EXPERIMENTAL OBSERVATIONS OF THE ION-RELATED COUPLED BUNCH INSTABILITY IN A BUNCH TRAIN IN TRISTAN AR

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Abstract

An experiment was carried out in TRISTAN AR for the search of the fast beam-ion instability(FBII). A train of 100 bunches with 2ns spacing was stored with the help of the transverse bunch feedback system. The nitrogen gas was intentionally leaked into the inside of the vacuum duct to enhance the ion effect. The oscillation patterns were recorded by the beam position monitor system which is capable of storing the transverse position of every bunch up to 1600 turns. The spectra of the bunch oscillation were also measured by a spectrum analyzer. This paper describes the results of the experiment and also discusses the possible explanation of them in terms of the FBII.

1 INTRODUCTION

It is well known that ions which are produced via ionization of residual gas by the beam can be trapped along the orbit due to the attractive force of the electron beam. The trapped ions may affect to the beam motion and cause the instability called ion trapping. The ion trapping is usually avoided by leaving the bunch gap in which the ions are over-focused and eventually disappear. In high intensity rings such as the KEKB the instability may occur even in single passage of the bunch train because enormous ions are created at each bunch passage. The ions created by the head bunch give a kick to trailing bunches. The disturbance to the bunches may resonantly grow along the bunch train. The oscillation amplitude also increases toward the end of the train. This instability is called the fast beam-ion instability (FBII)[1,2,3]. The FBII may affect to the performance of the KEKB because the growth time of the FBII is estimated to be less than 1ms which is merginal value for the bunch feedback system. Though it is very imortant to study the FBII experimentally, only one experiment on the FBII has been reported[4]. Thus we tried to directly observe the buch motion caused by the FBII in TRISTAN AR. This paper describes the results of the experiment.

2 THEORY

According to the linear theory by K. Yokoya[3], the center of mass position $y_n(s)$ of the unstable mode against ion perturbation is given by

$$y_n(s) \approx a_n e^{i(\Theta n - ks)}, \tag{1}$$

where k is the betatron wave number, s a distance along the orbit, n the bunch index counted from the head of the bunch train and Θ the phase advance of the ion oscillation between the arrival time interval of two adjacent bunches which is expressed as

$$\Theta = \sqrt{\frac{2zNm\, r_e L}{A\, M_N \Sigma_y (\Sigma_x + \Sigma_y)}}\,. \tag{2}$$

Here, z is the electrovalence, A the mass nunber of the ion, L the distance between bunches, N the number of electrons per bunch, $\Sigma_{x,y}$ the convolution of the beam size of electrons and ions, m and M_N the mass of an electron and a nucleon and r_e the classical electron radius. The conjugate mode $e^{i(-\Theta n - ks)}$ is damped.

The amplitude blowup factor G is approximately given by

$$G = \left|\frac{a_n(s)}{a_o}\right| \approx 1 + \frac{1}{\Gamma}\exp\left[\sqrt{\Gamma + (\alpha_o \Theta n)^2} - \alpha_o \Theta n\right] \tag{3}$$

where Γ is a constant defined in ref. [3] and proportional to Θ, s and n^2. α_0 (≈0.077) represents the non-linear smearing of the ion center-of-motion. Equation (3) shows that the amplitude of the motion rapidly increases along the bunch train.

3 EXPERIMENTAL SETUP

The experiment was carried out as a part of the high beam current experiments at the TRISTAN AR[5]. Principal parameters of the AR are shown in Table 1.

The vaccum pressure of the AR is maintained by the ion pumps and non-evapolated getter pumps. The pressure is monitored by 15 cold cathode gauges(CCGs). In the experiment the nitrogen gas was intentionally leaked into the vacuum duct to increase the growth rate of the FBII. The pressure near the injection point of the gas was measured by a residual gas analyzer(RGA). After the leak of the gas the partial pressure of the gas-component whose atomic number is 28, P_{28}, was increased to 6.0 x 10^{-6} Torr at the RGA. The pressure distribution around the injection point of the gas was calculated from the reading of the RGA and the pumping speed of the vacuum pumps[6]. From the calculated pressure distribution and the reading of CCGs we obtained the average value of P_{28}

Table: 1 TRISTAN AR parameters.

Beam energy(GeV)	2.5
Circumference(m)	377
RF frequency(MHz)	508.5808
Harmonic number	640
Revolution frequency(kHz)	795
Natural emittance(m)	4.46×10^{-8}
Average beta functions(H/V) (m)	8.7 / 9.4
Betatron tunes(H/V)	10.14 / 10.25

of 8.4×10^{-8} Torr. The vertical emittance growth by Coulomb scattering was estimated to be 3.8×10^{-10}m[7]. Before the leak of the gas vacuum pressure was 7×10^{-9} Torr.

Main instrument for the experiment was the beam position monitor(BPM) system[8] which was installed in the AR to study the prototype of the bunch feedback system for the KEKB. The signals from up- and bottom-button pickups were both converted to 2GHz signals using cable-delay and fed to the hybrid to make a difference of two signals. The difference-signal was mixed with the reference signal with the frequency of 4 x RF frequency (f_{RF}), then fed to the low pass filter and finally put into the two-tap filter board which can store the data of 1M bytes after digitizing the input signal with an 8-bit ADC. The ADC count U is expressed as $U = k_m\, y\, I_b$, where y is the vertical beam position and I_b the bunch current. The constant k_m was determined to be 46 count/mm/mA by making orbit bumps at the pick up. The trigger for the data taking by the BPM system was generated freely without synchronization with any signal.

As an auxiliary instrument a spectrum analyzer HP8562E(13.2GHz) connected with a vertical button pick up was used for taking the beam spectrum. The observed frequency range was $3f_{RF}$ to $4\, f_{RF}$. From the noise level of the beam spectrum, detectable oscillation amplitude was estimated to be larger than 30μm at the beam current of 100mA. The beam oscillation was also observed by the synchrotron light(SL) monitor.

The beam size was measured by a photodiode arrays. But at present we are not sure whether the monitor is reliable or not because it gives two times larger horizontal beam size than design value in the single bunch operation. In calculations of the growth time and Θ we used the beam size calculated from the design value of horizontal emittance and an estimated vertical-horizontal emittance ratio κ. For the calculation of κ the vertical r.m.s.-misalignment of the quadrupoles $\sigma_y(q)$ was estimated by the closed orbit(c.o.) without orbit correction which was obtained from the measured c.o. and corrector strength. The vertical r.m.s.-misalignment of the sextupoles was assumed to be equal to $\sigma_y(q)$ and the r.m.s.-rotational error of the magnets was also assumed to be 0.2mr. A simulation based on these errors shows that κ is less than 1 % after the orbit correction. Taking account of the emittance growth by Coulomb scattering the total κ is estimated to be several %.

Throughout the experiment the transverse bunch feedback system was employed to store the beam current of several hundred mA. The vertical damping time of the bunch feedback system was estimated to be 800 μs at the bunch current of 4mA[8]. Assuming κ of 2 % and P_{28} of 8.4×10^{-8} Torr the linear theory predicts the growth time of 140μs which is much shorter than the damping time of the bunch feedback system.

4 EXPERIMENTAL PROCEDURE AND RESULTS

A train of 100 bunches was stored with 2ns spacing. This means that about five sixths of RF buckets were left without the bunches. A calculation based on the conventional ion trapping theory[9] shows that the ions are not trapped in our experimental conditions, i.e. absolute value of the trace of the ion motion matrix is larger than 2.

Before the leak of the nitrogen gas we confirmed that the vertical betatron sidebands observed by the spectrum analyzer were disappeared at the beam current of 260 mA. Then we leaked into the gas in the ring. The vertical betatron sidebands remained down to the beam current of 173 mA. Then we added more gas. The beam was injected to 190 mA. Vacuum pressure was 8.4×10^{-8} Torr as described in section 3. The intermittent vertical oscillation, which was not observed before and at the first leak of the gas, appeared in the SL monitor. Beam loss accompanied with the oscillation was not observed. Strong vertical betatron sidebands were observed in the spectrum taken by the spectrum analyzer. The spectrum distribution shows that the large lower sidebands appear below 10th revolution harmonics as expected by the theory(See Figure 1). We also observed upper sidebands whose origin is not understood yet. The sidebands were observed down to 57 mA.

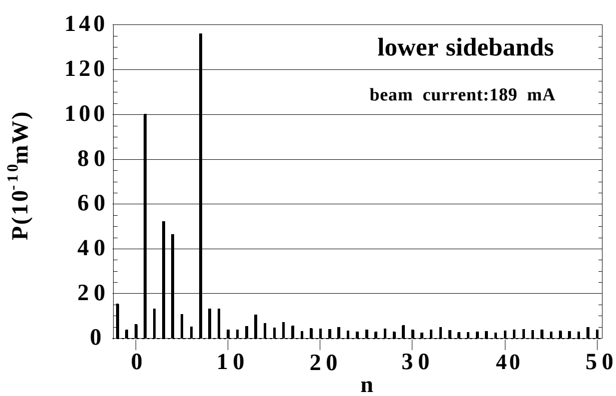
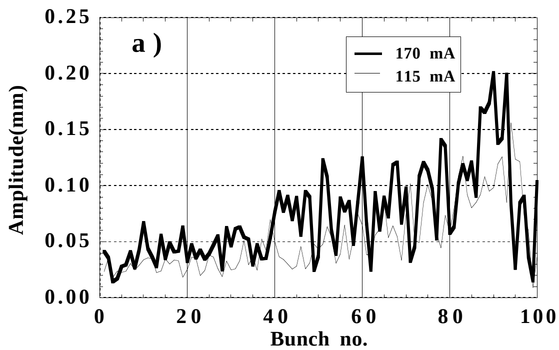


Figure 1: Spectrum of lower betatron sidebands at the frequency of $3\, f_{RF}+nf_r - f_\beta$, where f_r and f_β are the revolution and betatron frequency, respectively.

The bunch oscillation was taken by the BPM system after adding the gas. As the oscillation includes a



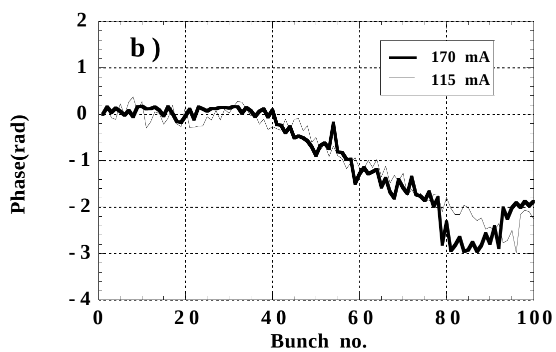


Figure 2: Amplitude a) and phase b) along the bunch train.

large component of synchrotron oscillation we applied Fourier analysis to the data of 1600 turns. The amplitude was normalized by the bunch current because the distribution of the bunch current was not uniform due to the short beam life of about 10-15 min. The obtained amplitude and phase are shown in Fig. 2 a) and b), respectively. Two set of the data were taken in same beam fill but at different beam current of 170 and 115 mA. Fig. 2 a) clearly shows the amplitude growth along the bunch train. The maximum amplitude is about 200μm at the beam current of 170 mA. As the amplitude of 200μm is well above the sensitivity of the spectrum analyzer and the sidebands were not observed by the spectrum analyzer at almost same current before adding the gas, we conclude that the observed oscillation was caused by the addition of the gas.

Fig. 2 b) shows that the phase decreases along the bunch train, which exhibits the oscillation mode is unstable as expected by the theory. The total phase shift from head to tail of the bunch train is about 3 radians. Assuming κ of 2 % the linear theory gives three times larger phase shift than the observation. We may need further study of the beam size to discuss the difference between observed and predicted phase shift. Eq. (2) shows that Θ is expected to be changed by 20% when the beam current decreases from 170 to 115 mA. In Fig. 2 b) expected change of Θ is not clear.

5 SUMMARY

An experiment for the search of the FBII was carried out at the TRISTAN AR. We observed the vertical coupled bunch oscillation caused by adding the nitrogen gas into the ring, which indicates the instability is ion-related. The amplitude of the oscillation along the bunch train increases from head to tail of the bunch train. The decrease of the oscillation phase along the bunch train shows that the unstable mode of the oscillation is excited. The phase shift from head to tail of the train agrees with the linear theory of the FBII within factor of 3. The growth rate of the instability is less than several ms which is the damping time of the bunch feedback system. Observed characteristics of the instability such as being ion-related, the oscillation amplitude increasing along the bunch train, short growth time of the instability and the phase shift from head to tail of the train which agrees with the theory within factors of magnitude shows that the observed instability can be interpreted as the FBII.

Further simulation studies and data analysis are in progress.

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