ILC 3.2 km damping ring design based on the FODO cell

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Received January 8, 2011; accepted February 17, 2011

We report on a new design for an ILC 3.2 km damping ring, with 2 arcs based on the FODO cell and 2 straight sections that are nearly the same as the newest version of the 6.4 km ring DCO4. This new lattice requires fewer magnets and a lower RF voltage, and has a better dynamic aperture than DCO4 while maintaining flexibility in regard to the momentum compaction factor. So far, this design is the only one satisfying all the requirements for a 3.2 km ring. The work on the lattice design and the dynamic aperture study is presented in detail.

ILC, damping ring design, FODO cell

Citation: Wang D, Gao J, Xu G, et al. ILC 3.2 km damping ring design based on the FODO cell. *Chinese Sci Bull*, 2011, 56: 1665–1670, doi: 10.1007/s11434-011-4483-2

The International Linear Collider (ILC) is a 200–500 GeV center-of-mass (CM) high-luminosity linear electron-positron collider, based on 1.3 GHz superconducting radio-frequency (SRF) accelerating cavities. As a large global research project, the ILC represents a collaboration of investigators from all over the world. Recently, an ever increasing number of Chinese scientists began contributing to this endeavor [1,2]. The overall design of the ILC has been chosen to realize collider physics requirements with a maximum CM energy of 500 GeV and a peak luminosity of $2 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$. Figure 1 shows a schematic view of the overall layout of the ILC.

Within the ILC, the damping rings are one of the most important subsystems because they must accept the e[−] and e⁺ beams with large transverse and longitudinal emittances and reduce the emittances to the required level within a 200 ms interval between the machine pulses. In addition, the relatively large bunch separation in the main linac beams means that the damping ring must be capable of injecting and extracting individual bunches without affecting the stored bunches. A design study of the ILC damping ring will be meaningful and helpful in building a light source

facility in China, for example, the Shanghai Synchrotron Radiation Facility [3] and the future Beijing Light Source.

In fact, the design study of the ILC 6 km damping ring started very early and went through intense competition [4–13]. Older versions of the ILC damping rings (OCS) [14] had used TME (theoretical minimum emittance) arc cells and had 6 arc sections. As early as 2005, the Chinese ILC group began using FODO (focusing and defocusing lens) cells in its design [13]. FODO structures have since replaced TME cells in the ILC damping design based on greater flexibility and large dynamic aperture. The 6.4 km DCO4 [14] based on FODO arc cells is the latest version adopted by RDR (Reference Design Report) baseline in 2008.

After the ILC had entered the Technical Design Phase 1 at the end of 2008, the Minimum Machine Study [15] based on RDR baseline was launched essentially with the premise to find cost-reductions. The term “minimum machine”, while reflecting the need to redesign the machine, did not refer to any definable true minimum, but instead was a euphemism for higher-level alternative-design concepts that could promise significant cost-reduction while maintaining machine performance. With the new machine parameters, a reduction in the number of bunches by a factor of two allowed

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Figure 1 Schematic layout of the ILC complex for 500 GeV CM.

a reduction by the same factor in the circumference of the damping ring, while keeping the current (bunch spacing) in the rings constant. This could result in a reduction in damping ring cost by almost a factor of two. However, actual cost savings will depend on the exact lattice design. Beginning at the end 2008, studies for the 3.2 km ring are still in their preliminary stages. The only existent design for the smaller ring is DSB3 [14] based on a SuperB lattice. However, this design still has some problems with its dynamic aperture. Considering the advantages of FODO lattices, such as fewer numbers of quadrupoles and sextupoles per cell, freely tunable momentum compaction, and a better dynamic aperture, we redesigned the smaller ring using FODO arc cells that can satisfy all the requirements for the ILC damping ring. For brevity, we term the new design DMC (Damping Ring-Minimum Machine-China).

1 Global consideration and parameter calculation

The basic requirements for the damping ring relate to damping time, normalized horizontal emittance, bunch length, sufficient aperture for injecting a large emittance positron beam and sufficiently large and flexible momentum compaction factor to maintain single bunch stability. The key parameters for the positron damping ring are listed in Table 1 (the electron damping ring is identical except for a smaller injected emittance).

In our design, we adopted the racetrack structure similar to the 6.4 km baseline design (DCO4). The layout of the 3.2 km damping ring is shown in Figure 2 with the electron and positron beams counter-rotating in their respective rings. The advantage of this kind of structure is that the injection and extraction beam lines for the e^+ and e^- rings can be located in the same tunnel. Also, the RF section and wigglers are located near each other to minimize cryogenic transfer lines, while the RF section must be upstream to avoid radiation damage.

Table 1 Positron damping ring parameters

Parameter	Value
Energy (GeV)	5.0
Bunch number	1320/2625
Bunch population	2×10^{10}
RF frequency (MHz)	650
Momentum compaction	$\sim 10^{-4}$
Injected normalized emittance x/y (mm)	10/10
Extracted normalized emittance x/y (μm)	8/0.02
Damping time (ms)	<25 ms
Bunch length (mm)	6
Energy spread (%)	<0.15

The first parameter that should be considered before the lattice design is the damping time. The ILC damping ring has a very fast damping time (about 25 ms) which is dictated by the 5 Hz machine repetition rate. The damping time for a damping ring is given by [16]

$$\tau = \frac{2E_0 T_0}{U_0}, \quad (1)$$

$$U_0 = U_{0,\text{arc}} + U_{0,\text{w}}, \quad (2)$$

$$U_{0,\text{arc}} = \frac{C_\gamma}{2\pi} E_0^4 I_{2,\text{arc}} = \frac{C_\gamma}{2\pi} E_0^4 \oint \frac{ds}{\rho^2} \approx C_\gamma E_0^4 \frac{B_{\text{arc}}}{(B\rho)} \propto B_{\text{arc}}, \quad (3)$$

$$U_{0,\text{w}} = \frac{C_\gamma}{2\pi} E_0^4 I_{2,\text{w}} = \frac{C_\gamma}{4\pi} E_0^4 \frac{B_{\text{w}}^2 L_{\text{w}}}{(B\rho)^2} \propto L_{\text{w}}, \quad (4)$$

where $C_\gamma = 8.846 \times 10^{-5} \text{ m/GeV}^3$, U_0 is the total energy loss from synchrotron radiation per turn, T_0 is the circling period, $U_{0,\text{arc}}$ and $U_{0,\text{w}}$ are the energy loss in the arcs and wigglers respectively, I_2 is the second synchrotron integral for storage ring, B_{arc} and B_{w} are the magnetic strength for the arc dipoles and wigglers, and L_{w} is the total length of wigglers. Because the circling period is decreased by a half, the

Figure 2 Layout of the 3.2 km ILC damping ring.

total energy loss per turn should be decreased by a half to maintain a constant damping time. We need to consider how to allot the energy loss in arcs and wigglers while maintaining total energy losses reduced by a half.

Next, we will consider the horizontal emittance of a damping ring. The formulae for equilibrium emittance are as follows [16]:

$$\varepsilon_0 = \varepsilon_{0,\text{arc}} \frac{1}{1+F_w} + \varepsilon_{0,w} \frac{F_w}{1+F_w} \left(F_w = \frac{U_{0,w}}{U_{0,\text{arc}}} \right), \quad (5)$$

$$\varepsilon_{0,\text{arc}} = \frac{F}{12\sqrt{15}} C_q \gamma^2 \frac{\theta^3}{J_x} \quad (F \approx 100 \text{ for the normal FODO cell}), \quad (6)$$

$$\varepsilon_{0,w} = \frac{8}{15\pi} C_q \gamma^2 \frac{\langle \beta_x \rangle B_w^3}{(B\rho)^3 k_w^2}, \quad (7)$$

where $C_q = 3.84 \times 10^{-13}$ m, $\varepsilon_{0,\text{arc}}$ and $\varepsilon_{0,w}$ are the equilibrium emittance contributions from the arcs and wigglers, F_w is the ratio of energy losses in the wigglers and arcs, and θ is the bending angle in each arc dipole. We find that the emittance contribution from the wigglers depends only on the peak magnetic strength but not related to their total length. If we choose the same wiggler as the baseline design (there is no strong reason for a new wiggler design), $\varepsilon_{0,w}$ will not change. In ILC 6.4 km damping ring, although $\varepsilon_{0,\text{arc}}$ is larger than $\varepsilon_{0,w}$ by one order of magnitude, the equilibrium emittance can be controlled at the required value by increasing the wiggler's contribution ($F_w \approx 10$). For the smaller ring, we elect for the same F_w value to satisfy the emittance requirements. Combined with eqs. (3) and (4), both the arc dipole strength B_{arc} and the total wiggler length L_w should be reduced by a half so that the ratio of the energy losses from arcs and wigglers is constant. During the actual design, we strengthened the arc dipoles a little; otherwise the total number of dipoles would have to be increased by one time.

In the ILC, the energy spread in the beam extracted from the damping ring is also an important parameter for the bunch compressors: the larger the energy spread, the more difficult the design and operation of the bunch compressors becomes. In the damping rings, the natural energy spread is essentially determined by the wiggler [16]:

$$\sigma_\delta^2 \approx \frac{4}{3\pi} \frac{e}{mc} C_q \gamma B_w. \quad (8)$$

Thus, the natural energy spread will be same as DCO4 (about 0.13% with beam energy of 5 GeV and wiggler field of 1.6 T).

For the momentum compaction factor,

$$\alpha_p = \frac{1}{C_0} \oint \frac{D_x}{\rho} ds = \frac{D_{x,\text{dipole}}}{C_0} \oint \frac{1}{\rho} ds = \frac{2\pi D_{x,\text{dipole}}}{C_0}, \quad (9)$$

where $D_{x,\text{dipole}}$ denotes the horizontal dispersion function in the dipole magnets. If we want to keep the momentum compaction factor at the same order as the 6 km ring, we have to reduce the horizontal dispersion in the dipoles by approximately half. In addition, the uncertainty in the impedance and instability estimation requires some flexibility in the momentum compaction factor and this can be realized by changing the phase advance of each FODO arc cell.

2 Linear lattice design

We use MAD (Methodical Accelerator Design) [17] to aid in the lattice design. There are 166 arc cells in total in our damping ring design. Therefore, including the dispersion suppressor, each dipole magnet provides a bending angle of $2\pi/340$ for the beam. By tuning the power supply of the quadrupoles in the arc cell, then adjusting the strength of the magnets in the dispersion suppressor, and finally matching sections, we can tune the momentum compaction from 2.77×10^{-4} to 6.19×10^{-4} , while the whole lattice design remains unchanged. The lattice functions in an arc cell for a 90 degree FODO cell are shown in Figure 3. During the design of the arc cell, we adjusted the Twiss parameters of the FODO cell according to eqs. (10) and (11):

$$\beta^\pm = \frac{L_c \left(1 \pm \sin \frac{\mu}{2} \right)}{\sin \mu}, \quad (10)$$

$$D^\pm = \frac{L_c \phi \left(1 \pm \frac{1}{2} \sin \frac{\mu}{2} \right)}{4 \sin^2 \frac{\mu}{2}}, \quad (11)$$

where β^+ and β^- are the maximum and minimum values of the beta function, D^+ and D^- the maximum and minimum values of the horizontal dispersion, L_c the length of the cell, μ the phase advance per arc cell, and ϕ the bending angle

Figure 3 Lattice functions in a 90° FODO arc cell.

per cell. For a smaller momentum compaction factor, the dipole magnet is located as close as possible to the defocusing quadrupole.

Aside from some main sections such as the wiggler section, RF section, injection and extraction section, we need to add a chicane for each straight section to provide a 10^{-6} adjustment capability on the circumference to counter thermal changes and ground motion effects. Figure 4 shows the Twiss parameters of the whole ring for the 90° lattice. The major parameters of our design and DCO4 are shown in Tables 2 and 3, respectively. For the same phase advance of arc cell, our design reduced the RF voltage by about 30%. Meanwhile the magnet details are shown in Table 4.

3 Dynamic aperture

The dynamic aperture should ensure efficient acceptance of

Figure 4 Twiss parameters of the whole ring.

Table 2 Major parameters for DMC3

Parameter	Value		
Beam energy	5.0 GeV		
Circumference	3258.68 m		
RF frequency	650 MHz		
Harmonic number	7065		
Transverse damping time	23 ms		
Natural bunch length	6 mm		
Natural energy spread	1.26×10^{-3}		
Phase advance per FODO cell	60°	75°	90°
Momentum compaction factor	6.19×10^{-4}	4.04×10^{-4}	2.77×10^{-4}
Normalized natural emittance (μm)	6.27	4.45	3.58
RF voltage (MV)	33.0	21.84	15.36
RF acceptance (%)	2.75	2.58	2.38
Synchrotron tune	0.067	0.044	0.03
Working point x/y	38.28/36.21	44.35/42.30	51.23/49.36
Natural chromaticity x/y	-42.3/-41.5	-51.2/-49.9	-63.7/-61.7
Maximum quadrupole gradient (T/m)	8.5	9.0	11.3
Maximum sextupole gradient (T/m ²)	50	88	151

Table 3 Major parameters for DCO4

Parameter	Value		
Circumference	6476.4 m		
Beam energy	5 GeV		
RF frequency	650 MHz		
Transverse damping time	21.1 ms		
Natural rms bunch length	6.0 mm		
Natural rms energy spread	1.27×10^{-3}		
Wiggler	216 m total length; 400 mm period; 1.6 T peak field		
Arc cell phase advance	72°	90°	100°
Momentum compaction factor	2.9×10^{-4}	1.6×10^{-4}	1.3×10^{-4}
RF voltage (MV)	32.6	20.4	17.1
Normalized natural emittance (mm)	6.4	4.4	3.9
Tunes (x/y)	61.12/60.41	71.12/71.41	76.12/75.41
Natural chromaticity (x/y)	-71.0/-72.6	-89.2/-91.0	-99.8/-100.7

Table 4 Magnet parameters

Parameter	Value		
	DMC3	DSB3	DCO4
Arc dipole length (m)	2.0	2.7	2.0
Arc dipole field (T)	0.154	0.26/0.36	0.27
Number of arc dipoles	344	128	200
Chicane dipole length (m)	1.50	1.0	1.0
Chicane dipole field (T)	0.1	0.27	0.27
Number of chicane dipoles	32	48	48
Quadrupole length (m)	0.40	0.6/0.3	0.3
Total number of quadrupoles	474	590	692
Maximum quadrupole gradient (T/m)	11.3	7.5	12.0
Sextupole length (m)	0.25		0.25
Total number of sextupoles	332	192	392
Maximum sextupole gradient (T/m ²)	151	145	215

Figure 5 DMC3 dynamic aperture. (a) Dynamic aperture for 60° lattice; (b) dynamic aperture for 75° lattice; (c) dynamic aperture for 90° lattice. The three dashed ellipses correspond to single, double and triple injected positron beam sizes respectively.

the large emittance for the positron beam. The required value is 3 times the injected e^+ beam size. For our design, we use one focusing sextupole and one defocusing sextupole per arc cell to correct the first order chromaticity to zero. The distance between sextupole and its adjacent

Figure 6 DCO4 dynamic aperture. (a) Dynamic aperture for 72° lattice; (b) dynamic aperture for 90° lattice; (c) dynamic aperture for 100° lattice. The three dashed ellipses correspond to single, double and triple injected positron beam sizes respectively.

quadrupole is set to 0.15 m. The results of DA tracking (300 turns) are shown in Figure 5. As a comparison, the DA results for DCO4 are also shown in Figure 6. In Figure 6, the unit for both horizontal and vertical axes is the injected positron beam size. We can see that the dynamic apertures of our design are apparently better than those for the DCO4.

4 Summary

An overall design of a ILC 3.2 km damping ring based on

FODO arc cells is presented; all the principle requirements for a smaller ring are satisfied. Compared with DSB3, our FODO-lattice design has larger and flexible momentum compaction factor that provides better stability (the momentum compaction factor is tunable over a large range from 2.77×10^{-4} to 6.19×10^{-4}). Also, the larger dynamic aperture is an important aspect favoring the choice of a FODO lattice. We have reduced the DR cost with a shorter tunnel, fewer magnets, and a lower RF voltage compared with the 6 km DCO4. Particularly, we obtained much better dynamic apertures than the larger ring. Our design is the only one to date that realizes all the requirements for a smaller ILC ring. Once the new machine parameters (minimum machine) and 3.2 km damping ring have been decided on by GDE, our design will prove highly-competitive among the candidates. Studies on a 3.2 km damping ring design are ongoing within the Chinese ILC group.

This work was supported by the National Natural Science Foundation of China (10525525 and 10775154).

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