Proposal of the Experiment on Direct Observation of e-cloud *

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Abstract

Measurements of the attenuation of the rf wave can be used for direct observation of the electron cloud in LER positron ring. A simple experiment is suggested. Estimates show that damping of the rf wave proportional to the density of the electron cloud should be possible to detect.

0.1 Introduction

Electron cloud in a positron storage ring can be generated by the primary synchrotron radiation (SR) or by the beam induced multipactoring provided the yield of the secondary electrons is more than one [1] [2].

The electrons may be trapped in the average potential well of the positron beam and the electron density initially grows linearly in time. It is usually assumed that the density at saturation is limited by the space charge of accumulated electrons. In this case, the density is given by the condition of neutrality: $n_e = \eta N_b / (S s_b)$, where N_b is bunch population, $S \propto \pi b^2$ is the beam pipe cross-section area, and η is the coefficient of neutrality. The energy of the electrons are of the order of $E \propto 2\pi m c^2 n_e r_0 b^2$. For a train of bunches, the electron cloud can reach saturation density after 20-30 bunches.

At $\eta = 1$ and for the nominal parameters of the LER of PEP-II, $N_b \propto 6 \cdot 10^{10}$, $b \propto 3.5$ cm, $s_b = 128$ cm, the density at saturation $n_e \propto 10^7$, and $E_e \propto 60$ eV. Actual η is lower, and the simulation show that n_e is of the order of 10^6 and typical $E \propto 10$ eV. If the secondary electron yield is less than one, the average density of electrons is given by the flux of SR. Estimates show that in this case the density of electron cloud is not much smaller, and is of the order of 10^5 [5] [4].

In the dipoles of the arcs, electrons of the cloud move vertically along the magnetic field lines and rotate in the horizontal plane with Larmor frequency $\omega_l = eH/mc$. The secondary electrons are produced in collisions with the upper and lower decks of the beam pipe. If the average field of the beam confines electrons vertically, the density grows in time proportional to the production rate of primary electrons. The $E \times B$ drift is slow and does not affect much the density especially for a beam with a clearing gap.

The dynamics of the cloud is quite complicated. The electron cloud is only in dynamic equilibrium and oscillates being driven by the passing bunches. The

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electrons at small distances r from the beam get a strong kick $v/c \propto 2N_b/r$ and get energy large enough both to reach the wall before the next bunch comes and produce secondary electrons. They are replaced by other electrons which are attracted by the beam.

The adverse effects of the electron cloud include both pressure rise due to induced desorption from the wall, coupled-bunch instability of the beam and the emittance growth [3] [6]. The growth rate predicted for the e-cloud induced instability is much stronger than the growth rate of conventional instabilities. All these effects may be quite strong and have been observed in experiments.

However, existing experiments provide only indirect indication of the generation of the electron cloud and direct observation of the electron cloud is highly desirable.

0.2 Proposed Experiment

One of the way to do this is to measure the dipole radiation associated with the Larmor precession. However, such a radiation is very small. For LER dipoles, $B = 0.45$ T, Larmor frequency $f_L = \omega_L/2\pi = 20.9$ GHz, and the Larmor radius of 10 eV electrons is $r_l = 15 \mu$. Power radiated by a single dipole $d = er_l$, $P = 4\omega_L^4 r_0 E_e/3c$ is negligible small, $P = 2 \cdot 10^{-19}$ W. The power radiated by electrons with density $n_e = 10^6 \text{ cm}^{-3}$ from a LER dipole with length $L = 0.45$ m and $S = 45 \text{ cm}^2$ is only 0.3 nW.

The better way to observe the e-cloud density is to measure the frequency dependence of the damping of the rf wave propagating through a dipole. Such a wave can be induced in the beam pipe by the antenna which would replace one of the BPM button downstream from a dipole and feeded by a wave guide from the external rf source. The wave produces a signal on the pick-up antenna placed in the same way upstream from the dipole. The frequency of the wave, of the order of Larmor frequency of 20 GHz, is much higher than the cut-off frequency of the beam pipe. The absorption length of the wave due to finite resistivity of the walls of the order of several hundred meters and is negligible. Therefore, the frequency dependence of the signal should be flat except at the frequency equal to the Larmor frequency where the wave is in the resonance with Larmor precession of the electrons. At such a frequency, the wave leads to growth of the Larmor radius and corresponding increase of the rotation energy of electrons. This will be seen as a dip in the ratio of the signals of the receiver and antenna plotted as function of the rf frequency.

Locating of the receiver (antenna) upstream (downstream) from the dipole is beneficial in two respect: first, it allows gating of the receiver to avoid large signals from passing bunches, second, the signal which may be induced by the direct or scattered SR is reduced. The later signal is small anyway by two reasons. First, the spectral intensity I_n of the SR at the harmonic number $n = \omega_L c/\rho$ where ρ is radius of curvature (for LER, $\rho = 13$ m, $n \simeq 5.6 \cdot 10^3$) is of the order of $I_n/I = (4/3)n^{1/3}/\gamma^4$ compared to the total intensity I of the SR. Second, the SR at such low harmonics is suppressed by screening similar to coherent SR. Indeed, only waves with transverse

component of the wave vector $k_{\perp} > \pi/b$ can propagate in the beam pipe with radius b . Because radiation angle $\theta \simeq n^{-1/3}$, the harmonic $n = k\rho$, $k = \omega/c$, can be radiated only with frequencies $f > (c/2b)\sqrt{\rho/b}$. For LER parameters, the lower limit is about 30 GHz.

The average energy gain dU/dt of an electron interacting with the linearly polarized rf wave $E = E_0 \cos(qz - \omega t)$ is given by $dU/dt = e \langle (dx/dt)E \rangle$, where $x(t)$ is given by the equation $d^2x/dt^2 + \omega_L^2 x = eE(t)$. In the zero approximation, the time average $\langle \dot{x}E \rangle \neq 0$ only in the resonance $\omega = \omega_L$. We consider a wave with Fourier harmonics E_{ω} with the spectral density

$$\langle E_{\omega} E_{\omega'}^* \rangle = \frac{2\pi}{\Delta} E_0^2 \delta(\omega - \omega') e^{-(\omega - \omega_0)^2 / \Delta^2}, \quad (1)$$

with bandwidth Δ around ω_L , where E_0^2 defines the antenna generated rf power

$$P = \frac{cS}{4\pi} E_0^2. \quad (2)$$

In the resonance, the amplitude x_0 of oscillations $x(t)$ grows linearly in time, $x_0 = eE_0 t / (m\omega_L)$, and electron energy grows as x_0^2 . The maximum energy gain is set either by the loss of a particle at the wall due to growth of the radius or by detuning from a resonance due to γ -dependence of ω_L . The second constrain is stronger if $eE_0 b / mc^2 \gg (\Delta / \omega_L)^2$. The LHS here is of the order of $3 \cdot 10^{-5} \sqrt{P/Watt}$, i.e. of the order of $\Delta / \omega_L \simeq 10^{-5}$ for $\Delta \simeq 1$ MHz, and much smaller than $(\Delta / \omega_L)^2$. The second constrain defines maximum energy gain of an electron, $\Delta\gamma / \gamma = \Delta / \omega_L$, or $\Delta U = mc^2 \Delta / \omega_L$. The power absorbed by a single electron is

$$\frac{dU}{dt} = e \langle (dx/dt)E \rangle = \frac{e^2 E_0^2}{2m\Delta} = \frac{2\pi c r_0}{S\Delta} P, \quad (3)$$

where r_0 is classical electron radius. The ratio of the absorbed power per electron to the rf power is 10^{-9} for $\Delta = 1$ MHz and $b = 3.5$ cm. The detuning time,

$$t = \omega_L \left(\frac{b}{c}\right)^2 \left(\frac{\Delta}{\omega_L}\right)^2 \left(\frac{mc^2}{eE_0 b}\right)^2, \quad (4)$$

is of the order of few ns scaling as $1/P$. This is much faster than the time b/v needed to go to the wall, where v is averaged velocity of vertical motion, $v/c \simeq 10^{-3}$ and with the revolution period of $7\mu s$ in the LER.

The total number of electrons in the dipole $n_t = nLS$ is of the order of $n_t \simeq 10^9$. Here we use density $n \simeq 10^6 \text{ cm}^{-3}$, $S = 45 \text{ cm}^2$ and the length $L = 0.45$ m. Hence, the total absorbed power is of the order of 1W, much higher than power of spontaneous Larmor radiation. The microwave power which can be expected from the HOM of the wake field is

$$P = \frac{Z_0 I_b^2 k_l s_b}{4\pi}, \quad (5)$$

where $Z_0 = 337$ Ohms, I_b is average beam current, and k_l is loss factor. It is of the order of $20W/m$ in the LER, but is suppressed by the factor $e^{-(\omega_L \sigma/c)^2}$ for the rigid body LER bunch with rms $\sigma_l = 1$ cm. Additionally, the microwave background has to be a smooth function of frequency in a smooth LER vacuum chamber.

0.3 Conclusion

A set up of antenna and receiver each replacing a button in two BPMs separated by a dipole allows direct measurements of the electron cloud density. The power radiated by the antenna with Larmor frequency is strongly absorbed what can be seen as a dip in frequency dependence of the signal at the receiver. With the 1W wave generated by the antenna at 20 GHz the signal dives to zero. The width of the dip depends on the density of the cloud at the ends of the dipole and the rate of the fringe field decay.

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