OBSERVATION OF FAST BEAM-ION INSTABILITY IN PLS

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Abstract
The fast beam-ion instability (FBII) has been directly observed in the Pohang Light Source(PLS) from the snapshots of the bunch train taken by a streak camera and a single pass beam position monitor. By measuring the amplitude of the snake-tail oscillation, the ion frequency, and the vertical bunch size along the bunch train, we observed characteristic signals of the FBII.

1 INTRODUCTION

A new kind of two-beam instability, so called the *fast beam-ion instability* (FBII), is of a great concern for the future high current and low emittance accelerators [1,2]. The FBII is distinguished as the transient beam-ion instability being established during a single passage of the bunch train, while the conventional *ion-trapping* [3,4] is excited by the ions trapped and accumulated in the beam potential over multiple passages of the beam. The characteristic signal of the FBII is the large coherent beam-ion oscillation in the tail due to the increase of the beam-generated ion density along the bunch train. The amplitude of oscillation $y(s,z)$ grows asymptotically as $y(s, z) \approx y_0 \exp[zl(s/c\tau)^{1/2}]$ with the phase factor $z\omega_i/c - s\omega_\beta/c$, where s is the azimuthal position of the bunch train, z is the position of a bunch 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 [1]. Although there is no analytical theory of the fully developed FBII, computer simulations 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 [1,2,5-7].

The FBII, if it exists, will cause emittance blow-up in the on-going B-factories such as KEKB [7], and PEP-II [8]. For the practical understanding of the FBII, there has been a series of experiments in the ALS [9], TRISTAN AR [10], and PLS [11]. In the ALS, the first observation of the FBII was made with the injection of 80 nTorr Helium gas into the storage ring to raise the growth rate of the FBII. Both the transverse and longitudinal beam feedback systems were also used to suppress the coupled bunch instabilities. Major observations were the blow-up of the vertical beam size by a factor of 2 - 3, the current and beam size dependence of the ion frequency, and the vertical beam size increase measured as a function of the bunch train length. The experimental results agree quantitatively with the theory and computer simulations. However, the beam oscillation amplitude could not be resolved from the beam size blow-up, because the response time of the scintillator and a CCD camera was not fast enough. On the other hand, a single pass beam position monitor (SBPM) was used in the TRISTAN AR and PLS to obtain the information of the phase and amplitude of the beam oscillation. In both experiments, the phase and amplitude of the tail oscillation were verified as to agree with the theory. In the PLS, it was also possible to demonstrate the turn by turn motion picture of the tail oscillation by reconstructing the bunch signals from the SBPM data.

In this paper, we will report on direct observation of the FBII in the PLS. The PLS is a 2 GeV electron synchrotron radiation source with parameters; rf frequency = 500MHz, tunes (ν_x, ν_y) = (14.28, 8.18), and harmonic number h = 468. The main purpose of this experiment was to observe the characteristic signals of the FBII directly from the synchrotron radiation radiated from a bending magnet. With the *turn by turn snapshots*, it was possible to measure the transient quantities for individual bunches along the bunch train such as the oscillation amplitude and the bunch size blow-up.

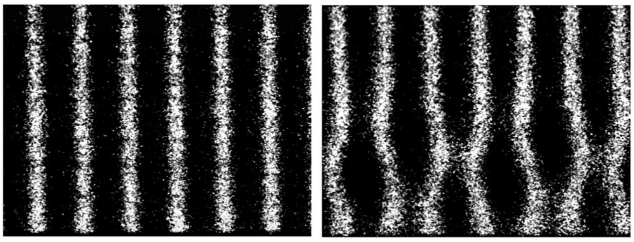
2 EXPERIMENTAL SETUP

To record the turn by turn snapshots, a streak camera was used. It consists of a Hamamatsu C5680 streak unit, a M5677 slow sweep unit, and a M5678 dual sweep module. The 500 kHz streak trigger signal is derived from the 1 MHz ring revolution frequency, and the 10 Hz injector trigger signal is used as the horizontal sweep trigger. A 1:1 visible light image was refocused in the horizontal direction to make a line image at the input slit of the streak camera. However, the diffraction-limited error was very large due to the small vertical radiation angle of the synchrotron radiation (~$1/\gamma$), which was measured to be about 90 μm. The diffraction error was subtracted properly from all the measured bunch sizes. The other instruments used for the measurement of FBII signals also include a pair of SBPM, a LeCroy 9370L digitizing oscilloscope, a HP8360 spectrum analyzer, and a CCD camera. The position detection circuit of the prototype transverse feedback system was utilized as a SBPM [12]. The system bandwidth of the SBPM is 250MHz, which is wide enough to detect the ion frequency without loss of the phase and amplitude information. The digitizing oscilloscope can store the bunch-by-bunch beam position data for more than 1024 turns in time series synchronized to the 500 MHz RF frequency. Since the higher order mode (HOM) induced coupled bunch instability were effectively suppressed by precise temperature control of the rf cavity, no active feedback system were used in the experiment to raise the growth rate of the FBII.

3 RESULTS AND DISCUSSONS

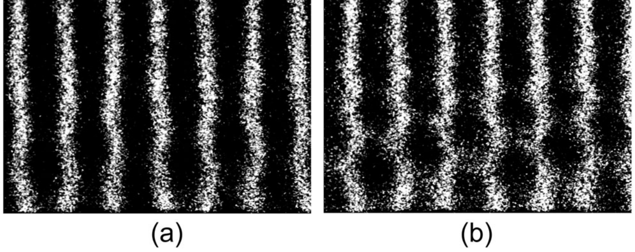
All the experiments were performed with the beam injection of 250 bunches at 0.72 mA/bunch in average, with the rest of 218 buckets remained empty as a clearing gap. The nominal bunch size was 95 μm vertically, and the vacuum pressure with stored beam was 0.4 nTorr. Beam current was stored stably up to 200 mA with 250 bunches without HOM induced instability. Nevertheless, the broad ion spectrum was routinely observed at the nominal pressure at the frequency of 6.8 MHz, which was identified as the CO peak [11]. Because there was a large clearing gap (131 m ~3 λ at 6.8 MHz) in the bunch train, the spectrum should not stand for the ion-trapping but indicates there exists a weak FBII being excited spontaneously. Indeed, very weak tail oscillation was observed in the snapshots shown in Fig. 1a.

To amplify the FBII signal, the residual gas density was raised to higher pressure by turning off all ion pumps around the storage ring. The vacuum pressure increased from 0.4 nTorr to 2.2 nTorr in six minutes and the partial pressure of CO increased dominantly from 0.03 nTorr to 0.16 nTorr. During the vacuum pressure increase, a clear



(a) (b)

Fig. 1. Snapshots taken every 4 μsec before and after the turn-off of the ion pumps. Total time span in horizontal direction is 25 μsec (6.4 mm in spatial unit), and 500 nsec in vertical direction. a) Snapshots taken at nominal condition. Very weak oscillation was observed at the very tail of the bunch train. b) After ion pumps were turned off, the snake-tail oscillation at the tail is clear.



(a) (b)

Fig. 2. Two series of snapshots taken after He injection. a) Snapshots for 0.2 nTorr He, and b) for 3.34 nTorr He.

The increase of the ion frequency from Fig. 1b is manifest. The beam size blow-up at the tail is also clearly shown.

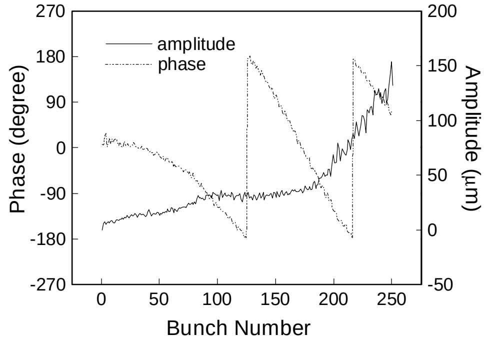


Fig. 3. The phase advance and amplitude of bunch train oscillation plotted from an SBPM data taken before the He injection. Phase advance per bunch is ~2π/95/bunch at the tail, which agrees with the frequency of 5.4 MHz measured with the spectrum analyzer

snake-tail motion appeared at about 1 nTorr in both the streak camera image (Fig. 1b) and in the SBPM signal associated with the betatron oscillation amplitude of 150 μm (~ 1.5σ_y). The ion frequency decreased from 6.8 MHz to 5.4 MHz, obviously due to the increase of beam size by the beam-gas scattering and the FBII. Figure 1b shows typical snapshots of the snake-tail oscillation with 57 m long wavelength. Each snapshot was taken every 4th turn with the refresh rate of 2 frames/sec. Since the fractional betatron tune is 0.18 (~1/6), the snapshot looks almost periodic with a period of 3 snapshots or 12 turns.

Helium gas injection followed to raise the ion density. In the first step, 0.2 nTorr of the He-gas was injected making total pressure increase to 2.4 nTorr. Since the partial pressures of CO and He were almost same at this pressure. The oscillation amplitude was decreased to 80 – 110 μm (~ σ_y) and the spectrum showed a broad He peak at 7MHz due to the mixing of two gas species. However, the CO peak was still dominant due to its large ionization probability [4]. As the He gas pressure increased further to 1.2 nTorr (total pressure became 4 nTorr), the amplitude increased to 150 μm again and only He peak appeared at 7 MHz, indicating that the beam-He ion interaction had become dominant. The change of ion frequency is apparent comparing two snapshots, Fig. 1b and Fig. 2b. Shown in Fig. 3 is the amplitude and phase advance of the bunch oscillation obtained from a SBPM data taken at the same condition with Fig. 1b but at slightly different time. The phase advance per bunch is around 2π/95/bunch (~ 5.3 MHz) at the tail of the bunch train, agreeing well with the ion frequency measured from the spectrum analyzer and from the streak camera snapshots. As the He pressure increased further, the waveform was intermittently distorted to a sharp triangular waveform (or a kink) at the tail with a large amplitude of oscillation. Sometimes, the kink appeared in the middle of the bunch train. In that case, the following bunch oscillation was rapidly stabilized to a small amplitude oscillation but increased again along the rest of the train. The appearance of the large kink motion was more frequent at the higher gas pressure and higher beam current. Occasionally, it developed even further to a turbulent oscillation of the tail, but soon stabilized to a smooth snake-tail again without loss of the beam current.

The transverse bunch size and the oscillation amplitude were measured separately along the bunch train from the snapshots by slicing the bunch train into 96 pieces. For each slice, the bunch size and the peak position were found by fitting it to a Gaussian bunch profile. The bunch size at the head of the bunch train grows along the bunch train by a factor of about 2 at the tail. Tthe increase of the bunch size is shown in Fig. 4 for three different cases of He pressures: 1.2 nTorr, 2.1 nTorr, and 3.34 nTorr. The 2.1 nTorr case shows the saturation of the bunch size at about 170th bunch. Nevertheless, all three curves show very similar pattern of the bunch size blow-up saturating at ~2σ_y. Observation of the bunch size blow-up is also consistent with the typical computer simulation results [6]. Another observation was the decrease of ion frequency along the bunch train due to the bunch size blow-up. It can be seen in Fig. 2b and Fig. 3b that the wavelength becomes longer at the tail of the bunch train. Figure 4 shows the decrease of phase advance from 5.6 MHz at the 170th bunch to 4.5 MHz at the tail of the bunch train. However, there was no bunch to bunch tune variation within the resolution of the fast Fourier transform ($\Delta \nu_y < 0.001$).

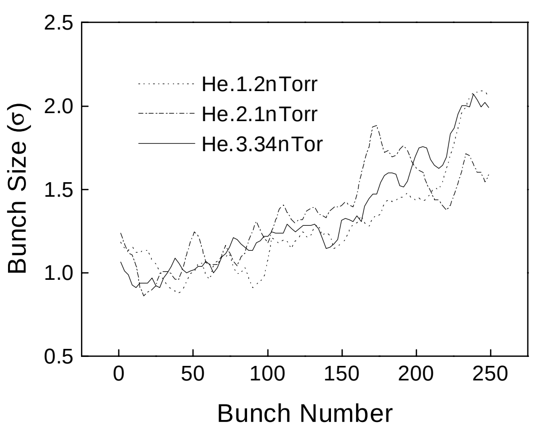


Fig. 4. Bunch size measured along the bunch train for three different cases of 1.2 nTorr, 2.1 nTorr, and 3.34 nTorr showing the same growth pattern. Bunch sizes are normalized to the initial bunch size.

4 CONCLUSION

In summary, we have investigated FBII by directly observing the snake-tail oscillation using a streak camera and a single pass beam position monitor. Since the streak camera images were directly taken from the synchrotron radiation, the distortion and noise of the signals were negligible compared to the SBPM signal. More importantly, it was possible to measure the amplitude of the beam oscillation and the bunch size blow-up separately along the bunch train. The oscillation amplitude increased to about 1.5σ_y at the tail of the train, but it became very large intermittently. The bunch size blow-up at the tail of the bunch train was about 2σ_y. Counting both the oscillation amplitude and the bunch size blow-up together, total beam size blow-up is by a factor of 2 - 3, as was observed in the ALS [9]. In addition, the intermittent large oscillation of the snake-tail may explain the triangular beam profile as was observed in the ALS with a CCD camera. Another important observation was that the FBII is excited spontaneously when the pressure is raised to about 1 nTorr (partial pressure of CO is 0.1 nTorr) in the PLS. It indicates that the FBII is an observable not only in the future accelerators, but also in the existing low emittance electron storage rings operating without feedback system. With an effective feedback system, however, FBII will appear at higher gas pressure showing the different characters by the competition between the feedback noise and the damping as discussed by Heifets [5], Byrd [9], and Chao [13].

Since the initial growth rate of the FBII is of the great concern, further experiment is planned in more controlled way to measure the initial growth of the FBII. The instruments should include both the longitudinal and transverse feedback systems, and a longtime recorder of the beam-ion oscillation to monitor the growth time and the intermittent behavior of the FBII signal. To measure the individual vertical bunch size with negligible diffraction limited error, a dual-scan x-ray streak camera with a x-ray imaging system will be most desirable.

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