Linear Colliders with Examples
From the SLC & the NLC

Lecture # 11

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Linear Colliders with examples from SLC and NLC

Tor Raubenheimer

SLAC

- Introduction
- IP issues
- Parameters
- Sources
- Polarization
- Damping rings
- Bunch compressors
- Linac beam dynamics
- Rf generation
- Collimation
- Final focus
- Advanced ideas
NLC Schematic

Electron Injector

-440 m
-11 m
-130 m

Pre-Linac 8 GeV (S)
Compressor 136 MeV (L)
Damping Ring (UHF)
2 GeV (S)
e-

-200 m
-220 m
3.85 GeV (S)
Compressor

Electron Main Linac 240-490 GeV (X)

-200 m
-9.5 km

RF Systems
(X) 11.424 GHz
(S) 2.856 GHz
(L) 1.428 GHz
(UHF) 0.714 GHz

Positron Injector

-440 m
-11 m
-440 m

Pre-Linac 8 GeV (S)
Compressor 136 MeV (L)
Damping Ring (UHF)
3-6 GeV (S)
2 GeV (L)

-180 m
-11 m
-130 m

Pre-Damping Ring (UHF)
136 MeV (L)
Compressor

Positron Main Linac 240-490 GeV (X)

-9.5 km
-10 km

3.85 GeV (S)

8047A607
Polarization and Spin Transport

- Thomas-BMT: \( \vec{S} = \vec{\Omega}_s \times \vec{S} \)

\[
\vec{\Omega}_s = \frac{-e}{m_e \gamma} \left[ (1 + a \gamma) \vec{B}_\perp + (1 + a) B_\parallel - \left( \frac{1}{1 + \gamma} + a \right) \gamma \vec{\beta} \times \frac{\vec{E}}{c} \right]
\]

where \( a = (g - 2)/2 \sim 10^{-3} \)

- Similar to electron motion: \( \vec{V} = \vec{\Omega}_c \times \vec{V} \) where \( \Omega_c = e/m_e/\gamma B_\perp \)

- For transverse fields, the precession of the spin vector is \( a \gamma \) times the bending angle while, for longitudinal fields, the precession is 2 times the beam rotation

- Two issues: spread in energy leads to a spread in spin orientation because of different rates of precession and spin-orbit coupling – this is an advantage in the SLC arcs!

- To rotate spin use horizontal bends and variable solenoids (ineffective at high energy) or variable horizontal and vertical bends (variable geometry)
Spin in SLC

Geometry in and out of DR is determined by spin rotation.

LTR

H-bend Solenoid

Spin Rotation Solenoid

Spin Rotation Solenoid (off)

Thermionic Source

Damping Ring:
Resonance Depolarization?

Injector:
Space Charge Depolarization?

Electron Spin Direction

Polarized e⁻ Source

3-94
7634A1
Spin Effects in Storage Rings

- Vertical field in storage rings causes rapid precession \( \Rightarrow \) orient spin vertically

- Spin-orbit (imperfection) resonances \( \nu_s = p \) are a problem \( \Rightarrow \) choose a half-integer spin tune \( \nu_s \): \( E = (n + 1/2)440 \text{ MeV} \)

- Betatron (intrinsic) resonances \( \nu_s = p \pm \nu_y \) are also a potential problem but with a 1/2 integer spin tune and far from the integer they are not very severe

- Siberian Snakes are an alternate approach

- Other effects such as polarization due to SR tend to be very slow compared to DR operation and can be ignored
Damping Rings

- Luminosity scales as $\mathcal{L} \propto P_{\text{beam}}\sqrt{\delta B/\epsilon_y}$

- Rf guns cannot yet deliver desired emittance or polarization – guns presently produce round beams

- Storage rings can damp large incoming emittances to equilibrium values and naturally produce asymmetric beams as desired at the IP

- The damping rate depends on the power radiated while the equilibrium emittance depends on the rms photon energy and the energy dependence of the trajectory

$$\gamma \epsilon_{\text{ext}} = \gamma \epsilon_{\text{inj}} e^{-2t/\tau} + \gamma \epsilon_0 (1 - e^{-2t/\tau})$$

$$\tau_{x,y}^{-1} = 9.4 \times 10^{-16} \frac{\gamma^3}{J_{x,y} T_0} \int G^2 ds$$

$G \propto \frac{B}{E}$

$$\gamma \epsilon_{x,0} = 3.84 \times 10^{-13} \frac{\gamma^3}{J_{x,y}} \frac{\int |G^3| H_x ds}{\int G^2 ds}$$

$$\mathcal{L}_x = \frac{(1+2\alpha)^2}{\beta_x^2} \eta_x + 2 \alpha \eta_x \eta_x + \beta_x \mathcal{L}$$

- Two effects scale the same way with energy and field but we want high damping and low emittance!

- Damp multiple trains of bunches at the same time.
Main Damping Rings

Parameters for main damping ring

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy</td>
<td>1.8 ~ 2.2 GeV; 1.98 GeV nominal</td>
</tr>
<tr>
<td>Circ.</td>
<td>223 m</td>
</tr>
<tr>
<td>Max. Current</td>
<td>1.2 A</td>
</tr>
<tr>
<td>Max. $N_{bunch}$</td>
<td>$1.57 \times 10^{10}$</td>
</tr>
<tr>
<td>Trains</td>
<td>4 trains of 90 bunches</td>
</tr>
<tr>
<td>Train Separation</td>
<td>60 ns</td>
</tr>
<tr>
<td>Bunch Separation</td>
<td>1.4 ns</td>
</tr>
<tr>
<td>$\nu_z$, $\nu_y$, $\nu_s$</td>
<td>23.81, 8.62, 0.004</td>
</tr>
<tr>
<td>$\gamma\epsilon_z$</td>
<td></td>
</tr>
<tr>
<td>$\gamma\epsilon_x$, $\gamma\epsilon_y$ w/ IBS</td>
<td>2.56 $\times 10^{-6}$ m-rad</td>
</tr>
<tr>
<td>$\sigma_\epsilon$</td>
<td></td>
</tr>
<tr>
<td>$\sigma_z$</td>
<td></td>
</tr>
<tr>
<td>$\tau_x$, $\tau_y$</td>
<td></td>
</tr>
<tr>
<td>$J_z$</td>
<td></td>
</tr>
<tr>
<td>$V_{RF}$</td>
<td>4.06 ms, 4.62 ms</td>
</tr>
<tr>
<td>$f_{RF}$</td>
<td>1.0 MV</td>
</tr>
<tr>
<td>Lattice</td>
<td>714 MHz</td>
</tr>
<tr>
<td></td>
<td>40 TME Cells</td>
</tr>
</tbody>
</table>
DR Focusing Lattices

- Need to minimize $H_x$ in the bending magnets to achieve emittance

- Optimize so that $\eta_x$ and $\beta_x$ are minimum at magnet center and $\eta_x^* \approx L_B \theta_B / 24$ and $\beta_x^* \approx L_B / 60$

- Lots of names: FOBO, TME, TBA, ... but all do the same basic thing

(SLC uses older lattice without $\eta = \beta = 0$)
Vertical Emittance

- Three are three sources of vertical emittance: vertical dispersion, betatron coupling, and radiation opening angle.

- Vertical dispersion is generated by vertical bending of the trajectory and by skew fields coupling to the horizontal dispersion.

- The effect of the trajectory tends to cancel but the skew fields which can arise from rotated quadrupoles or vertically misaligned sextupoles does not.

- Betatron coupling also is due to skew fields – this is less important in most small rings than the effect of the dispersion.

- Opening angle of the synchrotron radiation sets a more fundamental limit but is a factor of 10 smaller than NLC emittance.
Dynamic Aperture

- To attain $\gamma \epsilon_0$, need very small dispersion in bending magnets and strong focusing.

- Chromaticity correction relies on dispersion in the sextupoles and small dispersion implies strong sextupoles.

$\implies$ Geometric aberrations due to the sextupoles limit the maximum stable amplitude for the particles – high-order resonances and tune shifts.

- Solution is to place sextupoles and choose strengths so that aberrations cancel – one extreme is a non-interleaved sextupole arrangement.

$$\begin{array}{c}
\text{SF} \\
\ast \\
\text{SF}
\end{array}$$

![Graph](image_url)
Scattering

- Biggest effect is intrabeam scattering – beam-gas scattering can create a halo but has little effect on the emittance.

- In rest frame, beam momenta are very asymmetric:

\[
p_{x,y}^* = \frac{E_0}{c} \sigma_{x,y}^' \quad \quad p_z^* = \frac{E_0 \sigma_{\Delta E/E}}{c \gamma}
\]

⇒ The beam thermalizes and transfers transverse momenta to the longitudinal.

- Large momentum transfer can exceed the energy acceptance of the ring – Touschek lifetime – not really a problem in a damping ring where store time is fast.

- Multiple scattering can increase the beam emittance much like synchrotron radiation.

- IBS growth rate decreases very rapidly with beam energy.
Rf Systems

- The rf system is needed to replenish the energy lost by synchrotron radiation

- The SR determines the energy spread in the damping ring which along with the rf voltage and the momentum compaction determine the bunch length

- Beam also induces fields in the cavities and the rf voltage is the addition of the two

- Although the SR power loss is relatively small need power overhead to stabilize the beams and deal with transients – big issue in damping rings

- The fundamental must be detuned to prevent Robinson instability – need extensive feedback to stabilize rf and phase for extraction

- Higher-order modes can drive coupled bunch instabilities and must be damped
Instabilities

- Longitudinal microwave (SLC DR sawtooth) – single bunch instability from impedance due to small discontinuities in vacuum chamber – use large aperture and very smooth chamber

- Transverse and longitudinal coupled-bunch instabilities – use damped rf cavity and feedback (Pi-mode cavity in SLC DR)

- Electron cloud from photoelectrons and secondaries can couple bunches in the positron rings

- Ion trapping can do the same in the electron rings
Instabilities
Bunch Compression

- Bunches are relatively long (millimeters) in the damping rings to reduce peak current (instabilities, space charge, and IBS)

- Want bunches as short as possible to correct longitudinal wakefields in main linacs to reduce transverse wakefield dilutions – 1 millimeter in SLC, 100 microns in NLC
NLC Bunch Compressor

- Large degree of bunch compression in NLC requires two bunch compressors to reduce energy spread at low energy.

- But, a simple compressor rotates longitudinal phase space by about 90° so energy errors become phase errors and the energy in the pre-linac may be difficult to compensate.

⇒ Do 180° rotation of phase space – more complex.
Chromatic Correction

- Large energy spreads means that chromatic correction is very important.

- SLC bunch compressor is based on 2nd-order achromat but is difficult to operate, has tight tolerances, and tight apertures.

- Simple rectangular bending magnet chicane without quadrupoles is chromatically correct to all orders and does not require sextupoles etc.

\[ \chi(s) = \chi_0 + \eta_1 s + \eta_2 s^2 + \ldots \]

\[ \chi'' + k_0 \chi = 0 \]

\[ \eta_1'' + k_1 \eta_1 = -G \]

\[ \eta_2'' + k_1 \eta_2 = G + k_1 \eta_1 \]
Other Dilutions

- Incoherent synchrotron radiation causes $\Delta \gamma \epsilon \propto E^6$ — very hard to control at high energies

- Transverse space charge – self fields of the bunch – can be important at low energies and high bunch densities ($\vec{E}$ and $\vec{B}$ cancel as $1/\gamma^2$)

- Coherent synchrotron radiation is radiated at $\lambda > \sigma_z$ and $P_{SR} \propto N^2$ not $N$ — acts like a wakefield except reversed in time (tail affects bunch head) and causes an energy variation along the bunch which breaks achromaticity of compressor
Linac Dynamics

- Beam loading (long-range longitudinal wakefield)
- Long-range transverse wakefield
- Short-range longitudinal wakefield
- Short-range transverse wakefield and BNS damping
- Dispersive effects
- Rf deflections
- Betatron coupling
- Ground motion/jitter effects

- All effects are conservative so we can correct the emittance dilutions
Energy Compensation

- As beam passes through structure, it removes energy and induces fields ⇒ next bunch receives less energy than the first

- Two regimes: $t_{\text{train}} < t_{\text{fill}}$ or $t_{\text{train}} > t_{\text{fill}}$ — three different methods of correction: $\Delta f$, $\Delta t$, pre-loading

- $\Delta f$ — uses slightly different rf frequencies to generate a linear increase in field along the train

- $\Delta t$ — vary rf power in the structure to compensate loading (modulate rf or stagger rf phase)

- Pre-loading — fill structure with rf so that fields look like those after loading in equilibrium
Klystron Phase Profile and the Resulting SLED Amplitude for 13% Beam Loading (solid) and No Loading (dashed)
BEAM LOADING COMPENSATION

COMPENSATED

UNCOMPENSATED

TAIL

HEAD

120 ns BUNCH TRAIN

RF Station Unloaded Gradient (MeV/m) % Loading

<table>
<thead>
<tr>
<th>RF Station</th>
<th>Unloaded Gradient (MeV/m)</th>
<th>% Loading</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>47</td>
<td>14</td>
</tr>
<tr>
<td>1</td>
<td>44</td>
<td>17</td>
</tr>
<tr>
<td>2</td>
<td>37</td>
<td>17</td>
</tr>
</tbody>
</table>

0.3% ΔE/E
Beam Break-Up (BBU)

- Transverse modes are excited when the beam passes off-axis through a structure.

- These fields deflect trailing bunches and modulate the transverse position at the deflecting mode frequency.

$\Rightarrow$ Exponential growth of transverse positions.

- Detuning the transverse modes will reduce the BBU (wakefield dephases) – this was used after SLAC was built and is used in the NLC structures.

- With very long bunch trains detuning alone is insufficient since the modes can start to re-cohere.
Longitudinal Wakefield

- Wakefield induces a correlated energy spread along the bunch – fields from the head decelerate tail

- Compensate by running off the rf-crest with the tail getting more energy than the head
Transverse Wakefields and BNS Damping

- Problem is similar to long-range BBU – amplify incoming jitter and puts severe tolerances on linac components

- BNS damping is used to partially cancel the effect

- If beam is offset, tail is deflected towards nearest wall - like deflection from defocusing quadrupole except there is no focusing

$\Rightarrow$ lower energy of beam tail so it gets more net focusing

Two Particle Model

\[ x_1'' + k_1 (1-\xi) x_1 = 0 \]
\[ x_2'' + k_2 (1+\xi) x_2 = \frac{\Delta}{\varepsilon} x_1 \]
\[ \Delta'' + k_1 \Delta = -\omega_t x_1 + 2k_1 \xi (x_1 - \Delta/z) \]
Structure Tolerances

- Alignment tolerances are dominated by single bunch wakefields ($\sim 15\mu$m in NLC and $100\mu$m in SLC)

- Construction errors cause frequency errors in the cells of the structure – this causes the rf phase to slip from the accelerating mode ($2\pi/3$ in SLC and NLC)

$$\Delta \phi = \frac{L_{\text{cell}}}{v_g} \frac{df}{d\text{error}}$$

$$\Delta E = V_{\text{rf}} c_0 \gamma (\Delta \phi (z) + \phi)$$

- Tolerances is $\sim \mu$m in NLC and about two times looser in SLC

- Structure straightness is important because dipole mode frequencies have been chosen to dephase rapidly to decrease the long-range transverse wakefield – is a portion of the structure is misaligned there is no dephasing
Emittance Correction

- All sources of $\Delta \epsilon$ are conservative except scattering and synchrotron radiation $\Rightarrow$ emittance correction

\[ \text{No Filamentation} \]

\[
\begin{array}{c}
\text{Error} \\
2\pi(n-1/2) \\
\text{Correction}
\end{array}
\]

\[ \text{With Filamentation} \]

- Can correct static errors due to dispersion, wakefields, coupling, etc. however need to be able to measure the emittance and have knobs to correct

- In SLC, $\beta$-oscillations are used to compensate wakefield dilutions but with BNS orbit oscillations are not very effective

- In NLC, use orbit oscillations for dispersive errors, move structures to correct short-range wakefields, and use fast kickers to correct for long-range wakefields
LINAC BEAMLINE COMPONENTS

End View

Side View

- Thermal Distortion Shield
- Roller Bearing Cam
- Vertical Position Shim
- Concrete Base Pad
- Beam Position Monitor
- Stepping Motors
- Manual Position Adjust
- Quadrupole Magnet
- Input Coupler
- Accelerator Structure
- Ion Pump
- Support Slider