ANALYSIS OF THE ELECTRON CLOUD DENSITY MEASUREMENT WITH RFA IN A POSITRON RING*

K. Kanazawa#, H. Fukuma, KEK, Tsukuba, Ibaraki, Japan
J. Puneet, The Graduate Universiry for Advanced Studies, Tskuba, Ibaraki, Japan

Abstract

In a positron ring such as KEKB LER, clouding electrons receive an almost instantaneous kick from circulating bunches. Therefore, high energy electrons in the cloud are produced locally around the beam just after the interaction with the bunch. The authors gave an estimation of their density using a high energy electron current measured with RFA and a calculated volume neglecting their initial velocity before the interaction with the bunch [1][2]. To evaluate the accuracy of this estimation, the process of the measurement is analyzed using the phase space density for the motion of electrons in the transverse plane of the beam. The expressions that can evaluate the accuracy of the estimation with the help of simulation are obtained. One of the authors has shown that the accuracy for a drift space is within ±5% error [3]. For other applications such as in a solenoid field or in a quadruple field, the evaluation is not yet given. In addition to this discussion, some examples of the estimation of the electron cloud density with RFA are shown.

INTRODUCTION

The electron cloud in the accelerator ring of positively charged particles is one of serious obstacles to achieve a stable low emittance beam. The study of the electron cloud to clarify and to mitigate the effect is now a major issue for the design of the positron damping ring of ILC or for the upgrade of LHC. The positron storage ring of KEK B-Factory (LER), which was shutdown June 2010, had been suffering from the electron cloud problem in increasing the stored current to achieve a higher luminosity. During the study of the electron cloud in LER, a simple idea to estimate the density with a retarding field analyzer (RFA) attached to a vacuum chamber is developed.

The idea arises from the efforts to explain the measurement in a drift space. Most of bunches in LER are spaced by 6 ns (3 bucket space). The typical bunch population during collision experiment is around 7×10^{10}. The major part of electrons arrive at an RFA have low energies less than 20 eV. A time-resolved observation shows these low energy electrons arrive almost continuously except large train gaps. On the other hand high energy electrons, for example, with energies more than 2 keV, are observed as a rapidly changing current which has regular peaks corresponding to the bunch pattern [1].

Obviously the peak consists of electrons which get their energy through the interaction with the high electric field near a circulating bunch. Since the electric field of a relativistic positron bunch is contracted into the transverse plane of the beam, the resulting acceleration occurs essentially in this plane. The radius of the transverse area, where these high energy electrons stayed just before the interaction with the bunch, can be calculated from the bunch charge and the retarding bias with sufficient precision. A possible ambiguity due to the initial energies of electrons is small because the energy of most electrons before the interaction is less than few×10 eV. If the retarding bias is set so that electrons in the corresponding area can reach the duct wall before the next bunch arrives, from the pulse of electron current the density near the beam (and in front of the bunch) can be known. Usually, an RFA is set behind a small aperture of the duct wall. Therefore it cannot receive the whole electrons of the area but observes a finite portion of it. The estimation of this observed area is not simple because of the initial energies of electrons [3]. The point of our idea is to propose an approximation for the observed area to use the area obtained by assuming electrons are at rest before the interaction. Using the calculated observed area, the near beam electron cloud density (just before the interaction with a bunch) is estimated as:

$$\text{Density} = \frac{\text{No. of electron per bunch}}{\text{Observed area} \times \text{Detector length}}. \qquad (1)$$

This idea was first applied to drift spaces and gave a reasonable estimation of density [1]. The idea is further developed to apply for the measurement in a solenoid field and in a quadrupole magnetic field. The resulting estimation of the electron cloud density seems also reasonable [2].

In the following, the process of the high energy electron measurement with RFA is analysed using the phase space density of electrons and how the validity of the approximation adopted in our estimation can be checked with the help of the simulation on electron motion is shown. In addition the result of the density estimations under different types of a magnetic field is

*Work supported by The Japan/US Cooperation Program
#ken-ichi.kanazawa@kek.jp

summarized to give an idea for modelling the condition in simulation.

ANALYSIS OF MEASUREMENT WITH BIASED RFA

The goal of this section is to relate the number of electrons measured with a biased RFA with the density of the cloud just before the interaction with a circulating bunch, following the line of thought in the previous section. We use the density in the μ-space. Since the motion of electrons in a positron ring is nearly confined in the transverse plane to the beam, the form of the density in the six dimensional phase space (Ω) can be assumed to be,

$$\Omega(v_x, v_y, v_z, x, y, z, t) = \delta(v_z)\rho(v_x, v_y, x, y, t). \qquad (2)$$

At a certain location of an accelerator ring, special timings are specified. The time just before a circulating bunch arrives at the location is t_0, just after the bunch passes is t_1, and at t_B, the next bunch arrives.

At $t = t_1$, most high energy electrons are produced around the beam after the interaction with a positron bunch. We define a circular region S_0 that covers most, for example 99%, of the position (at $t = t_0$) of those electrons which get energies higher than certain value (= retarding bias) at $t = t_1$. Then we define some functions on this region.

Average density around the beam at $t = t_0$,

$$\rho_{AV} = \frac{1}{S_0 L}\int dv_x dv_y \int \rho(v_x, v_y, x, y, t_0) L dx dy \cdot \qquad (3)$$

Spatially averaged velocity distribution around the beam at $t = t_0$,

$$D(v_x, v_y) = \frac{1}{\rho_{AV} S_0 L}\int_{S_0} \rho(v_x, v_y, x, y, t_0) L dx dy \cdot \qquad (4)$$

This D is normalized as,

$$\int D(v_x, v_y) dv_x dv_y = 1 \,. \qquad (5)$$

Using these two functions, we rewrite the density function as,

$$\rho(v_x, v_y, x, y, t_0) = \rho_{AV} D(v_x, v_y) + \Delta(v_x, v_y, x, y, t_0). \qquad (6)$$

The newly introduced function Δ satisfies in the S_0,

$$\int dv_x dv_y \int_{S_0} \Delta(v_x, v_y, x, y) dx dy = 0 \cdot \qquad (7)$$

Now we relate the density at $t = t_0$ to the number of electrons per positron bunch observed with a biased RFA. For this we think as follows: the position of electrons that have a velocity (v_x, v_y) at $t = t_0$ and then observed with a biased RFA fill a specified region $S(v_x, v_y, t_0)$ with in S_0. We assume the bias of an RFA is set so that all electrons in $S(v_x, v_y, t_0)$ reaches an RFA before $t = t_B$. Then the number of observed electrons within the velocity space volume $dv_x dv_y$ around (v_x, v_y) is given by,

$$dN_e = dv_x dv_y \int_{S(v_x, v_y, t_0)} \rho(v_x, v_y . x, y, t_0) L dx dy \cdot \qquad (8)$$

Therefore, the total number of electrons per positron bunch observed with a biased RFA is,

$$N_e = \int dv_x dv_y \int_{S(v_x, v_y, t_0)} \rho(v_x, v_y . x, y, t_0) L dx dy \cdot \qquad (9)$$

To see the assumptions in our model more clearly in this formalism, we introduce Eq. (6) in this expression. Then we get,

$$\begin{aligned} N_e &= \int \rho_{AV} D(v_x, v_y) dv_x dv_y \int_{S(v_x, v_y, t_0)} L dx dy \\ &\quad + \int dv_x dv_y \int_{S(v_x, v_y, t_0)} \Delta(v_x, v_y, x, y) L dx dy \\ &= \rho_{AV} L \int S(v_x, v_y, t_0) D(v_x, v_y) dv_x dv_y \\ &\quad + \int dv_x dv_y \int_{S(v_x, v_y, t_0)} \Delta(v_x, v_y, x, y) L dx dy \\ &= \rho_{AV} L \cdot (\text{averaged observed area}) \\ &\quad + \begin{pmatrix} \text{correction mainly due to} \\ \text{the spatial nonuniformity} \end{pmatrix} \end{aligned} \cdot \qquad (10)$$

According to this formalism, approximations adopted in our model are expressed as,

$$\begin{aligned} S &\equiv \int S(v_x, v_y, t_0) D(v_x, v_y) dv_x dv_y \cong S(0,0,t_0) \\ R &\equiv \frac{\int dv_x dv_y \int_{S(v_x, v_y, t_0)} \Delta(v_x, v_y, x, y) L dx dy}{\rho_{AV} S L} << 1 \end{aligned} \,. \qquad (11)$$

All quantities appeared in this expression can be calculated by the simulation on the electron motion. Then we will have an evaluation on the accuracy of our estimation. Of course, by direct comparison between the estimated density and the simulated density, we can evaluate the accuracy of the measurement. In this case, however, such factor as the efficiency of an RFA comes into as an ambiguity. To see the validity of physics included in our idea, above evaluation is superior.

For a drift space, one of the authors has shown [3],

$$\begin{aligned} S &\approx S(0,0,t_0)\times(1\pm 0.05). \\ R &\approx 0.01 \end{aligned} \quad (12)$$

Thus, our working model gives sufficiently good estimation of the density in a drift space.

ESTIMATED ELECTRON CLOUD DENSITY

The measurement of the electron cloud density was performed for several bunch patterns. Here, the results for 6 ns bunch spacing are presented. In LER the bunch current of 1 mA corresponds to the bunch population of 6.3×10^{10}. The vacuum duct is made of OFC.

The number of electrons that enter an RFA per bunch is calculated from DC current measured by RFA, so it is average. The density is obtained by estimating $S(0,0,t_0)$ for a given geometry of measurement. The efficiency of the RFA is assumed to be determined by geometry only.

The estimated density corresponds to the density close to the beam and just before the interaction with a bunch.

In a Drift Space

In a drift space, RFA is attached to a pump port. The schematic view is given in Fig. 1. The pump port is separated from the beam with a grid that has deep slots facing the beam which are backed up with thin bars.

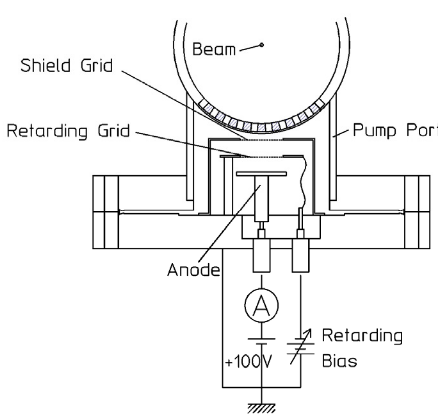

Figure 1: Schematic view if RFA at a pump port.

For a drift space, we use an analytical expression for $S(0,0,t_0)$ given by assuming a point bunch,

$$S(0,0,t_0) = F r_e^2 N_B^2 \frac{m_e c^2}{e V_b}, \quad (13)$$

where F is a reduction factor determined by the geometry of measurement and in general by the detector efficiency. In this example, only geometrical condition is considered. The remaining factor is an cross sectional area that is limited by the bias of an RFA (V_b).

Figure 2 shows an example of density estimation in a drift spaces. The effect of various surface coating is compared. The location of this measurement is in the middle of 200m straight section. The last bending magnet in the arc is nearly 100m far. Therefore the direct synchrotron radiation is negligible. The divergence of the density at low bunch currents is not real. It is because the detection limit is given as a constant current. The density is of the order of 10^{-11} m^{-3} and smaller than an arc section (typically ~10^{-12} m^{-3}, not shown here). This is due to the difference of the intensity of direct synchrotron radiation. The bump at around the bunch current of 0.9 mA is considered as a kind of trapping effect which depends on the bunch space.

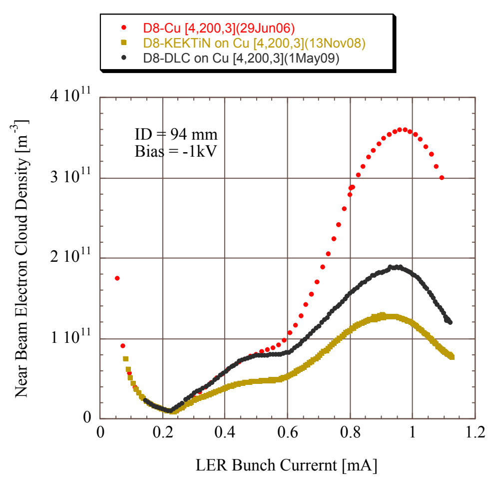

Figure 2: An example of the density estimation in a drift space. The effect of TiN coating and DLC (Diamond Like Carbone) is compared with copper surface.

In a Solenoid Field

In a solenoid field, electrons accelerated in the neighbour of a bunch must have an energy larger than a certain value to reach the duct wall, which is determined by the radius of the beam duct and the intensity of the magnetic field. For the detector on the duct wall, energy selection is thus automatic. The opening of the detector is set vertically to the wall and hidden in a groove of the wall. The detector needs in principle only a collector. However, actually it also has a retarding grid which is used to reject electrons migrating along the wall (Fig. 3).

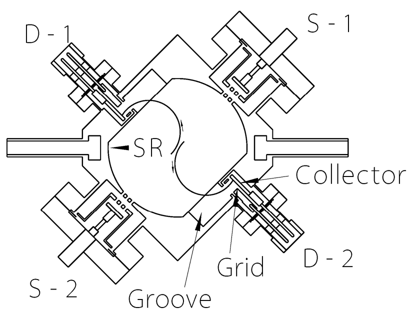

Figure 3: Cross section of the detector system for the measurement in a solenoid field. Detectors S-1 and S-2 are a standard RFA and are used to estimate the density without a solenoid field. Detectors D-1 and D-2 are used under a solenoid field. The diameter of the duct is 92 mm. Typical orbits of the electron which the detectors are expected to catch are shown. SR shows the location exposed to direct synchrotron radiation.

The observed area is calculated using a number of subroutines of CLOUDLAND [4]. At first, electrons are stationed on the grid of 0.1 mm by 0.1 mm in the transverse plane of the beam. Then, the motion of electrons after the interaction with a bunch is numerically traced. The initial position of electrons that enter the detector within 6 ns after passing of a bunch is marked on the grid. The time limit of 6 ns is selected for the present operational pattern of LER. The real size of a bunch at the location of measurement is used in the calculation. The bunch length is 6 mm.

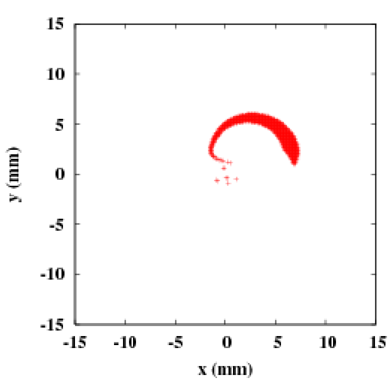

Figure 4: The observed area in a solenoid field. The bunch passes the centre (0, 0). The solenoid field is 50 G. The location of the detector is downward (different from Fig. 3).

Figure 4 shows the observed area for a solenoid field for the bunch current of 1.2 mA and B = 50 G. The area is confined around the beam as expected. Note in Fig. 4, the direction of the detector is downward. The observed area was calculated for different bunch currents and fitted by a polynomial of the bunch current. For both cases the area is nearly proportional to the square of the bunch current.

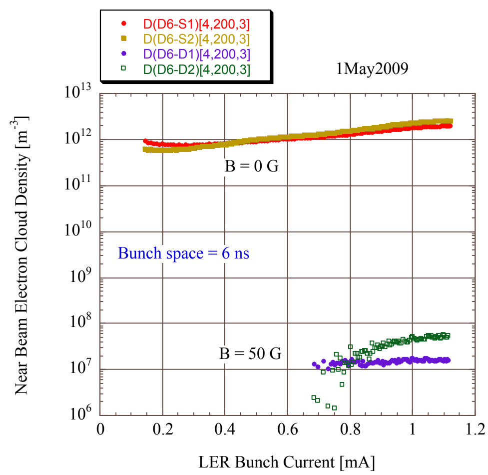

Figure 5: Electron cloud density with and without a solenoid field.

The solenoid coil with the inner diameter of 400 mm and the length of 530 mm was prepared to produce the central field of 50 G. The density without a solenoid field is estimated by standard RFAs. Under the solenoid field, two detectors D-1 and D-2 (see Fig. 3) show a large difference in measured currents. The ratio of both current is independent of bunch patterns. The difference is due to a background current that is proportional to the total beam current and is independent of bunch patterns. It is larger in the detector D-2 whose opening faces the surface directly illuminated by synchrotron radiation. This background was understood to be photo-electrons due to the reflected synchrotron radiation which are produced on the grid that is biased -100 V. For the estimation of cloud density, this background is subtracted. The remaining currents become similar for both detectors.

Figure 5 shows the comparison of the densities as a function of the LER bunch current, with and without a solenoid field. By applying the solenoid field of 50 G, the density becomes lower by four orders of magnitude. The effectiveness of the solenoid field is first demonstrated by the direct measurement of cloud density. The estimated density can be the upper limit of the central density. Simulations give the upper limit of 10^6 m^{-3} [5].

In a Quadrupole magnet

In a quadrupole magnetic field, electrons accelerated towards the magnet pole move spirally around the B-axis shown in Fig. 2, losing their energy along this axis to the spiral motion around this axis. An RFA is set in front of the magnet pole. Only here, electrons from the neighbour of the beam can be observed. The retarding bias of the RFA selects longitudinal energies along the above mentioned axis (Fig. 6).

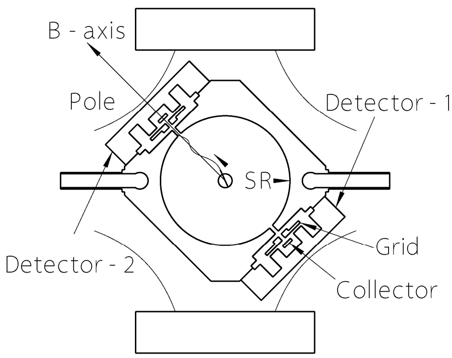

Figure 6: Cross section of the detector for a quadruple magnet. The detector opening is in front of the magnet pole. A sketch of an electron orbit that enters the detector is shown. The diameter of the duct is 94 mm. SR shows the location exposed to direct synchrotron radiation.

The observed area for a quadruple magnetic field case is calculated similarly as the case in a solenoid field. Figure 7 shows the result for a quadrupole magnetic field for the bunch current of 1.2 mA and the field gradient of -3.32 Tm^{-1}. The direction of the detector is up-left. The big ‘island’ in Fig. 7 is an expected region by rough analysis. The small islands correspond to electrons that get longitudinal velocity (normal to the figure) after the interaction with a bunch. In estimating an observed area, all points are included.

Figure 8 shows the density estimation in the quadrupole magnet QA1RP.Two detectors give different estimations of density though the general feature of two curves looks similar. This difference is observed to be sensitive to the position of beam orbit. It was not tried to adjust the beam to match the two curves. The green squares are the densities calculated by CLOUDLAND. Agreement with simulation is rather good for our way of approximation. From simulation, it has been long claimed that the central density in a quadrupole magnet is about two orders of magnitude lower than a typical drift space density. This measurement confirmed the assertion for the first time.

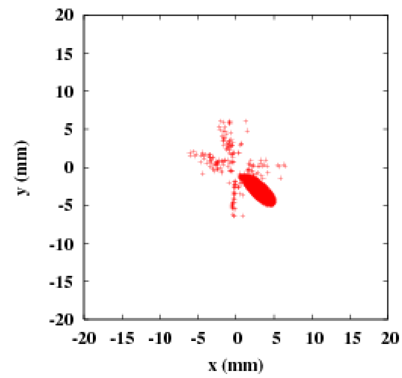

Figure 7: The observed area in a quadruple magnetic field. The field gradient is -3.32 Tm^{-1}. The location of the detector is top-left. Electrons whose energy of the motion in the direction normal to the detector is larger than 1 keV are selected (not selected by the total energy).

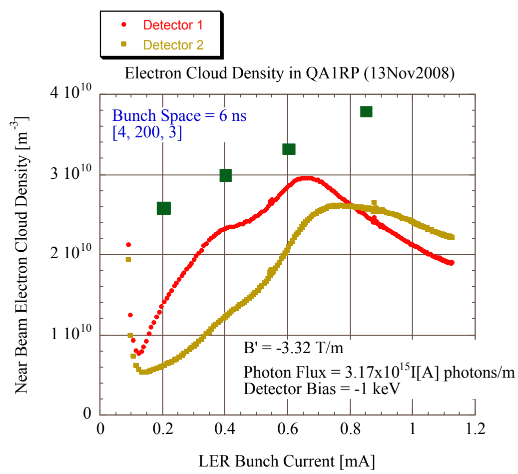

Figure 8: Electron cloud density in the quadrupole magnet QA1RP.

SUMMARY

We proposed an idea to estimate the electron cloud density using a high energy electron current measured with RFA and a calculated volume neglecting their initial velocity before the interaction with the bunch. To evaluate the accuracy of this estimation, the process of the measurement is analyzed using the phase space density for the motion of electrons in the transverse plane of the beam. The expressions that can evaluate the accuracy of the estimation with the help of simulation are obtained. One of the authors has shown that the accuracy for a drift space is within $\pm$5% error [3]

Estimated densities in a drift space give reasonable values. Based on our idea, it is found that the near beam cloud density is reduced by more than four orders of magnitude when a solenoid field of 50 G is applied. The estimated density in a quadrupole magnet is close to the value obtained by simulation.

Judging from these estimated densities, our idea seems to provide one of a reasonable method to estimate the local electron cloud density. The evaluation of the accuracy for measurements in a solenoid field and in a quadrupole magnet still remains.

ACKNOWLEDGEMENT

The authors wish to express sincere thanks to H. Hisamatsu for his preparation of detector electronics and to M. Tobiyama for his effort to stabilize stored beam during measurement.

REFERENCES

[1] K. Kanazawa, H. Fukuma, H. Hisamatsu, and Y. Suetsugu, “Measurement of the Electron Cloud Density around the Beam”, PAC’05, Knoxville, Tennessee, June 2005, FPAP007, p. 1054 (2005); http://www.JACoW.org.

[2] K. Kanazawa, and H. Fukuma, “Measurement of the Electron Cloud Density in a Solenoid Coil and a Quadrupole magnet at KEKB LER”, IPAC’10, Kyoto, Japan, May 2010, TUPD041, p. 2015 (2010); http://www.JACoW.org.

[3] P Jain, H. Fukuma, K. Kanazawa, and Y. Suetsugu, “Analysis of the Measurement of Electron Cloud Density under Various Beam-optics Elements in KEKB LER”, IPAC’10, Kyoto, Japan, May 2010, TUPC050, p. 1835 (2010); http://www.JACoW.org.

[4] L. F. Wang, H. Fukuma, K. Ohmi, S. Kurokawa, K. Oide, and F. Zimmermann, “Numerical Study of the Photoelectron Cloud in KEKB Low Energy Ring with a Three-Dimensional Particle in Cell Method”, Phys. Rev. ST-AB 5 (2002) 124402.

[5] L. Wang, H. Fukuma, K. Ohmi, and Y. Suetsugu, “3D Simulation of Photoelectron Cloud”, PAC’01, Chicago, Illinois, June 2001, FOAB010, p. 701 (2001); http://www.JACoW.org.