NLC Modulator Workshop
June 25, 1999

Summary of Presentations and Discussions
R. S. Larsen
Induction Modulators
Discussion Issues - 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 - 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.)
  – Thyatron replacement experiment
  – Tested 5-stack at 15 kV, 10 kA
  – Tf ~ 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 & Triton

• **EEV** (C. Perry)
  - New 3 gap tube meet 2 pack goals w/ target of 50k hrs lifetime
  - Oxide cathode 6 in dia.
  - Stabilized reservoir
  - Heater programming investigation
  - 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
  - First tube went 44K hours
  - Expect price reductions in quantity
Modulators & Xfmrs
- R. Adler, North Star

• New Modulator Concepts & Tests
  – Parallel primary banks switched with pair of thyratrons
  – 30 kV thyratrons 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 - quotes more reliable
  – Costs ~ $66K/tube @ 100 ea.
North Star - Cont’d

• IGBT Hybrid Design Variant
  – 30MW proof of concept for 300MW
  – 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% does not include Charger
  – Differential cost analysis indicates lower costs c.f. thyatron design
Solid State Alternatives
M. Kempkes, Diversified

- 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 requirements
  - 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 EFFICIENCY COMPARISONS
Diversified Technologies - Cont’d

- Charging Supply (HV Charger)
  - Present: $100K, 10K hours, small quantity
  - Achievable: $20K, 100K hours (1600 qty)
  - 10 yr Life cycle cost 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 quantity, conversion section only
  - Redundancy issues, distribution, outdoor vs indoor gear
DT - Cont’d

• 500 KV Solid State Switch  
  – AC-DC Inverter=> CAP Multiplier=>IGBT switch=>Klystrons  
  – Eliminates HV transformer for best waveform efficiency  
  – Design switch assembly for low capacitance  
  – Fits into 2-pack tank  
  – Silicon costs scale w/ power. Turn-off “100% reliable”~680nsec

• IGBT Reliability  
  – Switches ALWAYS fail short, so stack very robust

• BIG QUESTION: EFFICIENCY OF CAP MULTIPLIER  
  • Skeptics claim 50% max.  
  • Believers claim “very high.”  
  • Follow-up: Diversified will elucidate.
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 random 8-packs but not a sector
  – May need redundancy at main transformer-rectifier
  – Must be able to isolate 8-pack for repair
  – Personnel safety requires disconnect under load
  – **Proposal: Ross relay disconnect at 8-pack load point**

• Custom IBGTs?
  – Need to work with established companies - they have the HV silicon processes needed.
  – Companies will modify product for sufficient quantity, but are we big enough customer for full custom product?
Discussion - Continued

• Reliability
  – All proposed & present architectures need more reliability analysis
  – IGBTs $\sim 10^{9}$ hrs; 100 ea $\sim 10^{7}$ hrs; w/ redundancy @ 10%
    goes to $10^{11}$ hrs (Diversified)
  – Connections and other mechanics are main points of failure
  – Minimize parts counts and connections
  – Mil 217 analysis of the DT 140kV modulator is $\sim 10^{6}$ hrs

• Efficiency-Reliability-Cost (ERC)
  – Need to work up a table to compare the various proposals
    (homework)
  – Need a strong ERC incentives to justify seriousl exploration of
    new concepts.
Reliability - Z. Wilson

• Main tool is FMEA, Failure Modes & Effects Analysis
• Reliability vs. Availability discussed
  – Tradeoff with maintenance time & spares
  – Relative reliability, not absolute, as evaluation tool
• Reliability Block Diagram (RBD)
  – A logic diagram from reliability point of view
• Duane Plot - reliability growth with time
  – e.g. 5045 klystrons, 100’s hours => ~45K hours
• FMEA Definition:
  – A systematic methodology for interdisciplinary identification and recording of failure modes & effects, & development of corrective actions
Reliability - Continued

• Various graphics tools show how to visually evaluate effects of FMEA

• Iterative process, used in Design, Manufacturing, Installation etc.

• Mean Down Time (MDT)
  – Availability $A = \frac{MTBF}{MTBF+MDT}$

• NLC assumes a run time of 6575 hours/year (9 months) with overall availability target of 0.85 (85%)
  – A given subsystem must be much better than this
  – Availability of one part can be traded for another and still keep within target
  – All numbers being used are relative.
Maintainability & Economics

- O-I-D model described:
  - Organizational (field), Intermediate, Depot Levels
- Comparison of 2-Pack & 8-Pack maintainability models:
  - 2-Pack wins IF it is assumed that all 8 klystrons in an 8-pack are in common oil tank and can’t be moved as a group.
  - Questions:
    - Can an 8-pack assembly be connectorized?
    - Is there an economical 1-Pack solution with any of the new concepts that have been put forth?
- Note: conclusion of ‘98 Workshop was that economics favored solutions that increased number of klystrons driven by a single modulator. Is this still true?
Conventional Facilities

J. Ives & J. Sevilla

• Layout of the NLC described
• Water and Power layouts of Klystron Galleries shown
• Some of topologies for wallplug through regulators suggest alternate power levels need to be investigated.
• Cooling water calculations & assumptions should be checked by workshop interested parties.
Workshop Collaboration
Action Items & Ideas

• 1. Need rules for efficiency calculations
  – Action: S. Gold

• 2. Propose a white paper, reviewed by Workshop participants, on modulator topologies, and evaluations, for 8, 4, 2 or 1-Pack configurations

• 3. Include reliability and maintenance models

• 4. Include life cycle cost analyses

• 5. Identify R&D needs

• 6. Discuss desirable SBIR initiatives based on (5)
  – Action: SLAC-LLNL collaboration
Conclusions: ‘99 Workshop Accomplishments

– Reviewed progress of SLAC-LLNL and vendor R&D
– Proposed new Buck Regulator options that could save major costs in power supply systems
– Shed light on probable cause of effects observed in NLC klystron arc studies, and directions for follow-up
– Proposed several new and interesting options for 2-Pack implementations:
  • Hybrid 2-pack driving 1:6 conventional step-up
  • Induction design driving 1:50 conventional step-up
  • HV 500kV switch from Capacitor Multiplier supply (controversial efficiency)
– Established directions to help steer R&D toward optimizing NLC modulator design(s), capital and life cycle costs
– Improved communications among all participants.