OBSERVATION OF ELECTRON CLOUD INSTABILITY EFFECTS AT CESRTA USING CODED APERTURE X-RAY MONITOR *

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Abstract

CesrTA is a low-emittance and ILC damping ring study machine at Cornell University. A major research focus of the machine is to study instabilities in positron beams due to the build-up of electron clouds, which are a major issue for future colliders including SuperKEKB and the ILC, and the development of beam instrumentation techniques needed to measure these effects. To observe these effects, we are using an x-ray beam profile monitor system based on coded aperture imaging to measure single-bunch, turn-by-turn beam profiles and positions at the required range of resolutions, from ~10 μm up to several tens of micrometers in vertical beam size. Data have been taken at CesrTA starting in May, 2010, under various conditions. These data show clear bunch-by-bunch beam size changes associated with the build-up of electron cloud densities along the bunch train, as well as tune shifts due to the focusing effect of the electron clouds, both of which are visible in the x-ray monitor data and corroborated by separate lifetime and tune measurements. An electron-cloud density threshold is also seen above which the beam size rises rapidly, which appears to be associated with the appearance of synchro-betatron sidebands in separate measurements. We present data on the beam size and position measurements under various beam conditions, and compare with similar measurements made previously at the KEKB Low Energy Ring (LER).

INTRODUCTION

Electron Cloud Instabilities

Electron cloud build-up due to synchrotron radiation, multipacting, etc., has been found to cause head-tail instabilities and beam size blow-up at positron rings[1]. Beam size blow-up and vertical betatron sidebands have been found at KEKB which appear to be signatures of fast head-tail instability due to electron clouds, and which cause loss of luminosity during collision[2][3]. Electron-cloud instabilities and mitigation methods are being studied at CesrTA, for use at future machines. Beam-size studies have been performed at CesrTA using coded aperture x-ray monitor, and are compared here with KEKB results under the following conditions:

- Varying bunch current;
- Varying chromaticity;
- Varying initial beam size (emittance) below blow-up threshold;
- Varying transverse bunch-by-bunch feedback gain.

Measurement Techniques

At the KEKB Low Energy Ring (LER), measurements of overall beam blow-up were made using an SR interferometer. For bunch-by-bunch beam sizes, gated camera measurements were initially made, showing that the vertical bunch sizes blow up starting several bunches from the head of a train of bunches, where the electron cloud density had built up to a sufficient level. Later, BPM spectrum measurements were made showing the presence of a synchro-betatron sideband signal which appears at the cloud density threshold level for beam size blow-up. A series of studies with varying values of parameters such as chromaticity and emittance were carried out, using the sideband signal to study how the instability threshold was affected[4].

At CesrTA, bunch-by-bunch beam sizes are measured using an x-ray monitor built on the D Line of the CHESS light source for viewing positrons, as shown in Figure 1. (A similar line for viewing electrons is installed at the C Line.) The detector can read out bunch-by-bunch, turn-by-turn signals at 14 ns or 4 ns spacing[5][6]. Three sets of x-ray optics can be selected in the optics box: Coded Aperture mask (CA), Fresnel Zone Plate (FZP) and an adjustable slit. The coded aperture mask permits single-shot, photon-statistic-limited resolutions of ~2-3 μm at beam sizes of 10-20 μm[7]. This paper will discuss measurements made using this mask.

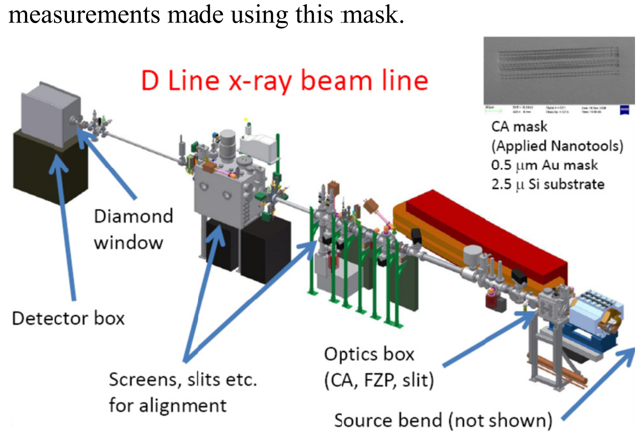

Figure 1: Layout of x-ray beam line for viewing positron beams at CesrTA.

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MEASUREMENTS

Bunch Current Dependence

Initial data were taken with the bunches at 14 ns spacing, using 45-bunch trains. For each bunch, the turn-by-turn vertical sizes and positions were fitted, and then the sizes were averaged over all turns. For each bunch the rms of the positions were calculated to represent the motion of the bunch. Figures 2, 3 and 4 show the bunch-by-bunch sizes and rms motions along the train at bunch currents of 0.5 mA, 1.0 mA and 1.3 mA, respectively. Error bars are statistical. For the 1.0 and 1.3 mA/bunch cases, a slow growth can be seen starting at the beginning of the train, with the bunch size growing more rapidly after around bunch 25 for 1.0 mA, and around bunch 20 for 1.3 mA. This is consistent with the cloud density increasing more rapidly along the train as bunch currents increase. In separate measurements of the BPM spectrum for each bunch, what appears to be a synchrotron-betatron sideband signal is seen in all bunches from the fast blow-up threshold to the end of the train [8], perhaps indicating that incoherent emittance growth is seen below the threshold, and a coherent instability after that.

The head of the train was also seen to be somewhat enlarged. The cause of this is under investigation, but is believed to be possibly due to long-lived trapped electrons in the CesrTA ring which is dipole- and wiggler-dominated (unlike KEKB, where no such effect was evident), and/or possibly due to feedback tuning issues. The tail of the train is also seen to fall off gradually in size, an effect which was not observed at KEKB, where the beam size simply saturated going to the back of the train. The reason for this difference is not yet understood. It is worth mentioning that the bunch lifetimes followed roughly the measured beam sizes, with longer lifetimes for bunches with larger measured sizes, as might be expected from Toushek effects, which provides backing evidence that the sizes really do vary in the manner reported by the x-ray monitor.

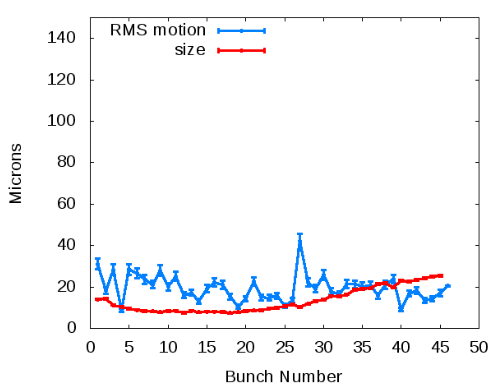

Figure 2: Bunch-by-bunch beam size and rms motion at 14 ns spacing with 0.5 mA/bunch (128 turns).

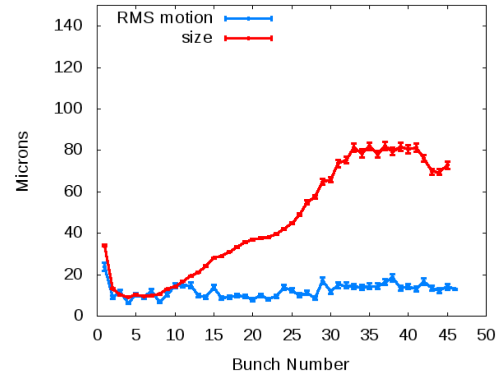

Figure 3: Bunch-by-bunch beam size and rms motion at 14 ns spacing with 1.0 mA/bunch (128 turns).

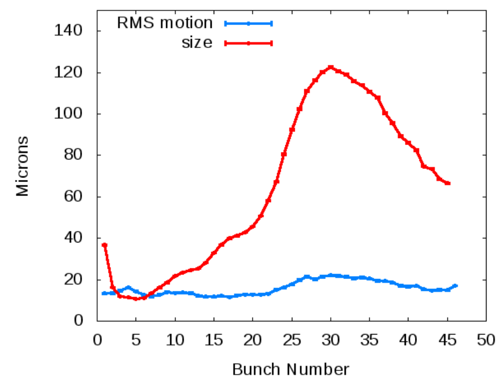

Figure 4: Bunch-by-bunch beam size and rms motion at 14 ns spacing with 1.3 mA/bunch (4096 turns).

Finally, Figure 5 shows the bunch-by-bunch position spectrum as measured by the x-ray monitor. The vertical tune line can be seen at the upper part of the plot, shifting downward in aliased frequency (upward in tune units), due presumably to the electron cloud density increasing along the train.

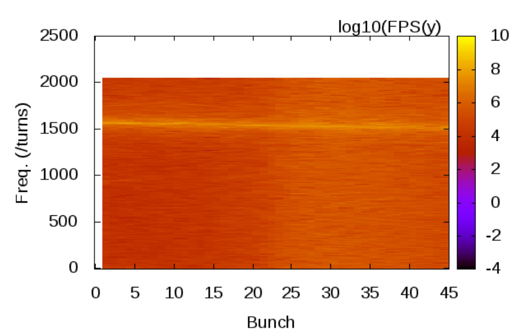

Figure 5: Fourier power spectrum of beam position measured by x-ray monitor at 14 ns spacing with 1.3 mA/bunch (4096 turns).

Chromaticity Change

At KEKB, the coherent instability threshold was found to change with the chromaticity, with higher chromaticities pushing the onset of the instability back along the train. At CesrTA, two sets of measurements were taken varying the chromaticity, one at 14 ns spacing and one at 4 ns spacing. Figure 6 shows the bunch-by-bunch size and rms motion for a vertical chromaticity of 1.2, and Figure 7 for a vertical chromaticity of 2.2. Here the transverse feedback gains were set very low (20% in vertical and horizontal directions, with longitudinal off), which is different from the cases shown in the preceding section, where all feedbacks were at full normal gain settings, resulting in greater dipole oscillations towards the tail of the train. It can be seen that while raising the vertical chromaticity suppressed the dipole oscillations to some extent, the beam sizes along the train do not change, and neither does the blow-up threshold appreciably.

Figures 8 and 9 show the results at 4 ns spacing, for vertical chromaticities of ~-0.8 and ~-0.4, respectively. Again, the blow-up threshold is not seen to change noticeably. (The reason for the sudden drop off in bunch size at the end of the train is not clear, in but may relate to the dipole oscillation becoming so large that much of the beam image is no longer contained on the detector, resulting in bad fits.)

It is also seen that the blow-up threshold does not change appreciably when changing from 14 ns spacing to 4 ns spacing. This may be due to the cloud lifetime being very long in the dipole-dominated CesrTA ring, and so does not decay appreciably over the space of 14 ns, making the cloud density roughly a function of the number of preceding bunches. This is different from KEKB, where the instability threshold depends on the bunch spacing as well as the bunch currents. Tune shift data are being studied to verify this. Another possibility is that the 14 ns spacing may be near a multipacting resonance in the dipoles[9]. The reason for the insensitivity to chromaticity change, in contrast to the case at KEKB, is not known, though it may be noted that the total chromaticity changes tried so far at CesrTA are smaller than those tried at KEKB (several units). It should also be mentioned that the sideband appearance threshold was observed to change with chromaticity[9]. These issues are under continued study.

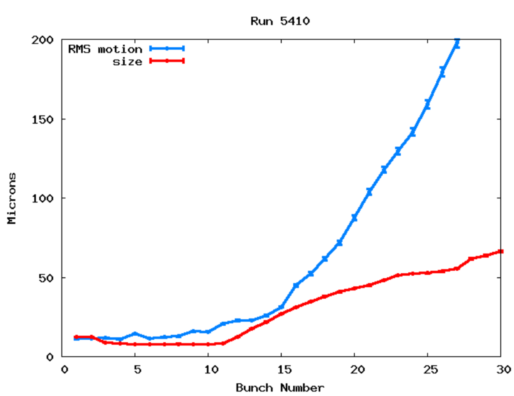

Figure 6: Bunch-by-bunch beam size and rms motion at 14 ns spacing, 0.75 mA/bunch, vertical chromaticity ~1.2.

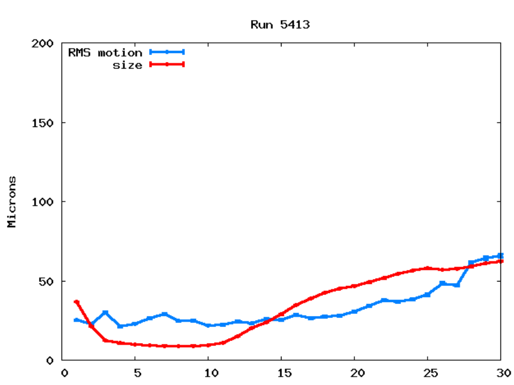

Figure 7: Bunch-by-bunch beam size and rms motion at 14 ns spacing, 0.75 mA/bunch, vertical chromaticity ~2.2.

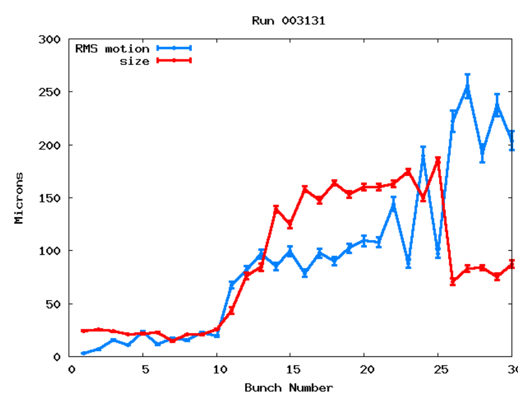

Figure 8: Bunch-by-bunch beam size and rms motion at 4 ns spacing, 0.75 mA/bunch, vertical chromaticity ~-0.8.

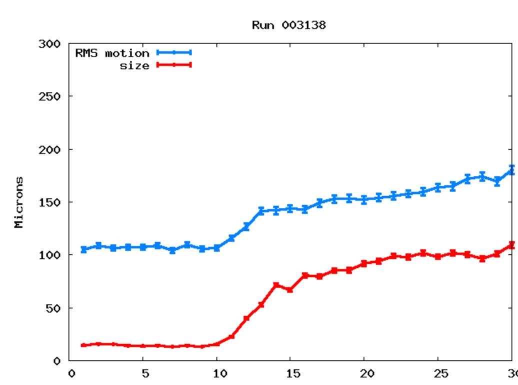

Figure 9: Bunch-by-bunch beam size and rms motion at 4 ns spacing, 0.75 mA/bunch, vertical chromaticity ~-0.4.

Emittance Variation

At KEKB, it was found that changing the initial beam size did not change the blow-up instability threshold[4]. The initial beam size at CesrTA was also varied, using dispersion bumps through two wiggler sections in the L1 and L5 regions of the ring. The data for the enlarged-emittance beam, with an estimated smearing function of ~30 μm (to be taken in quadrature with the natural beam size) are shown in Figure 10. This should be compared with the un-enlarged beam data of Figure 8. It can be seen that while the overall beam size is enlarged, the blow-up threshold is at the same location, around bunch 10. These data shown were taken at 4 ns spacing; similar results were found at 14 ns spacing.

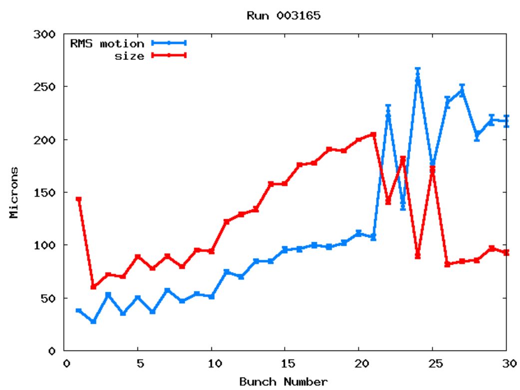

Figure 10: Bunch-by-bunch beam size and rms motion at 4 ns spacing with 0.75 mA/bunch, and increased base emittance. (Compare to low-emittance case in Fig. 8).

For KEKB, the reason for the lack of dependence of the threshold on the beam size was considered to be due to the effective Q of the cloud oscillation around the bunch being $\omega_e\sigma_z/c$, due to it being smaller than the numerically estimated natural Q for a coasting beam[1], where

$$\omega_e = \sqrt{\frac{\lambda_+ r_e c^2}{\sigma_y(\sigma_x + \sigma_y)}} \quad ,(1)$$

with λ_+ being the line density of the bunch, r_e the classical electron radius, c the speed of light in vacuum, and σ_x, σ_y and σ_z being the horizontal, vertical and longitudinal bunch sizes, respectively. This causes the vertical size dependence in the cloud density threshold to cancel out for small vertical chromaticities [10]. CesrTA has a bunch length about twice as long as the KEKB LER, but a blow-up threshold bunch charge and transverse sizes smaller than those of KEKB, so a similar effective Q. It also has a very small vertical chromaticity. It is possible that much larger vertical chromaticities would show a dependence of the blow-up threshold on initial beam size.

Feedback Gain Change

Finally, it was observed that the transverse bunch-by-bunch feedback had no effect on the coherent instability signal at KEKB[3]. Figures 11 and 12 show two different setting of the transverse feedback gain at CesrTA, with 20% and 40% gain settings respectively, for both vertical and horizontal feedback. While the dipole motion behaviour changes somewhat with the change in gains, the blow-up behaviour is not changed at all, consistent with results seen at KEKB.

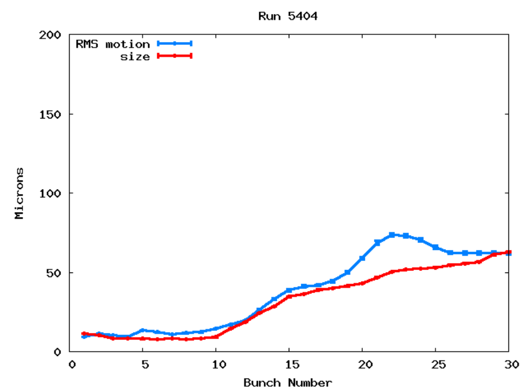

Figure11: Bunch-by-bunch beam size and rms motion at 14 ns spacing with 0.75 mA/bunch, LOW feedback gain.

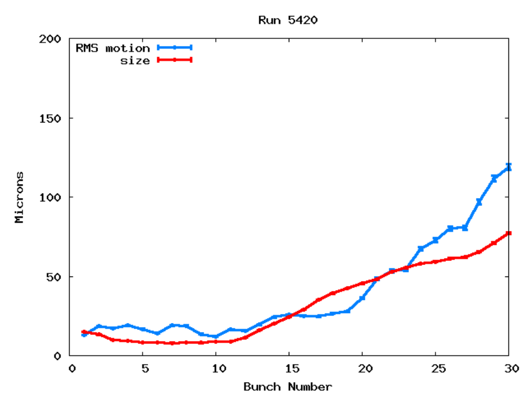

Figure12: Bunch-by-bunch beam size and rms motion at 14 ns spacing with 0.75 mA/bunch, HIGH feedback gain.

SUMMARY

Studies are underway to probe the mechanisms of electron-cloud-induced beam instabilities. Preliminary results show some fundamanental similarities to the behaviours seen at the KEKB LER, but also some differences that remain subjects of study. Further studies are planned to understand the similarities and differences between the effects seen at CesrTA and KEKB, with the goal of being able to extrapolate our understanding of electron effects to new machines being built or designed.

ACKNOWLEDGMENTS

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