STUDY OF THE FAST BEAM-ION INSTABILITY IN THE POHANG LIGHT SOURCE

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Abstract

The fast beam-ion instability (FBII) has been studied experimentally at the Pohang Light Source. As the vacuum pressure increased by turning-off all ion pumps or by injection of Helium gas into the storage ring, the FBII was spontaneously excited. The oscillation amplitude, ion frequency, and bunch size blow-up were first measured for individual bunches from the snapshots of the bunch train taken by a streak camera and a single pass beam position monitor. By measuring the bunch-by-bunch parameters along the bunch train, we obtained important parameters of the FBII: bunch size blow-up factor of $2\sigma_y$, and the amplitude of oscillation by a factor of $1.5\sigma_y$.

1 INTRODUCTION

As the stored bunch current and the number of bunch become large in a future low emittance accelerator, the new kind of beam instabilities may become important. The *fast beam-ion instability* (FBII) is one of such novel instability predicted by Raubenheimer and Zimmermann [1], and Stupakov [2]. The FBII is 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 trapped ions in the beam potential over multiple passages of the beam. The characteristic signal of the FBII is the coherent beam-ion oscillation at the train-tail due to the increase of the beam-generated ion density along the bunch train. According to the linear theory, the amplitude of oscillation $y(t,z)$ grows asymptotically as $y(t, z) \approx y_0 \exp[zl(t/\tau)^{1/2}]$ with the phase factor $z\omega_i /c - \omega_\beta t$, where 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]. 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 [1,2,5,6].

The FBII will cause the beam emittance blow-up and consequently degrade the luminosity seriously in the future accelerators such as B-factories and Linear Collider. There were experimental studies of the FBII in the ALS [7], PEP-II [8], TRISTAN AR [9], and PLS [10]. The first observation of the FBII was made in the ALS with 80 nTorr Helium gas injection into the storage ring to raise the growth rate of the FBII. Both the transverse and longitudinal beam feedback systems were used to suppress the coupled bunch instabilities. Major observations were the integrated vertical beam size measured by a CCD camera, current and beam size dependences of the ion frequency, and the onset of beam size blow-up measured as a function of the bunch train length. In the TRISTAN AR and PLS, single pass beam position monitor (SBPM) was used to measure the phase and amplitude of the beam oscillation.

Yet there has been an important question to explain the experimental results of this novel instability: whether the increase of integrated beam size is due to the increase of oscillation amplitude or by the increase of bunch size, or both. With direct observation of the bunch train snapshots, we measured the blow-up factor of the bunch-by-bunch oscillation amplitude and the bunch size along the bunch train at the PLS.

2 EXPERIMENTS

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, such as the oscillation amplitude and the bunch size blow-up, for individual bunches along the bunch train.

The turn-by-turn snapshots were taken with a SBPM and a streak camera. The position detection circuit of the prototype transverse feedback system was utilized as a SBPM. A LeCroy 9370L digitizing oscilloscope was used to digitize and store the bunch-by-bunch beam position data for more than 1024 turns in time series. The ion frequency was measured with HP8360 spectrum analyzer as well as by the fast-Fourier-transform(FFT) of time series taken by SBPM. The streak camera consists of a Hamamatsu C5680 streak unit, a M5677 slow sweep unit, and a M5678 dual sweep module. The advantage of streak camera is it takes the light image with negligible distortion or noise compared to the SBPM signal. The diffraction-limited error of the visible light image of the bunches was measured as about 90 μm, which is very large due to the small vertical radiation angle of the synchrotron radiation (~1/γ). The diffraction error was subtracted properly from all the measured bunch size, but the measurement error was large when the beam size is smaller than the diffraction-limited error.

Although no active feedback system was used in the experiment, beam current was stored up to 200 mA with 250 bunches without significant HOM induced instability.

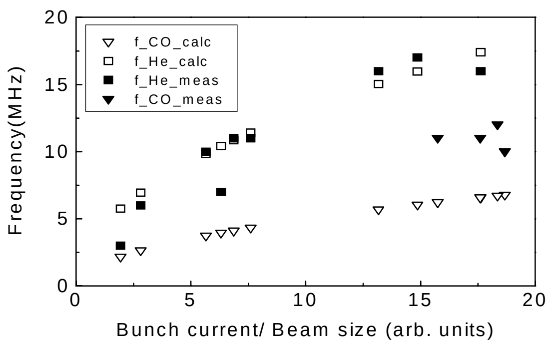

Figure 1. Ion frequencies measured and calculated with varying bunch current and bunch sizes.

For the control of the gas or ion pressure, ion pumps were turned-off, and the Helium gas was injected into the storage ring with a precise leak rate controller.

The first experiment was performed with 150 bunches to measure the ion spectra with respect to bunch size and bunch current with a spectrum analyzer and the FFT of SBPM data. For the second experiment, 250 bunches were injected into the storage ring with 218 empty buckets as a clearing gap. The bunch current was 0.72 mA/bunch in average, the nominal bunch size was 95 μm vertically, and the vacuum pressure with stored beam was 0.4 nTorr. The third experiment was performed to investigate the effect of clearing gap in the bunch train.

3 RESULTS AND DISCUSSONS

As the ion pumps were turned-off and He gas was injected, the FBII was excited and the integrated beam size increased with train-tail oscillation. With varying bunch currents, the ion spectra were measured as shown in Figure 1. It shows both theoretical numbers and measured values of ion frequencies. The ion frequency ω_i is given by $\omega_i = [4Nr_p / 3L_{sep}\sigma_y(\sigma_y + \sigma_y)A]^{1/2}$, where N is the number of particles in a bunch, L_{sep} is the distance between bunches, A is the mass number of ion, r_p is the classical proton radius, respectively [3]. It agreed well for He gas as the beam size became larger than the diffraction limit by the FBII, but it does not agree well for the CO gas, for which the beam size was smaller than the diffraction limit, giving large error in calculation of CO ion frequency. The second experiment was performed with 250 bunches with 0.72 mA/bunch. Only vacuum presure was controlled for data taking. When the ion pumps were turned-off, the vacuum pressure increased from 0.4 nTorr to 2.2 nTorr and the partial pressure of CO increased from 0.03 nTorr to 0.16 nTorr. During the vacuum pressure increase, a clear *snake-tail* motion appeared at about 1 nTorr in both the streak camera image (Figure 2b) and in the SBPM signal associated with the betatron oscillation with 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 2b shows typical snapshots of the train-tail oscillation with 57 m long wavelength. Each snapshot was taken every 4th turn (~ 4 μsec). Since the fractional betatron tune is 0.18 (~1/6), the snapshot looks almost periodic with a period of 3 snapshots (~ 12 turns).

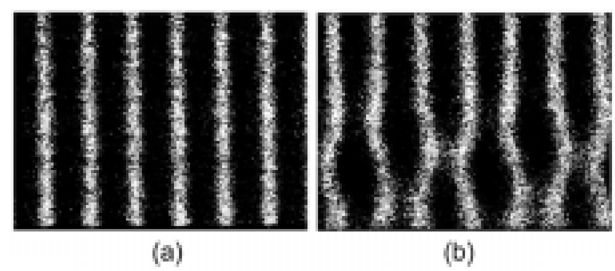

Figure 2. Snapshots taken every 4 μsec before and after the turn-off of the ion pumps. Total time span in horizontal direction is 25 μsec (6.4 mm in spatial unit), and 500 nsec in vertical direction. a) Snapshots taken at nominal condition. Very weak oscillation was observed at the very tail of the bunch train. b) After ion pumps were turned off, the snake-tail oscillation at the tail is clear.

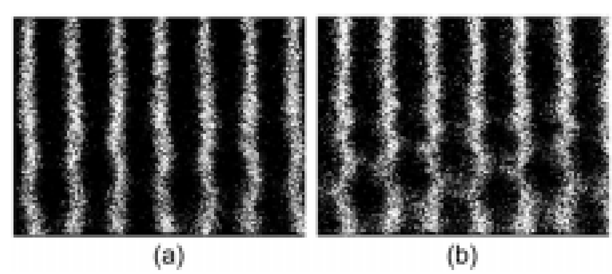

Figure 3. Two series of snapshots taken after He injection. a) Snapshots for 0.2 nTorr He, and b) for 3.34 nTorr He. The increase of the ion frequency from Figure 2b is manifest. The beam size blow-up at the tail is also clearly shown.

The Helium gas injection was followed in four steps. In the first step, 0.2 nTorr of the He-gas was injected to make total pressure increase to 2.4 nTorr. When this small amount of lighter gas molecules was injected, the oscillation amplitude was decreased to 80 – 110 μm (~ σ_y). It might be due to the detuning effect by coupling of two ion frequencies similar to the decoherence effect by ion frequency spread around the storage [1, 2].

As the He gas pressure increased further to 1.2 nTorr (the total pressure became 4 nTorr), the amplitude increased to 150 μm again and the He peak appeared clearly at about 9 MHz, indicating that the beam-He ion interaction became large. The change of ion frequency is apparent compared by two snapshots, Figures 2b and 3b. Figure 4 shows the amplitude and phase advance of the bunch oscillation obtained from a SBPM data taken at the same condition with Figure 2b. The phase advance per bunch is around 2π/95/bunch (~ 5.3 MHz) near the tail of the bunch train, agreeing well with the ion frequency measured from the spectrum analyzer and from the streak camera snapshots. Figures 2 and 4 also show the decrease of the ion frequency from 5.6 MHz at the 170th bunch to 4.5 MHz at the tail of the bunch train, due to the increase of bunch sizes.

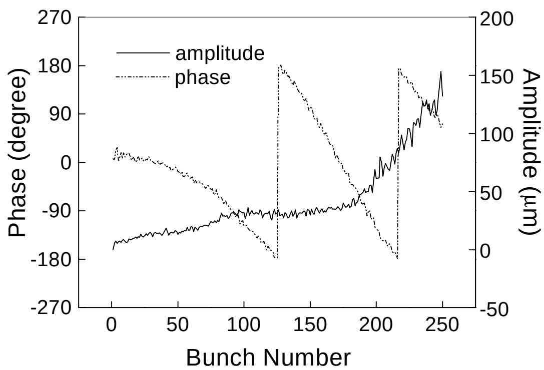

Figure 4. The phase advance and amplitude of bunch train oscillation plotted from an SBPM data taken before the He injection. Phase advance per bunch is ~2π/95/bunch at the tail, which agrees with the frequency of 5.4 MHz measured with the spectrum analyzer

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. The bunch size at the head of the bunch train grows along the bunch train by a factor of about 2 at the tail, independent of He pressure as shown in Figure 5 for three different cases of He pressures: 1.2 nTorr, 2.1 nTorr, and 3.34 nTorr. All three curves show similar pattern of the bunch size blow-up saturating at ~2σ_y. Observation of the bunch size blow-up along the bunch train with computer simulation was very recently reported by Raubenheimer [11] after this experiment.

In the third experiment, the effect of clearing gap in the bunch train was studied qualitatively. Starting from 250 bunches, the bunch train was split to two 125 bunches at the center. As the gap distance increased until to 25 L_{sep}, the FBII did not change significantly. The second bunch train oscillated like the tail of the first bunch train. When the gap distance was 50L_{sep}, however, there was no correlation between two bunch trains in the sense that the head of the second bunch train was at the equilibrium position. Both bunch trains showed tail oscillations with much smaller amplitude.

4 CONCLUSION

The FBII was investigated experimentally by directly observing the bunch-tail oscillation using a streak camera and a single pass beam position monitor. It was possible to measure the oscillation amplitude and the bunch size separately along the bunch train. The oscillation amplitude increased to about 1.5σ_y at the tail of the train, and the bunch size blow-up at the tail of the bunch train was about 2σ_y. The FBII was excited spontaneously when the pressure was raised to about 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 the feedback system. Since the initial growth rate of the FBII is of the great concern, further experiments are planned in the PLS to measure the initial growth of the FBII.

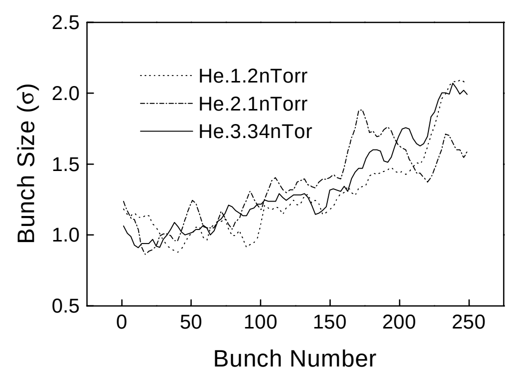

Figure 5. Bunch size measured along the bunch train for three different cases of 1.2 nTorr, 2.1 nTorr, and 3.34 nTorr showing the same growth pattern. Bunch sizes are normalized to the initial bunch size.

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