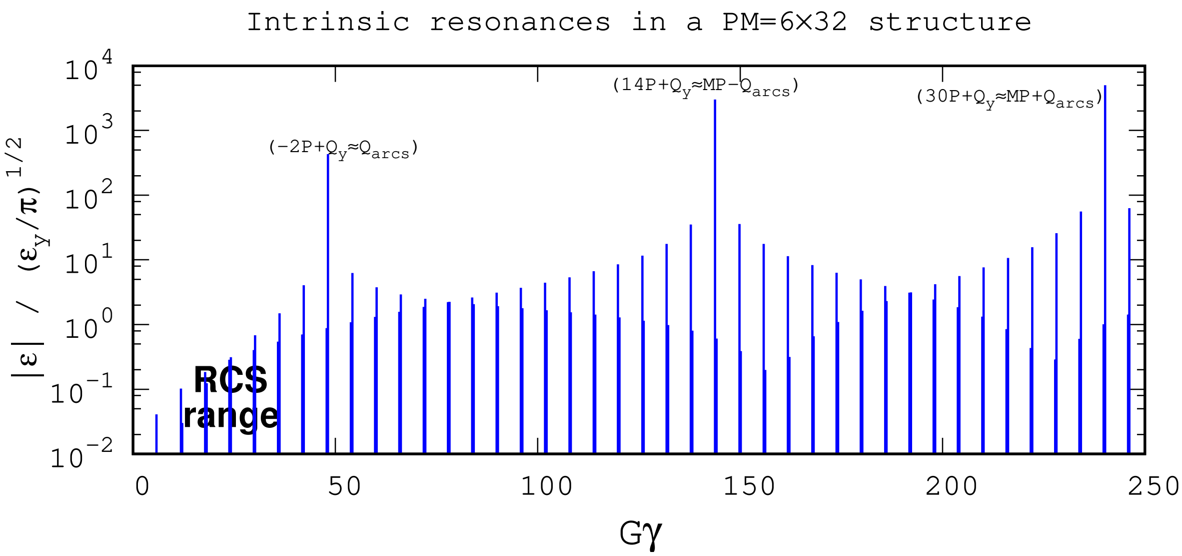
◇ An excerpt from the output ".res" data file, corresponding to the graphs above, details 1 GeV initial bunch characteristics:

```
---------------  Concentration ellipses :
   surface/pi              alpha        beta         <X>            <XP>           numb. of prtcls   ratio      space      pass#
                                                                                   in ellips,  out
   1.2401E-08 [m.rad]     -2.3463E-01   5.2415E+00  -1.419431E-06  -5.320063E-07    10000     7835   0.7835      (Y,T)         2
   1.2374E-08 [m.rad]      1.1856E-02   6.3279E+01   8.925807E-06   1.928701E-07    10000     7874   0.7874      (Z,P)         2
   4.8116E-04 [mu_s.MeV]   6.5891E-02   7.1856E-05   2.182283E-06   9.998553E+02    10000     7811   0.7811      (t,K)         2

(Y,T)  space (units : m, rad   ) :
      sigma_Y = sqrt(surface/pi * beta) =    2.549495E-04
      sigma_T = sqrt(surface/pi * (1+alpha^2)/beta) =    4.996104E-05

(Z,P)  space (units : m, rad   ) :
      sigma_Z = sqrt(surface/pi * beta) =    8.848836E-04
      sigma_P = sqrt(surface/pi * (1+alpha^2)/beta) =    1.398487E-05

(t,K)  space (units : mu_s, MeV) :
      sigma_t = sqrt(surface/pi * beta) =    1.859411E-04
      sigma_K = sqrt(surface/pi * (1+alpha^2)/beta) =    2.593287E+00


  Beam  sigma  matrix  and  determinants :

   6.499922E-08   2.909594E-09  -2.187532E-09   4.342228E-12
   2.909594E-09   2.496105E-09   5.959756E-10   3.056553E-12
  -2.187532E-09   5.959756E-10   7.830190E-07  -1.467025E-10
   4.342228E-12   3.056553E-12  -1.467025E-10   1.955765E-10

      sqrt(det_Y), sqrt(det_Z) :     1.240077E-08    1.237411E-08    (Note :  sqrt(determinant) = ellipse surface / pi)
      normalized (*beta*gamma) :     2.427516E-05    2.422296E-05
```

Spin

All spins are launched vertical in these simulations. The vertical orbit is zero (no orbit defect included) (Fig. 1), so integer resonances are ineffective.

Several intrinsic resonances are crossed over an acceleration range $\mathrm{E}:\ 400\,\mathrm{MeV} \to 18\,\mathrm{GeV}$ ($\mathrm{G}\gamma:\ 0.9 \to 40.8$), with typical strength landscape as in the figure below: due to the lattice symmetries, all intrinsic resonances in the RCS energy range have negligible strength (theoretically, zero), and imperfection resonance strengths are minimized [1].



4 Acceleration From 1 to 18 GeV in 7738 Turns

These results are from a 1,000 particle tracking. Given this number, statistics is not that accurate, however it yields the bulk of the behavior, further refinements will be dealt with on NERSC computers.

The transmission here is 929/1000, these 71 particles are lost during the first 233 turns. Note that optimization of the ramp is on-going at this stage, toward getting closer to zero loss.

Figure 4 displays the evolution of various parameters along the acceleration cycle (a 30 particle sample, taken from the 1,000 tracked). The horizontal emittance grows from about turn 3000 (upper right plot, below), toward its equilibrium value, which is greater than the value attained during the ramp (Tab. 6); as a matter of fact:

- the horizontal emittance damping time is $\tau_x \approx 450$ turns (Tab. 4),
- betatron damping time constant is n [turns] such that emittance(n)=emittance(0)/e, thus $\mathrm{n} \approx (1-1/\mathrm{e})\times \mathrm{E}/\Delta\mathrm{E}$; taking $\mathrm{E} = 18\times 10^9$ eV, $\Delta E = 18\times 10^9/8000 = 2.25\times 10^6$ eV/turn, that gives in the 18 GeV region $n = (1-1/e)*8000 \approx 5000$ turns
- 450 turns versus 5000, so SR dominates, the acceleration rate ΔE does not allow betatron damping to compensate SR growth.

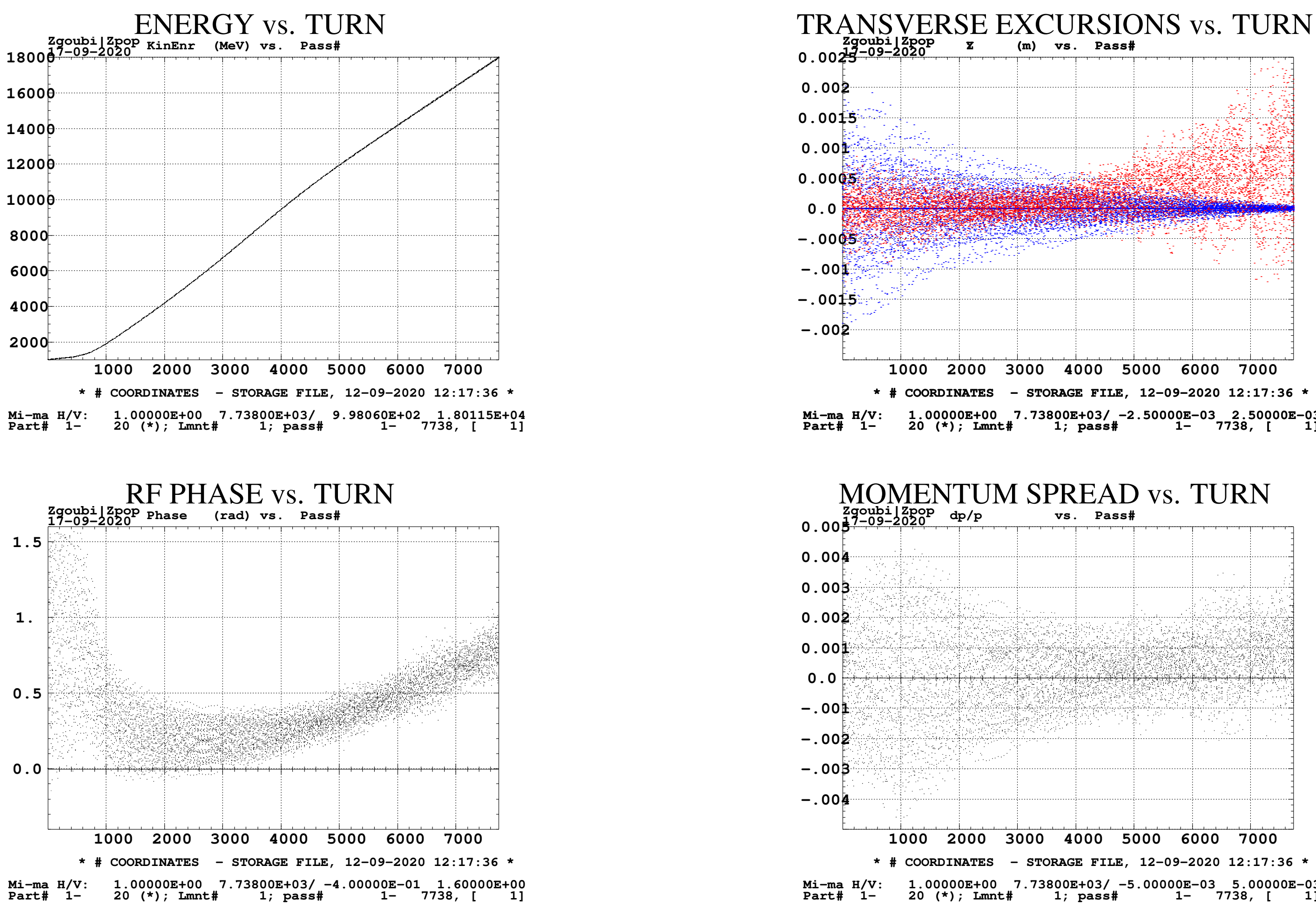


Figure 4: Dynamics during the ramp, 1,000 particle bunch, 1 to 18 GeV. Phase-space plots at the end the of acceleration cycle are displayed in p. 11.

5 Final Bunch Densities; Spin

Table 5 summarizes SR statistics data over the acceleration ramp. Final phase spaces are given in Fig. 5.

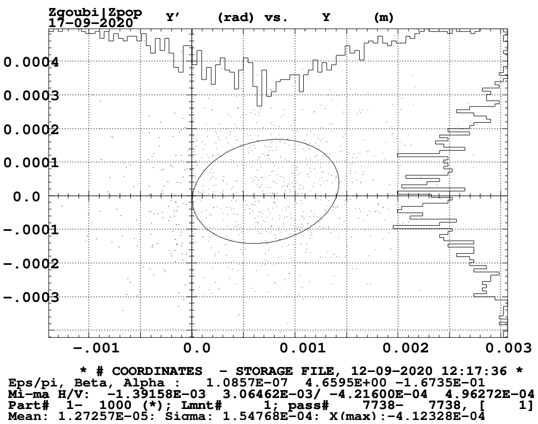
Table 5: SR statistics over the acceleration ramp, from 1 to 18 GeV. Monte Carlo tracking, 1,000 particles, 7738 turns

```
  * Monte Carlo S.R. statistics, from beginning of structure, on            1000 particles,  a total of      -196351350 integration
steps :
     Average energy loss per particle per pass :        7018.248      keV.       Relative to initial energy :  7.0160943E-03
     Average energy of radiated photon :                6.992134      keV
     rms energy of radiated photons :                   16.78377      keV
     Smallest, BIGEST photon :                         0.0000E+00      9.9831E+03      keV
     Number of photons radiated - Total :                         7.7679044E+09
                               - per particle per pass :           1003.735
```

TRANSVERSE HORIZONTAL

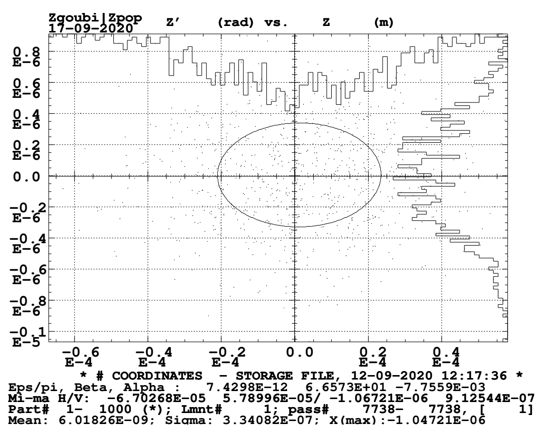
rms $\epsilon_x/\pi = 108.6\,\mathrm{nm}$

$\beta\gamma\epsilon_x/\pi = 3.83\,\mathrm{mm}$



TRANSVERSE VERTICAL

$\epsilon_y/\pi = 7.4\times10^{-3}\,\mathrm{nm}$



LONGITUDINAL (phase-dp/p)

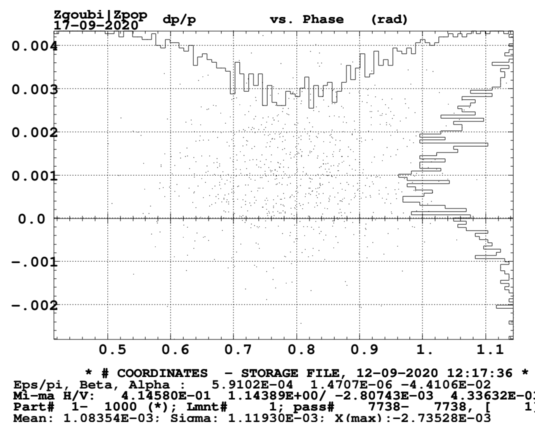
$<\delta p/p>= 1.08354\times10^{-3}$,

$\sigma_{\delta p/p} = 1.1193\times10^{-3}$

$<\phi>= 0.7984802\,\mathrm{rad}$,

$\sigma_{\delta\phi} = 0.1098435\,\mathrm{rad} \xrightarrow{/h\omega_{\mathrm{rev}}} \sigma_{\delta t} = 29.61\,\mathrm{ps}$

$\Delta\phi = 0.72930858 \longrightarrow \Delta\mathrm{t} = 196.6\,\mathrm{ps}$



Note: RF parameters above stem from CAVITE data (page 7), namely,

$\mathrm{f_{rev}} = \mathrm{c}/3841.35 = 78.1\,\mathrm{kHz},\quad \mathrm{h} = 7560$

$<E>= 17.9076\,\mathrm{GeV}$, $\sigma_{\mathrm{E}} = 20.0661\,\mathrm{MeV}$

Figure 5: Final phase spaces, after acceleration from 1 to 18 GeV.

Recap: SR Parameters at 18 GeV, on the Ramp

Equilibrium data are added, for comparison.

Table 6: Equilibrium emittances.

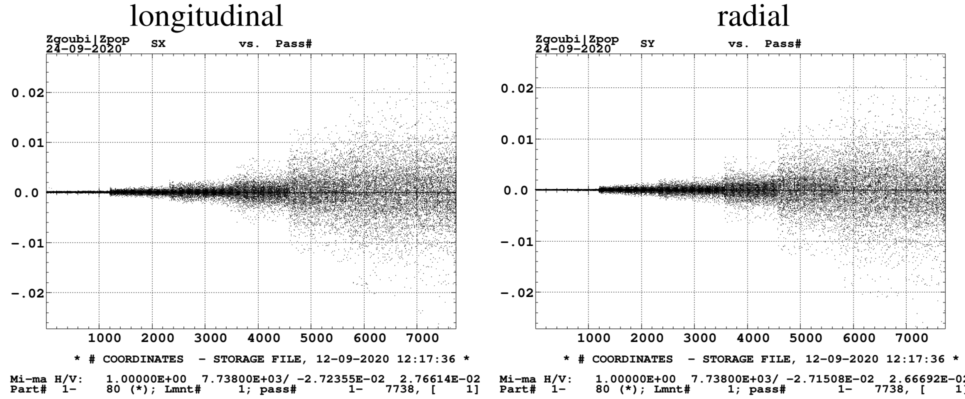
		– At equilibrium –			On the ramp
		ESR	RCS		RCS
		theory	theory	tracking	tracking
ϵ_y/π	pm			0	7
$\gamma\epsilon_x/\pi$	mm	2.85	4.61	4.2	3.83
ϵ_x/π	nm	81	131	120	109
ϵ_l/π	μeV.s		≈400	363	591

Spin

Resonance strengths are weak enough (page 9) that, in this perfectly aligned ring simulations, the rms spin tilt from vertical over the acceleration range is less than 10 mrad, figures below.

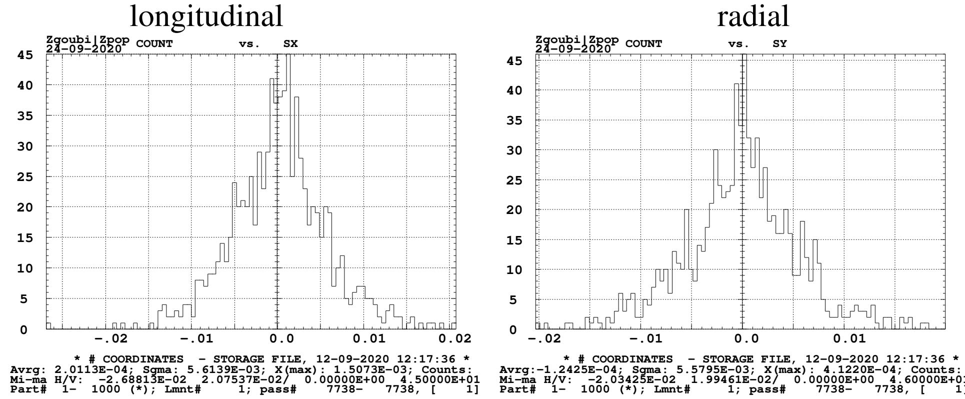
Evolution of horizontal spin components over 7738 turns (50 particle sample):

longitudinal radial



Horizontal spin component densities at 18 GeV, turn 7738, 1,000 particles:

longitudinal radial



References

[1] Electron-Ion Conceptual Design Report.
https://brookhavenlab.sharepoint.com/sites/eRHIC/cdr2020/Summary%20%20Status/Forms/AllItems.aspx?CT=1600103406774&OR=OWA%2DNT&CID=ec55f32b%2D0f57%2Dc5bb%2Dd8ab%2D2fa2b8df89f8&id=%2Fsites%2FeRHIC%2Fcdr2020%2FSummary%20%20Status%2FEIC%5FCDR%5FDraft%2Epdf&parent=%2Fsites%2FeRHIC%2Fcdr2020%2FSummary%20%20Status

[2] F. Méot, et als.: Polarized e-bunch acceleration at Cornell RCS. Tentative tracking simulations. eRHIC Note 57, BNL C-AD, Sept. 2017.
https://technotes.bnl.gov/PDF?publicationId=42654