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A Study of Single Pass Ion Effects at the ALS

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Abstract

We report the results of experiments on a "fast beam-ion instability"[1] at the Advanced Light Source (ALS). This ion instability, which can arise even when the ions are not trapped over multiple beam passages, will likely be important for many future accelerators. In our experiments, we filled the ALS storage ring with helium gas, raising the pressure approximately two orders of magnitude above the nominal pressure. With gaps in the bunch train large enough to avoid conventional (multi–turn) ion trapping, we observed a factor of 2–3 increase in the vertical beam size along with coherent beam oscillations which increased along the bunch train.

1 INTRODUCTION

Ion trapping has long been recognized as a potential limitation in electron storage rings. The ions, generated by beam-gas collisions, become trapped in the negative potential of the beam and accumulate over multiple beam passages. The trapped ions are then observed to cause a number of deleterious effects such as an increasing beam phase space, a broadening and shifting of the beam transverse oscillation frequencies (tunes), collective beam instabilities, and beam lifetime reductions[2, 3]. All of these effects are of concern for the next generation of accelerators, such as the B-factories or damping rings for future linear colliders, which will store high beam currents with closely spaced bunches and ultra-low beam emittances.

One of the standard solutions used to prevent ion trapping is to include a gap in the bunch train which is long compared to the bunch spacing. In this case, the ions are first strongly-focused by the passing electron bunches and then over-focused in the gap. With a sufficiently large gap, the ions can be driven to large amplitudes where they form a diffuse halo and do not affect the beam.

In this paper, we describe experiments that study a new regime of transient ion instabilities predicted to arise in future electron storage rings [1], and linacs with bunch trains. These future rings and linacs, which will be operated with higher beam currents, small transverse beam emittances, and long bunch trains, will use ion clearing gaps to *prevent* conventional ion trapping. But, while the ion clearing gap may suppress the conventional ion instabilities, it will not suppress a transient beam-ion instability where ions generated and trapped during the passage of a *single* train lead to a fast instability. While both conventional and transient ion instabilities have the same origin, namely ions produced by the beam, they have different manifestations and, more importantly, the new transient instability can arise even after the conventional ion instability is cured. This new instability is called the "Fast Beam-Ion Instability" (FBII). In many future rings, the FBII is predicted to have very fast growth rates, much faster than the damping rates of existing and proposed transverse feedback systems, and thus is a potential limitation.

To study the FBII, we performed experiments at the ALS, a 1.5 GeV electron storage ring. At the nominal ALS pressure of about 0.24 nTorr, the FBII is not evident. To study the instability, we intentionally added helium gas to the storage-ring vacuum system until the residual gas pressure was increased about 80 nTorr. This brought the predicted growth rate of the instability at least an order of magnitude above the growth rate of conventional multi-bunch instabilities driven by the RF cavities and above the damping rate of the transverse feedback system (TFB) in the ALS and, thereby, established conditions very similar to those in a future storage ring. We then filled the ring with a relatively short train of bunches, suppressing conventional ion instabilities. In the following, we will first briefly describe This paper describes the experiment and results in more detail.

2 FAST BEAM-ION INSTABILITY

The FBII can be compared with beam break–up in a linear accelerator. In a transport line or a storage ring with a large clearing gap, the ions are not trapped over multiple beam passages. Regardless, during a single passage of the beam, ions are created by each passing bunch which leads to a linear increase of the ion density along the bunch train. These collective oscillations of the ions in the beam's potential well drive the transverse oscillations of the beam at the ion oscillation frequency which in turn resonantly drives the ions to larger amplitudes. The result is an exponential growth of the vertical bunch offsets as a function of both the distance along the train and the distance along the accelerator. Furthermore, only the "slow" (phase velocity less than c) wave will be driven by the ions. The amplitude growth along the train is a distinct signature of a single-pass effect while the second statement implies that

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the Fourier spectrum of the signal seen on a beam position monitor will consist of many lower betatron sidebands peaking at the ion oscillation frequency which is a distinct signature of all beam–ion instabilities.

Because the beam–ion interaction is very nonlinear, the FBII will saturate when the oscillations reach amplitudes comparable to the beam size. At this point, the instability growth slows and the transverse oscillations of individual bunches begin to filament due to a spread in betatron frequencies. The resulting distribution depends on the speed with which the beam filaments, the damping, the nonlinearity of the beam-ion force, and the effect of any feedback which is acting to damp coherent oscillations. Thus, depending on parameters, the FBII will cause either the amplitude of the coherent oscillations or, if the bunches have filamented, the size of bunches to increase along the length of the train.

3 EXPERIMENTAL SETUP

The relevant parameters of the ALS are average horizontal and vertical beam sizes of 160 and 30 μm, harmonic number of 328, and betatron tunes of 14.28 (x) and 8.18 (y).

To increase the FBII growth rate so that the instability should be observable in the ALS, we added He gas to the vacuum system. The motivation for using He gas is that the vertical emittance growth from Coulomb scattering was only an 18–20% effect and that calculations indicated that an achievable level of He pressure (<100 nTorr) would give a growth rate of the FBII much faster than the damping rate of the TFB system. For all experimental conditions we expected He ions to be linearly unstable over multiple beam passages. During normal operation, the average pressure with beam is about 0.25 nTorr. To reach the high He pressure it was necessary to turn off all of the active ion pumps except for one pump on either side of the RF cavities. He was added through gas inlet ports located on either side of these pumps, balancing the gas distribution throughout the ring. By adjusting the gas inlet rate, we could maintain an average pressure of ~80 nTorr of He around the ring. The three residual gas analysers indicated that He was the dominant gas species by an order of magnitude; H and Ar were the next most populous species.

The experiments were all performed using the vertical, horizontal, and longitudinal feedback systems[4] to damp coupled–bunch instabilities driven by RF cavity and resistive wall impedances. In this mode, the coupled bunch oscillations are successfully damped by the feedback systems, as is the case for nominal pressure, while oscillations driven by the faster ion instability are not damped during their initial growth. For the conditions in the experiments presented below, the damping rate of the vertical feedback system was about $(400\ \mu\text{s})^{-1}$/mA.

Synchrotron radiation[5] from a bend magnet is used to image the transverse beam profile. Unfortunately the setup of the beamline does not allow measurement of the beam size at different points along the bunch train but instead simply measures the projected size of the entire train. We also observed the frequency spectrum of the dipole moment of the beam using an HP70000 spectrum analyser. One of the BPMs for the transverse feedback system was used as the input to the spectrum analyser.

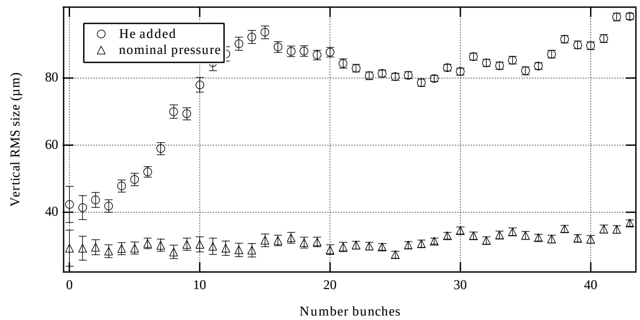

Figure 1: RMS vertical beam size vs. the number of bunches for nominal and elevated pressure conditions.

4 RESULTS

The experimental procedure was to record the synchrotron light image and vertical beam spectrum for a variety of bunch train lengths and bunch currents where conventional trapping of He was not expected. The measurements were made at the nominal pressure and at the elevated pressure after introducing He. We also measured the beam size for single bunches at both nominal and elevated pressure to ascertain the beam-size increase from Coulomb beam-gas scattering, which was of the order of 15-20%, in agreement with calculations.

We studied the onset of the instability by recording the beam behavior as the length of the bunch train was slowly increased. Starting with a single bunch of 0.5 mA, we slowly filled consecutive bunches. Shown in Figure 1 is a plot of the RMS vertical beam size as a function of the number of bunches continuing up to a total of 45 bunches. Also shown is the corresponding vertical beam size at nominal pressure. With He gas, the beam size strongly increased when the number of bunches exceeded 8. The FBII theory predicts that the growth rate for the 8th bunch under these conditions is about $(1\ \text{ms})^{-1}$, approximately equal to the feedback damping rate for a current of 0.5 mA/bunch.

The spectrum of coherent vertical oscillations for several different cases is shown in Figure 2. The frequency axis is scaled by the revolution frequency and only the first 164 revolution harmonics are shown. For simplicity, we have plotted the difference of the amplitude of lower and upper sidebands. The coherent vertical sidebands were not present at the nominal pressure. As He was added, a pattern of lower sidebands appeared with a peak amplitude at a frequency near that predicted by FBII simulations. As the beam current was increased, the coherent signal shifted in frequency as expected. A comparison of the frequency of coherent oscillations from experiments and theory shows good agreement. However, we did not observe a coher-

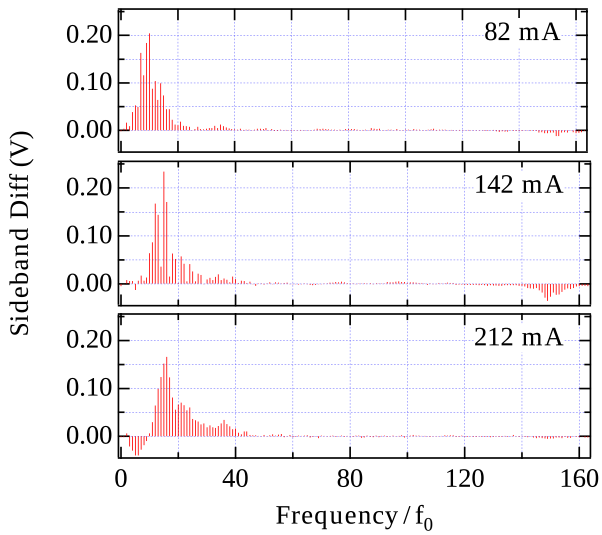

Figure 2: Vertical betatron sidebands measured in the 240/328 fill pattern for three different currents.

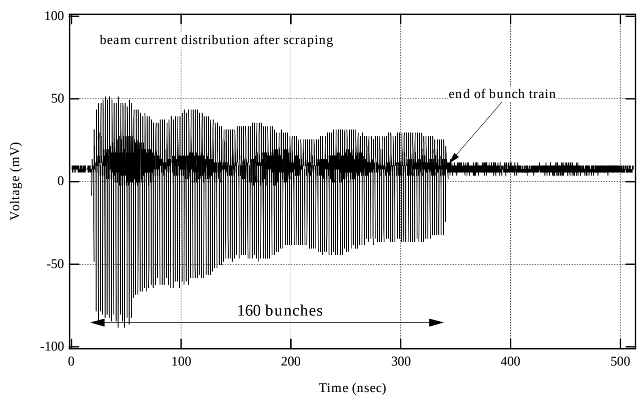

Figure 3: Beam current along the bunch train for 160 bunches after moving a vertical aperture close to the beam. The nonuniform loss pattern shows the increasing vertical oscillations (or beam size) along the bunch train.

ent signal for all cases even though we always observed a vertical blowup. The reason for this is not yet understood. One possible explanation is that for large growth rates the coherent vertical oscillations filament, only leaving an enhanced vertical size. We hope to resolve this question in future experiments.

We were able to measure the relative amplitude of oscillations (or the relative beam size) by moving a vertical aperture (i.e. scraper) close to the beam and detecting the relative current loss along the bunch train. Figure 3 shows the signal from a beam position monitor showing the relative current along the bunch train after scraping the beam. Starting from a uniform current distribution along the train, the scraper reduces the bunch population in the tail about 2.5 times more than that of the leading bunches, indicating that the instability increases along the train. The gradual loss of current along the bunch train demonstrates the transient nature of the instability, which is one of the main predictions of the FBII theory.

5 SUMMARY

In experiments at the ALS, we have made observations of an ion instability in a regime where conventional ion trapping is not expected. Our observations are qualitatively consistent with the FBII. In addition, we have measured the onset of the instability as a function of the bunch-train length. The beam size started to increase significantly with a bunch train of about 8–10 bunches which, based on the *expected* feedback performance, is very close to where the FBII is predicted to become significant. In the future, we plan further experiments to determine why the coherent signals do not always appear although the beam is clearly blown up, to make detailed measurements of the beam size and centroid motion along the bunch train, and to measure the instability growth times as a function of different parameters, especially vacuum pressure.

6 REFERENCES

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