ANALYSIS OF THE MEASUREMENT OF ELECTRON CLOUD DENSITY UNDER VARIOUS BEAM-OPTICS ELEMENTS IN KEKB LER

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Abstract

A method to measure the density of the electron cloud near beam is recently proposed by K. Kanazawa et al. [1]. It is based on the idea to measure the high energy electrons by a retarding field analyzer located on the chamber wall. In this paper the method is analyzed in detail with a dedicated simulation code.

INTRODUCTION

A group of electrons called an electron cloud (EC) can be formed in positron or proton accelerators. Seeds of the EC in positron rings are mainly photoelectrons produced by synchrotron radiation. The electrons receive kicks from the beam toward the center of a beam chamber, hit the opposite wall then produce secondary electrons. The number of the electrons can be increased by consecutive secondary electron production, which leads to formation of the EC. The EC causes harmful effects on the accelerator performance such as the coupled bunch instability, the single bunch head-tail instability, heat load to a chamber wall of super conducting accelerators and so on [2].

In order to study the EC the knowledge of the EC density near beam is important because the beam interacts with the electrons near beam to cause the single bunch instability. Recently K. Kanazawa et al. proposed a method to measure the electron density near beam [1] and reported a result of a measurement in LER at KEK B-factory (KEKB) [3]. The method is based on the idea to measure the high energy electrons by a retarding field analyzer located on the chamber wall. A source of high energy component of the detected electrons is expected to be strongly kicked electrons by beam. K. Kanazawa et al. estimated the EC density assuming that the electrons are stationary and the detected electrons receive a single kick from beam. However, in reality, the electrons will have finite velocity and some detected electrons will come from non-central parts of the chamber. In this paper the above naive assumptions are examined in detail with a newly developed simulation code.

SIMULATION CODE

A new code was developed because modelling of an electron monitor and special functions are required for the study. The code includes 1) generation of photoelectrons including those by reflected photons, 2) generation of secondary electrons based on Furman-Pivi model [4], 3) a beam-kick to an electron by the Basetti-Erskine formula [5], 4) calculation of space charge force of the EC by the Alternating Direction Implicit method, and also has the special functions such as 5) a back-track routine to track the trajectory of a detected electron to a position immediately after the beam-kick and 6) calculation of the EC density seen by beam. All macro electrons have a same macro charge. A bunch is sliced longitudinally, typically by 10 slices. Length of a slice divided by the light velocity is a unit of the time interval of the simulation when a bunch stays in a computational region. The interval is coarser in a bunch gap. Figure 1 shows an example of the x-y distribution of the electrons.

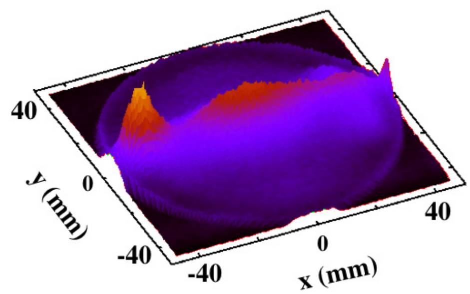

Figure 1: Simulated x-y distribution of the electrons in drift space at KEKB LER after the 60th bunch passed. Secondary emission yield is 1.2. Bunch current is 1.2mA. Bunch separation is 6ns.

ANALYSIS OF THE MEASUREMENT

Figure 2 shows a schematic drawing of the electron monitor installed in a drift region in KEKB LER [1]. The monitor is attached on a port of a vacuum chamber. It has an anode to collect the electrons and a retarding grid which repels the electrons whose energy is less than eV_b, where V_b is a bias voltage applied to the retarding grid. Assuming that the detected electrons are stationary at a moment of beam-kick and enter the monitor by a single kick, the detected electrons whose energy is larger than eV_b come from a small region near beam whose volume is given by

$$V_{obs}(V_b) = 2\pi A r_e^2 N_b^2 \frac{m_e c^2}{eV_b} \quad , \qquad (1)$$

where A is an acceptance of the monitor, r_e the classical electron radius, N_b the population of the bunch and m_e the mass of the electron. We call V_{obs} a detection volume.

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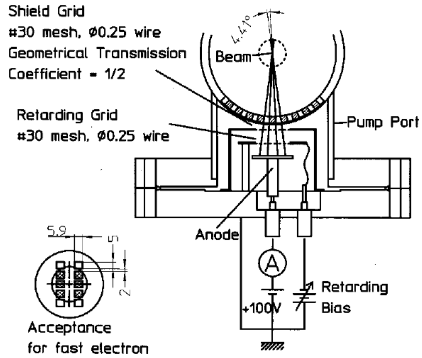

Figure 2: Schematic drawing of the electron monitor in KEKB LER [1].

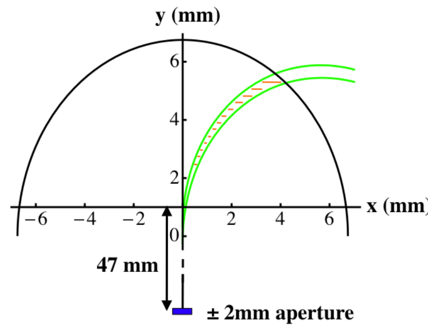

Figure 4: Calculation of an area where detected electrons are located. Green curves are calculated by Eq. (3).

The average EC density in the detection volume ρ_{ave} is obtained as

$$\rho_{ave} = Y_m(V_b)/V_{obs}(V_b) \quad , \qquad (2)$$

where $Y_m(V_b)$ is the number of the detected high energy electrons per bunch, i.e. the electron yield.

A detected electron was back-tracked to a position where the electron was located immediately after the beam-kick. Fig. 3 shows a simulated x-y distribution of the back-tracked electrons in drift space which are detected by the monitor with the bias voltage of -1 kV. The simulation modelled two openings at the bottom of the chamber through which the electrons enter the monitor. The size of each opening is ± 2mm. If the kicked electrons are stationary we expect that the electrons come from two narrow cones just above the beam axis, while Fig. 3 shows the occupied area by the electrons consists of heavily deformed four regions. The deformation is caused because the electrons have velocities at the beam-kick. A simple calculation shows that an electron passing (x_m, y_m) after the beam-kick satisfies following relation,

$$\begin{aligned}&(x_m - x)(v_{y0}(x^2 + y^2) - b \cdot y) \\ &-(y_m - y)(v_{x0}(x^2 + y^2) - b \cdot x) = 0\end{aligned} \quad , \qquad (3)$$

where b is $2cr_eN_b$, (x , y) and (v_{x0}, v_{y0}) are position and velocity of the electron at the beam-kick, respectively. If the monitor has an opening just bellow the beam axis, the detected electrons are confined between two curves shown in Fig. 4 as green curves. If v_{x0} is negative, curves are mirror symmetrical about y-axis. Since the simulation assumed two openings, four regions appear in Fig. 3. The calculation shows that v_{y0} does not much deform a hatched region in Fig. 4.

The effect of the deformation of the detection volume on the measurement was studied by the simulations. In the simulations Y_m and ρ_{ave} were calculated, then $V_{obs}(V_b)$ was obtained from Eq. (2). The EC density around the bunch was calculated every time step then averaged to get ρ_{ave} because a simulation at high bunch current, e.g. 1.2mA, shows that the average density seen by the beam, ρ_{ave}, is two times smaller than the EC density calculated from an electron distribution at a fixed time. Fig. 5 shows $V_{obs}(V_b)/I_b^2$ as a function of the bunch current I_b. Error bars are the statistical errors calculated from the number

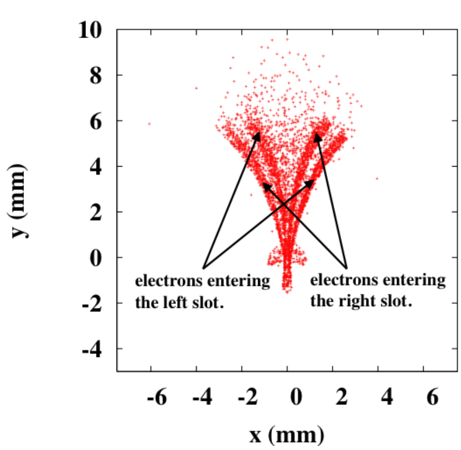

Figure 3: X-y distribution of the back-tracked electrons detected by the monitor with the bias voltage of -1 kV.

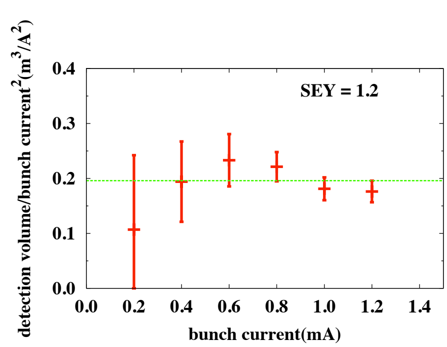

Figure 5: Detection volume divided by the bunch current square obtained by the simulation in drift space. The secondary emission yield (SEY) is 1.2, bunch separation is 6ns and the number of bunches is 60. The bias voltage is -1 kV.

of the detected macro electrons. A green dotted line is a value obtained from Eq. (1). Though the shape of the detection volume is strongly deformed, it is almost same as that of the analytic estimate assuming the stationary electrons. This fact can be understood as follows.

The average EC density ρ_{ave} and the electron yield Y_m are given as,

$$\rho_{ave} = \left(\int_{-\infty}^{\infty}\left\{\int_{S_d}\rho(x,y,v_x,v_y)dxdy\right\}dv_x dv_y\right)/S_d, \quad (4)$$

$$Y_m = \int_{-\infty}^{\infty}\left\{\int_{S(v_x,v_y)}\rho(x,y,v_x,v_y)dxdy\right\}dv_x dv_y, \quad (5)$$

where $\rho(x,y,v_x,v_y)$ is a phase space density of the electrons, S_d an area covered by the kicked electrons with the energy larger than eV_b at the beam-kick and $S(v_x,v_y)$ a region corresponding to the detection volume. Here we assume longitudinally uniform electron distribution. If $\rho(x,y,v_x,v_y)$ can be factorized as

$$\rho(x,y,v_x,v_y) = f_1(x,y)\cdot f_2(v_x,v_y), \quad (6)$$

then

$$\rho_{ave} = \int_{-\infty}^{\infty} f_2(v_x,v_y)dv_x dv_y \cdot \int_{S_d} f_1(x,y)dxdy/S_d \equiv F_2\cdot\bar{f}_1, \quad (7)$$

$$Y_m = \int_{-\infty}^{\infty} f_2(v_x,v_y)\left\{\bar{f}_1\int_{S(v_x,v_y)}dxdy + \int_{S(v_x,v_y)}\delta(x,y)dxdy\right\}dv_x dv_y, \quad (8)$$

where we separated f_1 into two parts as $f_1(x,y) = \bar{f}_1 + \delta(x,y)$. Furthermore, if

$$\int_{S(v_x,v_y)}dxdy = S_0, \quad (9)$$

and

$$\int_{S(v_x,v_y)}\delta(x,y)dxdy/(\bar{f}_1\cdot S_0) << 1, \quad (10)$$

then we get $Y_m = S_0\cdot\rho_{ave}$, where S_0 is an area of the detection volume for the stationary electrons. Thus if conditions (6), (9) and (10) are satisfied the yield at the monitor is obtained as a product of the observed volume for stationary electrons and the average EC density.

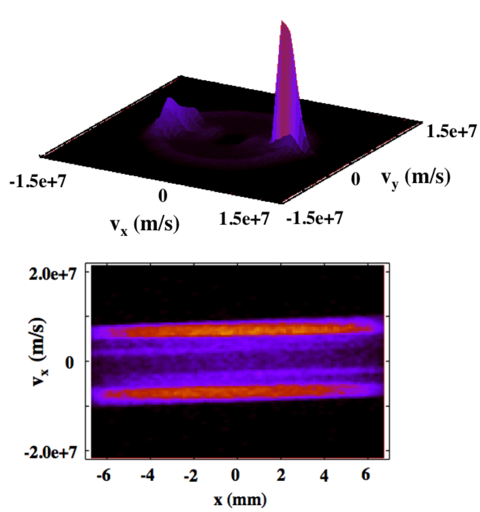

Figure 6: Correlations of the electron distribution, v_x-v_y(top) and x-v_x(bottom). The conditions of the simulation are same as those in Fig. 5.

To check the condition (6) we took the electrons within $x^2+y^2 < 6.8mm^2$, then plotted the distribution for all combinations of x,y,v_x and v_y, where 6.8mm is a radius of the detection volume at V_b of -1kV. The calculation showed that x-y and v_x-v_y had strong correlation, x-v_x had weak correlation and the rest had no correlation (See Fig. 6). Thus the condition (6) is reasonably satisfied.

For the condition (9), the hatched area shown in Fig. 4 was numerically integrated changing v_x and v_y in a range of $0 < v_x < 1.4\times10^7$ m/s and $-1\times10^6 < v_y < 1\times10^6$ m/s. The difference of the areas was within ±5%.

For the condition (10), we numerically calculated following quantities from the simulated electron distribution.

$$\Delta(x,y) = \int_{-\infty}^{\infty}\rho(x,y,v_x,v_y)dv_x dv_y - \int_{S_d}\left\{\int_{-\infty}^{\infty}\rho(x,y,v_x,v_y)dv_x dv_y\right\}dxdy/S_d, \quad (11)$$

$$R = \frac{\int_{S(v_x,v_y)}\Delta(x,y)dxdy}{\int_{-\infty}^{\infty}\left\{\int_{S_d}\rho(x,y,v_x,v_y)dxdy\right\}dv_x dv_y/S_d\cdot S_0}. \quad (12)$$

If condition (6) is satisfied, R is the left hand side of condition (10). Using the EC density distribution at the bunch current of 1.2 mA and the train of 60 bunches, and using $S(v_x,v_y)$ for v_x of 1.10^7 m/s and v_y of 0 m/s, we get 0.01 for R. Thus the three conditions are well satisfied.

The detected electrons coming from outside near-beam-region will introduce a measurement error. The simulation showed that those electrons are about 5% of all detected electrons.

CONCLUSION

A method to measure the EC density near beam is analyzed in detail by a simulation. The result shows that a shape and a position of a detection volume, where detected electrons stay immediately before kicked, strongly depend on horizontal velocity of the electrons. Nevertheless the result also shows that the detection volume calculated assuming the stationary electrons can be used for calculating the EC density. An analysis of the measurement of the EC density in a quadrupole magnet is in progress.

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