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TRANSVERSE ELECTRON BEAM TAILS AND BEAM LIFETIME IN THE EIC ELECTRON STORAGE RING *

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Abstract

While for most storage ring design activities it is sufficient to assume a Gaussian distribution of the beam particles, a more detailed prediction of the population in the transvese tails is necessary to predict the beam lifetime in a given aperture. Dominant processes that result in non-Gaussian distributions are the beam-beam interaction in a collider as well as beam-gas scattering. Simulations to determine the required apertures and vacuum levels in the EIC electron storage ring will be presented.

INTRODUCTION

When designing an electron storage ring and determining key parameters such as the minimum aperture or the vacuum pressure limit, an accurate model of the transverse electron distribution is often necessary because the beam-beam interaction as well as beam-gas scattering events result in an over-population of the transverse tails. This over-population occurs predominantly in the vertical plane due to the small vertical emittance, and it can severely limit the beam lifetime and detector background conditions if not taken into account during the machine design phase. In the following sections we describe simulation results for both beam-beam and beam-gas generated tails, determine the required vacuum pressure level for sufficient beam lifetime, and provide a simple fit to the transverse tail distribution to serve as input in simulation codes such as GEANT to study the detector background.

BEAM-BEAM TAILS

Non-Gaussian transverse tail distributions generated by the beam-beam interaction have been simulated using the method developed by D. Shatilov [1]. The vertical electron β-function at the interaction point of the EIC [2] approximately equals the proton bunch length, as shown in Table 1. As a result, the beam-beam kick experienced by the electrons is smeared out over a substantial amount of betatron phase advance, which leads 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.

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. Collisions with a zero-length proton bunch result in a significant build-up of non-Gaussian tails in the vertical plane, as shown in Figure 1. When the proton bunch is represented by 3 or more slices, these vertical tails essentially disappear, and the transverse distribution remains approximately Gaussian. This behavior converges rapidly with the number of slices; in fact, no significant difference is observed between cases with 3, 9, or 19 slices. Based on these simulations we conclude that the beam-beam interaction will only have a minor effect on transverse tails in the EIC elecron storage ring.

Table 1: Simulation Parameters at 10 GeV

Parameter	Value
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

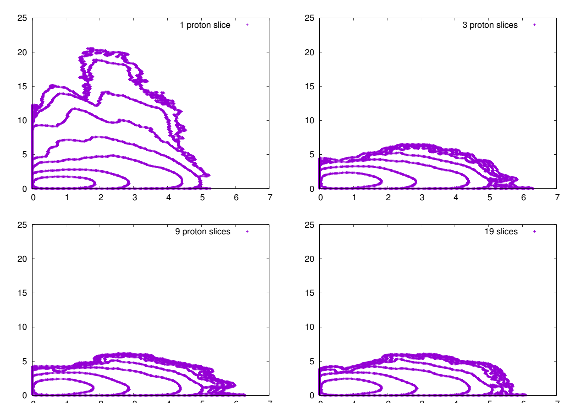

Figure 1: x - y distribution for different number of proton bunch slices.

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BEAM-GAS TAILS

A second leading mechanism that can potentially result in substantial over-population of the transverse tails is th elastic scatering of beam electrons off residual gas molecules. The simulation method used here is modeled after the one described in Ref. [3], 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 2.

Table 2: Simulation Parameters Corresponding to the Tail Distributions shown in Figure 2

Parameter	Value
$\langle \beta_{x,y} \rangle$ [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

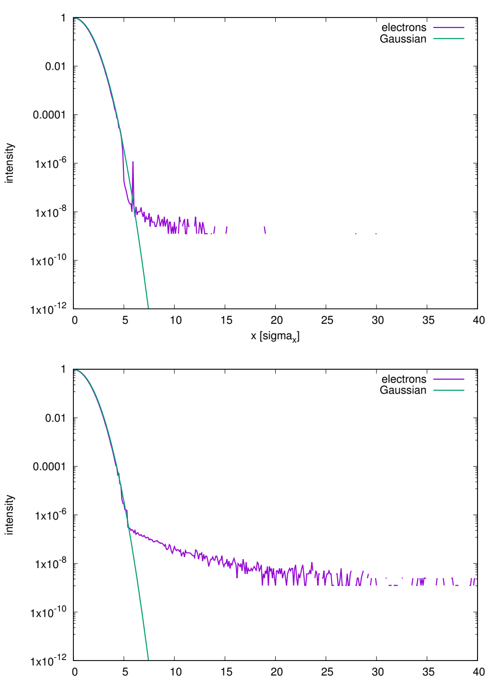

Figure 2: Horizontal (top) and vertical (bottom) electron distributions obtained in simulations, using the simulation parameters listed in Table 2.

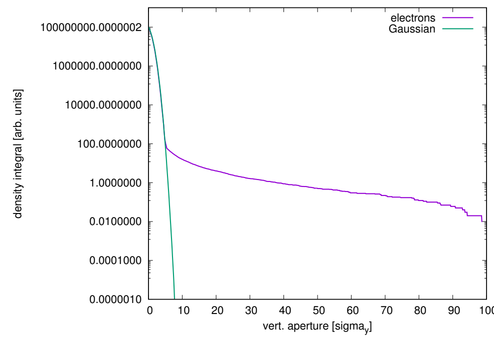

Figure 3: Integrated vertical equilibrium distribution.

BEAM LIFETIME VS. PRESSURE

The lifetime τ_{beam} of a Gaussian electron beam can be calculated as [4]

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

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. Simulation studies have been performed for three different electron beam energies, namely 5, 10, and 18 GeV. The residual gas pressure has been scanned in coarse steps to determine the vacuum levels required to achieve sufficient beam lifetimes for a minimum vertical aperture of 23σ. To determine the effect of an increased aperture, lifetimes were calculated for a minimum vertical aperture of 35σ as well for comparison. Increasing the vertical aperture in reality would require the use of novel superconducting IR magnets with elliptical apertures, because the horizontal aperture cannot be increased accordingly due to the presence of the nearby hadron beam.

FITTING THE DISTRIBUTION

For use as input data for synchrotron radiation and background simulation codes, the resulting distribution was fitted to an analytical expression. As Figure 4 shows, the non-Gaussian tail distribution can be described as

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

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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

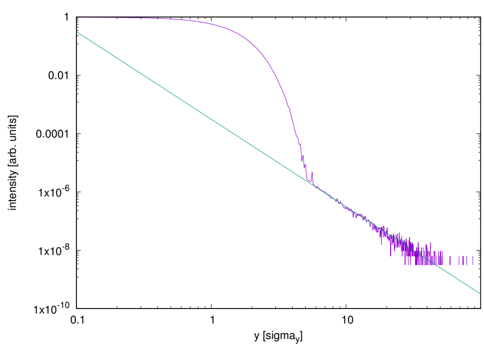

Figure 4: Log-log plot of the horizontal distribution for 5 GeV beam energy and a vacuum pressure of 5 ntorr, together with a fit to the tail distribution.

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

$$\rho_{\text{total}}(r) = \rho_{\text{core}}(r) + \rho_{\text{tail}}(r) \quad (4)$$

$$= \exp\left(-\frac{r^2}{2\sigma_r^2}\right) + K_r \cdot r^{-3}. \quad (5)$$

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 $\rho_{\text{core}}(0) = 1$ here.

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

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

CONCLUSION

The population in the non-Gaussian tails of the electron beam dominated by beam-gas scattering, while the beam-beam interaction contributes only a small fraction due to the long proton bunches. To ensure sufficient electron beam lifetime at all beam energies, the average vacuum pressure in the ESR, assuming a gas composition of 90% H_2, 10% N_2, must not exceed 5 nTorr. Special care needs to be taken in the interaction region with its large β-functions.

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