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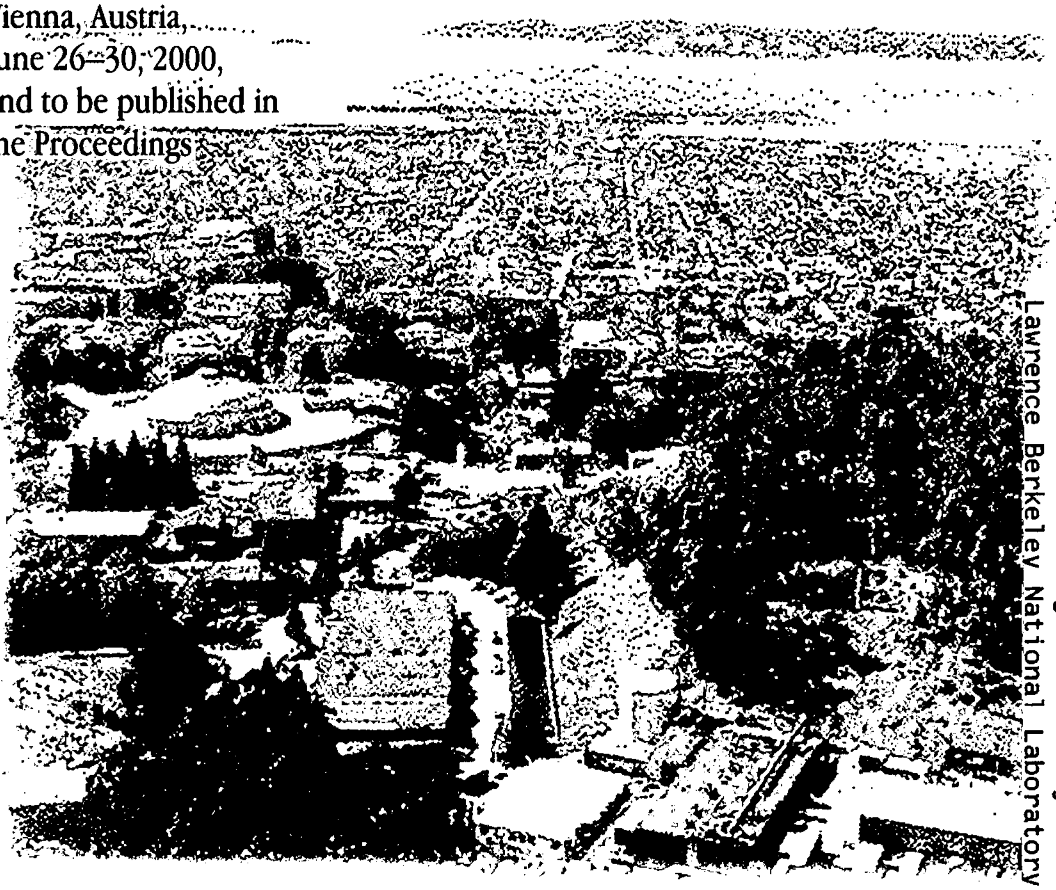

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Abstract

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. The horizontal and vertical emittances obtained from the measurements near the beam core suggest a presence of ~ 8.5 % coupling in the ring at the time of measurements.

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 ~100-femtosecond slice of the stored 30-picosecond electron bunch. The energy-modulated electrons are spatially separated from the main electron bunch by horizontal dispersion and are used to generate ~300-femtosecond 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.

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].

At the beginning of the experiment at the bend-magnet beamline the beam profile in the horizontal plane was measured to be gaussian up to ~ $5\sigma_x$, where σ_x is the rms beam size [3]. This allows a satisfactory signal-to-background resolution of the femtosecond x-ray pulses. In this paper we report the analysis of new measurements that reproduce previous results for the horizontal plane and provide additional information about the electron beam profile at the ALS in the vertical plane.

The information about the beam profiles at the ALS 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 GeV and at an approximately 5 mA average beam current distributed over 288 bunches.

In this note we also use the following additional information along with the experimental data:

Damping times of vertical, horizontal and energy oscillations at 1.5 GeV, msec [6]	17.6, 13.1, 10.7
Vertical/horizontal beta-functions at scrapers, β_y^* / β_x^*, m	5 / 11
Average vertical/horizontal beta-functions in the ring, $\bar{\beta}_y / \bar{\beta}_x$, m	8 / 6.7

We consider three leading mechanisms defining beam lifetime near the beam core: diffusion due to quantum fluctuations of the synchrotron radiation, intra-beam scattering of electrons (Touschek effect), and Coulomb scattering of electrons on atoms of the residue gas:

$$\frac{1}{\tau} = \frac{1}{\tau_q} + \frac{1}{\tau_i} + \frac{1}{\tau_g} .$$

Here τ_q, τ_i, τ_g are partial contributions to the beam lifetime due to quantum fluctuations, intra-beam scattering and residue gas scattering. The lifetime due to the residue gas scattering can be calculated using the following formula [7]:

$$\frac{1}{\tau_g} = \frac{4\pi r_e^2 Z^2 nc}{\gamma^2} \frac{\beta^* \bar{\beta}}{a^2} \tag{1}$$

Here a is the distance to the scraper from the beam center either in the horizontal or vertical plane and $\beta^*, \bar{\beta}$ are the horizontal or vertical beta-functions at the scraper location and the average beta-functions, 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), $n = 2.7 \times 10^{19} \frac{p[Torr]}{760}$ 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]:

$$\frac{1}{\tau_i} = \frac{r_e^2}{2\sqrt{\pi}} \frac{1}{\gamma^3 < \sigma'_x >< \sigma_x \sigma_y >} \frac{I_p}{e} \frac{1}{\delta_{\max}^2} Log\left[\frac{1}{1.78}\left(\frac{\gamma < \sigma'_x >}{\delta}\right)^2\right] \tag{2}$$

Here r_e is the classical electron radius, γ is the Lorentz factor, e is the electron charge, $<\sigma'_x>$ is the horizontal angular beam size averaged over the ring circumference, $<\sigma_x \sigma_y>$ is the transverse area of the beam taken at one sigma level and averaged over the ring circumference, $\delta_{\max} = \Delta P_{\max} / P$ is the momentum aperture of the ring, and I_p is the electron peak current defined as $ceN/\sqrt{2\pi}\sigma_z$, where N is the number of electrons in the electron bunch, σ_z is the longitudinal beam size and c is the speed of light. 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 event of the intra-beam scattering 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 $\Delta x^2 = D_{eff}^2 \left(\frac{\Delta P}{P}\right)^2$, where $\Delta P/P$ is the momentum change and D_{eff} is an effective dispersion function. We use D_{eff} to characterize excitation of the betatron oscillations averaged over the ring circumference. Finally, the momentum aperture defined by the scraper can be written as:

$$\delta_{\max}^2 = \frac{x^2}{D_{eff}^2} \frac{\overline{\beta_x}}{\beta_x^*}. \tag{3}$$

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 m calculated from the nominal lattice functions and $\delta_{\max}$≈0.023 [5] the scraper effects the momentum aperture if $x < 5\,\text{mm}$ $(\approx 25\sigma_x)$.

After substitution of this expression into Eq.2 one finds that the lifetime due to the intra-beam scattering has 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]:

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

Depending from the direction of the scraper motion (vertical or horizontal) τ_d assumes the value of vertical or horizontal damping time and η assumes y/σ_y or x/σ_x, where x, y are distances to the scraper from the beam center, $\sigma_y = \sqrt{\varepsilon_y \beta_y^*}$, $\sigma_x = \sqrt{\varepsilon_x \beta_x^*}$ are the vertical and horizontal betatron beam sizes at the scraper location and $\varepsilon_y, \varepsilon_x$ are the vertical and horizontal beam emittances.

2. Analysis

We begin with data obtained with two vertical scrapers. For these scrapers we ignored an intra-beam scattering of electrons because of a rather weak effect of the intra-beam scattering of electrons 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 $b_y/(\hat{y}-\hat{y}_o)^2$ (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. From this fit we found b_y and $\hat{y}_0$. Comparing b_y to the coefficient in the Eq.1 we determined the vacuum pressure $p \approx 2\text{x}10^{-10}$ 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 $\varepsilon_y = 3\times10^{-10}$ m-rad. Next we considered the data obtained with the bottom scraper. Fitting the data for this 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 damping time of vertical oscillations. 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 solid lines above and below the fitting curve. One can notice that there is, actually, 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.

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 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 mA and the vacuum pressure of $2\text{x}10^{-10}$ Torr. The curve 2 is given for the vacuum pressure of $2\text{x}10^{-9}$ Torr, which is a more likely value for a 400 mA electron beam current. In the later case the transition from a gaussian core to non-gaussian tails is shifted to $y/\sigma_y \approx 4.7$.

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 $b/(\hat{x}-\hat{x}_o)^2$ (see Eq's. 1 and 2). Here $\hat{x}$ is the scraper position relative to the instrumental zero, $\hat{x}_0$ is the scraper position at the beam center, and $b = b_x + b_i$, where b_x is a coefficient in Eq.1 for a 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 $p \approx 2x10^{-10}$ Torr as was derived from the measurements with the vertical scraper and found b_x using expression $b_x = b_y \frac{\beta_x^* \overline{\beta_x}}{\beta_y^* \overline{\beta_y}}$. It allowed us to find b_i from measurements of b. Comparing b_i to the coefficient in the Eq. 2 (after a substitution of Eq.3 for δ_{max}) we found D_{eff}= 0.2 m. This was in a fairly good agreement with the actual ALS lattice. Finally using $\hat{x}_0$ 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 obtained the horizontal beam emittance ε_x=3.5×10^{-9} m-rad (in a good agreement with the design value for a low beam current [6]).

At this point we would like to mention that the horizontal and vertical emittances measured with the above described technique suggest a fairly large coupling of ~8.5% at the time of measurements. Typically, the ALS operates at a much smaller coupling. It means that in the typical operational conditions the vertical beam size is narrower and the non-gaussian tails appear further out from the beam core in units of the rms beam size. For example in a case of vertical emittance of $\varepsilon_y = 6\times10^{-10}$ m-rad the non-gaussian tails will appear at a distance of $\sim 6\sigma_y$.

Figure 3 shows the original data and the result of the fit for the horizontal scraper. The vertical axes shows the inverse lifetime normalized by the inverse damping time of horizontal oscillations. The horizontal axis shows the distance from the beam center normalized on the rms horizontal betatron beam size.

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 $x/\sigma_x \approx 5.7$. Similar to the electron density distribution in the vertical direction, the non-gaussian tails appeared beyond this point. The electron population in the tails decreases $\propto x^{-3}$. Figure 4 shows the electron density distribution in the horizontal plane at 1.5 GeV deduced from the lifetime measurements obtained for the electron beam current of 5 mA and the vacuum pressure of $2x10^{-10}$ Torr.

Having defined the rate of the intra-beam scattering we were then able to reconstruct the energy distribution of electrons at 5 mA beam current and scaled it to 400 mA beam current. For higher beam current we assumed the rms energy spread of $8x10^{-4}$ and 20% greater beam emittances [3] than found above. The plot of the energy distribution obtained for this case is shown in Figure 5.

Finally we combined the above results to derive the horizontal beam profile in the middle of the ALS arc sector. Here we recreated the beam core using the horizontal dispersion function of 0.09m, the horizontal beta-function of 0.72 m, the rms energy spread of $8x10^{-4}$ and the horizontal beam emittance of $4.2x10^{-9}$ m. The plot of the distribution is shown in Figure 6.

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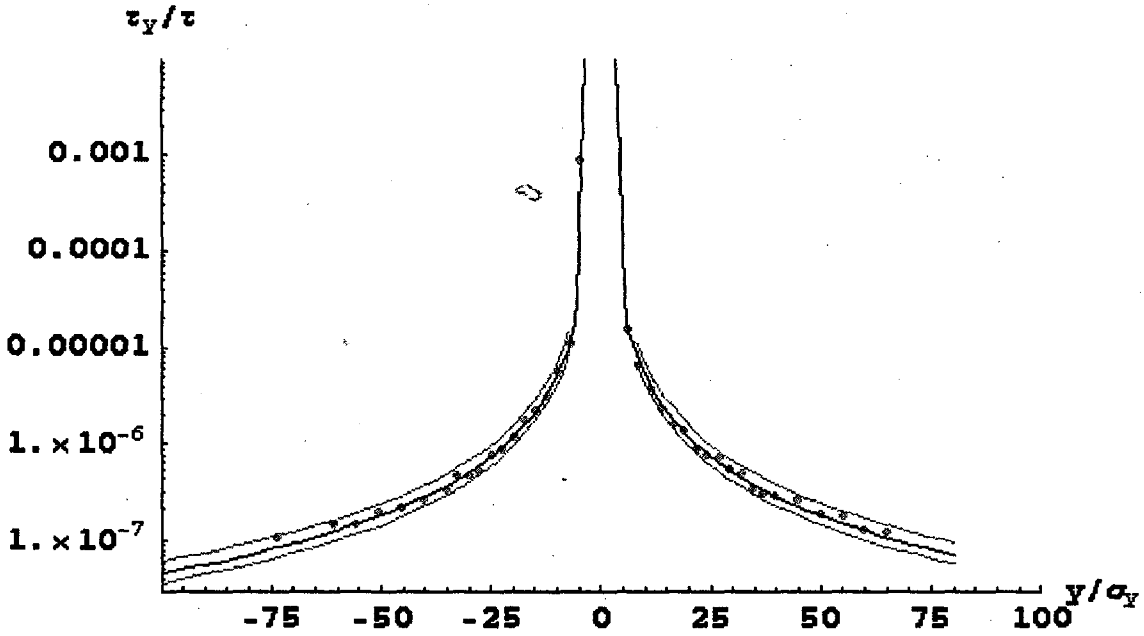

Figure 1. The inverse beam lifetime normalized on the damping time versus position of the top and bottom scrappers. Dots show the experimental data and solid lines show the fit based on Eq.1 and Eq. 4 and error bars for the fit.

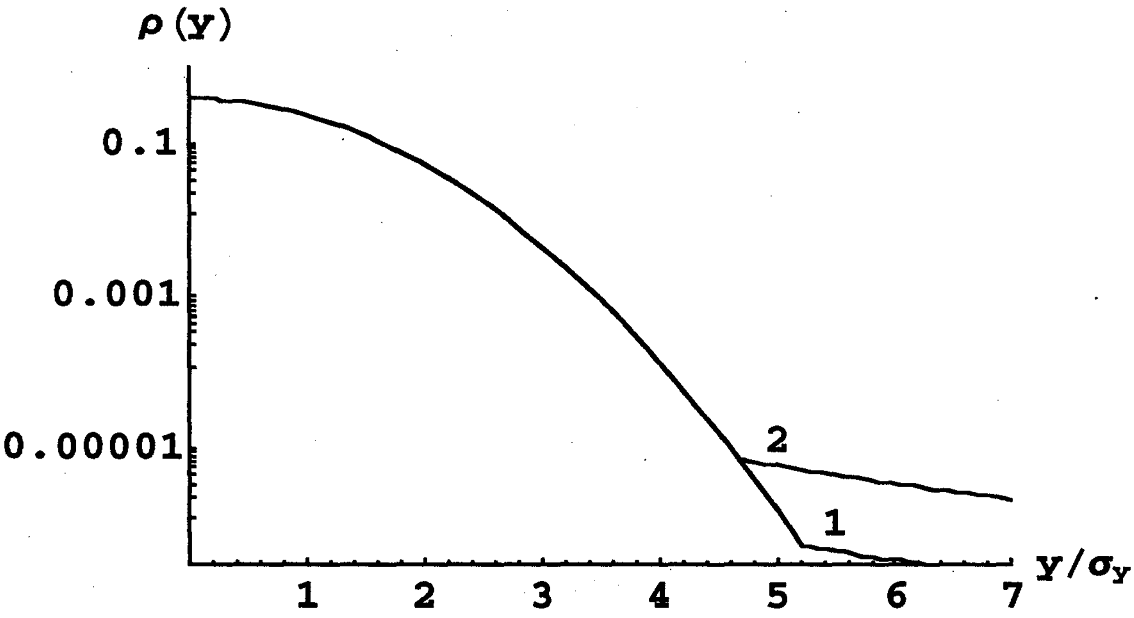

Figure 2. Electron density distribution in the vertical direction deduced from the lifetime measurements. Curve 1 corresponds to a low beam current and an average vacuum pressure of $2x10^{-10}$ Torr and curve 2 corresponds to a beam current of 400 mA and an average vacuum pressure of $2x10^{-9}$ Torr.

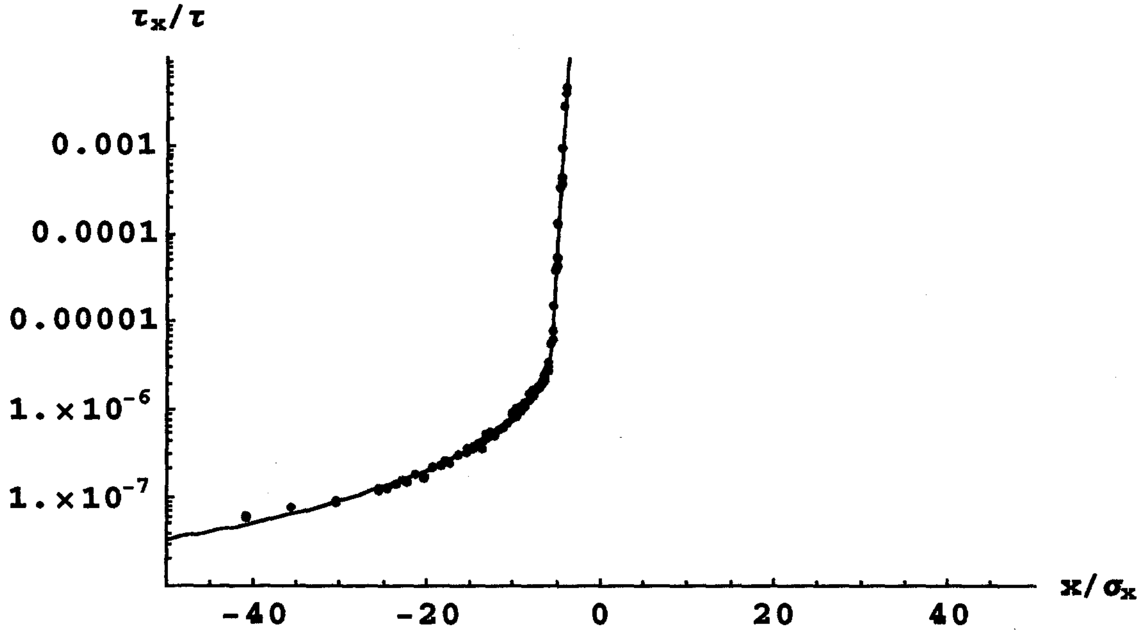

Figure 3. The inverse beam lifetime normalized on the damping time versus position of the horizontal scrapper. Dots show the experimental data and the solid line shows the fit based on Eq.1 and Eq. 4.

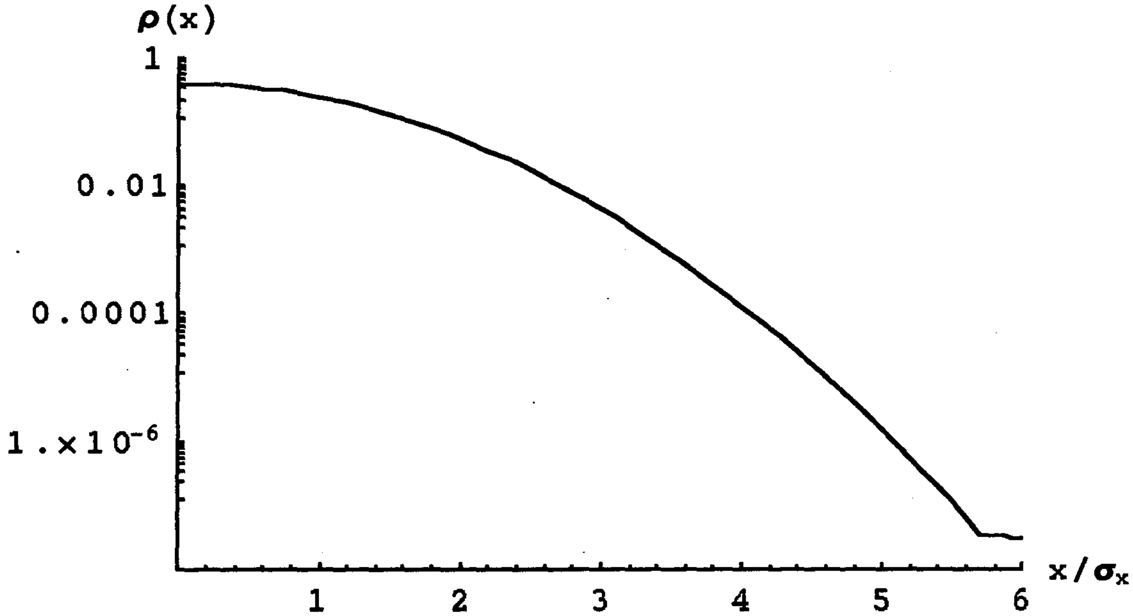

Figure 4. Electron density distribution in horizontal direction deduced from the lifetime measurements at 5 mA beam current and an average vacuum pressure of 2×10^{-10} Torr.

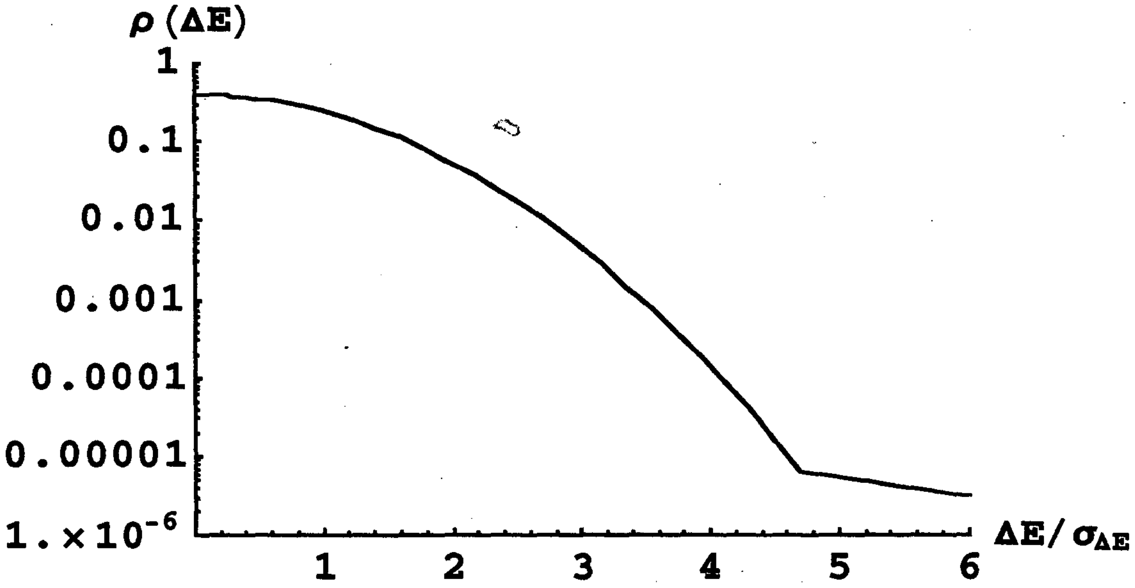

Figure 5. Energy distribution of electrons at 400 mA beam current.

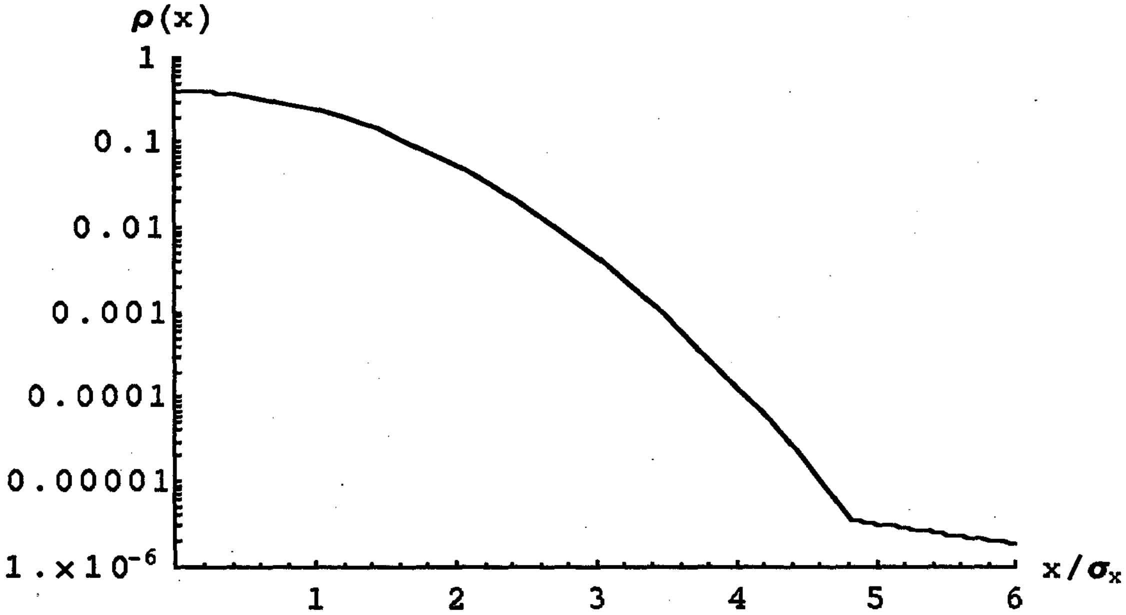

Figure 6. The electron density distribution in the horizontal plane in the middle of the ALS arc sector. Here σ_x is the total r.m.s. beam size that includes contributions from the synchrotron and betatron electron oscillations. This distribution is given for 400 mA beam current.

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