NLC Luminosity and Accelerator Physics

Tor Raubenheimer
Outline

- Talk will focus on luminosity design
  - Chris Adolphsen will discuss the rf hardware

1. Lessons from the SLC
2. Performance for peak luminosity
   - Beam emittance generation and preservation
   - Beam power issues
3. Design headroom and luminosity upgrade potential

- All aspects of the GLC/NLC design have been studied
  - Heavily based on experience (good and bad) from the SLC
  - Conservative design → rapid commissioning and luminosity
First Linear Collider: SLC

Built to study the $Z_0$ and demonstrate linear collider feasibility

Energy = 92 GeV
Luminosity = 3e30

Had all the features of a 2nd gen. LC except both e+ and e- shared the same linac

Much more than a 10% prototype
SLC Luminosity
Many Lessons Learned

Flexible design to allow parameter optimization

Extensive diagnostics for troubleshooting and tuning

Reliable and stable operation

Well designed collimation to limit backgrounds

→ Provides the basis for the next generation LC
Peak Luminosity
≈7,000 times larger than SLC

\[
L = \frac{f_{\text{rep}} n_b N^2}{4\pi \sigma_x \sigma_y} H_D
\]

- Focusing \((\beta_x \times \beta_y)^{-1/2}\) \(\text{NLC/SLC} \rightarrow 3\)
  - Demonstrated at FFTB
- Disruption \(H_D\) \(\text{NLC/SLC} \rightarrow 0.7\)
  - Demonstrated at SLC
- Emittance \((\gamma \varepsilon_x \times \gamma \varepsilon_y)^{-1/2}\) \(\text{NLC/SLC} \rightarrow 85\)
  - Low Emittance Transport and Damping rings
- Beam power term \((P_b * N)\) \(\text{NLC/SLC} \rightarrow 35\)
  - Bunch trains, Particle sources, Collimation and MPS
- Integrated luminosity \(\rightarrow\) Tom Himel this afternoon

\[
L = \frac{P_b N}{4\pi mc^2} \frac{H_D}{(\beta_x \beta_y)^{1/2} (\gamma \varepsilon_x \gamma \varepsilon_y)^{1/2}}
\]
<table>
<thead>
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<th>SLC</th>
<th>GLC/NLC</th>
<th>TESLA</th>
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<td></td>
<td>6668.90 11308.32</td>
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Goal: reduce transverse coupling between bunches to \( \sim 0 \)

Alignment and emittance issues are dominated by single bunch

Requires suppressing the accelerator structure long-range wakefield to <1V/pC/mm/m

- Detune and damp accelerator structure wakefield
- Focus of accelerator structure R&D in early 90’s

Slots for damping the dipole modes

Cell dipole mode frequencies which provide detuning

![Graph showing dipole mode frequencies](image)
Structure Long-Range Wakefield
Theory and Measurements

![Diagram showing wakefield amplitude over time]

- Ohmic Loss Only
- Detuning Only
- Measurements
- Time of Next Bunch
- Damping and Detuning
Bunch Trains
Long-Range Wakefields Have Small Effect

- Accelerator structure wakefield is suppressed by ~100
  - Use combination of detuning and weak damping
  - Sets requirements on dipole frequency distribution and structure fabrication – discussed by Chris Adolphsen

- Long-range wakefield has minimal effect on bunch train
  - Bunch train behaves like single bunch → alignment tolerances driven by short-range wakefield

- Damping rings: Beam current is smaller than in B-factories
  - Kicker stability is required to keep well aligned bunch train

- Intra-train feedback can remove pulse-to-pulse jitter
  - Demonstrated IP-style feedback with 60~70 ns latency (FONT)
  - Intra-train feedback requires well aligned bunch train
Peak Luminosity
~7,000 times larger than SLC

\[ L = \frac{f_{\text{rep}} n_b N^2}{4\pi \sigma_x \sigma_y} H_D \]

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  - Bunch trains, Particle sources, Collimation and MPS
1. Parameters chosen to make wakefields manageable

2. Make extensive use of demonstrated BBA techniques
   - Align magnets and structures for complete flexibility
   - Suite of BBA and tuning techniques
   - Necessary instrumentation and controls demonstrated

3. Multiple paths to ensure stable beams for tuning and luminosity

4. Completely modeled transport from DR → IP → Dump
   - Accurately represent operational tuning techniques
   - Generous emittance budgets through system
Transverse Wakefields

Wakefields in TESLA are 1000x Smaller

- Transverse wakefields in TESLA are 1000x smaller
  - True but incomplete statement
  - Effect of wakefields depends on charge, bunch length, and focusing

- Real comparison is effect of wakefields on the beam
  - Best quantified with the “BNS autophasing” energy spread $\delta_{\text{Auto}}$

Focusing quadrupole overfocuses low energy bunch tail
Transverse Wakefields

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<table>
<thead>
<tr>
<th></th>
<th>$\delta_{\text{Auto}}$</th>
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<tbody>
<tr>
<td>SLC Design</td>
<td>9.9%</td>
</tr>
<tr>
<td>SLC Operation</td>
<td>5.8%</td>
</tr>
<tr>
<td>FFTB</td>
<td>1.1%</td>
</tr>
<tr>
<td>X-band LC Design</td>
<td>1.1%</td>
</tr>
<tr>
<td>TESLA Design</td>
<td>0.11%</td>
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</table>

⇒ X-band LC wakefield control already demonstrated at FFTB

SLC Design parameters too difficult
⇒ Operation with lower charge

FFTB operation with still lower charge
⇒ very stable beam – easy operation
Tolerances
Lesson from the SLC: Beam-Based Alignment

- All linear collider designs have small $\varepsilon \rightarrow$ tight tolerances
  - All LC designs require Beam-Based Alignment (BBA)
  - SLC used BBA to align quadrupoles but could not align structures
  - X-band LC will use BBA for both quadrupoles and structures

- Linac tolerances
  - Align quadrupoles BPMs to magnetic center with 5 $\mu$m rms
  - Align the structures to the beam with a 6 $\mu$m rms
  - Align with high performance diagnostics and controls

- Tolerances achievable
  - Required diagnostics and controls demonstrated
  - Multiple BBA techniques demonstrated
Beam Based Alignment
All Necessary Techniques have been Demonstrated

X-band uses beam-based techniques to align the magnets and structures

**Yearly**
Conventional methods

- **Pre-Alignment**
  Install 50 ~100 μm level

- **Establish Beam**
  Steer to post-linac dump

**Monthly**
Methods from SLC & FFTB
Invasive to Luminosity

- **Beam-based alignment**
  Determine Q-BPM-to-quad offsets using quad-shunting

- **Establish ‘Gold’ Orbit**
  Use DF Steering (if nec.) to find low dispersion orbit

**Hourly**
Methods from SLC & ASSET
Non-invasive to Luminosity

- **Steer to Gold Orbit**
  Use quad movers to steer

- **Align structures to orbit**
  Use S-BPMs to center struct.

- **Tune Emittance bumps**
  Use ε-wires to opt. ε

- **Lock Beam-based Fbck.**
  Maintain orbit with feedback
Quadrupole Beam-Based Alignment
Utilize Robust, Local Alignment of Magnets

- Multiple quadrupole BBA alignment techniques
  - Quad-shunting (used many places; FFTB demonstrated <7 µm)
  - Dispersion-Free Steering (tested on SLAC linac)
  - Ballistic alignment (tested in SLC S-1 and FFS)
  - Emittance bumps (used routinely in SLC)

- Advantages and disadvantages to each
  - Quad-shunting most robust and most local technique and has demonstrated performance at NLC-level

- X-band LC BBA procedure is based on quad-shunting followed by other techniques to refine solution
  - Dispersion-Free Steering
  - Emittance bumps like those used in the SLC linac
BBA: Quadrupole Shunting
Robust, Local Alignment of Magnets

- Quadrupole shunting: find the magnetic center by varying the quad strength and measuring the resulting deflection

- Determine BPM-quad offset
- Nulling meas; good sensitivity
- Main systematic error: magnetic center shift with excitation
- Prototype is measured to be 2~3x better than spec.
1) Before installation, straighten and align structures on rf girder such that deviation of cell centers from best-line fit is 100 \( \mu \text{m} \) peak-to-peak

2) During operation, use S-BPM measurements (purple dots) to determine optimal beam trajectory and move girder to the beam with remote movers – want average offset less than 3\( \mu \text{m} \)
Structure BPM
High Performance Diagnostic

Horizontal CMM Data (Solid Line) and Beam Horizontal Positions at Minimum Dipole Signal Power (Diamonds)

HOM Manifold can be used to measure wakefields
Test of Structure-BPM in ASSET
Demonstration of Alignment Technique

Can also sweep LO frequency to map entire structure

Achieved 11\(\mu\)m alignment – limited by beam jitter
Vibration and Drifts
Stability is Necessary for Beam Tuning

- Extensive measurements of natural ground motion
- Many measurements of ‘cultural’ sources and transmission
  - Isolated measurements of modulators, accelerator structures with cooling, quadrupole magnets with cooling all look acceptable
  - Transmission between tunnels is large so must be careful in utility tunnel as well as the main tunnel
- Developing prototypes of main linac girder and utility clusters to measure vibration of full system
- Can always use active suppression for further improvement
  - Magnets and supports easily accessed
  - Stabilization systems developed at DESY, CERN, KEK, and SLAC
Three different approaches being pursued:
1. Quiet site and IR/Detector engineering (many suitable sites identified)
2. Active (inertial) stabilization
3. Fast intra-train feedback (FONT at NLCTA and FEATHER at ATF)

Inertial stabilization
- Developing compact non-magnetic sensors (in-house and commercial)
- Stabilizing an extended object that models a PM final quadrupole and cantilevered support tube

Feedback On Nanosecond Timescales (FONT) at NLCTA
- 2003 run demonstrated ~15x reduction of intra-train offsets
- Latency was about 60 ns ⇒ Significant effect on 75% of train
IP Stabilization Summary
Multiple Paths to Stabilize Collisions

IP collisions can be stabilized using any two out of the three approaches with >90% of peak luminosity.

<table>
<thead>
<tr>
<th>Quiet Detector</th>
<th>Active Stabilization</th>
<th>FONT</th>
<th>Luminosity, %</th>
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<tbody>
<tr>
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<td>No</td>
<td>30%</td>
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<tr>
<td>4 nm</td>
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<td>66%</td>
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<td>~20 nm*</td>
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<td>69%</td>
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<tr>
<td>4 nm</td>
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<tr>
<td>~20 nm*</td>
<td>Yes*</td>
<td>Yes*</td>
<td>90%</td>
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* based on measurements in NLCTA. 20 nm vibration measured on SLD.
Realistic Simulation Studies
Example: Emittance Bumps

- Emittance bumps are the classic ‘global’ correction method
  - Emittance bump technique used in SLC operation and TESLA sims.
  - 100% effective if used or studied with a single primary $\Delta \varepsilon$ source

- Performance less optimal in LC with many $\Delta \varepsilon$ sources
  - Techniques in simulation based on SLC operational procedures
  - Alternate approaches may yield better performance but ….

Bumps with combined wakefield and dispersive errors after nominal tuning are 30% effective

<table>
<thead>
<tr>
<th>Nominal Errors</th>
<th>US Warm $\Delta \varepsilon$</th>
<th>US Cold $\Delta \varepsilon$</th>
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<tbody>
<tr>
<td>25% $\rightarrow$ 19%</td>
<td>37% $\rightarrow$ 21%</td>
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</table>

Still useful technique to ‘finish’ emittance tuning and achieve best performance
DR → IP Simulations

Extensive Studies Refined for over 10 Years

- Tools developed and benchmarked against SLC
  - Different codes compared against each other during TRC
  - Reasonable agreement between simulations

- Studied many different techniques and many different effects
  - Complete simulations including ‘all’ static errors and many dynamic errors while modeling operational tuning procedures

- About 20,000 cpu-hrs in simulations of NLC, TESLA, US Warm, and US Cold over the last two years

- Emittance budgets based on detailed DR → IP simulations
  - Dilution budget has 100% $\Delta \varepsilon_y/\varepsilon_y$ in BC, BDS, and linacs
  - Budget does not assume use of $\varepsilon$-bumps
Emittance Preservation Summary
Preserve Small Emittances from DR → IP

1. Parameters chosen to make wakefields manageable

2. Make use of demonstrated BBA techniques
   - Align both magnets and structures for complete flexibility
   - Correct emittance dilution sources locally for stable solution
   - Demonstrated necessary instrumentation and controls
     - Most prototypes are better than spec → see poster

3. Multiple paths to ensure stable beams for tuning and luminosity

4. Completely modeled transport from DR → IP → Dump
   - Accurately represent operational tuning techniques
   - Generous emittance budgets through DR → IP system
Peak Luminosity
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Emittance Generation
Damping rings have most accelerator physics in LC

- Required to:
  1. Damp beam emittances and incoming transients
  2. Provide a stable platform for downstream systems
  3. Have excellent availability ~99% (best of 3rd generation SRS)

- Mixed experience with SLC damping rings:
  - Referred to as the “The source of all Evil”
  - Collective instabilities; Dynamic aperture; Stability

- X-band damping ring designs based on KEK ATF, 3rd generation SRS, and high luminosity factories
  - Experimental results provide high confidence in design
World’s lowest emittance beam:
\[ \varepsilon_y = 4 \text{ pm-rad} \]
below X-band LC requirements

Used to verify X-band DR concepts

Detailed measurements of emittance tuning, lattice properties, IBS, ions, collective effects, and instrumentation

**ATF Damping Ring**
1.3 GeV Damping Ring and S-band linac
Commissioning started in 1997

*ATF (Beam Transport Line)*
Collective Instabilities
Downstream Systems Sensitive to Rings

- Example: bursting microwave quadrupole instability in the SLC ring caused μm’s of jitter at end of the linac
- Complicated effect that involved interplay of the instability, damping ring feedback systems and linac beam dynamics

Bursting quadrupole instability in SLC DR redistributed 3% of charge

Correlation between DR instability and linac BPM – 20 μm of motion
Electron Cloud
Active R&D Program Aimed at Suppression

- Electron cloud is a known limitation in PEP-II and KEK-B positron rings
  - Electrons from photo-emission, ionization, or secondary emission are trapped in the potential well of the positron beam

- Thresholds for cloud formation are very similar in both X-band and TESLA damping ring designs
  - Low densities can cause large tune shifts, single, or multi-bunch collective instabilities → Address cloud everywhere in all rings

- Active R&D effort on vacuum surfaces and treatments
  - No single vacuum material sufficient

- Plan to test treated coupons in PEP-II and install treated chamber in ~ 2 years
Wiggler Nonlinearities
Ring Designed with $15\sigma_{\text{inj}}$ Dynamic Aperture

- X-band damping ring dynamic aperture $>15x$ injected beam
  - High power injector (55 kW) – cannot allow injection losses
  - Detailed modeling of dynamic aperture with wiggler field map

- Dynamic aperture with nonlinear wiggler
- Dynamic aperture with wiggler and octupole correction

$15\sigma_x$ $15\sigma_y$ $\ln \nu_{x,y}$
X-band Damping Rings
Designed with Care of 3\textsuperscript{rd} Generation SRS

- ATF and the ALS at Berkeley have demonstrated the specified vertical emittance
- Tolerance sensitivities require the care of 3rd generation SRS
- Collective effects are more important than in 3rd generation SRS
- Nonlinear dynamics enter new regime with long wiggler

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<th>TESLA DR</th>
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<td>17,000</td>
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<tr>
<td>Energy [GeV]</td>
<td>2.4</td>
<td>1.9</td>
<td>1.3</td>
<td>1.98</td>
<td>5</td>
</tr>
<tr>
<td>Bunch Charge [$10^{10}$]</td>
<td>0.5</td>
<td>0.6</td>
<td>0.9</td>
<td>0.75</td>
<td>2.0</td>
</tr>
<tr>
<td>Emittance x [nm] / y [pm]</td>
<td>4.8 / 15</td>
<td>6 / 5</td>
<td>1.2 / 4.5</td>
<td>0.61 / 4.9</td>
<td>0.8 / 1.4</td>
</tr>
<tr>
<td>Sextupole Alignment [$\mu$m]</td>
<td>70</td>
<td>30</td>
<td>50</td>
<td>55</td>
<td>10</td>
</tr>
<tr>
<td>Quadrupole Rotation [$\mu$r]</td>
<td>370</td>
<td>200</td>
<td>870</td>
<td>500</td>
<td>40</td>
</tr>
<tr>
<td>Impedance (Z/n) [m$\Omega$]</td>
<td>200</td>
<td>80</td>
<td>600</td>
<td>&lt;600</td>
<td>&lt;60</td>
</tr>
<tr>
<td>Wiggler length [m]</td>
<td>18</td>
<td>30</td>
<td>0</td>
<td>62</td>
<td>432</td>
</tr>
</tbody>
</table>
Emittance Generation Summary

KEK ATF is a full scale prototype for the X-band DR

- Demonstrated at ATF:
  - X-band DR alignment tolerances and emittance generation
  - X-band DR kicker rise/fall times and required stability
  - Single bunch collective effects in desired regime for X-band DR
  - Required instrumentation for LC

- Demonstrated at luminosity factories:
  - High current multi-bunch operation (B-factories)
  - Dynamic aperture with large wigglers (CESR-C)

- Outstanding:
  - Ongoing studies on electron cloud and ion instabilities for all LC damping rings

- To ensure stability and availability future damping rings will require engineering like 3rd generation light sources
Peak Luminosity
〜7,000 times larger than SLC

\[ L = \frac{f_{\text{rep}} n_b N^2}{4\pi \sigma_x \sigma_y} H_D \]

- Focusing \( (\beta_x \ast \beta_y)^{-1/2} \)  
  - NLC/SLC \( \rightarrow 3 \)
  - Demonstrated at FFTB

- Disruption \( H_D \)  
  - NLC/SLC \( \rightarrow 0.7 \)
  - Demonstrated at SLC

- Emittance \( (\gamma \varepsilon_x \ast \gamma \varepsilon_y)^{-1/2} \)  
  - NLC/SLC \( \rightarrow 85 \)
  - Low Emittance Transport and Damping rings

- Beam power term \( (P_b \ast N) \)  
  - NLC/SLC \( \rightarrow 35 \)
  - Bunch trains, Particle sources, Collimation and MPS

\[ L = \frac{P_b N}{4\pi mc^2} \left( \beta_x \beta_y \right)^{1/2} \left( \gamma \varepsilon_x \gamma \varepsilon_y \right)^{1/2} \]
Polarized Electron Source
Based on Cathode R&D for SLC and E-158

(1) Thick GaAs, LN2 Temp., Dye Laser
(2) Thick GaAs, RT, Dye Laser
(3) Thick AlGaAs, RT, Dye Laser
(4) 300-nm Strained GaAs, YAG-Ti Laser
(5) 100-nm Strained GaAs, YAG-Ti or Flash-Ti Laser
(6) 100-nm Gradient-doped Strained GaAs
(7) 100-nm Gradient-doped, Strained-superlattice GaAs/GaAsP

---

Calendar Year

Polarization and Source Availability (percent)

Operation (hours/year)

SLAC ITRP Meeting
Slide 36 of 46
Tor Raubenheimer
Positron Source Configuration
Independent Positron Source

- SLC Positron source used 30 GeV electron beam from shared electron linac

- Three operational problems:
  1. Difficult to commission and develop
     - Unable to commission or perform machine development on positron system without tuned 30 GeV electrons
  2. Low yield
     - Factor of 2 in yield lost due to apertures
     - Could not recover by increasing electron beam current
  3. Coupled system sensitive to cross talk
     - Fluctuations in either the electron or positron current would couple into other beam

- Design positron source with independent drive e-beam
Positron Source Target
Design is Based on SLC Experience with $WRe$

- SLC e+ target failed after 5 years at stress levels ~2x lower than previously measured and predicted for $WRe$ targets

- SLC target studied at LANL and modeled at LLNL
- Problem due to embrittlement from radiation damage
- NLC source is based on multiple targets to reduce stress

- Radiation damage problem is thought worse for the $Ti$ targets planned for undulator based sources
Conventional target is not more difficult than undulator target

<table>
<thead>
<tr>
<th></th>
<th>NC Conv.</th>
<th>NC Und.</th>
<th>SC Conv.</th>
<th>SC Und.</th>
</tr>
</thead>
<tbody>
<tr>
<td>E beam [GeV]</td>
<td>6.2</td>
<td>153</td>
<td>6.2</td>
<td>153</td>
</tr>
<tr>
<td>Ne-/bunch [1e10]</td>
<td>0.75</td>
<td>0.75</td>
<td>2.00</td>
<td>2.00</td>
</tr>
<tr>
<td>Undulator Len. [m]</td>
<td>-</td>
<td>150</td>
<td>-</td>
<td>150</td>
</tr>
<tr>
<td>Energy/pulse [J]</td>
<td>477</td>
<td>1130</td>
<td>28000</td>
<td>44300</td>
</tr>
<tr>
<td>Target Mat.</td>
<td>WRe</td>
<td>Ti</td>
<td>WRe</td>
<td>Ti</td>
</tr>
<tr>
<td>Target Thick. [rl]</td>
<td>4</td>
<td>0.4</td>
<td>4</td>
<td>0.4</td>
</tr>
<tr>
<td>Absorption</td>
<td>14.0%</td>
<td>8.6%</td>
<td>14.0%</td>
<td>8.6%</td>
</tr>
<tr>
<td>Spot size [mm]</td>
<td>1.6</td>
<td>0.75</td>
<td>2.5</td>
<td>0.75</td>
</tr>
<tr>
<td># targets/spares</td>
<td>3 / 1</td>
<td>1 / 1</td>
<td>2 / 1</td>
<td>1 / 1</td>
</tr>
<tr>
<td>Target radius [m]</td>
<td>0.125</td>
<td>0.125</td>
<td>0.8</td>
<td>0.8</td>
</tr>
<tr>
<td>Rotation [rpm]</td>
<td>46</td>
<td>46</td>
<td>1500</td>
<td>1200</td>
</tr>
<tr>
<td>ΔT [C]</td>
<td>189</td>
<td>422</td>
<td>256</td>
<td>410</td>
</tr>
<tr>
<td>Yield</td>
<td>1.5</td>
<td>1.5</td>
<td>1.5</td>
<td>1.5</td>
</tr>
</tbody>
</table>
Collimation system is integral to design and is part of Machine Protection System

- Collimation system designed for beam tails 1000x that expected
- Passive energy collimation and consumable betatron collimation
- Many advantages over SLC
  - No synchrotron radiation in IR
  - Beam tails from damping rings collimated at low energy
Excellent performance in length of 800 meters
- All tail particles removed 500 meters upstream of IP

Tails versus $s$ from IP
NLC BDS starts at $s = -1300$ meters

Final Doublet aperture
SR passes through IR $K < 1$

Fraction of bunch charge outside square region $K = 1$
$K > 1$

Particle amplitudes in final magnet
Collimator wakefields measured in SLAC test facility

- Measured collimators with Cu and Ti (and C from DESY)
- OK at 250 GeV but impact low E luminosity

Collimator wakefield jitter amplification from TRC Study

\[ \Delta y = y_0 \sqrt{1 + A_y^2} \]

<table>
<thead>
<tr>
<th></th>
<th>TESLA</th>
<th>NLC</th>
<th>CLIC</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \delta ) spoilers</td>
<td>0.054</td>
<td>0.045</td>
<td>0.16</td>
</tr>
<tr>
<td>( \delta ) absorbers</td>
<td>0.034</td>
<td>0.016</td>
<td>0.37</td>
</tr>
<tr>
<td>( \beta ) spoilers</td>
<td>0.55</td>
<td>0.59</td>
<td>1.67</td>
</tr>
<tr>
<td>( \beta ) absorbers</td>
<td>0.51</td>
<td>0.014</td>
<td>0.33</td>
</tr>
<tr>
<td>FF spoilers</td>
<td>0.73</td>
<td>--</td>
<td>0.32</td>
</tr>
<tr>
<td>FF absorbers</td>
<td>0.38</td>
<td>0.53</td>
<td>--</td>
</tr>
<tr>
<td>Total ( A_y )</td>
<td>2.26</td>
<td>1.20</td>
<td>2.84</td>
</tr>
</tbody>
</table>

- Octupole tail-folding opens gaps reducing \( A_y \)
Peak Luminosity Summary

- **Low Emittance Transport**
  - Parameters chosen to make wakefields manageable
  - Extensive use of demonstrated BBA techniques
  - Multiple paths to ensure stable beams for tuning and luminosity
  - Completely modeled transport from DR → IP → Dump

- **Damping rings**
  - Performance demonstrated at ATF and 3rd generation SRS

- **Beam power**
  - Long-range wakefields and coupled bunch instabilities not limitations
  - Particle sources based on SLC experience
  - Robust collimation design
Design Headroom
Faster Commissioning and Higher Luminosity

- Most sub-systems have substantial headroom
  - For example: E⁻ Source emittance – Simulations predict $\gamma \varepsilon$ half of design spec $\gamma \varepsilon = 10 \times 10^{-5}$; DR acceptance and damping for $\gamma \varepsilon = 15 \times 10^{-5}$

- Sources
  - 50% beam power
  - 3x emittance (described above)
  - 10x damping (injected beam 10% of extracted)
  - 20% bunch length ($\sigma_z > 90 \mu m$; spec=110$\mu m$)

- RF system
  - 10% energy (allocation for trips, phasing, repair)

- Dilutions
  - 100% vertical emittance
  - 4x horizontal IP beta function

- Provide stable operation and flexibility to optimize luminosity
  - Fast commissioning and higher luminosity with time
Potential for Luminosity Upgrades

- Design margins allow parameter optimization
  - Example 1: if low emittance transport component specs are met ⇒ \( \Delta \varepsilon_y < 50\% \) and \( L = 3 \times 10^{34} \)
  - Example 2: if damping ring alignment can attain and maintain the TESLA DR specs ⇒ \( \gamma \varepsilon_y \ll 1 \times 10^{-8} \) and \( L = 4.5 \times 10^{34} \)

- What are the limits? Disruption \( D_y \) and beamstrahlung \( \delta_B \)

\[
L \propto \frac{P_{\text{beam}}}{E_{\text{cms}}} \frac{D_y}{\sigma_z} \frac{H_D}{\gamma} \quad \delta_B \propto D_y^2 \sigma_y^2 \left( \frac{\gamma}{\sigma_z} \right)^3
\]

- \( L = 4.5 \times 10^{34} \) assumes \( \sigma_z = 110 \mu\text{m} \) and TESLA disruption: \( D_y \sim 25 \)
- Compress to \( \sigma_z = 90 \mu\text{m} \) ⇒ \( L = 5.5 \times 10^{34} \) (same \( \delta_B \))
- Assume TESLA-style 1\(^{st}\) compression stage of 20x ⇒ \( \sigma_z = 50 \mu\text{m} \) and \( L = 11.5 \times 10^{34} \) with 2x larger \( \delta_B \)
Summary

- The X-band design is based on:
  - 20 years of linear collider development including: SLC, NLCTA, ASSET, CollWake, ATF, FFTB, Stabilization, ...
  - Extensive beam tuning experience with SLC, FFTB, and ATF
  - Proven principles of structure wakefield suppression and S-BPMs

- The design luminosity is possible because:
  - Luminosity performance has been a focus of the design and R&D
    - Performance goals verified with in depth DR → IP simulations
    - Results from prototype testing support the performance goals
    - Essential experience from SLC, FFTB, and ATF included
  - Headroom in design → ensure luminosity goals are attained quickly

- X-band LC is the LC design which has been studied in depth
Energy Spectrum
Narrow Energy Spectrum for Special Measurements

Adjusting BNS phases allows control of energy spectra

Energy spectrum for different BNS configurations

Longitudinal phase space for different BNS configurations

Total voltage required for different BNS configurations

FWHM energy spread for different BNS configurations
Energy Spectrum
Luminosity Energy Bias → 0

- New BNS configuration has small $E_{\text{bias}}$

Luminosity rms spectrum
- Nominal
- Low $E_{\text{bias}}$

Nominal spectrum
- $E_{\text{bias}}$

Luminosity energy bias
- Nominal
- Low $E_{\text{bias}}$