Direct Observation of the Fast Beam-Ion Instability

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Direct evidence of the fast beam-ion instability (FBII) was obtained in the Pohang Light Source by measuring the bunch-by-bunch parameters from the snapshots of the beam image. With the direct observation, we confirmed the FBII signals and clarified uncertainties of the blowup factors quantitatively: bunch size blowup of $\sim 2\sigma_y$ and the oscillation amplitude of $\sim 0.75\sigma_y$. Suppression of the FBII was also demonstrated in the presence of the multiple gases or an extra clearing gap in the bunch train. [S0031-9007(98)07688-1]

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As the bunch current and the number of bunches become very large in future low emittance accelerators, a new kind of beam instability, so-called the *fast beam-ion instability* (FBII) [1,2], has become an important subject of the beam physics. The FBII is distinguished as a transient beam instability excited by the beam-generated ions accumulated in a single passage of the bunch train, while the conventional *ion trapping* [3,4] is excited by the trapped ions accumulated in the periodic beam potential over multiple passages of the beam. One of the characteristic signals of the FBII is a coherent beam-ion oscillation with increasing amplitude along the bunch train. According to the linear theory [1,2], the initial amplitude of oscillation $y(t,z)$ grows quasiexponentially as $y(t,z) \sim \exp[(z/l)\sqrt{t/\tau}\,]$ with the phase factor $\omega_i z/c - \omega_\beta t$, where z is the position within a bunch train, l is the length of the bunch train, τ is the characteristic growth time of the FBII, and ω_i, ω_β are the ion and betatron frequencies, respectively. As the amplitude increases, however, the nonlinearity becomes important. Computer simulation studies [1,2,5–7] have shown that the amplitude of oscillation saturates at about σ_y of the bunch size due to the nonlinearity of the beam-ion interaction. This fully developed FBII will cause harmful effects on the performance of the planned colliding beam facilities like the KEKB [7], PEP-II [8], and the future linear colliders. A more serious problem would be that the growth time of the FBII is too fast to be damped effectively by the existing active feedback systems, nor can it be cured by including a *clearing gap* long enough to overfocus the ions out of the beam path.

There have been experimental studies to confirm the FBII in ALS [9], TRISTAN AR [10], PEP-II [11], and PLS [12]. The first observation of the FBII was made in the ALS with the injection of helium gas into the storage ring to raise the growth rate. Both the transverse and longitudinal beam feedback systems were used to suppress the coupled bunch instabilities, and a charge-coupled-device (CCD) camera was used to observe the FBII by measuring the *projected beam size* of the whole bunch train. When the 80 nTorr He was injected, the projected vertical beam size blew up by a factor of 2 to 3. The growth time of the FBII was also estimated by measuring the onset of the FBII as a function of the length of the bunch train. On the other hand, a single pass beam position monitor (SBPM) was used in the TRISTAN AR and PLS to measure the phase and amplitude of the bunch oscillation.

These previous data agreed *qualitatively* with the theory and simulations. However, certain inconsistencies remain between the measured centroid oscillations and the observed increase in the projected beam size. In particular, the measured centroid oscillation saturated at $\sim 1\sigma_y$–$2\sigma_y$ but the observed increase of the projected beam size was $\sim$2–3 times larger, possibly implying a blowup of the *bunch size* along the bunch train as well as the centroid oscillation. This bunch size blowup has been reported in recent simulation results [7,13] and could be a more serious limitation for future low emittance accelerators than the centroid oscillation.

In this paper, we report on an experiment to directly measure the bunch size and centroid oscillation of the individual bunches to clarify the previously mentioned uncertainties, as well as new observations made during the experimental study of the FBII at PLS. The FBII was excited at the elevated pressure by turning off ion pumps or by injecting helium gas, and showed the bunch size blowup as well as the centroid motion. The bunch size saturated at $\sim 2\sigma_y$ for all cases of the FBII signal, and the amplitude saturated at $\sim 0.75\sigma_y$ with the intermittent blowups to a large amplitude. These results showed considerable difference from the simulation results, where the bunch size blowup was $\sim 1.3\sigma_y$ and the oscillation amplitude was $\sim 2\sigma_y$, implying further refinements are necessary in the modeling of the FBII. Possible methods of suppression of the FBII were also demonstrated in the

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presence of the multiple gases and an extra gap in the bunch train.

The PLS is a 2 GeV electron synchrotron radiation source composed of a twelve-period triple-bend-achromat lattice with the tunes $(\nu_x, \nu_y) = (14.28, 8.18)$, the rf frequency $\omega_{\text{rf}}/2\pi = 500.082$ MHz, the revolution frequency $\omega_{\text{rev}}/2\pi = 1.068\,55$ MHz, and the harmonic number $h = 468$. For the direct observation of the FBII signals, the *turn-by-turn snapshots* of the bunch train was taken using a SBPM and a streak camera [14]. The nth turn snapshot is a bunch train image taken at a fixed observation point. The centroid positions can then be written as $y_n(z) \sim y_0(n,z)\sin(z\omega_i/c - n\Delta\phi_L)$, where n is the turn number, L is the circumference of the storage ring, and $\Delta\phi_L = \omega_\beta L/c$ is the betatron phase advance per turn. In the saturated oscillation, the amplitude $y_0(n,z)$ should be almost independent of n. The merit of the streak camera was to obtain the precise spatiotemporal information from the 1:1 bunch image with a negligible distortion. Since the measure of the diffraction-limited error of the 1:1 visible light image was $\sim 90\ \mu$m due to the small vertical radiation angle $(\sim 1/\gamma)$, it was subtracted properly from all of the measured bunch sizes. The other instruments include a LeCroy 9370L digitizing oscilloscope, a HP8360 spectrum analyzer, and a CCD camera. Utilizing the position-detecting circuit of the transverse feedback system [15] as a SBPM, the bunch-by-bunch centroid position data was digitized and stored in the digitizing oscilloscope for 1024 turns.

The experiments started with an injected beam of 250 bunches having an average current of 0.72 mA/bunch, which was found as the optimum experimental condition in the preliminary experiments [12]. The bunch current was filled evenly within $\pm 4\%$, and the remaining 218 buckets (~ 131 m) were left empty as a clearing gap to prevent the conventional ion trapping. The vertical bunch size was measured as 95 μm, total vacuum pressure was 0.4 nTorr, and the beam lifetime was 10 h. The beam could be stored stably up to 200 mA with 250 bunches without the feedback system by controlling the rf-cavity temperature precisely to suppress the coupled-bunch instabilities induced by higher order modes. During the experiment, the bunch current decreased slowly due to the finite beam lifetime.

At this normal condition, the beam spectrum showed a CO-ion peak at 6.8 MHz in association with the lower betatron sidebands although the tail oscillation was not clearly observable in the snapshots as shown in Fig. 1(a). It was interpreted as a very early stage of the FBII not fully developed due to the low vacuum pressure, because the clearing gap was long enough to prevent ion trapping and the estimated initial growth time of the FBII at this condition was ~ 1 ms which is much shorter than the natural damping time of ~ 16 ms. Existence of the heavy molecules or metallic microparticles were not detected throughout the experiment. The possibility of the coupled-bunch instability was also ruled out in the preliminary experiment [12] by the fact that the ion frequency changed as the bunch size was varied.

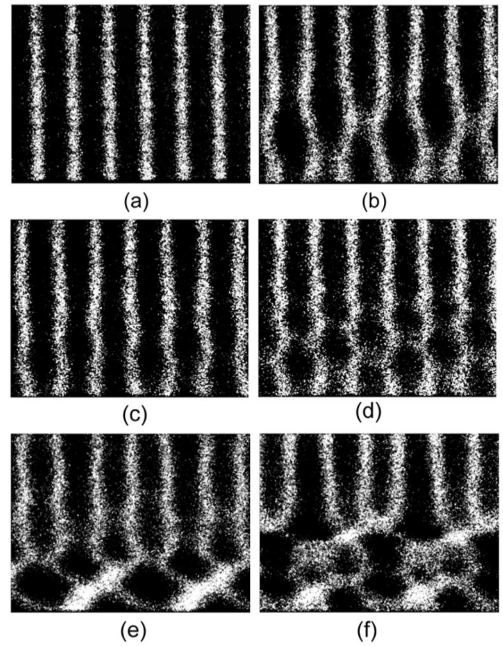

FIG. 1. Snapshots taken at (a) normal condition (0.7 mA/bunch), (b) ion pumps turned off (0.64 mA/bunch), (c) 0.2 nTorr He (0.61 mA/bunch), and (d) 3.34 nTorr He (0.52 mA/bunch). Two snapshots showing (e) a sharp triangular waveform (3.34 nTorr He, 0.6 mA/bunch), and (f) a turbulent centroid oscillation at the tail (3.34 nTorr He, 0.6 mA/bunch). All snapshots are taken every 4 μsec (4 turns). Horizontal span is 25 μsec (6.4 mm in spatial unit), and vertically 500 nsec from top to bottom.

To enhance the growth rate of the FBII, the residual gas density was increased by turning off all the ion pumps around the storage ring. The total vacuum pressure increased from 0.4 to 2.2 nTorr in 6 min, and the partial pressure of CO increased dominantly from 0.03 to 0.16 nTorr. As the vacuum pressure increased, indeed, a clear *snake-tail* centroid motion of the bunch train appeared at ~ 1 nTorr in both the streak camera image and the SBPM data. The ion frequency decreased from 6.8 to 5.4 MHz due to the increase of the beam size by the FBII. Figure 1(b) shows typical snapshots of the snake-tail oscillation with the ion frequency of ~ 5.4 MHz. The phase advance per bunch obtained from the bunch-by-bunch fast Fourier transform (FFT) of the SBPM data was also $2\pi/95$/bunch (~ 5.3 MHz), in agreement with the ion frequency measured from the spectrum analyzer and from the streak camera snapshots.

Helium gas injection was followed to further raise the ion density. In the first step, 0.2 nTorr of the He gas was injected to make the total pressure increase to 2.4 nTorr. The He peak appeared at around 9 MHz, but the CO peak was still larger than He peak due to the large ionization probability of CO molecules [4].

As the He gas pressure increased over 1.2 nTorr, only higher He frequency became dominant. The change of the ion frequency is apparent by comparing two snapshots Figs. 1(b) and 1(d).

For each snapshot, the transverse bunch size and the centroid position were measured separately along the bunch train by slicing the train image into 96 pieces, and by fitting it to a Gaussian bunch profile. Bunch profiles and centroid motion were thus reconstructed for the quantitative analyses. As the bunch size increased along the bunch train, the ion frequency decreased (or the wavelength increased) according to the linear theory [1,3] but the centroid motion was slightly suppressed as can be seen in Figs. 1(b) and 1(d). It was also confirmed quantitatively by the reconstructed beam profiles, the centroid positions (mountain views), and the bunch-by-bunch FFT result from the SBPM data.

The amplitude of the centroid oscillation saturated at about 75 μm ($\sim 0.75\sigma_y$) at the CO-dominant stage [Fig. 1(b)] before the He gas injection. By injecting 0.2 nTorr of He, the amplitude decreased to about ~ 40–55 μm ($\sim 0.5\sigma_y$) with smoother waveform [Fig. 1(c)], but it increased again to about 75 μm at the higher He pressure (≥ 1.2 nTorr) [Fig. 1(d)]. The smooth and small bunch oscillation was observed only for the 0.2 nTorr of He throughout the experiment, implying that the coupling between CO and He modes suppress the growth of the larger centroid motion similar to the decoherence effect predicted theoretically [1,2,7]. On the other hand, the saturated waveform showed triangular shape with the amplitude of $\sim 0.75\sigma_y$ for the single gas species, not only for the He dominant case, but also for the CO dominant case, indicating that the saturated FBII signal contains higher harmonic Fourier components excited by the nonlinear beam-ion interaction [5]. As the He pressure and bunch current increased further, the waveform showed intermittent blowup to a sharper triangular shape with a large amplitude of oscillation as shown in Fig. 1(e). Occasionally, it developed even further to a turbulent oscillation of the tail [Fig. 1(f)] but soon stabilized to a typical centroid motion again without loss of the beam current.

The typical FBII signal showed bunch size blowup of $\sim 2\sigma_y$ as well as the increase of the centroid motion by $\sim \pm 0.75\sigma_y$ along the bunch train as shown in Fig. 2(a). A simulation result using a code developed by Yokoya [7] with input parameters relevant to the experimental condition is also shown in Fig. 2(b) for comparison of the saturation factors. Although the increase of the bunch size and the bunch oscillation in the simulation resembles qualitatively the measured ones, the saturation factors were quantitatively different. The measured bunch size blowup factor was $\sim 2\sigma_y$ regardless of the vacuum pressure, bunch current, and the initial bunch size as shown in Fig. 3. Even when the bunch size was saturated in the middle of the bunch train, the bunch size blowup factor was always $\sim 2\sigma_y$ as shown in Fig. 4. However, it increased only 30% ($\sim 1.3\sigma_y$) in the simulation while the amplitude increased by $\sim 2\sigma_y$, considerably larger than the measured value of $\sim 0.75\sigma_y$. Another distinct observation was that once the bunch size was saturated to $\sim 2\sigma_y$ in the middle of the bunch train, it underwent a sharp transition to the normal bunch size (Fig. 4), while the simulation result showed that the saturation persisted in the following bunches as shown in Fig. 2(b).

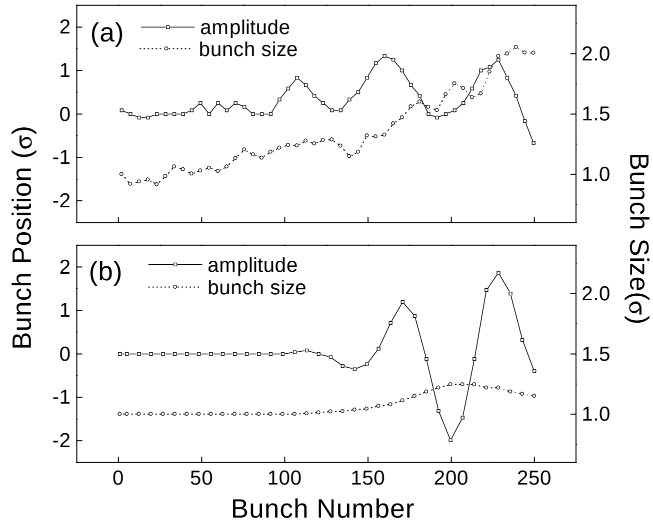

FIG. 2. (a) Typical FBII with centroid oscillation and bunch size blowup along the bunch train at 1.2 nTorr He (0.57 mA/bunch). (b) Simulation results for the same experimental condition.

The effect of the extra clearing gap in the bunch train has been investigated in a separate experiment as a possible method to cure the FBII. Theoretically [1], the gap length of $\sim 30L_{\mathrm{sep}}$ could overfocus ions out of the beam path at this condition. A bunch train of 268 bunches was split into two 134 bunches at the center, and the

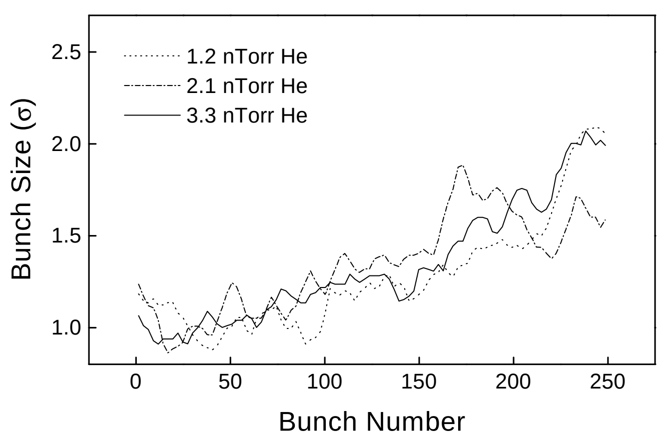

FIG. 3. Bunch size measured along the bunch train for three different cases of He pressures: 1.2 nTorr (0.57 mA/bunch), 2.1 nTorr (0.55 mA/bunch), and 3.34 nTorr (0.52 mA/bunch). Bunch size saturates at $\sim 2\sigma_y$ for all cases.

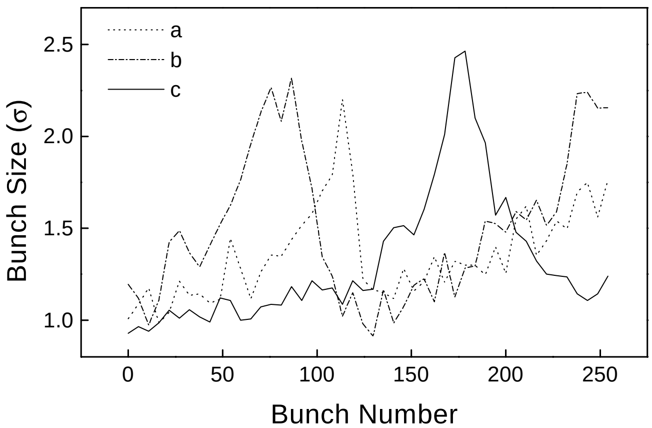

FIG. 4. Bunch size profile at three different cases [*a*: 2.1 nTorr He (0.55 mA/bunch); *b*: 3.34 nTorr He (0.52 mA/bunch); *c*: 3.34 nTorr He (0.6 mA/bunch)] also shows saturation of the bunch size at $\sim 2\sigma_y$ when the saturation occurs in the middle of the train. Once the bunch size saturates, however, it undergoes a transition to the normal bunch size and increases again in the following bunch train.

gap length was changed to $10L_{\text{sep}}$, $50L_{\text{sep}}$, and $100L_{\text{sep}}$. When the gap length was $10L_{\text{sep}}$, the FBII did not change significantly, but the second bunch train oscillates like the tail of the first bunch train with the oscillation amplitude of 40 μm as shown in Fig. 5(a). When the gap distance increased to $50L_{\text{sep}}$, however, there was no correlation between two bunch trains. Both bunch trains showed independent tail oscillations with much smaller amplitude (<15 μm) [Fig. 5(b)].

In conclusion, direct evidences of the FBII were obtained in a low emittance storage ring by the bunch-by-bunch measurement of the centroid oscillation and the bunch size. With the direct measurements, we could clarify uncertainties in the previous data about the increase of the bunch size and the oscillation amplitude quantitatively. Although the linear theory predicted only centroid motion of the bunch train, a typical signal of the FBII showed the bunch size blowup by $\sim 2\sigma_y$ for all cases and the amplitude of the centroid oscillation by $\sim 0.75\sigma_y$ at the saturated FBII. Once the bunch size saturated in the middle of the bunch train, it did not persist but decayed to the normal size and then started to increase in the following bunches. These observations were considerably different from the computer simulation results as discussed before, implying the further refinements are necessary for the modeling or simulation study of the FBII in the future.

The degree of the FBII decreased in the presence of the multiple gases and by an extra clearing gap in the bunch train, which indicates possible methods of suppressing the instability.

Finally, it is worth noting that the FBII was excited spontaneously at the total pressure raised to only 1 nTorr (with 0.1 nTorr CO pressure). Although most existing third generation storage rings are operated at lower pressure, it implies the FBII could be a non-negligible instability if the operating vacuum is poor.

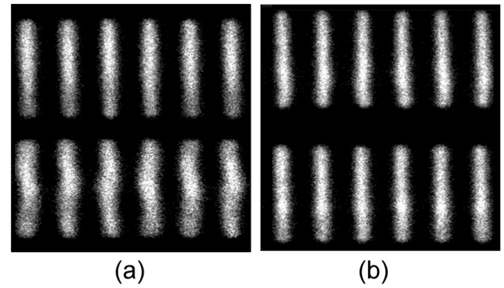

FIG. 5. Two snapshots taken for two different clearing gap lengths; (a) $10L_{\text{sep}}$ and (b) $50L_{\text{sep}}$ showing suppression of the tail oscillation at longer gap length.

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