Technologies for Electron-Positron Linear Colliders

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Outline

• International view
• Current contenders: parameters and layouts
• Status of critical technologies/energy
  – Accelerating Structures
  – RF Sources
• Status of critical technologies/luminosity
  – Damping Rings
• Variants as described in the U.S. warm/cold study
• CLIC
• Conclusions
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N. Walker
International Linear Collider View

• An internationally constructed and operated electron-positron linear collider, with an initial center-of-mass energy of 500 GeV, has received strong endorsement by advisory committees in North America, Europe, and Asia as the next large High Energy Physics facility beyond LHC.

• An international panel, under the auspices of ICFA, has established performance goals (next slide) as meeting the needs of the world HEP community. The performance document is available at:

  http://www.fnal.gov/directorate/icfa/LC_parameters.pdf

• An International Technology Recommendation Panel has now been convened under the auspices of ICFA with a charge to issue a technology recommendation by the end of 2004.
International Performance Specification

– Initial maximum energy of 500 GeV, operable over the range 200-500 GeV for physics running.

– Equivalent (scaled by 500 GeV/√s) integrated luminosity for the first four years after commissioning of 500 fb\(^{-1}\).

– Ability to perform energy scans with minimal changeover times.

– Beam energy stability and precision of 0.1%.

– Capability of 80% electron beam polarization over the range 200-500 GeV.

– Two interaction regions, at least one of which allows for a crossing angle enabling γγ collisions.

– Ability to operate at 90 GeV for calibration running.

– Machine upgradeable to approximately 1 TeV.
## Performance Parameters (TRC)

<table>
<thead>
<tr>
<th></th>
<th>TESLA</th>
<th>JLC-X/NLC</th>
<th>JLC-C</th>
<th>CLIC</th>
<th>GeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Center of Mass Energy</td>
<td>500</td>
<td>800</td>
<td>500</td>
<td>1000</td>
<td>500</td>
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<tr>
<td>Design Luminosity</td>
<td>34</td>
<td>58</td>
<td>20</td>
<td>30</td>
<td>14</td>
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<tr>
<td>Linac rf frequency</td>
<td>1.3</td>
<td>11.4</td>
<td>5.7</td>
<td>11.4*</td>
<td>30</td>
</tr>
<tr>
<td>Unloaded/loaded gradient</td>
<td>24/24</td>
<td>35/35</td>
<td>65/50</td>
<td>42/32</td>
<td>70/55</td>
</tr>
<tr>
<td>Pulse repetition rate</td>
<td>5</td>
<td>4</td>
<td>120</td>
<td>100</td>
<td>200</td>
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<tr>
<td>Bunches/pulse</td>
<td>2820</td>
<td>4886</td>
<td>192</td>
<td>192</td>
<td>154</td>
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<tr>
<td>Bunch separation</td>
<td>337</td>
<td>176</td>
<td>1.4</td>
<td>1.4</td>
<td>0.67</td>
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<tr>
<td>Particles/bunch</td>
<td>2</td>
<td>1.4</td>
<td>0.75</td>
<td>0.75</td>
<td>0.4</td>
</tr>
<tr>
<td>Bunch train length</td>
<td>950</td>
<td>860</td>
<td>0.27</td>
<td>0.27</td>
<td>0.1</td>
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<tr>
<td>Beam power</td>
<td>11</td>
<td>18</td>
<td>7</td>
<td>14</td>
<td>6</td>
</tr>
<tr>
<td>$\gamma_{H}/\gamma_{V}$ at IP</td>
<td>10/.03</td>
<td>8/.015</td>
<td>3.6/.04</td>
<td>3.6/.04</td>
<td>2/.01</td>
</tr>
<tr>
<td>$\sigma_x/\sigma_y$ at IP (before pinch)</td>
<td>554/5</td>
<td>392/3</td>
<td>243/3</td>
<td>219/2</td>
<td>243/4</td>
</tr>
<tr>
<td>Site AC power</td>
<td>140</td>
<td>200</td>
<td>195</td>
<td>350</td>
<td>233</td>
</tr>
<tr>
<td>Site length</td>
<td>33</td>
<td>32</td>
<td>33</td>
<td>10</td>
<td>33</td>
</tr>
<tr>
<td>Tunnel configuration</td>
<td>Single</td>
<td>Double</td>
<td>Double</td>
<td></td>
<td>Single</td>
</tr>
</tbody>
</table>

*JLC-C utilizes c-band for first 200 GeV, x-band for following 300 GeV of each linac
Current Round (ITRP) Contenders

TESLA

JLC-X/NLC
Linear Collider Performance Parameters
Technical Requirements

• Energy: 500 GeV, upgradeable to 1000 GeV
  – RF Structures
    ➢ The accelerating structures must support the desired gradient in an
      operational setting and there must be a cost effective means of fabrication.
      – TESLA: 24-35 MV/m
      – NLC/GLC: 65 MV/m (unloaded, 52 MV/m loaded)
  – RF power generation and delivery
    ➢ The rf generation and distribution system must be capable of delivering
      the power required to sustain the design gradient

⇒ Demonstration projects: NLC 8-pack test, NLCTA, TTF-I and II

• Luminosity: 500 fb\(^{-1}\) in the first four years of operation
  – The specified beam densities must be produced within the injector system,
    preserved through the linac, and maintained in collision at the IR.

⇒ R&D Facilities: ATF, ASSET
Linear Collider Technology Status
NLC/GLC Structures

NLC/GLC Linac RF Unit
(One of ~ 2000 at 500 GeV cms, One of ~ 4000 at 1 TeV cms)

Resolution of RF System

- 75 MW PPM-Focused Klystrons
- Solid State Induction Modulator (500 kV, 0.5 kA, 1.6 µs Pulses)
- Dual-Moded SLED-II
- Utility Tunnel
- Linac Tunnel

Eight 0.6 m Accelerator Structures (65 MV/m Unloaded, 52 MV/m Loaded)
Linear Collider Technology Status
NLC/GLC Structures

• The NLC/GLC structure has evolved over the last several years in response to difficulties encountered with structure damage after several thousand hours of operations.
  – Length = 60 cm
  – Group velocity = 3%
  – New input couplers lowering peak fields

• The resultant structure features:
  – Less stored energy, reduced ability for energy to flow within the cavity, and lower peak fields at the upstream end

• Operational criterion for breakdown rate is based on:
  – 99% availability with a 5 second recovery time (with 2% energy overhead)
  ⇒ <1 breakdown/structure/10 hours when operated at 60 Hz and the full (400 nsec) rf pulse width

• 8 structures operating at NLCTA meet the gradient/breakdown spec
Linear Collider Technology Status
NLC Test Accelerator (NLCTA)
Linear Collider Technology Status
NLC/GLC Structures Performance (circa April 2004)

Breakdown Rate at 60 Hz (#/hr)

Unloaded Gradient (MV/m)

Average Rate Limit
## Linear Collider Technology Status

### NLC/GLC Structures Performance (most recent 150 hours)

<table>
<thead>
<tr>
<th>Structure</th>
<th>Manufacturer</th>
<th>Gradient (MV/m)</th>
<th>Trip Rate (#/hr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>H60vg4S17-FXD1A</td>
<td>FNAL</td>
<td>65.4</td>
<td>0.18</td>
</tr>
<tr>
<td>H60vg3S17-FXC5</td>
<td>FNAL</td>
<td>64.5</td>
<td>0.10</td>
</tr>
<tr>
<td>H60vg4S17-3</td>
<td>KEK/SLAC</td>
<td>65.4</td>
<td>0.04</td>
</tr>
<tr>
<td>H60vg3S17-FXC3</td>
<td>FNAL</td>
<td>64.5</td>
<td>0.04</td>
</tr>
<tr>
<td>H60vg3-FXB6</td>
<td>FNAL</td>
<td>64.8</td>
<td>0.00</td>
</tr>
<tr>
<td>H60vg3-FXB7</td>
<td>FNAL</td>
<td>66.7</td>
<td>0.19</td>
</tr>
<tr>
<td>H60vg4S17-1</td>
<td>KEK/SLAC</td>
<td>63.2</td>
<td>0.10</td>
</tr>
<tr>
<td>H60vg3R17</td>
<td>SLAC</td>
<td>64.8</td>
<td>0.04</td>
</tr>
</tbody>
</table>

### Average (20-June-04)
- Gradient: 64.9 MV/m
- Trip Rate: 0.085/hr

### Average One Month Ago
- Gradient: 64.9 MV/m
- Trip Rate: 0.163/hr
Linear Collider Technology Status
TESLA Structures

**TESLA Linac RF Unit:** 10MW klystron, 3 modules × 12 cavities each

Total for 500 GeV: 572 units (includes 2% reserve for failure handling)
Linear Collider Technology Status
TESLA Structures

• The structure proposed for 500 GeV operation requires 24 MV/m.
  – Achieved in 1999-2000 cavity production run
  – 13,000 hours operation in TTF (not all modules at 24 MV/m)

• The goal is to develop and install cavities capable of 35 MV/m for the energy upgrade to 800-1000 GeV.

• Progress over the last several years has been in the area of surface processing and quality control.
  – Buffered chemical polishing
  – Electro-polishing
  – Several single cell cavities at 40 MV/m
  – Five nine-cell cavities at >35 MV/m

• Dark current criteria established based on <10% increase in heat load
  – 50 nA/cavity
Linear Collider Technology Status
TESLA Structures

Comparison of low and high power tests (AC73)

S. Holmes, EPAC2004
Linear Collider Technology Status
TESLA Structures: Dark Current

Radiation emissions of BCP and EP cavities (vertical test stand)

Dark Current measurement on 8-cavity CM (ACC4)
~15 nA/cavity at 25 MV/m
Linear Collider Technology Status
TESLA Structures

• One electropolished cavity (AC72) has been installed into cryomodule ACC1 in TTF-II (March)

• Cavity individually tested in the accelerator with high power rf.

• Result: 35 MV/m
  − No field emission detected
  − Good results with LLRF and piezo-tuner
  − Calibrated with beam and spectrometer
Linear Collider Technology Status

Summary: Structures

• Eight NLC/GLC structures are operating per performance specification in the NLCTA.
  – Built by three different institutions on two continents
  – Keys to success were reducing length, reducing group velocity, improving input coupler design.

• Five TESLA cavities have met the 35 MV/m performance specification
  – One has seen beam in a complete cryomodule
  – Key to success has been advancement in surface treatment procedures (BCP and EP)
NLC/GLC Power Sources

- **75 MW PPM Klystron**
  - (Nearly) full specification performance by two tubes

<table>
<thead>
<tr>
<th>Klystron</th>
<th>Peak Power</th>
<th>Pulse-Width</th>
<th>Repetition Rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>SLAC XP3 S/N 3</td>
<td>75 MW</td>
<td>1.6 μs</td>
<td>120 Hz</td>
</tr>
<tr>
<td>KEK PPM S/N 2</td>
<td>75 MW</td>
<td>1.7 μs</td>
<td>60 Hz</td>
</tr>
<tr>
<td></td>
<td>68 MW</td>
<td>1.7 μs</td>
<td>120 Hz</td>
</tr>
<tr>
<td>KEK PPM S/N 3</td>
<td>65 MW</td>
<td>1.5 μs</td>
<td>50 Hz</td>
</tr>
<tr>
<td>KEK PPM S/N 4</td>
<td>75 MW</td>
<td>1.6 μs</td>
<td>25 Hz</td>
</tr>
<tr>
<td>SLAC 75 MW Prototype</td>
<td>75 MW</td>
<td>1.5 μs</td>
<td>1 Hz</td>
</tr>
<tr>
<td></td>
<td>79 MW</td>
<td>2.8 μs</td>
<td>1 Hz</td>
</tr>
<tr>
<td>KEK PPM S/N 1</td>
<td>68 MW</td>
<td>1.5 μs</td>
<td>5 Hz</td>
</tr>
<tr>
<td>SLAC 50 MW</td>
<td>50 MW</td>
<td>1.5 μs</td>
<td>120 Hz</td>
</tr>
<tr>
<td></td>
<td>55 MW</td>
<td>2.4 μs</td>
<td>60 Hz</td>
</tr>
<tr>
<td></td>
<td>75 MW</td>
<td>1.5 μs</td>
<td>120 Hz</td>
</tr>
</tbody>
</table>

- Full-specification induction modulator operating in support of the 8–pack test.
Linear Collider Technology Status
NLC/GLC Power Sources

• Power to loads 580 MW at 400 ns (design is 475 MW)
• Operated 500 hours at ~500 MW

“8-pack” test at SLAC

S. Holmes, EPAC2004
Linear Collider Technology Status
TESLA Power Sources

• Three Thales TH1801 Multi-beam klystrons fabricated and test.
  – Efficiency = 65%
  – Pulse width = 1.5 msec
  – Peak power = 10 MW
  – Repetition rate = 5 Hz
  – Operational hours (at full spec) = 500 hours
• Independent R&D efforts now underway at CPI and Toshiba

• 10 Modulators have been built
  – 3 by FNAL and 7 by industry
  – 7 modulators are in operation
  – 10 years operation experience
Linear Collider Technology Status
Summary: RF Sources

• Modulators for both NLC/GLC and TESLA have been demonstrated and do not appear to have major issues.

• Klystrons remain a challenge
  – Modest numbers of klystrons meeting specs exist for both NLC/GLC and TESLA.
  – R&D programs are continuing to develop units that can meet requirements in a reproducible manner.
Linear Collider Technology Status

Damping Rings: ATF

- NLC/GLC requirement met
  - electrons, single bunch
- Performance consistent with intra-beam scattering
  ⇒ Need to move to multi-bunch;
  Better understanding of e-cloud;
  Alternatives to TESLA dogbone
• **Luminosity vs energy:** The opportunity exists to build a “500 GeV” collider in which luminosity can be traded for higher energy.
  – This happens naturally in the warm machine because beam loading is an inherent part of the design.
  – This can happen in the cold machine if the installed cavity capability is greater than the 500 GeV gradient.

\[
G \text{ (cold, capability)} = 35 \text{ MV/m} \\
G \text{ (cold, operational)} = 28 \text{ MV/m} \\
G \text{ (unloaded, warm)} = 65 \text{ MV/m} \\
G \text{ (loaded, warm)} = 52 \text{ MV/m}
\]
Design Variants (from the U.S. Study)

- **One vs. two tunnels**
  - Single tunnel saves \( \sim 5\% \) on total project cost.
  - Estimated impact on machine availability is \( \sim 10\% \).

\[ \Rightarrow \text{Increase energy overhead and/or improve component reliability (} \times 10) \]

\[ \Rightarrow \text{“Right” answer may be site specific} \]

- **Undulator vs. conventional source**
  - Advocate starting with a conventional source (more efficient startup commissioning) but leave space for undulator upgrade

- **Reliability analysis**
  - Monte Carlo analysis indicates modern MTBFs need to be improved by up to \( \times 10 \) to achieve availability of 85\%
Beyond the Next Generation
CLIC
Conclusions

• The technologies required to support either a room temperature or superconducting rf-based linear collider have made substantial progress over the last two years. It is my conclusion that a linear collider meeting the needs of the world HEP community could be built and operated based on either warm or cold technology.

• Our community should be very happy if given the opportunity to construct and operate a 500-1000 GeV linear collider based on either technology, no matter where it is situated in the world. So,…

Let’s support the decision of the ITRP when it is released later this year and do everything in our power to realize this forefront machine.