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Head-tail instability caused by electron cloud in positron storage rings

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Abstract

In positron or proton storage rings with many closely spaced bunches, a large number of electrons can be generated in the vacuum chamber due to photoemission or secondary emission. The density of this 'electron cloud' increases along a bunch train, until the growth saturates under the influence of its own space charge field. In this report, we discuss the possibility of a single-bunch two-stream instability driven by the electron cloud, where any initial head-tail perturbation of the bunch is amplified by the coherent motion of cloud electrons near the beam. Depending on the strength of the beam-electron interaction, the chromaticity and the synchrotron oscillation frequency, this instability either resembles a linac beam break up, or a head-tail instability. We present computer simulations of beam break up and head-tail instabilities for the Low Energy Ring of the KEK B factory, and compare the simulation results with analytical estimates.

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1 Introduction

A single-bunch instability of a positron bunch due to electrons created by ionization of the residual gas has been discussed for linear accelerators [1]. This instability can be considered as a two stream instability of the same type as studied in plasma physics. The electrons oscillate in the electric potential of the positron bunch. At first the oscillation is incoherent, but gradually a coherent oscillation of both electrons and positrons develops along the bunch. The coherent oscillation grows from any small initial perturbation of the bunch distribution, *e.g.*, from the statistical fluctuations due to the finite number of beam particles.

One of the authors (F.Z) has discussed the possibility that a similar two-stream instability may occur in positron storage rings due to interaction with electrons generated by photo-emission and secondary emission [2]. Such instability could be fast, since in the new generation of storage rings, operating with many closely spaced bunches, the density of the electron cloud which accumulates in the vacuum chamber can become large. The two-stream instability resembles the classical beam break up (BBU), and manifests itself in a coherent dipole oscillation of positrons along the bunch. It is well-known that in a storage ring the BBU appears as either strong or regular head-tail instability, due to synchrotron oscillation and, possibly, chromaticity. In this report, we study the BBU and the head-tail instability caused by the electron cloud using a computer simulation.

The photo-electrons produced by synchrotron radiation in positron storage rings may also cause a multi-bunch dipole-mode instability, where a variation in the electron-cloud centroid position couples the motion of subsequent bunches [3]. This multi-bunch instability is different from the instability discussed in this report, which is a single-bunch phenomenon caused by the photo-electron cloud. Although a single-bunch effect, the latter will, however, occur only in multibunch operation, since the electron cloud is built up from synchrotron radiation emitted by the preceding bunches. The head-tail mode of the single-bunch instability will be observed as a beam-size blow up.

As a concrete example, we study the single-bunch photo-electron instability for the Low Energy Ring of the KEK-B factory (KEKB-LER), with parameters as summarized in Table 1. At the beginning of the year 2000, the LER was operated with a beam current of 600 mA stored in 1000 bunches at 8 ns spacing. A blow up of the vertical beam size has been observed already early on during LER commissioning [4]. This blow up is not accompanied by any coherent beam motion, which is suppressed by transverse feedback and chromaticity, and the blow up is seen only in multibunch operation with a narrow bunch spacing. The single-bunch two-stream instability provides a plausible explanation of the observed beam blow up.

We, first, discuss the density of electron cloud near the beam, then describe the simulation model for the motion of a positron bunch passing through an electron cloud, next, present simulation results of beam break up and head-tail instability, and, finally, compare the simulated instability rise times with analytical estimates.

2 Electron Cloud Density

Photoelectrons produced by synchrotron radiation are the major source of electrons in the vacuum chamber of the KEKB LER. The number of photons emitted by a positron during one revolution is given by $N_\gamma = 5\pi\alpha\gamma/\sqrt{3}$, where α and γ are the fine structure constant and the

Table 1: Basic parameters of the KEKB LER

variable	symbol	value
particle type	—	e^+
circumference	L	3016 m
beam energy	E	3.5 GeV
current	I	2.6 A
number of bunches	n_b	~ 5000
bunch population	N_b	3.3×10^{10}
bunch current	I_b	0.5 mA
bunch spacing	t_{sep}	8 ns
geometric emittance	$\varepsilon_{x,y}$	$1.8 \times 10^{-8}/3.6 \times 10^{-10}$ m
rms beam sizes	$\sigma_{x,y,z}$	$0.42/0.06/4$ mm
average beta function	β_y	10 m
rms energy spread	σ_E/E	0.0007
momentum compaction factor	α	1.8×10^{-4}
chromaticity	$Q'_{x,y}$	$4/8$
betatron and synchrotron tunes	$Q_x,\ Q_y,\ Q_s$	$0.53,\ 0.11,\ 0.015$
damping decrement	$T_0/\tau_{xy,z}$	$2.5,\ 5.0 \times 10^{-4}$

relativistic factor, respectively. At the LER, a positron emits about 450 photons ($\gamma = 6850$) in one revolution, or, in other words, a positron bunch emits 5×10^9 photons per meter. Assuming a photo-electron yield of 0.1, the number of photo-electrons is estimated to be $5 \times 10^8/\mathrm{m}$. Though this number depends on the local flux density of the photons, which in turn is determined by the geometrical configuration of bending magnets and beam chamber, in the following we use the above average as a typical value.

We obtain the quasi-stationary electron-cloud density, ρ, from a computer simulation which models the motion of photo-electrons in the electric field of the positron beam during successive bunch passages. This calculation is performed following the same procedure as was used for studying the multi-bunch electron-cloud instability in Ref. [3]. At every passage of a positron bunch about 5×10^8/m photoelectrons are created. These are subsequently attracted towards the center of the beam pipe by the electric field of the positron beam. The initial energy distribution of the electrons is assumed to be a truncated Gaussian with peak energy 5 eV and standard deviation 10 eV, restricted to positive values. Most electrons are created at the side wall of the chamber where the primary synchrotron radiation impinges, but a significant portion (30%) are created uniformly around the chamber wall to represent the contribution from reflected photons. The motion of the electrons is also affected by their own space charge, which is calculated by solving the two dimensional Poisson equation [5].

We simulated the electron-cloud build up for two different bunch spacings, namely 2 ns (design) and 8 ns (present). The simulation shows that the photo-electrons are re-absorbed by the chamber wall several tens of nanoseconds after their creation. The number of photoelectrons increases at each bunch passage and, finally, saturates when a quasi-stationary value is reached representing a dynamic equilibrium between creation and absorption. Figures 1 (a) and (b) show electron cloud densities obtained by the simulation. Both average and local densities (at the beam-pipe center) are depicted. Near the beam, the electron-cloud build up levels off after about 100 ns. Density values above 10^{12} m^{-3} are reached after a few bunch passages. Since electrons are accelerated by the electric field of the positron bunches, they arrive at the center with an energy considerably higher than the initial photo-emission energy. The velocity distribution of electrons close to the bunch is shown in Fig. 1 (c) and (d).

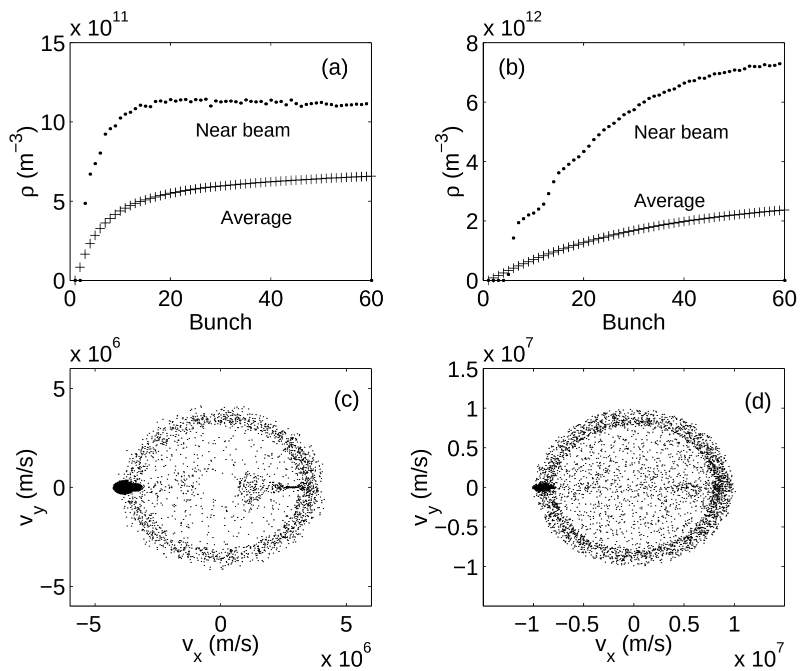

Figure 1: Density and velocity distributions of electron cloud. Pictures (a) and (b) show the electron densities for 8 ns and 2 ns spacing, respectively. The crosses and diamonds refer to the average density and to the local density near the beam. Pictures (c) and (d) give the velocity distributions corresponding to the two bunch spacings.

The electric field of the electron cloud induces an incoherent tune shift of the positron beam. If the cloud is cylindrically symmetric around the beam, the tune shift is given by

$$\Delta Q_y = \frac{r_e}{\gamma} \langle \beta_y \rangle \rho \, L. \tag{1}$$

For a flat electron distribution, the tune shift can be higher by up to a factor of 2. Assuming KEKB LER parameters and a typical near-beam electron density of $\rho = 10^{12}$ m^{-3}, the tune shift is $\Delta Q_y \sim 0.01$.

3 Simulation Model

A positron bunch interacts with the electron cloud during its passage (~ 27 psec for $2\sigma_z = 0.8$ cm). Since we here discuss only the single bunch effect of the electron cloud, perturbations of the cloud due to preceding bunches are neglected; that is, in the simulation a positron bunch always interacts with the quasi-stationary unperturbed electron cloud. Considering the finite electron velocity and the fall-off of the electric field of the beam at large distances, we assume that only the electrons in the vicinity of the bunch contribute to the instability. We have written a second simulation program to study the coupled motion of a single positron bunch and the cloud electrons. In this simulation, the initial electron distribution is taken to be Gaussian, with transverse rms sizes and electron-cloud density as input parameters. For simplicity, the electron cloud is assumed to be localized at a single position of the ring, denoted by s_e. The cloud density at this location is chosen such that the average electron density over the ring circumference is equal to the actual value. In other words, the effect of the electron cloud on a positron in the beam is approximated by a single kick per revolution. The positron bunch is sliced into a number of micro-bunches (N_p) in the longitudinal direction. Each micro-bunch has a transverse beam size determined by emittance and beta function. The interaction between the microbunches and the cloud electrons is expressed by two equations, [6]

$$\frac{d^2\bar{\boldsymbol{x}}_{p,i}(s)}{ds^2} + K(s)\bar{\boldsymbol{x}}(s)_{p,i} = -\frac{2r_e}{\gamma}\sum_{a=1}^{N_e}\boldsymbol{F}_G(\bar{\boldsymbol{x}}(s)_{p,i} - \boldsymbol{x}_{e,a};\boldsymbol{\sigma})\delta(s-s_e), \tag{2}$$

$$\frac{d^2\boldsymbol{x}_{e,a}}{dt^2} = -\frac{2N_+r_ec^2}{N_b}\sum_{i=1}^{N_p}\boldsymbol{F}_G(\boldsymbol{x}_{e,a} - \bar{\boldsymbol{x}}_{p,i};\boldsymbol{\sigma})\sum_k\delta(s_e - s_{p,i} - kL), \tag{3}$$

where the force $\boldsymbol{F}_G(\boldsymbol{x})$ is expressed by the Bassetti-Erskine formula [7] normalized so that $\boldsymbol{F}_G \to \boldsymbol{x}/|\boldsymbol{x}|^2$ as $\boldsymbol{x} \to \infty$. The position of a micro-bunch is represented by $\bar{\boldsymbol{x}}(s)_p = (x, y, z)$, where $z = s - ct$, and that of an electron (at s_e) by $\boldsymbol{x}_e = (x, y)$. $K(s)$ includes information of the lattice of the ring. Here we neglect the space charge force between the electrons, because we are only interested in the short time period of a bunch passage, and the beam field is much stronger than the space charge field.

If we ignore the bunch motion and linearize the force in Eq.(3), we find that near the beam center the electrons oscillate in the static beam potential with the angular oscillation frequency

$$\omega_e^2 = \frac{2\lambda r_e c^2}{\sigma_y(\sigma_x + \sigma_y)}, \tag{4}$$

where $\lambda = N_b/(2\sigma_z)$ denotes the line density of the positron bunch. For our parameters, $\lambda = 4 \times 10^{12}$ m^{-1}, and the angular oscillation frequency is $\omega_e = 2\pi \times 45$ GHz. The electrons perform about 1.2 oscillations during the passage of the positron bunch ($2\sigma_z$)

The simulation is performed by successively solving the motion of positron micro-bunches, Eq.(2), and macro-electrons, Eq.(3). The simulation is quite similar to that of ion trapping or fast ion instability [6]. A series of micro-bunches corresponds to a bunch train in the ion problem. Some differences are noteworthy: (1) the longitudinal spacing of the positron micro-bunches is much narrower than that between bunches in a train, (2) the longitudinal positions of the micro-bunches vary due to the synchrotron oscillation, and (3) the electron oscillation frequency in the bunch potential, Eq. (4), is considerably faster than the frequency of ion oscillations along a bunch train.

The simulation consists of the following steps. The electron cloud is represented by macro-particles. The distribution of these macro-particles is assumed to be Gaussian with a size of ~ 3 mm, which is 8 or 50 times larger than the horizontal and vertical rms beam sizes, respectively. As described earlier, the electron density at the bunch (center) position is obtained from an independent simulation of the electron-cloud build up along the train, and a value of 10^{12} m^{-3} is typical for the present operation of 4 bucket (8 ns) spacing in KEKB. Usually the initial velocities of the macro-electrons are set to zero, but they can be varied in order to study the dependence of the instability on this parameter. In the simulation, we represent a positron bunch by 1,000 micro-bunches and the electron cloud by 10,000 macro-particles. For easy visualization, we use a multiple air-bag model for the longitudinal micro-bunch distribution, in which the micro-bunches are initially distributed on concentric circles in the longitudinal phase space, characterized by the position z and the relative energy deviation $\Delta p/p$. The interaction starts between the micro-bunch with the largest value of z, *i.e.*, the first micro-bunch at the head of the bunch, and the unperturbed macro-electrons, and then continues for other micro-bunches at progressively smaller z coordinates. Between interactions with two successive micro-bunches, the macro-electrons drift freely. The micro-bunches are propagated around the ring using a linear transport matrix and applying a chromaticity kick directly after the beam-electron interaction. On every revolution, the electrons are regenerated with an unperturbed Gaussian distribution.

4 Simulation Results

Figure 2 shows the transverse amplitudes of micro-bunches distributed over the longitudinal phase space, for two cases. Figure 2 (a) depicts the deformation of the positron bunch without synchrotron oscillations. Clearly visible is a transverse oscillation along the bunch, the frequency of which is consistent with Eq. (4). The figure is reminiscent of the beam break up (BBU) observed in linear accelerators. Including also the synchrotron oscillation, the beam break-up changes its appearance and now resembles a strong head-tail instability. Figure 2 (b) shows the bunch shape deformation with synchrotron oscillations for a synchrotron tune $Q_s = 0.015$. We find a correlation of transverse amplitude and longitudinal phase space position, which is characteristic of head-tail motion. Note that the magnitude of the oscillation amplitudes is reduced by the synchrotron motion.

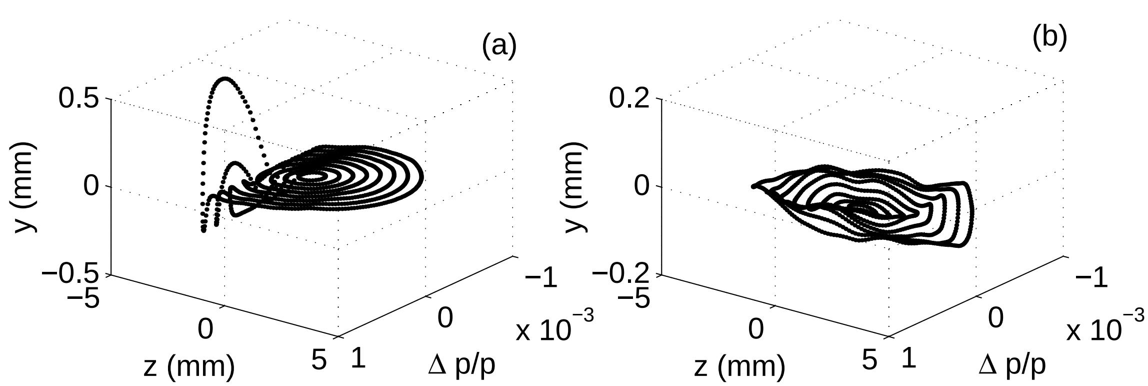

Figure 2: Bunch shape deformation due to the interaction with electron cloud. The position of the micro-bunches are plotted after 100 turns for a cloud density of 1×10^{12} m^{-3}. Pictures (a) and (b) refer to cases without and with synchrotron oscillations, respectively. The synchrotron tune for case (b) is $Q_s = 0.015$.

It is interesting to discuss the relation of the instability and the chromaticity. The conventional head-tail effect caused by a broad-band impedance or a short range wake force [8] results in damping of the dipole ($l = 0$) mode and a growth of higher order ($l \geq 1$) head-tail modes for positive chromaticity, and roughly the opposite behavior for negative chromaticity. For zero chromaticity, the beam is stable at low current. Above a certain current threshold some head-tail modes are coupled and strongly excited. This is called the strong head-tail instability. The simulation shows exactly the same dependence for the electron-cloud wake.

Excitation of the higher order head-tail mode is observed as a blow up of the vertical size of the positron bunch. We quantify this blow up by computing the root mean square of all micro-bunch amplitudes, $\sqrt{\langle y_p^2 \rangle}$. Figure 3 shows the growth of this quantity for the BBU mode, without synchrotron motion, in picture (a), and for the head-tail mode oscillation with a synchrotron tune $Q_s = 0.015$, in pictures (b) and (c). The latter two examples were calculated for horizontal and vertical chromaticities $Q'_{x,y} = \Delta Q_{x,y}/(\Delta p/p)$ of $(4, 8)$ and $(0, 0)$, respectively. The three curves refer to the three cloud densities $\rho = 2 \times 10^{11}$ m^{-3}, 4×10^{11} m^{-3}, and 1×10^{12} m^{-3}. The growth rate is of the order ~ 0.1 ms for the BBU mode, as illustrated in picture (a). The behavior with synchrotron motion is different for positive and for zero chromaticity. At $Q'_{x,y} = (4, 8)$ the growth time is about 1 ms for the two lower electron densities, whereas at $Q'_{x,y} = (0, 0)$ it is much slower. For the highest density, $\rho = 1 \times 10^{12}$ m^{-3}, the growth at both chromaticities is about the same and extremely fast, with a rise time of the order of 0.2 ms. Our interpretation is that there is a threshold value for the electron-cloud density above which we observe the strong head-tail instability.

All simulated growth times are much shorter than the radiation damping time (40 ms) except for the two cases of zero chromaticity and lower cloud density. The growth tends to slow down for large amplitudes at several σ_y. We attribute this to the nonlinearity of the forces between beam and electrons, which will also lead to filamentation and emittance growth.

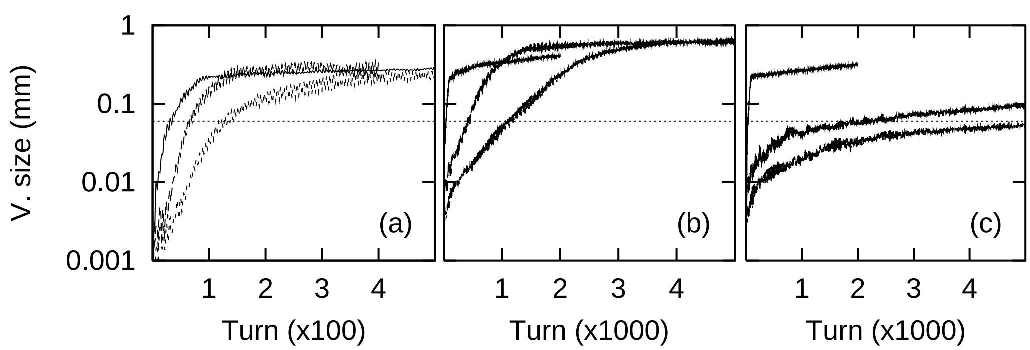

Figure 3: Growth of the vertical rms amplitude of the micro-bunches. The three curves are results for electron-cloud densities of 2×10^{11}, 4×10^{11}, and 1×10^{12} m^{-3}. The growth is faster for higher density. Picture (a) is obtained without synchrotron oscillations. Pictures (b) and (c) refer to chromaticities $Q'_{x,y}$ of $(4, 8)$ and $(0, 0)$, respectively, with synchrotron motion and $Q_s = 0.015$. The dashed lines indicate the natural beam size.

We repeated the same simulations for different values of the initial size and rms velocity of the electron cloud. The vertical rms size σ_y was decreased from 3 mm to 1.5 mm, and the rms velocity was varied between 0 m/s and 10^7 m/s, for constant electron-cloud density near the beam. The growth of the beam size was not much affected by these changes. The simulated growth rate depends primarily on the electron density, and is not particularly sensitive to either size or thermal velocity of the electron cloud, as long as the former is a few times larger than the rms beam size and the latter smaller than the typical velocity acquired in the beam potential, $v_e \approx \omega_e \sigma_y \approx 2 \times 10^7$ m/s.

5 Analytical Estimates

Our picture of the two-stream instability is that the cloud electrons oscillate incoherently at first, but, gradually, they and the positron bunch (the micro-bunches in the simulation) develop a coherent oscillation due to their interaction. After the bunch passage the coherence of the electrons is lost, and on the next revolution the further distorted positron bunch impresses an enhanced coherent motion on the newly formed electron cloud, which in turn increases the oscillation along the bunch.

The force from the electron cloud may be represented by an effective short range wake field with a characteristic frequency as in Eq. (4). The strength of the wake force can be obtained by the same method as in Ref. [3]. The order of magnitude of the wake force may also be estimated analytically. For example, considering a flat beam with $\sigma_x \gg \sigma_y$, we decompose the electron cloud into infinitely thin vertical slices, each producing the same vertical electric field, and study a two-particle model with a charge of $N_b e/2$ for both head and tail. We assume that the head particle has a finite length $l_{\rm head} \approx \sqrt{2\pi}\sigma_z/2$, and a uniform charge distribution. The tail particle is considered to be pointlike and to follow immediately after the head. Head and tail are vertically displaced with respect to each other by a small offset $\Delta y \ll \sigma_y$. From the resulting force on the tail we can then estimate the effective wake field. Electrons near the beam are attracted by the field of the head and perform linear or nonlinear oscillations during its passage. Due to the relative displacement of head and tail, these oscillations induce a net electron transfer from below to above the vertical position of the trailing particle. The electron charge transfer is maximum if $\omega_e l_{\rm head}$ is equal to an odd multiple of $\pi/2$, reflecting the effect of linearly oscillating electrons within about $\pm 2\sigma_y$ from the beam. At intermediate times, the net charge transfer amounts to the number of electrons which originally occupy a vertical stripe of thickness $\sim 2\Delta y$, *i.e.*, about twice the displacement. These electrons start their oscillation in the constant flat part of the electric field. The flat field region extends up to vertical amplitudes of about σ_x. Electrons with initial vertical amplitudes beyond σ_x approach the beam at times $t \geq (\sigma_x/\sigma_y)^{1/2}/\omega_e$, and then give rise to a slow decrease of the overall charge transfer, which we ignore in the following.

In this 2-particle model, the integrated wake field per revolution experienced by the tail of the bunch is of the order

$$W_0 \approx 8\pi\rho L/N_b. \tag{5}$$

On each turn the tail particle experiences a deflection of

$$\Delta y'_{\rm tail} = \frac{r_e W_0 N_b}{2\gamma}\,(y_{\rm head} - y_{\rm tail}), \tag{6}$$

where y' denotes the vertical slope of the trajectory. This estimate is valid if the distance between head and tail is large compared with $\sigma_x\sigma_y/(N_b r_e)$, where r_e denotes the classical electron radius. This is usually the case. Unlike an ordinary wake field, the wake W_0 decreases inversely with the population of the bunch considered. However, the population of the previous bunches also enters, indirectly, in the value of ρ, so that for equal bunch populations there is no dependence on N_b. Indeed, assuming that the equilibrium density ρ is equal to the average neutralization density $N_b/(\pi h_x h_y L_{\rm sep})$, where h_x and h_y are the horizontal and vertical chamber half apertures and $L_{\rm sep}$ the bunch spacing (in meters), our wake estimate can be rewritten as $W_0 \approx 8L/(h_x h_y L_{\rm sep})$, which depends only on geometric quantities.

On the other hand, if the bunch length is short compared with $\sigma_x\sigma_y/(N_b r_e)$, so that only electrons in the linear part of the beam field contribute to the charge transfer, the wake field can be estimated as $W_0 \approx 4\pi\rho L r_e l_{\rm head}/(\sigma_x\sigma_y)$, which differs from Eq. (5) by the additional factor $\frac{1}{2}\omega_e^2 l_{\rm head}^2/c^2$ and implies a stronger variation of instability growth rates with bunch population.

The growth rate for the BBU mode, without synchrotron motion, can be estimated in the two-particle model using the saturated wake field of Eq. (5):

$$\frac{1}{\tau} \approx \frac{2\pi\rho r_e c < \beta_y >}{\gamma} \tag{7}$$

For KEKB parameters the BBU growth time evaluates to about 100 μs, in good agreement with the simulation of Fig. 3 (a).

An alternative estimate can be obtained by modifying the theory for the single-bunch instability due to ionization electrons [1], if we assume a linear force between electrons and beam, only consider the small fraction of cloud electrons inside the beam volume and long bunches, $2\sigma_z\omega_e \gg 1$, and again neglect the effect of synchrotron motion. Adaptation to our situation then yields

$$\frac{1}{\tau} = 4\pi\rho \frac{N_b^{1/2} r_e^{3/2} \sigma_z^{1/2} \sigma_x \beta_y c}{\gamma \sigma_y^{1/2} (\sigma_x + \sigma_y)^{3/2}}. \tag{8}$$

In this case, the growth rate is estimated to be $15\ \mu$s for $\rho = 1 \times 10^{12}$ m^{-3}, and, thus, it appears to be a factor of 10 faster than that obtained by the simulation. However this growth time is not an e-folding time, but describes a quasi-exponential growth of the form $y \sim \exp\sqrt{t/\tau}$. In addition, the KEKB bunches are not that long, and the analytical formula not strictly applicable. The spread of electron oscillation frequencies due to the nonlinear beam force further reduces the growth rate [6, 9].

Inserting our wake field estimate, Eq. (5), into the standard expression for the regular head-tail growth time [8], we can estimate the growth rate of the $l = 1$ head-tail mode as

$$\frac{1}{\tau^{(1)}} \approx \frac{64}{3} \frac{\rho < \beta_y > r_e \sigma_z Q_y'}{T_0 \alpha \gamma} \tag{9}$$

where α is the momentum compaction factor. For $Q_y' = 8$ this equation predicts a growth time of about 0.5 ms, again in reasonable agreement with the simulation.

Finally, we can calculate the threshold of the strong head-tail instability for the two-particle model. Following Ref. [8], the threshold is reached when the parameter $N_b r_e |W_0| \beta_y c/(8\gamma L Q_s)$ is equal to 2. This translates into a threshold value for the electron-cloud density of

$$\rho_{\rm thr} = \frac{2\gamma Q_s}{T_0 r_e c \beta_y}, \tag{10}$$

which evaluates to 7×10^{11} m^{-3}, and agrees surprisingly well with the simulated threshold.

6 Conclusion

In conclusion, we have studied a single-bunch head-tail instability caused by the photo-electron cloud. The instability depends on the electron-cloud density near the beam. For the KEKB LER this density is estimated to be about $5 \times 10^{11} \sim 10^{12}$ m^{-3}, which would cause an incoherent betatron tune shift of $0.005 \sim 0.01$. Simulated instability growth times are of the order of 0.1–1 ms and consistent with analytical estimates. The typical equilibrium density of the electron cloud for present KEKB parameters is close to the threshold of the strong head-tail instability. In operation with bunch trains, the electron cloud is built up along each train and it is cleared by sufficiently large gaps between subsequent trains. The saturation of the oscillation amplitudes at $\sim 10\sigma_y$, found in the simulation, indicates that the beam is not lost, but that the instability will mainly increase the beam size. The beam size blow up should increase along a bunch train, in parallel with the build-up of the electron cloud at the center of the vacuum chamber. In particular, the instability may cause a beam size blow up as observed at KEKB. It could also explain similar observations at PEP-II [11] and at the CERN SPS [12].

In our computer simulation of the instability, the positron bunch was represented by a large number of micro-bunches with a fixed transverse beam size. In reality the transverse sizes of the slices will vary under the action of the electron cloud, and other incoherent effects may also become important [10, 13]. Therefore, in the future more realistic studies of this instability should be performed, *e.g.*, via particle-in-cell (PIC) simulations, as have recently been applied to the strong-strong beam-beam interaction [14].

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