PHOTOELECTRON TRAPPING IN ELECTRIC AND MAGNETIC FIELD

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Abstract

Trapping is a general phenomenon of photoelectron cloud. Photoelectron can be strongly trapped by the positron/proton beam electric field and mirror magnetic field. The electron cloud density increases due to the trap and the trap causes the lifetime of the electron cloud longer. The photoelectrons in drift region can be strongly trapped by the positron or proton beam electric field. There is a novel photoelectron-trapping phenomenon in the quadrupole and sextupole magnetic fields. The trapping phenomenon is strongly beam-dependent, especially on the bunch length. The trapped electron cloud can cause multi-bunch instability due to the long trapping time. The phenomenon and mechanism of photoelectron trapping in different magnetic and electric fields are studied.

1 INTRODUCTION

Photoelectron cloud has been studied in numerical and experimental way in many laboratories. Among them, trapping of photoelectron cloud is one main phenomenon and is very important for the build-up of the photoelectron cloud. It was observed that the photoelectrons could be trapped in the combined dipole magnetic field and quadrupole electrostatic leakage field from the distributed ion pumps [1]. One novel trapping of the photoelectrons in quadrupole and sextupole magnetic fields has been found in the numerical study of electron cloud of KEKB LER [2]. Machine study shows that there is still coupled bunch instability due to the electron cloud when all solenoids are turn on. The electron cloud trapped in quadrupole and sextupole magnets may be the remainder of the source of the coupled bunch instability. Experiment study in KEKB found that the coupled bunch instability due to the photoelectron cloud is very similar in the horizontal and vertical plane when solenoid is off [3]. This suggests a round electron cloud distribution in transverse section of the vacuum chamber. However, the photoelectrons are emitted non-uniformly because most of electrons are preliminary electrons. Simulation study confirms this result. The trap of photoelectron in the beam electric field can explain the physics of this phenomenon. The trapped photoelectrons may cause blow-up and coupled bunch instability of the proton or positron bunch. The trapping phenomenon in different electric and magnetic fields has been studied in this paper.

2 TRAPPING BY BEAM FIELD IN DRIFT REGION

Photoelectrons near the bunch can receive linear beam kick from the bunch and can get temporarily trapped in the beam potential as shown in FIGURE 1, and will thus oscillate around the bunch. The photoelectron near the beam oscillates about one period during the passage of one positron bunch in KEKB LER case. However, it can oscillate many periods in the proton bunch due to the longer proton bunch-length. The oscillation frequency of the trapped photoelectron is

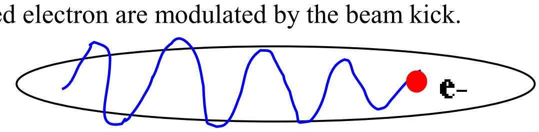
$$\omega_{x,y} = \sqrt{\frac{2r_e\lambda}{\sigma_{x,y}(\sigma_x+\sigma_y)}} \qquad (1)$$

where λ is linear density of beam charge.

Photoelectrons at large amplitude do not move much during the bunch passage due to their long oscillation period and simply receive a non-linear kick. It is interesting that most photoelectrons with large amplitude can still be trapped as shown in the Figure 2. The photoelectrons with small initial energy emit from the chamber wall and oscillate under the focusing beam force. They get energy during the process going close to the chamber center. The relationship of the energy and radial coordinate of the strongly trapped photoelectrons can be very roughly expressed as

$$\ln\varepsilon = -k(r-r_0) \quad (r < r_0), \qquad (2)$$

where r_0 is the radial coordinate with very small energy(almost zero). Figure 3 shows the energy and radial coordinate of the strongly trapped electron as shown in Fig. 2(left). The energy and radial coordinate of the trapped electron are modulated by the beam kick.



Proton/Positron bunch

Figure 1 The electron motion during a bunch passage

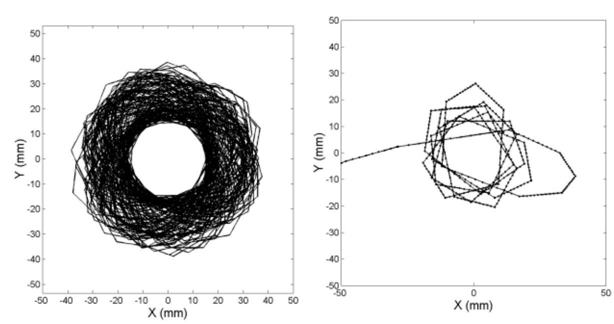


Figure 2 Orbit of tapped electron. Left: long time trapped electron; Right: short time trapped electron

As a result, photoelectron trapping in the beam field is one important phenomenon. This mechanism leads to the uniform distribution of the photoelectron cloud in the beam chamber although most photoelectrons are emitted in horizontal direction (preliminary photoelectron), and then such a round distribution of the cloud causes the same coupled bunch instability in horizontal and vertical direction [3]. Figure 4 shows the electron cloud distribution in transverse plane where all photoelectrons are preliminary photoelectron. The cloud distribution is roughly uniform with the azimuth angle due to the trap effect. There are more photoelectrons along the emission direction of preliminary photoelectron because these electrons basically oscillate in horizontal plane instead of a circle around the chamber centre due to their very small initial vertical velocity and coordinate.

The trapped photoelectron has short decay time during the bunch train separation because the trap mechanism is positron/proton bunch dependent.

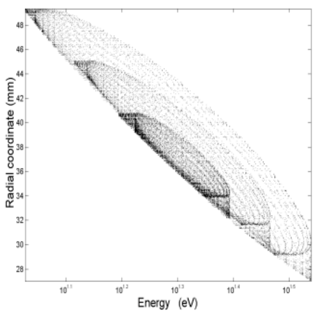


Figure 3 Energy and radial coordinate of a trapped electron

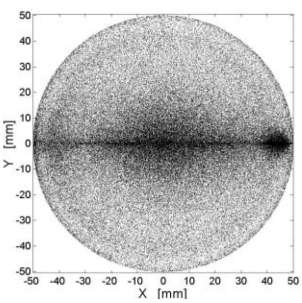


Figure 4: photoelectron cloud distribution in transverse plane

3 TRAPPING IN QUADRUPOLE AND SEXTUPOLE MAGNETS

A novel trapping of the electron in quadrupole and sextupole magnets has been found in the numerical study of electron cloud [2][4]. The photoelectron density is almost constant during the train gap in these two fields. It indicates that the photoelectrons have very long lifetime. Figure 5 shows one typical trapped electron orbit in normal quadrupole field during the bunch train gap. The drift time is about 960ns. There is a very similar trapping phenomenon in sextupole magnet.

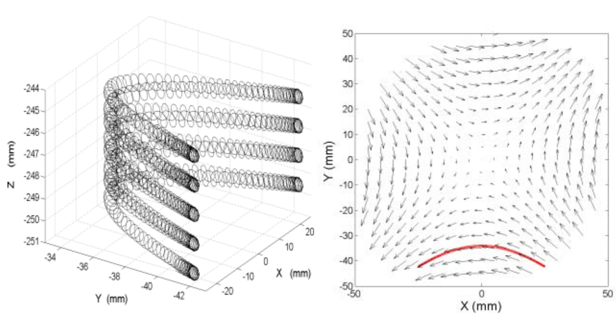


Figure 5 Photoelectron Trapping in Quadrupole Magnetic Field During the Bunch Train Gap. Left: 3D orbit; Right: 2D orbit (red line) and quadrupole field (black arrow)

The trapping mechanism is mirror field trap. The magnetic field of quadrupole and sextupole magnets is mirror field, in which magnetic filed is weaker at the centre of the field line and is stronger at both ends of the field line. We consider the case in which the magnetic field slowly varies in space. The variation is assumed to be sufficiently slow that the magnetic field at the electron position hardly changes during the cyclotron motion. For such a quasi-periodic motion, there exists one adiabatic invariation given by [5]

$$J_\perp = \oint m\upsilon_\perp \rho_s d\varphi = 4\pi m\mu_m / e\,, \qquad (3)$$

where

$$\mu_m = m\upsilon_\perp^2 /(2B) \qquad (4)$$

is the magnetic moment, $\upsilon_\perp$ is the gyration velocity, $\rho_s = m\upsilon_\perp /(|e|B)$ is the Larmor radius and $\upsilon_{\parallel}$ is the parallel or longitudinal velocity which is parallel to the magnetic field.

As the guiding center of the electron moves along the field line the magnetic field strength at the electron changes. Because the magnetic moment and kinetic energy of the electron are conserved, the kinetic energy of the parallel motion varies according to the relation

$$\frac{1}{2} m\upsilon_\parallel^2 + \mu_m B = const\,. \qquad (5)$$

When the guiding center of electron moves along the field line from weaker field region to stronger field region, the parallel velocity decreases and the gyration velocity increases. Therefore, the electron spirals in an ever-tighter orbit because the period of gyration motion and parallel velocity become smaller and smaller. When the electron comes to the point where the parallel velocity vanishes, the electron direction of motion is reversed. The parallel velocity of the reflected electron is increased when it moves along the field line and gets maximum value at the weakest field point (mirror point). Then it continues a similar motion along the other side of the mirror point. The trap happens if

$$\frac{\upsilon_{\perp 0}^2}{\upsilon_{\perp 0}^2 + \upsilon_{\parallel 0}^2} > \frac{B_0}{B_{\max}}\,, \qquad (6)$$

where B_0 is the field at one position with velocity $\upsilon_{\parallel 0}$ and $\upsilon_{\perp 0}$. The trap condition Eq.(6) can be more conveniently described as

$$\Gamma_{trap} > 1 \qquad (7)$$

with the trap factor

$$\Gamma_{trap} = \frac{F_\upsilon}{F_B} = \frac{\upsilon_{\perp 0}^2}{\upsilon_{\perp 0}^2 + \upsilon_{\parallel 0}^2} \frac{B_{\max}}{B_0}\,. \qquad (8)$$

Where F_υ and F_B is left and right part of Eq. (6), respectively. When the trap factor Γ_{trap} is bigger than 1, the electron is trapped. If the space charge force of the positron bunch and the electron cloud didn't disturb the electron during the whole drift process, the trap factor would be a constant value at any time with $\Gamma_{trap} = \upsilon_\perp^2 /(\upsilon_\perp^2 + \upsilon_\parallel^2)\,|_{at\ chamber\ surface}$ and it's always smaller than 1. Therefore, the electron couldn't be trapped if there was no other force, for instance, in the beam line of a light source.

According Eqs. (7-8), a photoelectron could be trapped if its kinetic energy of gyration motion increases. The electron can receive the energy of gyration motion around the mirror point where the electric field direction of positron bunch is in the gyration motion plane. However, a short bunch is required for the electron to efficiently receive the energy of gyration motion because the effect of a long positron bunch on the gyration motion energy can cancel over many periods of gyration motion. Therefore, a short positron bunch, when compared with the cyclotron period at the mirror point, is very effective to increase the photoelectron energy distribution F_υ by increasing the kinetic energy of the gyration motion and then can cause the trapping of the photoelectrons.

The orbit surface of the drift motion in the translationally symmetric quadrupole and sextupole field is given by $A_z = const.$ Where **A** is the vector potential of the magnetic field. Therefore, the orbit of the guiding center is the magnetic field line, which is clearly shown in FIG. 5 with $A_z = A_2(x^2 - y^2)$ for normal quadrupole field.

Besides the movement along the field line, the guiding center also moves along z-direction, which is the positron beam direction, as shown in FIG. 5. The drift along z-direction is due to the magnetic field gradient drift and the centrifugal force. The gradient of the magnet field causes the electron drift in the direction perpendicular to the magnetic field, **B** and the gradient of the field, **∇B** [5]

$$\boldsymbol{\upsilon}_{grad} = \frac{m\upsilon_\perp^2}{2eB^3}\mathbf{B}\times\nabla\mathbf{B}\,. \tag{9}$$

Where e is the charge of an electron with $e<0$.

Now we consider a curved magnetic field line as in the case of the quadrupole and sextupole magnets. The guiding center motion that follows the field line is deflected along the curve and as a result the electron undergoes an inertial force or a centrifugal force perpendicular to the field line

$$\mathbf{F}_c = \frac{m\upsilon_\parallel^2\mathbf{R_B}}{R_B^2} = \frac{m\upsilon_\parallel^2}{R_B}\mathbf{n}\,. \tag{10}$$

where **n** is the unit vector normal to the field line and R_B is the radius of local curvature of the magnetic field line. Therefore, the drift velocity of the guiding center due to the force $\mathbf{F_c}$ is

$$\boldsymbol{\upsilon}_F = \frac{\mathbf{F}_c\times\mathbf{B}}{eB^2} = \frac{\mathbf{n}}{B\Omega_s}\times\frac{\mathbf{B}}{R_B}\upsilon_\parallel^2 \tag{11}$$

The total drift velocity of the guiding center along z-direction is the sum of $\boldsymbol{\upsilon}_{grad}$ and $\boldsymbol{\upsilon}_F$. The average longitudinal drift velocity over one period of the parallel motion between the two turning points, which decides the trapping time of the electron, is

$$\bar{\bar{\upsilon}}_{gz} = \frac{1}{\oint dl/\upsilon_\parallel}\oint\frac{\bar{\upsilon}_{gz}}{\upsilon_\parallel}dl\,, \tag{12}$$

Most trapped photoelectrons in quadrupole and sextupole magnet have smaller $\bar{\bar{\upsilon}}_{gz}$ with level 10^{-3} mm/ns. The length of the quadrupole and sextupole magnets in KEKB LER is 0.4 m. Therefore, the quadrupole and sextupole magnetic field can strongly trap the photoelectrons for a very long time with level 10^5 ns until them drift out of the magnets in the beam direction. The revolution time of the positron beam around the accelerator is about 1×10^4 ns in KEKB LER. Therefore, most photoelectrons can be trapped more than one revolution time. As a result, the trapped photoelectrons can cause multi-turn effects to the positron beam.

4 TRAPPING IN SOLENOID FIELD

Solenoid has been installed in the LER ring in order to clear the photoelectron near the beam. The periodic solenoid field can also trap less than 1% of photoelectrons. The trap mechanism is still mirror magnetic field trap. Uniform field is better to confine the photoelectron to the vicinity of the vacuum chamber wall [6]. Therefore solenoids have been installed with equal polarity configuration. F_B is larger for such kind of solenoid field. One electron can receive gyration motion energy during the passage of one positron bunch due to the short bunch length. However, the energy gain is very small because the photoelectron is confined far from the positron bunch. Therefore, the photoelectron can't be trapped just after the passage of one positron bunch due to the small gyration energy gain and larger F_B. As a result, photoelectrons will move along the field line in beam direction. The average gyration energy gain over the multi-bunch passages may cancel. Therefore, the percentage of the trapped photoelectrons in such kind of solenoid field is much smaller compared with that in the strong quadrupole and sextupole fields.

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