X-Band Linear Collider
Path to the Future

X-Band Linear Collider Report*

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NLC Program Director

* Abstracted from recent presentations to the International Technical Recommendation Panel.

Stanford Linear Accelerator Center
June 2-4, 2004
Collaboration on X-Band Technology and Design

Extension of conventional warm accelerator technology from 3 GHz (S-Band) to 11.4 GHz (X-Band).

Led by KEK, BINP, HEPL, PAL.

Led by BNL, FNAL, LBNL, LLNL, SLAC.

Connected by SLAC-KEK R&D MOU signed in 1998.
Evolution of a common design strategy:

NLC Zero-Order Design (1996)


NLC Snowmass 2001 (2001)


GLC/NLC TRC (2003)
Energy for the Energy Frontier
(GLC/NLC TRC 2003)

A Partner for the LHC
The Challenges
(Presentations to the ITRP)

Luminosity (Raubenheimer)
   Beam Control – Emittance and Stability
   Beam Power

Energy and Cost (Adolphsen and Cornuelle)
   Gradient and Efficiency

Availability (Himel)
   Overhead and Margins
   Engineering and Design
The Challenges
(Presentations to the ITRP)

- Luminosity (Raubenheimer)
  - Beam Control – Emittance and Stability
  - Beam Power

- Energy and Cost (Adolphsen and Cornuelle)
  - Gradient and Efficiency

- Availability (Himel)
  - Overhead and Margins
  - Engineering and Design
Next Linear Collider Test Accelerator

1993  Construction began using first generation X-band components.

1997  Demonstrated 17% beam loading compensation in 1.8m structures at 40 MV/m.

→ Demonstrated ability to reach 500 GeV cms.

1999  Added second klystron to each linac rf station.

2000- High gradient studies, and extension using second generation components aimed at 1 TeV cms.
The NLCTA (ca. 1997)
X-Band 1 TeV Baseline RF Unit

(One of ~ 2000 at 500 GeV cms, One of ~ 4000 at 1 TeV cms)

75 MW PPM-Focused Klystrons

Solid State Induction Modulator
(500 kV, 0.5 kA, 1.6 μs Pulses)

150 MW
1.6 μs

475 MW
400 ns

Dual-Moded SLED-II

Utility Tunnel

Linac Tunnel

Eight 0.6 m Accelerator Structures (65 MV/m Unloaded, 52 MV/m Loaded)
Linac cost is a balance between cost of the power sources (increases with gradient), and cost of accelerator length (decreases with gradient).

Minimum occurs at about 80 MV/m where these are equal, but total collider cost is only 5% higher at 55 MV/m.

→ Baseline at 65 MV/m.

(*The linac is about half the total cost of the collider.)
“Demonstration of SLED-II pulse compression system at design power level.”

“Test of complete accelerator structure at design gradient with detuning and damping, including study of breakdown and dark current.”

→ Both R1 requirements have now been met.
Second Generation NLCTA
(X-Band 1 TeV Baseline Demonstration)
Solid State IGBT Modulator Test Stack

SUM MANY LOW VOLTAGE (~ 2 kV) SOURCES INDUCTIVELY

INDUCTION CIRCUIT (1 OF N)

Driver

IGBT

Power Supply

MetGlas Core

Storage Capacitor

Stack of 10 Cores

Insulated Gate Bipolar Transistors

Capacitors

MetGlas Cores

10 cm

Driver Circuit
8-Pack IGBT Modulator

76 Cores
Three-Turn Secondary
> 1000 Hours of Operation

Waveforms When Driving Four 50 MW Klystrons at 400 kV, 300 A Each
Next Generation: The ‘Two-Pack’

Features
- 6.5 kV IGBTs with in-line multi-turn 1:10 transformer.
- Industrialized cast casings.
- Improved oil cooling.
- Improved HV feed through.

2-Pack Layout

Bechtel-LLNL-SLAC Team

A hybrid 2-Pack modulator is currently running in the SLAC Power Conversion Department lab.
## Modulator Performance

*1.6 μs Pulse Width*

<table>
<thead>
<tr>
<th>Achieved</th>
<th>Config</th>
<th>Load</th>
<th>Voltage (kV)</th>
<th>Current (A)</th>
<th>Rate (Hz)</th>
<th>Efficiency (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>8-pack</td>
<td>Water</td>
<td>500</td>
<td>1000</td>
<td>10</td>
<td></td>
</tr>
<tr>
<td></td>
<td>8-Pack</td>
<td>Four XL4 Klystrons</td>
<td>400</td>
<td>1200</td>
<td>60</td>
<td>58</td>
</tr>
<tr>
<td></td>
<td>2-Pack Hybrid</td>
<td>Water</td>
<td>500</td>
<td>500</td>
<td>120</td>
<td>60</td>
</tr>
<tr>
<td>NLC/GLC Baseline</td>
<td>2-Pack</td>
<td>Two PPM Klystrons</td>
<td>500</td>
<td>500</td>
<td>120</td>
<td>70</td>
</tr>
</tbody>
</table>

Prototype modulators operate at voltages and currents exceeding NLC/GLC requirements.

2-Pack efficiency is lower than goal due to hybrid transformer – expect > 70% in next version with integrated transformer.
1 TeV X-Band Baseline RF Unit

(One of ~ 2000 at 500 GeV cms, One of ~ 4000 at 1 TeV cms)

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

150 MW
1.6 μs

475 MW
400 ns

Beam

Eight 0.6 m Accelerator Structures (65 MV/m Unloaded, 52 MV/m Loaded)
X-Band Klystrons

Solenoid-Focused Tubes: Have Twelve, 50 MW Tubes for Testing, However Solenoid Power = 25 kW.

Developing Periodic Permanent Magnet (PPM) Focused Tubes to Eliminate the Power Consuming Solenoid.

Axial Magnetic Field ~ 2 kG RMS
(~ 5 kG for Solenoid Focusing)
PPM Klystron Overview

PPM Klystrons being developed at SLAC, and at KEK in collaboration with Toshiba.

50 MW and 75 MW Tubes tested during past six years:

- Five at KEK/Toshiba.
- Six at SLAC.
- Two industrial (EEV and Toshiba).
- Two tubes to date have met NLC/GLC requirements (all key parameters concurrently).

TRC R2 requirement of 120 Hz operation has been met.
PPM Klystron Performance
(75 MW, 1.6 &mu;s, 120/150 Hz, 55% Efficiency Required)

KEK/Toshiba
Two tubes tested at
75 MW with
1.6 ms pulses at
50 Hz (modulator limited).
Efficiency = 53-56%.

SLAC
Two tubes tested at
75 MW with
1.6 ms pulses at
120 Hz.
Efficiency = 53-54%. 
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Beam

Eight 0.6 m Accelerator Structures (65 MV/m Unloaded, 52 MV/m Loaded)
Second Generation SLED II at NLCTA

For NLC/GLC, Use Dual Mode Delay Line to Reduce Delay Line Length in Half
Over-Height Planar Waveguide

Lower Surface Electric Fields (< 50 MV/m) and Limited Pulse Heating (< 40° C)

Example: Power Splitter
Solid-State Modulator and Dual-Mode SLED-II

TRC R1 Done.

Power 580 MW to loads (design is 475 MW) at 400 ns.

Operated 300 hours at 510 MW, and over a 1000 at 320 MW.

Turn-key with feedbacks.
1 TeV X-Band Baseline RF Unit

(One of ~ 2000 at 500 GeV cms, One of ~ 4000 at 1 TeV cms)

75 MW PPM-Focused Klystrons

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(500 kV, 0.5 kA, 1.6 μs Pulses)

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Beam

Eight 0.6 m Accelerator Structures (65 MV/m Unloaded, 52 MV/m Loaded)
High Gradient Structure Development

In 1999, discovered gradient limitations in original 1.8 m structures – have since:

Tested 34 structures with over 20,000 hrs of high power operation at NLCTA.

Improved structure preparation procedures – chemical etching, high temperature firing, and high-power processing protocol.

Found structures with lower input power (lower group velocity) more robust against damage from rf breakdown.

Developed designs with low surface currents, optimized gradient profiles, and needed wakefield detuning and damping.
Structure Fabrication

Inspection and Assembly at FNAL (Class 1000 Clean Room)

Chemical Etching of Cells at KEK

Hydrogen Brazing at SLAC

Complete structures are assembled at FNAL, SLAC, and KEK with parts made in industry.

Tests of first structures completely built in industry now beginning.
Processing Structures in NLCTA

![Graph showing gradient (MV/m) over hours of operation with pulse width of 400 ns indicated.]
High Gradient Performance of Recent Structures

Breakdown Rate at 60 Hz (#/hr)

Unloaded Gradient (MV/m)

- Average Rate Limit for 99% Availability
  (2% Overhead and 5 sec Station Recovery)

- Average Rate Goal

TRC R1 Done
System Demonstration and Operation

From SLED II

Phase 2a

Phase 2b

Overmoded

WR90

First four structures continue to be powered by original NLCTA stations.

Power Eight Accelerator Structures in NLCTA (TRC R2 Requirement)

Running 24/7 since first of April; 700 hours of operation with > 90% uptime … →
April Operation of NLCTA

<table>
<thead>
<tr>
<th>Structure</th>
<th>Manufacturer</th>
<th>Gradient (MV/m)</th>
<th>Trip Rate (#/hr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>H60vg4R17-1</td>
<td>SLAC</td>
<td>63.0</td>
<td>0.09</td>
</tr>
<tr>
<td>H60vg4R17-2</td>
<td>SLAC</td>
<td>62.0</td>
<td>0.14</td>
</tr>
<tr>
<td>H60vg3S17-FXC4</td>
<td>FNAL</td>
<td>60.8</td>
<td>0.13</td>
</tr>
<tr>
<td>H60vg3S17-FXC3</td>
<td>FNAL</td>
<td>59.9</td>
<td>0.09</td>
</tr>
<tr>
<td>H60vg3-FXB6</td>
<td>FNAL</td>
<td>60.6</td>
<td>0.03</td>
</tr>
<tr>
<td>H60vg3-FXB7</td>
<td>FNAL</td>
<td>62.4</td>
<td>0.07</td>
</tr>
<tr>
<td>H60vg4S17-1</td>
<td>KEK/SLAC</td>
<td>59.1</td>
<td>0.19</td>
</tr>
<tr>
<td>H60vg3R17</td>
<td>SLAC</td>
<td>60.6</td>
<td>0.07</td>
</tr>
<tr>
<td><strong>Average</strong></td>
<td></td>
<td><strong>61.1</strong></td>
<td><strong>0.10</strong></td>
</tr>
</tbody>
</table>
## May Operation of NLCTA

(* = Installed first of May)

<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>65.5</td>
<td>0.31</td>
</tr>
<tr>
<td>H60vg3S17-FXC5 *</td>
<td>FNAL</td>
<td>64.5</td>
<td>0.17</td>
</tr>
<tr>
<td>H60vg4S17-3 *</td>
<td>KEK/SLAC</td>
<td>65.5</td>
<td>0.23</td>
</tr>
<tr>
<td>H60vg3S17-FXC3</td>
<td>FNAL</td>
<td>64.5</td>
<td>0.13</td>
</tr>
<tr>
<td>H60vg3-FXB6</td>
<td>FNAL</td>
<td>64.7</td>
<td>0.01</td>
</tr>
<tr>
<td>H60vg3-FXB7</td>
<td>FNAL</td>
<td>66.6</td>
<td>0.05</td>
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<tr>
<td>H60vg4S17-1</td>
<td>KEK/SLAC</td>
<td>63.1</td>
<td>0.21</td>
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<tr>
<td>H60vg3R17</td>
<td>SLAC</td>
<td>64.7</td>
<td>0.19</td>
</tr>
<tr>
<td><strong>Average of All 8</strong></td>
<td></td>
<td><strong>64.9</strong></td>
<td><strong>0.16</strong></td>
</tr>
</tbody>
</table>

Average of Original 5 (was 0.09 @ 60.5)

64.7 0.12

→ Performance improved with running time.
Expect Lower Rates During Beam Operation

During Structure Testing
Average = 65 MV/m

During NLC/GLC Beam Operation
Average = 52 MV/m
Support for Industrialization
(Ultimately to be planned by Global Design Organization.)

Goals

Fully utilize existing infrastructures and facilities.

Provide intellectual ownership and experience with X-Band to those leading Main Linac work packages.

Provide liaison and testing facilities for participating industries.

Plan

Extensions of GLCTA and NLCTA test facilities.

Beams available for component and system testing.
Extension of NLCTA to 1 GeV
(See also GLCTA.)

Existing Modulator
(With two 75 MW Permanent Magnet Klystrons.)

Prototype 2-Pack
(Now running in PC lab.)

Replace Stations 1 and 2 with New 2-Packs
The Challenges
(Presentations to the ITRP)

Luminosity
   (Raubenheimer)

Beam Control – Emittance and Stability

Beam Power

Energy and Cost
   (Adolphsen and Cornuelle)

Gradient and Efficiency

Availability
   (Himel)

Overhead and Margins

Engineering and Design

Extended discussions in the afternoon break-out tour.
Polarized Electron Source

SLC and SLAC ESA

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

Graph showing polarization and source availability over calendar years from 1978 to 2004.
ATF Damping Ring at KEK

SLAC and KEK physicists survey the ring.

“Laser Wire”

The image shows a scatter plot of normalized beam emittance with horizontal and vertical emittance axes. The plot includes data points labeled with various facility names such as Photo-Cathode RF Gun, SLC, SLAC/NL, ALS, CLIC 3000, CLIC 5000, and SPring-8. The plot highlights goals for 2003 and 2004.
IP Stabilization

Three Layers

1. Site (many suitable sites identified) and facilities.

2. IR/Detector engineering and active (inertial) stabilization.

3. Fast intra-train beam feedback (FONT at NLCTA and FEATHER at ATF).
Site and Conventional Facilities

Site Studies in CA and IL

Measurements at the 8-Pack

Los Angeles MTA

Universal City
Beam Collision Stabilization

Inertial Systems

Inertial Sensor (SLAC)

Inertial Sensor (SLAC)

Extended Object

Sensor
Magnetic
Electrostatic
pusher
Support
tube

Extended Object

Sensor
Magnetic
Electrostatic
pusher
Support
tube

FONT at NLCTA (Oxford, Queen Mary)

• Demonstrated ~15x suppression of offsets.
• Latency was about 60 ns (c.f. 390 ns bunch train).
IP Stabilization Summary

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

<table>
<thead>
<tr>
<th>Quiet Detector</th>
<th>Active Stabilization</th>
<th>FONT</th>
</tr>
</thead>
<tbody>
<tr>
<td>20 nm</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>4 nm</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>~20 nm*</td>
<td>Yes*</td>
<td>No</td>
</tr>
<tr>
<td>20 nm</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>4 nm</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>4 nm</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>~20 nm*</td>
<td>Yes*</td>
<td>Yes*</td>
</tr>
</tbody>
</table>

* Measured 20 nm vibration on SLD. Demonstrated R&D solution.
New “Nested Serpentine” winding (based on HERA magnets).

- Allows continuous variation of the beam energy.
- Study vibrations introduced by cryogenic fluids.
Baseline technologies and design are proven.

Major improvements will come from value engineering and industrial design for manufacture, reliability, and serviceability.

Industrial technologies readily and widely available.

R&D will continue to look for ways to improve on the baseline – e.g., better power efficiency with DLDS – and support CDR/TDR engineering and design.
Independence of Sources, Damping Rings, Linacs, and Beam Delivery allow significant commissioning with beam during construction.