First Observations of a “Fast Beam-Ion Instability”

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We report the results of observations of a new regime of ion instabilities at the Advanced Light Source (ALS). With artificially increased pressure and gaps in the bunch train large enough to avoid multiturn 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. The observations are qualitatively consistent with the “fast beam-ion instability” [T. O. Raubenheimer and F. Zimmermann, Phys. Rev. E **52**, 5487 (1995); G. V. Stupakov *et al.*, Phys. Rev. E **52**, 5499 (1995)], which can arise even when the ions are not trapped over multiple beam passages. This effect may be important for many future accelerators. [S0031-9007(97)03488-1]

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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 [1–3]. 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 ultralow 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 studying a new regime of transient ion instabilities that was predicted to arise in future electron storage rings [4,5] 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.

In many future rings, this transient instability 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 this instability at the Advanced Light Source (ALS) at Lawrence Berkeley National Laboratory, we intentionally added helium gas to the storage-ring vacuum system until the residual gas pressure was increased from the nominal value of 0.25 nTorr by about 2 orders of magnitude. This brought the predicted growth rate of the instability at least an order of magnitude above the growth rate of conventional multibunch 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. Then, we filled the ring with a relatively short train of bunches, suppressing conventional ion instabilities. Under these conditions, we observed coherent vertical betatron oscillations and increases in the vertical beam size by a factor of 2–3. We also inserted a vertical scraper to verify that the amplitude of the coherent oscillations and the beam-size increase is largest at the end of the bunch train. Finally, we determined the minimum bunch-train length required to observe the effect. In the following, we will first briefly describe the “fast beam-ion instability” (FBII). Then, we will describe the experimental setup and the results of the experiments.

Fast beam-ion instability [4–7].—The FBII can be compared with beam breakup 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. The longitudinal momenta of the ions can be neglected compared to the time of the bunch-train passage, and thus, at each azimuthal position around the ring, the ions oscillate transversely in the potential well of the beam. These collective oscillations of the ions 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 a quasiexponential growth of the vertical bunch offsets as a function of both the distance along the train and the distance along the accelerator.

At small amplitudes, a simple linear theory predicts that the beam should be modulated as [4]:

$$y(s,z) \sim y_0 \exp\left(\frac{z}{l}\sqrt{\frac{s}{l_c}}\right)\sin\left(\frac{z\omega_i}{c} - \frac{s\omega_\beta}{c}\right), \quad (1)$$

where ω_i and ω_β are the coherent ion oscillation frequency and the betatron frequency, c is the speed of light, l is the length of the bunch train, and z is the distance along the bunch train while s is the azimuthal position; these are related to the observation time t by $ct = z - s$. Finally, l_c is a characteristic growth distance which depends on the transverse charge density and is inversely proportional to pressure. The amplitude increases more rapidly for higher density and longer trains.

A subsequent derivation of the effect, which includes the ion decoherence, predicts a substantially slower growth rate with a pure exponential dependence on the azimuthal position s [5]. Both theories predict that the oscillation amplitudes will increase along the length of the train. 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 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. Theoretical and numerical studies to accurately predict the growth rates and saturation levels for present and future storage rings are in progress.

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 the 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.

Experimental Setup.—The ALS is a third generation synchrotron light source with parameters listed in Table I. The ring is 196 m in circumference and uses a 500 MHz rf system which allows one to store up to 328 bunches in arbitrary fill patterns. In our experiments, we would fill as many as 240 sequential bunches, leaving a gap of at least 53 m. With a beam current of 1 mA/bunch and He gas, a gap of 4.2 m will cause the ions to be linearly unstable and will drive them out to large amplitude. In practice, some of the linearly unstable ions can still be trapped by the beam, but, because of the nonlinear forces, they form a large amplitude halo about the beam and do not significantly affect the dynamics.

TABLE I. Nominal ALS parameters.

Parameter	Description	Value
E	Beam energy	1.5 GeV
C	Circumference	196.8 m
f_{rf}	rf frequency	499.654 MHz
h	Harmonic number	328
σ_x	Average hor. beam size	160 μm
σ_y	Average vert. beam size	30 μm
ϵ_x	Norm. hor. emittance	1.2×10^{-5} m
ϵ_y	Norm. vert. emittance	4×10^{-7} m
$Q_{x,y}$	Betatron tunes (x, y)	14.28, 8.18

To increase the instability growth time so that it should be measurable 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. The ALS vacuum is normally pumped by a combination of passive titanium sublimation pumps which are distributed throughout the ring and 107 active noble diode ion pumps. 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 analyzers 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 [8] 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. The damping rate of the transverse feedback system is linearly dependent on the bunch current and also somewhat sensitive to the system phase adjustments, making it difficult to predict the precise damping rate of the system without a direct measurement. For the conditions in the experiments presented below, the damping rate of the vertical feedback system was about $(400\ \mu\text{s})^{-1}/\text{mA}$.

The beam behavior was monitored with two instruments. First, we imaged the transverse beam profile, at one location in the storage ring, using synchrotron radiation from a bend magnet ($0.1 < \lambda < 5$ nm) [9]. The soft x-ray synchrotron radiation is converted to visible light using

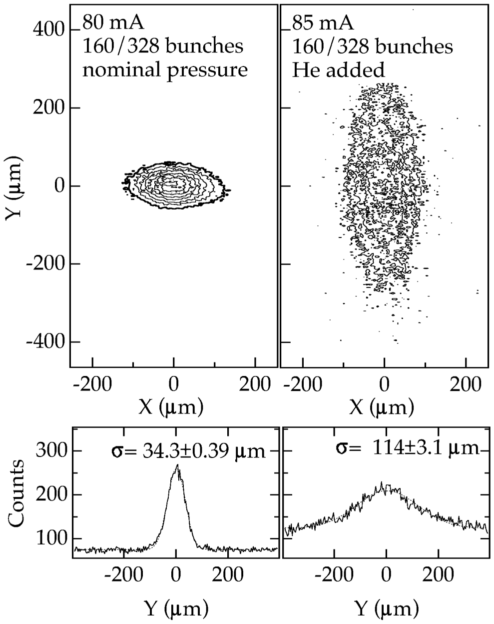

FIG. 1. Transverse profile images (shown as contour plots) of the beam for nominal pressure and with He added; the vertical profile for each image is also shown, along with a fit to a Gaussian distribution.

a scintillator and focused onto a CCD camera. Unfortunately, the response time of the scintillator (300 ns) 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.

Second, we observed the frequency spectrum of the beam using an HP70000 spectrum analyzer. One of the beam position monitors for the transverse feedback system was used as the input to the spectrum analyzer. Details of the feedback setup are described in Ref. [8].

Results.—The purpose of 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.

Shown in Fig. 1 are transverse beam profiles from the synchrotron light monitor measured for the case of a train with 160 bunches at both the nominal pressure and the elevated He pressure. At higher pressure, the vertical beam size dramatically increases while the horizontal beam size is unaffected. Underneath each image is a vertical profile of the image, fit to a Gaussian distribution with the rms value shown.

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 Fig. 2 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 ms)$^{-1}$, approximately equal to the feedback damping rate for a current of 0.5 mA/bunch.

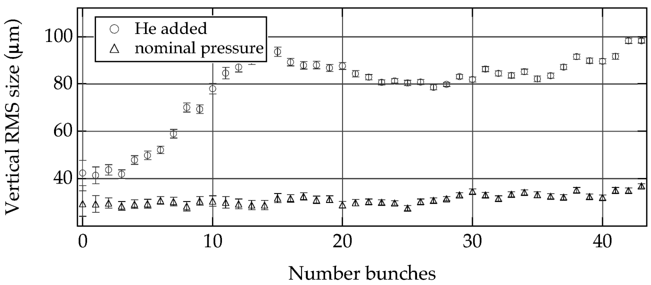

FIG. 2. rms vertical beam size vs the number of bunches for nominal and elevated pressure conditions.

The spectrum of coherent vertical oscillations for several different cases is shown in Fig. 3. 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 is shown in Fig. 4. However, we did not observe a coherent 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

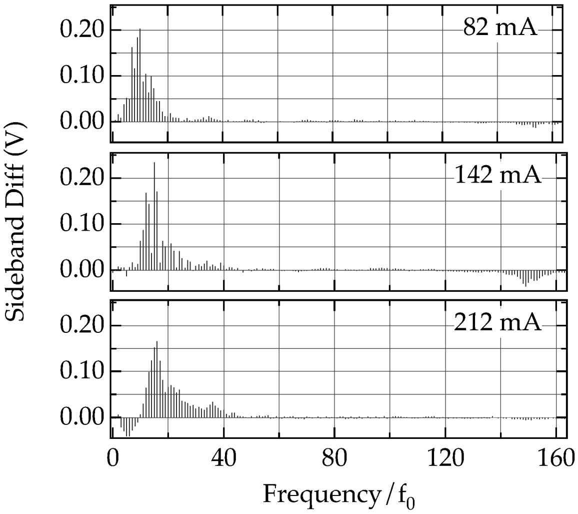

FIG. 3. Vertical betatron sidebands measured in the 240/328 fill pattern for three different currents.

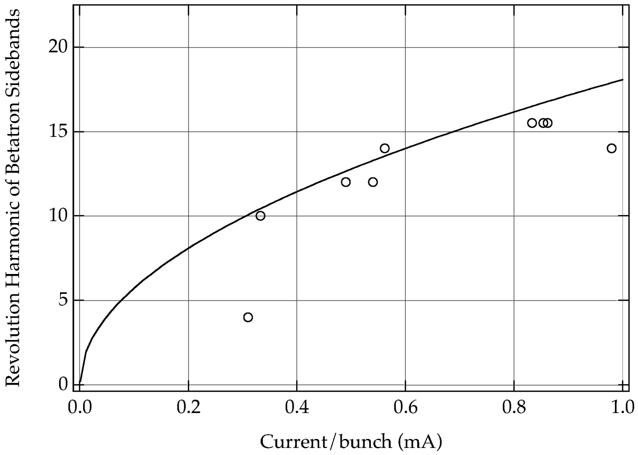

FIG. 4. Comparison between the measured and predicted frequency of coherent beam oscillations for the 240/320 fill pattern.

large growth rates the coherent vertical oscillations filament, leaving only an enhanced vertical size. We hope to resolve this question in subsequent experiments.

Although we did not have the instrumentation for measuring the vertical oscillations of each bunch in the train, 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 5 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. There is also a small modulation of the loss pattern with a period close to that of the expected ion frequency. However, more experiments are necessary to determine whether the modulations are relevant.

Discussion.—In experiments at the ALS, with an elevated vacuum pressure of about 80 nTorr and a large clearing gap to prevent multiturn ion trapping, we have routinely observed a significant increase of the vertical beam size by about a factor of 2–3 and have observed coherent vertical betatron oscillations characteristic of an ion induced instability. A comparison between the single bunch and multibunch behavior at the higher vacuum pressures confirms that the vertical blowup is not explained by beam-gas scattering. Furthermore, we have seen that the beam size or the coherent oscillations grow along the length of the bunch train since the trailing bunches are the first to be affected as a vertical beam aperture is moved close to the beam.

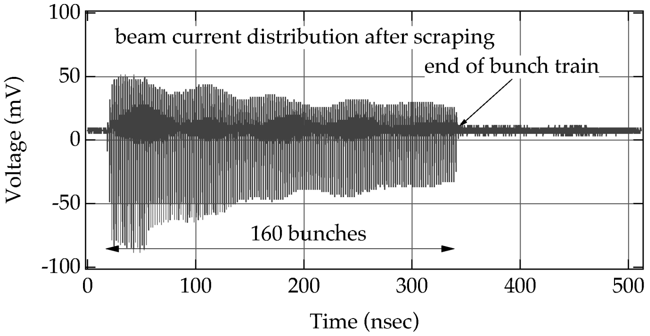

FIG. 5. Beam current along the bunch train for 160 bunches after moving a vertical aperture close to the beam. The nonuniform loss pattern shows the increasing vertical oscillations (or beam size) along the bunch train.

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.

All evidence accumulated is qualitatively consistent with the assumption that the observed instability is the fast beam-ion instability. Although a single estimate of the growth rate indicates rough agreement with theory, this quantity remains to be accurately measured. If this measurement is borne out in future experiments, this instability represents a significant limitation to many future storage rings.

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