A Damping Ring Primer

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- Linear collider emittance requirements
- Synchrotron radiation damping
- Specific damping ring designs and issues
- Summary
Linear Collider goals

The Linear Collider must achieve

- 5 to 10 times the energy, and
- 10,000 times the luminosity of the Stanford Linear Collider (SLC).

The large factor in luminosity is achieved, in part, by reducing the emittance (area in phase space occupied by beam particles).

<table>
<thead>
<tr>
<th>beam energy $E$ (GeV)</th>
<th>luminosity $L$ (cm$^{-2}$ s$^{-1}$)</th>
<th>normalized emittance at IP $\gamma\varepsilon_H \otimes \gamma\varepsilon_V$ (µm·rad)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SLC</td>
<td>45.6</td>
<td>$3 \times 10^{30}$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$\approx 50 \otimes \approx 10$</td>
</tr>
<tr>
<td>NLC</td>
<td>250</td>
<td>$2.0 \times 10^{34}$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$3.6 \otimes 0.04$</td>
</tr>
<tr>
<td>TESLA</td>
<td>250</td>
<td>$3.4 \times 10^{34}$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$10 \otimes 0.03$</td>
</tr>
</tbody>
</table>

*Note:* normalized emittance $\gamma\varepsilon$ is conserved during acceleration.
Damping rings

• Use synchrotron radiation damping to reduce the emittances of the beams to meet the interaction point requirements

• Reduce the jitter of the beam from the source

• Delay the beam so that downstream systems can compensate for variations in bunch intensity
The sequence of machines

NLC

TESLA
Luminosity & accelerator parameter choices

Luminosity can be written in terms of the beam power $P$ and beam size $\sigma_H, \sigma_V$ at the interaction point:

$$L = \frac{1}{4\pi E} \frac{N}{\sigma_H} H \frac{P}{\sigma_V}$$

($N$ is the number of particles/bunch and $H$ is an enhancement factor due to beam-beam focusing.)

- $N/\sigma_H$ is limited by the beamstrahlung the experiment can tolerate.
- $P$ is limited by the operating budget.
- The strategy is to make $\sigma_V$ small:
  - Disruption parameter $\propto N/(\sigma_H \sigma_V)$ must be moderate
  - Focusing by final quadrupole magnets is limited by synchrotron radiation in the magnets

Vertical emittance must be kept very small.
Warm linear accelerator option: parameter optimization

- High beam power requires multiple bunches per machine cycle.
- Achieve good wall-plug-to-beam-power efficiency by using a short RF pulse and relatively small accelerating structures (high frequency).
- Requires RF pulse compression to achieve high accelerating gradients.

Bunch trains in damping ring are short (so circumference can be small) and must damp quickly.

Superconducting option: parameter optimization

- High beam power requires multiple bunches per machine cycle.
- Achieve good wall-plug-to-beam-power efficiency by using a long RF pulse.
- Accelerating cavities can be relatively large (low frequency).
- High $Q$ permits high accelerating gradients with relatively low RF power.

Bunch trains in damping ring are long (circumference is large) but have more time to damp.
Emittance reduction

The damping rings must reduce the positron emittance by 6 orders of magnitude.

<table>
<thead>
<tr>
<th></th>
<th>normalized emittance from source $\gamma \varepsilon_H \otimes \gamma \varepsilon_V$ (μm·rad)</th>
<th>normalized emittance after damping $\gamma \varepsilon_H \otimes \gamma \varepsilon_V$ (μm·rad)</th>
</tr>
</thead>
<tbody>
<tr>
<td>e−</td>
<td>100 $\otimes$ 100</td>
<td>3 $\otimes$ 0.020</td>
</tr>
<tr>
<td>NLC</td>
<td></td>
<td></td>
</tr>
<tr>
<td>TESLA</td>
<td>40 $\otimes$ 40</td>
<td>8 $\otimes$ 0.020</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>normalized emittance from source $\gamma \varepsilon_H \otimes \gamma \varepsilon_V$ (μm·rad)</th>
<th>normalized emittance after damping $\gamma \varepsilon_H \otimes \gamma \varepsilon_V$ (μm·rad)</th>
</tr>
</thead>
<tbody>
<tr>
<td>e+</td>
<td>30,000 $\otimes$ 30,000 (edge)</td>
<td>3 $\otimes$ 0.020</td>
</tr>
<tr>
<td>NLC</td>
<td></td>
<td></td>
</tr>
<tr>
<td>TESLA</td>
<td>14,000 $\otimes$ 14,000</td>
<td>8 $\otimes$ 0.020</td>
</tr>
</tbody>
</table>
Synchrotron radiation

Radiation in instantaneous rest frame of accelerated charge:

- Power per unit solid angle is $\frac{dP}{d\Omega} \propto |\vec{v}|^2 \sin^2 \phi$
- Note: component of $\vec{v}$ along line of sight is $\vec{v} \sin \phi$
Instantaneous rest frame of particle:
Suppose a photon is radiated perpendicular to orbit

\[ \theta_{\text{rest}} = \frac{\pi}{2} \]

Lab frame:

\[ \tan \theta_{\text{lab}} = \frac{1}{\gamma \beta} \]. For \( \gamma >> 1 \), \( \theta \approx \frac{1}{\gamma} \)
So, in the lab frame, the radiation pattern is:

- Synchrotron radiation is highly directional (concentrated in a cone about the particle’s velocity, with an angular width $\sim 1/\gamma$).
Synchrotron radiation as a damping mechanism

Transverse momentum has decreased. (Similar damping mechanism for longitudinal momentum error).
Equilibrium emittances

Emission of photons results in excitation of horizontal motion:

- magnet (horizontal bend)
- photon emitted
- closed orbit, design momentum
- actual orbit
- closed orbit, particle momentum

Excitation + damping produces an equilibrium horizontal emittance.

Vertical emittance is mainly due to errors resulting in:
- vertical bends and
- $H$-$V$ coupling.

A fundamental lower limit for the vertical emittance comes from the distribution in out-of-plane angle of the emitted photons.
Minimizing damping time and equilibrium emittance

• Seek short damping time to match repetition rate requirement
  \[ \tau \propto CE^{-3} \rightarrow \text{minimize } C, \text{maximize } E \]

• Seek low equilibrium horizontal emittance to match interaction point requirement
  \[ \gamma \varepsilon_x \propto E^3 \rightarrow \text{minimize } E \]

• Seek low energy spread
  \[ \Delta E/E \propto E \rightarrow \text{minimize } E \]

Requirements conflict!

Can use a wiggler magnet to provide additional damping at low energy

In a wiggler-dominated machine with a maximum wiggler field of \( B_0 \) and wiggler length \( L_w \), (very roughly)

\[ \tau \propto L_w^{-1} B_0^{-2}; \quad \gamma \varepsilon_x \propto B_0; \quad \Delta E/E \propto B_0^{1/2} \rightarrow \text{low } E, \text{large } B_0 \]
Damping ring layout (warm design)

TME lattice in arcs with most damping provided by wiggler magnets in dispersion-free straight sections.

Three trains of bunches are damped simultaneously to allow for a 120 Hz repetition rate.
Damping ring layout (cold design)

TME lattice in arcs, very long straight sections, with most damping provided by wigglers in shorter straight sections. Long straights use x-y coupling to overcome space-charge tune spread. Bunches are injected/ejected individually to minimize circumference.

schematic:

QuickTime™ and a TIFF (LZW) decompressor are needed to see this picture.

to scale:

QuickTime™ and a TIFF (LZW) decompressor are needed to see this picture.
**Emittance correction**

Achieved and required *emittances* and sensitivities to misalignment (*not* tolerances)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>ALS</th>
<th>APS</th>
<th>ATF</th>
<th>SLS</th>
<th>NLC MDR</th>
<th>TESLA DR</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\gamma\varepsilon_x$ (µm·rad)</td>
<td>24</td>
<td>34</td>
<td>2.8</td>
<td>23</td>
<td>2.2</td>
<td>8</td>
</tr>
<tr>
<td>$\gamma\varepsilon_y$ (µm·rad)</td>
<td>500</td>
<td>140</td>
<td>28</td>
<td>70</td>
<td>13</td>
<td>14</td>
</tr>
<tr>
<td>y alignment (µm)</td>
<td>135</td>
<td>74</td>
<td>87</td>
<td>71</td>
<td>31</td>
<td>11</td>
</tr>
<tr>
<td>roll alignment (µrad)</td>
<td>860</td>
<td>240</td>
<td>1475</td>
<td>374</td>
<td>322</td>
<td>38</td>
</tr>
<tr>
<td>y jitter (nm)</td>
<td>850</td>
<td>280</td>
<td>320</td>
<td>230</td>
<td>75</td>
<td>76</td>
</tr>
<tr>
<td>$\Delta k/k$ (0.01%)</td>
<td>1.5</td>
<td>1.4</td>
<td>2.1</td>
<td>1.5</td>
<td>1.8</td>
<td>1.1</td>
</tr>
</tbody>
</table>
Accelerator Test Facility (ATF) at KEK
Accelerator Test Facility (ATF) at KEK

The ATF program includes emittance correction experiments; damping ring hardware development; precision instrumentation development; studies of collective effects,…
Wigglers

Wiggler magnets are unlike typical (dipole, quadrupole,...) magnets:

- the longitudinal field is comparable, in magnitude, to the transverse field;
- the design orbit is different from the wiggler axis (it wiggles!).

Effective field errors are produced by:

- the combination of the longitudinal field and the angle of the orbit with respect to the wiggler axis;
- the combination of the field roll-off away from the wiggler axis and the displacement of the orbit from the wiggler axis.
A “perfect” wiggler

A “perfect” wiggler has infinitely wide poles and a sinusoidal variation of field with longitudinal coordinate $z$:

\[
B_y = B_0 \cosh(k_w y) \cos(k_w z)
\]
\[
B_x = 0
\]
\[
B_z = -B_0 \sinh(k_w y) \sin(k_w z)
\]
But, even a “perfect” wiggler has effective field errors

The longitudinal magnetic field $B_z$ has a component that is transverse to the undulating path of the beam, and exerts a force on the particles.

The effective horizontal magnetic field, integrated over the particle path (where the wiggler length is $L_w$) is:

$$\int B_x ds \approx -\frac{L_w B_0}{2B\rho} \left(y + \frac{2}{3} k_w y^3 + \frac{2}{15} k_w^2 y^5 + \cdots \right)$$

resulting in a vertical (only) tune shift of:

$$\Delta Q_y \approx \langle \beta_y \rangle L_w \frac{B_0^2}{8\pi (B\rho)} \left(1 + 2k_w^2 y^2 + \frac{2}{3} k_w y^4 + \cdots \right)$$

An unavoidable nonlinearity!
Wiggler with a finite pole width

The combination of the field roll-off away from the wiggler axis and the displacement of the orbit from the wiggler axis produces an effective vertical magnetic field (integrated over the particle path) of:

\[
\int_{\text{wiggler}} B_y ds \approx -\frac{1}{k_w^2} \frac{L_w B_0}{2B\rho} \frac{\partial B_y}{\partial x}
\]

resulting in a horizontal (only) tune shift of:

\[
\Delta Q_x \approx -\langle \beta_y \rangle L_w \frac{B_0}{8\pi(B\rho)^2} \frac{1}{k_w^2} \frac{\partial^2 B_y}{\partial x^2}
\]

The optimum \(k_w\) is roughly determined by a compromise between longitudinal field (\(\propto k_w^2\)) and finite pole width (\(\propto k_w^{-2}\)) effects.
Wiggler modeling and tracking

(A. Wolski)

NLC MDR: no octupole correctors

with octupole correctors
Dynamic aperture

Dynamic aperture is limited by the nonlinearities produced by

- sextupole magnets (needed for chromaticity correction) and
- wiggler magnets.

Particle loss presents a hazard to equipment: injected beam power is:

- 55 kW in NLC and
- 226 kW in TESLA

Simulation of the NLC MDR dynamic aperture (A. Wolski):

*Dynamic aperture of the NLC MDR for on-momentum (left) and +1% off-momentum (right) particles. The red ellipse shows 15× the injected beam size.*
Electron cloud

Electrons from photoemission or ionization can multiply through secondary emission as the beam accelerates them toward the chamber walls.

- Strong effect for positron beams
- Can cause single- or multi-bunch instability
- Electrons can be focused toward the core of the positron beam, enhancing the effect
Electron cloud

Average electron density vs. secondary electron yield of chamber material (simulation by M. Pivi)

Effect controlled through the use of low-SEY coatings, chamber geometry, or weak solenoids
Other effects

• The high charge density of the beams results in a significant **space charge tune spread**. In the NLC MDR, the tune spread is comparable to the beam-beam tune spread in storage rings. In the TESLA DR, a coupling bump is needed to reduce the tune spread to this level.

• **Ion trapping** by a positron beam or the **fast ion instability** can cause beam blowup or loss. A gap in the bunch train is needed to avoid trapping ions, and the vacuum, particularly in the TESLA DR, must be exceedingly good.

• The broadband wake field **impedance** of the LC damping rings must be as good as or lower than that achieved in existing machines to avoid the microwave instability. A recent revision of the NLC MDR lattice relaxes this requirement.

• **Intrabeam scattering** can cause an emittance increase. This is a small but significant effect for the NLC MDR, but insignificant for the higher-energy TESLA DR. Theoretical uncertainties exist.

• **Coherent synchrotron radiation** may cause instability.
Extraction jitter

Extraction must not introduce beam jitter.

ATF double kicker experiment:
Extraction jitter (cont.)

(H. Hayano)

**Kick angle jitter reduction**
Summary

**Critical issues** in the damping rings are:

- Emittance control in the presence of misalignment, magnet motion, and imperfect instrumentation;
- Injection acceptance (dynamic aperture);
- Electron cloud effects;
- Ion effects;
- Space charge (and the TESLA DR coupling bump);
- Broadband impedance;
- Injection and extraction kickers.

Plenty of interesting accelerator physics and technology!
Related talks in other sessions

Friday, 8:30-10:30 am session:

Andy Wolski, LBNL, “Collective Effects in Damping Rings”

Mauro Pivi, SLAC, “Electron Cloud in the NLC and TESLA”