Chapter 3

Beam Dynamics

There are three critical issues for the damping rings in which beam dynamics effects play a major role:

- Acceptance. Achieving an injection efficiency close to 100% will be essential for operating the damping rings safely, and without damaging critical components by radiation from beam losses.
- Vertical emittance. The luminosity of the ILC will depend on generating extremely small vertical emittance in the damping rings (and preserving the emittance to the interaction point).
- Beam stability. Commissioning, tuning and reliable operation of downstream systems, and producing luminosity, will depend on producing highly stable beams from the damping rings.

In this chapter, we consider all three issues, and evaluate the reference lattices in terms of the likely difficulty of achieving the necessary acceptance, beam quality and stability. In addition, it will be important to maintain beam polarization in the damping rings, at least for the electron beam; although this is regarded as somewhat less of a challenge than some of the other requirements, there are effects which could cause problems, and we present results from an evaluation of the polarization preservation.

3.1 Acceptance

The average injected beam power into the damping rings in normal operation will be more than 225 kW. As a result, an injection efficiency of very close to 100% will be needed, to avoid radiation damage to damping ring components. Since the beam from the positron source will be much larger than that from the electron source, acceptance is principally an issue for the positron rings: assuming that the electron and positron rings are essentially the same, a solution that works for the positrons will also work for the electrons. The injected beam distribution is defined in terms of the normalized betatron amplitudes and energy errors of particles at the exit of the injection kicker. This is the first point at which the beam is nominally "on axis" and following the closed orbit.

The normalized betatron amplitude is defined as $A_x + A_y$ where:

$$\frac{A_x}{\gamma} = \gamma_x x^2 + 2\alpha_x x p_x + \beta_x p_x^2 \tag{3.1}$$

and similarly for A_y. γ is the relativistic factor; α_x, β_x and γ_x are the horizontal Twiss parameters; x and p_x are the horizontal coordinate and conjugate momentum (normalized to the reference momentum) of a particle with respect to the reference trajectory. The specification on the transverse distribution of the injected positrons is:

$$A_x + A_y < 0.09 \text{ m} \cdot \text{rad} \tag{3.2}$$

It is sometimes convenient to work with an "equivalent rms beam size". This is defined such that:

$$3\sigma_x = x_{\text{max}} \tag{3.3}$$

and similarly for y. x_{max} is the maximum horizontal coordinate of any particle in the beam. Since, in the absence of dispersion:

$$\sigma_x = \sqrt{\beta_x \epsilon_x} \tag{3.4}$$

where ϵ_x is the rms emittance,

$$\epsilon_x = \frac{\langle A_x \rangle}{2\gamma} \tag{3.5}$$

and

$$x_{\text{max}} = \sqrt{\beta_x \frac{A_x}{\gamma}} \tag{3.6}$$

it follows that:

$$\gamma \epsilon_x = \frac{1}{9} A_{x,\text{max}} \tag{3.7}$$

In other words, the specification on the transverse distribution of injected positrons can be expressed as an rms normalized emittance in each plane

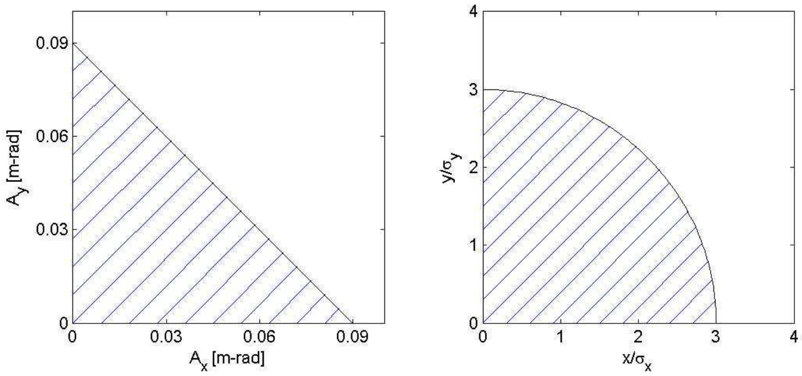

Figure 3.1: Specification on the transverse distribution of injected positrons. All particles in the injected positron beam should lie within the shaded areas. Left: specification on betatron amplitudes. Right: corresponding specification in coordinate space normalized to the rms beam size, with an equivalent rms emittance of $\gamma\epsilon = 0.01$ m·rad (only the sector with positive x and y is shown; the specification is rotationally symmetric about the origin).

$\gamma\epsilon = 0.01$ m·rad, truncated at 3σ. The specification on the transverse distribution of injected positrons is illustrated in Figure 3.1.

The specifications on the transverse amplitudes of particles in the injected bunch are independent of the longitudinal coordinates of the particles. A further specification on the injected positrons is that the energy deviations of the particles should all lie with $\pm 0.5\%$, i.e. the full-width of the energy distribution (normalized to the reference energy) is 1%. With this energy spread, the matched bunch length in the damping rings will be around 60 mm full-width. It is expected that the injected bunch length will be much less than this; however, the specification on the energy spread will be more demanding.

Note that the specifications on the transverse and longitudinal distributions include injection jitter, i.e. the centroid of the distribution may be non-zero, but all particles should still meet the specifications stated above.

The damping rings must have dynamic and physical aperture sufficient to accept a positron beam meeting the injection specifications. Generally, the acceptance of a given lattice is estimated using tracking studies. The goal of the lattice design should be to produce a lattice that has sufficient acceptance not just under ideal conditions, but also in the presence of alignment, tuning and systematic and random multipole errors. Synchrotron radiation, synchrotron oscillations and physical apertures should all be included in the tracking when determining the acceptance. Experience from operating machines is that the measured dynamic aperture can be significantly smaller than expected from tracking studies, even when all relevant effects are included. This is especially true in the early commissioning and operation stages; after careful characterization of machine errors and conditions, there can be good agreement between the measured and simulated dynamic aperture. Given the importance of good injection efficiency for operation of the damping rings, it seems prudent to aim for a design that has significant margin in the dynamic aperture beyond the bare requirements for acceptance of the specified positron distribution.

In this section, we analyze the acceptance of the reference lattices using a range of techniques and tools, under a number of different conditions. In Section 3.1.3 we consider the dynamic aperture determined by the survival of particles tracked at different amplitudes over some number of turns. The results presented include effects such as the nonlinear fields in the wiggler, and higher-order multipole errors in the main magnets. In Section 3.1.4 we present the results of Frequency Map Analysis (FMA) of the reference lattices. FMA gives more detailed information on the dynamics than a simple survival plot; however, since the technique is more computationally expen-

Table 3.1: Sytematic and random multipole errors in the dipoles used in tracking studies in the reference lattices. The reference radius is 30 mm.

n	systematic		random	
	b_n	a_n	b_n	a_n
3	1.60×10^{-4}	0	8.00×10^{-5}	0
4	-1.60×10^{-5}	0	8.00×10^{-6}	0
5	7.60×10^{-5}	0	3.80×10^{-5}	0

sive, the range of conditions investigated is not as wide as for the survival plots. In Section 3.1.6 we estimate the injection efficiency of the reference lattices using a simulated distribution of injected positrons. Finally, in Section 3.1.7 we consider the effects of the physical aperture in the wiggler (which is expected to be the limiting physical aperture in the damping rings).

3.1.1 Multipole Errors

For tracking studies with multipole errors in the main magnets, a consistent set of errors was used for all reference lattices. These errors were based on systematic and random higher-order multipole components measured in the PEP-II and SPEAR-3 magnets. The error values used in the tracking studies are shown in Table 3.1 (dipoles), Table 3.2 (quadrupoles) and Table 3.3 (sextupoles). The higher-order multipole error coefficients are defined by:

$$\frac{\Delta B_y + i\Delta B_x}{|B(r)|} = \sum_n (b_n + ia_n)\left(\frac{x}{r} + i\frac{y}{r}\right)^{n-1} \tag{3.8}$$

where ΔB_x and ΔB_y are the horizontal and vertical components of the field from the multipole error at the transverse position given by the coordinates x and y; and $|B(r)|$ is the magnitude of the field from the main magnet (dipole, quadrupole, or sextupole) at the reference radius r.

3.1.2 Wiggler Models

Wigglers have intrinsically nonlinear fields that can affect the dynamic aperture of a lattice. The damping rings will have relatively long sections of strong wigglers compared to conventional storage rings (see Table 3.4), so the effects of the wiggler need particularly careful consideration. In the studies reported here, there are four models of the wiggler commonly used. These are described below.