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Authors
Zholents, A.
Decking, W.

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NON-GAUSSIAN BEAM TAILS AT THE ADVANCED LIGHT SOURCE [*]

A. Zholents, E.O. Lawrence Berkeley National Laboratory, Berkeley, USA
W. Decking, Deutsches Elektronen-Synchrotron DESY, Hamburg, Germany

Abstract

The coordinate and energy distributions of the electron beam density at the Advanced Light Source have been obtained from measurements of the beam lifetime at various storage-ring apertures in the horizontal and vertical planes. It is shown that these distributions have a Gaussian core extended approximately up to five rms beam sizes. Beyond this point the electron density is defined by the electron scattering on the residue gas and electron intra-beam scattering and decreases as the cubic of the distance from the beam center. This behavior continues approximately up to ≈ 30 rms beam sizes in the horizontal plane and ≈ 60 rms beam sizes in the vertical plane.

1 INTRODUCTION

A source of femto-second x-ray pulses had been recently commissioning at the Advanced Light Source (ALS) [1]. This source utilizes the technique where an ultra-short laser pulse is used to modulate the energy of electrons within a $\approx 100\,\mathrm{fsec}$ slice of the stored $30\,\mathrm{psec}$ electron bunch. The energy-modulated electrons are spatially separated from the main electron bunch by horizontal dispersion and are used to generate $\approx 300\,\mathrm{fsec}$ synchrotron pulses at a bend-magnet beamline. For a good signal-to-background ratio it is important that the electrons that are displaced into the beam tail from the beam core dominate over the existing population of electrons in the beam tail. The horizontal beam profile at the bend-magnet beamline was measured to be Gaussian up to $\approx 5\sigma_x$ [3], where σ_x is the rms beam size. This allowed a satisfactory signal-to-background resolution of the femto-second x-ray pulses.

At present the generation of the femto-second x-ray pulses at an undulator beamline is being considered to increase the flux of photons. At the ALS all undulators are in the dispersion free straight sections. Therefore for a new source a vertical separation of energy modulated electrons by means of vertical dispersion is being considered [2].

In this paper we report the analysis of new measurements that reproduce the previous results for the horizontal plane and provide additional information about the electron beam profile in the vertical plane.

The information about the beam profiles has been deduced from measurements of the electron beam lifetime as a function of the vertical and horizontal apertures defined by movable scrapers. The actual measurements were performed in 1997 and had been previously used for analysis of the dynamic aperture of the ALS [4], [5]. Measurements were carried out at $1.5\,\mathrm{GeV}$ and at an approximately $5\,\mathrm{mA}$ average beam current distributed over 288 bunches[1].

We consider three leading mechanisms defining beam lifetime (τ) near the beam core: diffusion due to quantum fluctuations of the synchrotron radiation (τ_q), intra-beam scattering of electrons (Touschek effect) (τ_i), and Coulomb scattering of electrons on atoms of the residue gas (τ_g): $\frac{1}{\tau} = \frac{1}{\tau_q} + \frac{1}{\tau_i} + \frac{1}{\tau_g}$.

The lifetime due to the residue gas scattering can be calculated using the following formula [7]:

$$\frac{1}{\tau_g} = \frac{4\pi r_e^2 Z^2 cn}{\gamma^2}\frac{\beta^*\bar{\beta}}{a^2} \qquad (1)$$

Here a is the distance to the scraper from the beam center, β^* the beta-function at the scraper, and $\bar{\beta}$ the average beta-function around the ring, all taken either in horizontal or vertical direction. Z is the atomic number of the residue gas (an actual combination of the residue gases can be represented by a nitrogen equivalent with $Z = 7$), $n = 2.7 \times 10^{19}\frac{p\,\mathrm{Torr}}{760}$ is the density and p is the pressure of the residue gas.

The lifetime due to the intra-beam scattering of electrons can be calculated using the following approximate formula [7]:

$$\frac{1}{\tau_i} \approx \frac{r_e^2 c}{2^{\frac{3}{2}}\pi}\frac{N}{\gamma^3\langle\sigma_x'\rangle\langle\sigma_x\sigma_y\rangle\sigma_z}\frac{1}{\delta_{max}^2}\lg\left[\frac{1}{1.78}\left(\frac{\gamma\langle\sigma_x'\rangle}{\delta_{max}}\right)^2\right] \qquad (2)$$

Here r_e is the classical electron radius, γ is the Lorentz factor, e is the electron charge, c is the speed of light, $\langle\sigma_x'\rangle$ is the horizontal angular beam size averaged over the ring circumference, $\langle\sigma_x\sigma_y\rangle$ is the transverse area of the beam taken at one sigma level and averaged over the ring circumference, σ_z is the longitudinal beam size, $\delta_{max} = \Delta P_{max}/P$ is the momentum aperture of the ring, and N is the number of electrons in the bunch. In the ALS the horizontal scraper is located in a dispersion free region. Therefore, it can not limit the momentum aperture directly. But, it does it indirectly. Recall that each intra-beam scattering event produces a gain of the longitudinal momentum for one electron and a loss for another electron. If it occurs in a location with a non-zero dispersion function or its derivative, then momentum changes cause excitations of the betatron oscillations with the amplitude $\Delta x^2 = D_{eff}^2\,(\Delta P/P)$

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[1] The following additional information are used along with the experimental data:

- Vertical, horizontal, and energy oscillations damping times at $1.5\,\mathrm{GeV}$ [6]: $\tau_{d,y} = 17.6$, $\tau_{d,x} = 13.1$, $\tau_{d,e} = 10.7\,\mathrm{msec}$.
- Vertical and horizontal beta-functions at scrapers: $\beta_y^* = 5\,\mathrm{m}$, $\beta_x^* = 11\,\mathrm{m}$.
- Average beta-functions in the ring: $\bar{\beta_y} = 8\,\mathrm{m}$, $\bar{\beta_x} = 6.7\,\mathrm{m}$.

, where $\Delta P/P$ is the momentum change and D_{eff} is an effective dispersion function which characterizes the excitation of the betatron oscillations averaged over the ring circumference. The momentum aperture defined by the scraper can then be written as [2]:

$$\delta^2_{max} = \frac{x^2}{D^2_{eff}} \frac{\overline{\beta_x}}{\beta^*_x} \tag{3}$$

After substitution of this expression into Eq.2 one finds that the lifetime due to the intra- beam scattering has a similar $\propto x^2$ dependence from the aperture as the Coulomb scattering lifetime (apparent from a weak logarithmic correction).

The lifetime due to quantum fluctuations of the synchrotron radiation can be calculated using the following formula [7]:

$$\frac{1}{\tau_q} = \frac{1}{\tau_d}\eta^2 \exp\frac{\eta^2}{2} \tag{4}$$

Here τ_d is the damping time and $\eta = a/\sigma$, a again is the distance to the scraper from the beam center, $\sigma = \sqrt{\varepsilon\beta^*}$ is the betatron beam size at the scraper location and ε is the beam emittance. All values taken either for horizontal or vertical motion, depending on the direction of the scraper movement.

2 ANALYSIS

We begin with data obtained with two vertical scrapers. For these scrapers we ignored an intra-beam scattering of electrons because of its rather weak effect on electron motion in the vertical plane. First we considered the data obtained with the 'top' scraper. Initially we assumed that with the scraper positioned far from the beam core the lifetime was defined by scattering on the atoms of the residue gas. We fitted experimental points with the function $b_y/(\hat{y} - \hat{y_0})^2$ (see Eq.1), where $\hat{y}$ is the scraper position relative to the instrumental zero and $\hat{y_0}$ is the scraper position at the beam center. Comparing b_y to the coefficient in Eq.1 we determined the vacuum pressure $p \approx 2 \times 10^{-10}\,\mathrm{Torr}$ (the same as in [4]). Then using $\hat{y_0}$ we fitted the data at small aperture settings of the scraper where the lifetime was mainly defined by quantum fluctuations of the synchrotron radiation. From this fit we found the vertical beam emittance of $\varepsilon_y = 3 \times 10^{-10}\,\mathrm{radm}$. Fitting the data for the 'bottom' scraper we used the above defined emittance and vacuum pressure and fitted only the position of the beam center. Figure 1 shows the original data and the result of the fits for both scrapers. The vertical axes shows the inverse lifetime normalized by the inverse vertical damping time. The horizontal axes shows the distance from the beam center normalized on the rms vertical beam size. The plot also includes the error bars on the fit shown by two dashed lines above and below the fitting curve. One can notice that there is only a single experimental point on a sharp rise of the fitting curve where the lifetime is dominated by quantum fluctuations of the radiation. The fit of the vertical beam emittance is mainly based on this point. Nevertheless, this is a fairly accurate fit because of the high sensitivity of τ_q to the variations of ε_y.

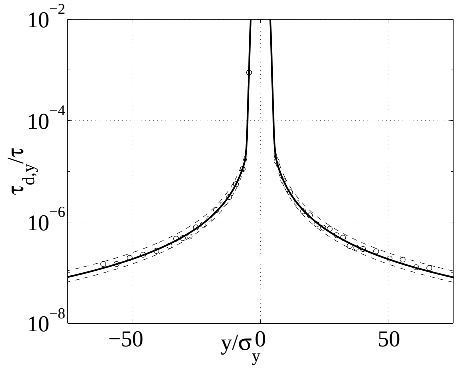

Figure 1: Inverse beam lifetime normalized on the inverse vertical damping time versus position of the vertical top and bottom scrapers normalized on the vertical beam size. Dots show the experimental data and solid line shows the fit. The dashed lines show the error margins for a 1σ confidence level.

We found that a transition from the lifetime dominated by quantum fluctuations of the radiation to the lifetime dominated by the Coulomb scattering occurs at $y/\sigma_y \approx 5.2$. It means that a transition from the Gaussian distribution of the electron density in the vertical direction to non-Gaussian tails happens near to this point. Because of the Coulomb scattering origin of the tails, the electron density beyond this point decreases $\propto y^{-3}$.

Figure 2 shows the electron density distribution in the vertical plane at $1.5\,\mathrm{GeV}$ deduced from the lifetime measurements. The curve 1 is given for the actual condition of the measurements, i.e. for the electron beam current of $5\,\mathrm{mA}$ and the vacuum pressure of $2 \times 10^{-10}\,\mathrm{Torr}$. The curve 2 is given for a vacuum pressure of $2 \times 10^{-9}\,\mathrm{Torr}$, which is a more likely value for $400\,\mathrm{mA}$ electron beam current. In the later case the transition from a Gaussian core to non-Gaussian tails is shifted to $y/\sigma_y \approx 4.7$. This should be sufficient for a satisfactory signal-to-background resolution of the femto-second x-ray pulses.

We performed the analysis of the data obtained with the horizontal scraper including all three effects: Coulomb scattering, intra-beam scattering and quantum fluctuations of the radiation. First we considered the data at large aperture settings and fitted the experimental points with the function $b/(\hat{x} - \hat{x_0})^2$ (see Eq.1 and Eq.2). Here $b = b_x + b_i$, where b_x is a coefficient in Eq.1 for the horizontal plane, and b_i is a coefficient in Eq.2 obtained after substitution of δ_{max} from Eq.3. From the fit we found b and $\hat{x_0}$. Then we assumed the vacuum pressure $p \approx 2 \times 10^{-10}\,\mathrm{Torr}$ as was derived from the measurements with the vertical scraper

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[2] Eq.3 holds as long as the momentum aperture defined by the scraper is smaller than the momentum aperture defined by the RF-bucket height or dynamic aperture effects. With $D_{eff} = 0.174\,\mathrm{m}$ calculated from the nominal lattice functions and $\delta_{max} \approx 0.023$ [5] the scraper effects the momentum aperture if $x < 5\,\mathrm{mm}$ ($\approx 25\sigma_x$).

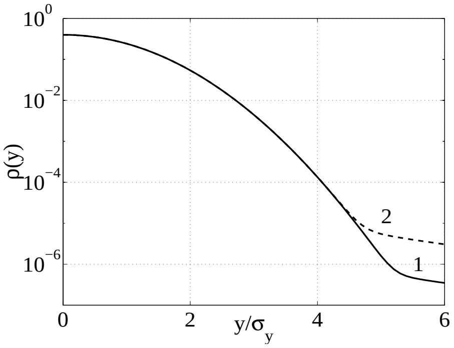

Figure 2: Electron density distribution in the vertical plane. Solid curve deduced from lifetime measurements at $5\,\mathrm{mA}$ beam current yielding an average vacuum pressure of $2\times10^{-10}\,\mathrm{Torr}$, while dashed curve is calculated for a beam current of $400\,\mathrm{mA}$ and an average vacuum pressure of $2\times10^{-9}\,\mathrm{Torr}$.

and found b_x using expression $b_x = b_y\frac{\beta_x^*\bar{\beta_x}}{\beta_y^*\bar{\beta_y}}$. It allowed us to find b_i from measurements of b. Comparing b_i to the coefficient in Eq.2 (after a substitution of Eq.3 for δ_{max}) we found $D_{eff} = 0.2\,\mathrm{m}$ in fairly good agreement with the actual ALS lattice. Finally using $\hat{x_0}$ we fitted the data at small aperture settings of the scraper and obtained the horizontal beam emittance $\varepsilon_x = 3.5\times10^{-9}\,\mathrm{radm}$ (in good agreement with the design value for a low beam current [6]).

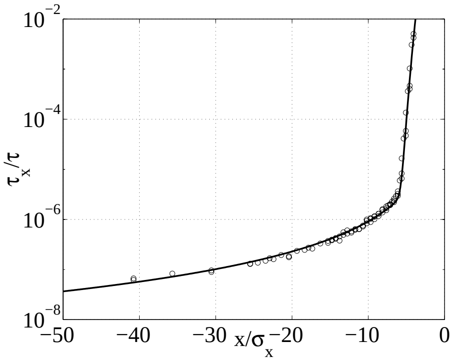

Figure 3: Inverse beam lifetime normalized on the inverse horizontal damping time versus position of the horizontal scraper normalized on the horizontal beam size. Dots show the experimental data and solid line shows the fit.

The horizontal and vertical emittances measured with the above described technique suggest a fairly large coupling of $\approx 8.5\,\%$ at the time of measurements. Typically, the ALS operates at a much smaller coupling which means that the vertical beam size is smaller and the non-Gaussian tails appear further out from the beam core in units of the rms beam size. For example with a vertical emittance of $\varepsilon_y = 0.6\times10^{-10}\,\mathrm{radm}$ the non-Gaussian tails will appear at a distance of $\approx 6\sigma_y$.

Figure 3 shows the original data and the result of the fit for the horizontal scraper. We found that a transition from the lifetime dominated by quantum fluctuations of the radiation to the lifetime dominated by the intra-beam scattering and Coulomb scattering occurs at $x/\sigma_x \approx 5.7$. Figure 4 curve 1 shows the electron density distribution in the horizontal plane at $1.5\,\mathrm{GeV}$ deduced from the lifetime measurements obtained for the electron beam current of $5\,\mathrm{mA}$ and the vacuum pressure of $2\times10^{-10}\,\mathrm{Torr}$.

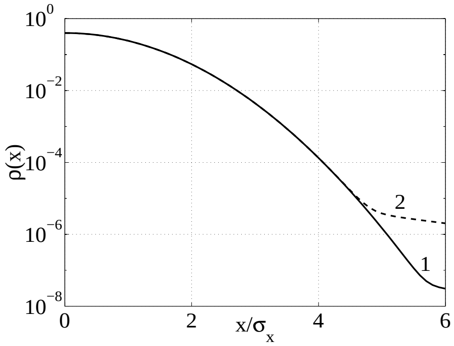

Figure 4: Electron density distribution in the horizontal plane. Solid curve 1 deduced from lifetime measurements at $5\,\mathrm{mA}$ beam current yielding an average vacuum pressure of $2\times10^{-10}\,\mathrm{Torr}$. Dashed curve 2 shows the density distribution in the ALS arcs for a beam current of $400\,\mathrm{mA}$ and an average vacuum pressure of $2\times10^{-9}\,\mathrm{Torr}$, normalized to the rms beam size taking into account contributions from betatron and synchrotron oscillations.

Having defined the rate of the intra-beam scattering we were then able to reconstruct the energy distribution of electrons at $5\,\mathrm{mA}$ beam current and scaled it to $400\,\mathrm{mA}$ beam current. For higher beam current we assumed a rms energy spread of 8×10^{-4} and $20\,\%$ greater beam emittances [3] than found above. We combined the above results to derive the horizontal beam profile in the middle of the ALS arc sector using a horizontal dispersion function of $0.09\,\mathrm{m}$ and a horizontal beta-function of $0.72\,\mathrm{m}$. The plot of the distribution is shown in Figure 4 curve 2.

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