NLC Engineering Organization

NLC Conventional Facilities (J. Ives)

NLC Mechanical Systems (J. Cornuelle)

NLC Electrical Systems (R. Larsen)

Modulators

Sources
Vacuum
Magnets
Supports/Movers
Instruments
Facilities
Installation
Manufacturing
Protection Systems
Global Controls
Low Level RF

NLC Program Engineers

Plant Engineering
Metrology
Mechanical Design
Klystron
Power Conversion
Controls
LLNL & Bechtel NV
LBNL

R. S. Larsen 6/23/99
Page 2
Decisions after 1998
Modulator Workshop

• Adopt Dual Track development program
  – Baseline (Line Type)
  – Induction IGBT design

• Continue prototyping of 2-pack tank

• Support SBIR initiatives for incremental improvements

• Pursue 8-Pack design for major improvements
  – Efficiency
  – Reliability
  – Cost

• Establish strong collaboration with LLNL-Bechtel to accelerate progress
Decisions - Continued

- Develop full prototype for full power RF tests
- Procure industrial prototypes from two vendors
- Use 2-Pack as test bed
- Other Modulator Technologies: Retain interest in hybrid solid state possibilities:
  - Thyatron solid state substitution driving conventional transformers
  - Solid state on-off switches driving conventional transformers
  - IGBTs driving short stack induction transformer with multiple secondary
NLC Modulators
Baseline Cost Model

- 2-Pack line type modulator (2 Klystrons per Package)
- Proven design with low technical risk
- Current cost model for X band
- Scale for S & L bands
NLC Baseline Modulator

Thyratron
PFN Coil
PFN Capacitors
EOLC Diode
Klystrons
Expansion/Access Port
HV Cable
Pulse Transformer

TANK LAYOUT- Side View
## NLC Baseline Modulator

### X, S & L Band Load Comparison

<table>
<thead>
<tr>
<th>Modulator</th>
<th>No. Klystrons</th>
<th>Klystron Voltage</th>
<th>Current</th>
<th>P.Width</th>
<th>PRF-Hz</th>
<th>Avg Pwr</th>
<th>Est. Pwr</th>
<th>Qty for 0.5 TEV</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>% Eff.</td>
<td>kV Peak</td>
<td>A - Peak</td>
<td>uSec</td>
<td>Out-kW</td>
<td>In-kW</td>
<td>*</td>
<td>**</td>
</tr>
<tr>
<td>X Band</td>
<td>2 @75 MW</td>
<td>60</td>
<td>490</td>
<td>510</td>
<td>1.5</td>
<td>120</td>
<td>45</td>
<td>75</td>
</tr>
<tr>
<td>S Band</td>
<td>1 @ 65 MW</td>
<td>50</td>
<td>350</td>
<td>373</td>
<td>5.0</td>
<td>120</td>
<td>78</td>
<td>156</td>
</tr>
<tr>
<td>L Band</td>
<td>1 @ 75 MW</td>
<td>50</td>
<td>388</td>
<td>387</td>
<td>6.0</td>
<td>120</td>
<td>108</td>
<td>216</td>
</tr>
</tbody>
</table>

*Assume 60% efficiency
**Assume 50% efficiency
NLC Modulators
R&D Goals 1

• Deficiencies of Line Type
  – Low energy efficiency ~60%
  – Thyatron switch tube lifetime and maintenance
  – High cost

• Goal 1: Develop 2-Pack
  – Proof of 500 kV driving 2 klystrons in parallel
  – Test bed for klystrons
  – Extend thyatron lifetime through re-design (SBIR program)
  – Investigate solid state switch alternatives (potential SBIR for hybrid line type or on-off switched capacitor)
  – Develop lower loss components for higher efficiency (Industry collaboration)
NLC Modulators
R&D Goals 2

• Goal 2: New Solid State design:
  – Efficiency >75% through faster switching & lower losses
  – Insulated Gate Bipolar Transistor (IGBT) high reliability
  – *Fail-soft* modular induction stack design
  – Lower cost ~ 2x in 8-Pack configuration

• Induction design capable of driving 8 klystrons.
• Partnership with LLNL & Bechtel to expedite design of full prototype.
NLC Modulators
R&D Goals 2

- R&D Plan: SLAC-LLNL - Bechtel Team
  - Test HV performance of basic cell mid FY99
  - Prototype stack test (1/4 full unit) end FY99
  - Full Prototype 500 kV 2000A test into dummy load mid FY00
  - Full Power RF NLCTA tests FY01-02
  - Fast track two industrial prototypes for delivery by mid FY02
R&D Plan Schedule
Baseline Modulator Production Cost Estimates

- **Basis of Estimate** - 2 Pack X & 1-Pack S&L
  - Bottoms up w/ vendor quotes & recent pricing for components in quantity ten (10) modulators
  - Add 10% vendor ED&I and 10% in-house ED&I = 117K$/Klystron
  - Apply learning curves
    - **X-Band 2-Pack unit quantity** = 117K$/klystron => 58.5K/Klystron
    - **S-Band 1-Pack unit quantity** = 264K$/klystron => 173K$/klystron
    - **L-Band 1-Pack unit quantity** = 300.3K$/klystron => 277K/Klystron
Baseline Modulator Production Cost Estimates

- X band uses a 2-Pack modulator, S&L bands are 1-Packs
- Assume 75/25 parts/labor and apply 92/85% Learning Curves
  - **X Band** 1800 2-Packs => 58.5 K$/klystron => 211M$
  - **S Band** 170 1-Packs => 173 K$/klystron = 29.4M$
  - **L-Band** 33 1-Packs => 277 K$/klystron = 9.1M$
8-Pack Induction Modulator
Production Cost Estimates

• Current pricing Metglas & IGBTs:
  • 20% total ED&I
  • 414 + 10 spares = 424 Units
  • => 970 K$/8-pack
    – Learning curves => 396K$ => $49.5K$/Klystron
      => $168M$

• Assume price drops in Metglas & IGBTs:
  – Learning curves => 168K$ => $21K$/Klystron => $71M$
Induction Modulator Production Cost Estimates

- Induction Modulator (8-Pack)
  - BLM: Baseline = 211M$
  - IM1: Conservative Model
  - IM2: Assumes future price reductions in Metglas & IGBTs

- Apply learning curves
  - $\text{IM1}= 970K$$\Rightarrow 49.5K$/Klystron$\Rightarrow 168M$
  - $\text{IM2}= 412K$$\Rightarrow 21k$/Klystron$\Rightarrow 71.3M$
NLC Modulators
R&D Risk Factors

• Baseline Modulator
  • Moderate technical and cost risks.
  • Moderate vendor & schedule risk.

• Solid State Modulator
  • Costs risks higher because of Metglas, IGBT price uncertainties
  • Higher schedule risk due to Metglas and IGBT new product suppliers.

• Common Technical Risk
  • Protection of multiple loads from arc in one load. Higher risk for 8-Pack due to higher stored energy. Protection must be bullet-proof.
Production Schedules

• Early industrialization needed to meet schedule.
  – Modulator Workshops, July 98, (see NLC Web page for papers & talks) and June 23-25, 1999, bring together researchers and industrial component and system integrator companies to discuss NLC requirements.

• Following Graph shows example production with 3-1/2 year installation schedule:
  – Monthly production (2-pack units)
  – Inventory (2-pack units)
  – Installation (Linac Sectors, 46 total)
Modulator Production Rates & Inventory: No. 2-Pack Units

M-K Mthly Production  Cum Installation  Modulator Inventory
<table>
<thead>
<tr>
<th>ISSUE</th>
<th>RESPONSE</th>
<th>WHO</th>
<th>STATUS</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Klystron arc fault studies &amp; protection circuit design</td>
<td>1. Measure arcs &amp; evaluate klystron protection on NLCTA 2-klystron tests</td>
<td>Gold</td>
<td>2/99 start</td>
</tr>
<tr>
<td></td>
<td>2. Continue circuit modeling and arc simulations of 8-pack solid state model</td>
<td>Cassel/Nguyen</td>
<td>Ongoing</td>
</tr>
<tr>
<td>2. System considerations under klystron or thyatron faults</td>
<td>Evaluate overall linac beam stability achievable with assumed fault rates for both klystrons and thyatrons, for 1, 2, 4 and 8-pack designs</td>
<td>Gold/Cassel</td>
<td>FY99</td>
</tr>
<tr>
<td></td>
<td>2. Study Drive requirements and losses of SI Thyristors vs. IGBTs</td>
<td>Akemoto/Gold</td>
<td></td>
</tr>
<tr>
<td></td>
<td>3. Study control &amp; monitoring requirements of stacked SIs or IGBTs</td>
<td>Akemoto/Gold</td>
<td></td>
</tr>
<tr>
<td>4. Capacitor Development</td>
<td>1. Specify requirements for pulse capacitors for hybrid design (~80kV)</td>
<td>Akemoto</td>
<td>Ongoing</td>
</tr>
<tr>
<td></td>
<td>2. Research suppliers for capacitors @ 5kV for solid state design</td>
<td>DeLamare</td>
<td>Ongoing</td>
</tr>
<tr>
<td></td>
<td>3. Study capacitor reliability</td>
<td>Akemoto/DeLamare</td>
<td>Starting</td>
</tr>
<tr>
<td></td>
<td>4. Promote SBIR development</td>
<td>Gold</td>
<td></td>
</tr>
</tbody>
</table>

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<table>
<thead>
<tr>
<th>5. Primary Power Supply Development</th>
<th>1. Develop power supply and distribution architecture for solid state modulator</th>
<th>Merritt/Cassel et al</th>
<th>Started</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2. Study power supply requirements for line or hybrid type stacked switch design</td>
<td>Gold/Akemoto</td>
<td>Started</td>
</tr>
<tr>
<td>6. Modulator-klystron (MK) Protection</td>
<td>1. Develop protection package and controller for line type &amp; study applicability to solid state induction</td>
<td>Gold/Eichner</td>
<td>Ongoing</td>
</tr>
<tr>
<td>7. Diagnostics &amp; Control</td>
<td>1. Specify requirements for triggering, monitoring of slow and fast waveforms, and controls for solid state induction unit</td>
<td>Cassel/Merritt et al</td>
<td>Not started</td>
</tr>
<tr>
<td></td>
<td>2. Design architecture and control/monitoring system to meet (1)</td>
<td>SLAC Controls Engr</td>
<td>Not started</td>
</tr>
<tr>
<td>8. Cooling Design</td>
<td>Design cooling architecture and strategy for solid state induction unit</td>
<td>Cassel/Merritt et al</td>
<td>Ongoing</td>
</tr>
</tbody>
</table>
### KEK- SLAC ISG-3 R&D Workshop January, 1999 - c.

<table>
<thead>
<tr>
<th>No.</th>
<th>Task Description</th>
<th>Responsible Party</th>
<th>Status</th>
</tr>
</thead>
<tbody>
<tr>
<td>9.</td>
<td>Packaging Design</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>1. Complete design and prototyping of 2-Pack Tank</td>
<td>Gold</td>
<td>Ongoing</td>
</tr>
<tr>
<td></td>
<td>2. Design complete package for solid state induction unit</td>
<td>Merritt/Cassel et al</td>
<td>Started</td>
</tr>
<tr>
<td>10.</td>
<td>TWT Klystron Driver</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>1. Evaluate TWT prototypes delivered from SBIR vendor.</td>
<td>Akre</td>
<td>Pending delivery</td>
</tr>
<tr>
<td></td>
<td>2. Investigate alternate suppliers for TWT drivers</td>
<td>Gold</td>
<td>Started</td>
</tr>
<tr>
<td></td>
<td>2. Design &amp; build prototype TWT package for 8-pack full power testing support</td>
<td>Akre</td>
<td>FY00</td>
</tr>
<tr>
<td>11.</td>
<td>Vendor Investigations</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>1. Research availability, price and delivery of (a) prototype and (b) production</td>
<td>Akemoto</td>
<td>3/99</td>
</tr>
<tr>
<td></td>
<td>quantities of: **FineMet &amp; Metglass induction transformer core material</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>**IGBTs</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>2. Investigate design improvements for pulse transformer for line type</td>
<td>Gold</td>
<td>6/99</td>
</tr>
</tbody>
</table>
Major Issues for Workshop Discussion

- Klystron protection on internal arcs - Both types
- Cooling designs - Both types
- Hybrid designs - Baseline
  - Solid state switch options
  - Low transformer ratio options
  - Other
- Hybrid Designs - Induction
  - Tradeoffs with various stack lengths and transformer configurations
- Cost optimization to minimize cost per klystron
- Reliability optimization - Both types
- Other
Induction Modulators
Discussion Issues - p.1

- 1. Capacitors:
  - Failure modes for pulsed operation, supplier list, cost optimization
- 2. Load Arc Protection
  - Fast turnoff & energy recovery, passive current limiting, other
- 3. Switches
  - IGBT cosmic problems, current limits, fast turnoff
- 4. Fuses/ Protection
  - Current zero switching, fusing, active switches - Ref. Maxwell
- 5. Metglas
  - Insulation, winding shorts, performance vs. aging, testing, production costs
Induction Modulators
Discussion Issues - p.2

• 6. Diodes:
  – Inadequacy as clamps for fast Tr
• 7. Board Layout:
  – Low L designs, contacts, manufacturing issues w/ 5 mil Cu
• 8. Induction Multi-Turn Stack
  – 1:2, 1:4 options, simulations, current strategy, mfg. Issues
• 9. Gate Drivers & Core Reset
  – Prototyping, simulations, delay control(?), opto-isolation
• 10. Power Supplies (4 kV, 250 kW/8-Pack)
  – DC Buck Regulator, Line Xfmr w/ multiple 2y, best eff’y, shielding(?), fanout/ protection, controls & safety design, turn-off mechanism on fault conditions
Baseline Modulator - SG

• Efficiency 61.5%
  – Can we do better? Waveform eff’y ~83%. Better for S&L?

• Costs
  – Charger 38.4% - how to reduce? Tank ass’y 46%

• PFN Tuning
  – Will factory cold tuning work?

• Industry collaboration
  – Components (in progress), Integrated systems, tank ass’y cost reduction issues.
SBIR Initiatives - RK

- Hybrid Modulators
  - Chargers, cap banks, solid state switches, pulse xfmr, thyratrons
- Chargers
  - More efficient designs with larger units?
- Capacitors
  - Can we fit cap bank in the tank design?
- IGBT Switches
  - Stacking options
- Pulse Transformers
  - Faster, more efficient designs? What are limitations?
Klystron Issues - RK

• Power vs Voltage
  – Ideally for power combiners tubes need to be matched
  – 2-pack idea - do it in factory
  – More of a problem for an 8-pack
  – We do not have a spec on matching. How good?
  – Do we need matching on ALL tubes in a group of 8?
  – What are servicing, maintenance implications?

• Lifetime
  – Early tubes likely to have MTBFs of 6-10k hours
  – 90% early failures will be arcing
  – Protection must be bulletproof
Hybrid Modulators - SG

Klystron Arcing

- IGBT Switch options, Other components
  - Faster speeds help efficiency
  - May allow more cap droop to reduce cap sizes
  - Pursue improvements in caps, HVPS, xfmrs to reduce costs

- Arc Protection
  - Arc studies show current pulses lasting for microseconds, 20-60J
  - Tests on single tubes and dual modulator tubes
  - NO APPARENT TUBE DAMAGE!
  - Theory: Arcs initiate briefly, form space charge limited plasma, & extinguish due to short pulse before causing catastrophic failure (R. Adler).
  - Suggests a worse problem for longer pulses (S&L)?
  - Must detect OC in EACH tube in a group for fast shutoff.
KEK Developments - M. Akemoto

- Line Type Solid State Switch Modulator
  - Developing a line type modulator using SI Thyristor (NGK Co.)
  - Thyratron replacement experiment
  - Tested 5-stack at 15 kV, 10 kA
  - $T_f \sim 128$ nsec 10-90%
  - 100A peak drive required per device
  - Goal: 45 kV stack
  - Availability of devices not known
  - nshimizu@ngk.co.jp
Thyratron Developments

- **EEV (C. Perry)**
  - New 4 gap tube meet 2 pack goals w/ target of 50k hrs lifetime
  - Oxide cathode 6 in dia.
  - Stabilized reservoir
  - Heater programming?
  - Tube no. 1 of 4 starts processing week of 6/28/99

- **Triton (T. Clymer(sp?))**
  - Current designs are Wagner derivatives
  - New 3 gap design for NLC ran to 60 kV
  - Delivered to SLAC for test
  - Dispenser cathode
  - Old tube went 44K hours
  - Expect price reductions in quantity
Modulators & Xfmrs
- R. Adler, North Star

- New Modulator Concepts & Tests
  - Parallel primary banks switched with thyatrons
  - 30 kV thyatrons operate in air
  - Hot tunable PFN w/ conventional caps
  - “Bi-Pyramidal” transformer
  - Standard rack packaging
  - Tested at 10 Hz into 900 Ohm load
  - Tr 450 ns, Tf 500-700 ns
  - Quantity pricing of components for cost estimates
  - Cautioned about application of learning curves - prefer quotes
  - Costs ~ $66K/tube @ 100 ea.
North Star - Cont’d

- IGBT Variant
  - 30MW proof of concept for 300MW
  - Differential cost analysis for IGBT fractional turn model driving multi-turn secondary 1/4=>50T
  - 4 sections w/ 1 Ohm striplines
  - W/ 30 devices competitive w/ 2-pack (~400ns Tr, Tf)
  - Eff’y 68% not incl. Charger
  - Lower costs
Solid State Alternatives
M. Kempkes, DT

• Solid State Modulators
  – 140 kV 500 A unit in operation at CPI
  – Long pulses, high power, crowbar works flawlessly
  – Up to 10 kHz, Tr~1 usec, 3.2MW supply

• NLC Hybrid Modulator Proposal
  – 80 kV 3.2 kA IGBT switch into 6:1 step-up
  – Peak power determines size
  – Costs of switch scale linearly with power reqmts
  – Switches very robust & fail-soft w/ redundant sections
  – Costs of PS and Xfmr vary with size
  – 400 nsec Tr, Tf in 6:1 (LV test)
  – Design has life cycle cost advantages
  – NEED DEFINITIONS FOR EFF’Y COMPARISONS
• Charging Supply (HV Charger)
  – Present: $100K, 10K hours
  – Achievable: $20K, 100K hours (1600 qty)
  – 10 yr Life cycle dominated by power costs
  – Cost tradeoffs versus size of components

• HV Buck Regulator
  – Building 3.2 MW for CPI (7/99)
  – 8-10 KHz operation
  – Conversion section very efficient
  – 3.2 MW avg drives 75 NLC Klystrons (9-8 packs, 1 NLC Sector)
  – Cost $3K/klystron in qty
  – Redundancy issues, distribution, outdoor vs indoor gear
• 500 KV Solid State Switch
  – Inverter=> CAP Multiplier=>IGBT switch=>Klystrons
  – Eliminates HV transformer
    best waveform efficiency
  – Design switch for low capacitance
  – Fit into 2-pack tank
  – Silicon costs scale w/ power. Turn-off “100% reliable”~680nsec

• IGBT Reliability
  – Switches ALWAYS fail short, so stack very robust
  – If klystrons gor to 300 kV, much more attractive & easier

• BIG QUESTION: EFFy OF CAP MULTIPLIER
  • Skeptics claim 50% max. Believers claim “very high.”
    (Maxwell will eventually have his due.)
Systems Issues
General Discussion

- Topology of a Sector
  - 72 klystrons in 9 groups of 8 in 50 m long alcove
  - Buck regulators with separate 2y xfmrs for each 8 pack
  - Can lose 8-pack but not a sector
  - May need redundancy at main xfmr-rectifier
  - Must be able to isolate for repair
  - Personnel safety requires disconnect under load
  - Proposal: Open Ross relay at 8-pack load point

- Custom IBGTs?
  - Need to work with established ocmpanies - they have the HV processes needed.
  - Companies will modify product for sufficient quantity, but we are not big enough customer for full custom product(?)
• Reliability
  – All proposed and present systems need more reliability analysis
  – IGBTs ~10^9 hrs; 100 ea ~ 10^7 hrs; w/ redundancy @ 10%
    goes to 10^11 hrs.
  – Connections and other machinery are main points of failure
  – Minimize parts counts and connections
  – Mil 217 analysis of the DT 140kV modulator is ~10^6 hrs

• Efficiency-Reliability-Cost (ERC)
  – Need to work up a table to compare the various proposals
    (homework)
  – Need a strong ERC incentive at this point to seriously explore a
    new concept.