THE CHALLENGES OF ULTRA-LOW EMITTANCE DAMPING RINGS*

D. L. Rubin†, Cornell University, Ithaca, NY 14853, USA

Abstract

The science of designing damping rings for linear colliders continues to mature with the ongoing investigations of damping ring physics and technology at the Accelerator Test Facility (ATF) at KEK and the CESR Test Accelerator (CesrTA) at Cornell. We review lattice design, emittance tuning techniques, electron cloud and other collective effects that are manifested in the ultra low emittance regime, and specialized instrumentation for monitoring and manipulating low emittance beams.

INTRODUCTION

The damping ring for the ILC is required to accept trains of hot bunch of positrons, and to reduce their phase space volume by more than 6 orders of magnitude at a repetition rate of $\sim 5-10$ Hz. The short damping time requires that the synchrotron radiation from the normal dipole magnets be supplemented by that from high field wigglers. The circumference of the ring is defined by the number of bunches that fill each linac pulse and the inter bunch spacing that can be managed with state of the art fast kickers. The specification for vertical emittance of the extracted beam is a few pm-rad. The ring is therefore necessarily instrumented to make possible identification and correction of emittance diluting misalignments and lattice errors. We discuss the challenges for lattice design, techniques and instrumentation for low emittance tuning, electron cloud and ion effects and mitigations, and a test of a fast injection/extraction kicker in the context of the research at the damping ring test facilities ATF at KEK and CesrTA at Cornell.

LOW EMITTANCE OPTICS

The ILC linac will operate with a $\sim$ 1ms pulse at a repetition rate of 5Hz with 1300 bunches accelerated into collision in each pulse. In a ring with 3.2km circumference the beam current is anticipated to be below thresholds for emittance diluting instabilities and the bunches will be sufficiently separated that a fast kicker can inject and extract a single bunch without interference with its neighbors. A racetrack configuration is convenient for integrating the damping rings into the larger accelerator complex and minimizing facilities costs[1]. The equivalent horizontal and vertical emittances of the injected bunch at 5GeV are 10^{-6} m-rad, and on extraction 200ms later $\epsilon_x \sim 5\times10^{-10}$m-rad and $\epsilon_y \sim 2\times10^{-12}$m-rad. The combined requirements of:

- large dynamic aperture, many orders of magnitude greater than the equilibrium beam size
- short damping time of order 2000 turns
- ultra low equilibrium emittance
- momentum compaction small enough to yield short bunches with reasonable RF voltage, but large enough to inhibit single bunch instabilities

can all be satisfied with a wiggler dominated design. In the ILC damping ring, as much as 90% of the synchrotron radiation is emitted in wigglers. The wigglers increase the damping rate by an order of magnitude and reduce emittance by a factor of 5. The lattice adopted for the baseline design has a 3.2km circumference, 5GeV beam energy, 24ms transverse damping time, and momentum compaction of 3.3×10^{-4}. There are 54, 2m superconducting damping wigglers with 2.1T peak field, and 12, 650MHz single cell superconducting RF cavities providing a total of 14MV for a 6mm bunch length. An advantage of damping wigglers as a mechanism for reducing emittance, as compared to stronger focusing, is that with wigglers there is very little degradation of the dynamic aperture. And a large dynamic aperture is essential for a ring that is required to accept beams with 10,000 times the equilibrium emittance.

CesrTA has been configured to operate at low emittance and with short damping time by exploiting damping wigglers in the same manner as for the ILC damping ring described above. At 2.1 GeV beam energy, superconducting wigglers with 1.9T peak field increase the radiation damping rate by an order of magnitude (from 2/second to 20/second), and reduce the emittance by a factor of 4, from 10nm to 2.5nm. With 4 single cell superconducting RF cavities at 500 MHz, the bunch length is 9mm at total accelerating voltage of 8MV. As the beam energy is somewhat lower than the ILC damping ring, the effects of the very instabilities under investigation are enhanced. The circumference of the CESR ring is 768m. There are 55 horizontal, 58 vertical, and 25 skew correctors. The high band width beam position monitors have bunch by bunch and turn by turn capability.

The ATF damping ring is designed to produce a very small vertical emittance. It has a circumference of 138.6m with two 27.6m straights and 41.7m arcs. It is instrumented with 48 horizontal and 50 vertical corrector magnets, 68 skew quadrupoles and 96 very high precision beam position monitors recently upgrade to $< 1\mu$m resolution. Beam energy is 1.3GeV and zero current horizontal emittance is calculated to be 1.1 nm.

---

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

† david.rubin@cornell.edu

LOW EMITTANCE TUNING

Vertical dispersion in bends and wigglers is the principle source of vertical emittance. Vertical dispersion is generated directly by vertically offset quadrupoles, and rolled dipoles, and indirectly by coupling of horizontal into vertical by tilted quadrupoles or vertically displaced sextupoles. To routinely achieve and then maintain low emittance the following are required:

- Periodic survey and alignment of guide field elements
- Beam based techniques for calibrating position monitors and identifying sources of coupling and vertical dispersion
- Algorithms for compensating the misalignments with corrector magnets

Simulations are the principle tool for assessing sensitivity to alignment errors, effectiveness of correction algorithms and number and disposition of correctors and beam detector specifications. If we can demonstrate the reliability of our simulations at ATF and CesrTA, we can extrapolate with some confidence to the ILC damping ring.

Tuning ATF for low emittance

The procedure for tuning low emittance in the ATF damping ring[2] consists of three consecutive corrections: orbit correction, simultaneous correction of vertical orbit and vertical dispersion, and finally a coupling correction. The closed orbit distortion is minimized using all of the steering magnets. Following orbit correction, dispersion is measured and a weighted sum of vertical-dispersion and orbit is minimized using steering magnets. The dispersion is obtained as the difference of orbits measured with different frequencies of RF accelerating cavities. The fractional energy difference of the two orbits is typically about 1%. To achieve few picometer vertical emittance in the ATF lattice, rms residual vertical dispersion must be less than about 5mm, corresponding to an orbit difference of 50μm[14], well within the resolution of the beam position monitors. The dispersion measurement is insensitive to BPM quadrupole offsets. The coupling is defined as the change in vertical orbit due to the change in the strengths of a non degenerate pair of horizontal steering magnets. The measured coupling is minimized using the skew quadrupole correctors.

The β-functions at each quadrupole can be measured as the variation of tune with quadrupole strength. Alternatively the orbit response matrix is fit to a machine model using quadrupole strengths and tilts, BPM gains and couplings, and corrector strengths and tilts. At ATF, the matrix is constructed as the response of all BPMs in each plane, to all of the steering magnets. Collecting the data can be slow.

BPM centering at ATF The effectiveness of the low emittance tuning procedure outlined above, (and the orbit correction in particular) for ATF depends on minimizing the offset error of the BPM with respect to the adjacent quadrupole. The offset is measured as follows[3]:

- A closed orbit bump (horizontal or vertical) is made through the target quadrupole.
- The strength of the quadrupole is varied, and the change in the orbit recorded.
- The orbit change is fitted in a lattice model, to determine the beam-quad offset.

The effectiveness of the low emittance tuning procedure is tested in simulations. Magnet and BPM misalignments are introduced into the machine model. The tuning algorithm is applied to the machine modeled for each of 500 seeds based on simulated measurements of orbit, dispersion and coupling and the correction is applied to the model. The simulation shows that the tuning procedure yields $\epsilon_y < 5$pm for most seeds if the quadrupole-BPM offset is less than 100μm. Indeed with the installation of higher resolution BPMs improving from 20μm to 5μm, and beam based alignment of BPMs with respect to quad centers, correction yielded emittance of 3.5-5pm[3], in reasonable agreement with the simulations. Further study indicated that in order to consistently achieve emittance less than 5pm, BPM quadrupole offset must be know to better than $\sim 20\mu$m[3].

CesrTA Low Emittance Tuning

At CesrTA we have developed techniques that allow us to make complete characterization and then correction of lattice errors a routine affair. To that end the high bandwidth capability of the beam position monitor system is exploited. The procedure is to:

- Measure and correct closed orbit using all steerings
- Measure betatron amplitudes, phase advance and coupling and correct with all skew quads and lattice quads. The phase and coupling derives from turn by turn position data of a resonantly excited beam[4].
- Remeasure closed orbit, phase and coupling, and measure dispersion. The dispersion measurement is conceptually the same as the coupling measurement except the beam is resonantly excited at the synchrotron tune. Simultaneously minimize closed orbit errors, coupling and vertical dispersion using vertical steerings and skew quadrupoles.

The machine is modeled with magnet and BPM misalignments and resolution that can be readily achieved including differential position resolution of 10μm and BPM tilt of 22mrad. With these assumptions the low emittance tuning procedure yields $\epsilon_y < 8.9$pm-rad for 95% of seeds, consistent with our control room experience where we routinely achieve sub 10pm-rad vertical emittance.

The simulations show that if the BPM tilt is reduced from 22mrad to 10mrad, then 95% of seeds yield a corrected emittance less than 5pm and if in addition the differential resolution of the BPMs is reduced from 10μm to 4μm that 95% of seeds can be corrected to less than 2pm-rad. Clearly the ability to identify sources is limited by the differential BPM resolution and systematics, and not by the number or disposition of correctors. Absolute BPM position resolution is not a fundamental limit, as the measurement of dispersion is independent of BPM offsets. The systematic that limits the quality of the dispersion measurement in CesrTA is the BPM tilts.

Note that while CesrTA and KEK-ATF achieve nanometer horizontal emittance in very different ways (CesrTA depends on damping wigglers and ATF on strong focusing), the low emittance tuning procedures have comparable performance, and depend principally on regular survey and alignment, careful measurement of quadrupole offsets, and most importantly to achieve $\epsilon_y < 10$pm, on 5-10μm BPM resolution. We find further that vertical emittance can be consistently reduced to less than 2pm in both rings as long as the dispersion can be measured with adequate precision, and that precision requires BPMs with $\sim 1-4\mu$m accuracy.

Instrumentation for low emittance tuning

Evidentally, essential instrumentation for low emittance tuning includes precision and very stable beam position monitors for measuring orbit, optical errors, and transverse coupling and dispersion, and beam size monitors for measuring the emittance.

Beam Position Monitors The CesrTA beam position monitors are designed specifically for the high resolution measurements required for low emittance optics correction for CesrTA. The front end bandwidth is 500MHz providing a bunch by bunch and turn by turn capability for bunches spaced as few as 4ns apart. The single shot resolution and differential position accuracy are both about 10μm. Absolute position accuracy is determined by the BPM offsets.

The ATF beam position monitors can operate in a turn-by-turn wide band mode, or a narrow band high resolution mode. An average vertical resolution of 800nm is measured in the narrow band mode, providing the capability to measure dispersion with 100μm precision.

BPM systematics Systematic effects that limit measurements of orbits and dispersion, and that are accessible to beam based diagnosis, include BPM offsets and tilts, and button to button gain variations. The technique for beam based alignment of BPMs with respect to quadrupole centers at CesrTA is similar to that used at ATF. At CesrTA, with each change of the strength of the target quadrupole, there is a measurement of betatron phase, along with the orbit measurement. A subsequent fit to the phase as well as the orbit resolves problems due to hysteresis and quadrupole calibrations, and yields rapid convergence.

Button to button gain variation is measured by driving the beam simultaneously at both normal mode tunes, and collecting turn by turn position data at each of the BPMs for several thousand turns. In this way most of the active region of the BPM is efficiently sampled. Since each x-y position can be determined with only three of the four button measurements, the system is over constrained and a simple fitting procedure yields a set of button gains consistent with the multiple measurements[5] . BPM tilts can be extracted from the coupling measurements by taking advantage of the fact that the out of phase component of the coupling matrix $\bar{C}_{12}$ is insensitive to tilt. Then if $\bar{C}_{12}$ is corrected with skew quads, the in phase components $\bar{C}_{11}$ and $\bar{C}_{22}$ provide a direct measure of the physical tilt.

Normal Mode Correction Alternatively we calibrate the response of the BPMs to the normal mode motion of the beam, and then rather than measure horizontal and vertical dispersion, we measure A and B normal mode dispersion. The calibration of the response to normal mode motion is accomplished by collecting turn by turn data while driving the beam resonantly at first the A mode and then the B mode. Dispersion is then measured by exciting the beam at the synchrotron tune and using the calibrated normal mode response to identify A and B mode components. The measurement is completely insensitive to BPM offsets, tilts and button to button gain variations, and it precludes the need for a distinct measurement and correction of coupling[6].

Beam size monitors

The CesrTA xray beam size monitor (xBSM) vertically focuses 2-4keV dipole radiation through an optical element onto a 32 channel photo-diode array. The three different optics that have been tested include a simple pinhole, a Fresnel zone plate and a coded aperture. The optics reside in the storage ring vacuum and are selected remotely[7]. The pinhole is effective for beam sizes greater than $\sim 15\mu$m, the coded aperture for beams as small as 10μm. In CesrTA optics 6m$< \beta_y < 40$m at the source point. The digitizer is synchronized with the storage ring timing system and the bandwidth of the system is compatible with distinguishing bunches with as few as 4ns separation, providing multi-bunch and multi-turn bunch size data.

A laser wire at ATF is capable of measuring both horizontal and vertical beam sizes of a few microns. The measured width of the distribution of Compton scattered laser light is a convolution of the widths of the laser beam and the electron beam. The laser is scanned vertically through the stored beam to obtain a profile. A scan takes several minutes. It necessarily includes some smearing from beam motion. The laser wire measurements demonstrated a 4pm emittance of an electron beam. Intensity dependent measurements of emittance are shown in Figure 1[9]. The measurements also show some evidence for intra-beam scattering.

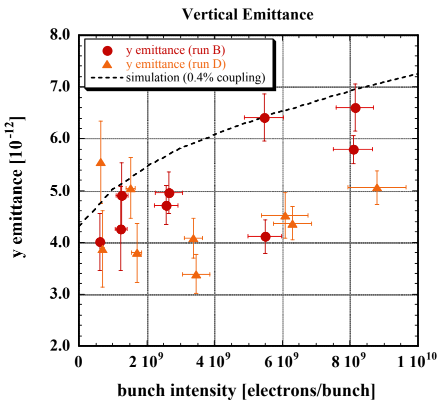

Figure 1: Intensity dependence of electron beam vertical emittance measured with laser wire at ATF.

ELECTRON CLOUD EFFECTS

The electron cloud that develops in a positron ring and that is trapped in the potential well of the beam can couple motion of the head of the bunch to the tail and of leading to trailing bunches, diluting vertical emittance and generating multi-bunch instabilities.

Measurements of the electron cloud

Retarding field analyzers (RFA) provide information about the time averaged spatial distribution and energy spectrum of the cloud. Shielded pickups (SPU) give a time resolved (nanosecond scale) measurement of the growth of the cloud. Synchrotron radiation from a lead bunch initiates development of a cloud near the SPU. A trailing bunch kicks the cloud electrons generated near the bottom of the chamber into the pickup at the top. The signal on the pickup is a measure of the density of the cloud at the time of its passage. By varying the delay between lead and trailing bunch it is possible to measure the time development and decay of the cloud and to learn something of its energy spectrum[10]. The time dependence of the signal, following the growth and decay of the cloud, depends on the reflective properties of the vacuum chamber and the quantum efficiency.

Codes that model the development of the cloud depend on a large number of input parameters to characterize the production of secondary electrons specific to the machine environment including; the energy of the peak true secondary electron yield, the low energy elastic yield, the rediffused yield at high energy, and the peak secondary production. There are also primary emission parameters such as; the quantum efficiency, the peak energy and width of the photoelectron energy distribution, and its shape, and the photon reflectivity.

RFA and SPU measurements under various conditions of beam and bunch current, bunch spacing, beam energy, magnetic field, and vacuum environment are fit to the modeled cloud using the parameters as variables, to identify the correct physics models.

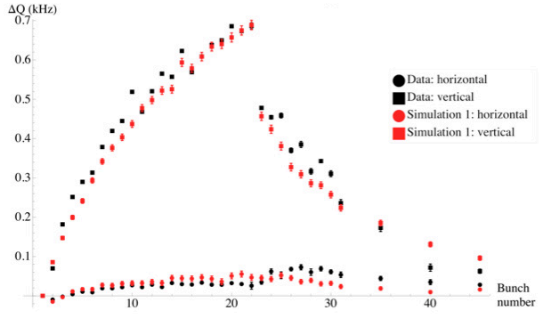

Figure 2: Tune shifts vs bunch number for a train of 20 bunches with 14 ns spacing. Witness bunches measure the decaying cloud density beyond the end of the train at 14ns intervals. Black points are data, squares are vertical and circles horizontal tune shifts. The red points are from POSINT simulations using best fit physics parameters.

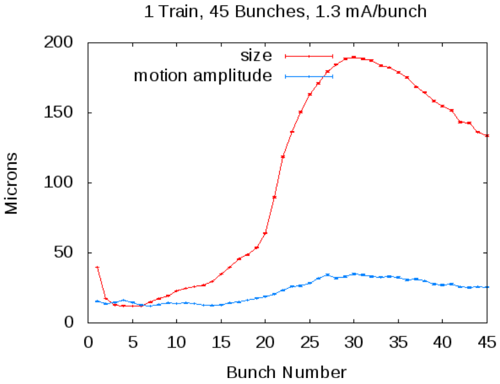

Figure 3: Vertical size (red) and centroid motion (blue) of each bunch measured with the xBSM vs bunch number in a 45 bunch train, with $2 \times 10^{10} e^+/\mathrm{bunch}$.

Beam Dynamics

Positrons are focused and electrons defocused on passage through an electron cloud. The bunch dependent tune shifts are a measure of the local cloud density. Tune shift data collected at a variety of beam energies and in different bunch configurations are fit to the simulated cloud density by varying the physics parameters of the model. This procedure has helped to further refine our understanding of the dependencies on the model parameters[11].

An example of electron cloud induced tune shift data is shown in Figure 2. The red points are computed with electron cloud modeling code using physics parameters that are the best fit to dozens of measurements.

Bunch dependent emittance growth has been observed in long trains and the electron cloud density for each of the bunches determined from the measured tune shift. Bunch by bunch vertical emittance in a 45 bunch train is shown in Fig. 3. (Bunch one is blown up by cloud generated on the previous turn). Head tail lines (synchro-betatron sidebands) are observed in the spectrum of the bunches, with amplitude increasing monotonically with cloud density.

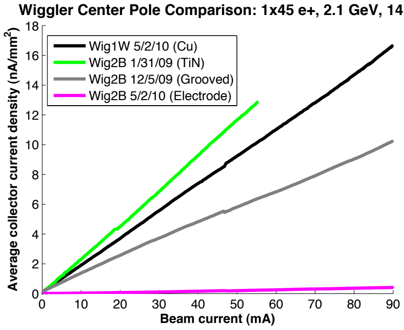

Figure 4: Wiggler mitigation comparison: 1x45 e+, 2.1GeV, 14ns

Mitigations

The physics models of the electron cloud have been and continue to be refined for consistency with the ever growing set of measurements of electron cloud phenomena. Currently, our understanding of electron cloud growth and the interaction of the cloud with the beam suggests that without mitigations to suppress the cloud, it will not be possible to achieve the damping ring performance goals. A variety of mitigations have been tested at CesrTA and at KEK-B, including grooved chambers, TiN coatings, carbon coatings, copper, aluminum, and clearing electrodes. An example of RFA measurements of different mitigations[12] in the CesrTA superconducting damping wigglers is shown in Fig. 4. Based on such measurements, mitigations have been specified for the ILC damping ring vacuum system, including TiN coating in drifts and quadrupoles, TiN coated grooved chambers in dipoles, and clearing electrodes in wigglers, and synchrotron radiation trapping antechambers in all bends and wigglers.

FAST ION INSTABILITY

Whereas the electron cloud is trapped by a positron beam, ionized residual gas can be trapped by an electron beam. Emittance growth due to the fast ion instability (FII) has been observed at the ATF[13] and the ALS. In both cases the vacuum was spoiled by turning off pumps or introducing a controlled leak to enhance the production of ions. Measurements of vertical beam size with a laser wire at ATF suggest that the threshold for the emittance growth depends on the zero current emittance of the electron beam. As regards the specifications for the ILC damping ring, it is anticipated that if the average pressure in the damping ring is less 0.1 nTorr CO-equivalent and $\alpha_p > 2 \times 10^{-4}$ that the fast ion instability can be controlled with bunch by bunch feedback. Further investigations of FII at ultra-low vertical emittance are planned at ATF and CesrTA.

FAST KICKERS

Bunches are spaced 3ns or 6ns apart in the trains that circulate in the damping rings. Injection and extraction of individual bunches requires a very fast kicker, that can rise and fall in the time between passages, and deliver a highly reproducible kick. The kicker pulser will operate in a burst mode, delivering about 2000 pulses at 3MHz with a 5-10Hz repetition rate. Stripline kickers have been tested at ATF. The 60cm striplines have a gap of about 10mm. A 10kV solid state pulser drives each strip. Two pairs of striplines give a 3mrad kick field with $<$ 5ns rise time. Stability of the kick angle of bunches extracted from a train with 5.6ns spacing, was measured to be 3.5×10^{-4}, meeting the ILC requirements[15].

ACKNOWLEDGEMENT

Many thanks to all of the CesrTA and ATF collaborators who have contributed so much to our understanding of damping ring phenomena.

REFERENCES

[1] "International Linear Collider Reference Design Report", August 2007, ILC-REPORT-2007-001.

[2] K.Kubo, et. al., "Update on Optics Modelling for the ATF Damping Ring at KEK", PAC09, Vancouver,BC, May, 2009, FR1RAC05, p. 4213, `http://www.JACoW.org`.

[3] M. Woodley, et. al., "Beam Based Alignment at the KEK-ATF Damping Ring", EPAC'04, Lucerne, July 2004, MOOCH01, p. 36, `http://www.JACoW.org`.

[4] D.Sagan, et.al., "Betatron phase and coupling measurements at the Cornell Electron/Positron Storage RIng", Phys. Rev. ST Accel. Beams 3, September, 2000 (092801)

[5] D.Rubin, "Beam based measurement of beam position monitor electrode gains" Phys. Rev. ST Accel. Beams, September 2010 (Vol. 13, No. 9)

[6] A. Wolski, et. al., Low-Emittance Tuning of Storage Rings using Normal Mode Beam Position Monitor Calibration, Phys. Rev. ST Accel. Beams 14, July 2011, 072804.

[7] D.P.Peterson, et. al., "CesrTA X-Ray Beam Size Monitor Operation", IPAC10, Kyoto, Japan, pp. 1194-1196.

[8] N. T. Rider, et. al., Development of an X-Ray Beam Size Monitor with Single Pass Measurement Capability for CesrTA, in PAC11, New York, NY, March, 2011

[9] H.Hayano, "Low Emittance Beam Generation at ATF", APAC 2004, Gyeongju, Korea, pp. 533-535.

[10] J.A.Crittenden,et . al., "Electron Cloud Modeling Results for Time-Resolved Shielded Pickup Measurements at CesrTA", PAC11, New York, NY, March 2011.

[11] D.L.Kreinick, et. al.,"Application of Coherent Tune Shift Measurements to the Characterization of Electron Cloud Growth", PAC11, New York, NY, March, 2011

[12] M.Palmer, et.al., editors, "The CesrTA Electron Cloud Research Program Phase I Report", to be published.

[13] N.Terunuma, et. al., "Recent Experimental Study of Fast Ion Instability in the ATF Damping Ring", EPAC08, Genoa, Italy

[14] K.Kubo, "Simulation study of low emittance tuning of the Accelerator Test Facility damping ring KEK",

[15] T.Naito, et. al.,"Multi-bunch Beam Extraction Using Strip-Line Kicker at KEK-ATF", IPAC10, Kyoto, Japan, 2010