ION INSTABILITY ISSUE IN ELECTRON RINGS *

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Abstract

The fast beam-ion instability attracts interests recently for the International Linear Collider Project. In this paper, we will briefly review and discuss the instability in relation to the ILC project, and we will present a new observation of the instability in the PLS in-vacuum undulator, which shows that the vacuum pressure increase only in a small part of a ring can stimulate the instability.

INTRODUCTION

The so called fast beam-ion instability (FBII) was predicted by simulation and verified later by experiments. FBII is excited by attractive forces between electrons and ions created by passing electrons like other ion-induced instabilities. However, its unique point is that it is excited not by trapped ions but by transient ions; ions that are created by passing electron bunches and cleared by a large gap. Hence there is no periodicity but (approximate) linearity in the interacting ion density. Without trapped electrons, the number of ions that an electron bunch faces is proportional to the number of electrons that are ahead of the electron bunch. Therefore, the number of ions (and the strength of electron-ion interaction) is approximately linear with the position along the electron bunch train. Hence the amplitude of the coherent FBII oscillation grows along the electron bunch train. The difference from the ion trapping is clear. The electron-ion interaction depends also on the electron emittance, especially the vertical one.

The theoretical (and simulational) prediction and description of this picture was firstly given in Ref. [1, 2]. The first experimental observation of FBII was given in Advanced Light Source [3]. With artificially increased pressure and gaps in the bunch train large enough to avoid ion trapping, they observed a factor of 2-3 increase in the vertical beamsize along coherent beam oscillations which increased along the bunch train. Similar experiment was carried out later in Pohang Light Source (PLS) with more visual clarity [4, 5]. Especially, Ref. [5] captured the visual images of FBII with streak camera, which shows clearly the coherent oscillation increasing along the electron bunch train. Also, in the commissioning phase of Canadian Light Source when the vacumm pressure was very high, vertical beamsize blowup was observed, which could be attributed to FBII [6].

Interestingly and accidentally, the strength of FBII is such that it is hardly observed in a currently active electron storage ring of normal operation condition. A few years ago, the B-factory electron ring was considered a candidate for the FBII observation even in the normal operation condition, because of the high electron bunch current. However, FBII turned out to be invisible even in the B-factory. Recently, interests in FBII have been revived because of the future International Linear Collider (ILC) of electron and positron [7]. In ILC, electron beam (and positron beam) will have an extremely low vertical emittance. For that purpose, a damping ring will be constructed. The ILC electron damping ring is considered a strong candidate for the FBII observation, because of its tiny vertical emittance and high bunch current. In this paper, we will review and discuss FBII in relation to the ILC project, and we will present a new observation of FBII in the PLS in-vacuum undulator, which shows that the vacuum pressure increase only in a small part of a ring can stimulate FBII.

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FAST BEAM-ION INSTABILITY

A schematic figure of FBII is shown in Fig. 1. The force that stimulates FBII is the attracting linear force between the electron bunch and the ion cloud [8]. The linear force on the n-th electron bunch has the following dependence

$$f_e(n) \propto \frac{\lambda_i(n)}{\sigma_y(\sigma_x+\sigma_y)}, \quad (1)$$

where $\lambda_i(n)$ is the ion density at the position of the n-th electron bunch and σ_x, σ_y are the horizontal and vertical sizes of the electron beam. On the other hand, the linear force on the ions f_i depends on the electron density λ_e instead of λ_i. Because of these linear forces, both electrons and ions oscillate coherently with separate oscillating frequencies. For example, the ion frequency has the dependence of

$$w_i \propto \left[\frac{N}{\sigma_y(\sigma_x+\sigma_y)A}\right]^{1/2}, \quad (2)$$

where N is the number of electrons in a bunch and A is the mass number of the ion. Normally A is that of CO ion.

Obviously λ_i depends on λ_e because ions are created by electrons. Note that $\lambda_i(n)$ is proportional to the vacuum pressure P and the number of electrons from the electron head to the n-th bunch, as described by

$$\lambda_i(n) \propto PNn, \quad (3)$$

where P is the vacuum pressure and N is the number of electrons per bunch. Hence we can rewrite $f_e(n)$ as

$$f_e(n) = K\frac{PNn}{\sigma_y(\sigma_x+\sigma_y)}, \quad (4)$$

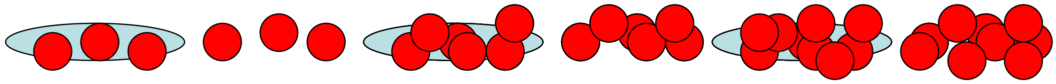

Figure 1: A schematic figure of FBII. A big ellipse represents an electron bunch and small circles represent ions. The number of ions increases along the bunch train.

where K is the overall constant. The FBII growth rate is not linear to $f_e(n)$ but depends on it in a complicated way. However, it is obviously true that the growth rate gets smaller when $f_e(n)$ gets smaller, and vice versa.

Does the bunch separation, L_{sep}, affect on FBII? Yes, it does, although it is not involved in $f_e(n)$. L_{sep} is not the source of ions but a space at which ions are created. The longer L_{sep} is, the longer the ion beam is. Hence the more effective the electron-ion interaction is and the faster the growth rate is. However, a straightforward inclusion of L_{sep} in the theoretical treatment may mislead as in [1], where the growth rate is proportional to $L_{sep}^{1/2}$. But, obviously, it does not mean that the growth rate decreases to 0 as L_{sep} goes to 0. And it does not mean either that the growth rate increases indefinitely as L_{sep} increases continuously. The derivation is valid only for some range of L_{sep}. In reality, the freedom to choose a L_{sep} is not very big. Therefore, assuming L_{sep} is restricted to a narrow range of values, it is possible to ignore the L_{sep} dependence from the discussion.

OBSERVATION OF FBII

It is interesting that FBII is such that it is not observed in any electron storage ring of normal operation condition. It has been observed only when the vacuum pressure was increased order of magnitude-wise. Figure 2 shows the FBII picture at the PLS experiment by the streak camera [5]. The electron beam was composed of 250 bunches and the total current was approximately 170 mA. The streak camera picture in the normal operation condition is shown in (a), and (b) shows the FBII picture taken with the vacuum pumps off. The observed coherent oscillation was that of CO. By turning off the vacuum pumps, the pressure was elevated from 0.16 nTorr to 2.2 nTorr.

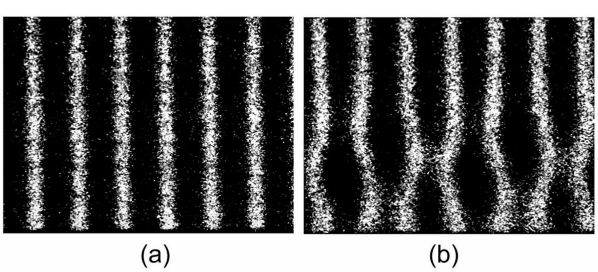

Figure 2: Streak camera images of FBII taken at the PLS experiment. (a) Normal condition (0.16 nTorr). (b) Increased vacuum pressure with ion pumps turned off (2.2 nTorr)

However, a recent experiment at PLS shows that FBII is closer to the observation. In this experiment, vacuum pressure is elevated only in a small portion of the storage ring, in an in-vacuum undulator. One of the PLS undulators is RIVXUN (Revolver In-Vacuum X-ray Undulator) that was designed at SPring 8 [9]. The length of RIVXUN is 1.2 m and the minimum undulator gap is 5 mm. It was found that if the electron beam orbit is distorted when the undulator gap is narrowed, the vacuum pressure of the undulator area is increased up to one order of magnitude. This is because the undulator synchrotron radiation hits the internal undulator wall. We used this situation for an experimental observation of FBII. The experimental setup was like this; we left the orbit distorted and measured the vacuum pressure while narrowing the undulator gap. In this way, it was possible to control the vacuum pressure step by step as shown in Fig. 3.

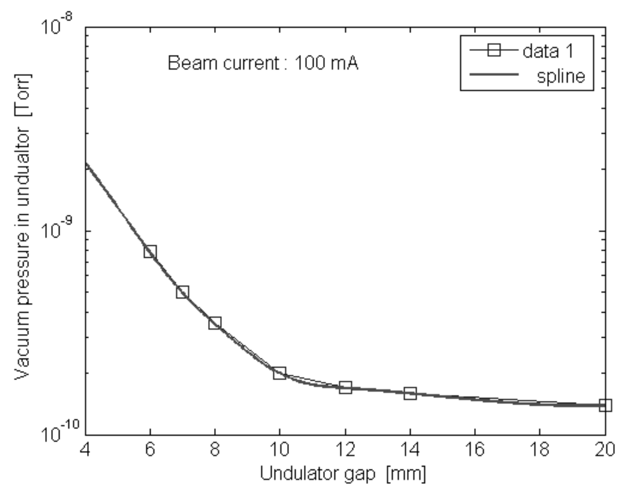

Figure 3: Vacuum pressure measured with varying undulator gap.

Figure 4 shows the streak camera image of the initial stage of FBII. The number of bunches was 350, the undulator gap was 6.4 mm, and the vacuum pressure was approximately 0.6 nTorr. When the undulator gap was lowered further, the oscillation growed and beam loss occurred as shown in Fig. 5. The cause of beam loss is probably the reduced physical aperture. The undulator gap was 5 mm and the vacuum pressure was apprxomately 1.3 nTorr.

The point of this experiment is that the vacuum pressure was higher (5-6 times) only in a small part, approximately 1/300 of the whole ring circumference. The average pressure of the ring would be almost unchanged. But FBII was excited in the small area and sustained in the other

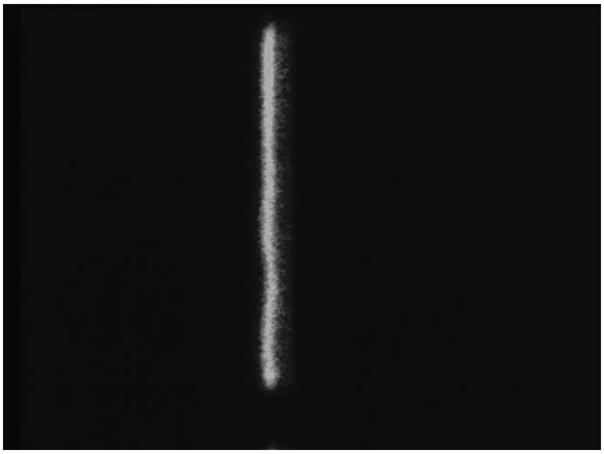

Figure 4: The streak camera image of FBII taken at the new PLS experiment. The undulator gap was 6.4 mm and the vacuum pressure was approximately 0.6 nTorr.

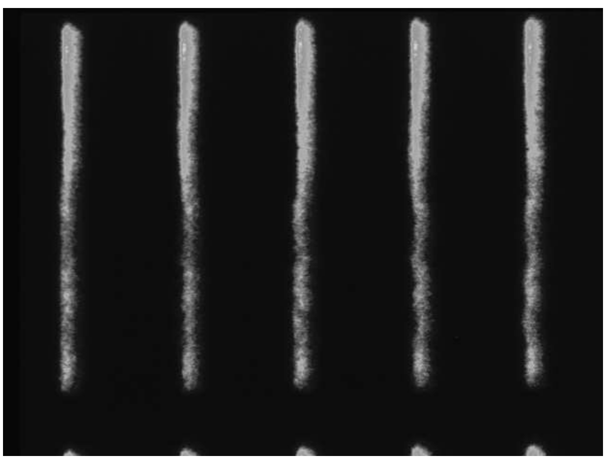

Figure 5: The streak camera image of FBII taken at the new PLS experiment. The undulator gap was 5 mm and the vacuum pressure was approximately 1.3 nTorr.

whole area. This is an important result, because it demonstrates that FBII is potentially more dangerous than previous experiments indicated. We see that the vacuum pressure needs to be homogeneous to suppress FBII effectively. Digital BPM was used to measure the coherent oscillation of FBII as shown in Fig. 6. The digital BPM data in the figure is an average value of all bunches for each turn. Vertical oscillation amplitude of the tail of the bunch train is twice the peak value in the figure. In Fig. 6, coherent oscillation grows until 2500-3500 turns and then damps, and This procedure repeats. The cause of the damping is considered the ion beam blow-up at the saturation of FBII. One turn in PLS is approximately 1 μsec. Hence the growth time in this experiment was around 2-3 msec. The damping time of the PLS storage ring is 8 msec. Future experiments are planned to obtain more quantitative conclusions.

ILC DAMPING RING

The FBII issue is now the main concern of the ILC damping ring. It is one of the key factors of the damping ring design, especially the ring circumference. The central design issue of ILC is to provide the luminosity as high as possible. For the purpose, ILC electron and positron beam must have high bunch current and low emittance. The electron and positron damping rings are supposed to make the electron and positron beam have emittance as low as possible, respectively. However, high bunch current and low emittance bunch train is subject to a possible FBII. As we have seen, FBII has never been observed in a ring of normal vacuum pressure. But the extremely low vertical emittance of ILC damping ring might grow FBII enough to be observed. Therefore, FBII is one of the most serious problems of the electron damping ring and its counterpart for the positron damping ring is the electron cloud effect.

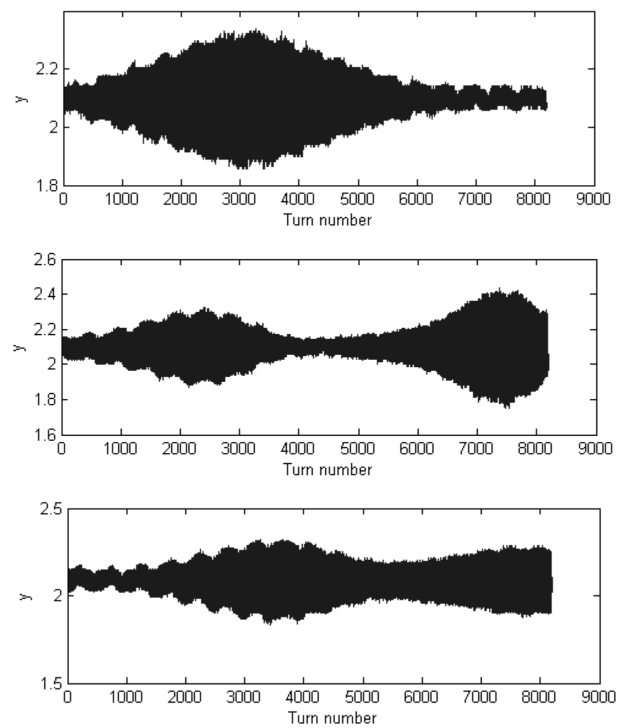

Figure 6: Digital BPM data of FBII. One turn is approximately 1 μsec.

Equation (4) shows how we should design the damping ring not to be affected by FBII. The pressure P should obviously be kept as low as possible and can not be lowered further. The number of electrons in a bunch N can not be lowered significantly because a high luminosity is required. The only parameter that we can handle is the number of bunch n. Since n can range from 1 to a few thousands, it is a very effective tool to control FBII. Even in Fig. 2 of the high vacuum case, the first 1/4 of the bunch train does not show any coherent oscillation. In other words, it is possible not to see FBII if the bunch train is short enough. Hence the electron damping ring should be designed to allow a number of mini bunch trains with sufficient gap between them to clear ions. Careful simulation study should be done to decide how many bunches are needed in a mini bunch train and how long a gap should be.

SUMMARY

The importance of FBII is determined by the ratio of parameters,

$$\frac{PNn}{\sigma_y(\sigma_x+\sigma_y)}. \tag{5}$$

If this number is big enough, FBII is stimulated. It happens that FBII is not stimulated in the existing electron rings unless the vacuum pressure is elevated deliberately. The new PLS experiment shows that FBII can be stimulated if P is high enough only in a small part of the ring. This is particularly important for ILC damping ring that will have extremely small σ_x and σ_y. To compensate for the low emittance, the number of bunch n should be small enough. Hence the bunch train should be divided into many mini trains and long enough gap between the mini bunch trains.

REFERENCES

[1] T. O. Raubenheimer and F. Zimmermann, Phys. Rev. E 52, 5487 (1995).

[2] T. O. Raubenheimer and F. Zimmermann, Phys. Rev. E 52, 5499 (1995).

[3] J. Bird, A. Chao, S. Heifets, M. Minty, T. O. Raubenheimer, J. Seeman, G. Stupakov, J. Thomson, and F. Zimmermann, Phys. Rev. Lett. 79, 79 (1997).

[4] M. Kwon, J. Y. Huang, T.-Y. Lee, I. S. Ko, Y. H. Chin, H. Fukuma, M. Isawa, K. Ohmi, and M. Tobiyama, Phys. Rev. E 57, 6016 (1998).

[5] J. Y. Huang, M. Kwon, T.-Y. Lee, I. S. Ko, Y. H. Chin, and H. Fukuma, Phys. Rev. Lett. 81, 4388 (1998).

[6] J. C. Bergstrom and J. M. Vogt, Nucl. Instr. and Meth. A 562, 495 (2006).

[7] http://www.linearcollider.org

[8] G. Koshkarev and P. Zenkevich, Particle Accelerators 3, 1 (1972).

[9] Kitamura et al., Nucl. Instr. and Meth. A 467, 110 (2001).