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Transverse Beam Tails and Beam Lifetime in the EIC Electron Storage Ring

C. Montag

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Christoph Montag

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Abstract

For most storage ring design purposes it is sufficient to assume a Gaussian distribution of the electrons in a bunch. However, a more detailed knowledge of the population in the transverse tails beyond a few sigma is necessary to predict the beam lifetime and the synchrotron radiation load in the interaction region due to beam-gas scattering and the beam-beam interaction. This report presents simulations to determine the required vacuum level as well as to serve as input data for detailed synchrotron radiation simulations.

1 Introduction

For most design purposes, assuming a perfectly Gaussian distribution of the electrons within the bunch is sufficiently accurate. However, processes such as the beam-beam interaction or scattering off residual gas molecules can result in an enhancement of the electron population at large amplitudes. This enhancement occurs predominantly in the vertical plane due to the flatness of the electron beam, $\sigma_y \ll \sigma_x$. As a consequence of the modified distribution, vacuum chamber apertures need to be designed sufficiently large to accommodate these enhanced beam tails in order to ensure sufficient beam lifetime. Furthermore, the enhanced number of electrons in the transverse tails leads to an increase in hard synchrotron radiation photons generated by electrons at large amplitudes in the low-β quadrupoles which has to be taken into account when designing the synchrotron radiation masking scheme. This note describes simulation results for transverse electron tail distributions caused by beam-beam and beam-gas scattering events.

2 Beam-Beam Tails

The transverse electron distribution has been studied using a simulation code based on the method developed by D. Shatilov [1]. As the parameter list shown in Table 1 indicates, the vertical β-function for the EIC electrons approximately equals the proton bunch length. This results in a "smear" of the beam-beam kick experienced by the electrons over a significant betatron phase advance as they traverse the long proton bunch, leading to a net reduction of the effective beam-beam kick. It is therefore worthwhile studying the associated effect of collisions with long proton bunches on the transverse electron tails.

For this purpose, a number of tracking runs have been performed with the proton bunch divided into different numbers of slices, namely 1, 3, 9, and 19 slices. While the case with the proton bunch represented by a single slice corresponds to zero proton bunch length, the cases with multiple slices correspond to a non-zero bunch length. As Figure 1 shows, collisions with a zero-length proton bunch result in a significant build-up of non-Gaussian tails in the vertical plane. When the proton bunch is represented by 3 or more slices, these vertical tails essentially disappear, and the transverse distribution remains approximately Gaussian. Increasing the number of slices to 9 or 19 yields the same result as for 3 slices, indicating rapid convergence as a function of number of slices. From these simulations we can conclude that the beam-beam interaction will only have a minor effect on transverse tails.

Table 1: Simulation parameters at 10 GeV

E [GeV]	10
τ_{parallel} [turns]	2500
σ_z [m]	0.01
α_x	0.0
β_x [m]	0.43
ϵ_x [m]	20×10^{-9}
α_y	0
β_y [m]	0.05
ϵ_y [m]	1.2×10^{-9}
Q_x	0.09
Q_y	0.07
Q_z	0.0537
ξ_x	0.073
σ_s	0.06
$\beta_{x,p}$ [m]	0.90
$\beta_{y,p}$ [m]	0.04
$\epsilon_{x,p}$ [m]	9.6×10^{-9}
$\epsilon_{y,p}$ [m]	1.5×10^{-9}
λ_{crab} [m]	1.52

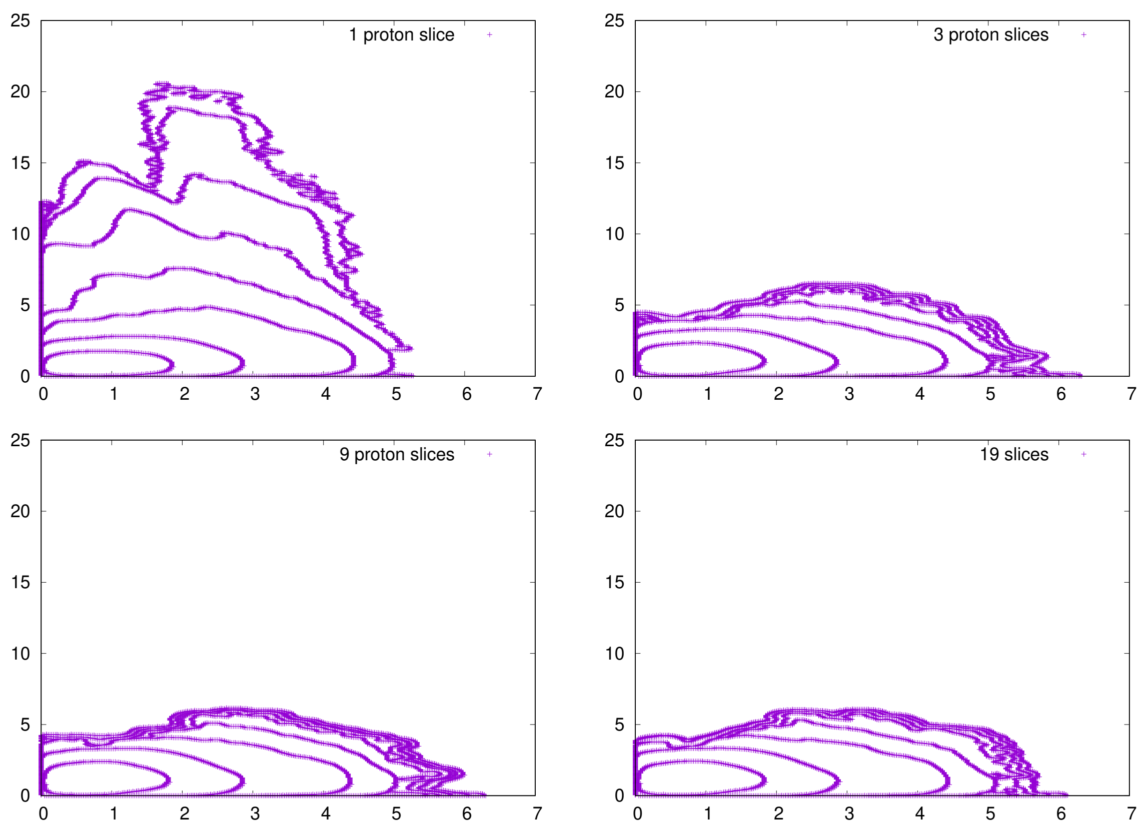

Figure 1: x - y distribution for different number of proton bunch slices.

Table 2: Simulation parameters corresponding to the tail distributions shown in Figure 2

$\langle\beta_{x,y}\rangle$ [m]	15
ϵ_x [nm]	20
ϵ_y [nm]	1.2
$\tau_\perp$ [turns]	5000
E [GeV]	10
Z	1 (90%), 7 (10%)
P [ntorr]	5

3 Beam-Gas Tails

Elastic scattering of beam electrons off residual gas molecules is another leading mechanism that can potentially result in substantial over-population of the transverse tails. The simulation method is modeled after the one described in Ref. [2], with the entire storage ring represented by a linear one-turn matrix. In all these simulation studies, we assume a gas composition of 90% H_2, 10% N_2. The β-functions at the beam-gas scattering location are set to their average value around the actual ESR. Figure 2 shows the equilibrium distribution in the horizontal and vertical planes, obtained using the simulation parameters listed in Table 3.

4 Beam Lifetime vs. Pressure

The lifetime τ_{beam} of a Gaussian electron beam can be calculated as [3]

$$\tau_{\text{beam}} = \frac{\tau_{\text{damp}}}{N_\sigma^2} \exp\left(\frac{N_\sigma^2}{2}\right), \tag{1}$$

where τ_{damp} is the radiation damping time and N_σ denotes the aperture limitation in units of RMS beam sizes. Since this quantum lifetime depends on the fractional amount of electrons that are clipped off by the aperture restriction at N_σ, we can determine the expected lifetime of an arbitrary equilibrium distribution as a function of the available aperture A by integrating the arbitrary beam profile from the aperture restriction A to infinity, and comparing the result to the corresponding value for a Gaussian distribution. Figure 3 shows the resulting integrals

$$\int_A^\infty \rho(y)\,\mathrm{d}y \tag{2}$$

for both a Gaussian distribution and the equilibrium vertical distribution presented in Figure 2.

Simulations have been performed electrons at 5, 10, and 18 GeV, and for different residual gas pressures, assuming a rest gas composition of 90 percent hydrogen and 10 percent nitrogen. The calculated beam lifetimes for a vertical design aperture of 23σ are listed in Table 3, together with the corresponding values for an increased aperture of 35σ that could be realized using more exotic IR magnets with an elliptical aperture.

As Table 3 shows, the vacuum pressure at 10 GeV should not exceed 10 ntorr for a nominal aperture of 23σ in order to provide a beam lifetime of 2 h, which is sufficiently long compared to the polarization-driven bunch exchange rate of $0.1\,\text{min}^{-1}$ at 10 GeV.

The situations at 5 and at 18 GeV requires attention as well. While typical scattering angles are smaller than at 10 GeV, and the bunch exchange rate of $0.4\,\text{min}^{-1}$ is higher than at 10 GeV, radiation damping times are also shorter. Since the beam lifetime depends on the radiation damping time (see Eq. (1)) this situation has been simulated. For a vacuum pressure $P = 5\,\text{ntorr}$ and the same rest gar composition as for 10 GeV, a lifetime of 9 h was obtaied for a 23σ vertical aperture, which is 2.5 times longer than at 10 GeV under otherwise identical conditions.

At 5 GeV the situation is more complicated, because the radiation damping time is adjustable using the super-bends in the ESR arcs. In the simulations presented here, a transverse damping time of $\tau_{\text{damp}} = 10000$ turns was

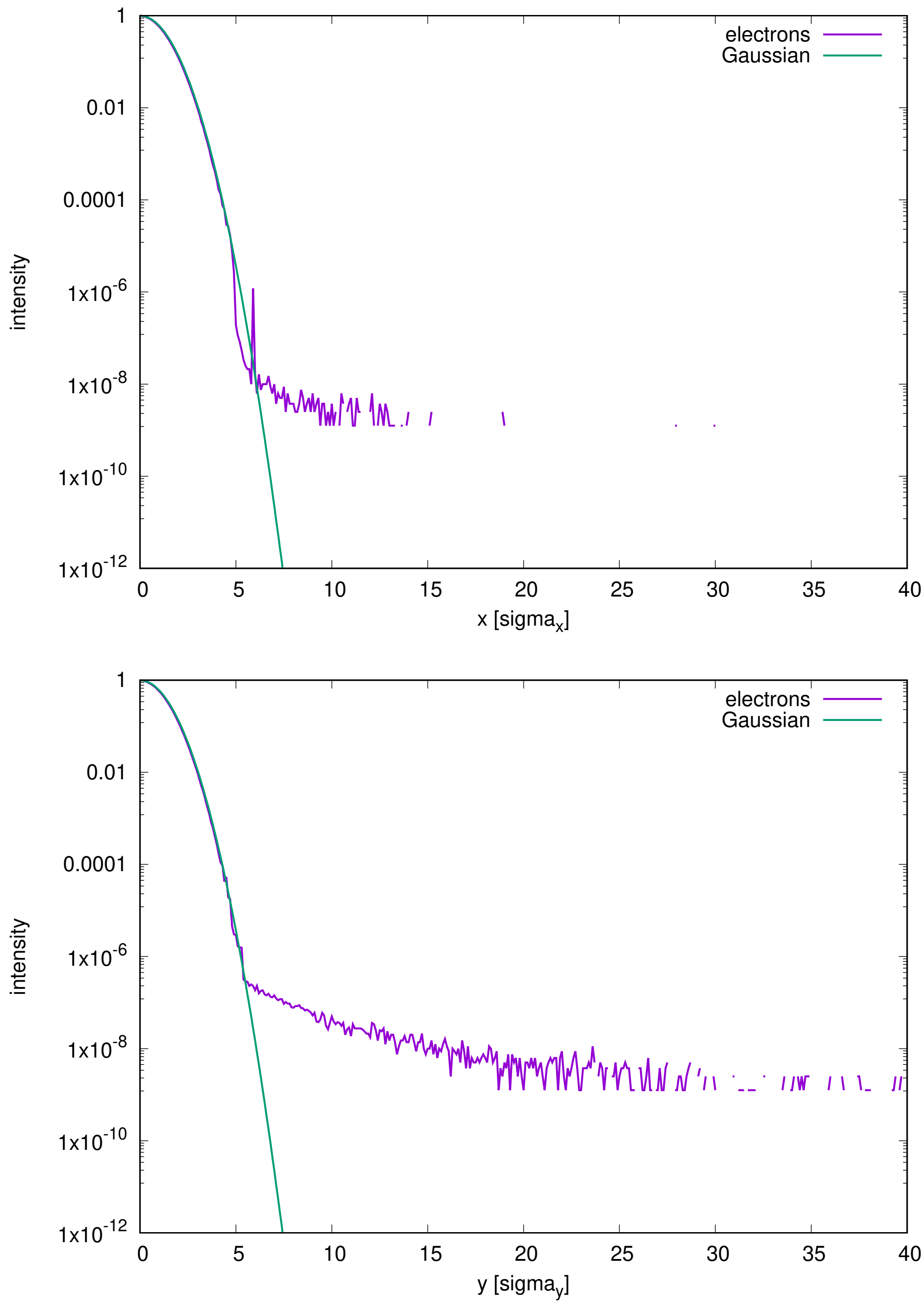

Figure 2: Horizontal (top) and vertical (bottom) electron distributions obtained in simulations, using the simulation parameters listed in Table 3.

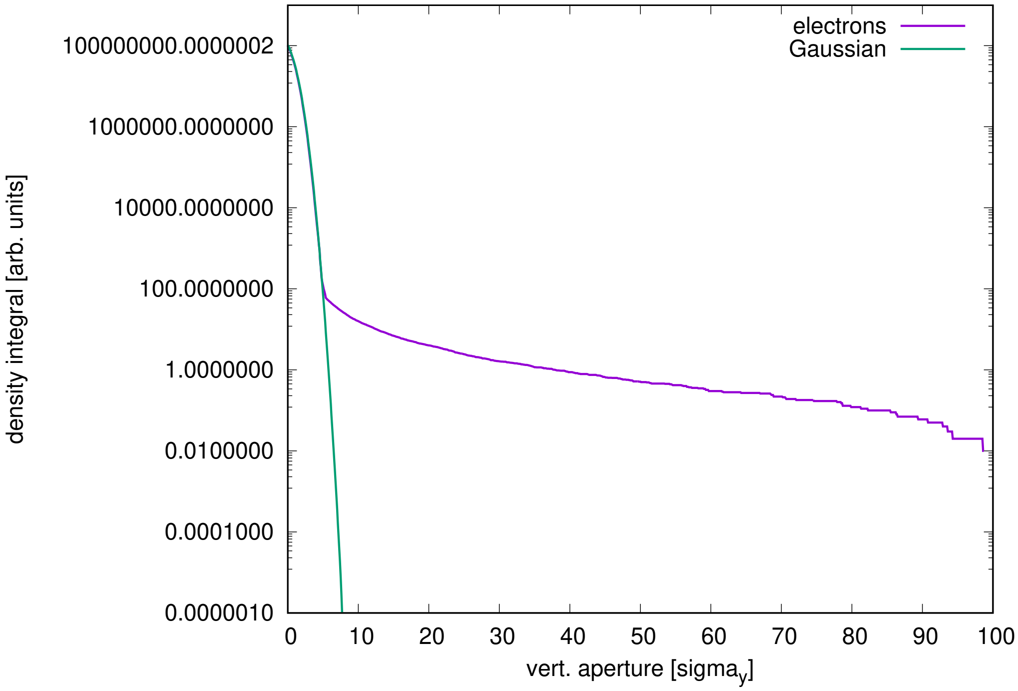

Figure 3: Integrated vertical equilibrium distribution.

Table 3: Lifetime simulation results vs. vacuum pressure, for two different vertical aperture values

energy	H_2 pressure	lifetime at 23σ	lifetime at 35σ
5 GeV	5 ntorr	1.1 h	2.7 h
	10 ntorr	0.6 h	1.6 h
10 GeV	1.25 ntorr	10.0 h	22.9 h
	2.5 ntorr	6.5 h	13.1 h
	5 ntorr	3.4 h	8.0 h
	10 ntorr	2.0 h	4.5 h
18 GeV	5.0 ntorr	9.0 h	21.3 h

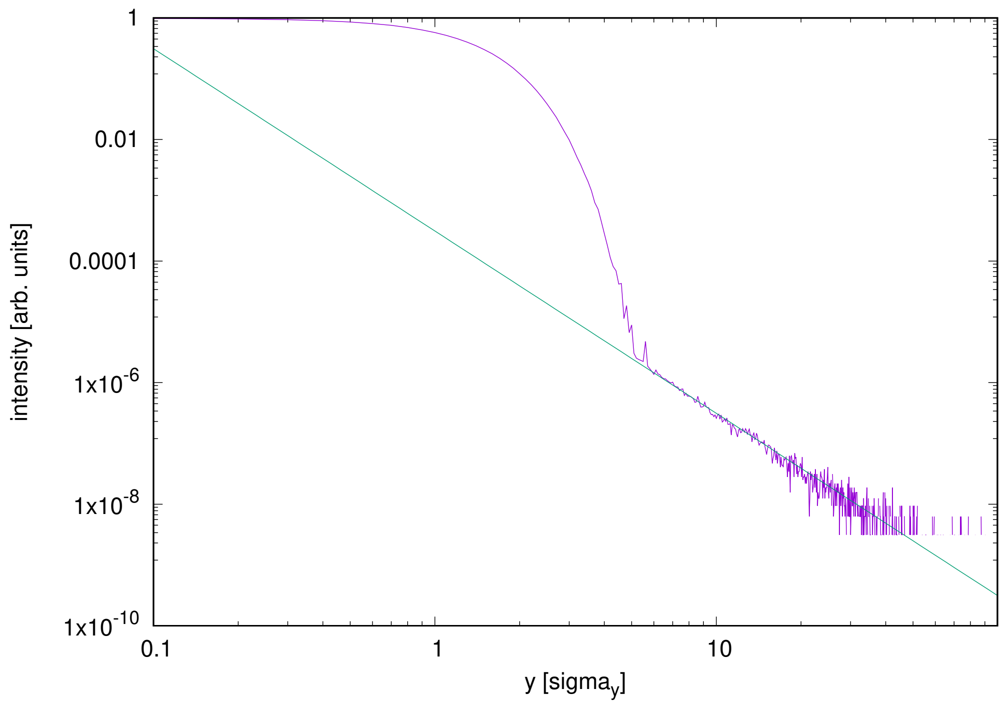

Figure 4: Log-log plot of the horizontal distribution for 5 GeV beam energy and a vacuum pressure of 5 ntorr, together with a fit to the tail distribution.

assumed. This is much faster than the natural damping time of the lattice without super-bends, but assumed to be necessary to support the large design beam-beam parameters. According to these simulations, the vacuum pressure must not exceed 5 ntorr in order to ensure sufficient electron beam lifetime at 5 GeV.

5 Fitting the Distribution

To serve as input data for synchrotron radiation simulation codes, the resulting distribution was fitted to an analytical expression. As Figure 4 shows, the non-Gaussian tail distribution is very well described as

$$\rho_{\text{tail}}(r) = K_r \cdot r^{-3}, \tag{3}$$

with $r = x$ or $r = y$. The entire distribution therefore consists of a Gaussian core and a non-Gaussian tail,

$$\begin{aligned} \rho_{\text{total}}(r) &= \rho_{\text{core}}(r) + \rho_{\text{tail}}(r) & (4)\\ &= \exp\left(-\frac{r^2}{2\sigma_r^2}\right) + K_r \cdot r^{-3}. & (5) \end{aligned}$$

Note that the total number of electrons in the bunch is irrelevant for our purposes, and for simplicity the normalization of the Gaussian distribution is defined such that $\rho_{\text{core}}(0) = 1$.

Table 4 lists the fit parameters K_x and K_y for the tail distributions for different beam energies and vacuum pressures.

6 Conclusion

Based on the simulation results presented here, the average vacuum pressure in the ESR must not exceed 5 ntorr, assuming a gas composition of 90% H_2, 10% N_2, in order to ensure sufficient beam lifetime at all energies from

Table 4: Fit parameters for different beam energies and vacuum pressures

E [GeV]	P [ntorr]	K_x [10^{-7}]	K_y [10^{-7}]
5	5	190	3125
5	10	380	6250
10	1.25	6.25	110
10	2.5	12.5	220
10	5	25	450
10	10	50	900
18	10	0	25

Table 5: Simulation parameters used for benchmarking against KEKB experimental data

$\beta_{x,y}$ [m]	10
ϵ_x [nm]	28
ϵ_y [nm]	0.36
damping time [turns]	4600
E [GeV]	8
Z	1 (90%), 7 (10%)
pressure [ntorr]	5
aperture [σ_y]	30 to 50
τ_{measured} [h]	3
$\tau_{\text{simulated}}$ [h]	1.6 to 5.2

5 to 18 GeV. Since beam-gas scattering has a larger effect on the tails the larger the β-function at the scattering location, special care should be taken in the low-β IR magnets to ensure this.

7 Acknowledgments

I would like to thank Derong Xu for his help with Ref. [2], and Charles Hetzel for his input regarding the vacuum pressure and rest gas composition. I am also indebted to Katsunobu Oide for providing KEKB data.

References

[1] D. Shatilov, INP 92-79, Novosibirsk, 1992

[2] Lu-Xin Yu, et al., Simulation of beam-gas Coulomb scattering in HALS, arXiv:1404.2661 [physics.acc-ph]

[3] M. Sands, "The Physics of Electron Storage Rings. An Introduction", SLAC-121, UC-28

[4] K. Oide, private communication

A Benchmarking against KEKB Data

To check the validity of the beam-gas scattering results, the simulation code was benchmarked against the actual KEKB high energy ring, with parameters such as vacuum pressure, lifetimes and collimator apertures provided by K. Oide [4]. The simulation parameters and results as well as measured lifetimes are listed in Table 5. Simulated lifetimes agree within a factor of 2 with measured data.