Experimental results on the fast beam-ion instability

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The so-called fast beam-ion instability, if it really exists, is going to be a serious problem for future accelerators such as *B* factories. A series of experiments has been conducted at the Pohang Light Source to test the existence of this new instability. An adequate amount of He gas was injected into the ring to enhance the ion effects. The results of the experiment strongly support the existence of the instability. The measured ion frequencies agree well with the linear theory. They even appear in normal operation condition with enough bunch current and bunch train length. Above all, measurements of the single pass beam position monitor clearly show the coherent oscillations with the amplitude increasing along the length of the bunch train, as predicted by the theory of this new instability. [S1063-651X(98)09005-9]

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I. INTRODUCTION

The new ion induced instability predicted by Raubenheimer and Zimmermann [1] has been a subject of recent interest. Although the source of this instability is ions created by passing electrons as in the conventional ion trapping, it is an instability different from ion trapping. Ion trapping is caused by ions trapped and accumulated in the potential of the beam. Hence one or a few gaps in the bunch train, long enough to kick the ions out of the beam, successfully cures the ion trapping. It has been believed that there is no more ion related instability without trapped ions. However, according to [1], there can still exist an instability due to transient ions; ions created by passing bunches perturb the electrons of the following bunches before they are cleared out by a gap. Due to the interaction of the electron bunches and ions, each perturbation by transient ions adds coherently to give instability of the electron beam. Therefore this instability can arise even in linear accelerators. Since the number of transient ions increases along the length of the bunch train, the oscillation amplitude also grows along the length of the bunch train and thus the tail part shows the maximum growth rate. This is a particular characteristic of this new instability that does not belong to the conventional ion trapping.

Simulation studies show that the coherent oscillation continuously increases but saturates at a level comparable to the beam size due to the increasing nonlinearity [1–3]. According to the present theories and simulation studies, the saturated states can be either the persisting coherent oscillation with the amplitude increasing along the length of the bunch train, or the increasing transverse bunch sizes along the length of the train, depending on various parameters [4].

Apparently, there is no serious indication of this new instability in the existing electron rings around the world. But in future accelerators with ultrahigh current and long bunch train, such as *B* factories, the effect could be a serious obstacle for successful operation, because the growth rate increases with increasing current and number of bunches. In future *B*-factory machines, the growth is predicted to be so fast that the conventional feedback systems may not suppress it [3].

There have been a few experiments to study this *fast beam-ion instability* (FBII) [4,5]. The experiment at the Pohang Light Source (PLS) is one of those attempts. In these experiments there are two points to be assured to verify the existence of FBII. First, the signal of ion oscillation frequency should necessarily be measured and compared with the theory. Second, the saturated states should be observed: either the increasing coherent oscillation or the increasing bunch size along the length of the bunch train. Obviously the coherent oscillation appears at the photon beam line as the increased beam size. Hence if we measure only the bunch sizes, we can not know what we measure, the coherent oscillation or the increased bunch sizes. The Advanced Light Source (ALS) experiment gave excellent results for the first point. For the second point, however, only the bunch size measurements (including the scraper) were performed. The experiment of this paper is complementary to the ALS one in that a single pass beam position monitor (SBPM) was used to observe the vertical coherent oscillation. The experiment performed at the TRISTAN accumulator ring of KEK also conducted the SBPM measurements [5].

The PLS experiment is also complementary to the ALS experiment (and the KEK experiment) in that the latter used transverse feedback systems (TFB) to suppress the multibunch instabilities driven by rf higher order modes (HOMs), while the former did not. Certainly TFB makes the experiment more controllable and makes it possible to store a high current. But TFB itself becomes a part of the equation of motion for the FBII, and it could change characters of pure FBII. Also in order to make the FBII detectable, the gas pressure should be raised to a very high value (~80 nTorr of He in the ALS experiment, and ~80 nTorr of N_2 in the KEK experiment) to make the growth faster than the TFB damping [4]. On the contrary, in the PLS experiment, a relatively small amount of He injection (~5 nTorr) is enough to observe FBII, although the stored current is limited by the threshold of the rf-driven multibunch instability. The condi-

TABLE I. Parameters of the Pohang Light Source.

Parameters	Values
Nominal beam energy (GeV)	2.0
Circumference (m)	280.56
Lattice type	TBA
rf frequency (MHz)	500.082
Harmonic number	468
Designed beam emittance (nm rad)	12.1
Horizontal tune, ν_x	14.28
Vertical tune, ν_y	8.18
Synchrotron tune, ν_s	0.0011
Vertical damping time (msec)	16

tions of the ALS experiment are more or less like those of future accelerators, as far as the growth rate is concerned. But the experiment of this paper searches the FBII in conditions weaker than those of the ALS one. Certainly both experimental regions should necessarily be explored, for the purpose of investigating the FBII.

II. EXPERIMENTAL ARRANGEMENT

The PLS is a third generation synchrotron light source utilizing a 2 GeV electron beam. The full energy linac injects electron bunches to the storage ring, which has twelve Triple Bend Achromat superperiods. The rf frequency is 500 MHz and the circumference is 280 m. Major machine parameters are listed in Table I.

The beam stability in PLS is limited mostly by collective instabilities induced by the HOMs of four rf cavities. The most harmful modes are the longitudinal ones and the threshold currents for the transverse modes are comparably higher. Since no feedback systems were working at the time of the experiment, the maximum current for the FBII experiment was limited by the threshold currents of these instabilities.

Some auxiliary systems and diagnostics were prepared for this experiment; the vertical tune spectrum scanning system, the beam size measurement system, the He gas injection system, the bunch-by-bunch measurement system, and the beam scrapers. The vertical tune scanning system consists of a spectrum analyzer and the HP-VEE [6] software in PC, IEEE-488 interfaced with the spectrum analyzer. The vertical oscillation signal is obtained from the tune measurement pickups. To measure the spontaneous signal, however, the rf kick signal should be turned off. The software automatically scans, displays, and stores data for the whole frequency band (250 MHz) in 15 min.

In PLS, the beam size is measured by the visible photon beam from the bending magnet diagnostic beamline, since x-ray optics were under construction at the time of the experiment. Due to the long wavelength of the visible light, there exists a rather big diffraction limit for the resolution of the measurements. According to the calculation, the limit should be at around 90 μm, which is good enough to measure the horizontal beam size. The vertical beam size in PLS, however, is estimated to be about 30 μm. This estimate comes from the calculation with the linear coupling value measured by the cross-resonance method, which gives the coupling less than 1%. Hence it is not possible to measure the vertical beam size accurately, unless it becomes bigger than 90 μm, which happens in elevated gas pressure. It should also be noted that in the present experiment there are no means to measure the increase of the electron bunch size separately from the coherent beam oscillations. The uncertainty in the vertical beam size makes it difficult to compare the observed ion frequency with the linear theory, which is given by [7]

$$\omega_i = \left(\frac{4 N r_p}{3 L_{\rm sep} \sigma_y (\sigma_x + \sigma_y) A} \right)^{1/2}, \qquad (1)$$

where N is the number of particles in a bunch, $L_{\rm sep}$ is the distance between bunches, A is mass number of the ion, r_p is the classical proton radius, and σ_x and σ_y are horizontal and vertical beam sizes, respectively.

A He gas injection system was prepared for elevating pressure. At a cell of the storage ring, a manually operating He gas injection nozzle is placed. There are several reasons for the choice of He gas. Physically, the light mass of helium makes sure that the helium gas is cleared by the long bunch gap. Technically, gases such as nitrogen cannot be used in PLS due to the non-evaporable-getter (NEG) pumps installed along the ring.

The bunch-by-bunch beam position measurement can be realized by a digital storage oscilloscope with an external clock, which is the same as the storage ring RF clock. The LeCroy 9370L is used with 2 MB memory per channel, which will store the position data up to 1000 turns. The front end of the transverse feedback system that is under commission is used. The system resolution of the vertical oscillation measurements is better than 20 μm. The data taken by the oscilloscope is transported to a PC and analyzed by commercial software. A beam scraper was installed in PLS, consisting of two vertical and a horizontal blade at a fixed position in the ring. The positional resolution is less than few μm in the forward direction and few tens of μm in the backward direction due to the backlash.

In addition to these, a set of standard monitoring tools are used for detecting vacuum pressure along the ring, beam current and rf characteristics.

III. EXPERIMENTAL RESULTS

The experiment proceeded to confirm the existence of the FBII and to characterize it quantitatively. To achieve these goals, the frequency spectrum of the vertical tune was always measured, and the SBPM measurements were done for a few selected cases. Helium gas was added to enhance the ion effects. The numbers of bunches were less than half of the harmonic number to keep a bunch gap long enough.

Target beam conditions are explored in terms of the beam current and the number of bunches. Figure 1 shows the window, in terms of the bunch current and the number of bunches, that represents conditions where measurements were performed. The marker at the upper right position denotes all bunch filling cases (ion trapping). Most of the points represent two different cases at the same time: the normal condition and the helium-added condition. Vertical tune spectra were measured for every case in Fig. 1. With helium injection, the ion frequency peaks appear in every

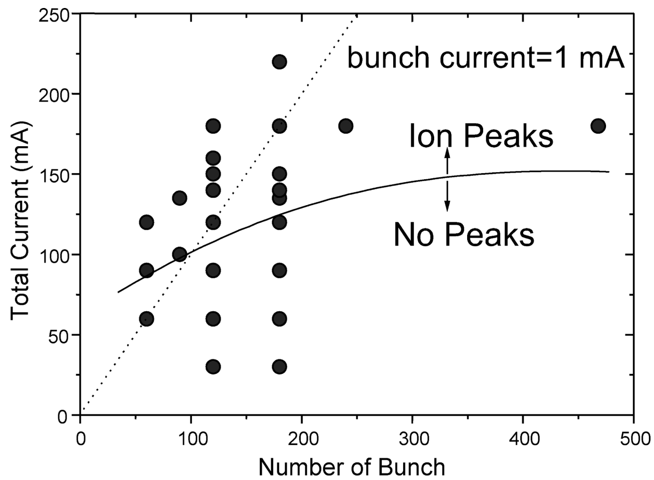

FIG. 1. Conditions for measurements in terms of the beam current and the bunch number.

case. Even without helium injection, the ion peaks appear above the line dividing the *peaks–no peaks* region. Note that this figure supports the theoretical expectation in the sense that the FBII gets stronger as the bunch train length increases at the same bunch current. With no He, the observed frequency of normal condition agrees fairly well with the theoretical ion frequency [Eq. (1)] of CO, which is a dominant ion species in the normal operation. Since the SBPM measurements show no tail growth in these cases, it is reasonable to conclude that the frequency signals represent the early stage of FBII, which could not develop further due to the slow growth rate in the normal operation. The typical gas pressure with stored current was about 0.6 nTorr. The supporting evidence for this conclusion is that the growth time calculated from the linear theory of [1] is in the order of 1 ms, which is smaller than the natural damping time of 16 ms in PLS. Simulation for the low pressure case was difficult to perform because of a huge amount of calculation time. The result is quite different from the ALS case [4], in which no clear spectrum appeared without helium injection. The reason for the difference is clearly TFB system which reduces the growth rate.

Figure 2 displays a typical spectrum, showing a coherent ion peak. The shape of the peak is different from those of

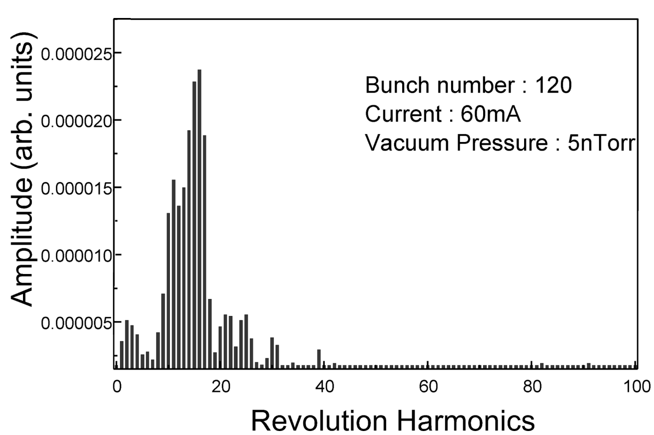

FIG. 2. A typical spectrum of the left betatron side band of each revolution frequency, representing a coherent ion oscillation frequency.

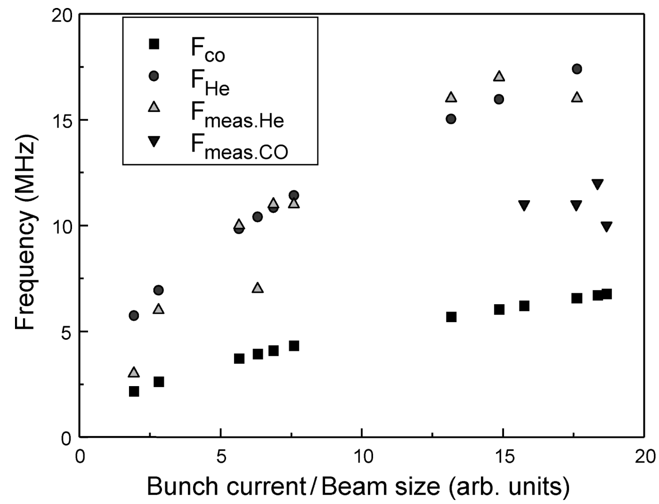

FIG. 3. The measured and calculated ion peak frequencies for different cases in terms of the beam current, the beam size and the ion mass.

HOM-induced peaks. The ion peak is broader in the frequency domain [8]. Figure 3 compares the measured and calculated ion peak frequencies as a function of (*bunch current*)/(*beam size*), which actually means $N/\sigma_y(\sigma_x+\sigma_y)$ of Eq. (1). The σ_x and σ_y values are the measured ones from the visible diagnostic beamline. The agreement is not good for the CO peaks of the normal operation. But this can be explained by the fact that the measured vertical beam sizes are not real beam sizes but reflections of the diffraction limit as mentioned in the previous section. The fact that there is a good agreement for the He peaks of elevated pressure indicates that the measured vertical beam sizes are correct. This means the vertical beam sizes increased substantially by the helium injection to values larger than the diffraction limit. If the FBII really exists, the beam size increase would be partly due to the beam-gas scattering and partly due to the FBII effect. Note that coherent oscillations will appear as beam size increase.

It was observed that the amplitude of the peaks increases substantially with the helium injection, although it was not specified in Fig. 3. It was also observed that the peak amplitudes increase with the length of the bunch train and the bunch current. All these observations agree fairly well with the linear theory, expressed in Eq. (1).

The SBPM measurements show exciting features for the cases of helium injection. They strongly indicate the existence of the FBII, showing coherent oscillation with the amplitude increasing along the length of the bunch train. Applying FFT to each turn data, the amplitude and phase of the vertical oscillation were obtained as shown in Fig. 4. No filters and data conditioning were used for obtaining this figure. It is apparent that the amplitude grows toward the tail. The saturated amplitude is estimated to be about 200 μm. According to the linear theory, the phase advance per bunch is related to the ion frequency by [1,3]

$$\Theta = \frac{\omega_i L_{\rm sep}}{c}. \tag{2}$$

The observed phase advance in Fig. 4 is about 0.08, which gives $f_i = \omega_i/2\pi = 7$ MHz according to Eq. (2). This value is

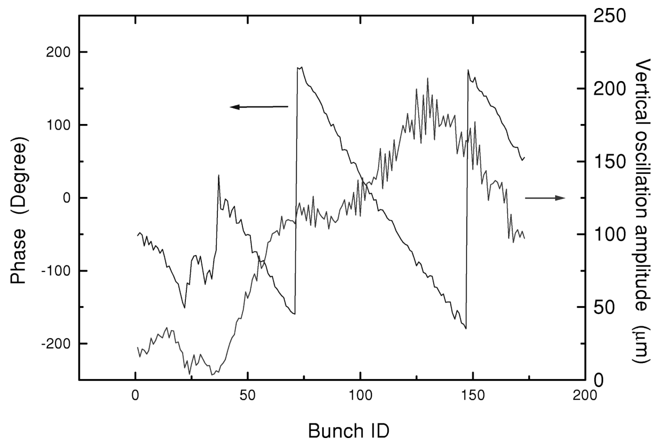

FIG. 4. A plot of the amplitude and phase of each bunch for a period of 200 turns. This was obtained by performing fast Fourier transform on the raw SBPM data over 200 turns.

very close to the ion frequency calculated from Eq. (1). Hence the SBPM measurements are quite consistent with the vertical tune measurements and the linear theory.

A vertical scraper was used in ALS [4] to measure the relative amplitude of oscillation by detecting the relative current loss along the bunch train after scraping the beam. The same experiment was performed in PLS and the results are equivalent to the ALS ones. Hence the explicit presentation is omitted here.

IV. DISCUSSIONS AND SUMMARY

In the PLS, no action has been taken seriously for suppressing the HOM-induced longitudinal and transverse instabilities, while a precise cavity temperature control system and active feedback systems are under development. Thus the operation window for the FBII experiment was limited in terms of the beam current. But this limitation is not a limitation for the FBII effect. On the contrary, this limitation defines another experimental region different from the cases with TFB. We believe it is reasonable to say that the above results of the experiment strongly indicate the existence of the FBII in electron accelerators.

Due to the diffraction limit of the visible diagnostic beamline, the measured vertical beam sizes are not correct at all in the cases of no helium injection. But with the helium injection, the vertical beam size data are quite reliable, because the vertical beam sizes increased over the diffraction limit. The beam size increase is partly due to the beam-gas scattering and partly due to the FBII effect. We measured the ion frequencies in two different methods, vertical tune spectrum measurement and SBPM measurement, and these two measurements are coincident. Also with the elevated gas pressure, the measured ion frequencies agree fairly well with the linear theory calculation.

As mentioned in the Introduction, the present theories and simulation studies say that the saturated states are either the coherent oscillation amplitude, or the bunch size, increasing along the length of the train. In this experiment, the SBPM measurement clearly shows the coherent oscillation with the amplitude increasing along the length of the bunch train. In Fig. 4, not only the oscillation amplitude but also the phase advance between bunches is displayed, which clearly shows that there exist coherent oscillations. The KEK experiment gave results that agree qualitatively with the results here [5].

In PLS an ion peak that is considered a CO peak was detected in the normal operation condition, even though there is no sizable effect on the SBPM measurement. Hence it is reasonable to interpret the CO peaks as an early stage of the FBII, which could not develop to the saturation due to its slow growth rate. Therefore the experiment of this paper indicates that the FBII can happen not only in the future accelerators of ultrahigh current and very long bunch train but even in current accelerators. However, in current accelerators, it can be cured by the usual TFB system depending on the growth rates.

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