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Ion Instability Experiments on the ALS *

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We report the results of experiments to study ion effects at the Advanced Light Source (ALS) in two pressure regimes. At the nominal pressure of 0.25 nTorr, we observe small vertical coherent beam oscillations for the nominal filling pattern (2.5% gap) that correlate with the expected ion frequency for nitrogen or carbon monoxide. The signals disappear for larger gaps in the filling pattern. We observe little increase in vertical beam size. We have also made experiments to look for unconventional ion effects at elevated gas pressures that may be important for future accelerators. In these experiments, we introduce a single gas species (helium) into the storage ring, raising the pressure approximately two orders of magnitude above the nominal pressure. For filling patterns with gaps in the bunch train large enough that conventional ion trapping should not play a role, we observe roughly a doubling of the vertical beam size along with coherent beam oscillations. We compare the results of the experiments with the predictions of one possible mechanism: the fast beam-ion instability.

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Abstract. We report the results of experiments to study ion effects at the Advanced Light Source (ALS) in two pressure regimes. At the nominal pressure of 0.25 nTorr, we observe small vertical coherent beam oscillations for the nominal filling pattern (2.5% gap) that correlate with the expected ion frequency for nitrogen or carbon monoxide. The signals disappear for larger gaps in the filling pattern. We observe little increase in vertical beam size. We have also made experiments to look for unconventional ion effects [1,2] at elevated gas pressures that may be important for future accelerators. In these experiments, we introduce a single gas species (helium) into the storage ring, raising the pressure approximately two orders of magnitude above the nominal pressure. For filling patterns with gaps in the bunch train large enough that conventional ion trapping should not play a role, we observe roughly a doubling of the vertical beam size along with coherent beam oscillations. We compare the results of the experiments with the predictions of one possible mechanism: the fast beam–ion instability.

I INTRODUCTION

Ions are recognized as a potential limitation in storage rings with negatively charged beams where ions generated by beam-gas collisions can become trapped in the negative potential of the beam. These trapped ions are observed to cause effects such as beam emittance increases, betatron tune shifts

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and a broadening of the tunes, collective instabilities, and lifetime reductions. These effects are of particular concern for the current and next generation of accelerators which require large beam currents with closely spaced bunches and ultralow beam emittances.

Conventional ion trapping refers to an ion cloud which develops as a train of pulses circulates in the accelerator. The ions are trapped in the potential well of the beam over many turns. The vacuum pressure can be reduced with higher quality vacuum. Alternatively, a gap between bunches or in the train may be included so that the ions become over-focused and thus diffuse and become too diluted to harm the electron beam upon subsequent passage [5,6].

A new regime of ion trapping has been theoretically predicted in future storage rings [1,2] which will be operated at higher current with very small transverse beam emittances and longer bunch trains. Here the ion clearing gap is no longer sufficient in suppressing transient beam-ion instabilities. In this case, ions generated and trapped within a *single* train may lead to a fast instability in which the electrons are resonantly driven by the ions [1–4]; this instability could arise in either a storage ring of a transport line.

This paper reports the status of experiments to study both types of ion effects. For conventional ion trapping we have studied the beam behavior as a function of gap in the filling pattern. For sufficiently small gaps we observe coherent vertical oscillations of the beam with a frequency signature indicating the presence of ions and possibly a small increase in the vertical beam size. To study ion effects with large gaps in the filling pattern, we intentionally increased the gas pressure by two orders of magnitude with helium gas. We have observed coherent vertical oscillations and increases in the vertical beam size by a factor of 2–3 while the expected rms emittance growth due to the beam-gas scattering is relatively small with 80 nTorr He; this will be discussed subsequently.

Section II provides a description of conventional ion trapping and the theory of one possible unconventional ion effect: the fast beam–ion instability. Section III describes the instrumentation used in the experiments. Section IV gives the results of measurements in both the nominal and high pressure regimes. Section V provides a discussion of the results, conclusions and our plans for future experiments.

II THEORY OF ION INSTABILITIES

A Ion Trapping

The effect of ion trapping has been observed and studied at many laboratories. Ionized gas molecules accumulate in the potential well of the beam and can lead to host of effects including: lifetime reductions, large tune spreads

Parameter	Description	Value
E	Beam energy	1.5 GeV
C	Circumference	196.8 m
f_{rf}	RF frequency	499.654 MHz
σ_ϵ	RMS $\delta E/E$	7.1e-4
h	Harmonic number	328
σ_x	av. hor. beam size	100 μm
σ_y	av. vert. beam size	17 μm
ϵ_x	norm. hor. emittance	1.2×10^{-5} m
ϵ_y	norm. vert. emittance	4×10^{-7} m
α	momentum compaction	1.594e-3
Q_s	Synchrotron tune	0.0075
σ_ℓ	RMS natural bunch length	4.5 mm
$Q_{x,y}$	Betatron tunes (x,y)	14.28, 8.18

TABLE 1. Nominal ALS parameters.

with a corresponding increase in the beam size, and collective instabilities in a storage ring.

There are several standard solutions to the problem of ion accumulation: clearing electrodes, a gap in the bunch fill pattern, and beam shaking. Beam shaking, which is typically used when clearing electrodes or a gap is ineffective, involves shaking the beam at the collective ion oscillation frequency to drive the ions to large amplitudes and out of the beam. A clearing gap can be used when the ions are strongly focused by the beam. In this case, one adds a gap in the bunch train so that the ions are over-focused in the gap and drift out to large amplitudes before the train returns. Characteristically, the required length of the gap is determined from the condition of linear stability where the beam is modeled as linear focusing elements:

$$L_{gap} > \frac{2\sigma_y(\sigma_x + \sigma_y)A}{r_p N_b} . \tag{1}$$

Here, A is the atomic number of the ions, N_b is the number of electrons/bunch, σ_x and σ_y the horizontal and vertical beam sizes, and r_p the classical proton radius. With He gas and 1 mA per bunch in the ALS, a gap of roughly seven RF buckets (4.2 m) should be sufficient to prevent ion trapping.

In practice, some of the "unstable" ions can still be trappped 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. One can estimate the density of the residual ions in the beam after the clearing gap:

$$\rho \approx \frac{\rho_0}{\sqrt{(1 + L_{gap}^2 \omega_x^2)(1 + L_{gap}^2 \omega_y^2)}} \tag{2}$$

where ρ_0 is the ion density at the end of the bunch train and $\omega_{x,y}$ are the ion oscillation frequencies:

$$\omega_{x,y} = \frac{2N_b r_p}{L_{sep} A \sigma_{x,y}(\sigma_x + \sigma_y)} \tag{3}$$

where L_{sep} the bunch spacing.

Again, with He gas and 1 mA per bunch in the ALS, an 84 bucket gap, ie. operating with 240 bunches filled out of 324 buckets, reduces the ion density to roughly 3% of the value at the tail of the bunch train. Furthermore, because the ions are "unstable", this value does not increase significantly over time. Thus, the coupling from the tail of the bunch train to the head is thought to be small.

B Fast ion instability [1–4]

The fast ion instability can be compared with beam break-up in a linac. In a transport line or a storage ring with a large clearing gap the ions are not trapped from turn-to-turn. 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 for the bunch train to pass and thus, at each azimuthal position around the ring, the ions oscillate transversely in the potential well of the beam.

The frequency of the collective ion motion is given by the overlap of the beam and ion distributions and, at small amplitudes, is approximately:

$$f_{ion} = \frac{c}{2\pi}\left[\frac{4N_b r_p}{3L_{sep}\sigma_y(\sigma_x + \sigma_y)A}\right]^{1/2} . \tag{4}$$

where the factor of 4/3 arises because the ion beam size is roughly $\sqrt{2}$ smaller than the electron beam size and all other terms have been previously defined.

The collective oscillations of the ions modulate 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 quasi-exponential growth of the 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:

$$y(s, z) \sim y_0 \exp(z\sqrt{s/l_c}) \sin(z\omega_i - s\omega_\beta) \tag{5}$$

where l_c is a characteristic growth distance, ω_i and ω_β are the coherent ion oscillation frequency and the betatron frequency in units of m^{-1}, and z is the distance along the bunch train while s is the azimuthal position; these are related by the observation time as $ct = z - s$. A more detailed derivation, including the ion decoherence, predicts a slightly slower growth rate with a pure exponential dependence on the azimuthal position s. Regardless, both theories predict that only the "slow" (phase velocity less than c) wave will be driven by the ions. This implies that the Fourier spectrum of the signal seen on a BPM will consist of many lower betatron sidebands peaking at the ion oscillation frequency.

Because the beam–ion force is very nonlinear, the oscillations saturate when they reach amplitudes comparable to the beam size. At this point, the instability growth slows and the amplitude of the transverse oscillations of individual bunches begins to filament due to the spread in betatron frequencies induced by the ions. 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.

III BEAM INSTRUMENTATION

A Synchrotron light monitor

Our principal diagnostic in the experiment is an image of the transverse profile of the beam at one location of the storage ring using light from synchrotron radiation [8]. The photon optics consist of grazing incidence mirrors with an optical magnification of unity. A high pass filter (carbon foil) eliminates light with $\lambda > 5$ nm. For longer wavelengths the resolution of the image is limited by diffraction from the small vertical beam emittance. Carbon foils of varying thickness are used to vary light attenuation. The soft x-rays are converted to visible light using a scintillator and focussed onto a CCD camera. Unfortunately the response time of the scintillator (300 nsec$\approx \frac{T_0}{2}$) does not allow measurement of the beam size at different points along the storage ring fill pattern. We plan to install a faster scintillator and use a gated CCD camera in future experiments. We have not yet determined if it is possible to use a streak camera at optical wavelengths to measure the vertical beam size along the bunch train.

B Transverse coupled–bunch feedback system

The ALS transverse coupled–bunch feedback (TFB) systems [11,12] are integral to our studies for two reasons. First, the beam in the ALS executes large amplitude coupled–bunch oscillations in both the horizontal and vertical directions for multibunch beam currents above $\sim$50 mA for a typical fill pattern with nearly all RF buckets full. Previous studies have correlated the beam oscillations with known RF cavity HOMs and the resistive wall impedance [10].

In the results presented in the next section, our hypothesis is that the coupled bunch oscillations are successfully damped by the feedback system while the ion effects are not damped during their initial stage of growth. For all data presented in the next section, vertical, horizontal, and longitudinal FB systems are operational. Second, our primary monitor of transverse oscillations is a signal from one of the TFB receivers.

The transverse moments of the bunch $I\Delta x, I\Delta y$ are detected at two points in the ring, with nominal betatron phase differences (modulo 2π) of approximately 65 and 245 degrees in the x, y directions. The TFB receivers are implemented as heterodyne detectors centered at 3 GHz ($6\times f_{rf}$) with a bandpass of $\pm$250 MHz. 3 GHz was chosen as the local oscillator frequency because it is near the frequency of maximum impedance of the button pickups. We use a monitor of the baseband signal from one of the receivers as a diagnostic of coherent centroid oscillations in the control room.

Two features of the TFB are particularly relevant to our studies. First, the sensitivity of the heterodyne receivers to vertical oscillations is less than a micron, significantly smaller than the average vertical beam sizes. Second, the damping rate of the TFB 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 time of the vertical FB system is about 0.3–0.4 msec at 1 mA/bunch current although this was not measured at the time of the experiments.

C Transverse Beam Spectrum

Another diagnostic in the experiment was the spectrum of transverse dipole beam oscillations. Following is a brief review the spectrum expected for a multibunch beam.

Consider a filling pattern of equally populated and equally spaced bunches. Assume the bunches can be treated as point charges and that there are no synchrotron oscillations of the beam. The normal modes of oscillations are described by the relative phase of betatron oscillation from bunch to bunch. Each normal mode appears as either a lower or upper sideband in a frequency range from 0 to $\frac{1}{2T_b}$, where T_b is the bunch spacing in time. The pattern of sidebands is reflected in the frequency range $\frac{1}{2T_b}$ to $\frac{1}{T_b}$. The sideband pattern subsequently repeats. The sideband pattern can be measured in any of the frequency ranges, 0 to $1/2T_b$, $1/2T_b$ to $1/T_b$, etc. Measurement of the beam spectrum can yield the relative betatron phase of the individual bunch oscillations. The fill patterns used in our experiments were not symmetric but rather a train of bunches with a gap. Although the normal mode structure is more complicated, each normal mode appears as a sideband of a rotation harmonic.

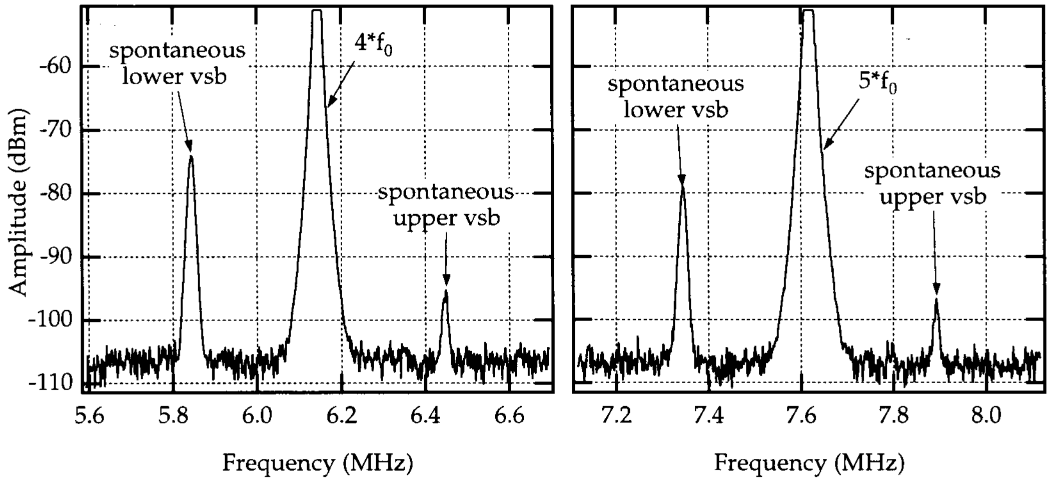

FIGURE 1. Raw spectrum of vertical pickup shown near the 4th and 5th revolution harmonics.

We observed the beam spectrum in the control room using an HP70000 spectrum analyzer. Computer control of the analyzer allowed automatic recording of the amplitudes of all 328 betatron sidebands from 0 to 250 MHz (0 to $\frac{1}{2T_b}$). For most of the data taken in the high pressure regime, we were able to expedite this lengthy process by taking advantage of the presence of a Tektronix 3052 spectrum analyzer, which uses 1024 parallel digital signal processors to quickly produce a Fourier transform of the input signal with a bandwidth of 10 MHz. We used this in combination with the HP70000 spectrum analyzer in the following way. The 321.4 MHz IF signal from the spectrum analyzer was downconverted to 7.5 MHz using a Tektronix 162 downconverter and input to the TEK3052. The rapid processing of the TEK3052 allowed us to reduce the time to scan all of the betatron sidebands from about 70 minutes to less than 10 minutes. The spectra taken from either method are essentially identical. Shown in Figure 1 is the raw spectrum from some of the experiments described in the next section. The figure shows the spontaneous vertical upper and lower sidebands near the 4th and 5th rotation harmonics. The term spontaneous refers to motion which is not externally excited.

D ALS Vacuum System

This section provides a brief description of the ALS vacuum system and the modifications made to the system for adding helium gas as discussed in Section IV. For UHV operation, the vacuum is pumped by a combination of passive titanium sublimation pumps (TSPs) which are distributed throughout the ring and 107 active noble diode ion (DI) pumps. The pressure is read using 12 ion gauges and currents in the ion pumps. The ion gauges are calibrated to read the equivalent pressure for diatomic nitrogen. For normal operation of the ring, the average pressure with beam is about 0.25 nTorr. For the experiment where helium was added to the vacuum, we installed a small gas inlet in the ring that could be used to bleed in gas to maintain a consistent high gas pressure.

To reach the high pressure it was necessary to turn off all of the ion pumps except for a pump on either side of the RF cavities, which are located adjacent to one another in one of the ring's twelve straight sections. The gas inlet ports are located on either side of these pumps in order to balance 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 as measured using ion gauges. 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. Following the completion of a high pressure experiment, the DI pumps were turned on and the vacuum recovered in 10–15 minutes. To date, we have not been able to measure the effect on the beam of other He pressures. We are currently exploring the feasibility of adding other gas species.

IV RESULTS

A Nominal Ring Pressure

Since commissioning of the storage ring in March 1993, no harmful ion effects such as sudden lifetime decrease or unexplained dramatic vertical blowup have been observed. However, during commissioning of the transverse coupled–bunch feedback systems in spring of 1995, we noticed small residual vertical betatron sidebands with a pattern suggestive of ion effects which we could not damp with feedback systems. The amplitudes of upper and lower sidebands at the first 20 revolution harmonics for three different currents are shown in Figure 2. Shown in Figure 3 are the differences between lower and upper sidebands. We originally believed these oscillations were driven by a cavity higher order mode. Further investigations noted the increase in the peak of the frequency of the signals with current. There were not any other significant residual sidebands over the 0–250 MHz span. The oscillations are on the order of a micron. We did not qualitatively observe any oscillations or increase in the average beam size on the transverse profile monitor.

Although the signals are not inconsistent with coupled–bunch motion driven by a cavity higher order mode that changes frequency with current because of cavity detuning, we became suspicious of an ion effect because of the dependence of the frequency shift with current and because all other beam signals present without feedback were damped to the noise floor of the spectrum analyzer. Consider the ion coherent oscillation frequency given by Eq. 4. Notable features are the increase in the ion frequency with the square root of the beam current, and decrease in the frequency with the vertical beam size.

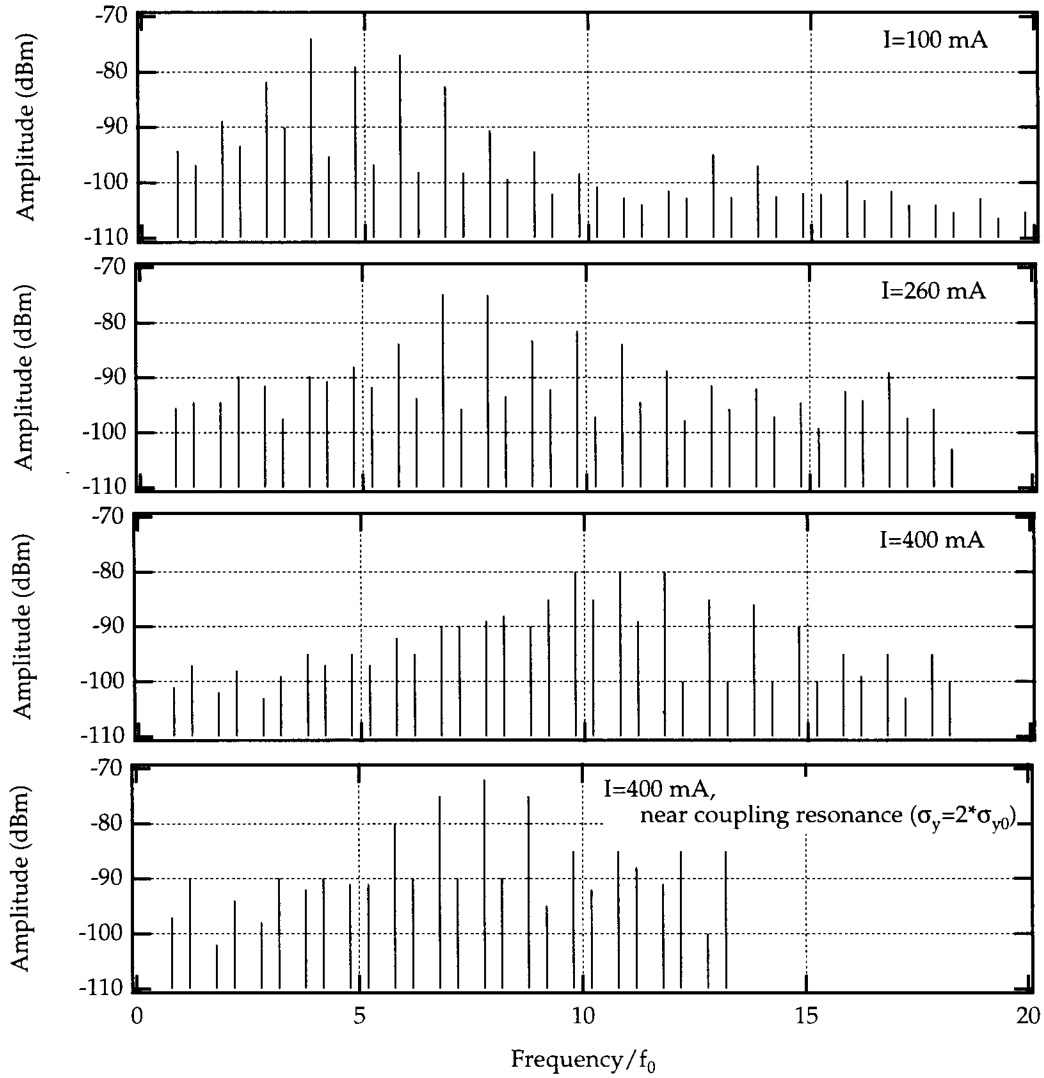

FIGURE 2. Amplitudes of residual vertical betatron sidebands measured in the 320/328 fill pattern at 3 total beam currents.

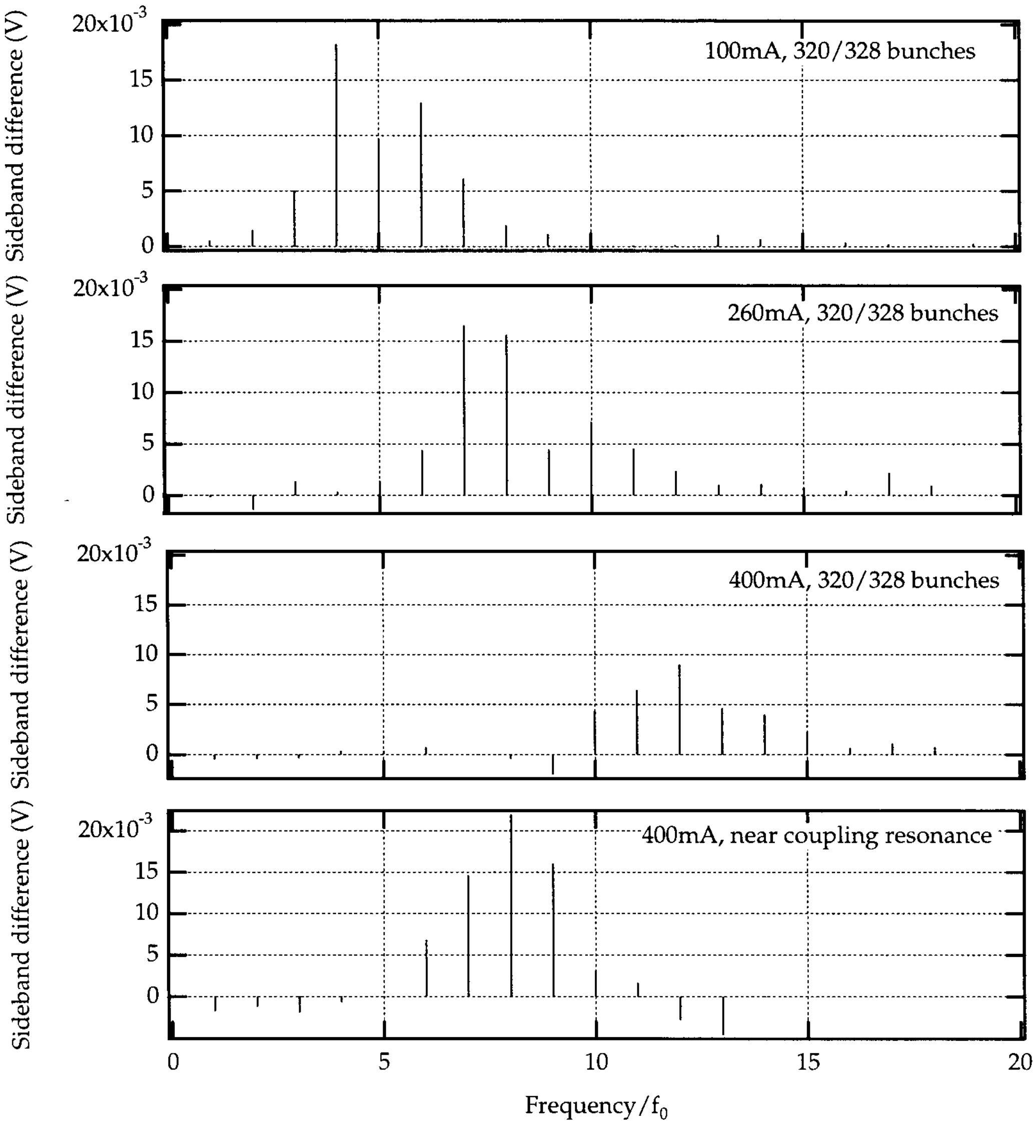

FIGURE 3. Difference between lower and upper residual vertical betatron sidebands measured in the 320/328 fill pattern at 3 total beam currents.

Using approximate average beam sizes and assuming that the ion species is CO (A =28), the calculated ion frequency at 400 mA is 17 in units of the revolution frequency. The peak frequency of the signals in Figures 2 and 3 increases approximately with the square root of the beam current. Furthermore, beam-ion interactions destabilize beam modes corresponding to lower sidebands. The absolute frequency of the peak is somewhat lower than expected but this could possibly be improved by using more accurate values for the vertical emittance or may be due to detuning of the ion oscillations at larger amplitudes.

The effect of a static increase in the vertical beam size is shown in the last sideband spectrum Figures 2 and 3. An increase of about a factor of 2 causes a corresponding decrease in the peak frequency of the betatron signals. This effect is not consistent with motion driven by an HOM and strongly suggests the presence of ions. The beam size was adjusted by running closer to the betatron coupling resonance.

For fill patterns with gaps of 1/4 and 1/2 of the ring, the residual signals disappeared. A quantitative measure of the vertical beam profile indicates a 2–3 μm decrease. However, we have not been able to conclusively link the change in vertical beam size to the presence of the coherent oscillations. One alternative explanation for the change in beam size is a slight decrease in the growth rates of cavity driven coupled bunch oscillations as the gap is increased.

Our working hypothesis is that the signals in the 320/328 fill pattern result from a relatively mild form of beam–ion instability, probably ion–trapping. We assume that at small amplitudes the instability has a growth rate exceeding the damping rate of the TFB system but a larger amplitude the instability either saturates or the growth rate decreases below the damping rate of the TFB. If the effect is ion trapping, it is interesting that it has such a small effect on emittance. We have not yet looked at the effect on beam lifetime, although this may be difficult in practice because the lifetime is dominated by the Touschek effect and strongly dependent on single bunch current. We are currently planning additional experiments to study this effect in more detail.

B High Pressure

Our results in the previous section indicate that whatever ion effects may be present disappear when the gap is at least 1/4 of the ring circumference. However, we were motivated by an interest in looking for unconventional ion effects, particularly the fast ion instability. As described in Section III, we installed a small gas inlet in the ring that could be used to bleed in gas to maintain a consistent high gas pressure. The physics motivation for using helium gas is that the vertical emittance growth from Coulomb scattering was only a 18–20% effect and that calculations indicated that an achievable level of helium pressure (<100 nTorr) would give a growth rate of the fast ion instability (FII) much faster than the damping rate of the TFB system. Our goal was to create a condition where the coupled bunch oscillations driven by ring impedance are stabilized by the TFB system but oscillations driven by the FII are unstable, allowing us to distiguish between the two effects.

The experimental procedure was to record the synchrotron light image and vertical beam spectrum for fill patterns of 240/328, 200/328, and 160/328 bunches (roughly 3/4, 5/8 and 1/2 of the ring) at the nominal pressure and again at the elevated pressure with helium. We also record the beam image with only a signal bunch filling pattern at both the nominal and elevated pressure to determine the effect of vertical beam size increase from gas scattering. Measurements of single bunch beam size increase with pressure are in agreement with calculations. To date we have taken three sequences of data.

Shown in Figure 4 are transverse beam profiles from the synchrotron light monitor measured for the case of 160/328 bunches at the nominal pressure and at elevated He pressure. The vertical beam size dramatically increases while the horizontal beam size is unaffected. Shown in Figure 5 are vertical profiles of the transverse beam image for the cases of 160/328 and 240/328 bunches for nominal and elevated pressures. Each profile is fit to a gaussian distribution with the RMS value shown. Both filling patterns show dramatic increase in the vertical beam size when He is added. The beam size also appears to further increase with increased total current.

The vertical beam spectrum for several different cases is shown in Figure 6. To simplify the data we've plotted the difference between the lower and upper sidebands. A positive value indicates a larger lower sideband. As described above, the coherent vertical sidebands are not present at the nominal pressure. As He is added, the sidebands appear at a frequency near that expected from simulations of the FII. As the beam current increases, the coherent signal also increases as expected.

However, we do not always observe a coherent vertical signal. Following the second experimental study it was discovered that an imbalance in the storage ring injection system was leading to a variation in the individual bunch currents by as much as a factor of 2. We do not know if this was the case during our first two measurements but we were able to avoid this problem during our third experiment. In the third experiment we observed vertical beam size increases similar to what we observed in the previous experiments. However, we only observed coherent oscillations for fill pattern of 240/328 bunches at 120 mA. We do not yet understand the reason for this. One possible explanation is for large growth rates, the coherent vertical oscillations filament with only a large vertical size as a result. We hope to resolve this in subsequent experiments.

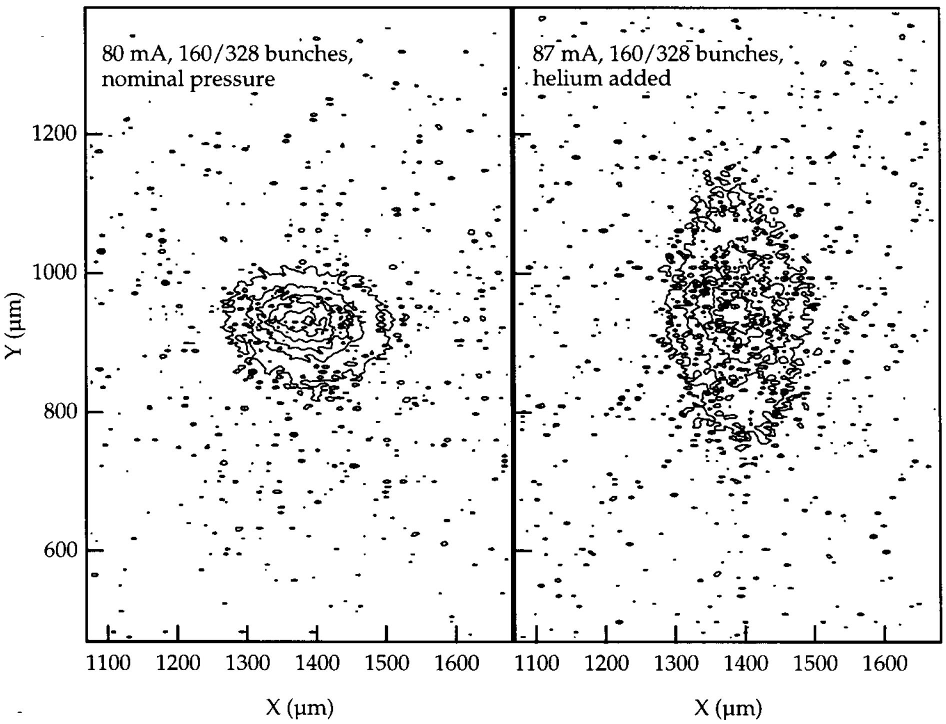

FIGURE 4. Transverse profile images (shown as contour plots) of the beam for nominal pressures and with helium added.

V DISCUSSION AND CONCLUSIONS

We have observed ion–induced coherent vertical betatron signals in the ALS when operating with a small gap of 8 buckets which disappear for larger gaps. We have also observed what are believed to be ion induced signals when operating with a large gap at higher vacuum pressures. In particular, with a gap that is between 10 to 20 times larger than that required to make the ions unstable in the linear approximation, we routinely observe a significant increase of the vertical beam size (about a factor of 2–3) and we sometimes observe coherent vertical betatron oscillations characteristic of an ion induced instability. A comparison between the single bunch and multi-bunch behaviour at the higher vacuum pressures confirms that the vertical blowup is explained by beam–gas scattering. Furthermore, we do not believe the effect is an incoherent blowup of the beam sizes due a structral resonance in betatron tune space because we do not observe a significant vertical tune shift. We also do not observe a dependence of effect on small variations about the nominal vertical tune.

Although we have not clearly demonstrated that this later effect is due to the predicted single pass ion instability, it would appear to an important effect that arises when normal ion trapping is clearly not expected. In the future, we plan further experiments to determine why the coherent signals

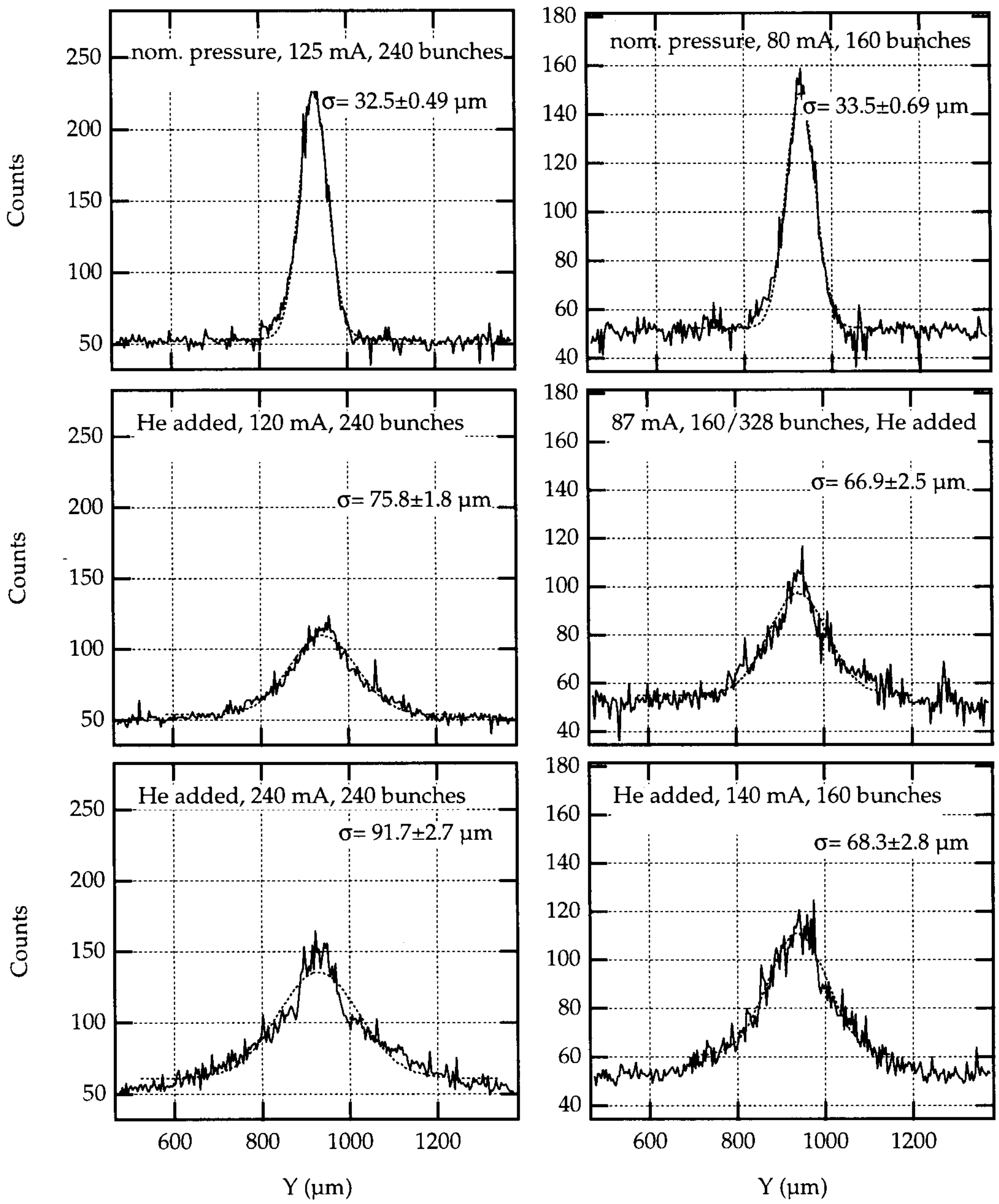

FIGURE 5. Vertical profile through the bunch center for nominal pressures and with helium added. The left column shows the case for 240/328 bunches and the right column is for 160/328 bunches. Each profile is fitted to a gaussian with the RMS shown.

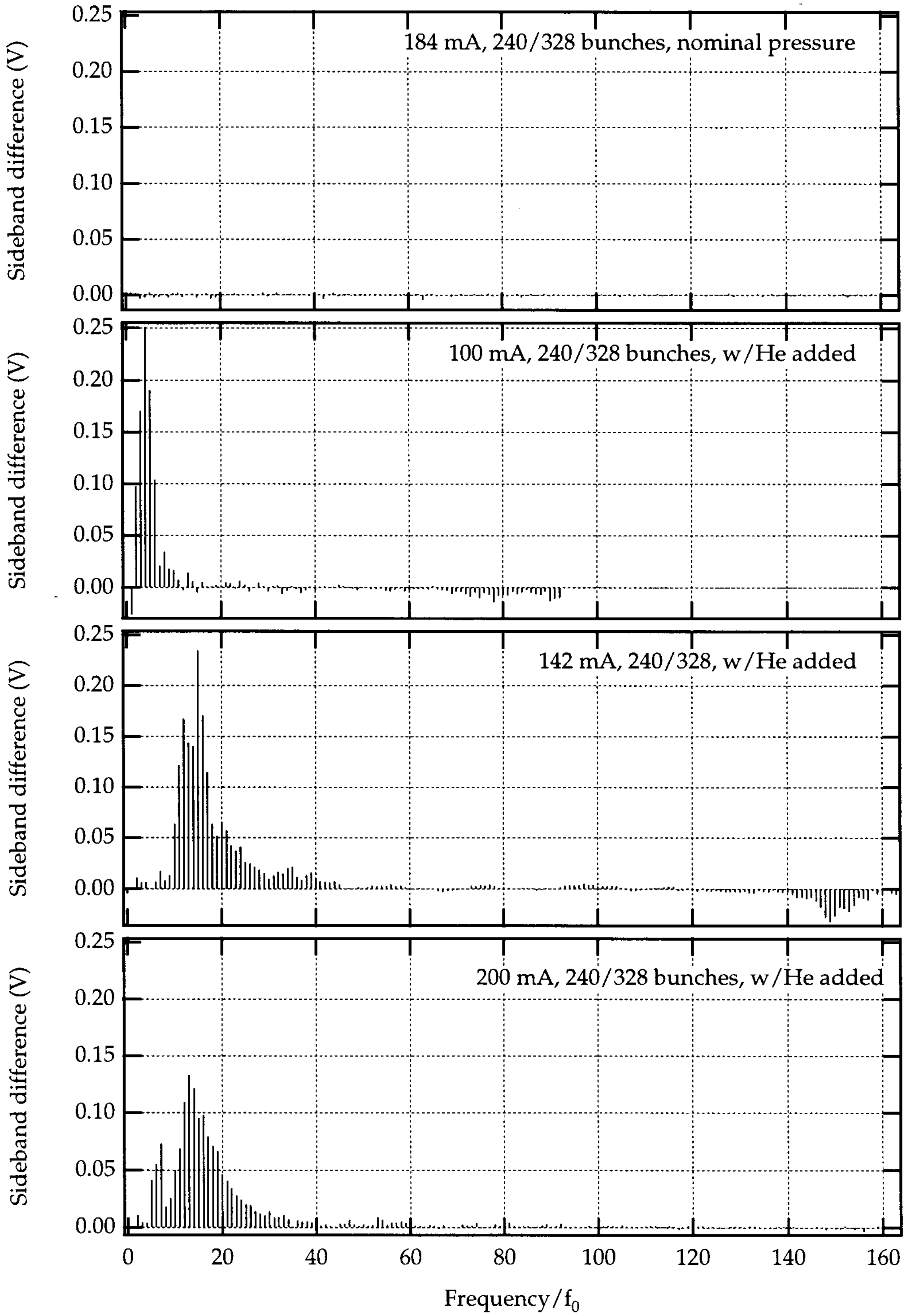

FIGURE 6. Difference between lower and upper residual vertical betatron sidebands measured in the 240/328 fill pattern at for several different conditions. A coherent signal appears when helium is added to the vacuum.

seem to disappear and to measure the variation of the beam positions and sizes along the bunch train to confirm whether the observed effect is a single pass phenomena.

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