

Observation of Vertical Betatron Sideband due to Electron Clouds in the KEKB Low Energy Ring

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The effects of electron clouds on positively charged beams have been an active area of research in recent years at particle accelerators around the world. Transverse beam-size blowup due to electron clouds has been observed in some machines and is considered to be a major limiting factor in the development of higher-current, higher-luminosity electron-positron colliders. The leading proposed mechanism for beam blowup is the excitation of a fast head-tail instability due to short-range wakes within the electron cloud. We present here observations of betatron oscillation sidebands in bunch-by-bunch spectra that may provide direct evidence of such head-tail motion in a positron beam.

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The development of clouds of electrons in positively charged beam storage rings has been observed at several machines, including the KEKB Low Energy Ring (LER), a 3.5 GeV positron storage ring which is part of the KEK B factory. Observations at the KEKB LER of betatron tune shifts along a bunch train via gated tune meter [1], and of transverse bunch size along the train via a high-speed gated camera [2] and a streak camera [3], show a characteristic increase of transverse tune shifts and beam size starting near the head of the train, reaching saturation at some point along the train. Simulations of electron-cloud density due to photoelectrons being drawn towards the positron beam have shown a similar buildup of cloud density along the train, reaching saturation at some point [4,5]. Electrons from the cloud have also been measured directly via an electrode [6]. Solenoids have been wound around approximately 95% of the drift space in the LER, with a maximum field at the center of the beam pipe of 45 G [7]. The beam-size blowup has been observed to occur above a threshold average bunch current of ~ 0.35 mA/bunch at 4-rf bucket spacing between bunches with the solenoids off; this threshold is raised when the solenoids are powered on [8]. The beam blowup has been found to reduce the specific luminosity of the affected bunches [8].

One proposed mechanism for the beam blowup due to the presence of electron clouds is a strong head-tail instability caused by wake fields created by the passage of the bunch particles through the cloud [9]. Attempts have been made to observe this head-tail motion directly via a streak camera [3] but have been unsuccessful, possibly due to a lack of sufficient light intensity. A vertical sideband peak has been reported for a proton beam at the CERN Super Proton Synchrotron which could be an indication of head-tail motion [10], though no clear signature has yet been reported at a positron machine. We report here on observations of a sideband peak, above the betatron tune, which may provide direct evidence of such a coupled-mode spectral peak in a positron beam.

The sideband peak first appears near the bunch-current threshold of beam blowup—the sidebands cannot be seen when the average bunch current is below the beam blowup threshold and can be seen when the average bunch current is over the threshold. In addition, the presence of the sideband is affected by the electron-cloud-suppression solenoids; for example, it has been observed to appear in bunches at 1 mA per bunch and a four-bucket spacing only when the solenoids are turned off and does not appear when the solenoids are turned on. These behaviors cannot be explained by ordinary head-tail mechanisms; we conclude that the sidebands, as the beam blowup, are caused by the presence of electron clouds.

Observations were made using signals taken from a pair of beam position monitor (BPM) electrodes, which are mounted on the beam pipe, and measure 6 mm in diameter. The difference signal from two electrodes on opposite sides of the beam pipe is detected at 2.032 GHz ($=4 \times f_{rf}$) and recorded by the bunch oscillation recorder (BOR), which is a diagnostic tool in the bunch-by-bunch feedback system [11,12]. The BOR itself consists of an eight-bit digitizer front end, with a 20-MByte memory, which is capable of storing one beam centroid position measurement per bunch for all 5120-rf buckets in the ring over 4096 turns.

Data were taken at the LER on 24 June 2004, in single-beam mode (no colliding bunches in the High Energy Ring) and with the majority of the solenoids turned off. The fill pattern consisted of four trains of bunches, spaced evenly around the ring. Each train consisted of 100 bunches, spaced 4-rf buckets (≈ 8 ns) apart. In Fig. 1, the spectrum for each bunch is plotted, with the fractional tune on the horizontal axis and the bunch number on the vertical axis. The betatron tune (made visible by lowering the gain of the bunch-by-bunch feedback system) is seen as the left curved line. The betatron tune is seen to shift successively higher as one moves from the head of the train towards the tail, saturating at around the fortieth

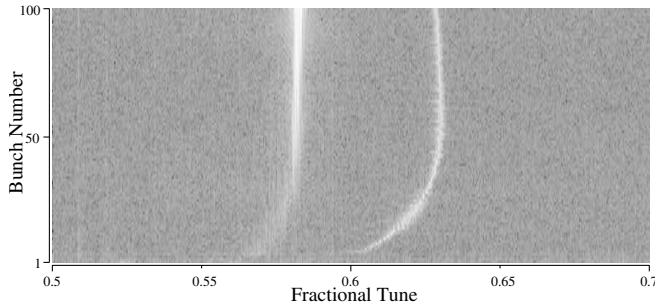


FIG. 1. Two-dimensional plot of vertical bunch spectrum versus bunch number. The horizontal axis is the fractional tune, from 0.5 on the left edge to 0.7 on the right edge. The vertical axis is the bunch number in the train, from 1 on the bottom edge to 100 on the top edge. The bunches in the train are spaced 4-rf buckets (about 8 ns) apart. The bright, curved line on the left is the vertical betatron tune, made visible by reducing the bunch-by-bunch feedback gain by 6 dB from the level usually used for stable operation. The line on the right is the sideband.

bunch. To the right of the ν_y peak is the sideband peak, which likewise shifts along the train, until saturating a little after the ν_y peak. In experiments that have been performed over the past year, it has been observed that changing the vertical betatron tune causes the sideband peak to shift by an equal amount, and in the same direction as that of the betatron tune. Changing the horizontal tune has no effect on this sideband.

Figure 2(a) shows the observed bunch spectra with the feedback gain set at the nominal value for physics running, -9.45 dB. In this plot, the Fourier power spectrum of each bunch in the ring is calculated individually; then the power spectra of all bunches are averaged together. The horizontal scale is in units of fractional tune, and the vertical scale is in units of μm^2 . The vertical betatron tune can be seen as a broad, low peak at a fractional tune of approximately 0.58–0.59. To the right of it can be seen the sideband peak

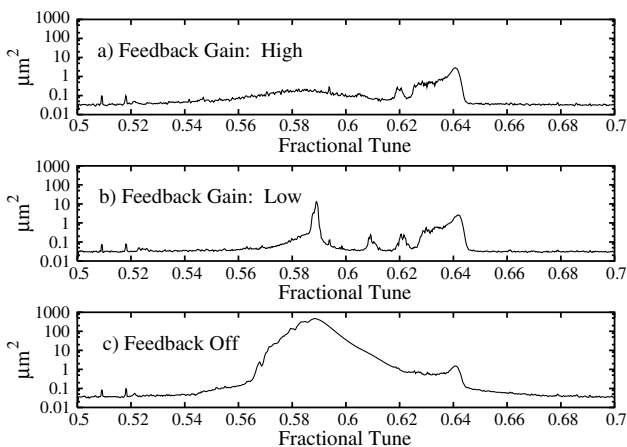


FIG. 2. Averaged spectra of all bunches with the feedback gain (a) high, (b) low, and (c) set to zero. The vertical betatron peak is visible at 0.588, and the sideband peak can be seen around 0.64.

at approximately 0.64. The broad, pedestal-like tail to the left of the peak is due to the projection of a succession of narrow peaks, one for each bunch, which have lower tunes near the head of the train.

The vertical gain of the feedback system was lowered by 6 dB, to the point where the beam started to become slightly unstable, as seen in oscilloscope traces and as reflected in a reduced lifetime for the beam. Under these conditions, the vertical betatron peak becomes enhanced, as shown in Fig. 2(b); however, the sideband peak amplitude is virtually unchanged.

Finally, the feedback was turned off entirely. The BOR was set to record the 4096 turns immediately following the feedback being turned off. As seen in Fig. 2(c), the betatron peak grows enormously, but the sideband peak height is again essentially unchanged. This indicates that this peak does not respond to dipole kicks from the feedback system. The estimated amplitude of the motion at this peak is approximately $1.6 \mu\text{m}$, or half of 1% of the vertical beam size of $320 \mu\text{m}$ at the pickup location.

Experiments were done with changing the synchrotron tune. In one set of measurements, the rf voltage was reduced, which lowered the synchrotron tune by 0.0012. The position of the sideband relative to the vertical betatron tune for both values of ν_s are shown in Fig. 3(a); the sidebands are visible starting from the fifth bunch in the train. The difference between the two curves is shown in Fig. 3(b). The average of the peak separation over all bunches is not statistically different from zero.

Observations have also been made using the same BOR memory recorder, but using a fast photomultiplier tube (PMT) as the input device instead of a BPM electrode. A Hamamatsu H6780 PMT was set up to record the light intensity from a focused image of the beam using synchrotron radiation. The image was partially obscured in the

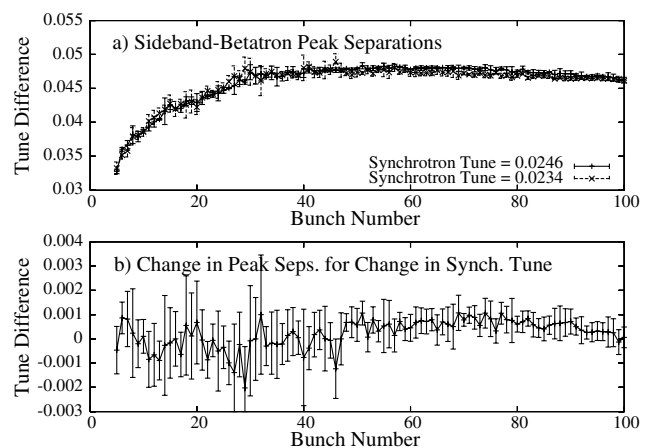


FIG. 3. Effect of changing synchrotron tune on the separation between sideband peak and betatron peak. In (a), the sideband-betatron peak separation is plotted along the bunch train for $\nu_s = 0.0246$ (solid lines) and $\nu_s = 0.0234$ (dashed lines). In (b), the difference between the two curves is plotted. Statistical $1\text{-}\sigma$ error bars are shown.

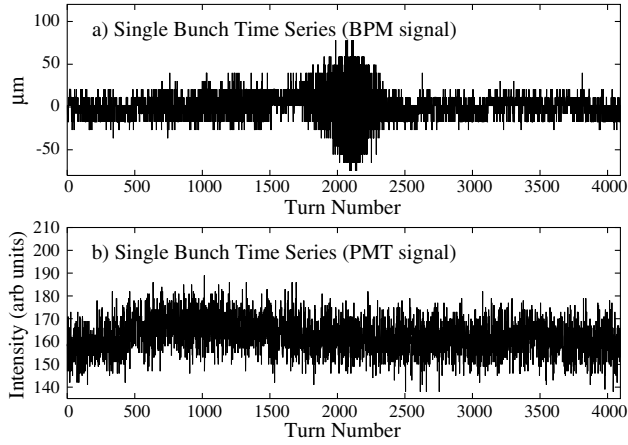


FIG. 4. Example time series of single bunches taken via (a) BPM and (b) PMT. Different bunches are shown for each detector; the data were taken within 1 min of each other. A burstlike behavior is visible in the BPM signal. A fast ramp-up behavior with a similar rise time as the BPM burst is seen in the PMT signal, followed by a gradual ramp-down.

vertical direction, leaving only the upper edge of the image visible. The spectra obtained via PMT were identical to those obtained from the BPM electrode, though with a lower signal-to-noise ratio. The amplitude of the peak seen by PMT can be only crudely estimated but agrees roughly with that seen by the BPM electrode. One feature that the PMT can detect that the BPM cannot is changes in the beam size.

The time-series data of the BPM, shown in Fig. 4(a), reveal a burstlike time structure to the sideband oscillations. The sideband peak is present as a low level oscillation that suddenly grows and damps in a burst lasting ~ 500 turns (5 ms). A breakdown of the data into 512-turn slices shows that the sideband peak is seen most strongly during the burst and disappears entirely just after the burst.

In the PMT data, as seen in Fig. 4(b), a similar 500-turn-duration phenomenon is observable wherein the light level (beam size) increases over the course of 500 turns, then slowly damps afterwards, over the course of ~ 1500 turns. A slice-by-slice breakdown of such events reveals that the sideband peak is a maximum during the ramp-up and disappears momentarily just after the burst.

The two sets of observations suggest that in the blown-up state, a series of bursts and quiescent periods alternate. During the bursts of violent dipole motion, the beam size increases by a further $\approx 5\%$ from its already blown-up state. After it blows up, the dipole motion is temporarily absent, as the emittance of the beam damps down.

One possible interpretation for this sideband is that it is a signature of mode coupling due to the head-tail instability predicted by Ohmi, Zimmermann, and Perevedentsev [13]. A notable feature of the sideband is that it occurs on the upper side of the betatron peak, which suggests that the effective wake function in the region of the tail of the bunch is a focusing wake. A possible mechanism for

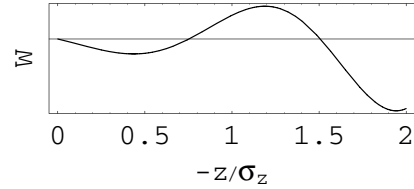


FIG. 5. Model focusing wake. The horizontal axis is the longitudinal coordinate in units of the bunch length.

producing such a wake is a pinching effect on the electron cloud. Simulations of wakes that change from defocusing to focusing with distance along the bunch have been found in simulations using the KEKB parameters [13,14].

When the synchrotron tune is changed, the average separation between the sideband peak and the betatron peak does not change significantly. In the case of strong head-tail instability, the coupled-mode frequency does not necessarily depend strongly on ν_s . As an illustration, mode spectra were generated using a toy model with an airbag charge distribution and a simple effective wake, shown in Fig. 5, which uses a resonatorlike wake W , increasing along ($-z$) to represent the enhancement of the wake near the tail of the bunch due to pinching of the electron cloud:

$$W(z) = c \frac{R}{Q} e^{-\alpha z/c} \sin \omega_R \frac{z}{c}, \quad (1)$$

where $\alpha = \omega_R/4$, and $\omega_R = 2\pi \times 40$ GHz. (The oscillation frequency of cloud electrons as calculated from the LER beam size and positron charge density is $\sim 2\pi \times 43$ GHz.)

Plots of mode spectra as a function of effective R/Q are shown in Fig. 6 for synchrotron tunes of 0.022 and 0.024. As can be seen, the tune of the coupled mode in the region far above the coupling threshold does not change significantly with the synchrotron tune. However, the coupling point between the $l = +1$ mode ($\nu_y + \nu_s$) and the $l = +2$ mode ($\nu_y + 2\nu_s$) shifts to the right.

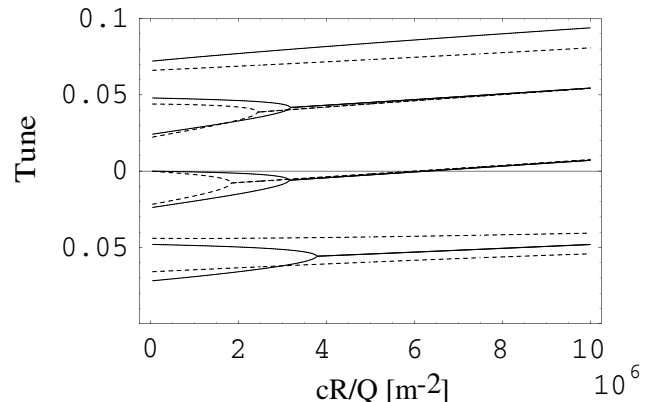


FIG. 6. Example mode spectrum for model focusing wake at $\nu_s = 0.022$ (dashed lines) and $\nu_s = 0.024$ (solid lines).

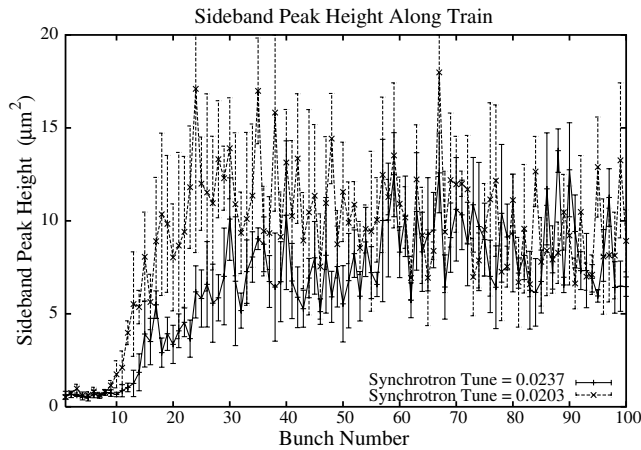


FIG. 7. Peak heights of maximum-amplitude frequency bins in the sideband region of a bunch spectrum, plotted for the first 100 bunches in the train, for two values of ν_s . Error bars are $1-\sigma$ statistical error bars.

cloud density increases along the leading bunches of the train, this change in the threshold would lead one to expect the position of the first bunch exhibiting the sideband to shift as the synchrotron tune is changed. To investigate this behavior near the threshold, data originally taken on 23 December 2003 at two different values of the synchrotron tune were reexamined. The LER was in single-beam mode, with all solenoids off. The bunches were stored at a four-bucket spacing, at a bunch current of 0.52 mA/bunch. Because of the lower bunch current, the growth of the sideband peak is more gradual in this data set than it is in the July 2004 data set. (Due to a high feedback gain, the betatron peak is not pronounced enough to measure.) One set, of four measurements, was taken at an rf voltage of 8 MV, and the other set, of three measurements, was taken at 6 MV. The synchrotron tunes of the two sets, as measured from the synchrotron peak visible in the spectra, were 0.0237 and 0.0203, respectively. The maximum-height frequency bin in the region of the sideband was found for each bunch in the train, and the peak heights of those maximum bins were averaged together within each set. The average peak heights, and $1-\sigma$ statistical error bars at each synchrotron tune are plotted as a function of the bunch number along the train in Fig. 7. As can be seen, the development of the sideband peak height occurs earlier in the train at the lower synchrotron tune, in agreement with expectation.

Simulations and linear theory also indicate that for a given cloud density, larger beam sizes should be more stable due to a weaker beam-cloud interaction [13]. The burstlike activity of the blown-up beam may be the result of the beam size varying around some threshold value, as the bunch alternates between states of emittance growth due to the instability occurring when the beam size is below the threshold, and the beam size damping down once over the threshold.

A betatron sideband peak has been found in the vertical tune spectrum of positron bunches in the presence of beam-size blowup due to electron clouds. The sideband peak is on the upper side of the betatron peak in terms of fractional tune, first appears early in the bunch train, and the separation between this peak and the betatron tune peak increases going along the train, until it saturates at a certain point. The best explanation for it is that it is a signature of the head-tail instability hypothesized to explain transverse beam blowup due to electron clouds. The presence of this sideband peak also provides a sensitive diagnostic for the presence of electron clouds.

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