Progress in the Next Linear Collider Design

DPF2000 Meeting
August 12th, 2000

Tor Raubenheimer
Next Linear Collider

- $e^+/e^-$ linear collider based on X-band rf technology
- Initial cms energy of 500 GeV with $\mathcal{L} \geq 5\times10^{33} \rightarrow 20\times10^{33}$
- Straight-forward upgrade to 1 TeV with $\mathcal{L} \geq 10\times10^{33} \rightarrow 30\times10^{33}$
- Upgrade routes to 1.5 TeV and beyond
- Technology based on results from test facilities: FFTB, NLCTA, ASSET, KEK ATF
- Incorporates knowledge gained from SLC operation
NLC Project Scope

- **Injector Systems** 1.5 TeV
- **Main Linac** 0.5 - 1.0 TeV
  - Housing with all internal services
  - Half filled for initial 500 GeV cms
  - Upgrade by adding rf, water, power to the 2nd half of the tunnels
  (1.5 TeV with increased gradient or length)
- **Beam Delivery** 5 TeV
  - Two BDS tunnels and IR halls with services
Established collaborations with KEK, LBNL, LLNL, and Fermilab

Optimized parameters and established common rf design with KEK

Performed bottoms-up cost estimate for Lehman review

Successful Lehman review—questionable project cost!

Have demonstrated most necessary rf hardware although rf damage limits in structures are still a question

Improving rf designs for reduced cost and improved efficiency

Working on cost reduction throughout design!
SLAC / KEK Collaboration

- MOU signed in ‘98 to pursue common R&D towards LC
- Optimized JLC and NLC designs towards common parameters and rf designs
- ‘ISG’ meetings every 6 months alternating between SLAC and KEK sites:
  - Six working groups from Parameters to Interaction Region
  - Focus is on RF development (accelerator structures, rf pulse compression, klystrons, and modulators)
    - Accelerator structures built at KEK and tested at SLAC
    - Multi-mode DLDS components built at SLAC verified at KEK
- ISG document summarizes progress: SLAC-R-559 or KEK-Report-2000-7
MOUs signed with LBNL and LLNL
  - Berkeley concentrating on magnet design and damping ring issues
  - Livermore focusing on solid-state modulators

Fermilab taking responsibility for main linac beamline:
  - Emittance preservation, structure design, optics layout
  - Structure manufacture, magnet design, vacuum systems

1st US collaboration meeting at SLAC in January with all parties

1st MAC meeting in June at Fermilab; 2nd MAC meeting in October at SLAC

Numerous SBIRs to further technology development
NLC RF System

- RF system consists of 4 primary components:
  - **Modulators**: line ac $\rightarrow$ pulsed dc for klystrons (500 kV, 250 A)
  - **Klystrons**: dc pulse $\rightarrow$ 75MW at 11.424 GHz
  - **RF Pulse Compression (DLDS)**: compresses rf pulse temporally, increasing the peak power, and delivers the power to the structures
  - **Accelerator Structures (DDS & RDDS)**: designed to transfer power to the beam while preventing dipole mode driven instabilities

- Each linac has 100 modules consisting of 1 modulator, 8 klystrons, 1 DLDS system, and 24 accelerator structures
- Need good efficiency, reliability, and low cost!
NLC RF System Highlights

- Developing solid-state modulator with LLNL
  - Much less expensive, more reliable, smaller package
- Demonstrated (periodic permanent magnet) PPM 75 MW klystron operation for NLC with 3µs rf pulse (2x expected!)
  - Half as many klystron/modulator systems required!
- Tested mode propagation needed for multi-moded DLDS
  - Less expensive rf pulse compression system
- Built DDS3 structure and RDDS1 structure with KEK
  - DDS3 exceeded alignment requirements and demonstrated rf BPM
  - RDDS will shorten linac length by 6%—sub-micron errors in cell fabrication
  - Observed structure damage at high gradients!
- High power component tests finished in 2001 and full system test in 2003
Solid-State Modulator

• Conventional modulators are expensive and inefficient with short pulses: ~ 60%

• Program at LLNL to develop ‘Induction Modulator’ based on solid-state IGBTs: efficiency ~ 80%

• IGBTs developed for e-trains with 2 to 3 kV and 3kA

• Drive 8 klystrons at once

• Full modulator finished this winter
Solid State Induction Modulator
Advantages

- High efficiency > 75%
  - Low stray inductance for fast voltage rise time
  - Energy recovery with fast turn off
- Redundancy
  - Up to 5% of core drivers can fail without effecting modulator operation
- High availability
  - Replacement of core driver PC boards is simple and in air
- Lower cost from mass production
  - Printed circuit board assembly line production and testing
  - Solid State production switches (>40,000 IGBTs)
- Compact package
  - Switch and capacitor bank compact and drive 8 klystrons
PPM Klystrons
XP-1 75 MW Klystron

- XP-1 based on very successful 50 MW Periodic-Permanent Magnet (PPM) klystron but included many ‘simplifications’
- XP-1 testing results:
  - 71 MW @ 300 ns @ 10 Hz
    - Limited by gun oscillation
  - 75 MW @ 1.5 µs @ 5 Hz
    - After installation of load in gun region
    - Limited by 20 GHz oscillation in collector region!
  - 72 MW @ 3.1 µs @ 1 Hz
    - After installation of tailpipe rf load in collector
    - Repetition rate limited by heating
    - Pulse length limited by modulator
- Designing a second 75 MW tube with better field profile and features to improve manufacturing—to be tested this fall
DLDS Pulse Compression

- All components have been designed
- Multi-mode transmission properties have been verified
- High power tests will start in 2001
- Full system test in 2003
DDS3 Structure
DDS3 Structure BPM Test

NLC Tolerance

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

Distance Along Structure (m)
Need to damp or decohere long-range dipole modes to prevent the Beam Break-Up instability

Each X-band structure has 206 cells, each with a different dipole mode frequency

Manifolds provide signal for beam-based alignment

Latest structure design: RDDS has cells with +12% shunt impedance
RDDS1 Structure Construction

- RDDS1 cells were designed at SLAC and machined at KEK
- Final machining performed on diamond-turning lathe
- Attained excellent results: frequency errors less than 1 MHz, i.e. <1µm errors
- Tolerances for dipole mode frequencies are 5 times looser!
High Power Damage

- Have had difficulty processing 1.8m long structures to 70 MV/m (NLC design gradient)
  - Observed damage to structure irises at 50 MV/m

- 1.8m structures consist of 206 cells
  - Single cells can operate at 150 ~ 200 MV/m without damage
  - A 26 cm structure has been run to 140 MV/m
  - A 75 cm structure has been run at 90 MV/m

- Theoretical model predicts the damage is related to the group velocity of the rf power in the structure

- Building 12 structures with KEK this summer to study length and group velocity dependence – will be tested in fall
NLC Cost Reduction Strategy

- Costs distributed throughout system ⇒ attack all
- Primary changes:
  - Solid state modulator (powers 8 klystrons for 40% of the cost)
  - Longer linac rf pulses (half as many klystrons/modulators)
  - Permanent magnets (eliminate cable plant/PS, improved reliability)
  - Cut & cover tunnels (lower cost but may need terrain following)
  - Moving electronics to tunnel (eliminate cable plant)
  - Redesign bunch compressors (lower final energy, shorter system)
  - Redesign collimation system (reduce length of by factor of two)
  - New final focus (reduce length and components in BDS)
- Expect reduction in cost by 30% with another ~10 to 15% in scope reduction if desired
- Additional gains from further R&D and layout changes
Magnet Issues

- Had assumed **all** magnets had individual (redundant) power supplies
- Variable permanent magnets
  - Many places where PM bends with or without trims might be used
  - Many places where PM quads with trims might be used
- Power supply strings with trim supplies
  - Use in regions of BDS and collimation regions
- Large savings from reduced cable plant and power supplies
- Variable permanent magnet quadrupoles being developed at FNAL and LBNL—first prototype has been constructed
Goal: Reduce cable, tray, rack, building etc. costs by installing electronics in the beamline tunnels and simplifying power and communication links.

- House BPM, Mover, LLRF and Vacuum electronics in tubular tunnel niches: ‘rat holes’
- Consider use of wireless communications, DC power distribution, and local vacuum pump PS’s.

Concerns

- Radiation: estimates based on SLAC Linac data.
- Access/Reliability: use redundancy and perhaps robotic maintenance units to swap modules.
NLC - The Next Linear Collider Project

Post-Linac Collimation System

- High power beams will damage collimators unless beam sizes are increased
- Studying ‘consumable’ and ‘renewable’ collimator systems

Consumable Collimators

- ‘Conventional’ collimators not damaged
- ‘Consumable’ collimators damaged \( \sim 1000 \times \) per year

‘Renewable’ collimators damaged each pulse

Optics Tolerances

Tighter

Looser

Beam damage
MPS and Beam Damage

• Thermal shock wave from high density beam will damage materials—use SLAC FFTB beam to study damage

• SEM photographs of damage produced by a single $2 \times 10^{10}$ bunch with a $9 \times 11$ µm cross section: expect a temperature rise of about $1800$ °C
Post Linac Collimation

- Most main linac faults will be energy errors $\Rightarrow$ design for passive energy collimation
- Infrequent betatron errors $\Rightarrow$ ‘consumable’ betatron collimation
- Reduce collimator system length from 2.5 km to roughly 1.2 km—still working on optimal design
Final Focus and Interaction Region

- Old final focus was a scaled up model of the SLAC Final Focus Test Beam (FFTB) beamline.
- Modular design with orthogonal control using symmetry.
- Chromatic correction is performed with pairs of sextupoles at large dispersion points separated by $\pi$ to cancel geometric aberrations—requires lots of bending to generate $\eta$.
- Length of system: was roughly 1.8 km—driven by synchrotron radiation at 1.5 TeV.
- New design: chromatic correction is performed at final doublet so synchrotron radiation has little effect.

$\Rightarrow$ Length is roughly 700m and will operate at 5 TeV!
New Final Focus

- One third the length
- Can operate with 1.5 TeV beams
- 4.3 meter L* (twice 1999 design without tighter tolerances)
- Optical functions are not separated and dispersion in the FD

1999 Design

2000 Design
IR Layout Issues

• Final focus aperture is set by low energy beams $\sigma \sim 1/\sqrt{\gamma}$ but magnet strength is limited by highest energy operation
  – Final focus has limited energy range without rebuilding magnets and vacuum system

• Simplify design by dedicating one IR to ‘low’ energy operation and one to ‘high’ energy operation
  – ‘Low’ energy range of 90–350? GeV
  – ‘High’ energy range of 250–1000 GeV
  – Need to specify reasonable ranges!

• High energy beamline would have minimal bending to allow for upgrades to very high collision energies
  – ‘High’ energy BDS could be upgraded to multi-TeV operation!
A Multi-TeV LC Facility

A poorly drawn schematic of a LC facility with an factor of 50 in energy range

- Optional low energy IP 92-350 GeV
- Low energy (50 - 175 GeV) beamlines
- Site roughly 25 km in length with two 10 km linacs
- Return lines: production and possibly drive beam - share main linac tunnel
- Centralized injector system possibly for TBA drive beam generation also
- High energy IP 0.25-5.0 TeV upgraded in stages
Route to High Luminosity in NLC

- NLC design has built-in margins to cover nominal operating plane including 50% charge overhead and 300% emittance dilution
  - NLC damping rings spec. to produce 0.02 mm-mrad although design requires 0.03 mm-mrad
  - SLC used ‘emittance bumps’ to reduce emittance dilution from 1000% to 100%—technique not included in NLC emittance budgets
  - Use margins to achieve higher luminosity

- Present prototypes and R&D results are better than initial specs (see RDDS cell frequencies and DDS3 alignment & S-BPM)
  - $\Delta \varepsilon_y < 25\%$ in linac if production components are similar to prototypes

$\Rightarrow$ Both will lead to increased luminosity ($34 \times 10^{33}$ at 880 GeV)
# NLC - The Next Linear Collider Project

## Parameters for 500 GeV and 1 TeV

<table>
<thead>
<tr>
<th>IP Parameters for the JLC / NLC (2/24/00)</th>
<th>500 GeV</th>
<th>1 TeV</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>CMS Energy (GeV)</strong></td>
<td>510</td>
<td>500</td>
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<tr>
<td><strong>Luminosity ((10^{33}))</strong></td>
<td>5.3</td>
<td>5.4</td>
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<tr>
<td>Repetition Rate (Hz)</td>
<td>120</td>
<td>120</td>
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<tr>
<td><strong>Bunch Charge ((10^{10}))</strong></td>
<td>0.7</td>
<td>0.82</td>
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<tr>
<td>Bunches/RF Pulse</td>
<td>95</td>
<td>95</td>
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<tr>
<td>Bunch Separation (ns)</td>
<td>2.8</td>
<td>2.8</td>
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<tr>
<td><strong>Eff. Gradient (MV/m)</strong></td>
<td>58.7</td>
<td>57.3</td>
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<tr>
<td>Injected (\gamma x / \gamma y \times 10^{-8})</td>
<td>300 / 3</td>
<td>300 / 3</td>
</tr>
<tr>
<td>(\gamma x) at IP ((10^{-8}\text{ m-rad}))</td>
<td>400</td>
<td>450</td>
</tr>
<tr>
<td>(\gamma y) at IP ((10^{-8}\text{ m-rad}))</td>
<td>6.5</td>
<td>8.5</td>
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<tr>
<td>(\beta x / \beta y) at IP (mm)</td>
<td>12 / 0.12</td>
<td>12 / 0.12</td>
</tr>
<tr>
<td>(\sigma x / \sigma y) at IP (nm)</td>
<td>310 / 4.0</td>
<td>330 / 4.6</td>
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<tr>
<td>(\sigma z) at IP (um)</td>
<td>90</td>
<td>120</td>
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<tr>
<td>(\Upsilon) ave</td>
<td>0.11</td>
<td>0.09</td>
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<tr>
<td>Pinch Enhancement</td>
<td>1.46</td>
<td>1.35</td>
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<tr>
<td>Beamstrahlung (\delta B) (%)</td>
<td>3.2</td>
<td>3</td>
</tr>
<tr>
<td>Photons per (e^+e^-)</td>
<td>0.86</td>
<td>0.96</td>
</tr>
<tr>
<td>Two Linac Length (km)</td>
<td>5</td>
<td>5</td>
</tr>
</tbody>
</table>
Multi-TeV Colliders

- Need improvements in rf technology to make higher energy cost effective:
  - multi-beam klystrons, active rf pulse compression, or TBA
- Need high gradients to keep length reasonable and balance cost of rf system
  - At 35 MV/m (SC max gradient), 3 TeV linac would be 110 km
  - Optimum gradient in NLC is between 75 and 100 MV/m depending on how components scale with rf power
    \(\Rightarrow\) Normal conducting cavities with lower cost rf system and higher gradient of 100 \text{~} 200 \text{ MV/m}
- Need very small beam emittances and small spots to achieve luminosity – injection complex similar to present NLC
- Reuse next-generation LC injection system and beam delivery, and use linac tunnels with modified components
Figure 1: Overall Layout of the CLIC complex at 3 TeV c.m.
Future Developments

**Parameters**
- Rounder IP spots & lower charge

**Injector Systems**
- Consider centralized injector
- Test e- superlattice cathodes
- Improved e+ source based on undulator or laser back-scattering
- Use advanced cell structure in DRs

**Main Linac**
- Use 4 mode DLDS for 8x pulse compression - factor of 2 reduction in waveguide
- Active high power rf switches for pulse compression

**Integrated structure and quadrupoles**
- Consider MDS structure for relaxed tolerances
- Use RF quads or integrated structure quad to ease alignment tolerances
- Rf recirculation for reduced ac power requirements
- Use energy recovery techniques for reduced ac power requirements

**Beam Delivery**
- Consider single IR with push-pull detector and remove second IR, big bend, and IP switch
Outstanding Issues (a few of many!)

- **Sources**
  - Current limit in e- source and target limits in e+ source

- **Damping rings**
  - Require excellent stability
  - In addition to conventional instabilities, new effects may be important

- **RF breakdown**
  - Difficulty processing up to 70 MV/m and damage at 50~60 MV/m
  - 450 Joules in DLDS rf pulse compression system

- **Collimation and IR**
  - Have to collimate ‘all’ particles outside $8\sigma_x$ and $40\sigma_y$ without destroying collimators or beam emittance
  - Need high field magnets in IR with nm-level stability

- **Reliability**
Summary

• Lots of progress on NLC design in last year!
• Lehman review positive but cost was too high!!
  
• Continual improvement in rf components ⇒ cost reductions
• More aggressive approach to design ⇒ cost reductions
• New concepts ⇒ cost reductions
• Lots of ideas for further improvements
  
• Expect ~30% cost reduction with further reduction possible from additional R&D and/or scope reduction
  
• NLC is designed for high luminosity (similar to TESLA) however neither design has much margin at these parameters
• NLC facility will be designed to support a future multi-TeV LC