CesrTA Program Overview*

D. Rubin, Cornell University, Ithaca, NY 14850, USA

Abstract

The Cornell Electron/Positron Storage Ring has been configured as a damping ring test accelerator. The principle objective of the CesrTA program is to investigate electron cloud physics in the ultra-low emittance regime characteristic of a linear collider positron damping ring. The storage ring is equipped with 12 superferric damping wigglers to increase the radiation damping rate and decrease the emittance. At a beam energy of 2GeV, the 1.9T wigglers increase the damping rate by an order of magnitude and decrease the emittance by a factor of 5 to 2.6nm. Instrumentation to measure, and techniques to minimize sources of transverse coupling and vertical dispersion routinely yield sub 10pm vertical emittance. More than two dozen multi-channel retarding field analyzers have been installed throughout the magnetic guide field in order to characterize cloud buildup. Shielded button pickups have been deployed to measure cloud decay and energy spectra. Techniques to measure electron cloud induced tune shift, instability, and emittance dilution have been developed. We are building and extending simulations of electron cloud phenomena in order to interpret the measurements and to establish the predictive power of the models. We give an overview of the CesrTA ring parameters, the diagnostic instrumentation for low emittance tuning and electron cloud studies. Details will appear in the references to other articles in this proceedings.

CESRTA PROGRAM OBJECTIVES

The damping ring is the source of low emittance bunches of positrons for the international linear collider. The damping ring is required to store the full complement of bunches that will be delivered to the collision point in each linac cycle. The circumference of the damping ring is determined by the spacing of the bunches in the ring. And the spacing is limited by electron cloud effects. CesrTA aims to measure the development of the electron cloud and the dependence of that development on bunch spacing and bunch charge, on local magnetic field, and on the chemistry and geometry of vacuum chambers. Retarding field analyzers are used to measure the time averaged density of the electron cloud. Shielded button pickups yield a measure of the growth and then decay time of the cloud. In addition, we measure the effect of the electron cloud on the beam. We observe cloud induced tune shift, emittance growth, and head tail instability.

Measurements of the sensitivity of the beam-cloud dynamics to the beam size require that we achieve ultra-low vertical emittance, as near to that of the linear collider damping ring as possible. Beam based instrumentation and techniques for identifying and then compensation of sources of vertical dispersion and transverse coupling have been developed. An xray beam size monitor yields bunch by bunch and turn by turn measurement of vertical beam heights of order 10 microns with a few micron precision.

Vacuum chamber materials are characterized in terms of secondary (electron) emission yield (SEY). Knowledge of SEY is essential to predictions of electron cloud growth and equilibrium electron density. At CesrTA we have implemented an in situ SEY measuring device that provides a means of determining the secondary yield of sample materials at various stages of beam processing with no intermediate exposure to atmosphere.

CESRTA LAYOUT AND OPTICS

The Cornell Electron Storage Ring (CESR) layout is based on simple FODO optics. There are two diametrically opposed straights in which low beta insertions focused colliding beams of electrons and positrons. Superconducting damping wigglers, located in the machine arcs, served to reduce the radiation damping rate in low energy (2GeV/beam) operation from 500ms to 50ms, and to increase the horizontal emittance to order 100nm. The decreased damping time and increased emittance were necessary in order to maintain a high beam-beam current limit and to maximize luminosity. At the conclusion of the colliding beam program, the guide field optics were modified for low emittance operation as a damping ring test accelerator. The low beta optics were removed. Half of the damping wigglers were moved to one of the former low beta straights. The opposite straight was instrumented for measuring electron cloud effects.

The storage ring lattice is reconfigured with zero horizontal dispersion in all of the damping wiggler straights. The effect of the wigglers is to decrease the damping time as before, but to decrease horizontal emittance as well. At 2GeV, with the 12, 1.3m long damping wigglers operating at 1.9T, we achieve horizontal emittance of 2.6nm. Because the CESR quadrupoles and sextupoles are all independently powered, there is extraordinary flexibility of the lattice. As required by the experimental program we operate the storage ring over the energy range of 1.8-5.3GeV, with from zero to 12 damping wigglers, and with integer part of the betatron tune ranging from 10 to 14 with corresponding range of emittances, momentum compaction and bunch length. Parameters of a few of the many CesrTA

---

* Work supported by the National Science Foundation and by the US Department of Energy under contract numbers PHY-0734867 and DE-FC02-08ER41538.

Table 1: CesrTA Lattice Parameters

Energy[GeV]	2.085	4.0	5.0	5.3
No. Wigglers	12	6	6	0
Wiggler Field [T]	1.9	1.9	1.9	0
Q_x	14.57	14.57	14.57	10.59
Q_y	9.6	9.6	9.6	9.6
Q_z	0.055	0.051	0.043	0.045
V_{RF}[MEV]	4.5	8.1	8	4.6
ϵ_x[nm-rad]	2.6	23	40	144
$\tau_{x,y}$[ms]	57	32	19.6	23.9
α_p	6.76×10^{-3}	6.29×10^{-3}	6.23×10^{-3}	11.2×10^{-3}
σ_l[mm]	12.2	9	15.8	20.1
$\sigma_E/E[\%]$	0.81	0.89	0.93	0.656
bunch spacing [ns]		≥ 4, steps of 2		

lattice configurations are summarized in Table 1.

LOW EMITTANCE TUNING

Principle sources of vertical emittance are residual vertical dispersion and transverse coupling. Transverse coupling is generated by tilted quadrupoles and vertical misalignment of sextupoles. Vertical dispersion arises from coupling in regions of horizontal dispersion, and vertical kicks from offset quadrupoles and tilted dipoles. Careful alignment of the guide field elements is crucial to achieving ultra-low vertical emittance. As of our most recent survey we have achieved the alignment tolerances shown in Table 2.

Table 2: CESR magnet alignment

Element	misalignment
Quadrupole tilt [μrad]	126
Quadrupole offset [μm]	36
Sextupole offset [μm]	300
Dipole tilt [μrad]	73

We measure residual coupling and vertical dispersion by resonant excitation of the normal mode frequencies. We drive the beam at the normal mode tunes (horizontal, vertical and longitudinal) and measure the amplitude and phase of the vertical and horizontal motion at each beam position monitor for each of the three frequencies. We extract betatron phase advance, coupling of horizontal and vertical motion, and coupling of transverse and longitudinal motion (dispersion). By this method we measure phase with precision of about 0.2 degrees, coupling at the 0.1% level, and vertical dispersion with mm precision. Three minutes of machine time are all that is required to collect a complete set of data to identify sources of vertical emittance. Then based on a fit to the measured data, corrector magnets, (100 quadrupoles, 24 skew quadrupoles and 60 vertical dipoles) are deployed to correct betatron phase advance and to minimize coupling and vertical dispersion. The technique routinely yields vertical emittance < 20 pm in a single iteration. We have developed and refined beam based methods for centering the beam position monitors and calibrating BPM electrode gains[15]. The vertical beam size is measured with an xray camera. x-ray photons from a bend magnet are imaged through a pinhole, fresnel zone plate, or a coded aperture onto a linear photo - diode array, yielding a measurement of the size of a single bunch in a single pass[5, 8].

ELECTRON CLOUD DIAGNOSTIC INSTRUMENTATION

The storage ring has been extensively instrumented for the study of the electron cloud. Retarding field analyzers are used to measure the time average density of electrons near the surface of the vacuum chamber[2]. RFAs are the essential tool for determining the effectiveness of various mitigations[1]. Shielded button pickups give information about the growth and decay of the cloud on the time scale of a few nanoseconds[13]. The x-ray beam size monitor has the capability to measure the size of a bunch with micron resolution in a single pass. Thus we can measure the dilution of the emittance of bunches in the tail of the train due to the cloud generated by bunches at the head. We can further distinguish real emittance growth from the apparent growth that arises due to beam motion. The beam position monitor system also has single pass measurement capability and local processors that can store the data for many thousands of beam passages. The turn by turn position data for the individual bunches in a train yields information about the cloud induced tune shift and instabilities[11, 8].

Retarding Field Analyzers

A retarding field analyzer is a simple detector for measuring the density of the electron cloud near the wall of the vacuum chamber. A variety of geometries have been deployed in CESR. An example of an RFA designed to measure electron density in a standard CESR dipole magnet is shown in Figure 1. There are 9 sets of small holes in the wall of the vacuum chamber. Immediately beyond the holes there is a grid, (here in 3 parts) and beyond the grid, the collectors. A negative bias on the grid determines the energy of electrons that will make it to the collector. Then collector current is proportional to the electron density. Although it is not visible in this picture, the collector is segmented into 9 sections, to coincide with the nine sets of holes in the chamber wall, thus providing information about the dependence of the density on the horizontal position. There is some subtlety in interpreting the energy spectra of the cloud electrons and a detailed model of the RFA has been developed for that purpose[2]. The device is deliberately compact so that it will fit between the poles of the arc dipole. RFAs have been installed in wiggler chambers, drifts, quadrupoles, and in the dipole chicane that permits a measure of the dependence of cloud density on dipole field.

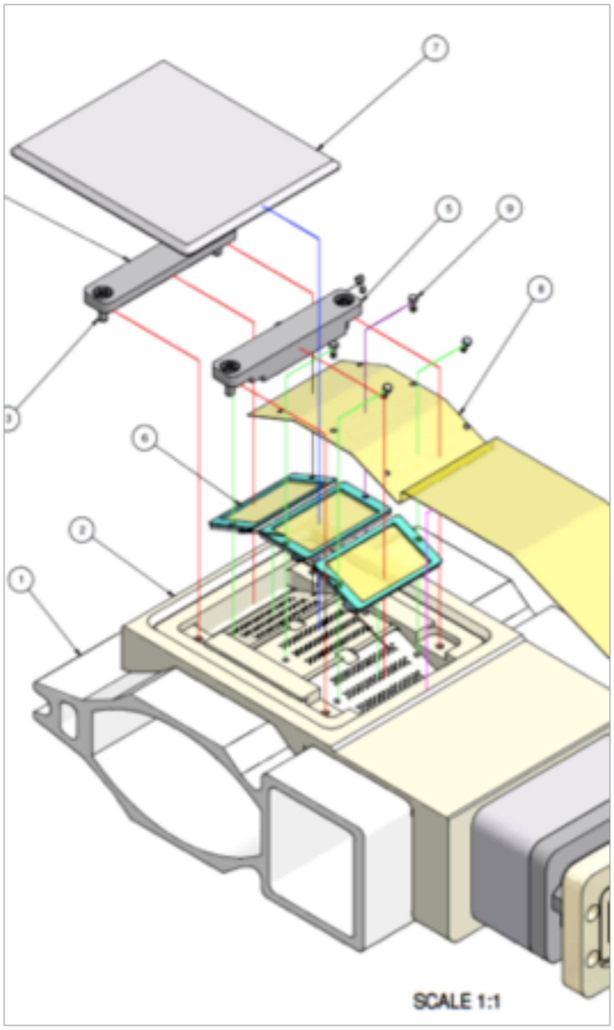

Figure 1: Exploded view of a dipole RFA.

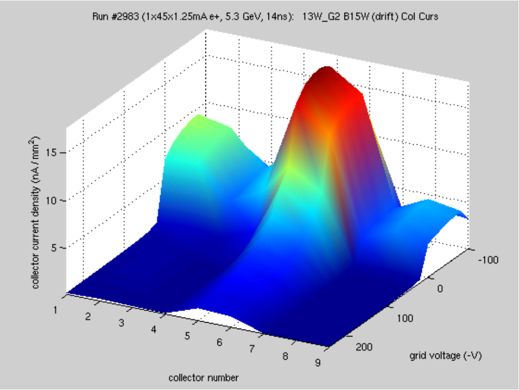

Figure 2: Drift RFA. There is a single train of 45 bunches with 14ns spacing and 1.25mA/bunch at 5.3GeV

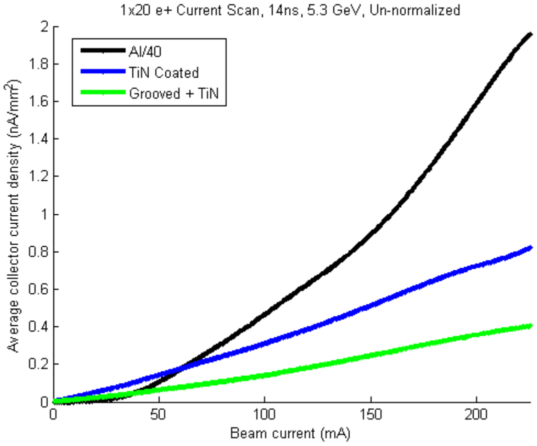

Figure 3: Dipole RFA data for three different chamber treatments. RFA collector current is measured as a function of total current in a 20 bunch train. Collector current for plain aluminum is divided by 20.

Cloud development in Drifts RFA data for a drift (zero magnetic field) is shown in Figure 2. The RFA has nine segments, and the grid voltage is varied from -250 Volts to 100 Volts. The 3-d plot shows the current on each of the nine collectors (horizontal position) vs grid voltage (electron energy). Evidently the electron density is greatest near the center (horizontally) of the chamber and it falls off rapidly with energy to something greater than 250eV.

Mitigation in Dipoles We use the RFA measurements to determine the effectiveness of mitigations. Data from dipole RFAs is shown in Figure 3. The plot shows the collector current density (averaged over the 9 collectors), as a function of beam current for three different chamber treatments. The black line is for the standard aluminum chamber, blue for TiN coated aluminum and green for TiN coated and grooved aluminum. Note that the data in the black line (bare aluminum) is divided by 20. Otherwise it would be off the scale of this plot.

Cloud development in Wigglers The vertical component of the magnetic field in the superconducting damping

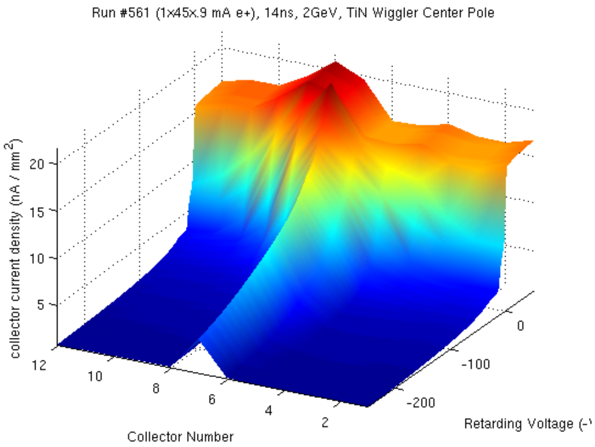

Figure 4: Collector current vs grid voltage for a wiggler RFA at the peak of the magnetic field (1.9T) in a TiN coated copper chamber.

wigglers varies sinusoidally with longitudinal position. In order to understand the dependence of the electron cloud density on the field, the wiggler chamber is designed with three distinct RFAs located at the position of the peak field, half of peak, and at zero vertical field. Each of the three RFAs has 12 collectors to provide information about the transverse dependence. We show measurements from an RFA at the peak wiggler field for a chamber that is coated with TiN in Figure 4. The maximum density is at the center of the chamber (collectors 6-7) and for the lowest energy electrons. Comparison of the collector currents shows that the grooves are a bit more effective at mitigating the electron cloud than the TiN coating.

Measurements of the electron spectrum in a copper wiggler chamber with grooves is shown in Figure 5 for the RFA at the peak of the field. The grooves effectively suppress the electron density. Nevertheless the evidence of the grooves (the grooves are cut longitudinally in the floor of the chamber) is apparent in the dependence of collector current on collector number.

Table 3 summarizes the mitigation tests completed and underway. To learn more about RFA measurements, modeling, and comparison with simulation see the articles by J.Calvey in these proceedings.

Shielded button pickup

The RFA gives a time averaged measurement of the electron cloud density. The shielded pickup has a much higher bandwidth, essentially that of a beam positon montor (nanoseconds), so can inform details of the time evolution of the cloud. A schematic of the shielded pickup is shown in Figure 6 in a cross section of the vacuum chamber. The three button electrodes arrayed transversely across the chamber provide some coarse position information. The electrodes are shielded from the wall current and direct beam pulse by a screen. Low energy electrons are detected as a current on the electrodes. An example of the shielded pickup measurement is shown in Figure 7. The probe bunch generates the cloud and the witness bunch that trails the probe by 14ns kicks the cloud electrons into the pickup. The passage of the first 8mA probe bunch is marked by the early pulse in the plot with peak just past the 20ns (the second) time division. This small pulse is the direct beam signal that is imperfectly shielded by the screen. The current in the witness bunch is varied from 1mA to 8mA. The (positive) witness bunch drives the electrons from the floor of the chamber towards the detector, the velocity increasing with the witness bunch charge.

The shielded pickup[13] gives us information about the decay time of the cloud. As we learned from the witness bunch measurement in Figure 7, the witness bunch signal is a measure of the cloud density at the time of passage. If we vary the delay of the witness with respect to the probe

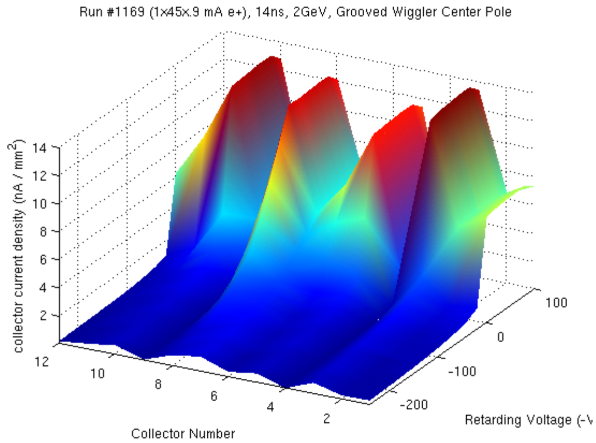

Figure 5: Collector current vs grid voltage for a wiggler RFA at the peak of the magnetic field (1.9T) in a grooved copper chamber. The grooves are cut longitudinally in the floor of the chamber, the RFA is on the ceiling. There is a single train of 45 bunches, with 0.9mA/bunch and 14ns spacing.

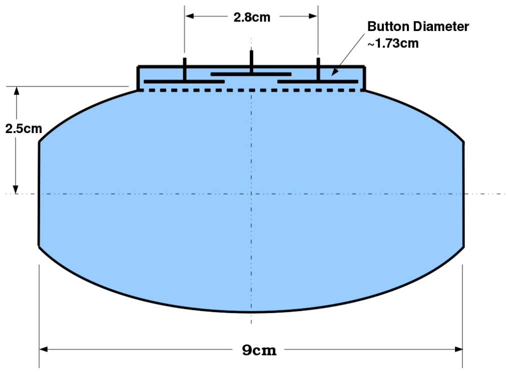

Figure 6: The 3 pickup electrodes are shielded from the direct beam signal by a screen.

	Drift	Quad	Dipole	Wiggler	VC Fab
Al	×	×	×		CU, SLAC
Cu	×			×	CU,KEK,LBNL,SLAC
TiN on Al	×	×	×		CU,SLAC
TiN on Cu	×			×	CU,KEK,LBNL,SLAC
Amorphous C on Al	×				CERN, CU
NEG on SS	×				CU
Solenoid Windings	×				CU
Fins w/TiN on Al	×				SLAC
Triangular Grooves on Cu				×	CU,KEK,LBNL,SLAC
Triangular Grooves w/TiN on Al			×		CU, SLAC
Triangular Grooves w/TiN on Cu				○	CU,KEK
Clearing electrode				×	CU,KEK,LBNL,SLAC

Table 3: Surface characterization and mitigation tests. × indicates that the chamber and accompanying RFA is deployed and ○ that the test is planned.The last column names the laboratories that contributed to the design and fabrication of the chamber.

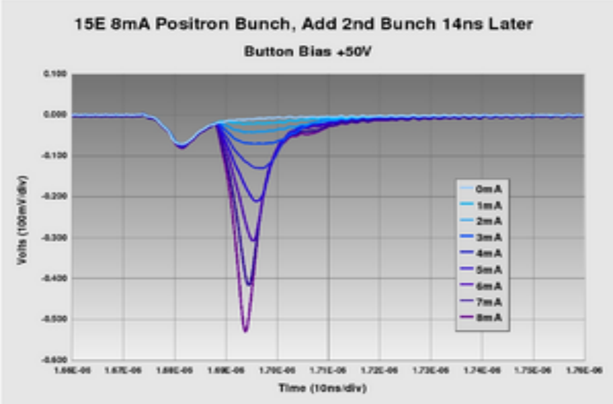

Figure 7: The small pulse just past the second time division is the direct signal from the probe. The pulse that follows 14ns later is the electrons that are accelerated off of the floor of the chamber towards the detector.

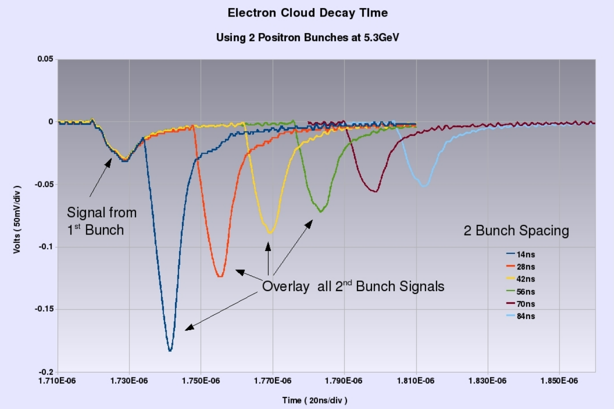

Figure 8: The witness bunch follows the probe at 14ns, 28ns, 42ns,56ns,70ns, and 84ns. The current in both probe and witness is fixed at 8mA

we measure the evolution of the cloud density. Such a witness bunch measure of the cloud decay is shown in Figure 8. The delay time of the witness with respect to probe is varied in 14ns steps. The exponential decay of the cloud is evident.

Measurements with the shielded pickup in the field of a solenoid tell us something about the energy spectrum of the photo-electrons. Figure 9 is a schematic of the detector in a longitudinal magnetic field. The holes in the screen that shield the electrodes are 2.5mm long and 0.76mm in diameter. Therefore, the screen is only transparent to electrons with trajectories very nearly perpendicular to the screen. And since most of the electrons are produced when the synchrotron radiation strikes the outside wall of the chamber, the detector becomes a momentum analyzer.

TE wave

We are exploring both theoretically and experimentally the so-called TE wave technique for measuring electron cloud density. A carrier electromagnetic wave is injected into the vacuum system at a beam position monitor and then detected at a nearby monitor. The electron cloud density modifies the wave number associated with the propagation of electromagnetic waves through the beampipe. Gaps in the fill pattern result in a modulation of the phase shift. In the frequency domain this results in sidebands of the fundamental frequency. The amplitude of the sidebands is related to the cloud density[4, 10]. The method has the advantage

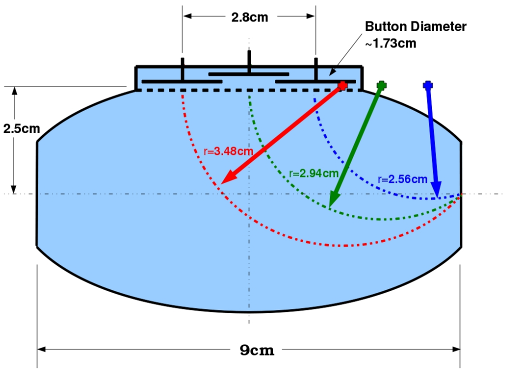

Figure 9: The shielded pickup in a longitudinal magnetic field becomes a momentum analyzer. The schematic shows that photo-electrons emitted from the outside wall of the vacuum chamber will be detected by one of the three shielded buttons depending on their energy and the local magnetic field.

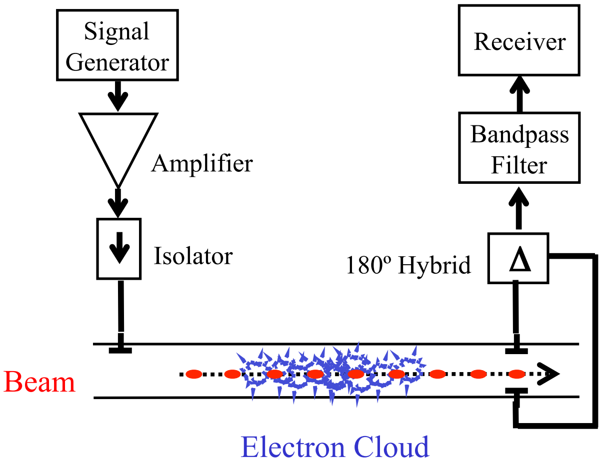

Figure 10: The TE wave measurement method

that no special vacuum instrumentation is required. The disadvantage is that interpretation of the results is complicated. The TE wave method is illustrated in Figure 10.

Beam Dynamics

Tune shift The positron beam is focused by the electrostatic field of the electron cloud[6]. The effect of the focusing is to shift the tune of the positron bunches. The tune shift then serves as the principle measurement of the electron cloud density around the ring. In a long train, the bunches near the tail of the train are focused by the cloud generated by bunches near the head. We have developed two techniques for measuring the spectrum of each bunch in a train. One strategy is to kick the entire train coherently, exciting betatron oscillations, and then to collect turn by turn position data for each bunch. We use an FFT to extract the tune. The results of a measurement by the coherent excitation method are shown in Figure 11. We circulate a train of 21 bunches spaced at 14ns intervals and a witness bunch at some number of 14ns intervals beyond the end of the train. We see the increasing cloud density, (increasing shift in tune), along the train and then the decay of the cloud as measured by the shift in the tune of the witness bunch. The measurements are in reasonably good agreement with the POSINST simulation[3, 6, 12].

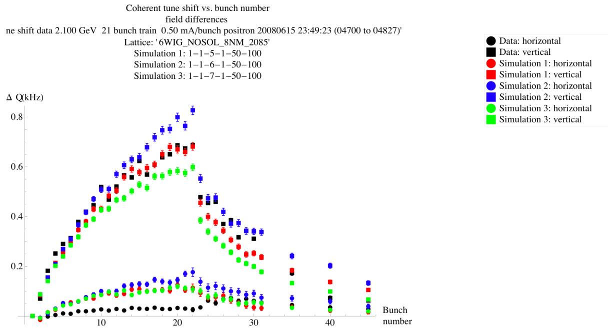

Figure 11: The vertical tuneshift (square points) is much larger than the horizontal tune shift (round points). The data are the black points. Simulation requires knowledge of the secondary (electron) emission yield. The simulation was performed with SEY=2.0 (red), SEY=2.2 (blue), and SEY=1.8 (green). The best fit to the data is SEY=2.0

.

Instability - head tail mode Another technique for extracting information about the bunch spectra and the interaction of the circulating positrons and the electron cloud is to use a gated spectrum analyzer. We thus measure the power spectrum of each of the bunches in the train. In addition to the induced tune shift we observe synchrobetatron sidebands for bunches near the tail of the train. Evidently, the cloud induces a head tail instability[6, 9].

Emittance Growth Another effect of the increasing cloud density along the train is the dilution of the vertical emittance. We use the x-ray beam size monitor to measure the vertical size of each of the bunches in the train[5, 8]. A measurement of the emittance growth in a 20 bunch train is shown in Figure 12 for bunch currents from 0.3mA to 0.75mA. The emittance of the first few bunches is $\sim$ 7pm. We see no emittance growth at the lowest current of 0.3mA/bunch and certainly no significant growth with 0.4mA. But with 0.5mA/bunch emittance dilution is observed in bunch 15 and at 0.75mA at bunch 11. The cloud induced emittance growth is anticipated by simulations[9].

MEASUREMENT OF SECONDARY EMISSION YIELD

The development and equilibrium density of the electron cloud is critically sensitive to the secondary emission yield

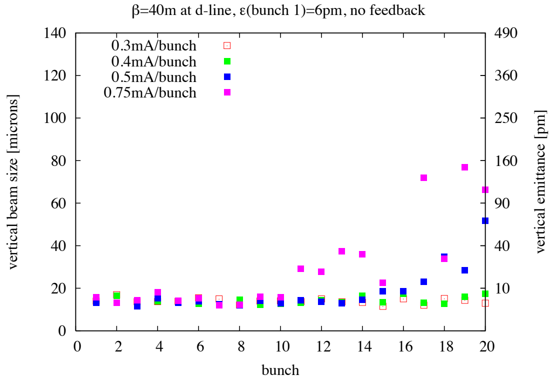

Figure 12: Vertical size of each bunch in a 20 bunch train is measured with the x-ray beam size monitor. Emittance growth is observed in bunch 15 for the train with 0.5mA bunches and at bunch 11 at 0.75mA/bunch.

of the vacuum chamber material. And the SEY is typically reduced with beam processing. Of course, exposure to atmosphere after beam processing immediately contaminates the surface. Therefore, in order to determine the effective secondary yield it is useful to be able to measure SEY in situ. We have implemented an in situ station that allows for the extended exposure of a sample to synchrotron radiation and associated electron bombardment, and then measurement of the SEY while it remains in the CESR vacuum[14]. A plot of the SEY for TiN coated aluminum versus exposure is shown in Figure 13.

CONCLUSION

The instrumentation that has been deployed in CESR for the CesrTA experimental program provides the capability for characterization of the development of the electron cloud and the interaction of the electron cloud with circulating beams of positrons and electrons. Low emittance tuning techniques have been employed to minimize vertical emittance to facilitate exploration of electron cloud phenomena in the ultra-low emittance regime typical of damping rings. In this article we present an overview of the CesrTA instrumentation and a very brief sampling of the measurements. The interested reader is directed to the references to other articles in these proceedings for more details.

REFERENCES

[1] J.Calvey, "Electron Cloud Mitigation Investigations at CesrTA", *these proceedings*

[2] J.Calvey, Methods for Quantitative Interpretation of Retarding Field Analyzer Data, *these proceedings*

[3] D. Kreinick, "Using Coherent Tune Shifts to Evaluate Electron Cloud Effects on Beam Dynamics at CesrTA", *these proceedings*

[4] J.Sikora, "TE Wave Measurements at CesrTA", *these proceedings*

[5] J.Flanagan, "xBSM bunch-by-bunch measurements in EC conditions at CesrTA", *these proceedings*

[6] Dugan, G., "CESR TA Electron Cloud induced beam dynamics", *these proceedings*

[7] Li, Y., " Implementation and operation of electron cloud diagnostics for Cesr TA", *these proceedings*

[8] Rider, Nathan, " Bunch by bunch instrumentation upgrades for CESR based on requirements for the CESR TA research program", *these proceedings*

[9] S., Kiran, " Simulation of electron cloud induced instabilities and emittance growth", *these proceedings*

[10] S., Kiran, "Simulations using VORPAL on the effect of imperfections and non-uniformities in TE wave", *these proceedings*

[11] M. Billing, "Beam dynamics techniques" , *these proceedings*

[12] G. Dugan, "Synrad3D photon propogation and scattering simulation" , *these proceedings*

[13] J. Crittenden, "Electron cloud modeling results for time resolved shielded pickup measurements at Cesr TA" , *these proceedings*

[14] J. Kim, "In situ SEY measurements in CesrTA" , *these proceedings*

[15] D. Rubin, et.al., "CesrTA Low Emittance Tuning", *these proceedings*

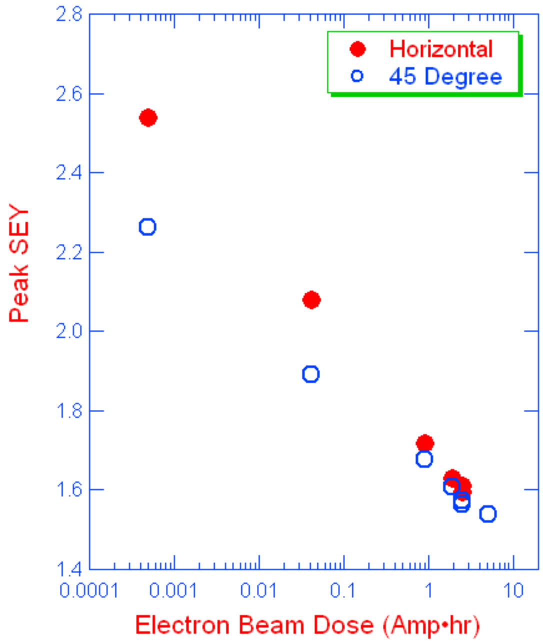

Figure 13: SEY versus electron beam dose. The horizontal (red) points are for sample material that is in the mid plane and recieves direct synchrotron radiation. The blue points are for a sample that is at 45 degrees above the midplane.