FURTHER STUDIES ON BETATRON SIDEBANDS DUE TO ELECTRON CLOUDS

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Abstract

We have observed vertical betatron sidebands in the transverse beam spectra of positron bunches at the KEKB LER which are associated with the presence of electron clouds in single-beam studies[1], and which are also associated with a loss of luminosity when the KEKB beams are in collision[2]. The sidebands appear to be signals of a fast head-tail instability due to short-range wakes within the electron cloud, providing a diagnostic for exploring the mechanism for transverse beam blow-up due to electron clouds. We report here on further studies on the behavior of the sidebands under varying beam conditions, including varying chromaticity, emittance and synchrotron tune. These results strengthen the interpretation of the spectra as being due to head-tail oscillations. The sideband is also found to disappear in the presence of forced excitation.

INTRODUCTION

We have previously reported observations of bunch-by-bunch beam position spectra taken at the KEKB LER, which show evidence of a betatron sideband peak when transverse beam blow-up due to electron clouds is occurring[1]. This sideband appears above the betatron tune in terms of fractional tune. A simple analytic focusing wake model reproduces some of the basic features of the peak. Recently, numerical simulations of beam-cloud interactions have succeeded in reproducing the spectrum[3].

Some predicted features were not measurable before, however, so further measurements have been made to verify that the behavior of the spectral peak conforms to expectations for a cloud-induced head-tail instability. In particular, the onset threshold should change with chromaticity, and the separation between the sideband peak and the betatron peak might be expected to depend on the synchrotron tune. In addition, some exploratory measurements were made on the effect of initial beam size on the blow-up and sideband appearance thresholds with respect to beam current, and on the effect of intentionally shaking the beam.

EXPERIMENTAL OBSERVATIONS

Beam signals from BPMs are digitized in the Bunch Oscillation Recorder[5], which records 4096 turns worth of data for each bunch. From these data, individual Fourier power spectra are computed for each bunch.

Effect of Changing Chromaticity

Head-tail theory predicts that the electron-cloud density threshold for the onset of the instability should go up if the vertical chromaticity, ξ_y, is increased. Measurements were conducted to investigate the effect of changing the chromaticity on the sideband-appearance threshold.

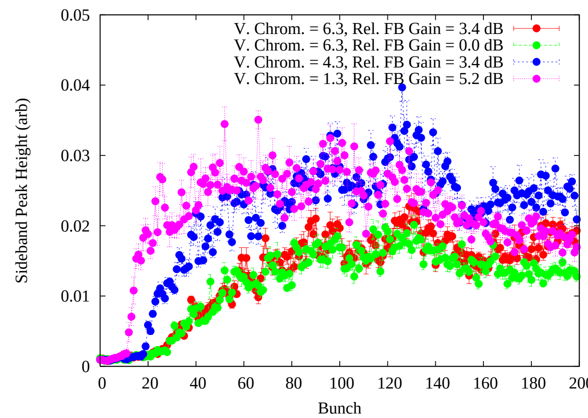

Figure 1: Effect of changing vertical chromaticity on sideband height along bunch train.

Data were taken with the LER in single-beam mode, with four trains of 200 bunches each, and a 4-bucket ($\sim$ 8 ns) spacing between bunches. The beam current was topped up to 500 mA before each measurement, for a bunch current of 0.624 mA/bunch. The electron-cloud suppression solenoids[4] were turned off, and vertical beam blow-up (increase in σ_y from $1-2$ μm to $3-4$ μm, as expressed at the interaction point in the physics detector) was present. Figure 1 shows the spectral power height of the sideband as a function of bunch position along train, for $\xi_y = 1.3, 4.3$, and 6.3. In order to be able to see the betatron tune line as well, the gain of the vertical bunch-by-bunch feedback system[5] was changed at each chromaticity. Previous observations have shown no change in the sideband height when the feedback gain is changed[1], but to verify that the gain would have no effect, data were taken at two different feedback gains at the highest chromaticity.

As seen in the figure, the lower the chromaticity is, the earlier in the train the sideband appears. (No change is seen for two different feedback gains at the $\xi_y = 6.3$, as expected.) Raising ξ_y from 1.3 to 4.3 pushes the onset of the instability back ~ 10 bunches along the train, as does further increasing ξ_y from 4.3 to 6.3. From simulations of electron cloud build-up[7], these would correspond do changes in the electron cloud density of $\sim 20-40\%$.

An estimate of the dependence of the threshold cloud density on chromaticity is given by[8]:

$$\rho_{e,th} = \frac{2\gamma\nu_s(\omega_e + \omega_0\xi_y/\alpha)\sigma_z/c}{\sqrt{3}KQr_e\beta L}, \qquad (1)$$

where γ is the relativistic factor, ν_s is the synchrotron tune, ω_e is the vertical oscillation frequency of the cloud electrons, ω_0 is the revolution frequency, α is the momentum compaction factor, σ_z is the longitudinal beam size, c is the speed of light, K is an enhancement factor due to the cloud size, Q is the quality factor of the effective wake due to the cloud, β is the average betatron function, and L is the circumference of the accelerator. For KEKB, where $\omega_e = 2\pi\times 43$ GHz, $\omega_0 = 2\pi\times 10^5$ Hz, and $\alpha = 3.3\times 10^{-4}$, a change of one unit in ξ_y would correspond to a change of $\sim 1\%$ in threshold electron cloud density. This change is one order of magnitude smaller than the observed value.

In numerical simulations[6], changing ξ_y from 0 to 12 raises the threshold by a factor of 2, from 5×10^{11} electrons$/m^3$ to 1×10^{12} electrons$/m^3$. Scaling from this, each change in ξ_y used in the machine study would be expected to change the threshold by $\sim 20\%$, which is in good agreement with the experimental results. Equation 1 is based on a coasting beam, and the bunch length is likely too short compared to the wake frequency for this equation to give a good estimate for the chromaticity dependence.

Effect of Changing Initial Emittance (Beam Size)

To investigate the beam-current threshold dependence on initial beam size (emittance), data were taken at a range of beam currents with the LER in single beam mode, 4 trains of 200 bunches each, 4 buckets per bunch, and cloud-suppression solenoids off. The vertical chromaticity ξ_y was 3.7. At a low current (200 mA) below the blow-up threshold, the vertical emittance of the beam was adjusted via dispersion bumps that are used for luminosity tuning. The beam size was set to 1, 2.3, and 3.2 μm (as expressed at the interaction point) in successive runs, and at each initial beam size the beam current was then ramped up to 600 mA while recording beam sizes and spectra.

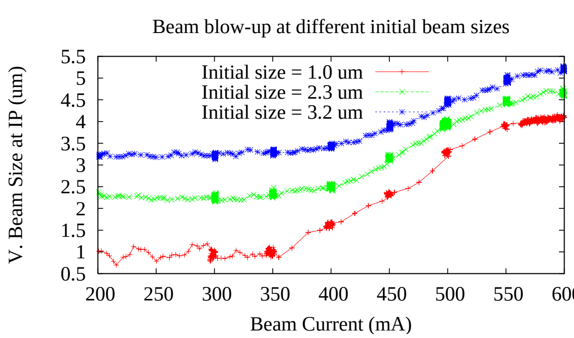

Figure 2: Beam blow-up as a function of beam current for initial beam sizes of 1, 2.3 and 3.2 μm.

The beam sizes as functions of beam current are shown in Figure 2. As can be seen, the larger the initial beam size, the larger the final, blown-up beam size was, however the beam current threshold was $\sim 350 - 400$ mA for the onset of the blow-up at all beam sizes, with little if any change. Figure 5 shows the integrated spectral power over the region of the spectrum where the sidebands appear. The sideband appearance threshold is ~ 400 mA for all initial beam sizes, consistent with the beam size data.

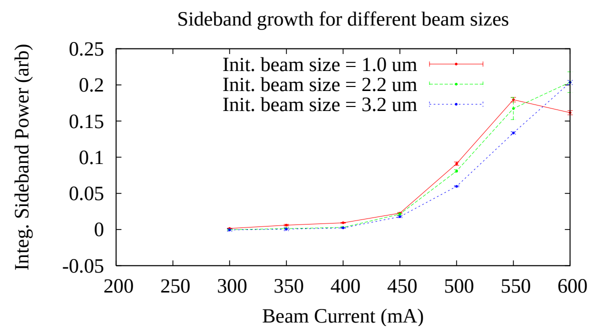

Figure 3: Effect of changing initial beam size on integrated sideband peak power along train.

This lack of threshold dependence on initial beam size can be explained by examining the beam size dependence in Equation 1, which comes in from ω_e:

$$\omega_e = \sqrt{\frac{\lambda_+ r_e c^2}{\sigma_y(\sigma_x + \sigma_y)}}, \qquad (2)$$

where λ_+ is the beam line density in the bunch, r_e is the classical electron radius, and σ_x and σ_y are the horizontal and vertical beam sizes, respectively. As discussed in Reference [8], Q is a measure of the range of the effective wake due to the electron cloud, but since it can only act on the bunch within the length of the bunch, the effective Q is the lesser of either the natural Q or $\omega_e\sigma_z/c$. For KEKB, with a bunch length of ~ 5.5 mm, $\omega_e\sigma_z/c \approx 5$, which is at the lower end of a numerical estimate for Q of $5 - 10$ for a coasting beam[9]. Substituting $\omega_e\sigma_z/c$ for Q in Equation 1, and noting that $\omega_e \gg \omega_0\xi_y/\alpha$ for low values of ξ_y, the head-tail instability threshold is seen to be almost insensitive to the initial beam size σ_y. This agrees with the data; finer-grained data at higher chromaticity may show a measurable change in threshold.

Changing Synchrotron Tune (RF Voltage)

In initial observations[1], the separation of the sideband peak and the betatron peak did not change by a statistically significant amount when the value of the synchrotron tune ν_s was changed from 0.0246 to 0.0234 by lowering the total RF cavity voltage V_c.

New data were taken at a larger $\Delta\nu_s$ of ~ 0.0032, and with better statistics. The values of the sideband-betatron peak separations along the train are shown in Figure 4a, and the change in peak separations is plotted in Figure 4b.

The separation is found to be close to $\Delta\nu_s$ towards the head of the train, and it decreases going towards the back of the train, where the cloud density is higher. The mode spectrum for an airbag model with a resonator-like focusing wake which was presented in Reference [1] also showed a mode separation which starts out near $\Delta\nu_s$ at the instability threshold value of cloud density, and which decreases as the cloud density increases. Thus with better statistics and a larger $\Delta\nu_s$, the sideband-betatron peak separation does change, and in a manner consistent with the model.

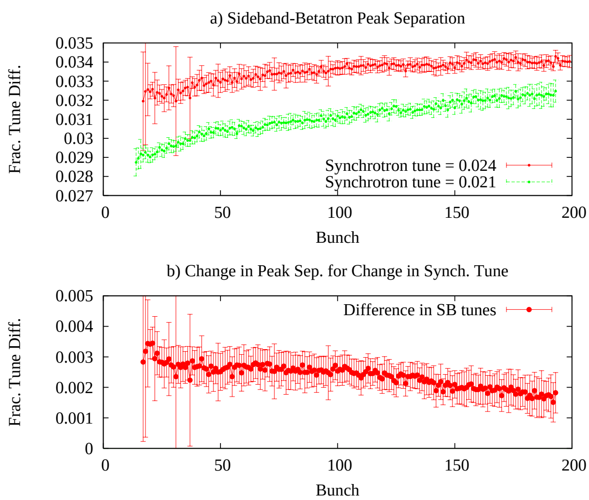

Figure 4: Effect of changing synchrotron tune (RF voltage) on sideband-betatron peak separation along train.

Effect of Forced Excitation

Finally, an exploratory experiment was performed on a non-colliding bunch during physics operation, with the cloud-suppression solenoids on. A test bunch was inserted between two bunches that are spaced 4 buckets apart, so that the new bunch is only two buckets behind the bunch in front of it. Enough electron cloud is present at this spacing for the test bunch to show sidebands even with the solenoids on. Next, the test bunch was excited near the vertical tune, with a CW signal, gated so as not to directly excite the other bunches in the ring. The bunch-by-bunch feedback was turned off for this bunch by gating. As shown in Figure 5, as the excitation amplitude increased, in addition to the betatron peak amplitude increasing, the sideband amplitude decreased, dropping below detectable levels at the highest excitation amplitude, indicating that the development of the head-tail instability has been blocked in that bunch. Further investigations are needed to investigate the mechanism and potential utility of this intriguing phenomenon.

SUMMARY

Investigations into the dependence of blow-up threshold on chromaticity and beam size show results which confirm and cast further light on the mechanism of electron-cloud induced head-tail instability. A dependence on the synchrotron tune of the sideband-betatron peak separation was demonstrated which agreed with model predictions, and a means of reducing the sideband peak by forced excitation was discovered.

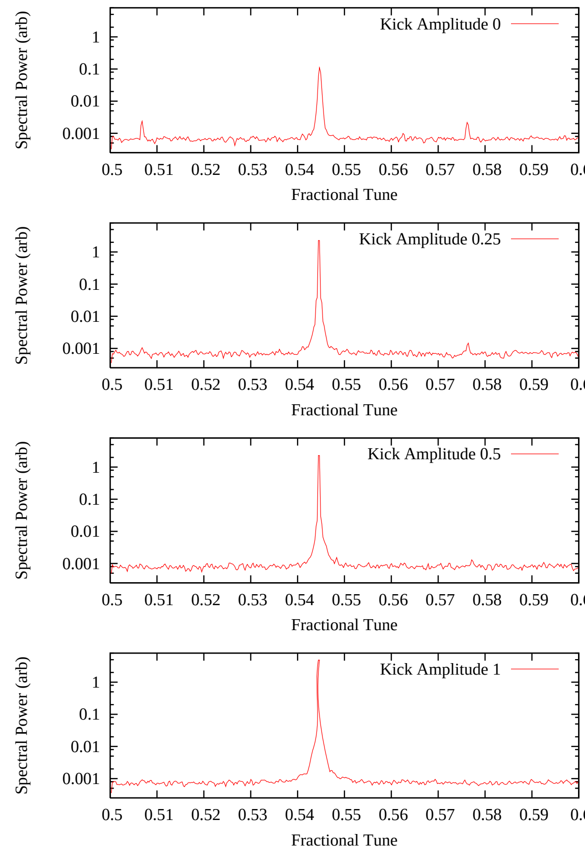

Figure 5: Effect of applying a continuous excitation at the betatron frequency on non-colliding bunch spectrum. Kick amplitude increases going from top to bottom. The vertical betatron peak is seen near 0.544 and the sideband peak near 0.577. The peak near 0.507 in the top plot is the horizontal betatron tune.

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