NLC - The Next Linear Collider Project

SLAC/FERMILAB NLC Collaboration Meeting

Klystron Development
February 28, 2001

Jongewaard & Sprehn
2/28/2001
Presentation Outline

• History
  – Previous devices to the current development

• 75XP3
  – Electrical and Mechanical Design
  – Schedule

• Discussion
Route to an NLC Power Source

- The X-band effort has been one of the longest continuously running and most ambitious tube development in history
- A foray into CFA’s, RKO’s, SBK’s >10 years ago
- XC Program - 100 MW 1 μs >8 years ago
- XL Program - 50 MW 1.2 μs >4 years ago
- 50XPdiode and 50XP1 - 50 MW 1.5 μs >2 years ago
- 75XPdiodes - scrapped, funding
- 75XP1 - 75 MW 1.5 μs >2 years ago
- 75XP1B, 75XP2A & B scrapped, funding
- 75XP3 - 75 MW 1.5 (3) μs 120 (180) Hz ongoing
- MBK’s, SBK’s, 75XP4 research ongoing
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NLC Power Source - Moving Specification

• Target rep rate for design - 60?, 120, 180 Hz

• Target Pulsewidth - 1?, 1.1, 1.2, 1.5, 2.4, 3 μs

• Target bandwidth - unspecified to 120MHz (?)

• Average power increase is at least a factor of 4
  – Note that a factor of 2 is not insignificant

• Each increase is a new frontier to the state-of-the-art
XC Klystron Program

- Specs
  - 100 MW, 1µs, 1.8 µK gun, >40% efficiency
- Results - XC1 through XC8 designs tested
  - XC8 - 86 MW at 800 ns - multiple output coupling with 2 cavities
  - XC6 - 50 MW at 1µs - 4-cell TW output
- Issues
  - Gun - gassing and magnetic compression
  - window - TE11 design inadequate
  - rf breakdown - cavity noses, symmetry and gradients used
- Because of difficulties, specification reduced to 50 MW
  - Lower perveance to increase efficiency
XL Klystron Program

- Specification 50 MW, 1.2 \( \mu \)s, 1.2 \( \mu \)K, 120 Hz,

- 4 designs tested, different output types and tunings
  - 1, 2 and 3 (low power, efficiency or oscillations)
  - XL4 currently the “workhorse” design

- 11 XL4’s built
  - Improved windows installed on the latest productions
  - Total operation of any tube currently <10kh

- Operation above specification
  - Efficiency, Pout, Pulsewidth

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## Operation Range of the XL4 Klystron

<table>
<thead>
<tr>
<th>RESULT</th>
<th>Limiting factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>50 MW @ 2.4 $\mu$s @ 120 Hz</td>
<td>(Pulse XFMR)</td>
</tr>
<tr>
<td>72 MW @ 1.5 $\mu$s @ 60 Hz</td>
<td>(Time constraint)</td>
</tr>
<tr>
<td>$\approx$5 hrs. integrated operation</td>
<td>(Output W/Gfaults)</td>
</tr>
<tr>
<td>90 MW @ 0.1 $\mu$s @ 60 Hz</td>
<td>(Sheer fright)</td>
</tr>
</tbody>
</table>
Operation Range of the XL4 Klystron

XL4-6 data of March 99 shows integrated 2.4 microseconds at 50 MW

Power out, MW

\[ \text{t, microseconds} \]

2.4 \mu s
A 50MW PPM Program

- Question - Can it be done?
  - Experts very skeptical
- SmCo magnetic design
  - Eliminate the costly solenoid power, no shunting possible
- Diode test
  - 99.9% transmission, 2.8 $\mu$s, 120 Hz
- 50XP1 Klystron test
  - After TiN coating, tube met and exceeded specification
  - Shielded and confined flow tested
- Industry Delivery of SLAC design
  - Toshiba has delivered, Marconi device is due April
50MW PPM |Bz| 1690 & 1950 Gauss RMS

Axial Position, (cm)

Bz on axis (Gauss)
A Beam Stick Test - 120 Hz 99.9%
A 50MW PPM Klystron
A 50MW PPM Klystron

- May 1999 re-test for wider 2.4 μs pulsewidth
75XP1 Klystron

- Extrapolate 50XP1 design to higher power
  - Eliminate gun coils
  - Use NdFeB magnets
  - Raise Vb, increase drift tube diameter
  - Remove iron from vacuum envelope - SS drift tube and cavities
  - Optics and transport “verified” with multiple codes
  - rf “verified” with multiple codes (and testing)

- Testing
  - Magnet deliveries - 3 strikes and you’re out!
  - Gun oscillation - fixed
  - Output oscillation - fixed
  - Transport issues paramount
75XP1 Results

• Despite operation difficulties, 75XP1 was not a failure
  - 75MW (full pulsewidth) to 100MW output “verifies” rf design
  - Ongoing radiation experiments for NdFeB - confidence
  - Complex vendor qualification study - confidence
  - Gun oscillation study reveals exact oscillation, and no others
  - Output oscillation forces redesign and understanding
  - Ammo for clamp-on magnet design
  - Forces deeper look into thermal-mechanical issues

• Caveats
  - Stability range is small
  - Beam transport unsolvable with this design
  - Limited rep rate
75XP1 rf output after oscillation fixes

- A tiny signal is found well below the second harmonic
75XP1 Maximum Joule output

Actual waveform and average value from pk pwr head w filter at 1 Hz. 2.82uS rf pulsewidth, 534kV. Peak is 104 MW, average 9.727 dBm = 79 MW, eff=50 to 67%.

100MW231199_cal.xls
75XP1 rf output vs. pulselenath

MW

nanoseconds

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NdFeB Radiation Tests

- Exposures to date are about 3 times the listed values with no detectable affect on magnetic field

<table>
<thead>
<tr>
<th>Magnet No.</th>
<th>Exposure Method</th>
<th>Gauss on Nov 98</th>
<th>Gauss on Feb 99</th>
<th>Exposure MRad</th>
</tr>
</thead>
<tbody>
<tr>
<td>35-1</td>
<td>$^{130}$Cs</td>
<td>4935</td>
<td>4940</td>
<td>10.5</td>
</tr>
<tr>
<td>35-2</td>
<td>$^{130}$Cs</td>
<td>4916</td>
<td>4950</td>
<td>10.5</td>
</tr>
<tr>
<td>SH-1</td>
<td>$^{130}$Cs</td>
<td>5090</td>
<td>5092</td>
<td>10.5</td>
</tr>
<tr>
<td>SH-2</td>
<td>$^{130}$Cs</td>
<td>5003</td>
<td>5004</td>
<td>10.5</td>
</tr>
<tr>
<td>35-3</td>
<td>Klystron</td>
<td>4346</td>
<td>4283</td>
<td>2.69</td>
</tr>
<tr>
<td>35-4</td>
<td>Klystron</td>
<td>4625</td>
<td>4570</td>
<td>2.69</td>
</tr>
<tr>
<td>SH-3</td>
<td>Klystron</td>
<td>4737</td>
<td>4701</td>
<td>2.69</td>
</tr>
<tr>
<td>SH-4</td>
<td>Klystron</td>
<td>4615</td>
<td>4570</td>
<td>2.69</td>
</tr>
<tr>
<td>35-5</td>
<td>Klystron</td>
<td>4695</td>
<td>4621</td>
<td>2.68</td>
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<td>35-6</td>
<td>Klystron</td>
<td>4696</td>
<td>4678</td>
<td>2.68</td>
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<tr>
<td>SH-5</td>
<td>Klystron</td>
<td>4280</td>
<td>4242</td>
<td>2.68</td>
</tr>
<tr>
<td>SH-6</td>
<td>Klystron</td>
<td>4665</td>
<td>4610</td>
<td>2.68</td>
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### 75XP-3 Klystron Specification

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
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<tbody>
<tr>
<td>OUTPUT POWER</td>
<td>75 MW</td>
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<tr>
<td>BEAM VOLTAGE</td>
<td>490 kV</td>
</tr>
<tr>
<td>BEAM CURRENT</td>
<td>257 A</td>
</tr>
<tr>
<td>PERVEANCE</td>
<td>.75 μK</td>
</tr>
<tr>
<td>PULSE LENGTH</td>
<td>3.0 μs (New)</td>
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<tr>
<td>PRF</td>
<td>120 Hz</td>
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<tr>
<td>AVERAGE RF POWER</td>
<td>27 kW</td>
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<tr>
<td>GAIN</td>
<td>55 dB min</td>
</tr>
<tr>
<td>EFFICIENCY</td>
<td>60% min</td>
</tr>
</tbody>
</table>
75XP-3 Design Improvements

- Magnetic design
  - Higher magnetic field - gun confinement, rf spreading
  - More uniform field - improved transmission, simpler magnets
  - Slip-on gun coils - tune-ability, reduced magnet variation
  - Clamp-on magnetics - exchangeable, verifiable, variable

- Anode shell and HV seal
  - Superior mechanical design
  - Optimization of gradients
  - Reduce possibility of gun oscillation

- Cooled drift tube
  - Allows higher duty operation before thermal run away
75XP1 Magnetics Achieved

75XP1 Bz on axis as built

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75XP3 Magnetic Design

75XP3 B field on axis

Bz (G)

Z (inch)
75XP-3 Design Improvements (cont.)

- Longer drift length between penultimate and O/P cavities
  - Improves magnetic field variation
  - Reduces coupling between penultimate and O/P cavities
  - Some effect on rf (~1MW)

- Longer, reduced drift tube diameter after O/P cavity
  - Decreases coupling between collector and O/P cavity
  - Some effect on rf (~1MW)

- Stepped drift tube diameter
  - Smaller diameter for first half of tube
  - Reduces propagation of higher order modes
  - Increases coupling to gain cavities
75XP-3 Devices

- **Diode**
  - Same gun and collector as klystron
  - Reduced length drift section to simulate the klystron drift tube and magnetic field, cavity magnetics and output

- **Klystron**
  - Seven cavity with 5-cell TW output
  - Clamp-on magnet structure with integral cooling
  - Dual $\text{TE}_{01}$ output windows
### 75XP-3 Tuning

<table>
<thead>
<tr>
<th>cavity</th>
<th>7XP1</th>
<th>75XP3</th>
</tr>
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<tbody>
<tr>
<td>1</td>
<td>11416</td>
<td>11430</td>
</tr>
<tr>
<td>2</td>
<td>11380</td>
<td>11376</td>
</tr>
<tr>
<td>3</td>
<td>11479</td>
<td>11480</td>
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<tr>
<td>4</td>
<td>11498</td>
<td>11493</td>
</tr>
<tr>
<td>5</td>
<td>11710</td>
<td>11701</td>
</tr>
<tr>
<td>6</td>
<td>11824</td>
<td>11750 / 11828</td>
</tr>
<tr>
<td>7</td>
<td>11798</td>
<td>11690 / 11800</td>
</tr>
</tbody>
</table>
75XP-1 Small Signal Performance

\[ \log_{10}(P_{\text{omag}}) \]

\[ P_{\text{omaxdB}} \]

\[ P_{3\text{dB}} \]

\[ f_l \]

\[ f_h \]

\[ f_0 \]

11.3
11.35
11.4
11.45
11.5
11.55

60
50
40
30
20
10

65.388411
42.952104

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75XP-3 Small Signal Performance

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75XP-3 Klystron
75XP-3 Drift Tube and Magnets
75XP-3 RF Output Window
75XP-3 O/P Magnet Simulations

output magnet
75XP-3 Electron Gun Simulations

Electron gun electrostatic model, 500 kV applied
75XP-3 Electron Gun Simulations

NLC and XL-4 seal gradients

Normalized distance along seal
75XP-3 Electron Gun Simulations

- 200 kV/cm peak negative electrode gradient, 268 kV/cm peak positive electrode gradient at 500 kV gun voltage

- HV seal ceramic gradients at 500 kV are below XL-4 seal gradients at 410 kV
75XP-3 Beam Transport Simulation

- DC electron beam through penultimates and output structure shows good confinement
Drift tube thermal simulations

Drift section magnet structure
Drift tube thermal simulations

Drift section magnet, 50 W/in^2 heat flux
Drift tube thermal simulations
Drift tube thermal simulations

Buncher section magnets, 50 w/in^2 drift tube flux
Drift tube thermal simulations

- Drift section
  - Magnets reach 50 C with a surface flux of 80.6 W/in^2
    (12.5W/cm^2)
  - Allowed uniformly distributed total power loss is 1580 W

- Buncher section
  - Magnets reach 50 C with a surface flux of 90.0 W/in^2
    (14.0W/cm^2)
  - Allowed uniformly distributed total power loss is 775 W
75XP-3 Current Status

- 75 XP-3 Diode
  - Sumitomo magnets (2 sets) in house, in QC
  - Tube in bake, finish bake 2 March 2001
  - Test preparation to begin first week of March
  - Testing to begin mid March

- 75 XP-3 Klystron
  - Gun and collector fabricated
  - Drawings for RF section in engineering check
  - O/P windows and mode converters being fabricated
  - Magnets on order
  - Pursuing second magnet order to reduce risk
  - Magnet shell and tooling to be designed/drawn
Industrial Partners

- Toshiba XL-PPM
  - Initial testing in Japan promising
    - 50 MW output at 50% efficiency
    - 95% transmission
  - Tube shipped and arrived at SLAC before the holiday shutdown
  - Tube appears to be very well built
  - Testing at SLAC to begin mid May

- EEV/Marconi XL-PPM
  - Currently being pumped
  - Ship in March
Industrial Partners (cont.)

- CPI 75XP-3
  - Will design and build RF section and magnets
  - Will be mated with SLAC electron gun, collector and RF waveguide hardware to complete the klystron
  - Pursuing a variation of the clamp-on magnetic structure with directly cooled pole pieces
  - Scheduled to ship the RF section and magnet stacks September 10, 2001
75XP-3 Design Issues

- **RF performance**
  - PIC simulations short on power (~70 MW thus far)
  - Progress being made on understanding the issues
  - Expecting simple tuning changes will yield the desired performance

- **Thermal performance**
  - Cooling sufficient for interception of ~5% of the beam power evenly distributed (assuming 45.4 kW beam)
  - Collector conservatively designed for 120 Hz, 1.5 μs diode beam (no RF). Likely to survive at 120 Hz, 3.0 μs with increased coolant flow.
75XP1 Large-signal 1D simulation
75XP3 Large-signal 1D simulation

- RF performance is very similar to 75XP1
75XP3 Large-signal 1D simulation

- Spent beam energy and efficiency and within design goals
75XP1 Large-signal 2.5D simulation
75XP3 Large-signal 2.5D simulation

- Antibunch not optimal, "tails" rob available power
75XP3 Large-signal 2.5D simulation

- Preliminary results show no "tails" yet

XP3 after beam fix, drive at 80W
75XP3 Beam before and after code fix

- Note Drift tube has 2 step changes to large radii not shown
75XP3 Large-signal 2.5D simulation

- Injection solved to model reality
- Improvement of phasespace expected (increased Pout)
- PIC simulations currently running
  - Remeshing of cavities ongoing due to bug "fix"
  - Four penultimate tunings at four drive levels, 16 hours each is about 11 CPU days (1.5GHz P3)
  - No affect on 75XP3 delivery date
75XP-3 Design Issues (cont.)

- HV performance
  - Gun conservatively designed for 1.5 μs 500 kV pulses, XL-4 operated at these same gradients for 2.8 μs pulses

- RF windows
  - Direct testing yielded disappointing results in comparison with resonant ring results
  - Two windows used to improve design margin

- Stability analysis
  - Ongoing preemptive effort concerning understanding the issues and reducing the risk
FY 01 Goals

- Finish and test 75XP-3 diode
  - Verify lack of gun oscillations
  - Verify beam transmission
  - Verify collector power capability
  - Operate at high duty
  - Life test?
- Build and test 75XP-3 klystron
  - Verify clamp-on magnet focusing
  - Verify high duty RF operation
- Test Toshiba XL-PPM
- Test EEV/Marconi XL-PPM
FY 01 Goals (cont.)

- Assemble and test CPI 75XP-3
  - Comparison against SLAC built tube
- Build and test 75XP-4 klystron
  - Verify clamp-on magnet focusing
  - Verify high duty RF operation
FY 02 Goals

- Understand window issues
- Redesign collector for higher duty operation as required
- Continue cost-reduction efforts
- Continue analysis into stability and robustness
- Construct and test similar klystrons
Presentation Summary

- Historical perspective presented

- 75XP3 difficulties, design and current status presented

- 75XP3 diode test next month, klystron(s) this year

- Related research presented