CRITICAL R&D ISSUES FOR THE ILC DAMPING RINGS AND NEW TEST FACILITIES *

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Abstract

The damping rings for the International Linear Collider will be required to accept large beams from the electron and positron sources, and produce highly stable, very low emittance beams for tuning and operation of downstream systems. While many of the parameters for the damping rings are within range of storage rings presently operating, beams meeting the full quality and stability specifications have yet to be demonstrated. We discuss the principal goals of the damping rings research and development program, and the roles that could be played by some proposed future damping rings test facilities.

FUNCTIONS OF THE DAMPING RINGS

For the International Linear Collider (ILC) to achieve its luminosity goal of 2×10^{34} cm^{-2}s^{-1}, the normalised beam emittances at the interaction point must be 10 μm horizontally and no larger than 40 nm vertically [1]. It is not possible to produce either an electron or a positron beam with the necessary quality and stability direct from a source; therefore, the beams in the ILC are stored in damping rings for the 200 ms between linac pulses, during which time radiation damping reduces the emittances by several orders of magnitude. The damping rings also provide the capability of improving beam stability in a number of respects (for example, reducing bunch-to-bunch jitter), and delay the beam so that downstream systems can be tuned to compensate for effects such as variations in bunch charge.

The configuration and parameters of the damping rings are highly constrained by the configuration choices made for other systems within the linear collider. For example, the millisecond pulse length of the ILC linacs means that bunch trains must be compressed in the damping rings by injecting and extracting bunches individually; and with only a few nanoseconds between adjacent bunches in the damping rings (in order to keep the circumference within reasonable limits) the kickers for the injection and extraction pose significant technical challenges.

A range of studies [2] over recent years, including considerations of beam dynamics, technical issues and costs, have led to a baseline configuration that specifies a single damping ring for each beam (electron and positron), with ring circumference between 6 and 7 km, and beam energy 5 GeV. While every effort has been made to find a configuration that minimises technical risk, the equally important need to reduce costs means that a number of critical R&D issues remain. These include: the fast injection/extraction kickers; tuning the lattice for ultralow vertical emittance; design and construction of a low-impedance vacuum chamber; fast ion and electron cloud effects. In this paper, we outline the issues associated with each of these items, and indicate the plans leading to the necessary developments or demonstrations in each case. We begin by describing the lattice design studies: given the fundamental role of the lattice in nearly all design work, and particular technical challenges with the lattice itself, design of the damping rings lattice is another very high priority R&D issue.

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LATTICE DESIGN

A schematic layout of the positron damping ring lattice [3] used for the ILC Reference Design Report (RDR) [4] is shown in Fig. 1. The layout of the electron ring is the same, except that the beam circulates in the opposite direction, and the RF cavities are upstream of the wigglers in each lattice.

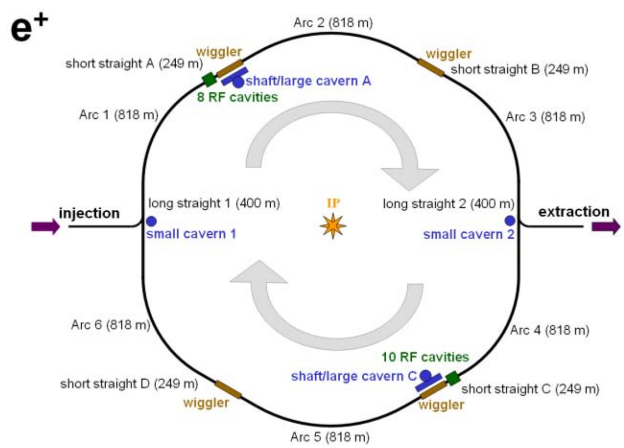

Figure 1: Layout of the positron damping ring.

One of the major challenges associated with the lattice design is achieving a sufficient dynamic aperture to ensure good injection efficiency for the positron beam (which has an injected normalised emittance of 0.01 m) [5]. The dynamic aperture can be significantly affected by field errors in the magnets. Intrinsic nonlinearities in the field of the damping wiggler are a particular concern, because of the significant length of the wiggler. To reduce the vertical emittance of the injected positron beam by more than five orders of magnitude in 200 ms, a damping time of around 25 ms is required: this is achieved by including 200 m of damping wiggler with peak field 1.6 T. The baseline configuration for the damping rings specifies a superconducting wiggler (based on the CESR-c wigglers [6]) which provides large physical aperture and very good field quality.

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Significant progress has been made in recent years with techniques to provide maps in a form suitable for tracking, based on detailed field data that may be obtained from a magnet modelling code [7, 8]. Presently, it is believed that with designs based on the CESR-c wigglers, the intrinsic nonlinearities in the magnetic field of the wigglers should not limit the dynamic aperture, and that the main limitations will come from the sextupoles, and (potentially) higher-order multipoles in the dipoles, quadrupoles and sextupoles [2, 6].

INJECTION/EXTRACTION KICKERS

To accommodate a bunch train of up to 6000 bunches, the bunch spacing in a 6 km ring must be 3 ns or less. Since the bunch spacing in the main linac will be very much larger than this (180 ns or more), bunches must be extracted individually from the damping rings. The injection process will simply be the extraction process in reverse; because of the limited time available to damp the beam before extraction, injection must be on-axis, and with injection of the full charge in any RF bucket in one shot. Thus, kickers for injection and for extraction are required that have rise and fall times less than the 3 ns separation between two bunches.

Although some novel kicker schemes have been considered [9], the baseline configuration for the ILC damping rings specifies conventional strip-line kickers driven by fast, high-power pulsers. The rise/fall time specification for the kickers limits the length of the striplines to about 30 cm. The injection and extraction components must have sufficient aperture for the beam to be transported without losses; hence, the deflection angle needed from the kickers is set by emittance of the beam. Given these considerations, the injection system for the positron beam will consist of roughly 20 consecutive pairs of striplines, with each stripline within a pair driven by a 10 kV pulser. With the smaller emittances of the injected electron beam, and the extracted electron and positron beams, the kicker parameters may be relaxed in these cases. However, pulsers providing voltages of 10 kV with rise and fall times of a little over a nanosecond are critical components for the ILC. Further important, and challenging, specifications are for a burst repetition rate of 6 MHz (corresponding to the 180 ns bunch spacing in the linacs) over a pulse length of 1 ms; and pulse-to-pulse stability of order 0.1%.

Several technologies exist that have the potential to provide the pulsers for the damping ring injection and extraction kickers [10]. Fig. 2 shows a prototype pulser using MOSFET technology in an "inductive adder" configuration [11]. This type of pulser is designed to provide a high level of reliability, though achieving the required rise/fall times could be very challenging. Other technologies being investigated include fast-ionisation dynistor (FID) devices [12], and drift-step recovery diodes (DSRD) [13]. It is possible that a hybrid could be developed, using one type of device to sharpen the pulse provided by another.

The Accelerator Test Facility (ATF) at KEK [14] provides a valuable facility for beam tests of such devices; such tests have been performed with kickers operating at low amplitudes. Observing the coherent oscillations induced on bunches in the ATF allows detailed characterisation of the kicker performance, including the evaluation of critical parameters such as the rise/fall time, and amplitude stability. Fig. 3 shows the kick amplitude measured on a bunch in ATF, as a function of the timing between the bunch passage and the kicker pulse [15]. The pulser in this case was an FID device. The rise and fall times (between 1% and 100% kick amplitude) are 3.2 ns and 4.0 ns respectively, and the output voltage is 5.8 kV. An improved version of the pulser (to achieve shorter rise and fall times and larger amplitude) is presently being developed, and should be tested before the end of 2007.

Figure 2: Inductive adder pulser.

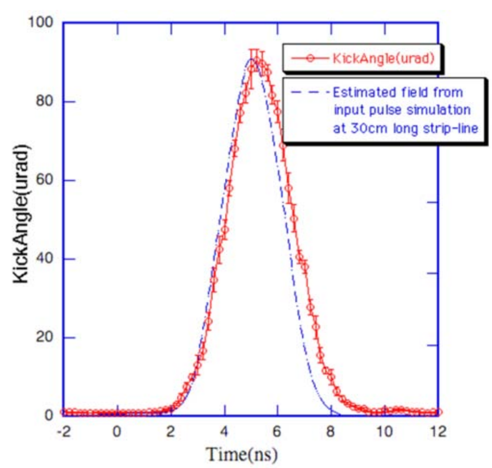

Figure 3: FID kicker pulser measured with beam at ATF.

ULTRALOW VERTICAL EMITTANCE

The ILC luminosity goal requires that the damping rings reduce the vertical emittance of the beam to 2 pm at full current. Allowing for effects that increase the emittance with increasing bunch charge (such as intrabeam scattering), the lattice design, magnet alignment, and coupling correction must be such as to achieve a vertical emittance at low current somewhat below 2 pm.

The vertical opening angle of the synchrotron radiation in a storage ring imposes a fundamental lower limit on the vertical emittance [16]. However, in the ILC damping rings (as in most electron storage rings) this fundamental lower limit on the emittance is of the order of a tenth of a picometre. The practical limits come from magnet alignment and steering errors, and collective effects.

The lowest vertical emittance achieved in any operating storage ring is 4.5 pm, in the ATF [17]. The experience from the ATF shows that four elements are essential for achieving vertical emittances in the picometre regime. First, very good initial magnet alignment is needed: in the case of the ATF quadrupoles, 30 μm rms was achieved. Second, the diagnostics system must be capable of very good performance, particularly with regard to the resolution and stability of the BPMs. Third, effective use must be made of beam-based alignment techniques to determine compensation for coupling errors. And finally, instrumentation capable of making rapid measurements of emittances in the picometre regime is needed. In the ATF, a laser wire is available for measuring beam sizes of a few microns.

A significant improvement in the ATF vertical emittance, leading to 4.5 pm, was achieved after the BPM system was upgraded, to improve the resolution from around 20 μm to 5 μm. This was consistent with the performance requirements indicated by computer simulations [18]. Further improvements in performance and functionality are needed to demonstrate 2 pm vertical emittance in the ATF. Digital receivers [19] for the BPMs were tested in early 2006, and showed very promising results, with excellent resolution, turn-by-turn capability, and low systematic errors (including variation in measured beam position with bunch charge). Further tests were performed in early 2007 [20], and an upgrade to most of the BPMs in the ATF is planned over the next year.

The studies at the ATF (and other facilities) have two major implications for the R&D for the ILC damping rings. First, for the results from the ATF to be significant for the damping rings, the damping rings should not be significantly more sensitive than the ATF to errors that generate vertical emittance. Simulation studies [21] are running in parallel with lattice design work, to ensure that the eventual lattice design has acceptable sensitivity to errors. Second, the technical designs for the ring components must be consistent with the performance specifications indicated by the ATF studies. One example is the BPM resolution, which depends not only on the BPM electronics, but also on the geometry of the BPM buttons and the vacuum chamber. Further examples include the support structures for the magnets, the temperature stability in the ring tunnel, and the instrumentation for measuring the beam emittance. In addition to ongoing work at the ATF, proposed future test facilities, including CesrTA [22], will be important for validating design choices and tuning techniques.

IMPEDANCE

A major issue for modern storage rings is the design of the vacuum chamber to minimise the ring impedance, and hence avoid impedance-driven instabilities. For high current machines, such as the B-factories, the ring impedance becomes critical. Although the beam current in the ILC damping rings will be low compared to that in the B-factories, machine operation will be significantly more sensitive to effects that could degrade beam quality or stability. At the SLC, it was found that effects from small variations in charge distribution within a bunch, driven by the chamber impedance in the damping rings, became amplified in the downstream systems, and significantly hampered tuning and stable operation [23]; and ultimately, problems with impedance in the damping rings led to the entire replacement of the vacuum chambers (something that ought to be avoided for the 6 km ILC damping rings). Presently, the parameter specifications for the ILC damping rings suggest that the impedance budget must be comparable to the rather challenging B-factories [2].

While there are still considerable difficulties, there is by now a significant amount of good experience with the design and construction of storage rings with challenging impedance budgets [24]. For the ILC damping rings, a preliminary impedance model is being constructed, based on scaling from existing machines. This will allow initial evaluation of instability thresholds to be performed in parallel with the design of the damping ring lattice, to ensure that the lattice parameters (momentum compaction factor, synchrotron tune) allow a realistic impedance budget. By the end of 2007, the lattice design will be “frozen” to allow detailed design work to proceed on a range of subsystems, including the vacuum system. As technical designs for the vacuum system components are developed, an increasingly detailed impedance model will be constructed, allowing careful modelling of impedance-driven instabilities. This will be necessary, since the thresholds and character of the instabilities can be sensitive to details of the impedance.

As work on the vacuum system design and impedance and instability modelling proceeds, there is likely to be scope for optimisation affecting a number of other systems. For example, the present specification on the momentum compaction factor may be somewhat conservative. If the momentum compaction factor can be reduced while still allowing a reasonable safety margin for the instability thresholds, it may be possible to reduce the RF voltage needed to give the specified bunch length. Reducing the RF voltage, and hence the number of cavities, will reduce costs as well as having technical benefits.

FAST ION INSTABILITY

Ion trapping in electron storage rings is a familiar effect that is usually overcome by introducing gaps into the fill, or by use of clearing electrodes. However, in certain parameter regimes, notably at very small beam sizes, sufficient ions can accumulate in the passage of just a few bunches that the stability of the following bunches is significantly affected. Effects consistent with the theory of fast ion instability [25] have been observed in a number of machines, including the ALS [26], the PLS [27] and the ATF. Fig. 4 shows the results of measurements [28] in the ATF, where a correlation was observed between emittance growth along a train of 20 bunches, and the beam current and vacuum pressure. An emittance growth dependent on the vacuum pressure is one of the signatures of the fast ion instability; however, a more thorough investigation is needed to determine whether fast ion instability is the true cause of the effects observed in this case. Experiments are planned at the ATF for late in 2007, which will include the use of a wider range of instrumentation, and the installation of a gas-inlet vacuum chamber to allow greater control over the vacuum conditions.

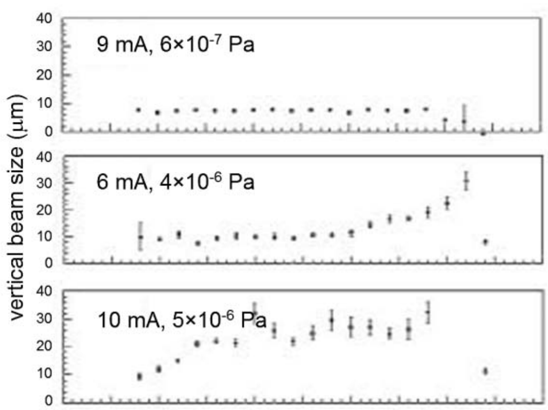

Figure 4: Observations of emittance growth correlated with beam current and gas pressure in the ATF. The horizontal axis is the bunch number (there are 20 bunches in the train, with 2.8 ns bunch spacing), with leading bunches at the left.

The present configuration of the ILC damping rings specifies a fill pattern consisting of many short trains of up to 45 bunches, with gaps of at least 45 ns between trains to clear ions. The vacuum pressure must also be kept very low (0.1 ntorr in the straights, and a maximum of 1 ntorr in the arcs and 5 ntorr in the wiggler sections). Simulations of fast ion instability for the ILC damping rings [29, 30] suggest that under these conditions, the growth rate of coherent oscillations in the beam driven by the ions may be within range of a bunch-by-bunch feedback system. If this is the case, then the emittance growth from the ion effects would also be suppressed by the feedback system. The goal of the experimental studies is to collect quantitative data for validation of the simulations.

ELECTRON CLOUD

The B-factories have been able to operate successfully at much higher beam currents than the ILC damping rings, but required installation of solenoid windings around the positron rings vacuum chambers to suppress build-up of electron cloud [31]. In the case of the ILC positron damping ring, there will be long wiggler sections (200 m in total) where solenoid windings will be ineffective. Furthermore, the beam emittances in the ILC damping rings will be about two orders of magnitude smaller than in the B-factories, which can affect the build-up of the electron cloud and potentially make the beam much more sensitive to lower densities of electron cloud.

An active and wide-ranging R&D programme is underway to ensure that the performance of the damping rings is not limited by electron cloud. There are two main strands to the programme: first, characterisation of the build-up of electron cloud and evaluation of techniques for suppressing the build-up in field-free, dipole and wiggler regions; and second, evaluation of the impact of electron cloud on beam quality and stability under the conditions expected in the positron damping ring. Mitigation techniques that have been proposed include: coating the inner vacuum chamber surface with low secondary yield materials (such as titanium nitride or non-evaporable getters); cutting grooves in the inner chamber surface [32, 33]; using clearing electrodes [32, 34]; using solenoid windings around the vacuum chamber. Some of these techniques may only be effective in particular regions (for example, solenoid fields would not reduce electron cloud in the wigglers). Coated or grooved surfaces would reduce the cloud density, while the goal of clearing electrodes would be to eliminate the cloud completely from the beam region. Whichever techniques are used have to be consistent with the design of the vacuum chamber. For example, NEG coatings would need activation, so a bake-out system would be required. Grooved surfaces and clearing electrodes have potential impedance issues, though these issues are expected to be manageable.

Many of the potential mitigation techniques have been studied under laboratory conditions; for example, data have been collected on the secondary yield of titanium nitride and NEG coatings [35]. However, data collected under machine conditions are still lacking, and this motivates many of the studies already underway or planned for the near future. Measurements of NEG coatings exposed to beam in a field-free region in PEP-II have shown very promising reduction in secondary yield [36]. Studies are proposed at CesrTA [22] and at KEKB [37] that will directly address the suppression of electron cloud in the particularly difficult wiggler sections.

Test facilities will also be critical for validating models of beam instabilities driven by electron cloud. Although the simulation codes have mostly been benchmarked against available data, no existing positron storage rings operate in the ultra-low emittance regime of the ILC damping rings: in applying the simulation codes to these rings, we make an extrapolation of two orders of magnitude in emittance. While a full-scale system test is not practical, experiments at appropriate test facilities are possible that would give an acceptable level of confidence in the predictions of the simulation codes. Foremost among the facilities proposed for electron cloud studies are CesrTA and KEKB. Each of these machines could perform detailed measurements of cloud build-up (including in wigglers) and beam instabilities, in parameter regimes very relevant for the ILC positron damping ring.

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