Main Damping Ring Design for the NLC

P. Emma
and
T. Raubenheimer

- Design process and goals
- Parameters and results
## NLC Parameters...

<table>
<thead>
<tr>
<th>Parameter</th>
<th>unit</th>
<th>0.5 TeV</th>
<th>1 TeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Luminosity</td>
<td>$10^{33}$ sec$^{-1}$ cm$^{-2}$</td>
<td>7.7</td>
<td>15</td>
</tr>
<tr>
<td>Repetition Rate</td>
<td>Hz</td>
<td>120</td>
<td>120</td>
</tr>
<tr>
<td>Bunch Population</td>
<td>$10^{10}$</td>
<td>0.75</td>
<td>0.75</td>
</tr>
<tr>
<td>Bunches/RF Pulse</td>
<td></td>
<td>95</td>
<td>95</td>
</tr>
<tr>
<td>Bunch Separation</td>
<td>nsec</td>
<td>2.8</td>
<td>2.8</td>
</tr>
<tr>
<td>Injected $\gamma \varepsilon_x / \gamma \varepsilon_y$ (rms, norm.)</td>
<td>μm</td>
<td>3 / 0.03</td>
<td>3 / 0.03</td>
</tr>
<tr>
<td>$\gamma \varepsilon_x / \gamma \varepsilon_y$ at IP (rms, norm.)</td>
<td>μm</td>
<td>4 / 0.06</td>
<td>4 / 0.06</td>
</tr>
<tr>
<td>$\beta_x / \beta_y$ at IP</td>
<td>mm</td>
<td>10 / 0.1</td>
<td>10 / 0.125</td>
</tr>
<tr>
<td>$\sigma_x / \sigma_y$ at IP (rms)</td>
<td>nm</td>
<td>277 / 3.4</td>
<td>197 / 2.7</td>
</tr>
<tr>
<td>$\sigma_z$ at IP (rms)</td>
<td>μm</td>
<td>90</td>
<td>90</td>
</tr>
<tr>
<td>Pinch Enhancement</td>
<td></td>
<td>1.41</td>
<td>1.41</td>
</tr>
<tr>
<td>Beamstrahlung $\delta E_{rms}/E_0$ (rms)</td>
<td>%</td>
<td>4.5</td>
<td>10.9</td>
</tr>
</tbody>
</table>
Parameters which drive the design choices...

<table>
<thead>
<tr>
<th>parameter</th>
<th>symbol</th>
<th>value</th>
<th>unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>number of bunches per train</td>
<td>$N_b$</td>
<td>95</td>
<td></td>
</tr>
<tr>
<td>bunch to bunch spacing within train</td>
<td>$\tau_b$</td>
<td>2.8</td>
<td>nsec</td>
</tr>
<tr>
<td>gap between bunch trains for kicker rise/fall</td>
<td>$\tau_k$</td>
<td>65</td>
<td>nsec</td>
</tr>
<tr>
<td>maximum collider repetition rate</td>
<td>$f$</td>
<td>120</td>
<td>Hz</td>
</tr>
<tr>
<td>injected hor./ver. emittance (norm., rms)</td>
<td>$\gamma \epsilon_{x0,y0}$</td>
<td>$&lt;150$</td>
<td>$\mu m$</td>
</tr>
<tr>
<td>extraction hor. emittance desired (norm., rms)</td>
<td>$\gamma \epsilon_x$</td>
<td>$&lt;3.0$</td>
<td>$\mu m$</td>
</tr>
<tr>
<td>extraction ver. emittance desired (norm., rms)</td>
<td>$\gamma \epsilon_y$</td>
<td>$&lt;0.03$</td>
<td>$\mu m$</td>
</tr>
</tbody>
</table>

- First 3 parameters, plus $N$-trains ($N_t$), set ring circumference
- Last four parameters drive the lattice (damping) design
Circumference and Store Time

Require at least 3 trains ($N_t \geq 3$) for reasonable cell packing. Circumference is then, $C = c T_0$ ...

$$C \geq c N_t [(N_b - 1) \tau_b + \tau_k] = 295.27 \text{ m}$$

$$C = \frac{hc}{f_{RF}} = \frac{(708)c}{(714 \text{ MHz})} = 297.273 \text{ m}$$

Extracted vertical emittance ...

$$\varepsilon_y = \varepsilon_{y0} e^{-2N\tau} + \varepsilon_{ye} \left(1 - e^{-2N\tau}\right) < 0.03 \mu\text{m}$$

- Keep equilibrium $y$-emittance large (sets $y$-tolerances)
- Initial $y$-emittance, $\gamma_0 \leq 150 \mu\text{m}$, sets the number of damping times required per train, $N\tau$...
Equilibrium $y$-emittance and $y$-tolerances

$$r \equiv \frac{\varepsilon_{ye}}{\varepsilon_y} \ldots$$

$$N_\tau = \frac{1}{2} \ln \left( \frac{\varepsilon_{y0}/\varepsilon_y - r}{1 - r} \right)$$

Vertical alignment tolerances scale as $\sim r^{1/2}$, so push $r \to 1$
yet with reasonably small damping, $N_\tau$

*NLC MDR…*

$\varepsilon_{y0}/\varepsilon_y = 5000$, $r = 2/3$, $\varepsilon_{ye} = 0.02 \mu m$, $N_\tau = 4.8$
Damping Time-Constant of Ring

Vertical damping time-constant, $\tau_y$, is set by repetition rate, $f$, trains stored, $N_t$, and the store time per train, $N \tau \tau_y$, as...

$$\tau_y \leq \frac{N_t}{N \tau f} = \frac{3}{4.8 \cdot (120 \text{ Hz})} \approx 5.2 \text{ msec} \geq \frac{(2.9 \times 10^{12} \text{ kG}) T_0}{B_0 \gamma^2}$$

$B_0 < 18 \text{ kG}$ requires $\gamma mc^2 > 2.8 \text{ GeV}$ (RF costs $\uparrow$, $\sigma_z \uparrow$), therefore, at $1.98 \text{ GeV} (a \gamma = n+1/2)$, we need a long wiggler.

$$B_0 \propto \frac{f N \tau [(N_b - 1) \tau_b + \tau_k]}{2 \gamma^2 (1 + F_w)}$$

$F_w \equiv \frac{I_{2w}}{I_{2a}} = \frac{\text{wiggler energy loss/turn}}{\text{arcs energy loss/turn}}$
For increased momentum compaction (see next slides) we choose $F_w = 2.3$, which sets $L_w = 46.2$ m and $B_0 = 11.2$ kG.
Use TME-cells for the arcs...
(Theoretical Minimum Emittance)

- Efficient: one bend magnet per cell
- Excellent dynamic aperture in studies (‘NLC ZDR’)
- Tools for analysis well developed
- No field gradient necessary in bend
Equilibrium $x$-emittance & TME-cells...

With symmetry in bend...

\[
\frac{d\beta_0}{ds} = \frac{d\eta_0}{ds} = 0
\]

get minimum emittance at ‘optimal’ $\beta_0$ and $\eta_0$ ...

\[
\gamma \bar{\varepsilon} \approx \frac{C_q \gamma^3}{J_x} \frac{\theta^3}{12\sqrt{15}}, \quad \bar{\beta}_0 = \frac{L}{2\sqrt{15}}, \quad \bar{\eta}_0 = \frac{L\theta}{24}
\]

Now define relative parameters where cell is ‘detuned’ for $\varepsilon_r > 1$...

\[
\varepsilon_r \equiv \varepsilon/\bar{\varepsilon} \geq 1, \quad \beta_r \equiv \beta_0/\bar{\beta}_0 \geq 1, \quad \eta_r \equiv \eta_0/\bar{\eta}_0 \geq 1
\]
Maximize dispersion in the detuned cell...

$$\varepsilon_r = \frac{5}{8} \frac{\eta_r}{\beta_r} [\eta_r - 2] + \frac{9}{2} \left[ \frac{1}{4 \beta_r} + \frac{\beta_r}{9} \right]$$

Finally, maximize $\eta_r$ “for weaker sextupoles”
[Potier, Rivkin: PAC-97]...

$$\frac{d\eta_r}{d\beta_r} = 0 \rightarrow \beta_r = \varepsilon_r, \quad \eta_r = 1 + \frac{2}{\sqrt{5}} \sqrt{\varepsilon_r^2 - 1}$$

move along dashed line
Detune factor, phase advance & emittance

$\varepsilon_r$ is the horizontal phase advance per half-cell, $\mu_x$:

$$\tan \mu_x = \frac{\sqrt{3} \varepsilon_r}{\sqrt{\varepsilon_r^2 - 1 - \sqrt{5}}}$$

[Rivkin, LC-97]

Now add wiggler’s contribution to equilibrium emittance and study effects of $\varepsilon_r$ and $F_w$ variations...

$$\gamma \varepsilon_x \approx \frac{C_q \gamma^3}{12(J_{x0} + F_w)} \left[ \varepsilon_r \frac{\theta^3}{\sqrt{15}} + \frac{\langle \beta_x \rangle \hat{B}_w^3 \lambda_w^2 F_w}{16(B\rho)^3} \right] < 3 \mu m$$
Detuning, momentum compaction and $N$-cells...

\[ \alpha_p \propto \frac{\gamma}{C} (1 + F_w)^{5/3} \left( \gamma \varepsilon_0 - \frac{C_q \langle \beta_x \rangle \hat{B}_w^3 \lambda_w^2 \gamma^3}{192(B \rho)^3} \cdot \frac{F_w}{J_{x0} + F_w} \right)^{2/3} \left( 1 + \sqrt{\frac{\varepsilon_r^2 - 1}{5}} \right) \frac{1}{\varepsilon_r^{2/3}} \]

$\alpha_p$ not very sensitive to $\varepsilon_r$, but number of cells, $N_c \sim \varepsilon_r^{1/3}$, is.

Choose $\varepsilon_r = 1.647…$

- reasonable $\mu_x$ (=108°)
- near maximum $\alpha_p$
- near minimum $N_c$ cells
Effects of more wiggler damping...

As $F_w$ increases...

- Momentum compaction increases: $\alpha_p \sim (1 + F_w)^{5/3}$
- Wiggler length asymptotes: $L_w \sim \frac{F_w}{1 + F_w}$
- Arc bend field decreases: $B_0 \sim \frac{1}{1 + F_w}$
- Wiggler’s emittance asymptotes: $\Delta\varepsilon_w \sim \frac{F_w}{J_{x0} + F_w}$
Parameter choices...

- For simplicity, use bend with no gradient ($J_{x0} ≈ 1$)
- Use $B_w = 21.5$ kG (probably too high)
- Keep $\langle \beta_x \rangle$ and $\lambda_w$ reasonably small ($\langle \beta_x \rangle ≈ 4.5$ m, $\lambda_w = 27$ cm)
- Choose $F_w$ for ‘large’ $\alpha_p$ ($F_w = 2.3$, $\alpha_p = 6.6 \times 10^{-4}$)
- Solve $\theta$ for $\gamma \varepsilon_x = 3 \ \mu$m ($\theta = 12^\circ$)
- Calculate arc bend field for $\tau_y = 5.2$ msec ($B_0 = 11.2$ kG)
- Find total number of cells ($N_c = 2\pi/\theta = 30$)
- Get length of arc bends ($L_B = \theta(B\rho)/B_0 = 1.23$ m)
- Set TME-cell length ($L_c = (C - 2L_w - \Delta L_{match})/N_c = 6$ m)
- Build the arc TME-cell...
The arc TME-cell...

- $\beta_x / m$
- $\beta_y / m$
- $w / m$
- $\mu_x = 108^\circ$, $\mu_y = 45^\circ$
- 30 cells (28 full)
- 6-m cell length
- 25-cm quad length
- 4-cm quad bore
- 7-kG max. field
- 4 sextupoles/cell?

Reversed quadrupole scheme possible $\Rightarrow$ more study
Wiggler straight section...

- 20 wiggler sections
- 2.2-m section length
- ten $\psi_x = 90^\circ$ cells
- 15-cm quad length
- 6-cm quad bore
- 7.5-kG max. field
- adjustable matching

$\langle \beta_x \rangle \approx 4.5$ m
Injection/extraction straight section...

- $\beta_{x,\text{max}} \approx 14$ m

- Inj. & ext. kickers
- $-I$ between kickers
- Inj. & ext. septa
- six $\psi_x = 108^\circ$ cells
- 15-cm quad length
- 6-cm quad bore
- 5.0-kG max. field
- adjustable matching
- 3.6-m chicane
- 3 RF cavities
### Some more parameters...

<table>
<thead>
<tr>
<th>Parameters (wiggler on full)</th>
<th>symbol</th>
<th>value</th>
<th>unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>electron/positron energy</td>
<td>$E_0$</td>
<td>1.98</td>
<td>GeV</td>
</tr>
<tr>
<td>horizontal tune</td>
<td>$\nu_x$</td>
<td>23.85</td>
<td>$2\pi$</td>
</tr>
<tr>
<td>vertical tune</td>
<td>$\nu_y$</td>
<td>11.23</td>
<td>$2\pi$</td>
</tr>
<tr>
<td>horizontal damping time constant</td>
<td>$\tau_x$</td>
<td>5.171</td>
<td>msec</td>
</tr>
<tr>
<td>vertical damping time constant</td>
<td>$\tau_y$</td>
<td>5.162</td>
<td>msec</td>
</tr>
<tr>
<td>extracted horizontal emittance (rms)</td>
<td>$\gamma\varepsilon_x$</td>
<td>2.98</td>
<td>$\mu$m</td>
</tr>
<tr>
<td>momentum compaction</td>
<td>$\alpha_p$</td>
<td>6.6</td>
<td>$10^{-4}$</td>
</tr>
<tr>
<td>length of each straight section</td>
<td>$L_s$</td>
<td>58</td>
<td>m</td>
</tr>
<tr>
<td>total number of TME-cells</td>
<td>$N_c$</td>
<td>30</td>
<td></td>
</tr>
<tr>
<td>TME-cell length</td>
<td>$L_c$</td>
<td>6.013</td>
<td>m</td>
</tr>
<tr>
<td>average radius of each arc</td>
<td>$\langle \rho_a \rangle$</td>
<td>28.85</td>
<td>m</td>
</tr>
<tr>
<td>extracted relative energy spread (rms)</td>
<td>$\sigma_\delta$</td>
<td>0.089</td>
<td>%</td>
</tr>
<tr>
<td>energy loss per turn</td>
<td>$U_0$</td>
<td>760</td>
<td>keV</td>
</tr>
<tr>
<td>bunch length (rms @ 1.5 MV)</td>
<td>$\sigma_z$</td>
<td>4.00</td>
<td>mm</td>
</tr>
<tr>
<td>synchronous rf phase (@ 1.5 MV)</td>
<td>$\varphi_{rf}$</td>
<td>30.5</td>
<td>deg</td>
</tr>
</tbody>
</table>
Circumference adjustment...

$\Delta C_w = \frac{N_s B_w^2 \lambda_w^3}{3072(B\rho)^2} [8N - 1]$

($\approx 1.7 \text{ mm}$) $\Rightarrow$ Need at least $\Delta C_w$-correction for ‘wiggler-off’ and also for unexpected errors.

Emittance increase $\sim 1.3\%$ @

$\Delta C = +2 \text{ mm}$ for chicane length of $L_T = 3.6 \text{ m}$ ($\pm 2 \text{ mm} \Delta C$ range).

Other parameters, $\alpha_p$, $\tau_y$, $\sigma_z$, ...etc., are changed insignificantly.
Work remaining...

- Dynamic aperture (studied in ZDR but not for new ring)
- Abort kickers (not added yet)
- Skew quads (for correction* and/or fast MPS $\varepsilon_y$-blowup)
- Wiggler radiation deposition problem
- Termite inspection
- Lots more...

* Full skew correction is available immediately after extraction in 1st bunch compressor