Beam-Photoelectron Interactions in Positron Storage Rings

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The possibility of a coupled-bunch instability caused by beam-photoelectron interactions is discussed. Very many photoelectrons are produced in a storage ring when photons emitted by synchrotron radiation hit the beam chamber. Since electrons are not trapped by a positron beam in ion-trapping theory, they are not considered to affect the beam. However, it is possible that an enormous number of photoelectrons would have sufficient density to cause a coupled-bunch instability. A simulation has shown that such an instability may be serious for positron storage rings with high current and multibunches.

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Recently, high-current, multibunch lepton storage rings have been designed and have begun to be operated as synchrotron light sources. Some of them are planned to be operated with positron beams. In *B* factory projects at KEK and SLAC, higher current ($\gtrsim$1 A) and multibunch positron storage rings have been designed. This Letter presents the result of a simulation in which positron storage rings may suffer a strong coupled-bunch instability.

In a positron and/or electron storage ring, the beam emits an enormous number of synchrotron photons. Each photon hits the beam chamber, resulting in the production of photoelectrons with considerable probability. It has been reported that in proton rings a coasting proton beam trapped electrons [1]. Since the positron and/or electron beam is bunched in storage rings, particles around the beam feel a pulsated force. Though positively charged ions are trapped by a bunched beam in an electron storage ring, electrons are not trapped because their mass is too small [2]. However, the number of photoelectrons is much greater than the number of ions. For example, in the case of the KEK Photon Factory 2.5-GeV storage ring (PF), the number of photoelectrons produced by a bunch in a bending section is nearly equal to the number of positrons in the bunch. The photoelectrons propagate in the beam chamber and are absorbed into its surface about 10–100 ns later. The photoelectrons, which interact with beam transiently, cause a coupled-bunch instability. Recently, in electron storage rings, the possibility of a coupled-bunch instability caused by the transient motion of ions was proposed [3]. The mechanism that might cause this instability is similar to that presented here; that is, coupling between beam bunches is intermediated by particles.

In the PF, a very strong vertical instability has been observed since the time that positron operation started [4]. The threshold current was found to be about a few tens of mA. Based on experimental studies, the instability was considered to be caused by a coupled-bunch phenomenon: Electrons traveling near the beam were suspected as the cause [5]. This instability has been overcome by exciting octupole magnets. It seems to be the same as that discussed here.

We now start a discussion on synchrotron photon emission. The number of photons emitted from one positron during one revolution is given by [6]

$$N_\gamma = (5\pi/\sqrt{3})\,\alpha\gamma\,, \qquad (1)$$

where α and γ are the fine-structure constant and the relativistic factor, respectively. Here, the bending radius is assumed to be a constant.

When synchrotron photons hit a metal vacuum chamber, photoelectrons are emitted. The probability depends on the energy of the photons, the angle of incidence, and the metal of the chamber. Studies of the probability have been carried out for the purpose of estimating the gas desorption induced by photoelectrons in the vacuum chamber [7]. We consider the PF ring, for example, where $\gamma = 4892$, so that $N = 320$ in each revolution. In each bending section (the number of bending magnets is 28) $\sim$12 photons are emitted. The beam chambers are made of aluminum. Since an incident photon has an energy of $\sim$1 keV, a primary photoelectron also has an energy of $\sim$1 keV. Here, secondary electrons with an energy of 1 to 10 eV are considered [8]. The emission probability is roughly 0.01 to 0.2 at an incident photon energy of $\sim$1 keV [7], if the angle of incidence of the photons is perpendicular to the metal surface. When it is smaller, the probability is enhanced by several times or more. An emission probability of 0.1 is used later in this Letter as a typical value. It is difficult to know the actual energy and the emission probability of a photoelectron. In order to determine the growth rate exactly, exact values become important. However, this is not the purpose of this Letter.

Since the photoelectron distribution has a very high density near a metal surface, photoelectrons lose an energy of several eV while escaping from the surface due to a mirror charge effect. However, this energy loss is not essential for photoelectron emission.

Emitted photoelectrons propagate in a beam chamber while experiencing an electric force due to the following

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bunches. Since the photoelectrons are not trapped by the beam, they are eventually absorbed. The number of bunches passing through until they are absorbed depends on the parameters of the storage ring, that is, the bunch spacing, the number of positrons in a bunch, and the energy of the photoelectrons. Under multibunch operation with uniformly filled bunches, a constant number of photoelectrons is supplied into the chamber during every passage of the bunches. Thus the distribution becomes stationary; that is, the absorption is canceled by the supply. In the first stage of the simulation, the motion of electrons is tracked and the stationary distribution is obtained.

Next, we consider a perturbation of the beam motion. The stationary distribution of electrons is disturbed, and the disturbance affects the following bunches. In the second stage we obtain a transverse wake force by giving a transverse displacement to a bunch and calculating the kicks experienced by the following bunches. The growth rate of the coupled-bunch instability is obtained by using the wake force.

First stage.—The stationary distribution is constructed here. We chose the coordinate z to be the beam direction, and x and y to be the horizontal and vertical directions, respectively. Let us consider a cylindrical beam chamber with a diameter of 10 cm as a model. The beam bunches were assumed to be rigid and to travel along the center of the chamber. The photoelectrons were produced at the position illuminated by the synchrotron radiation; that is, x equaled the horizontal half width of the beam chamber ($x_{\rm wall}$) and y was distributed as a Gaussian with the rms value σ_y. Several values were tried for the initial kinetic energy (ϵ_0) in the simulation. They included a 10% deviation of $\delta\epsilon = 0.1\epsilon_0$. The direction of emission was assumed to be distributed as $\cos\theta$, where θ is the normal angle of photoelectron motion for the chamber surface. Thus, the initial distribution function was

$$\psi(x, y, \epsilon, \theta) \sim \delta(x - x_{\rm wall}) \exp(-y^2/2\sigma_y^2) \exp[-(\epsilon - \epsilon_0)^2/2\delta\epsilon^2] \cos\theta\,. \tag{2}$$

When synchrotron photons emitted by a bunch hit the beam chamber, photoelectrons were assumed to start at the chamber surface. Now, 1000 particles, which were virtual photoelectrons, started at the chamber wall with the distribution given by Eq. (2).

When the bunched beam arrives, the photoelectrons experience momentum kicks from it. Here, the force was treated as a single kick. The strength of the kick was determined by Coulomb's law. If the transverse beam distribution is a Gaussian with rms values of σ_x and σ_y in each direction, the momentum kicks are represented by the Bassetti-Erskine formula [9],

$$\Delta v_y + i\Delta v_x = N_b r_e c \sqrt{\frac{2\pi}{\sigma_x^2 - \sigma_y^2}} \left[w\left(\frac{x + iy}{\sqrt{2(\sigma_x^2 - \sigma_y^2)}}\right) - \exp\left(-\frac{x^2}{2\sigma_x^2} - \frac{y^2}{2\sigma_y^2}\right) w\left(\frac{(\sigma_y/\sigma_x)x + (\sigma_y/\sigma_x)y}{\sqrt{2(\sigma_x^2 - \sigma_y^2)}}\right)\right], \tag{3}$$

where N_b is the number of positrons in a bunch and $w(x)$ is the complex error function.

Between the kicks, the photoelectrons drift such that

$$\Delta x = v_x \tau \quad \text{and} \quad \Delta y = v_y \tau\,, \tag{4}$$

where the drift time (τ) is expressed by $\tau = 1/f_{\rm rf}$ with the rf frequency $f_{\rm rf}$.

The photoelectrons propagate while drifting and feeling the kicks repeatedly. Figure 1 shows typical transient distributions of photoelectrons emitted by a bunch. To emphasize the accumulation of electrons near the beam, some lower energy ($\epsilon_0 = 0.1$ eV) was chosen. We chose the following set of parameters of the PF: $\sigma_x = 1.1$ mm, $\sigma_y = 0.11$ mm, $\tau = 2$ ns ($f_{\rm rf} = 500$ MHz), and $N_b = 1.25 \times 10^9$ ($I = 100$ mA).

We now consider the motion of electrons with an actual energy of 1–10 eV. In this model after 50 bunches pass through, most of the photoelectrons produced by the first bunch are lost due to absorption into the chamber surface. Stationary distributions for several ϵ_0 were obtained by integrating the transient distributions. Figure 2 shows that for $\epsilon_0 \leq 5$ eV. It should be noted that, though these distributions are time dependent, every bunch always encounters the same electron distribution.

We now consider the actual density of the distributions. In our example of the PF ring, 10^9 photoelectrons are emitted by a bunch in a bending section. If the synchrotron photons are assumed to be distributed for 5 m along the z

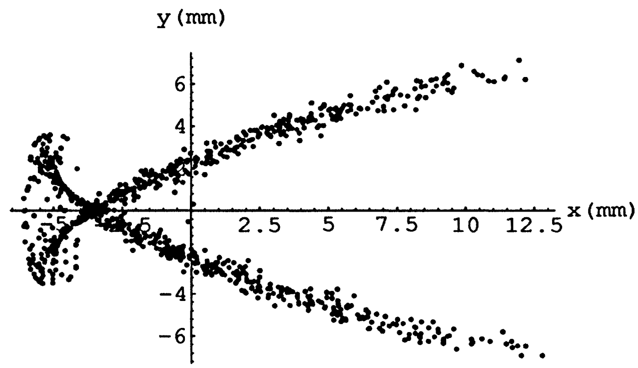

FIG. 1. Transient distributions of photoelectrons emitted by a bunch. The initial electron energy is 0.1 ± 0.01 eV. This is the distribution after the following 27 bunches pass.

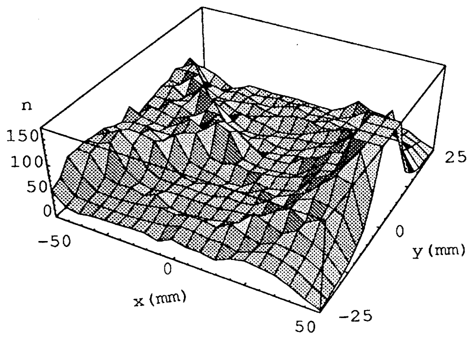

FIG. 2. A stationary distribution of photoelectrons with $\epsilon_0 =$ 5 eV.

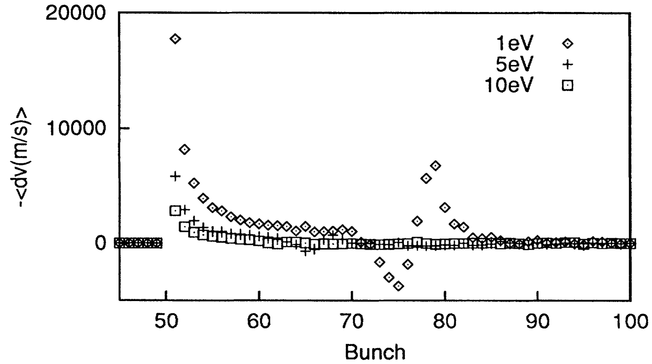

FIG. 3. Wake forces for each initial photoelectron energy. To obtain the wake, 10^6 virtual electrons in every bunch were used.

direction, the practical density is given by multiplying 2×10^4 by the value from Fig. 2 in cm^3. Typically, if we use 100, as in the figure, the density is $2 \times 10^6\ \mathrm{cm}^{-3}$. We consider the space-charge effect of the electron distribution. The electric field due to the peak distribution, which is a few hundreds in the figures, can be estimated to be ~ 100 V/m. The field from the beam is ~ 600 V/m at a distance of 1 cm from the beam center. Thus, when the electron motion is near the beam, the field of the beam is dominant.

Second stage.—We now consider the wake force and the growth rate of the instability. We first discuss the motion of a rigid beam, especially for the case in which the vertical motion is focused. After obtaining a stationary distribution, we introduce a vertical displacement for a bunch. Since the distribution is disturbed, it has an effect on the following bunches. If the loading bunch is shifted to the positive y direction, photoelectrons are attracted toward the new position. The loading bunch feels a kick in the negative y direction from the stationary distribution. On the other hand, the following bunches feel kicks from a positively displaced distribution, and are kicked in the positive y direction. We can interpret the momentum kick as being the wake force of the transverse dipole mode. The characteristic of the wake function is the same as that of an impedance problem; that is, it is negative near the loading bunch.

Figure 3 plots of an averaged velocity kick ($\Delta \bar{v}$) for all photoelectrons from each rigid bunch including N_b positrons. The 50th bunch, which is not plotted in the figure because of a negative kick, is a loading bunch. The loading bunch is given a vertical displacement of 0.5 mm, which is $3\sigma_y$ in the PF ring. The wake force is observed in the following several bunches. The short-range feature results from the light mass of an electron. In the lower energy case, we could observe a structure after 15–25 bunches from the loading bunch; it comes from interactions by returning electrons. The linearity and superpositron characteristics of the wake are important for treatment as a conventional wake by impedance. The linearity was checked by obtaining the wake force for a loading bunch with twice the displacement, while the superposition was checked by obtaining it for two displaced loading bunches.

The same calculation is performed for the electron beam. Photoelectrons cannot propagate near the beam due to the repulsive force when $\epsilon_0 \leq 10$ eV. However, the calculation shows a wake force of the following ~ 20 bunches in $\epsilon_0 = 10$ eV. There is no denying that they may have some effects in electron rings.

We can now use the conventional theory of the coupled bunch instability [10] with this wake force. The equation of motion for a positron in a bunch, with subscript 0, is

$$\frac{d^2 y_0(t)}{dt^2} + \omega_\beta^2 y_0(t) = -\frac{N_{e\gamma}}{N_b} \sum_{n=1}^{n_0} \frac{\Delta \bar{v}_y(-ncT_{\mathrm{rev}}/h)}{\gamma T_{\mathrm{rev}}}, \tag{5}$$

where T_{rev} and h are the revolution time and the harmonic number, respectively. The index (n) devotes a bunch which is the nth ahead of the 0th bunch. It is assumed that all bunches include N_b positrons and that a bunch produces $N_{e\gamma}$ photoelectrons during one revolution.

By defining the mode number (m) and its frequency (Ω_m) as

$$y_n^{(m)}(t) = e^{2\pi i m n/h} y_0^{(m)}(t), \tag{6}$$

$$y_j^{(m)}(t) = \tilde{y}_j^{(m)} e^{-i\Omega_m t}, \tag{7}$$

the following dispersion relation is obtained:

$$\Omega_m - \omega_\beta = \frac{i}{4\pi\gamma\nu_y} \frac{N_{e\gamma}}{N_b} \sum_{n=1}^{n_0} \frac{d\bar{v}_y}{dy}\left(\frac{-ncT_{\mathrm{rev}}}{h}\right) e^{2\pi i n(m+\nu_y)/h}. \tag{8}$$

The imaginary part of Eq. (8) gives the growth rate of the instability with the mode number m.

By putting the wake force $\bar{v}(-ncT_{\mathrm{rev}}/h)$ given by Fig. 3 into Eq. (8), the growth rate of each mode was obtained. Figure 4 shows the growth rates for various photoelectron energies. The growth rates are very high compared to thdamping rate of the PF ring, 120 s^{-1}. Now, $N_{e\gamma} = 30N_b$ is assumed. (In each revolution, 312 photons are emitted from a positron, and the emission probability of a photoelectron is 0.1.) The growth rate depends linearly on $N_{e\gamma}$ in the model, that is, on the emission probability. On the other hand, the linearity for a stored beam current is not guaranteed, because the wake force depends on the characteristics of interaction between beam and photoelectron. Thus, the features of the instability will vary with the beam current.

We have ignored the influence of magnetic fields. If it is assumed to be due to the strength of geomagnetism, electrons with 1 eV would have a Larmor radius of 11 cm. Since the electrons are accelerated near the beam center, the radius becomes ~40 cm. These values are larger than that of the beam chamber. The actual radius depends on the existing magnetic field at the place of electron production. If there is a horizontal magnetic field in the region where photons illuminate, the electrons are bound on the horizontal plane, and thus the interaction will be enhanced. A simulation including magnetic fields is being carried out.

Scattered or reflected photons may also be important. Photoelectrons will be produced in every location illuminated by the photons. Though the number would be less than that due to direct production, it may be important if the direction of the magnetic field matches the electron motion.

The instability considered here may cause some problems in positron storage rings. To overcome this instability, we should avoid producing photons near the beam as much as possible. Otherwise, we may be forced to control the magnetic field so as to restrict the motion of the electrons. This discussion is not limited to photoelectrons. Any other rich source of slow electrons [11] could cause a similar instability by the same mechanism.

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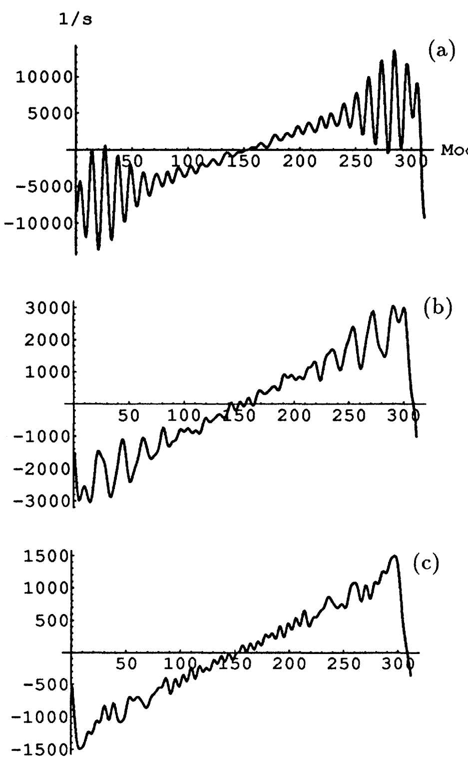

FIG. 4. Growth rates of the coupled-bunch instability. The positive values mean unstable modes. The wakes of 51 to 100 bunches in Fig. 3 were summed with Eq. (8). (a) $\epsilon_0 = 1$ eV. (b) $\epsilon_0 = 5$ eV. (c) $\epsilon_0 = 10$ eV.

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