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SOLENOID EFFECTS ON AN ELECTRON CLOUD

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Abstract

Electron cloud due to beam-induced multipacting can generate transverse instabilities and beam size blow-up in both positron and proton accelerators. A solenoid satisfactorily suppresses multipacting in the drift region by confining the electrons close to the walls' surface. There is a long drift region in the KEKB LER, wherein a solenoid occupies most of the beam's pipe. We investigated the solenoid's effects on the build-up of the electron cloud, the wake field and transverse coupled instabilities induced by electron cloud.

INTRODUCTION

An electron cloud was first observed at the INP PSR in 1965[1]. Shortly thereafter, an electron cloud and beam-introduced multipacting was found at CERN-ISR [2, 3]. Instability in that beam caused by the electron cloud was cured using clearing electrodes. More recently, electron clouds have s been observed in almost all high intensity beams. Solenoids have been employed in these machines to clean electron clouds, especially in the two B-factories [4, 5]. This paper summarizes solenoid effects on the electron cloud as a further study of that work [6]. Table 1 shows the typical parameters of the three accelerator-storage rings we studied. Among of them, the KEKB LER has a short bunch length and SNS's bunch is long. In the former, we considered both the real beam and an assumed high-beam current to check the state that an electron cloud may take in future under such conditions.

Table 1: Basic parameters of the KEKB LER, RHIC, and the SNS ring

Variable	KEKB	RHIC	SNS
Particle type	e^+	p	p
rms beam size (mm)	0.42/0.06	2.4	28
Chamber radius (mm)	50	60	100
Bunch length (ns)	0.05	15	700
Beam intensity ($\times10^{10}$)	3.3/8	10	20000

MECHANISM OF ELECTRON CLEARING WITH A SOLENOID

Example I; electron motion with a solenoid in RHIC, a short bunch case

In short bunch machine, the bunch spacing is much longer than its length. The electron's orbit is close to a half circle if the bunch gap is longer than the half period of electron's gyration motion. Therefore, a weak solenoid with gyration period less than half a bunch gap can efficiently confine electrons near the wall's surface in the vacuum chamber. The required strength of the solenoid field can be estimated using the criterion

$$\rho << a \qquad (1)$$

where ρ is the Larmor radius

$$\rho = \frac{\sqrt{2Em_e}}{eB} \qquad (2)$$

where E is the electron energy, and m_e and e are the mass and charge of the electron, respectively.

In a static model, for an electron near the beam chamber's surface, the energy received from the bunch is

$$\Delta E \approx 2m_ec^2r_e^2\frac{N^2}{r_b^2} \approx 8.12\times10^{-18}\frac{N_b^2}{r_b^2[mm^2]}[eV] \qquad (3)$$

where r_e is the classic radius of the electron, N_b the bunch intensity, and r_b the radius of beam chamber. From the parameters given in Table 1, the energy calculated from Eq. (3) is about 21 eV, and 23 eV, respectively, for the KEKB LER and RHIC. For this given energy gain, we can roughly estimate the radius of the electron's gyration orbit by Eq. (2) because the preliminary electron's energy is only a few eVs. This energy gain can also be used to assess the secondary emission yield. If the estimated yield is bigger than unity, multipacting happens. Note that the reflected electrons may have a high initial energy up to the value given by Eq. (3). Fig. 1 shows the simulated electron's orbit and energy at the wall in RHIC with a 20 G uniform solenoid field. In this example, the bunch's length is close to electron's gyration period. The energy at wall usually is less than that given by Eq. (3), but is higher for reflective electrons.

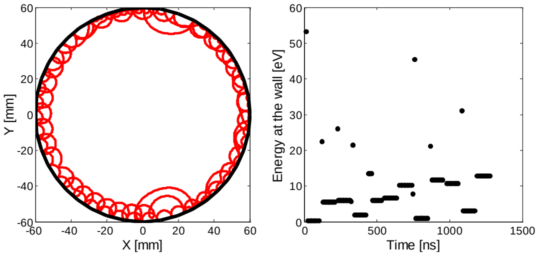

Figure 1: Electron orbit and energy at the with 20 G solenoid fields in RHIC drift region

When the bunch's gap is shorter than the half period of electron's gyration, the electron's energy gain from the beam is difficult to be estimated. An electron receives multiple kicks from the beam before it hits the chamber

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wall. The electron's energy at the wall has large spread because it strongly depends on the positions of interaction between the electrons and bunches. Consequently, multipacting random occurs with low threshold at this case.

Example II; electron motion with a solenoid in the SNS, a long bunch case

Multipacting in a long bunch accumulator occurs around the bunch's tail due to the high energy-gain at the wall [7]. A weak solenoid of 30G can confine the electrons near the wall and totally suppress multipacting by reducing the electron's energy. Fig. 2 compares the energy at wall and orbit for 0G and 60G solenoid fields. The peak energy with 60G is less than 30 eV, below the multipacting threshold. Note that Eq. (3) doesn't apply in long bunch case.

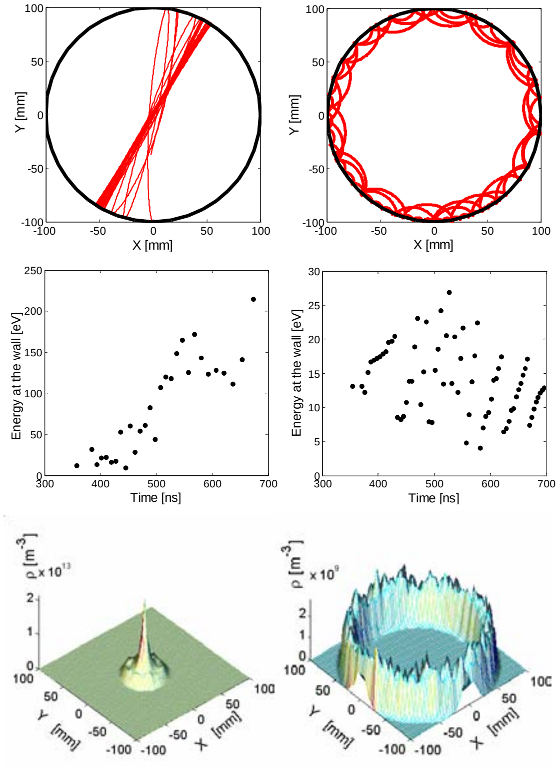


Figure 2: Electron orbit (top row), energy at the wall (middle row), and electron-cloud distribution (bottom row) with 0 G (left column) and 60G (right column) solenoid fields in the SNS's accumulator drift region

EFFECT OF BEAM INTENSITY

In this section, we discuss the effect of the beam's intensity on multipacting and electron distribution for the short bunch machine. For a given solenoid field, the electron's orbit and energy at the wall depends on the beam's parameters, such as bunch spacing, and bunch current. Fig. 3 shows the distribution of the electron cloud with a 10 G solenoid field for different bunch intensities in the KEKB LER. The bunch spacing is 4 ns. The electron cloud is closer to the chamber's center when bunch intensity is high due to the stronger beam's space-charge-force. Therefore, a stronger solenoid field is required for a high beam current.

When the bunch gap is longer than the half period of electron's gyration, the threshold of multipacting depends only on the beam's intensity as given by Eq. (3) [8]. However, when the gap is shorter, it also depends on the bunch's spacing and the solenoid field.

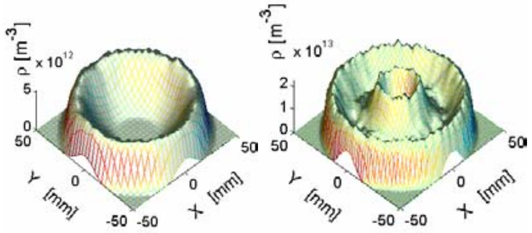


Figure 3: Electron-cloud distribution at bunch intensity 4×10^{10} (left) and 8×10^{10} (right) with a 10G solenoid field in the KEKB low-energy ring.

RESONANCE OF E-CLOUD BUILD-UP

With short bunches, such as in B-factories, resonance occurs when the time taken by an electron to emerge from the wall and be bent back by the magnetic field coincides with the interval between two consecutive bunches [8, 9]

$$T/2 = S_b/c \tag{4}$$

where T is the period of gyration motion $2\pi m_e/(eB)$. This period is 7.2 ns for a 50 Gauss field. Resonance at 22G and 45G is, respectively, for 8ns and 4ns spacing in the KEKB LER. Fig. 4 shows the solenoid effect on the electron cloud's density for 4 ns. Simulation reveals a peak of electron density at 45 G, as predicted by Eq. (4), when the reflected electrons are included. However, without them, the electron density is a monotonic function of the solenoid field. Therefore, the reflected electron contributes to the peak density at resonance.

Figure 5 depicts the electron-cloud distributions at different solenoid fields. The distribution in 10G already was shown in Fig. 3. The stronger the field, the closer to the wall is the electron cloud. Although the electron cloud density is peak at the resonance, a stronger field always more effectively confines the photoelectron cloud near to the wall.

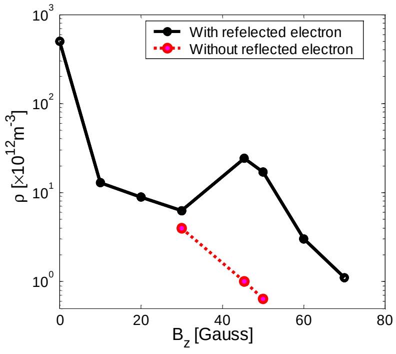


Figure 4: Electron density as a function of solenoid fields in the KEKB LER. Bunch spacing is 4ns and bunch intensity is 8×10^{10}

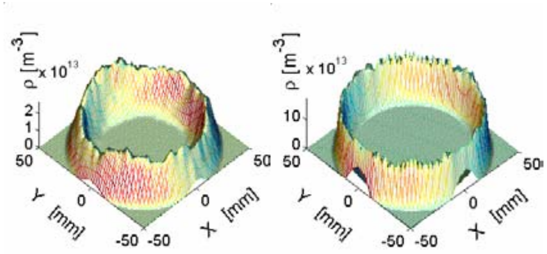


Figure 5: Electron-cloud distribution in the transverse plane with 20G (left) and 45G (at resonance) (right) solenoid fields. Reflected electrons are included. Bunch spacing is 4ns and bunch intensity is 8×10^{10}

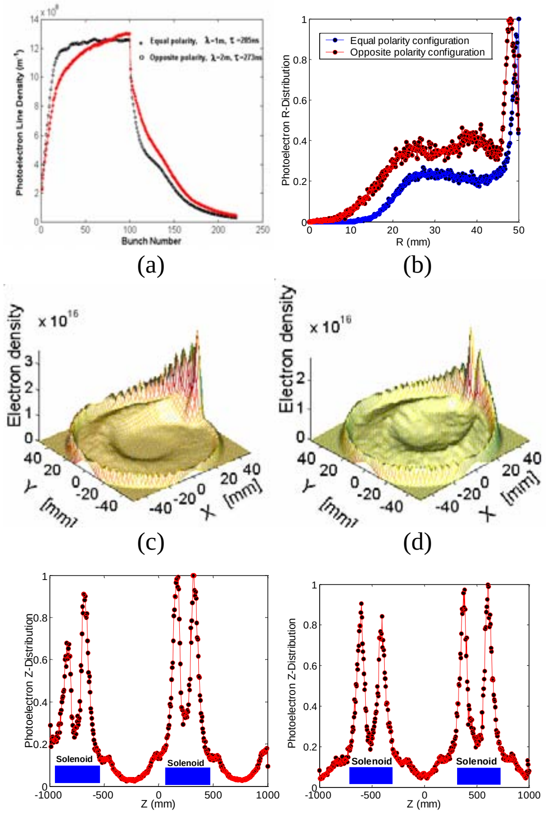
SOLENOID CONFIGURATION

In the above study, we assumed that the solenoid fields were uniform. However, real solenoid fields must be discussed because magnets and other devices occupy most of the ring. When the periodic solenoids are arranged in the coil with their current in the same direction, this geometry is called equal polarity configuration. When the solenoids' currents take an alternating direction, it is termed an opposite polarity configuration.

Fig. 6 shows the effects of solenoid configuration on the electron cloud's build-up and distribution for equal and opposite polarity in the KEKB LER. The bunch's spacing and intensity are 8 ns and 3.3×10^{10}. The electron densities in the two polarities are close to each other. But the radial distribution under equal polarity is a little better with more electrons staying close to the wall. Interestingly, the electron cloud in both configurations is trapped inside the solenoids rather than in the gap between them. The distributions are peaks around the ends of the solenoids that reflect the combined effect of the space-charge force and the solenoid fields. Fig. 7 shows the electrons' transverse distribution without a solenoid field. The solenoid field significantly reduces the density of electrons at the chamber's center.

In the KEKB LER, the original solenoids were arranged in the opposite configuration. The direction of the solenoid fields switch once at the middle of each drift region, so that locally their effects are cancelled out. After changing 75% of the solenoids in the arcs to the equal polarity configuration, almost no change was observed in the beam' tune and vertical size [10]. This finding indicates that the difference in the electron cloud in these two cases is small. Simulation shows that the electrons' average densities are almost the same, but equal polarity entails a better distribution. The comparison between experiment and simulation suggests that the difference in distribution of the electron cloud inside the solenoids does not contribute much, compared with the whole electron cloud along the ring.

We note that real solenoid periodic fields should be used in simulations. The assumed sinusoidal solenoid fields give a 20% difference in electron density for the two configurations. On the other hand, the real fields give the same average density [6].



(a) (b)

(c) (d)

(e) (f)

Figure 6: Effects of the solenoids' configuration on the build-up and distribution of the electron cloud in the KEKB LER. (a) electron cloud's build-up; (b) its radial distribution; (c) its transverse distribution with equal polarity configuration; (d) its transverse distribution with opposite polarity configuration; (e) its longitudinal distribution with equal polarity configuration, and, (f) its longitudinal distribution with opposite polarity configuration.

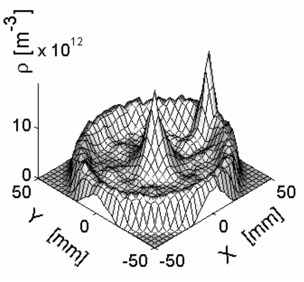
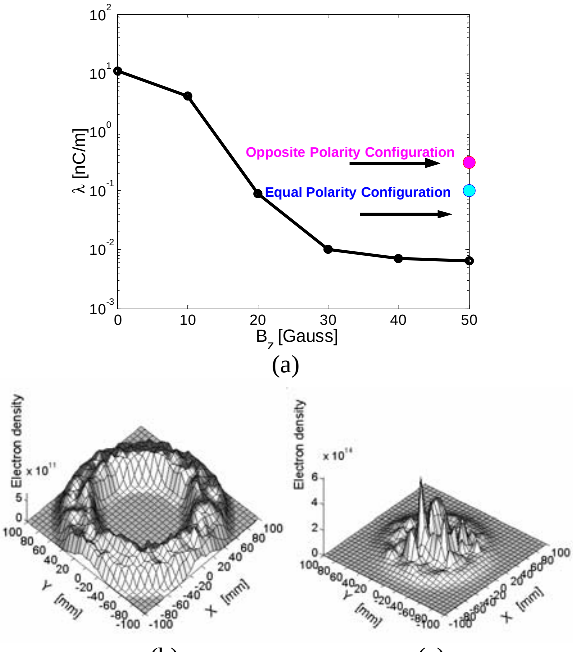


Figure 7: Electron-cloud distribution without a solenoid field in the KEKB LER.

In the case of long bunches, the effects of the solenoids' configuration is clearer, as shown in Fig. 8 for the SNS.

The electron density with the opposite configuration is six times larger than that with the equal polarity. There are no electrons near the chamber center with the equal polarity configuration. The electron cloud is longitudinally trapped inside a solenoid of opposite polarity. However, it is almost uniform for an equal polarity configuration.



(a)

(b) (c)

Figure 8: Effects of solenoids' configuration on the electron cloud in the SNS. (a) electron cloud's density; (b) its transverse distribution with equal polarity configuration; (c) its transverse distribution with opposite polarity configuration.

WAKE FIELD AND COUPLED BUNCH INSTABILITY INDUCED BY THE ELECTRON CLOUD

The photoelectron cloud with solenoid fields induces a long-range wake field. When the head of the bunch in the bunch train is disturbed, this wake field will affect the tail bunches. Such a long-range wake field excites coupled bunch instability in a storage ring. We calculated, the wake force induced by the electron cloud for a region with a weak solenoid field. The wake field was evaluated from a numerical program CLOUDLAND [11]. When bunches pass through the center of the chamber, they are not affected by the electron cloud and the center of mass of the cloud does not move. However, if a bunch with a small transverse displacement passes through the cloud, the cloud is perturbed and its center of mass changes. Then, subsequent bunches are deflected by the perturbed cloud. The wake force is calculated as the response to a small displacement of a bunch, $\bar{x}_{p,i} = \Delta x$,

$$W_1(z_i - z_j) = \frac{\gamma}{N_b r_e} \frac{\Delta \bar{x}'_{p,i}}{\bar{x}_{p,i}} \quad \text{for} \quad z_i > z_j \qquad (5)$$

The wake field depends on the offset of test bunch due to the nonlinearity of the force, which depends on the electron cloud's distribution.

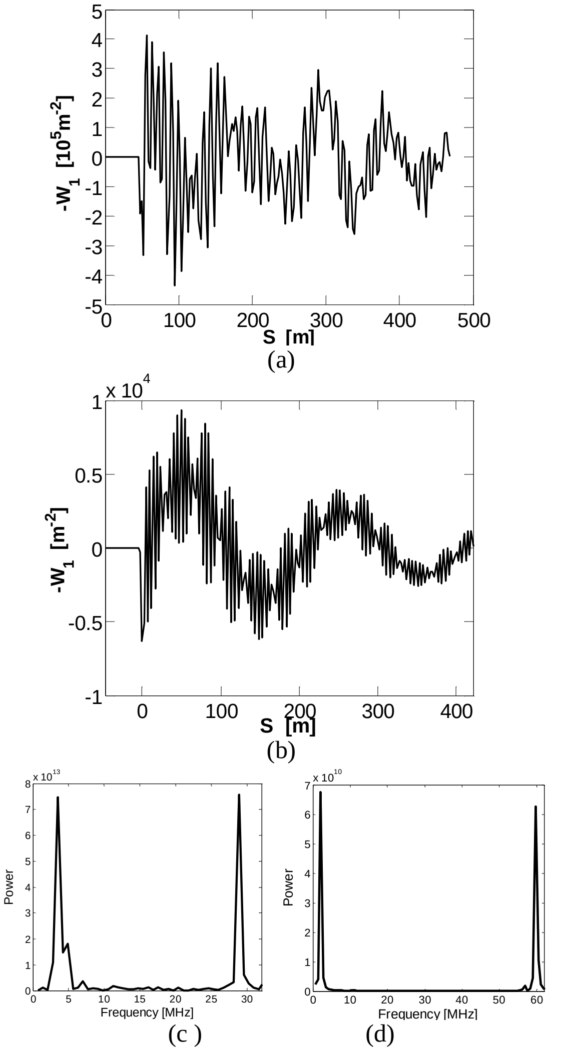
Fig. 9 shows the wake field with 10 G and 20 G uniform solenoid fields in the KEKB LER. The bunch spacing and intensity are 8 ns and 3.3×10^{10}. Two frequency components appear as shown by the FFT of the wake. One depends on the electron cloud's space charge: Therefore, it is modulated by both the distribution and density of electron cloud. It is similar to the traditional bounce frequency. As shown in Fig. 9, the frequency of this mode usually decreases with increasing strength of the solenoid fields because electrons are confined far from the beam when the field is strong. This wake field contributes a low instability mode due to its low frequency. Its frequency ranges from a few MHz to 50 MHz in the KEKB machine, which strongly depends on the electron cloud's density and distribution. Another frequency component comes from the gyration of the electrons. For example, the cyclotron frequency is about 29MHz in a 10G field, as clearly shown in Fig.9. Simulation demonstrates that the amplitude of the cyclotron mode is smaller than that of the first mode when the electron cloud is confined close to the wall as in Fig. 10 (4 ns bunch spacing and 8.0×10^{10} beam intensity). Fig. 11 gives the wake at resonance, as Fig. 4 predicted. Although the cloud's density is peak, the amplitude of the wake field is small because the electrons stay far from beam. The wake depends on the electrons distribution.

Besides solenoid fields, there are many other magnetic fields in a storage ring. According to the above model, the wake fields may have plentiful frequency spectra that may cause resonances.

Fig. 12 shows the horizontal-mode spectra of coupled-bunch instability observed in the experiment at the KEKB LER with or without a solenoid field. Without a solenoid field, the mode appears around mode number 800 (the total mode number is 1280) as shown in Fig. 12 (a). The mode spectra change markedly when a solenoid field is applied (Fig, 12 (b)). The typical solenoid field applied is 45 G at the center, and about 75% of the ring circumference is covered with the solenoids. The peak of the horizontal-mode spectra appears around mode number 35 (total mode number is 1280).

From these measurements, the horizontal growth rates are faster than the vertical growth rates with or without solenoid field. The horizontal growth rate is ~1.5 ms^{-1} and the vertical growth rate is ~1 ms^{-1} when the solenoid is off. The horizontal growth rate decreased to ~0.5 ms^{-1} and the vertical growth rate to ~0.3 ms^{-1} with a 45 G solenoid field.

The simulated frequency of the wake is lower than the experimental one. The frequency at the peak instability mode in Fig. 12 with a 45G solenoid is about 8MHz, which is close to the simulated value, 7.5MHz, as shown in Fig. 10. However, the beam current in Fig. 10 is three times more compared with that in the experiment (Fig. 12). Therefore, we may conclude that the simulation will give a lower electron density. One possible reason is that we chose too small a secondary emission yield 1.5 in the simulation. Another reason is that uniform solenoid fields were used in the simulation, which give a lower electron density. A more detail benchmark should be done.



(a)

(b)

(c) (d)

Figure 9: Wake field and FFT of the wake for (a) a10G and; (b) a 20G solenoid field ; (c)FFT of wake with 10G; and, (d) FFT of wake with 20G. Bunch intensity 3.3×10^{10} and bunch spacing is 8 ns.

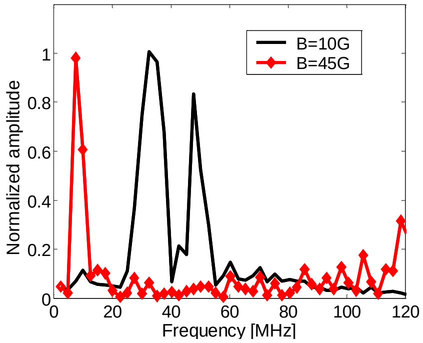


Figure 10: The variation in the wake's frequency for different solenoid fields. Bunch intensity 8.0×10^{10} and bunch spacing is 4 ns.

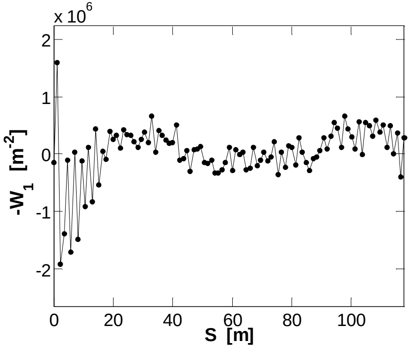


Figure 11: Wake field at resonance for the electron cloud shown in Fig. 5(right).

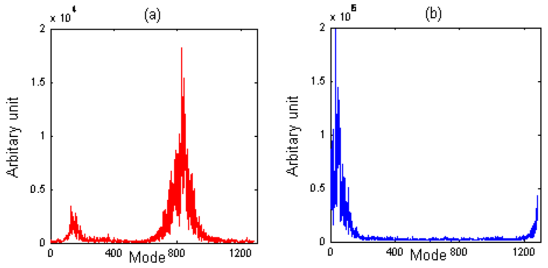


Figure 12: The horizontal-mode spectrum (a) without a solenoid field and (b) with a 45 G solenoid field. The beam current is 600 mA, and betatron tunes are 45.52/44.1.

SUMMARY

A weak solenoid can confine electrons near the wall and suppress multipacting by reducing the electron's energy at the wall. The required solenoid field depends on the beam's current: a stronger solenoid field is required for a high beam current. An equal polarity configuration is better with lower electron density at the chamber center. A synchrotron mode was found in the wake, induced by an electron cloud with a solenoid field.

REFERENCES

[1] G.I. Budker, G.I. Dimov, V.G. Dudnikov, Proceedings of the International Symposium on Electron and Positron Storage Rings, Saclay, 1966 (Orsay, Universitaiers De France, 1966), page VIII-6-1.

[2] H.G. Hereward, Coherent instability due to electrons in a coasting proton beam, CERN Report No. 71-15, 1971.

[3] E. Keil and B. Zotter, CERN Report No. CERN-ISR-TH/71-58, 1971

[4] H. Fukuma, Mini-Workshop on Electron Cloud Simulation for Proton and Positron Beams, Proceedings ECLOUD'02, CERN-2002-001, Edited by G. Rumolo and F. Zimmerman, 2002, pp.1-10.

[5] Sam Heifets, Proceedings of 8th Advanced Beam Dynamics Mini-workshop on Two-stream Instabilities in Particle Accelerators and Storage Rings, Santa Fe, New Mexico, USA, 2000. URL: http://www.aps.anl.gov/conferences/icfa/two-stream.html.

[6] L. Wang, H. Fukuma, K. Ohmi, KEK Report 2001-2

[7] L. Wang, et. al. Phys. Rev. E., in press.

[8] Y. Cai, M. Pivi, M. Furman, PRSTAB, Vol. 7, 024402, 2004

[9] A. Novokhatski, J. Seeman, SLAC-PUB-9950

[10] H. Fukuma, these proceedings.

[11] L. F. Wang, H. Fukuma, K. Ohmi, S. Kurokawa and K. Oide, F. Zimmermann, Physics Review Special Topics-Accelerators and Beams, Vol. 5, 124402, 2002.