Characterization of Single Particle Dynamics for the International Linear Collider Damping Ring Lattice*

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Abstract

We describe the layout and lattice for the 3238 m circumference ILC damping ring, and characterize tolerances to guide field misalignments, field errors, and multipoles. With minor adjustment, the design of the DTC04 lattice is compatible with the four distinct operating modes of the collider. The differences in radiation damping times of the modes are easily accomplished with adjustment of the magnetic field of the 54 superconducting damping wigglers. While 8 superconducting RF cavities provide sufficient accelerating voltage to attain the specified 6mm bunch length in the default 5Hz mode, there is space in the lattice for as many as 16 cavities as required for the 10Hz and/or high current configurations. Evaluation of dynamic aperture and sensitivity to wiggler nonlinearities, magnet multipole errors and magnet misalignments indicates that beam based emittance tuning is effective provided the beam position monitors are sufficient in number and accuracy.

INTRODUCTION

The layout[1] of the damping ring is a racetrack, with long straights[2] to accommodate damping wigglers, RF cavities, phase trombone, injection, extraction, and circumference adjusting chicane as shown in Figure 1.

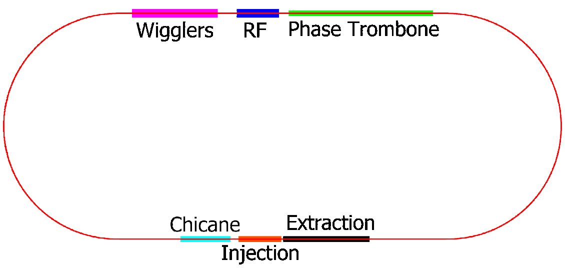

Figure 1: Damping ring layout. Circumference is 3238.7m. The length of each straight is 710.2 m.

Damping ring parameters for three ILC operating modes, corresponding to four distinct configurations, have been developed: 1) For baseline operation with 5 Hz repetition rate and 1312 bunches in both rings; 2) for operations with 10 Hz repetition rate (required for positron production in the ILC when the center-of-mass collision energy is less than twice the operating point of the positron production undulator; in this case different damping times are specified for the positron and electron rings); and, finally, 3) for the high luminosity upgrade to 2625 bunches. This is summarized in Table 1.

Alignment tolerances, and emittance tuning procedures, consistent with the required 2pm-rad equilibrium geometric vertical emittance are specified. The peak field of the 54, 2.2m long superconducting damping wigglers is 1.51T for a 26 ms damping time for the 5Hz mode and 2.16T gives a 13 ms transverse damping time for 10Hz operation. The horizontal emittance is near 0.5 nm-rad over the range of relevant wiggler fields. In the 5Hz mode, the 8 single cell 650 MHz superconducting cavities deliver a total of 14MV for a 6 mm bunch length. For 10Hz operation the number of cavities is increased to 12 and the accelerating voltage to 22.2 MV for the same 6mm bunch length. A phase trombone provides for adjustment of betatron tune and a chicane for small variations of the circumference.

LATTICE

While a circular layout has the advantage of symmetry and therefore greater tolerance to machine resonances, the racetrack conveniently locates hardware like superconducting wigglers and RF cavities in a single straight, minimizing the requisite cryogenic plumbing. We then maximize the length of the arcs consistent with the equipment destined for the straights.

The arc cell consists of one focusing and two defocusing quadrupoles that surround a single 3m bend. Focusing and defocusing sextupoles are located adjacent to the corresponding quadrupoles. There are 75 cells in each arc. The arc cell configuration was found to have somewhat better dynamic aperture than the FODO cell with comparable emittance. There is one each vertical and horizontal dipole corrector and a skew quad corrector in each cell, and two beam position monitors adjacent to the defocusing sextupoles.

Dispersion suppressors, at the ends of the arc, match the finite dispersion in the arcs to zero dispersion in the straights. The dispersion suppressor beam line includes two dipole bending magnets and seven quadrupoles. There is a skew quad corrector at each of the two dipoles.

The superconducting damping wigglers[5] are based on the CESR-c design, but with 14 poles and 30cm period. Peak field is 2.16T. There are 54 wigglers in the baseline design. The lattice can accommodate as many as 60. In order to evaluate the effect of the wiggler nonlinearities on dynamic aperture we compute the field with a finite element code (Vector Fields), and fit an analytic form as a fourier expansion that automatically satisfies Maxwell's equations. A symplectic tracking algorithm ensures that

* Work supported by National Science Foundation and by the US Department of Energy under contract numbers PHY-0734867, PHY-1002467 and DE-FC02-08ER41538, DE-SC0006505
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Table 1: DTC04 lattice parameters

Parameter	5 Hz (Low)	10 Hz(e^+)	10 Hz (e^-)	5 Hz (High)
Circumference[km]	3.238	3.238	3.238	3.238
RF frequency[MHz]	650	650	650	650
τ_x/τ_y [ms]	23.95	12.86	17.5	23.95
τ_z [ms]	12.0	6.4	8.7	12.0
σ_z [mm]	6.02	6.02	6.01	6.02
σ_E/E [%]	0.11	0.137	0.12	0.11
α_p [$\times 10^{-4}$]	3.3	3.3	3.3	3.3
$\gamma\epsilon_x$[μm]	5.7	6.4	5.6	5.7
RF [MV] Total/Per cav[1]	14.2 /1.775	22.4/1.9	17.9/1.49	14.2/1.17
RF synchronous phase [deg]	18.5	21.9	20.3	18.5
ξ_x/ξ_y	-51.3/-43.3	-50.9/-44.1	-51.3/-43.3	-51.3/-43.3
Wigglers-N$_{cells}$@B[T]	27@1.51	27@2.16	27@1.81	27@1.51
Energy loss/turn [MeV]	4.5	8.4	6.19	4.5
sextupoles[m^{-3}]	3.34/-4.23	3.34/-4.34	3.34/-4.23	3.34/-4.23
Number of bunches	1312	1312	1312	2450
Particles/bunch [$\times 10^{10}$]	2	2	2	1.74
Power/RF coupler [kW][2]	218 (389mA)	272 (389mA)	200 (389mA)	237 (632mA)

[1] Assume 8 cavities in 5Hz(Low power) configuration and 12 cavities in all others.
[2] Power/coupler is computed as (Current) X (Energy loss/turn)/(Number of cavities)

the phase space is not distorted by numerical noise.

The phase trombone consists of five cells, each constructed from six equally spaced, alternating gradient quadrupoles. The overall length of the phase trombone is 339 m. The range of the phase trombone is a full betatron wavelength in both horizontal and vertical. There is a single skew quadrupole corrector in each of the five cells.

The machine circumference is adjusted by varying the field of the chicane dipoles. For a chicane dipole field that changes path length by 4.4 mm, ϵ_x increases by $< 3\%$.

There are horizontal and vertical dipole correctors and a beam position monitor adjacent to each quadrupole in the straights. The lattice functions for the ring are shown in Figure 2.

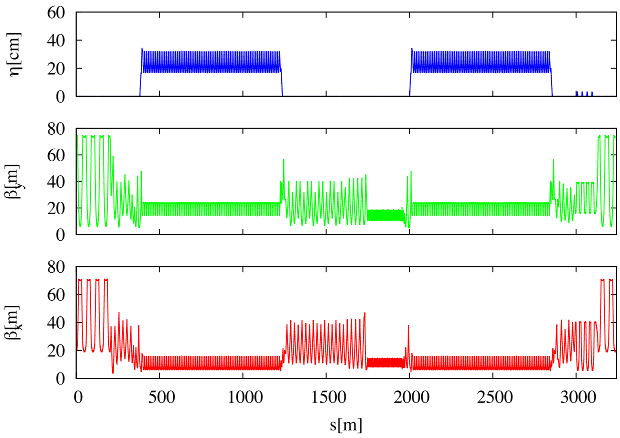

Figure 2: Damping ring lattice functions. From left extraction, arc, phase trombone, RF, wigglers, arc, circumference chicane, and injection

ERROR TOLERANCE

We consider the effect of magnetic multipoles and misalignments. Multipoles limit dynamic aperture. The principle effect of misalignments is to dilute vertical emittance. For the purpose of this study we assume that an emittance tuning procedure similar to that developed at CesrTA[3] is used to compensate misalignments and field errors.

Emittance Tuning

The tuning algorithm depends on beam based measurements and its effectiveness on the accuracy of the beam position monitors. We use the BPM specification given in Table 2. The tuning procedure has three basic steps.

1. Measure and correct the closed orbit errors using all BPMs and all dipole correctors
2. Measure by resonant excitation betatron phase and coupling and correct errors, using all quadrupoles and skew quadrupole correctors
3. Repeat measurement of orbit and coupling, and measure dispersion by resonant excitation of the synchrotron motion, and then fit simultaneously using vertical dipole correctors and skew quadrupoles

In order to evaluate the effect of lattice errors we create N (typically N=100) lattice files, each with a randomly chosen gaussian distribution of multipole and alignment errors. We assume the alignment tolerances given in Table 2, and the multipole errors measured at SLAC for the SPEAR and

PEPII dipoles, quadrupoles and sextupoles[4]. For each of the N lattice files, we apply the emittance tuning algorithm defined above. The results of the emittance tuning procedure are summarized in Figure 3. We find that for the given alignment tolerances, multipole errors, and measurement accuracy we consistently achieve the specified geometric vertical emittance of 2pm-rad.

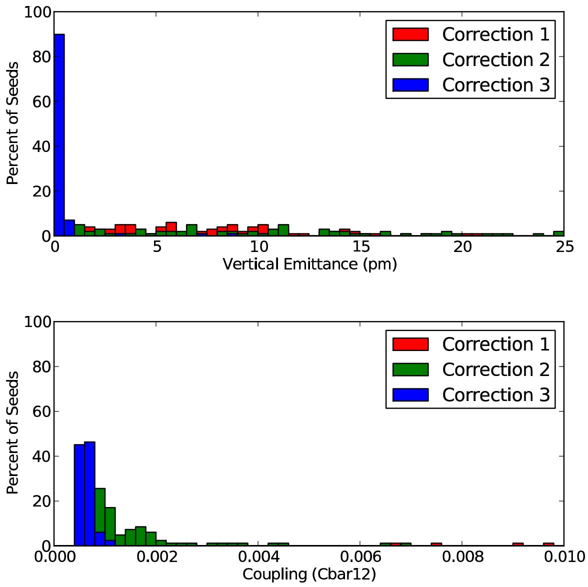

Figure 3: Histogram of the vertical emittance(top) and rms coupling ($\overline{C}_{12}$)(bottom) at the conclusion of each step in the low emittance tuning procedure for 100 lattice files with randomly chosen misalignments and multipole errors.

Dynamic aperture

We assume the positron beam will be collimated to a final phase space distribution with amplitude $A_x + A_y \leq 0.07$ m-rad (normalized) and $\Delta E/E \leq 0.75\%$. It is essential that the dynamic aperture of the damping ring be sufficient to accept all of the particles in that distribution. Dynamic aperture for a lattice with a distribution of misalignments and multipole errors, and wiggler nonlinearities including those due to end effects and finite pole width, is shown in Figure 4. We find that 100% of the injected positrons are accepted.

CONCLUSION

The DTC04 design meets the specifications for a 3.2 km ILC damping ring lattice. Dynamic aperture, including effects of magnet multipoles, magnet misalignments and wiggler nonlinearities is shown to have adequate acceptance for the large injected positron beams. The emittance tuning procedure is demonstrated to consistently yield sub 2pm-rad (geometric) vertical emittance for the deployment of correctors and beam position monitors included in our lattice model. Further study is underway to determine the minimum number of correctors and BPMs required to achieve the damping ring vertical emittance specification.

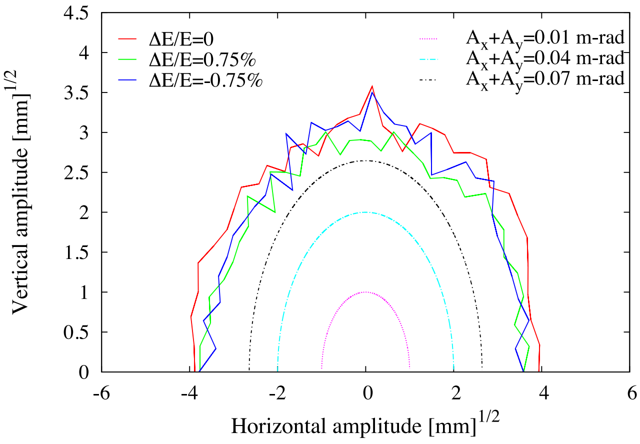

Figure 4: Dynamic aperture including multipoles, wiggler nonlinearities and magnet misalignments. Defined as the largest stable amplitude after tracking 1000 turns.

Table 2: BPM and magnet alignment tolerances.

Parameter	RMS
BPM Differential resolution	2 μm
BPM Absolute resolution	100 μm
BPM Tilt	10 mrad
BPM differential button gain	1%
Quad & Sextupole Offset (H&V)	50 μm
Quadrupole Tilt	100 μrad
Dipole Roll	100 μrad
Wiggler vertical Offset	200 μm
Wiggler - Roll	200 μrad

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