X-Band Linear Collider
Path to the Future

X-Band Linear Collider
Introduction and Overview

D. L. Burke
NLC Program Director

Stanford Linear Accelerator Center
April 26-27, 2004
Our Message for the ITRP

A collider built with X-Band technology will meet the physics goals of the TeV energy frontier.

We are ready to initiate a project to build an electron-positron collider to partner with the LHC.

X-Band is the path to future HEP technology.
Experience and Expertise

High-power room-temperature RF technology – five decades of experience.

A comprehensive design grounded in facility operations and R&D validates all aspects of use of X-Band technology.

Strong interregional collaboration of major institutions.
Introduction and Overview

1. The Challenges and Key Milestones
2. Technology of Choice
3. Collider Design and TRC Demonstrations
4. Overview of the X-Band Collider Project
5. The Path to the Future
The Challenges

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

And Key Milestones ... (DLB personal view)
The SLAC 3-Kilometer Linac

From a 17 GeV electron linac in the 1960s ...

... to the 50 GeV SLC electron-positron collider in the 1990s.
Wakefields and Beam Break Up

Detuning
Wakefields in
the SLAC
Linac
(ca 1970)
The First Linear Collider – the SLC

New Territory in Accelerator Design and Operation

On-line real-time instrumentation, data analysis, and control.

Automated second-order tuning and control of precision beams.

→ Lessons built into the NLC design and technology.
Vertical beam size of 60-70 nm … the needed demagnification.
Alignment Step 1. Align magnetic centers to create a straight beam trajectory (to control dispersive emittance growth).

FFTBB beam-based alignment of magnets to microns.
A Key Concept: Accelerator Structures are Beam Instruments

Alignment Step 2. Align structures to the beam trajectory created by the magnets (to control wakefield emittance growth).

Measure beam trajectory through the structure using manifold signals.

→ Move and orient structures to null wakefields.
Beam-Based Structure Alignment

Structure straightness measured in the shop.

Beam test – fit position and angle of the structure measured by the manifold BPMs to the shop data.

-20 -10 0 10 20
0.2 0.4 0.6 0.8 1.0 1.2 1.4 1.6

Cell Offset or Beam Position at Min. Power (µm)

Distance Along Structure (m)

NLC Tolerance

Manifold BPM Data

Shop Data

Structure meets straightness criteria; and Manifold BPM precision 1 µm – five times better than needed.
The Test Accelerator at SLAC

The NLCTA with 1.8 m accelerator structures (1997).

Accelerating gradient 40 MV/m (unloaded) with good wake-field control and energy spread.

Demonstrated ability to reach 500 GeV cms.
Two Teams – One Choice

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

SLAC-KEK R&D MOU signed in 1998.
X-Band Project Reports

NLC ZDR (1996)
SLAC, FNAL, LBNL, LLNL, 12 other institutions.

KEK, HEPL, PAL, BINP, 117 other institutions.
Evolution of a common design strategy:

NLC Zero-Order Design (1996)


NLC Snowmass 2001 (2001)


GLC/NLC TRC (2003)
Test Facilities Cover All Parts of the Collider

SLC, FFTB, ASSET, E-158

SLC, E-158

ATF, 3rd Gen Light Sources, SLC

Bunch Compression

SLC and FEL’s

ε Preservation

BDS & IR

e+ / e- Sources

Linac RF

Damping Rings

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

A Partner for the LHC
Introduction and Overview

1. The Challenges and Key Milestones

2. Technology of Choice

3. Collider Design and TRC Demonstrations

4. Overview of the X-Band Collider Project

5. The Path to the Future
“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.”
Solid-State Modulator and Dual-Mode SLED-II

TRC R1 Done.

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

Operated over 600 hours.

Turn-key with feedbacks.
High Gradient Performance of Five Recent Structures

Unloaded Gradient (MV/m)

Breakdown Rate at 60 Hz (#/hr)

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

Average Rate Goal

TRC R1 Done
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.*)
NLCTA Today

Eight structures installed and running at > 60 MV/m.

(http://www-project.slac.stanford.edu/lc/local/Projects/NLCTA/nlctasumm.html)
Ready to Initiate International Linear Collider Project

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.
X-Band Linear Collider Project Overview

Project Mission

Build a linear collider at 500 GeV that is upgradeable to 1 TeV.
Deliver physics concurrently with the LHC ... begin about 2015.
Deliver 500 fb⁻¹ at 500 GeV in four years after commissioning.

Project People

Talented and experienced team of people at major laboratories.
BNL, Fermilab, KEK, LBNL, LLNL, SLAC

Project Philosophy

Multi-billion dollar Mission like those of large technology companies.
Bring to it the best industrial and business practices.
Industrial Practices and Management

Learn from people who do large projects that must make money.

We consulted with a few “West Coast” technology companies.

- Boeing
- Applied Materials
- HP

- Aircraft
- Chip Development
- Printers, computers, etc.

- Value engineering and design for manufacture.
- “People who can talk to us.”
Industrial Experience

People …

G. Caryotakis  President, Varian Electron Device Group.
R. Larsen  President and CEO, Analytek/Tektronix, LTD.
F. Asiri  Technical Manager of LIGO Facilities.
J. Ives (retired) Rear Admiral U.S. Navy, SSC Associate Director for Conventional Construction, PB&Q Head of Northridge Earthquake Recovery.

Collaboration with Stanford University …

K. Ishii  Professor, School of Engineering
Students from Manufacture Modeling Laboratory
NLC Cost Estimates

First “ZDR” in-house estimate in 1996.

Comprehensive estimate with input from industry and continued laboratory R&D reviewed by DOE “Lehman” Committee in 1999.

“… all major systems and subsystems covered … and other project costs appear to be conservative.”


Present 2003 Baseline Total Cost is 6.3 B$.

Full U.S. accounting in 2003 dollars with 30% contingency, but no detectors or land acquisition costs.
NLC 2003 Cost Breakdowns

**Technical Systems**

- Machine Area
  - Beam Delivery 9%
  - Injector 10%
  - Damping Rings 3%
  - Common 22%
  - Main Linac 56%

**Cost Type**

- Installation & Test 6%
- Controls 6%
- Vacuum 2%
- Systems Eng 9%
- Magnets 6%
- Rf 27%
- Operations 4%
- Instrumentation 3%
- Structures 8%
- Management 3%
- Preops 5%
- Edi & A 16%
- Installation 3%

**Hardware**

- Cf 24%
- Hardware 49%
Independence of Sources, Damping Rings, Linacs, and Beam Delivery allow significant commissioning with beam during construction.
# NLC Technically-Limited Schedule

<table>
<thead>
<tr>
<th>YEAR</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
</tr>
</thead>
<tbody>
<tr>
<td>Milestones</td>
<td>Gain Access to Site</td>
<td>Approve Site and Baseline</td>
<td>Start Production</td>
<td>Start On-site Construction</td>
<td>Start Installation</td>
<td>Start Beam Commissioning</td>
<td>Linac Beam in Region 1</td>
<td>Collide Beams</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Systems Engineering/Mgmt</td>
<td>Systems Engineering</td>
<td>Design</td>
<td>Sustaining Systems Engineering</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hq</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Electron Injector Housing</td>
<td>Civil Eng. Concepts</td>
<td>A-E Design</td>
<td>Construct</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Positron Injector Housing</td>
<td>Civil Eng. Concepts</td>
<td>A-E Design</td>
<td>Construct</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Components</td>
<td>R&amp;D/Design</td>
<td></td>
<td>Fab / produce / procure</td>
<td>Install</td>
<td>e*</td>
<td>Commissioning</td>
<td>Operations/Development</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Electron Source &amp; Booster</td>
<td>R&amp;D/Design</td>
<td></td>
<td></td>
<td>Install</td>
<td>e*</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Positron Driver Linac</td>
<td>R&amp;D/Design</td>
<td></td>
<td></td>
<td>Install</td>
<td>p*</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Positron Source &amp; Booster</td>
<td>R&amp;D/Design</td>
<td></td>
<td></td>
<td>Install</td>
<td>p*</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>DR Components</td>
<td>R&amp;D/Design</td>
<td></td>
<td>Fab / produce / procure</td>
<td>Install</td>
<td>e*</td>
<td>p*</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Electron DR</td>
<td>R&amp;D/Design</td>
<td></td>
<td></td>
<td>Install</td>
<td>p*</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Positron PreDR</td>
<td>R&amp;D/Design</td>
<td></td>
<td></td>
<td>Install</td>
<td>p*</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Positron DR</td>
<td>R&amp;D/Design</td>
<td></td>
<td></td>
<td>Install</td>
<td>p*</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Prelinac Components</td>
<td>R&amp;D/Design</td>
<td></td>
<td>Fab / produce / procure</td>
<td>Install</td>
<td>e*</td>
<td>p*</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Electron Prelinac</td>
<td>R&amp;D/Design</td>
<td></td>
<td></td>
<td>Install</td>
<td>e*</td>
<td>p*</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Positron Prelinac</td>
<td>R&amp;D/Design</td>
<td></td>
<td></td>
<td>Install</td>
<td>e*</td>
<td>p*</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>R&amp;D</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>NLCTA/GLCTA testing in support of industrialization of components</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Linac Components</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Produce spare klystrons</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Main Linac Components</td>
<td>R&amp;D/Design</td>
<td></td>
<td>Industrial ramp-up and production of linac components</td>
<td>Install</td>
<td>e**</td>
<td>e*</td>
<td>p*</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Electron Main Linac</td>
<td>Civil Eng. Concepts</td>
<td>A-E Design</td>
<td>Construct</td>
<td>Install</td>
<td>e**</td>
<td>e*</td>
<td>p*</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Positron Main Linac</td>
<td>Civil Eng. Concepts</td>
<td>A-E Design</td>
<td>Construct</td>
<td>Install</td>
<td>e**</td>
<td>e*</td>
<td>p*</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Beam Delivery Components</td>
<td>R&amp;D/Design</td>
<td></td>
<td>Fab / produce / procure</td>
<td>Install</td>
<td>e*</td>
<td>p*</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Electron Delivery Line 1</td>
<td>Civil Eng. Concepts</td>
<td>A-E Design</td>
<td>Construct</td>
<td>Install</td>
<td>e**</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Positron Delivery Line 1</td>
<td>Civil Eng. Concepts</td>
<td>A-E Design</td>
<td>Construct</td>
<td>Install</td>
<td>e**</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>I. R. Hall 1</td>
<td>Civil Eng. Concepts</td>
<td>A-E Design</td>
<td>Construct</td>
<td>Install I.R. &amp; Detector</td>
<td>e*</td>
<td>x*</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Electron Delivery Line 2</td>
<td>Civil Eng. Concepts</td>
<td>A-E Design</td>
<td>Construct</td>
<td>Install</td>
<td>e*</td>
<td>x*</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Positron Delivery Line 2</td>
<td>Civil Eng. Concepts</td>
<td>A-E Design</td>
<td>Construct</td>
<td>Install</td>
<td>e*</td>
<td>x*</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>I. R. Hall 2</td>
<td>Civil Eng. Concepts</td>
<td>A-E Design</td>
<td>Construct</td>
<td>Install I.R. &amp; Detector</td>
<td>e*</td>
<td>x*</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>System Engineering</td>
<td>Civil Eng.</td>
<td>A-E System Design</td>
<td>Sustaining Engineering</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>NEPA/EA/EIS</td>
<td>Environmental Process</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Site Infrastructure/Utilities</td>
<td>Civil Eng. Concepts</td>
<td>A-E Design</td>
<td>Construct</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Campus Buildings</td>
<td>Civil Eng. Concepts</td>
<td>A-E Design</td>
<td>Construct</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Accelerator Control Center</td>
<td>Civil Eng. Concepts</td>
<td>A-E Design</td>
<td>Construct</td>
<td>Outfit</td>
<td>Commissioning</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Control System</td>
<td>R&amp;D/Design</td>
<td>Acquire / Install</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

* Establish electron (e), positron (p), or colliding (x) beams for initial system commissioning.

** First electron beam in Main Linac, Region 1.
Project Initiation – The First Years
Internationally Sharable Activities

Engineering and Design

Accelerator Physics

Value Engineering and Design: Reliability, Serviceability, Cost

Aspects of Site and Civil Engineering and Design

Risk Analysis, Project Planning, and CDR/TDR

R&D

Continued Technology Development

Instrumentation, controls, and software

Specialized components – e.g., collimators, kickers, etc.

Options beyond the Baseline

Support for Industrialization

Prototyping

QC and Testing
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.)

- Replace Stations 1 and 2 with New 2-Packs
- Dual Mode SLED Lines
- Existing Modulator
  (With two 75 MW Permanent Magnet Klystrons.)
- Prototype 2-Pack
  (Now under test in PC lab.)
Internationally Sharable Engineering, Design, and R&D

<table>
<thead>
<tr>
<th>GDO Internationally Sharable Budget*</th>
<th>2005 CDR</th>
<th>2006 Engineering</th>
<th>2007 EDR and Baseline</th>
<th>Cumulative Prebaseline</th>
<th>2008 Site selection and Long-lead Procurement</th>
<th>Cumulative Preconstruction</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Accelerator Systems</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Material &amp; Subcontracts ($M)</td>
<td>10</td>
<td>22</td>
<td>33</td>
<td>65</td>
<td>70 ^</td>
<td>135</td>
</tr>
<tr>
<td>Employee Labor (US FTE)</td>
<td>91</td>
<td>136</td>
<td>182</td>
<td>409</td>
<td>273 ^</td>
<td>682</td>
</tr>
<tr>
<td><strong>Engineering Test Facility</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Material &amp; Subcontracts ($M)</td>
<td>3</td>
<td>6</td>
<td>17</td>
<td>26</td>
<td>29 ^</td>
<td>55</td>
</tr>
<tr>
<td>Employee Labor (US FTE)</td>
<td>18</td>
<td>36</td>
<td>55</td>
<td>109</td>
<td>73 ^</td>
<td>182</td>
</tr>
<tr>
<td><strong>Systems Engineering</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Material &amp; Subcontracts ($M)</td>
<td>2</td>
<td>3</td>
<td>15</td>
<td>20</td>
<td>46 ^</td>
<td>66</td>
</tr>
<tr>
<td>Employee Labor (US FTE)</td>
<td>27</td>
<td>64</td>
<td>91</td>
<td>182</td>
<td>109 ^</td>
<td>291</td>
</tr>
<tr>
<td><strong>Program Management</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Employee Labor (US FTE)</td>
<td>9</td>
<td>27</td>
<td>45</td>
<td>82</td>
<td>73 ^</td>
<td>155</td>
</tr>
<tr>
<td><strong>Total Internationally Sharable Budget</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Material &amp; Subcontracts ($M)</td>
<td>15</td>
<td>31</td>
<td>65</td>
<td>111</td>
<td>145 ^</td>
<td>256</td>
</tr>
<tr>
<td>Total Employee Labor (US FTE)</td>
<td>145</td>
<td>264</td>
<td>373</td>
<td>782</td>
<td>527 ^</td>
<td>1,309</td>
</tr>
</tbody>
</table>

* Figures are budget authority and labor (in US FTE units, 1300 h) without contingency or detector costs.
^ Assumes approval for groundbreaking in 2009.

“Technical” limit is experienced people.

^Assumes approval for “Ground Breaking” in 2009.
Resources
(2003 USD and US Accounting)

The ILC Mission will need redirection of some existing world-wide HEP resources (which total nearly 2 B$ per year).

For example, LHC now consuming much of the CERN yearly budget.

U.S. HEPAP Report (Bagger and Barish, 2002) recommends clear identification of redirected resources.

(Redirected resources already included in NLC US-based cost estimate – that is, the Project pays for these from its budget.)

This will amount to 200-250 M$ per year (10%) of existing world-wide HEP resources (cash, people, infrastructure).
Operating Costs
(2003 USD and US Accounting)

NLC estimate of 500 GeV cms X-Band collider yearly* operating costs (based on Fermilab and SLAC budgets for the Tevatron and PEP-II):

- Labor (900 FTEs) 90 M$
- Consumables: Power and Klystrons 115 M$
- Maintenance & Improvements (procurements) 25 M$
- Miscellaneous Materials & Services 20 M$
- Total 250 M$

Match of operating costs and resources redirected for construction:

* Nine months with 85% availability at 500 GeV cms energy.
Life-Cycle Costs
(2003 USD and US Accounting)

Operating Costs

20-Year Operations @ 250 M$/yr  5.0 B$

Upgrade to 1 TeV

With baseline technology, a “new start” is estimated to be 40% of initial construction, but significantly cheaper if contiguous with initial construction.

1 TeV Upgrade ("new start")  2.5 B$

Total Upgrade and 20-Year Ops  7.5 B$

(Compare with construction cost of 6.3 B$.)
Path to the Future

X-Band technology today meets the demands of the TeV energy frontier.

X-Band is a critical step to future HEP technologies such as CLIC.

X-Band is the right choice for the international HEP community.