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ION EFFECTS AT SUPERKEKB*

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Abstract

Ion effects at SuperKEKB is discussed when the electron beam is stored in the low energy ring. We introduced train gaps in order to mitigate the fast ion instability and the tune shift by ions. Results show that the pressure of carbon monoxide of 1 nTorr will be necessary for keeping the luminosity reduction due to the insertion of the train gaps below 15 %.

INTRODUCTION

SuperKEKB is an upgrade plan of KEK B factory [1]. Its target luminosity is 5 to 10 times 10^{35} cm^{-2} sec^{-1}. Main parameters of SuperKEKB are shown in Table 1.

Unlike KEKB the electron beam may be stored in the low energy ring (LER) at SuperKEKB in order to mitigate the electron cloud effect. In this case, compared with KEKB, the beam energy is decreased from 8 to 3.5 GeV, the beam current is increased from 1.1 to 9.4A and the pressure in beam chambers will be increased from 1 to 5 nTorr due to the large stored current. All factors contribute to the increase of ion effects, i.e. the coupled bunch instability and the tune shift. The ion effects would be strong enough to degrade the luminosity at SuperKEKB.

In this report we estimate the ion effects in SuperKEKB when the electron beam is stored in LER.

Table 1: Main parameters of SuperKEKB

	LER/HER
Luminosity (cm^{-2} sec^{-1})	5 - 10 10^{35}
Beam energy (GeV)	3.5 / 8.0
Beam current (A)	9.4 / 4.1
Number of bunches	5018
Bunch spacing (m)	0.6
Emittance (nm)	24

ION TRAPPING

Ions, which are produced by ionization of residual gases by the beam, can be trapped in a beam potential for a long time due to the attractive electric force of the beam. The phenomenon is called the ion trapping. The beam interacts with ions again and again in many turns, and then the motion of the beam becomes unstable due to the interaction between the beam and the ions. The ion trapping is usually avoided by introducing contiguous RF buckets ("a train gap") that are unoccupied by the bunches. While the train gap in KEKB amounts to 10% of the total RF buckets, the train gap in SuperKEKB will be reduced to 2 % to relax the effect of beam loading on the RF system [1].

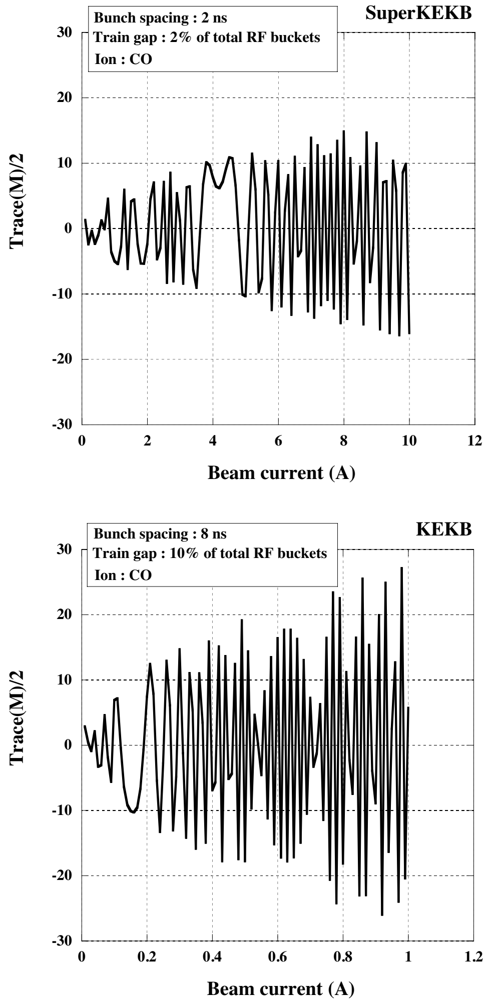

Figure 1: Trapping condition of ions for SuperKEKB (top) and KEKB (bottom). Parameters in the calculation are shown in the figures.

In a simple theory of the ion trapping [2] an ion can be trapped if the absolute value of the trace of the following matrix M,

$$M = \left\{ \begin{pmatrix} 1 & \tau \\ 0 & 1 \end{pmatrix} \cdot \begin{pmatrix} 1 & 0 \\ -K & 1 \end{pmatrix} \right\}^p \begin{pmatrix} 1 & (h-p)\tau \\ 0 & 1 \end{pmatrix}, \qquad (1)$$

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is less than 2, where τ is the bunch spacing in unit of time, h the total number of RF buckets and p the number of bunches in a train. K represents a kick by a bunch to the ion and is given by

$$K = \frac{2N_b r_p c}{A\sigma_y(\sigma_x + \sigma_y)} \quad , \qquad (2)$$

where A, N_b, $\sigma_{x,y}$, r_p and c are the atomic mass number of ions, the number of electrons in a bunch, horizontal and vertical beam size, the classical proton radius and the speed of light, respectively. Figure 1 shows the trace of M as a function of the beam current at SuperKEKB when the ions are carbon monoxide (CO). |Trace M|/2 is much larger than 1. The figure also shows the result for KEKB where the ion trapping is not observed. |Trace M|/2 is of the same order of magnitude as that in SuperKEKB. According to the linear theory, the ions will not be trapped with the train gap of 2 % in SuperKEKB.

FAST ION INSTABILITY

Even if the conventional ion trapping does not occur, the ions can be trapped in a single passage of the beam and cause the instability called the fast ion instability (FII). The ions created by the head of the bunch train affect to the tail. The FII is transient, which means that if a damping such as the radiation damping exists, the oscillation is damped from the head to the tail in the train, and then the oscillation of all bunches is finally damped [3]. Actually the oscillation of the beam would be excited by noises such as those in a bunch-by-bunch feedback system. Equilibrium amplitude is determined by a balance of the excitation of the FII by the noises and the damping.

As will be shown later the growth time of the FII in a long train whose length is about the circumference is estimated to be very short, i.e. less than one turn. As one of the simplest ways to mitigate the FII is to divide the train into several short trains by introducing the train gaps, we will discuss here the effects of the train length on the growth time.

Theory of the FII

We briefly summarize the theory of the FII. According to the linear theory by G. V. Stupakov et al. [4] the offset of the centroid of a continuous beam y(s,z) is given by

$$\frac{\partial^2}{\partial s^2} y(s,z) + \frac{\omega_\beta^2}{c^2} y(s,z) = -\kappa \int_0^z z' \frac{\partial y(s,z')}{\partial z'} D(z-z')dz' \qquad (3)$$

, where s is longitudinal position in a ring, z the distance measured from the head of a train and D a decoherence function of the ion oscillation defined by an ion distribution function $f(\omega_i)$ as

$$D(t-t') = \int d\omega_i \cos\omega_i (t-t') f(\omega_i) \ . \qquad (4)$$

The $f(\omega_i)$ has a peak at

$$\omega_{i0} = \sqrt{\frac{4N_b r_p c^2}{3As_b\sigma_y(\sigma_x + \sigma_y)}} \qquad (5)$$

, where s_b is the bunch spacing. The coefficient κ is given by

$$\kappa = \frac{4\lambda_{ion} r_e}{3\gamma s_b \sigma_y(\sigma_x + \sigma_y)} \ , \qquad (6)$$

where γ is the Lorenz factor and λ_{ion} is the ion line density per bunch given by

$$\lambda_{ion} = N_b \sigma_{ionization} n_{gas} \ , \qquad (7)$$

where $\sigma_{ionization}$ is the ionization cross section and n_{gas} is the gas density. Assuming a solution of

$$y(s,z) = \mathrm{Re}\, A(s,z) \cdot e^{-i\omega_\beta s/c + i\omega_{i0} z/c} \qquad (8)$$

the equation is transformed into

$$\frac{\partial A(s,z)}{\partial s} = \frac{\kappa\omega_{i0}}{4\omega_\beta} \int_0^z z' A(s,z') \hat{D}(z-z') dz' \qquad (9)$$

where

$$\hat{D}(z) = \int d\omega_i f(\omega_i) e^{i(\omega_i - \omega_{i0})z/c} \ . \qquad (10)$$

If we use $\hat{D}(z) = e^{-\alpha z}$ where α is defined as $\alpha = \omega_{i0}/(2Qc)$ with a quality factor of ion oscillations Q, the analytic solution is obtained as

$$A(s,z) = \exp(-\alpha z) \cdot I_0\left(\frac{z}{\ell}\sqrt{\frac{s}{c\tau}}\right) + \alpha \int_0^z dz' I_0\left(\sqrt{\frac{s(z^2 - z'^2)}{c\tau\ell^2}}\right) \cdot \exp(-\alpha(z-z')) \ . \qquad (11)$$

Without the decoherence of the ions (i.e. α = 0) the amplitude growth has a form of $\exp(const. \cdot \sqrt{s})$. If zA(s,z) has slow variation in z, the amplitude growth is exponential as,

$$A(s,z) = A_0(z) \cdot \exp\left(\frac{s}{\tau_e c}\right) \qquad (12)$$

where τ_e is an exponential growth time given by

$$\frac{1}{\tau_e} = \frac{2cr_e\lambda_{ion}}{3\gamma\omega_\beta s_b \sigma_y(\sigma_x + \sigma_y)} Q \cdot z \cdot \qquad (13).$$

In a nonlinear regime where the oscillation amplitude exceeds σ_y, the amplitude growth is linear on s or time [5].

Amplitude growth

The oscillation amplitude by the FII saturates at about σ_y due to the nonlinear effect of the beam-ion force as described in the previous section. In the nonlinear regime the growth is slow and would be cured by the feedback system. However, the oscillation of σ_y is not tolerable for SuperKEKB because the luminosity is largely lost. We should damp the oscillation in the linear regime where we may use the linear theory. Thus our method to discuss the amplitude growth of the FII is

1) Use the analytic linear theory which takes into account the decoherence of the ion oscillation to obtain acceptable fill patterns of the bunches,
2) Perform a simulation to confirm the result of 1) and get more realistic results than the analytic estimate then,
3) Estimate the effect of the noise and the feedback system to get the equilibrium amplitude of the oscillation.

Following conditions were taken into account here.

1) The train gap should be less than 200 ns to avoid the effect of the transient beam loading on the RF system [6],
2) The vacuum pressure should be smaller than 5 nTorr for CO and 10 nTorr for H_2 to get a lifetime of 10 hr. A target pressure of LER is about 5 nTorr at arc sections [1],
3) Typical damping time of the bunch-by-bunch feedback system is 0.2 ms from the experience of KEKB [1],
4) Fluctuation of the vertical offset at IP should be less than about ± 0.01 σ^*_y, which causes 5 % loss of the luminosity according to a beam-beam simulation [7].

a) Analytic estimate of the growth

The Figure 2 shows the analytic estimate of the amplitude growth which was obtained by the numerical integration of the equation (11). Note that the pressure is five times smaller than the expected pressure in SuperKEKB. From Fig. 2 the e-fold growth times for the train length of 3016 m and 60.3 m are 3.5 μsec and 0.29 ms respectively. Considering that the expected damping time of the feed back system is 0.2 ms, the train length of 60 m (i.e. 50 trains in the ring) would be a good starting value for the simulation.

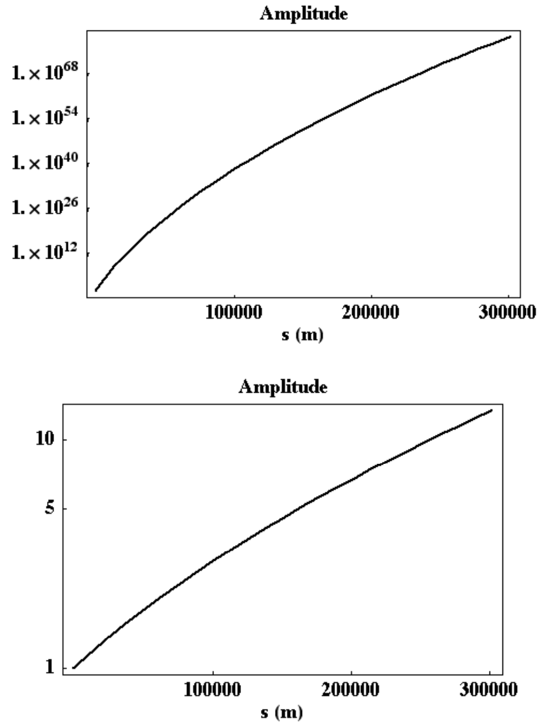

Figure 2 : Amplitude growth by the linear theory for the train length of 3016 m (top) and 60.3 m (bottom). Assumed parameters are the energy of 3.5 GeV, the bunch current of 2 mA, the bunch spacing of 0.6 m, the horizontal and vertical beta functions of 15 m, the horizontal and vertical emittance of 2.4 10^{-8} and 9.6 10^{-10} m respectively, Q of 10 and the partial pressure of CO of 1nTorr.

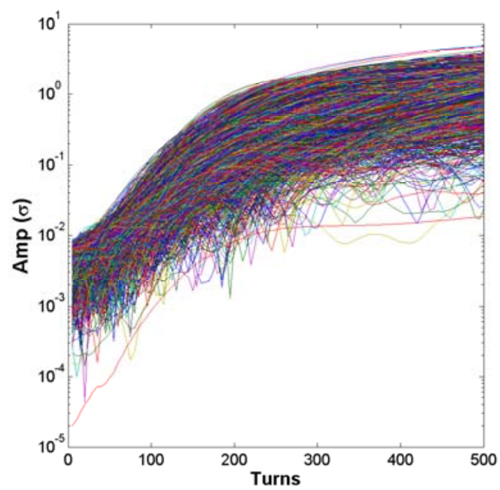

Figure 3 : Amplitude in unit of 1 σ_y as a function of turns by the tracking. Amplitudes of all bunches are displayed. The number of trains is 50, the train gap is 20 buckets, the number of bunch per train is 82 and the pressure of CO is1n Torr. The growth time is 0.35 ms.

b) Growth time by the Simulation

A code developed by one of the authors (L. Wang) was used for the simulation [8]. The code treats the rigid Gaussian beam and the ions represented by macro particles. The kick between the beam and the ion is calculated from two dimensional space charge force. Tracking of the beam through accelerator elements is possible so that the modulation of the ion oscillation due to the change of the beam size is taken into account. The density of the ions is calculated for various pressures and multi-gas species.

We have two ways to calculate the amplitude growth from the simulation. One is a tracking of the bunch motion. The other uses the ion density from the simulation to calculate the growth time by an analytic formula.

Figure 3 shows an example of the result of the tracking. The growth time by the tracking has a good agreement with that of the analytic estimate.

Figure 4 shows the ion density obtained by the simulation. The parameters in the simulation are same as those in the tracking except that the pressure is 0.75 nTorr in this case. The growth time τ_e is estimated from

$$\frac{1}{\tau_e} \approx \frac{c r_e \rho \beta_y}{3\sqrt{2}\gamma}\frac{1}{(\Delta\omega_i/\omega_i)_{rms}} \ , \qquad (14)$$

where ρ is the ion density [8]. We estimated the relative width of the ion frequency $\Delta\omega_i/\omega_i$ by the simulation and set it to 0.3. The growth time from (14) is 0.38 ms which is almost same as that from the tracking. Thus the growth time from the tracking in 1 nTorr is almost equal

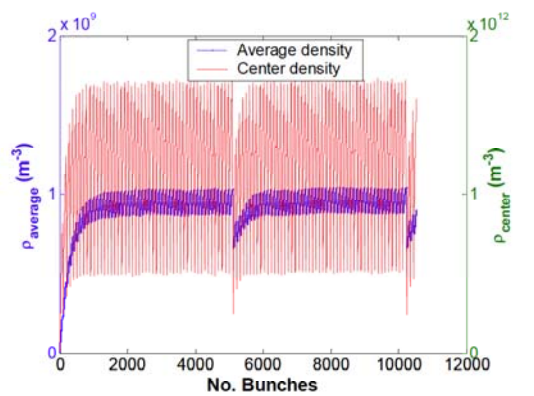

Figure 4 : Density of CO ions by the simulation. The number of trains is 50, the train gap is 20 buckets, the number of bunch per train is 82 and the pressure is 0.75n Torr.

to the estimated growth time from the ion density in 0.75 nTorr. We confirmed that this relation is valid even if the train gap was changed. Thus we estimated the growth rate at 1nTorr from the ion density at 0.75 nTorr in order to save the cpu time for the tracking. Figure 5 shows the growth rate as a function of the train length (i.e. the number of bunches in a train) for the train gap of 10, 15 and 20 buckets.

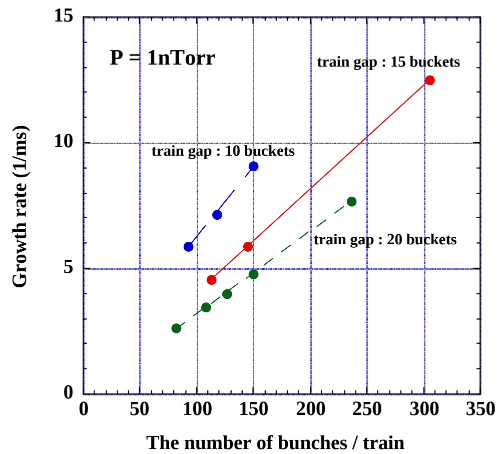

Figure 5 : Growth rate as a function of the number of bunches in a train for train gaps of 10, 15 and 20 buckets.

c) Train length vs. the total number of bunches

The total number of the bunches, which is proportional to the luminosity, was calculated as a function of the train length. Figure 6 shows the result when the train gap is 20 RF buckets. The total number of the bunches saturates when the train length is larger than 150 bunches.

d) Train length vs. growth rate

The allowable train length is obtained from the relation between the growth rate and the train length assuming the maximum damping rate of the feedback

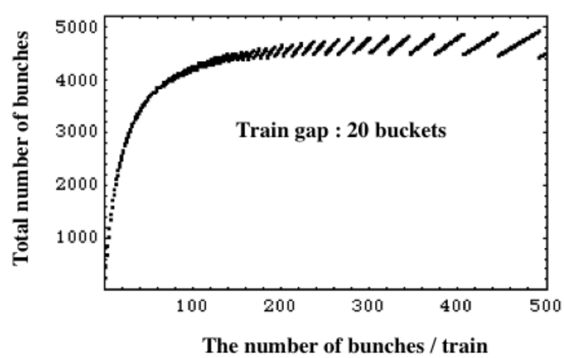

Figure 6 : The total number of bunches as a function of the train length when the train gap is 20 buckets.

system. Then the luminosity reduction due to the insertion of the vacant train gaps is calculated from the relation between the total numbers of the bunches and the train length. The results are,

1) if the pressure of CO is 5 nTorr and the growth rate less than 5 ms^{-1} which is the damping rate of the feedback system is required, the train length should be less than 35 bunches, which leads to the luminosity reduction of about 40% comparing with the case where all buckets are occupied by the bunches,
2) if the pressure of CO is reduced to 1 nTorr, the train length of 150 bunches would be possible, which leads to the luminosity reduction of about 15%.

e) Noise and Feedback

An equation with the noise and the feedback damping by A. W. Chao and G. V. Stupakov [3] was modified to include the ion decoherence function exp(-αz) as,

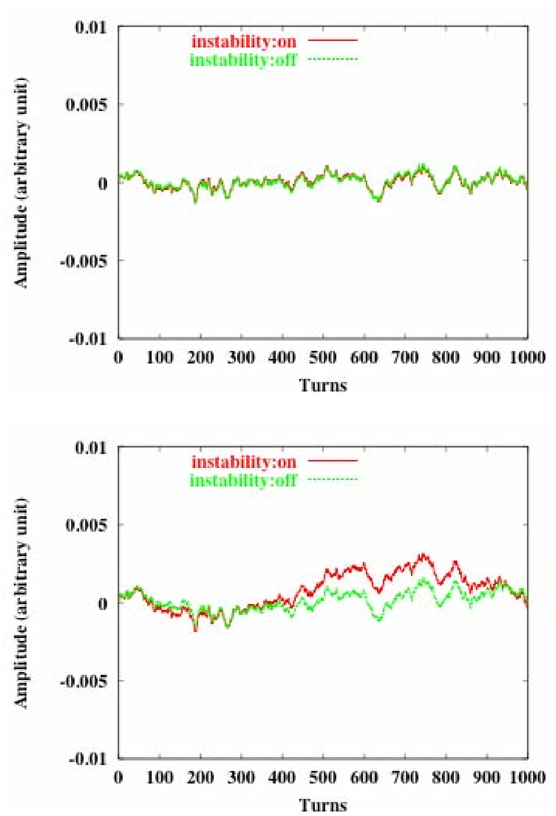

Figure 7 : Amplitude of the last bunch up to 1000 turns with noise and the feedback for the damping time of the feedback of 0.48 ms (top) and 1.44 ms (bottom). Red (green) line means that the instability turns on (off).

$$\frac{\partial A(s,z)}{\partial s}+\frac{1}{c\tau_d}A(s,z)$$
$$=\frac{1}{2s_0}\int_0^z dz'z'A(s,z')\cdot e^{-\alpha(z-z')}+f(s,z),\quad s_0=\frac{2\omega_\beta}{\kappa\omega_i}\ ,\qquad (15)$$

where τ_d is the damping time of the feed back system and f(s,z) represents random noise.

The equation (15) was numerically integrated. Figure 7 depicts the amplitude growth for τ_ds of 0.48 and 1.44 ms. The same sequence of random numbers was used in each calculation. The assumed parameters were those which the simulation gave the e-fold growth time τ_e of 0.35 msec.

Fig. 7 shows that τ_d of the same level as τ_e seems enough to damp the instability to the noise level.

TUNE SHIFT

Beam-ion force changes the tune of the bunches. As the ion density changes along the train, the tune also does along the train. The vertical tune shift of the last bunch in a train was estimated using the ion density obtained by the simulation as [8],

$$\Delta\nu_y=\frac{r_e n_{bunch}\lambda_{ion}}{6\pi\gamma}\int_{trapped\ region}\frac{\beta_y}{\sigma_y(\sigma_x+\sigma_y)}ds\ ,\qquad (16)$$

where n_{bunch} is the total number of the bunches.
A way to reduce the tune shift is to divide the train with the train gaps like the mitigation technique of the FII.

Figure 8 shows the tune shift of the last bunch as a function of the train length for the several pressures and the train gaps. From Fig. 8 the tune shift at the last bunch

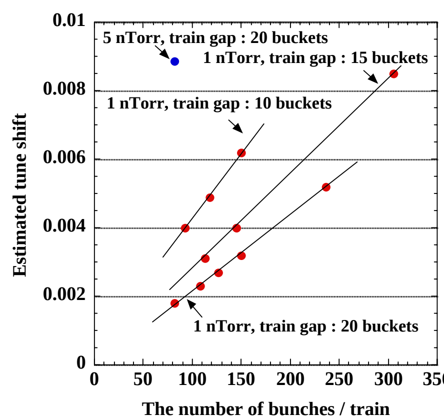

Figure 8 : Tune shift of the last bunch as a function of the train length for several pressures and train gaps in unit of RF buckets.

is 0.009 when the train length is 82 bunches, the train gap is 20 RF buckets and the pressure is 5 nTorr. Note that the tune shift from the head to the tail is about 70 % of the tune change of the last bunch because the first bunch in the train also has a tune shift due to the survived ions from the last train gap as shown in Fig. 4. The experience in KEKB shows that the tune change of 0.001 affects the luminosity and the vertical tune in LER changes 0.0018 along the train due to the electron cloud. Thus the tune change of 0.002 along the train would be the maximum permissible value in SuperKEKB. The tune change of 0.009 would not be acceptable in SuperKEKB. Fig. 8 shows that

1) if the pressure of CO is 5 nTorr and the tune shift along the train less than 0.002 is required, the train

length should be less than 25 bunches, which leads to the luminosity reduction of 45 %,

2) if the pressure of CO is reduced to 1 nTorr, the train length of 135 bunches would be possible, which leads to the luminosity reduction of 15 %.

SUMMARY

The maximum allowable train length to mitigate the FII and the tune shift by the ions was discussed when electrons are stored in LER at SuperKEKB. Assuming that the pressure of CO is 5 nTorr, 1) if the growth rate of the FII should be less than the damping rate of the feedback system of 5 ms^{-1} the train length would be limited to 35 bunches and 2) if the tune shift due to the ions should be less than 0.002 the train length would be limited to 25 bunches. The luminosity reduction by inserting the train gaps to divide a long train into allowable short trains is about 40 and 45% for the cases 1) and 2) respectively.

If the pressure of CO is 1 nTorr, the luminosity reduction will be 15 %. Thus the CO pressure of 1 nTorr which is about five times smaller than the target pressure will be necessary for SuperKEKB if the electrons are stored in LER.

Our calculation shows that the tune shift would be as much serious as the amplitude growth by the FII as pointed out by F. Zimmermann before [9].

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