MEASUREMENT OF THE ELECTRON CLOUD DENSITY IN A SOLENOID COIL AND A QUADRUPOLE MAGNET AT KEKB LER*

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Abstract

The near beam electron cloud density in a magnetic field was estimated with a simple electron current detector at KEKB LER. The estimation is based on the assumption that high energy electrons which hit a chamber wall come directly from the region around the beam after the interaction with a circulating bunch. The first successful application of this idea for drift spaces was reported at PAC05 by the authors [1]. In a solenoid field of 50 G, the near beam cloud density is reduced by about four orders of magnitude compared to the no field case. In a quadruple magnet, the density around the beam is by two orders of magnitude lower than the density in drift spaces, as most simulations show.

INTRODUCTION

Electrons in the duct of positively charged beams grow in number through the interaction with the beam and with the duct wall. Resulting 'electron cloud' seriously affects the quality and the stability of a high-current beam. The positron storage ring of KEK B-Factory (LER) has been suffering from the electron cloud problem in increasing the stored current to achieve a higher luminosity. As the mitigation, solenoid coils were wound around the beam duct in drift spaces as possible as the space allows. This resulted in a certain amount of improvement in the beam behaviour [2]. At the same time, several retarding field analyzers (RFAs) are installed at a pumping port of the ducts in drift spaces to monitor the electron current showering on the duct wall from the cloud.

Most of the 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.

Obviously the peak consists of electrons accelerated by the high electric field near the circulating bunch. Since the electric field of a relativistic bunch is contracted into the transverse direction of the beam, the motion of electrons is essentially two-dimensional. 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

*Work supported by The Japan/US Cooperation Program

initial energies of electrons is small because the energy of most electrons before the interaction is of the order of few×10 eV. If the retarding bias is set so that electrons in the corresponding area 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]. In the previous paper, an approximation is proposed 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 is estimated as:

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

This idea was first applied to drift spaces and gave a reasonable estimation of density [1]. In this paper, the idea is applied to the measurement in a solenoid field and in a quadrupole magnetic field. The purpose of this paper is to explain this application and to show some results.

DETECTOR DESIGN AND OBSERVED AREA

The detectors are designed so that they can catch the high energy electrons which come from the region around the beam in a given magnetic field.



Figure 1: 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.

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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.



Figure 2: 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.

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.



Figure 3: The observed are 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. 1).

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. For other bunch patterns, this is an approximation. The real size of a bunch at the location of measurement is used in the calculation. The bunch length is 6 mm. The result is shown in Fig. 3 and Fig. 4 for the bunch current of 1.2 mA. Figure 3 shows the observed area for a solenoid field. The area is confined around the beam as expected. Note in Fig. 3, the direction of the detector is downward. Figure 4 shows the result for a quadrupole magnetic field. The direction of the detector is up-left. The big 'island' in Fig. 4 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. 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 4: 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).

ESTIMATION OF THE 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.

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 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

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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].



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



Figure 6: Electron cloud density in the quadrupole magnet QA1RP.

Quadrupole Magnet

Figure 6 shows the results in the quadrupole magnet QA1RP. The magnet has a large bore radius of 83 mm, and the field gradient is -3.32 Tm⁻¹.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.

SUMMARY

The near beam electron cloud density was estimated with RFA for the electron cloud in a magnetic field using an approximation that electrons are at rest before the interaction with a bunch. 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 the estimated density, the idea explained in this paper seems to provide one of a reasonable method to estimate the local electron cloud density. On the validity of the assumption used in calculating an observed area, a detailed study by simulation is now underway [3].

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.

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