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Effect of the e-cloud and CSR on the upgrade of the PEP-II *

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1 Abstract

Effects of the electron cloud and of the coherent synchrotron radiation (CSR) on the possible upgrade of the PEP-II B-factory are studied.

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2 Introduction

PEP-II B factory operates with parameters shown in Table 1 and already exceeds the design luminosity. Nevertheless, a possibility of upgrading the machine to even higher luminosities is under consideration [1]. Several scenarios are summarized in Table 2. This paper describes effects of the electron cloud and of the coherent synchrotron radiation (CSR) on the proposed upgrades of the PEP-II B-factory. The first effect was observed [3] and caused [4] the degradation of the emittance at KEK B-factory. The analytic expression for the e-wake [2] is used in calculations of the head-tail instability. Other obvious effects of higher beam currents such as additional heat load are not considered. The short wave length CSR has been recently observed at Brookhaven [6]. Consideration of the effect of such CSR on the beam dynamics is based on our previous paper [7].

Parameter	Symbol	Value
Energy, LER	E, GeV	3.1
average radius	R,m	350
bend radius, LER	ρ_c,m	13.752
relat.factor	γ	$6.103\,10^3$
momentum compaction	α	$1.23\,10^{-3}$
bunch length	σ_l, cm	1.1
relative energy spread	δ	$7.7\,10^{-4}$
emittance,nm	$\epsilon_{x,y}$	49.5/1.2
tune	$Q_{y,x}$,	38.57/36.6
average x beta, m	β_x	9.370
average y beta,m	β_y	12.47
synchrotron tune	ν_s	0.0251
vertical half gap	b cm	2.5
Bunch population	N_b	1.010^{11}
number of bunches	n_b	692

Table 1: Main Parameters of the LER PEP-II

3 Density of the electron cloud

The main uncertainty in the theory of the beam-electron cloud interaction is the density of the electron cloud. The density depends on the beam current, the bunch transverse rms $\sigma_{x,y}$, the rms bunch length σ_l, the bunch spacing $s_b = 2\pi R/n_b$, the beam pipe aperture b, and material of the walls. The density is dynamic parameter which depends itself on the beam-cloud interaction. The cloud is not static: the spatial and temporary variations of the

Parameter	(I)	(II)	(III)	(IV)
n_b	750	1658	3400	3492
I_b	1.750/0.95	4.0/1.4	10.0/3.3	18.0/6.2
$I_{bunch}/mA, LER$	2.33	2.41	2.94	5.15
σ_z	1.1/1.1 9	0.8/0.8	0.5/0.5	0.13/0.14
$\alpha, 10^{-3}$	1.23/2.41	1.23/2.41	2.41/1.23	2.41/1.23
$\delta_0, 10^{-4}$	7.7/6.1	7.7/6.1	7.7/6.1	7.7/6.1
$N_b 10^{-11}$	1.07/0.58	1.1/0.387	1.35/0.445	2.36/0.814

Table 2: Parameters for upgraded PEP-II (LER/HER)

density are important. Calculation of the density is a serious but separate problem. Here we want to notice that, at high currents, calculation of the density may be simpler than at low currents as it is discussed below.

There are two mechanisms for accumulation of the electrons.

First, electrons may be trapped in the field of the beam. An electron at the distance r from the beam gets a kick from a bunch $v/c = 2r_e N_b/r$, where r_e is the classical electron radius. At low currents, electron remains within the beam pipe when the next bunch comes and gets another kick. Electron trajectories in the last case are complicated but, generally, electrons make several oscillations due to the kicks of the following bunches before they reach the wall. Such, at least a temporary trapping, may take place if

$$I_{beam} < ecb^2/(r_e s_b^2), \tag{1}$$

or $I_{beam} < 1.8$A for $b = 2.5$ cm and $s_b = 240$ cm. An electron, trapped in the close vicinity to the beam, oscillates with frequency defined by the average field of the beam,

$$(\frac{< \Omega_0 >}{c})^2 = \frac{2N_b r_e}{s_b \sigma_x \sigma_y}. \tag{2}$$

At a high current, an electron kicked by a bunch, generally, goes wall-to-wall in one pass. The secondary electrons generated at the wall spread slowly to the beam line but, for small bunch spacing, can remain at a relatively large distances from the beam line. Such swiping by the passing bunches reduces the electron density at the beam line making distribution of electrons hollow and reduces the growth rate of e-cloud driven instability.

These arguments do not take, however, into account the finite length of a bunch. The frequency of oscillations of an electron in the field of a long bunch changes from $< \Omega_0 >$ to Ω_0,

$$(\frac{\Omega_0}{c})^2 = \frac{2N_b r_e}{l_b \sigma_x \sigma_y}, \tag{3}$$

where the bunch length $l_b = \sigma_z \sqrt{2\pi}$.

If $\Omega_0 l_b/c << 1$, then the interaction of the electron with the bunch produces a kick considered above. If, however, $\Omega_0 l_b/c >> 1$ then interaction is adiabatic. The amplitude of oscillations decreases while the frequency of oscillations increases but then both come back to the initial values. The electron in this case remains trapped, and the density at the beam line can be high.

The adiabatic trapping takes place, first, for electrons in the close vicinity of the beam at

$$I_{bunch} > ec\frac{\sigma_x\sigma_y\sqrt{2\pi}}{2r_e\sigma_z R}. \tag{4}$$

This criterion corresponds to $I_{bunch} = 0.5$ mA at $\sigma_x\sigma_y = 8\,10^4\ cm^2$,$\sigma_z = 1$ cm, and $2\pi R = 2.2$ km. For electrons with initial amplitudes large than $\sigma_\perp$, the adiabatic trapping takes place but at larger I_{bunch}. The pinching of electron trajectories additionally increases the density in the bunch-cloud interaction. If there is a gap in the train, the adiabatic trapping is one-turn effect.

It seems that the minimum density can be achieved for the beam current higher than in Eq. (1) and for the bunch current lower than in Eq. (4). Both conditions are consistent for the bunches with

$$\sigma_z < s_b(\frac{\sigma_x\sigma_y(2\pi)^{3/2}}{2b^2}). \tag{5}$$

For PEP-II parameters, it means the bunch length of few mm.

Electrons kicked to the wall can produce secondary electrons if the yield of the walls and the energy of the incoming electrons are large enough. The later gives a weak limit on the bunch current of the order of 0.1 mA. Usually, the secondary electrons come out of the wall too late to see the parent bunch. Their motion is defined then by the space charge of accumulated electrons. The average density of the cloud n_e produces potential $U \simeq \pi e^2 n_e b^2$ at the wall which can prevent the secondary electrons with the typical energy $E_{sec} \simeq 5$ eV to get out of the wall provided $U > E_{sec}$. This limit the density in the vicinity to the wall to $n_e \simeq 1.8\,10^6\ cm^{-3}$ for $b = 2.5$ cm. The limit in this case is independent of the beam current.

These qualitative arguments show that the electron density at the beam line at high currents may be substantially reduced. In this paper, however, we assume the usual estimate of the average density is given by the criterion of neutrality: the average in time field of the beam $E_b(b) = 2eI_{beam}/(ecb)$ at the wall is equal to the average space-charge field $E_c(b) = 2\pi n_e b$. This gives

$$n_e = \frac{I_{beam}}{ecS}, \tag{6}$$

where $S = \pi b^2$ and $ec = 4.8\,10^{-9}$ A cm.

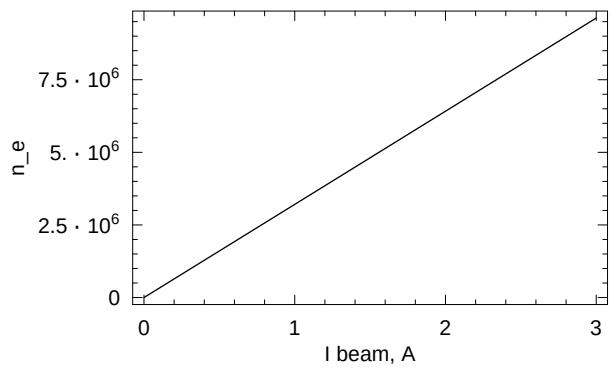

Figure 1: *The estimate of the average electron cloud density per cm^3 as function of beam current.*

For typical parameters of the B-factories, $S = 60\,cm^2$, and for the beam current $I_{beam} \simeq$ 1Amp, $n_e \simeq 3\,10^6\ 1/cm^3$, cf. Fig. 1. This is a conservative estimate. However, it is worth to underscore again that temporary and spatial variation of the cloud affect the density at the beam line, and more simulations are needed to calculate the density relevant to the head-tail instability which would include the finite bunch length.

4 Wake field of the cloud

Derivation of the effective wake field induced by the electron cloud is complicated by the substantial nonlinearity of electron motion in the cloud. A simple estimate of the wake field is known [3], [4], and was recently used to study the emittance blow up [8]. More accurate derivation of the transverse wake induced by the electron cloud was given recently [2]. This derivation includes frequency spread of the electrons of the e-cloud.

The transverse dipole wake per unit length as a function of $\zeta = \Omega_0(z' - z)/c$ proportional to the distance $z' - z$ between leading and trailing slices, and $\zeta_0 = \Omega_0 z/c$, the position of the leading slice from the head of the bunch:

$$W(z, z') = \frac{8n_e}{\lambda_b(1+p)}(\frac{\Omega_0}{c})W_{eff}(\zeta, \zeta_0). \tag{7}$$

Here,

$$W_{eff}(z, z') = \int_0^\infty dx \int_0^\infty dy e^{-\frac{x^2}{2}(\frac{\sigma_x}{\Sigma_x})^2 - \frac{Y^2}{2}(\frac{\sigma y}{\Sigma y})^2} [\frac{\sin[\psi(z)]Cos[\psi(z')]}{\Omega(z)/\Omega_0} - \frac{\sin[\psi(z')]Cos[\psi(z)]}{\Omega(z')/\Omega_0}]$$
$$[S_0(x, y_z) - y_z^2 S_1(x, y_z)][S_0(x, y_z') - y_{z'}^2 S_1(x, y_z')], \tag{8}$$

where $y_z = y\cos[\psi(z)]$, $y'_z = y\cos[\psi(z')]$, and $d\psi/dz = \Omega(z)/c$.

In the integrals we used dimensionless $x = X/\sigma_x$, $y = Y/\sigma_y$. The functions $S_0(x,y)$ and $S_1(x,y)$ in this variables are

$$S_{0;1}(X,Y) = (\frac{1+p}{2p})\int_0^\infty \frac{d\mu}{(1+\mu)^{3/2}\sqrt{1+\mu/p^2}} e^{-\frac{\mu}{1+\mu}\frac{y^2}{2}-\frac{\mu x^2}{2(\mu+p^2)}}[1;\frac{\mu}{1+\mu}]. \quad (9)$$

The wake Eq. (8) is a weak function of parameters $p = \frac{\sigma_y}{\sigma_x}$, z, and $\Sigma_{x,y}/\sigma_{x,y}$, the ratio of the cloud-to-beam rms sizes. The typical wake W_{eff} calculated for parameters $z' = 0$, $p = 0.2$, $\Sigma_x/\sigma_x = \Sigma_y/\sigma_y = 5$ is shown in Fig.2.

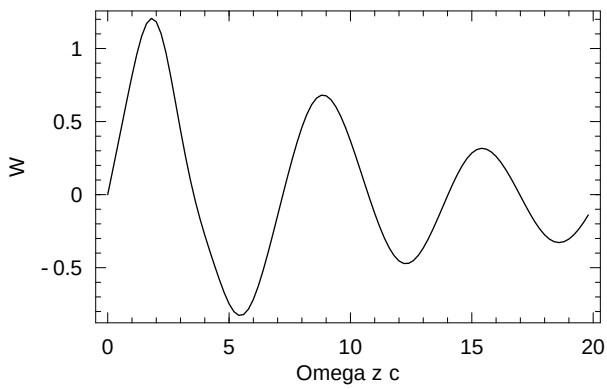

Figure 2: *Effective wake $W_{eff}(\zeta,0)$ of the cloud as function of $\zeta = \Omega_0 z/c$.*

For the nominal LER PEP-II parameters, Table I, the average cloud density $n_e = 4.75\,10^6$, $\Omega_y/(2\pi) = 14.0$ GHz, the number of oscillations within the bunch rms $\Omega_y\sigma_z/(2\pi c) = 0.6$, and the amplitude of the wake field is 695 $V/pC/cm$ what corresponds to the shunt impedance 4.7 MOhm/m. This should be compared with the resistive wall transverse wake

$$W_x(s) = \frac{4\delta_0}{b^3}\sqrt{\frac{2\pi R}{s}}, \quad (10)$$

where δ_0 is the skin depth at the revolution harmonics. For PEP-II parameters, $\delta_0 \simeq 0.17$ mm, and $W_x = 2.0$ $V/pC/cm$ at $s = 1$ cm.

The wake, see Fig. 2, can be approximated by the wake of a single mode with frequency $\mu\Omega_0$,

$$W_{eff}(\zeta) = W_{max}\sin(\mu\zeta)e^{-\frac{\mu\zeta}{2Q}}. \quad (11)$$

The best fit in all cases was for $\mu = 0.9$.

4.1 Effect of the cloud on the beam stability

The simplest effect of the cloud would be the direct resonance of oscillations in the cloud with the bunch separation frequency, $\Omega_0 s_b/(2\pi c) = integer$. Such resonances may take place at certain beam currents, but are suppressed by the strong nonlinearity of the cloud oscillations.

Other effects are the tune shift and the tune spread

$$\Delta\omega_\beta = \frac{2\pi r_e c^2 n_e}{\gamma\omega_\beta} G(\frac{\Omega_0 z}{c}) \tag{12}$$

caused by the e-cloud. The function $G = 1$ in the linear approximation. For the PEP-II nominal parameters, $I_{beam} = 1.45$ A, and for $n_e = 4.75\,10^6$ $1/cm^3$, the tune shift $\Delta Q_y/G = 0.046$ is comparable with the beam-beam tune shift and scales proportional to n_e. The factor $G(\Omega_0 z/c)$ describing variation of the tune shift along the bunch due to pinch of the cloud. It is shown in Fig. 8 vs $\Omega_0 z/c$ where z is the distance from the head of a long bunch, $\Omega_0\sigma_z/c >> 1$. The tune variation along the bunch can be of the order of the tune shift and can cause the transverse emittance degradation and set some particles on the betatron resonances.

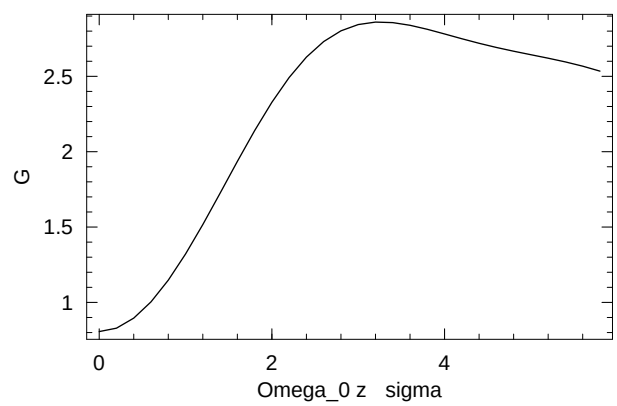

Figure 3: *Variation of the tune shift along a long bunch.* $p = 0.2$, $\Sigma_{x,y}/\sigma_{x,y} = 5$.

The coherent signal, which drives the instability, is dominated by the contribution of electrons with small amplitudes. Contrary to that, the tune spread is produced by all electrons in the cloud because the growing phase volume of remote electrons compensates decreasing force of interaction at large distances.

Variation of the tune with z does not lead to the chromatic head-tail effect. This is well known for the linear variation of the tune along the

bunch [11] but remains valid for arbitrary dependence $Q_b(z)$ what is easy to see in the two-particle model.

The KEK experience shows that the main dynamics effect of the cloud is the strong head-tail instability due to the effective transverse wake of the cloud [4]. The head-tail instability driven by the beam interaction with the cloud differs from that driven by the geometric wake because the effective wake of the cloud itself depends on the beam current.

The e-cloud wake obtained above allows us to estimate the threshold of the head-tail instability [5] in the high-current upgrades of the B-factory. As it was mentioned above, the main uncertainty here is the density of the cloud which is set, generally speaking, by the beam-cloud interaction and only in the sharp-edge regime can be defined in simulations which models a bunch train as a set of point-like macro particles.

The Satoh-Chin's formalism [10] is used to define the threshold of instability. The coherent shift $\lambda = (\Omega_{coh} - \omega_\beta)/\omega_s$ and the increment of the head-tail instability $\tau = 1/Im[\Omega_{coh}]$, $Im[\Omega_{coh}] > 0$, can be defined from the determinant

$$\mathrm{Det}[\delta_{h,l} + C_{h,l} G_{h+l}(\lambda)] = 0, \tag{13}$$

where $h, l = 0, 1, ..,$ and

$$C_{h,l} = \frac{I_{bunch}\beta_y}{8\pi(E/e)\nu_s}\frac{R_s}{Q}(\frac{\omega_r}{\omega_0})(\frac{\sigma_l}{\sqrt{2}R})^{h+l}\frac{\beta_h(\lambda)}{\sqrt{h!l!(1-1/4Q^2)}}. \tag{14}$$

Here $\omega_0 = c/R$, parameters $\beta_0(\lambda) = 1/\lambda$, $\beta_1(\lambda) = 2\lambda/(\lambda^2 - 1)$, etc. The wake field parameters: the resonance frequency ω_r, the shunt impedance R_s and the Q-factor, are related to the parameters of the wake field defined above:

$$\omega_r = \mu\Omega_0, \frac{R_s}{Q} = \frac{2Z_0 n_e}{\pi\mu\lambda_b(1+p)}W_{max}, \tag{15}$$

where $Z_0 = 120\pi$Ohm and λ_b is the linear bunch density. Parameters $W_{max} = 1.2$ and $Q = 5$ were used in calculationsc̃itehei1. Functions $G_m(\lambda)$ in Eq. (13) are given by the sums

$$G_m = \sum_{p=-\infty}^{\infty} e^{-s^2(p-p_1)^2}[\frac{1}{p+p_-} - \frac{1}{p+p_+}](p-p_1)^m, \tag{16}$$

where $s = \sigma_l/R$, $p_1 = \xi/\alpha - \lambda\nu_s - \nu_\beta$, $p_\pm = \lambda\nu_s + \nu_\beta + (\omega_r/\omega_0)[\pm\sqrt{1-1/4Q^2} + i/2Q]$. To simplify calculations, we derived and used the identity

$$\sum_{p=-\infty}^{\infty}\frac{e^{-s^2(p-p1)^2}}{p+p_0} = \pi e^{-s^2(p_0+p_1)^2}[\cot[\pi p_0] + i\mathrm{Erf}[is(p_0+p_1)]$$
$$-4\sqrt{\pi}\sum_{k=1}^{\infty}(-1)^k e^{-(\pi k/s)^2}\int_0^\infty dx e^{-x^2}\sin[2s(p_0+p_1)x + 2\pi k p_1]. \tag{17}$$

For small $s << 1$, only the first two terms are needed to be taken into account. Eq. (17) speeds up calculations by several orders of magnitude. Functions G_m, $m > 0$, can be obtained as derivatives of Eq. (17).

Results of calculations are illustrated in Fig. 4 for upgrades of the PEP-II LER at the zero chromaticity $\xi = 0$. Parameters of the upgraded B-factory [1] (I)-(IV), see Table 2, are different from the nominal parameters mostly by the beam current and the rms bunch length.

The threshold currents, where the modes $m = 0$ and $m = -1$ cross, are of a fraction of a mA in all cases except of the first scenario. The unusual dependence of the growth rate on the beam current is due to the fact that the e-cloud wake itself varies with current. The stabilization at a high current can be understood as a result of growing frequency of electron oscillations Ω_0 with current what shifts Ω_0 out of the bunch spectrum.

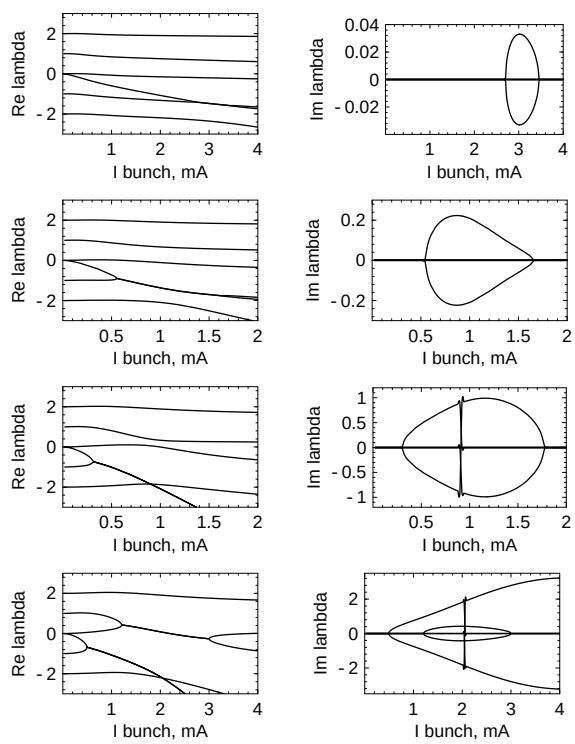

Figure 4: *The threshold of the head-tail instability for upgrades of the PEP-II. In the left column: the tune shift* $Re[\lambda] = (\Omega - \omega_\beta)/\omega_s$ *vs. bunch current. In the right column: the dimensionless growth rate* $Im[\lambda] = 1/(\omega_s \tau)$. *The rows are for the I,II, III, and IV upgrade parameters, see Table 2, respectively. The density of the cloud is scaled proportional to the beam current as in Eq. (1). Parameters of the wake are explained in the text.*

It is worth to remind that the lattice chromaticity combined with the e-cloud wake leads to the chromatic head-tail effect, which does not have a threshold.

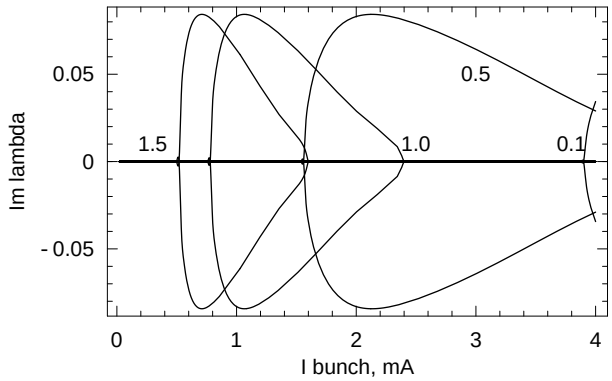

Figure 5: *Dependence of the threshold of the head-tail instability on rms bunch length σ_l. Four curves correspond to σ_l shown in cm. The synchrotron tune Q_s was scaled as Q_s $1/\sigma_l$ with other parameters for the scenario II, see Table 2.*

5 Effect of the coherent synchrotron radiation

Usually it is assumed that a bunch can radiate coherently in the beam pipe if the bunch length is sufficiently small,

$$\sigma_l < b\sqrt{\frac{b}{R}}, \tag{18}$$

where R is the bend radius.

Recently, however, the coherent radiation with the wave length much smaller than the bunch length, $\lambda << \sigma_l$, was observed experimentally [6]. A similar effect was noticed also by other groups. The radiation may indicate a micro-structure within a bunch. A coherent synchrotron radiation (CSR) was proposed as a possible cause of such micro-structures [7]. The micro-bunching in this model with the density modulation $\delta n(z,s) = \delta n(0)e^{ikz-i\Omega s/c}$, where $k = 2\pi/\lambda$, and Ω is coherent frequency, is a result of the longitudinal microwave instability driven by the CSR impedance $Z(k)$. The CSR impedance of a bend with the radius R is [12], [13]

$$Z(k) = iA(\frac{k}{R^2})^{1/3}, \quad A = 1.63i - 0.94. \tag{19}$$

The instability produces a micro-structure within a bunch. The CSR radiation of the micro-structure supports the instability in a self-consistent

way. As usually, the threshold of instability can be defined from the dispersion relation (DR). For a wave length of modulation small compared to the bunch length, the answer can be obtained considering a coasting beam with the linear beam density $\lambda_b = N_b/\sqrt{2\pi\sigma_l^2}$ equal to the linear density of a bunch. The dispersion relation for a Gaussian bunch takes in this case the form

$$1 = -\frac{\Lambda A}{\sqrt{2\pi}}(\frac{1}{kR})^{2/3}\int_{-\infty}^{\infty}\frac{pdp}{p+\tilde{\Omega}}e^{-p^2/2}. \tag{20}$$

Here, $\tilde{\Omega} = \Omega/(ck\eta\delta_0)$, and

$$\Lambda = \frac{\lambda_b r_0}{\eta\gamma\delta_0^2} \tag{21}$$

depends on the slip factor η and the rms energy spread δ_0.

Numerical solution of Eq. (20) shows that the growth rate of instability $\Gamma = \mathrm{Im}[\Omega]$ becomes positive and the instability takes place for $\Lambda > 1.6(kR)^{2/3}$. The growth rate $1/\tau$ of the instability above the threshold is

$$\frac{1}{\omega_0\tau} \simeq \frac{\Lambda}{4}(\frac{\eta\delta_0}{R})(kR)^{1/3}. \tag{22}$$

Note that the threshold is minimum while the growth rate is maximum at the lower wave lengths.

For a bunch in a beam pipe with the half-gap b, the screening effect has to be taken into account: the CSR occurs only at $kR > (\pi R/2b)^{3/2}$. Let us introduce parameters

$$S = (kR)(\pi R/2b)^{-3/2}, \quad \mu_p = 1.6\Lambda(kR)^{-2/3}. \tag{23}$$

The CSR instability in a beam pipe can take place if both parameters are larger than one. These parameters as functions of the wave length of modulation is shown in Fig. 6 for the upgrade (III) and two scenarios of the upgrade (IV) (for two values of the momentum compaction number). Only in the case (IV) the instability is possible. In all other cases (including the nominal parameters and the cases (I-II), not shown in Fig. 6) both parameters S, μ are smaller than one for the modulation with the wave length less than σ_l.

Above the threshold, the amplitude of the density modulation increases, in the linear approximation, exponentially. Due to nonlinear effects, the amplitude saturates at some finite amplitude δn_{max}. The estimate gives [14]

$$\delta n_{max} \simeq \frac{\eta\gamma\delta_0^2}{Ar_0}(kR)^{2/3}. \tag{24}$$

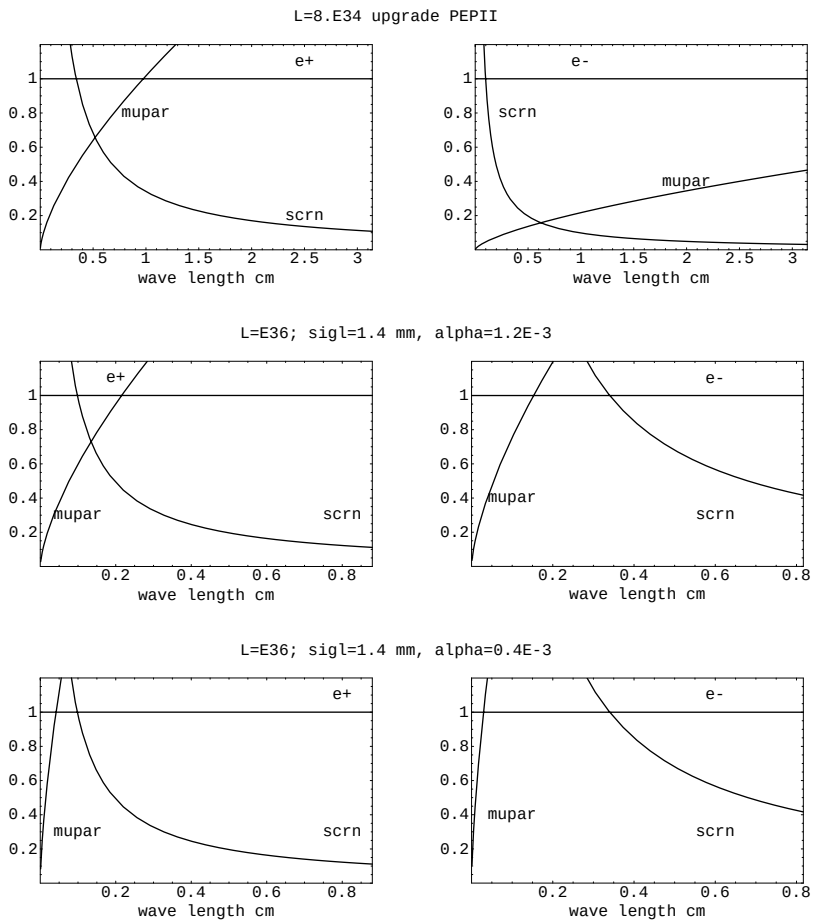

Figure 6: *Parameters S and μ_p for high-luminosity upgrades. In the last case, the CSR instability is possible.*

6 Summary

The paper presents discussion of two dynamics effects, the beam instability driven by the electron cloud and the CSR instability, on the performance of the future upgrades of the PEP-II B-factory. The threshold of the head-tail instability depends on the density of the electron cloud on the beam axis. The threshold of instability depends on the density of the electron cloud on the beam axis. The density of e-cloud formation can be different for the case of the kick regime ($\Omega\sigma_z/c << 1$) and the adiabatic regime ($\Omega\sigma_z/c >> 1$). Because $\Omega\sigma_z/c$ can be substantially different in x/y planes, the distribution of the cloud across beam pipe, electron trajectories, and beam dynamics in the x/y planes can depend on this parameter. It would be interesting to see whether the absence of the e-cloud effects at DAFNE can

be related to this parameter. The adiabatic trapping described in the first section shows that tracking of a train as a chain of point-like macro particles may not be good enough to define the density and the effect of the finite bunch length has to be included in simulations. We presented arguments that the density, actually, may be reduced at high currents. However, this has to be studied more accurately. With this uncertainty, the wake of the cloud can be calculated giving the tune variation along the bunch and determines the threshold of the head-tail instability for several scenarios of the B-factory upgrades. Dependence of the growth rate on current is unusual because the density and the wake field of the cloud depends on the current as it is implied by the condition of neutrality. In the last section, we discuss effect of the CSR on the beam dynamics. It is shown, that this effect can be noticeable only for the last scenario with the highest luminosity.

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