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- 3. Typical estimations of the cloud density under different magnetic fields.



What simulation tells

Drift space as an example

The initial position of high energy electrons at $t = t_0$.



The initial position of the electrons that enter the biased RFA.



High energy electrons are still confined around the beam. However the spatial boundary is blurred due to the initial velocity distribution. The position of the observed electrons spreads and overall shape is blurred and deformed due to the initial velocity distribution.

How the number of the observed electrons is related to the density around the beam when electrons have a velocity distribution?

Analysis of the measurement with a biased RFA

Use the density in the phase space.

Only consider the motion in the transverse plane.

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

Only consider the region around the beam: S_0 .

 S_0 : Circular region around the beam that contains 99% (for example) of high energy ($E > eV_b$) electrons in the duct dross section.



Some definitions

Average density around the beam (at $t = t_0$)

$$\rho_{av} \equiv \frac{1}{S_0 L} \int dv_x dv_y \int_{S_0} \rho(v_x, v_y, x, y, t_0) L dx dy$$

(Average) velocity distribution around the beam (at $t = t_0$)

$$D(v_{x}, v_{y}) \equiv \frac{1}{\rho_{av}S_{0}L} \int_{S_{0}} \rho(v_{x}, v_{y}, x, y, t_{0}) L dx dy, \quad \int D(v_{x}, v_{y}) dv_{x} dv_{y} = 1$$

Rewrite the phase space density

$$\rho(v_x, v_y, x, y, t_0) = \rho_{av} D(v_x, v_y) + \Delta(v_x, v_y, x, y)$$

The newly introduced function $\Delta(v_x, v_y, x, y)$ satisfies,

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

Number of observed electrons



To calculate the number of electrons observed with the biased RFA (N_e) , we think as follows:

The positions of electrons that have a velocity (v_x, v_y) at $t = t_0$ and are observed with a biased RFA, fill a specified region $S(v_x, v_y, t_0)$ within S_0 .

The observed number of such electrons is given as:

$$dN_{\rm e} = dv_{x}dv_{y} \int_{S(v_{x},v_{y},t_{0})} \rho(v_{x},v_{y},x,y,t_{0}) Ldxdy$$

Therefore, the total number of electrons observed with the biased RFA is:

$$N_{e}(\text{per bunch}) = \int dv_{x} dv_{y} \int_{S(v_{x},v_{y},t_{0})} \rho(v_{x},v_{y},x,y,t_{0}) L dx dy$$

Final expression

Relation between the number of observed electrons and the density around the beam

Combining the expressions in previous slides, one obtain the relation between the number of observed electrons and the density around the beam

$$N_{e} = \int \rho_{av} D(v_{x}, v_{y}) dv_{x} dv_{y} \int_{S(v_{x}, v_{y}, t_{0})} Ldxdy + \int dv_{x} dv_{y} \int_{S(v_{x}, v_{y}, t_{0})} \Delta(v_{x}, v_{y}, x, y) Ldxdy$$
$$= \rho_{av} L \int S(v_{x}, v_{y}, t_{0}) D(v_{x}, v_{y}) dv_{x} dv_{y} + \int dv_{x} dv_{y} \int_{S(v_{x}, v_{y}, t_{0})} \Delta(v_{x}, v_{y}, x, y) Ldxdy$$
$$= \rho_{av} L \times (\text{average observed area}) + \begin{pmatrix} \text{correction mainly due to the nonuniformity} \\ \text{of the spatial density} \end{pmatrix}$$

Working model and its evaluation

•Conditions used in the working model according to this formalism.

$$S \equiv \int S(v_x, v_y, t_0) D(v_x, v_y) dv_x dv_y \approx S(0, 0, t_0) \int D(v_x, v_y) dv_x dv_y = S(0, 0, t_0)$$

$$R \equiv \frac{\int dv_x dv_y \int \Delta(v_x, v_y, x, y) L dx dy}{\rho_{av} SL} \ll 1$$

By the simulation on the evolution of electron cloud and the simulation to calculate $S(v_x, v_y, t_0)$, one can evaluate the accuracy of the above approximation.

Drift Space [Puneet Jain, Thesis] $R \approx 0.01$ $S \approx S(0,0,t_0) \times (1 \pm 0.05)$

For a drift space our working model gives a good estimation of the electron cloud density.

•Evaluations for a quadrupole field and a solenoid field are still remaining.

Examples of estimation

 $S(0, 0, t_0)$ for various conditions



For a solenoid field, the energy range of observed electrons is determined by the geometry of detection.

Estimation of the electron cloud density in a drift space **RFA for a drift space**

Retarding field analyzer (RFA) type electron monitors are set at pump ports of KEKB LER.









Estimation of the electron cloud density in a drift space Effect of coatings



Direct synchrotron

radiation is negligible

Estimation of the electron cloud density in a drift space Synchrotron radiation and electron cloud



'a' represents the photon intensity of direct synchrotron radiation. (Linear photon density per meter) = (a/360)•(Total photon number)

Estimation of the electron cloud density in a solenoid field Detector chamber



groove



The entrance of RFA used without a solenoid field



Dimension of the solenoid





Electron cloud density in a solenoid field Cloud density with and without a solenoid field



Electron cloud density in a quadrupole magnet **Detector chamber**





Detector



QA1RP Bore radius = 0.083 m B' = -3.32 T/m Effective length = 0.5844 m Electron cloud density in a quadrupole magnet Cloud density in QA1RP



Simulation by CLOUDLAND Photon reflectivity: 0.3 Photo-electron yield: 0.1 $\delta_{MAX} = 1.2$ at 250 eV

> Two RFA's gave different estimation.
> The behavior of the density against the bunch current is qualitatively similar.

•The difference in two detectors is sensitive to COD.

The estimated density of the order of 10⁻¹⁰ m⁻³ in QA1RP is consistent with the simulation.

Summary and Remark

- The estimation of the electron cloud density with a biased RFA is based on a simplified working model. The evaluation of the accuracy of this estimation is possible by combining a formalism using a phase space density and simulations. For a drift space the estimation is shown to be a good approximation by Puneet Jain.
- Though there is no such evaluations for a solenoid field and a quadrupole field, the estimated electron cloud density with a biased RFA looks reasonable compared with simulations.
- For the measurement with RFA, there are other issues to be considered such as an efficiency of RFA in a magnetic field, photo-electron background from a grid etc.

Back-up Slides

Observation with MCP



• High energy electrons show sharp peaks that coincide with the bunch pattern.

Example of $S(v_x, v_y, t_0)$

 $i_{b} = 1.2mA$



<u>Understanding observed volume : a general case</u>

• Green curves show the distribution of kicked electrons entering into a hypothetical RFA one-hole opening.

• Region shown by red lines represents an area corresponding to an observed volume of the detected electrons.

• If $v_x < 0$, a mirror symmetrical curve about y-axis is obtained.

- Effect of v_y is less on the deformation of the observed volume compared to v_x .

$$(x^{2}+y^{2})[(y-y_{m})v_{x}-(x-x_{m})v_{y}] + 2cr_{e}N_{b}(xy_{m}-yx_{m})=0$$

[Puneet Jain]

Calculation of $S(0, 0, t_0)$ by simulation

•Put electrons at rest on the grid of 0.1 mm by 0.1 mm in the x-y plane that stands right in front of the detector.

Neglecting the initial energy of electrons is an approximation.

• Count the number of electrons that enter the detector within 6 ns (3 bucket space) after the interaction with a three dimensional bunch.

The time limit of 6 ns is for the present operational pattern of KEKB LER. For other bunch patterns, this is an approximation.

The bunch is longitudinally sliced into 100 pieces.

Each slice kicks electrons according to the Bassetti-Erskine formula.

•Volume = No. of electrons $\times 10^{-8}$ m² × detector length.

Electron cloud density in a solenoid field Detector design

• Given a solenoid field, only high energy electrons produced near the bunch can enter the groove and reach the detector behind it. (Energy range is determined geometrically.)

• With the help of simulation, the detector current is converted into the density near the beam.



RFA type

Electron cloud density in a solenoid field $S(0, 0, t_0)$ for different N_B



-15mm < x,y <15mm

Electron cloud density in a solenoid field Discussion on the measured current

Collector current for different bunch patterns





•Measured current with the old detector (above) always show a large difference between the detectors.

•To reject the effect of possible low energy electrons, a new detector with a grid is provided.

•The new detector shows the same tendency as the old detector (left).

•Both detector seem to have a background which is proportional to the total current.

Electron cloud density in a solenoid field Photon background

A plausible source of the background is a photo-electron current from the grid.

- •It is proportional to the total beam current and independent of bunch pattern.
- •It is larger in the detector 2 whose opening faces the surface directly illuminated by synchrotron radiation.

If the grid is positively biased, photons on a collector will be measured as a positive current. This is actually so, though the ratio of the current is different from the negatively biased case.

The effect of photon is also seen in the density estimation without a solenoid field at a low bunch current where S1 always shows higher value.



Electron cloud density in a solenoid field Cloud density with a solenoid field for different bunch patterns



Electron cloud density in a quadrupole magnet **Detector design**



In a quadruple magnetic field, electrons accelerated by a bunch along X-axis reach the detector.

Electrons accelerated with small angle to Xaxis moves spirally around X-axis losing their energy along Xaxis to the spiral motion.

Electrons with sufficient energy and direction close to X-axis reach the detector.

With the help of simulation detector current is converted into the density near beam.

Electron cloud density in a quadrupole magnet $S(0, 0, t_0)$ for different N_B





-20mm < x,y < 20mm

Electron cloud density in a quadrupole magnet Cloud density in QA1RP with different bunch patterns

