OBSERVATION OF BEAM ION INSTABILITY IN SPEAR3*

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Abstract

Weak vertical coupled bunch instability with oscillation amplitude at μm level has been observed in SPEAR3. The instability becomes stronger when there is a vacuum pressure rise by partially turning off vacuum pumps and it becomes weaker when the vertical beam emittance is increased by turning off the skew quadrupole magnets. These confirmed that the instability was driven by ions in the vacuum. The threshold of the beam ion instability when running with a single bunch train is just under 200 mA. This paper presents the comprehensive observations of the beam ion instability in SPEAR3. The effects of vacuum pressure, beam current, beam filling pattern, chromaticity, beam emittance and bunch-by-bunch feedback are investigated in great detail.

INTRODUCTION

In an electron accelerator, ions generated from the residual gas molecules can be trapped by the beam. Then these trapped ions interact resonantly with the beam and cause beam instability and emittance blow-up. Most existing light sources use a long single bunch train filling pattern, followed by a long gap to avoid multi-turn ion trapping. However, such a gap does not preclude ions from accumulating during one passage of the single bunch train beam, and those ions can still cause a Fast Ion Instability (FII) as predicted by Raubenheimer and Zimmermann [1]. FII has been observed in ALS [2], and PLS [3,4] by artificially increasing the vacuum pressure by injecting helium gas into the vacuum chamber [2,3,4] or by turning off the ion pumps [3] in order to observe the beam ion instability. In some existing rings, for instance B factory, the beam ion instability was observed at the beginning of the machine operation after a long period of shutdown and then it automatically disappeared when the vacuum was better. However, when the beam emittance becomes smaller, the FII can occur at nominal conditions as observed in PLS [5], SOLEIL [6] and SSRF [7]. This paper reports the observations of beam ion instabilities in SPEAR3 under different condition during a period of one year, which includes single bunch train instability (FII) and multi-bunch train instability. Note that the instability may be not the same even with the same beam due to the change of the vacuum with time.

SPEAR3 has a circumference of 234 m with a harmonic number of 372. SPEAR3 runs with six bunch train filling pattern in order to suppress the possible beam ion instability. Table 1 lists the main parameters of SPEAR3. The vacuum of SPEAR3 ranges from 0.1 to 0.5 *nTorr*, which varies from section to section.

*Work supported by DOE contract No. DE-AC02-76SF00515
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Table 1: Typical Parameters of SPEAR3

Physics	Symbol/Unit	
Horizontal Emittance	nm	10
Vertical Emittance	pm	14
Bunch Number		280
Harmonic Number		372
Beam Energy	*GeV*	3
Circumference	*m*	234
Bunch spacing	*ns*	2.1
RF frequency	*MHz*	476.315
Radiation Damping time	$\tau_x/\tau_y/\tau_z$ $[ms]$	4.0/5.3/3.2
Vacuum	*nTorr*	0.1~0.5

DEPENDENCE OF VERTICAL INSTABILITY ON EMITTANCE AND VACUUM PRESSURE

Beam-ion instability was first observed in 200mA operation with a single bunch train filling pattern. Figure 1 shows the observed typical beam spectrum. The observed unstable modes of the lower vertical sidebands agree with the theoretical prediction of the beam ion instability and the frequencies of the unstable modes agree with theory. There is no horizontal instability. The observed bunch oscillation amplitude increases along the bunch train and saturates at the order of beam size as shown in Fig. 2. Coupled-bunch instabilities driven by the traditional impedances either do not saturate or saturate at much larger amplitudes. This indicates the observed instability is driven by the ions in the vacuum. Further tests have been carried out to confirm it. All skew quadrupole magnets were turned off to increase the vertical emittance. Figure 3 shows the measured vertical lower sidebands observed on the beam spectrum analyzer when the skew quadrupole magnets were on and off. When the skew quadrupole magnets were off, the maximum frequency of the observed sidebands reduced from 26.0 MHz to 13.0 MHz, and the maximum amplitude also dropped as predicted by the theory of beam ion instability. This indirectly confirms that the instability is driven by ions in the vacuum instead of the impedance inside the vacuum chamber because the traditional impedance doesn't change with the beam emittance.

In order to further test that the vertical instability is driven by ions, the vacuum pressure was raised by partially turning off the vacuum pumps. Figure 4 shows the vertical sidebands at different average vacuum pressures along the ring with 300 mA total beam current.

The beam fill pattern was a six bunch train, and there was no vertical beam instability at pressure 0.37 nTorr when all vacuum pumps were on. The instability appeared as the pressure increased, and it became stronger with a higher pressure. This directly confirms that the vertical instability observed in SPEAR3 is driven by ions in the vacuum chamber.

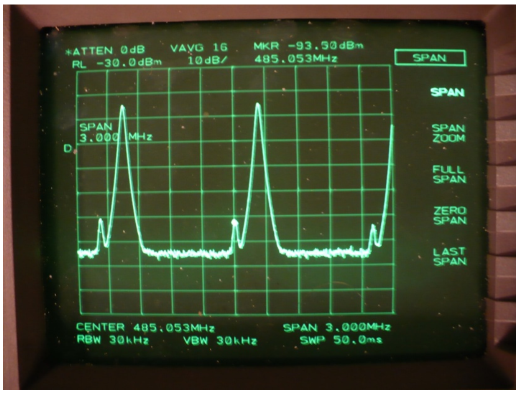

Figure 1: Beam spectrum at 200 mA with a single bunch train filling pattern. There are 280 bunches along the bunch train. The large peaks are the revolution harmonics and the low peaks are the vertical lower sidebands.

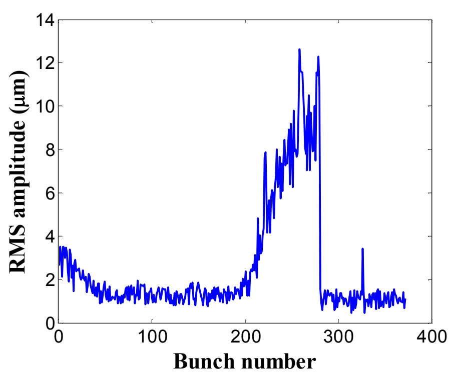

Figure 2: Measured beam's vertical oscillation amplitude with single bunch train filling pattern. Bunches 1-280 and 326 are filled with a total beam current of 200 mA.

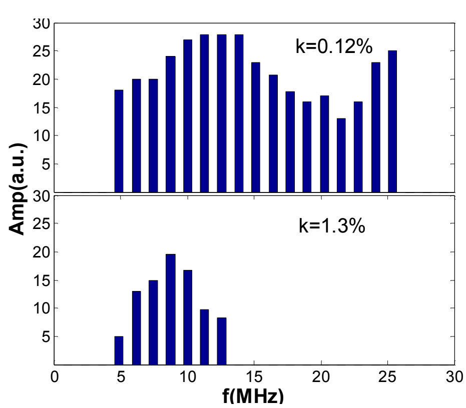

Figure 3: Observed vertical lower sidebands in a single bunch train filling pattern with 280 bunches and total beam current of 192 mA for different beam coupling: k=0.12% when skew quadrupole magnets are on (top) and k=1.3% when skew quadrupole magnets are off (bottom).

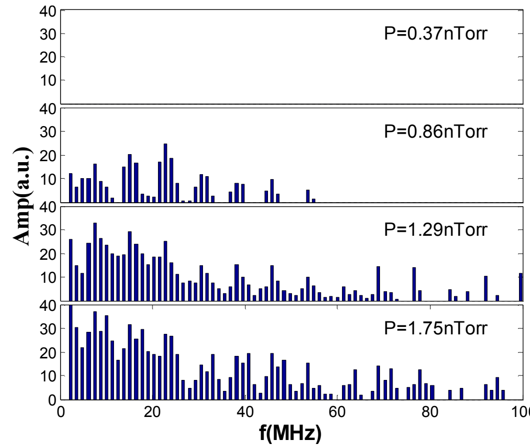

Figure 4: Observed vertical lower sidebands at different vacuum pressures. The beam consists of six bunch trains with total bunch number of 280. The beam current is 300 mA. There are no sidebands with the nominal pressure of 0.37nTorr. The vacuum pressure is increased by partially turning off the ion pumps.

BEAM CURRENT EFFECTS

Beam current affects the instability in two ways: the frequencies of the unstable modes increase with the square root of the beam current and the instability growth rate increases linearly with beam current (with the assumption of a constant vacuum). Fig. 5 shows the vertical lower sidebands with various beam currents. The observation qualitatively agrees with the theory.

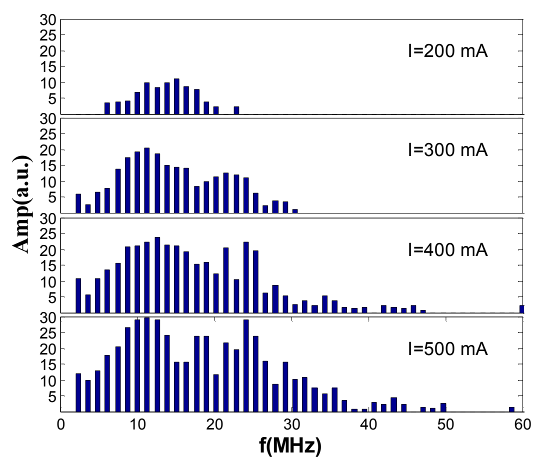

Figure 5: Observed vertical lower sidebands at different beam currents. The beam has single bunch train with 280 bunches.

BEAM FILLING PATTERN EFFECT

The beam ion instability is sensitive to the beam filling pattern since in most cases more ions can survive from a shorter bunch train gap. Most light sources run with a single bunch filling pattern followed by a long gap to avoid multi-turn ion trapping and often to support a single isolated bunch for timing experiments. Figure 6 shows the vertical lower side band with different bunch train gaps. There is a stronger instability for a short train gap and a vertical beam size blowup is also observed with short gap as shown in Fig. 7.

A multi-bunch train filling pattern can mitigate the instability in a low emittance ring by reducing the number of ions trapped by the beam [8]. Figure 8 shows the vertical oscillation amplitude of the unstable modes (at sidebands) with one, four and six bunch trains. The beam current is 500 mA in all the cases. There is significant reduction with four bunch trains compared with a single bunch train. However, the reduction is small from four bunch trains to six bunch trains. The instability with six bunch trains was completely suppressed by increasing the vertical chromaticity from 2.0 to 2.6.

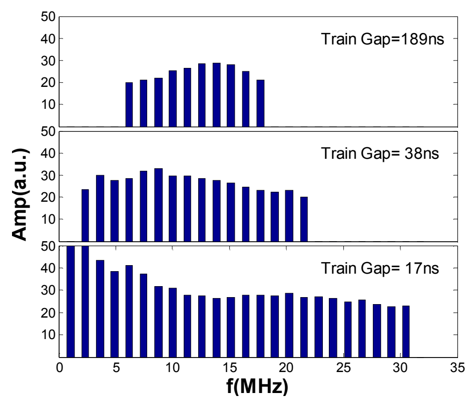

Figure 6: Measured vertical lower sidebands for different train gap length 189ns, 38ns and 17ns. The beam filling pattern is a single bunch train with total beam current 200mA.

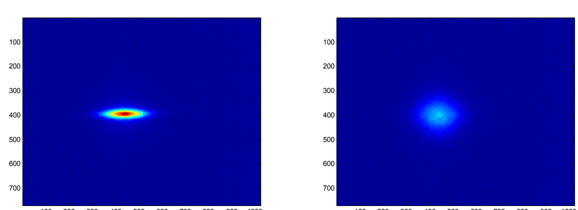

Figure 7: Beam profile with different bunch train gaps: 42 ns spacing (left) and no gap (right). The operational beam typically has a single bunch-train filling pattern.

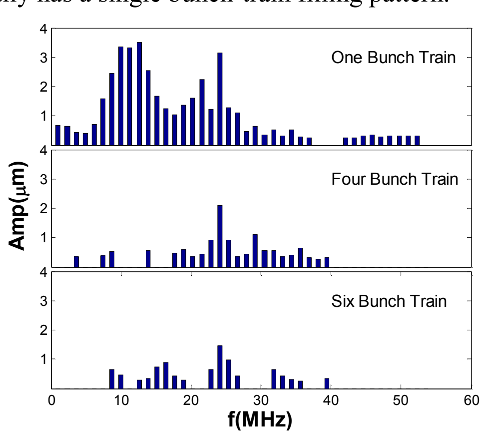

Figure 8: Oscillation amplitude of vertical lower sidebands for different beam filling patterns: one, four and six bunch trains. The total beam current is 500 mA with a total bunch number of 280 in all cases.

SUMMARY

This paper summarizes the comprehensive observations of the beam-ion instabilities in SPEAR3. A weak vertical instability with oscillation amplitude order of a few μm has been observed with nominal vacuum pressure. The instability varies with vacuum pressure and beam emittance, which directly confirms that it is driven by ions in the vacuum chamber. The instability causes the beam to oscillate with amplitude order of the rms beam size. A blow-up of the beam emittance has been observed when the bunch-train gap is very short. Besides vacuum pressure, the instability is sensitive to the beam emittance, filling pattern and chromaticity.

Multi-bunch train filling pattern is very helpful to suppress the instability and can be further mitigated by increasing the chromaticity at sacrifice of beam's lifetime. The bunch-by-bunch feedback with a damping time shorter than the growth time can suppress the instability. SPEAR3 runs without beam ion instability even at 500mA without feedback. The feedback may become necessary in a future SPEAR3 low emittance upgrade. The effects of chromaticity and feedback are not presented in this paper due to the limited page number.

ACKNOWLEDGEMENTS

We would like to acknowledge the SPEAR3 operation team for its help on the observations and thank Rodney Pak for providing the vacuum data.

REFERENCES

[1] T. O. Raubenheimer and F. Zimmermann, Phys. Rev. E 52, 5487 (1995).
[2] J. Byrd, et al., Phys. Rev. Lett. 79, 79(1997).
[3] J. Y. Huang, et al., Phys. Rev. Lett. 81, 4388 (1998).
[4] M. Kwon, et al., Phys. Rev. E 57, 6016 (1998).
[5] H. S. Kang, et. al., in Proceeding of 2006 European Particle Accelerator Conference, Edinburgh, UK, 2771(2006).
[6] R. Nagaoka, et al., in Proceedings of 2007 Particle Accelerator Conference, Albuquerque, USA, 2019(2007).
[7] B. Jiang, et. al., Nuclear Instruments and Methods A 614, 331(2010) .
[8] L. Wang, Y. Cai, T. O. Raubenheimer and H. Fukuma, SLAC-PUB-14387.