ISBN: 978-3-95450-168-7 doi:10.18429/JACoW-IPAC2015-WEXB2

MEASUREMENT AND SIMULATION OF ELECTRON CLOUD INDUCED EMITTANCE GROWTH AT CESRTA

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Abstract

This paper presents recent observations obtained on the study of electron cloud induced instabilities and emittance growth on positron beams at the Cornell Electron-Positron Storage Ring Test Acceleartor (CesrTA), and the simulation of these phenomena under similar beam conditions using the program CMAD. Results show that the transition to large bunch oscillations ocurrs at similar electron cloud densities in experiments as well as simulations. Beam size measurements were carried out using an x-ray beam size monitor (xBSM). The spectrum of the motion of the bunches were recorded using beam position monitors. The experiment consisted of using a train of positron bunches to generate the electron cloud, and observation of a “witness bunch" at different positions behind the train. Motion of the bunches in the train were controlled using feedback, thus suppressing multi-bunch effects. This experimental set up was suitable for comparison with simulations because the simulations were carried out only to study single bunch effects.

INTRODUCTION

The CesrTA program consists of using the Cornell Electron-Positron Storage Ring as a test facility to study physics associated with linear collider damping rings [1]. One of the activities of the program was the study of the response of the positron beams to electron clouds under different conditions. This paper reports the results of experiments carried out in April 2014, along with simulations performed under similar conditions. Table 1 gives the conditions under which experiments were performed.

Table 1: CesrTA Parameters

Parameter	Value
Energy	2.085 GeV
Horizontal Emittance	2.6 nm
Vertical Emittance	20 pm
Bunch Length	10.8 mm
Bunch Spacing	14 ns
Momentum Compaction	6.8e-3
Revolution Frequency	390.1 kHz
Horizontal Tune	0.58
Vertical Tune	0.62
Synchrotron Tune	0.055

Earlier simulation studies using the program CMAD [3] were performed for CesrTA Ref [6], that showed several qualitative features also observed in the experiments. Since then, the CMAD program has undergone various improvements that has enabled better comparisons with simulations. At the same time, the method of observation underwent a change, which made it more suitable for comparison with simulations. The so called "witness bunch"(WB) method of observation consists of using a train of positrons to generate the electron cloud. The sole purpose of the train is to generate the cloud rather than for studying its response to electron clouds. The transverse motion of the bunches in the train was always well suppressed with the help of feedback. This helps eliminate multi-bunch effects. The witness bunch was placed at varying positions behind the train, and the behavior of this bunch alone was observed under different conditions. It should be noted that the witness bunches used for different measurements never existed. That is, when the observation of one of them was completed, the bunch was removed and replaced by the next one under a different condition. The instrumentation associated with performing this swap of bunches is given in Ref [7]. One of the conditions that was varied was the position of the WB behind the train, which is equivalent to varying cloud density encountered by the bunch. Other experiments on varying the chromaticity, witness bunch charge, emittance etc were attempted but the data obtained was insufficient and it was clear that a more exhaustive study is necessary to study these effects.

TUNE SHIFT ANALYSIS

The spectrum of the witness bunch was obtained by gating BPM signal from a single bunch and feeding the signal to a spectrum analyzer. The details of the instrumentation is given in [9]. These measurements provide information on tunes that are most prominent in the motion of the bunch. Figure 1 shows plots of the fractional tune vs signal amplitude, of the first bunch in the train and the witness bunch. It is assumed that the first bunch does not encounter any cloud, and thus the tune shift of the witness bunch with respect to the corresponding first bunch in the train is the electron cloud induced tune shift. These results shown had a current of 0.5mA in all the bunches (train + witness). The figure shows the tune shifts of witness bunches at positions 74 and 47, behind the 45 bunch train. The spacing between the WB and the end of the train may be computed by (WB position − no of bunches in train) × bunch-spacing. Thus WB at 47

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corresponds to 28ns behind the last bunch in the train and WB at 74 corresponds to 406ns behind the train.

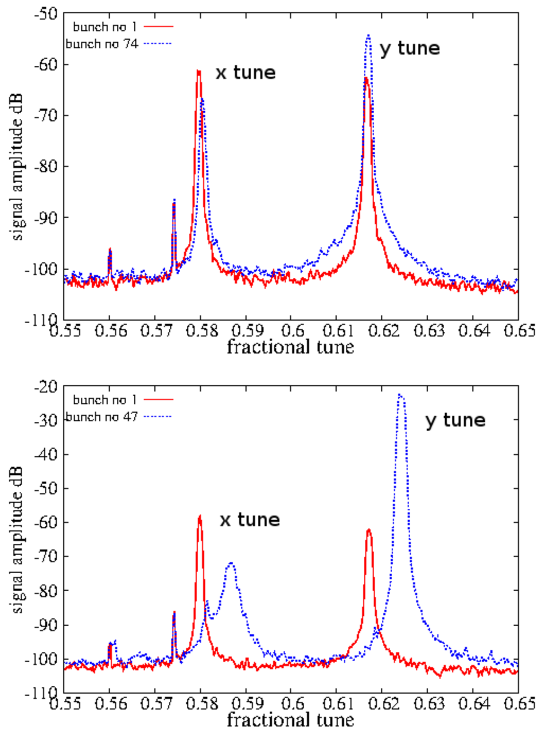

Figure 1: Spectra of the first bunch and witness bunch, for a 45 bunch train with WB at spots 74 and 47.

The electron density may be estimated from the tune shift as described in Refs [2] or [10]. While in experiments, the electron cloud density may be estimated indirectly from the tune shift, in simulations, this is an input parameter. One can obtain the cloud density estimated from the simulated tune shift and compare the value to the corresponding input cloud density. This was done after estimating a reasonable range of values for the electron cloud densities encountered by the witness bunches from the observed spectra, and performing simulations for values within the same range of cloud densities.

Using a fast Fourier transform, the power spectra is calculated from the simulated turn by turn positions of the bunch centroid. The resulting spectra at varying electron cloud densities is compared to an identical run in which no cloud was present, as shown in Fig 2. To obtain these tune tune shifts, it was necessary to perform the simulations with a small initial vertical offset of 0.5 × the rms size of the beam. Otherwise the spectrum was noisy. A similar calculation using a horizontal offset still needs to be carried out.

The tune shifts calculated from simulations are then plotted against the input electron cloud density along with the points corresponding to experimental tune shifts and their corresponding calculated electron cloud densities. These calculations were performed using only the vertical tune shift as the horizontal tune shift in the simulations is not available. The calculation is illustrated in Figure 3. A linear fit to simulated results produces a slope within 7% of the expected slope. This agreement is confirmation that the electron cloud densities under which simulations were performed were in the same range as those observed experimentally.

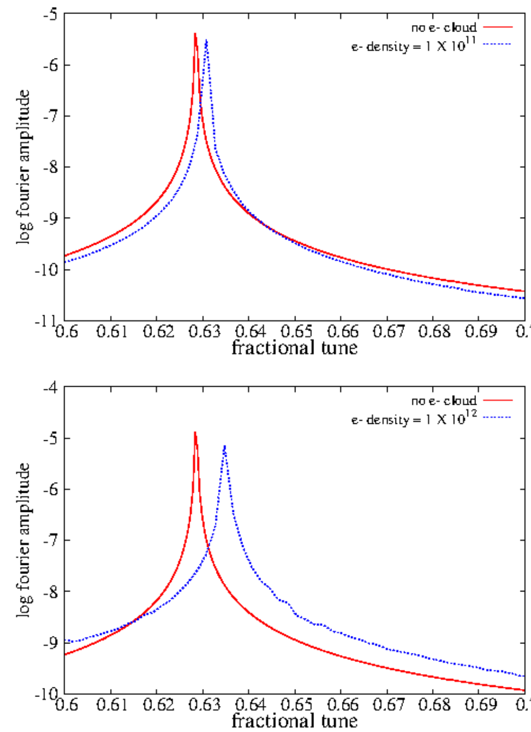

Figure 2: Spectra illustrating a tune shift in simulations at 0.5 mA/bunch with 1×10^{11} and $1 \times 10^{12}\,\mathrm{m}^{-3}$ cloud densities respectively.

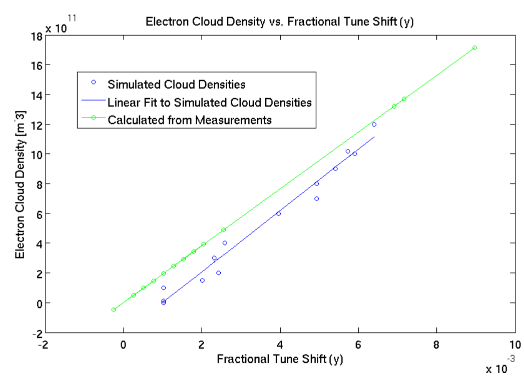

Figure 3: Estimate of electron cloud density from tune shift in experiments and comparison with simulated data, 0.5 mA/bunch.

MEASUREMENT OF BEAM SIZE

The X-ray beam size monitor (xBSM) [13] was used to obtain vertical beam sizes of the bunches in the train as well as the witness bunches. Measurements of vertical beam size taken for a 45 bunch train in April 2014 from xBSM data are shown in Figure 4. The values for the first 45 bunches represent the average value for each bunch in the train over

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all trials, while witness bunches after bunch 45 are a single measurement from the trial corresponding to that location. Feedback was always turned on for bunches in the train, and measurements were made with feedback on and off on the witness bunches. The beam size was measured over 4096 turns. For witness bunches just behind the train, the bunch would execute large betatron oscillations. As a result, when feedback was off on the witness bunch, the number of turns with valid data reduced as one approached the train from behind. This effect, coupled with a possible large expansion in beam size made the signal in the last 3 bunches too weak get any valid measurement. Figure 5 shows the measurements under the same conditions with feedback turned on for the witness bunches. In this case all the bunches were visible as the betatron motion was well suppressed and it is expected that suppression of the bunch motion would result in a reduced beam size. However, the size expansion due to incoherent effects arising from the electron cloud would still be present. These results clearly show that single bunch feedback cannot fully cure emittance dilution due to electron clouds.

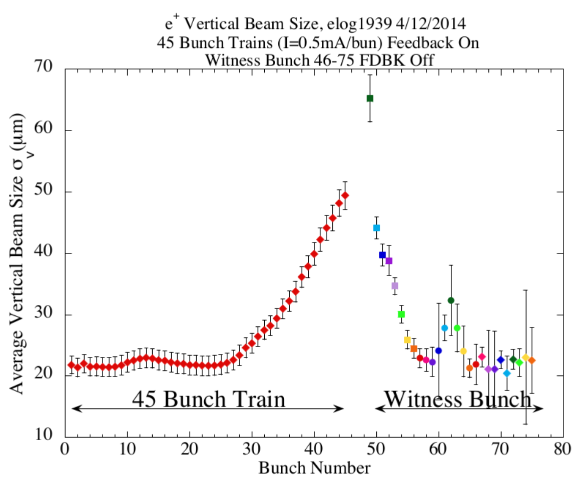

Figure 4: xBSM vertical beam size, 45 bunch train, 0.5 mA/bunch, with WB under no feedback.

TRANSITION TO LARGE BUNCH OSCILLATIONS AND EMITTANCE GROWTH RATES

Given that we have performed simulations of at the most $\tilde{2}000$ turns, It should be noted the beam is still evolving in this case, while all observations are made when for a beam that has evolved over several damping times, and has reached a quasi equilibrium state. Despite this, the simulated beam is still a very useful comparison because the behavior in the first two thousand turns is an indicator of overall beam growth under different conditions. The same is true for the turn by turn bunch oscillations. Figure 6 shows the beam emittance growth rate as predicted by simulations. A tradition to exponential growth rate occurs at a cloud density of 1.2×10^{12} m^{-3}. Figure 7 shows the simulated turns by

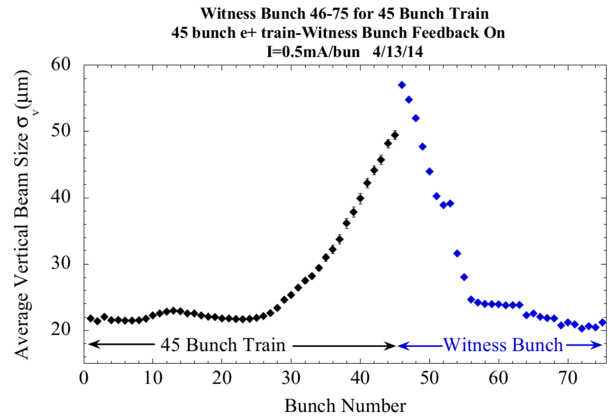

Figure 5: xBSM vertical beam size, 45 bunch train, 0.5 mA/bunch, with WB under feedback.

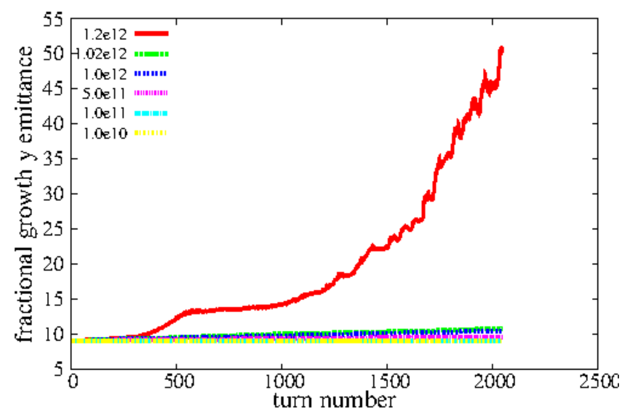

Figure 6: Simulated vertical emittance growth for varying electron cloud density, bunch current at 0.5 mA/bunch.

turn bunch oscillation for the same cases. We see that a transition to large emittance growth rate is accompanied by a transition in growth of the bunch oscillation amplitude. Figure 9 shows the cloud density encountered by the witness bunches, which is estimated by the observed tune shifts. Observation of the turn by turn oscillations from BPMs show that a transition to large amplitude oscillations occurs between witness bunch 48 and 49. This is shown in Fig 8. The value of cloud density 1.2×10^{12} m^{-3}, at which the transition occurred in simulations, lies between the values of cloud density estimates of witness bunches 48 and 49 shown in Fig 9. It should also be noted that witness bunches 46,47 and 48 did not produce a strong enough signal for a valid beam size measurement most likely due to a large expansion in the beam size. This postulate is consistent with the transition to exponential growth rate in emittance observed in the simulations.

HEAD-TAIL MOTION

While it is not easy to obtain direct evidence of head-tail motion in the experiments, simulations clearly show that head-tail oscillation is strongly correlated to beam emittance

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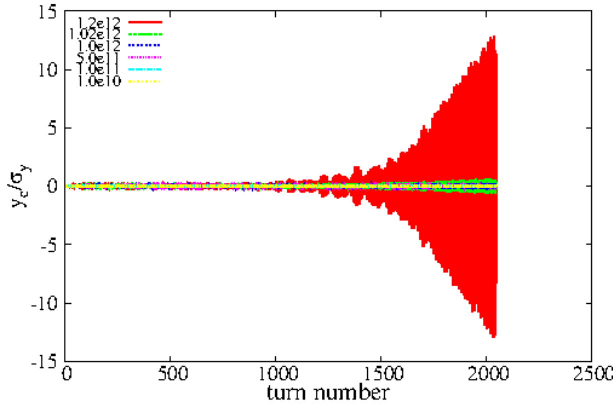

Figure 7: Turn by turn Y position for varying electron cloud density, 0.5 mA/bunch.

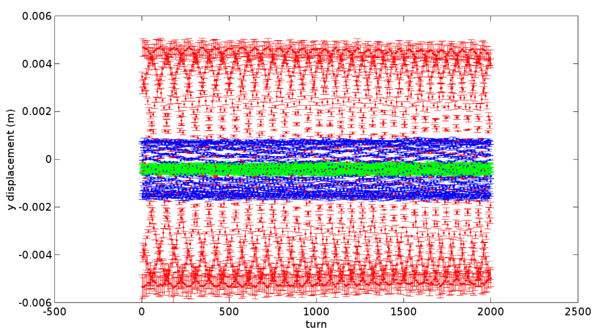

Figure 8: Turn by turn vertical position of WB numbers 48 (red), 49 (blue), 50(green), behind a 45 bunch train.

growth. In the simulations, the bunch is divided into about 100 slices, and the centroid motion of each of them is tracked. This data enables us to obtain information on the turn by turn evolution of the shape of the bunch.

To analyze the linear component of the head-tail motion, the linear fit between the vertical and longitudinal positions, weighted by the charge per slice, is calculated. The position of the centroid (center of charge) of the bunch is calculated and subtracted off so that the fit does not take into account overall displacement of the bunch, but rather just the orientation. As an example, the linear fits corresponding to the orientation of the bunch for every twentieth turn of a 2048 turn simulation are plotted in Figures 10 and 11. This shows that the amplitude of oscillation of the orientation increases by an order of magnitude when the electron density is increased by a factor of 10.

The curvature of the bunch, given by a second order weighted fit that similarly disregards centroid motion and the linear orientation, is a way of expressing the magnitude of the distortion in the shape of the bunch turn by turn, as shown in the curves in Figures 12 and 13. The maximum vertical displacement of the bunch appears to increase by a factor of 10, from 0.15 to 1.5, in the two cases shown, corresponding to an increase in electron cloud density by a factor of 10 as well. The curvature also increases significantly between the two cases as shown in these figures.

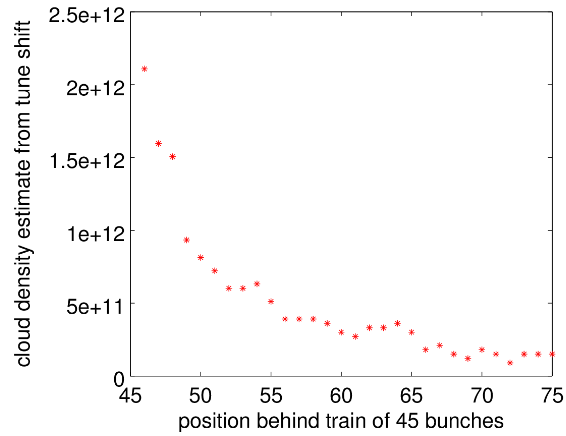

Figure 9: Electron cloud density estimates of all witness bunches behind the 45 bunch train.

Figure 14 shows an overlay of the turn by turn slope values for the orientation of the bunch for varying electron cloud density. The slope increases significantly at the higher end of the range shown, and the oscillation in the magnitude of the slope is more dramatic at higher electron cloud densities.

Figure 15 shows the spectra of the turn by turn variation of the linear slope for varying electron cloud densities with labels showing the location of the vertical tune, lower sideband corresponding to $Q_y - Q_s$, and upper sideband corresponding to $Q_y + Q_s$. The peak at vertical tune is only prominent at the highest electron cloud density, when distortion of the bunch is highest, while peaks for the lower and upper sidebands are continually present, along with the effect of the betatron tune shift. This result is expected, and is expected and is a confirmation of the behavior of typical head-tail motion in the simulations.

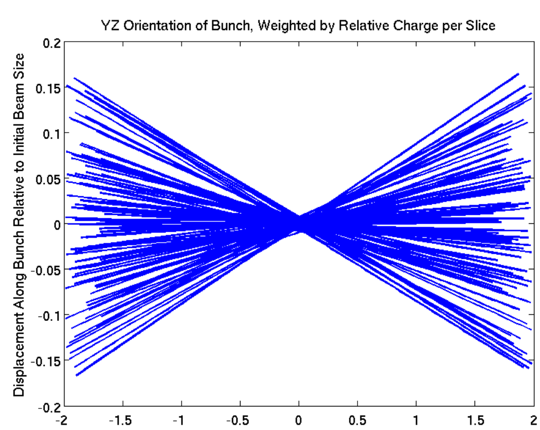

Figure 10: Linear fit to orientationl of the bunch in the YZ plane, weighted by relative charge per slice with an electron cloud density of 1.0×10^{11} m^{-3}

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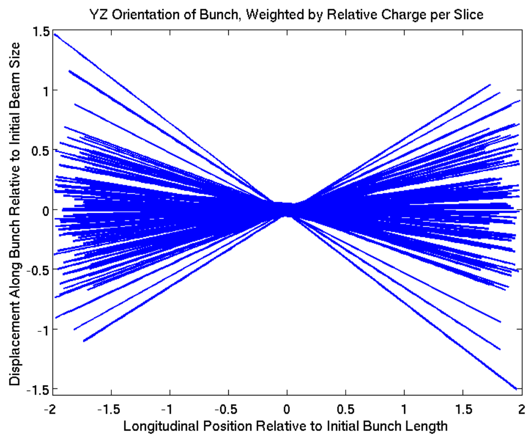

Figure 11: Linear fit to orientation of the bunch in the YZ planel, with an electron cloud density of 1.0×10^{12} m^{-3}

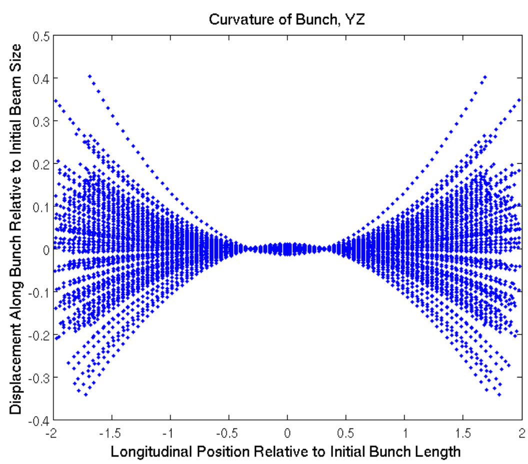

Figure 12: Curvature of bunch in the YZ Plane, with an Electron Cloud Density of 1.0e11 m^{-3}

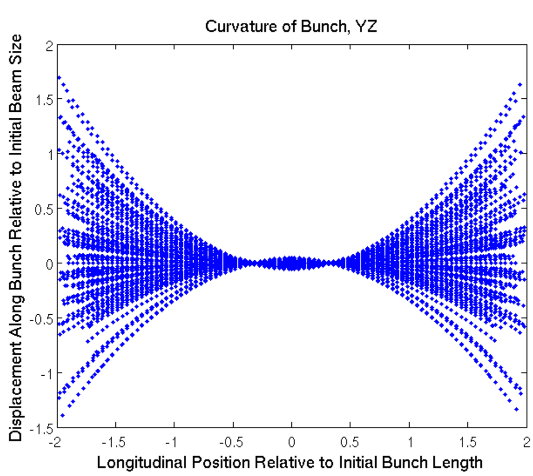

Figure 13: Curvature of bunch in the YZ Plane with an Electron Cloud Density of 1.0e12 m^{-3}

CONCLUSION

In conclusion, the correspondence between simulations and measurements provide validity to similar calculation

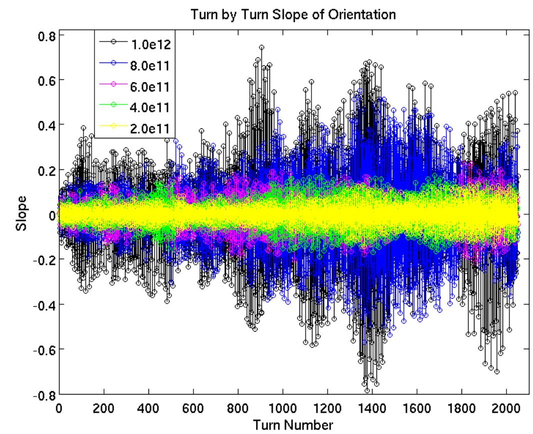

Figure 14: Turn by turn slope of orientation of the bunch in the YZ plane, weighted by relative charge per slice with varying electron cloud density [m^{-3}], bunch current 0.5 mA/bunch.

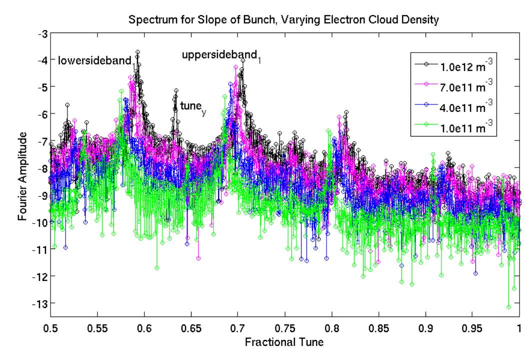

Figure 15: Spectra of slope of orientation of bunch for varying electron cloud density.

made for other proposed accelerator facilities such as the ILC damping ring [14]. It is clear that single bunch feedback cannot cure electron cloud induced emittance growth. The simulations show a clear signature of head tail oscillation, providing us with a guidance to the mechanism of electron cloud effects on positron beams.

ACKNOWLEDGEMENTS

These experiments would not have been possible without the support of the CESR Operations Group, the xBSM team and the CESR Instrumentation group. This work was supported by DOE Award DE-FC02- 08ER41538, NSF Award PHY-0734867, PHY-1068662 PHY-1002467, and PHY-0849885 and the Lepton Collider Research and Development, Coop Agreement: NSF Award PHY-1002467. The Japan-US Collaborative agreement. This research used resources of the National Energy Research Scientific Computing Center, a DOE Office of Science User Facility supported by the Office of Science of the U.S. Department of Energy under Contract No. DE-AC02-05CH11231.

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