RF Power Upgrade at Jefferson Lab

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CEBAF (circa 2013)

- Upgrade halls
- 5 new zones
- Double capacity of CHL
- Existing RF 'zones' (20)
- Central Helium Liquefier (Refrigeration)
- Existing RF 'zones' (20)
- Upgrade existing arc
- New 'arc 10'
- injector
- 6 GeV → 12 GeV
- Hall A
- Hall B
- Hall C
- Hall D
- Hall D + new beam transport
- Upgrade existing arc
- 10 new cryomodules (5 per linac)
- 10 new RF zones
- Refrigeration capacity doubled
- Arc magnets and PSU’s upgraded
- Extraction system upgraded
- Additional Arc
- New beam line to Hall D
Background

- **New systems must fit available footprint, even with power increase from 5 to 13 kW**
  - CEBAF was originally conceived as a 4 pass/25 zone per linac machine capable of 4GeV
  - Built as 5 pass, 20/linac (for cost savings)
  - Service buildings and tunnel built for 25 zones
  - Upgrade fills empty slots - 5 zones per linac
  - Runs at 6 GeV with relatively minor upgrades

- Energy increase to from 6 to 12 GeV
- Hall-D (new): 12 GeV, Halls-A,B,C 11 GeV
- For RF: new systems with higher power
High Power RF

- Upgrade includes ten ‘C100’ cryomodules (8 x 7 cell cavities, 100 MV/m per unit)
- Ten new RF zones (5 per linac)
  - New designs for both high power and low level
  - Redesign some existing components
    - (Compatibility goals)
      - 13kW (saturated) RF to each cavity
      - HV DC power supplies, aux PS, interlocks, controls
      - Waveguide components (circulator, coupler, tuner, HOM filter, sweeps, flexes…)
      - Mechanical assemblies - water manifolds, etc.
      - New FPGA-based phase/amplitude control for LL
Equipment in accessible gallery, SC cryomodules in tunnel
Existing System

CEBAF RF zone: LLRF at left, HPA, HV at right
Existing System

4 klystrons stacked

Filament & mod anode PSU
Some Backwards Compatibility

- Overall design similar to old systems
  - Future plans include upgrading existing zones
    - Eliminate CAMAC
    - Upgrade to digital LL controls (for use with refurbished cryomodules)
    - Minimize variety of spares: new filament & mod anode PS work with old or new zones (not reverse)
- New systems have similar interfaces as old systems
  - Largely same group of signals, interlocks, requirements, down to key connector pin-out
  - Goal is to use new HPA controller in upgrades
    - (monitors klystrons, interlocks, etc.)
RF System overview

Drive From LLRF

To LLRF

Driver

Klystron

Transition

Reflected Coupler

Dual Coupler

Load

Detector

To Control System

RF Out to SC cavity

Driver PS

Filament PS

Mod Anode PS

Instrumentation

HV DC (-14.5 kV)

Prime Power 480/120 VAC

Solenoid Power

LCW (cooling)

HPA

Jefferson Lab
How many RF Sources?

1 per cavity
(current system)
Minimum impact of failures (existing design)

1 per zone or per linac
Larger impact
High power splitters
Amplitude and phase regulated to high precision.

Additional controls and high power modulator found to be more $$$ than individual RF sources.
Step 1: Tube or SSA?

Solid state
- Our past experience was not the best (SS has improved since then)
  - Concerns about transistors going obsolete
  - Size/cost too large
  - SSA not included in bid package (SBIR in the works)

IOT
- Promising, but not there yet
- Better efficiency than a klystron, but lower gain -- high cost driver
- Reliability reasonable for UHF designs
- Product at 1.5 GHz not yet built
- Budgetary pricing was higher than klystron before driver cost added

Klystron
- Current 5kW design (run at up to 8) has been reliable (>150k hours between failures)
- Could fit available space
A New Klystron

- Klystron or IOT at RFI
  - Narrowed to klystron only at RFP
- Received two (US only)
- Awarded to L-3 Communications
  - New design (Williamsport division)
  - Higher efficiency
  - Same gun assembly as our old tube
  - Original collector was upgraded
    - Dissipation nearly unchanged from 8kW tube due to efficiency increase
  - Solenoid focusing vs. PM
## Old-New Comparison

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Old Spec</th>
<th>New Spec</th>
<th>Actual</th>
<th>Units</th>
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<tbody>
<tr>
<td>Power</td>
<td>5 &amp; 8</td>
<td>13</td>
<td>13</td>
<td>KW</td>
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<td>Center frequency</td>
<td>1497</td>
<td>1497</td>
<td>1497</td>
<td>MHz</td>
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<tr>
<td>Bandwidth, -1dB</td>
<td>5</td>
<td>5</td>
<td>5+</td>
<td>MHz</td>
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<tr>
<td>Bandwidth, -3 dB</td>
<td>6</td>
<td>6</td>
<td>6+</td>
<td>MHz</td>
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<td>0.5 dB incremental gain at</td>
<td>4</td>
<td>10</td>
<td>meets</td>
<td>kW</td>
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<tr>
<td>Efficiency (at rated power)</td>
<td>32</td>
<td>&gt;50</td>
<td>50.9</td>
<td>%</td>
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<tr>
<td>Gain</td>
<td>38</td>
<td>&gt;42</td>
<td></td>
<td>dB</td>
</tr>
<tr>
<td>Harmonics</td>
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<td>-20</td>
<td>meets</td>
<td>dBC</td>
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<tr>
<td>Beam voltage</td>
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<td>&lt;16</td>
<td>14.5</td>
<td>kV DC</td>
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<tr>
<td>Heater voltage</td>
<td>7.3</td>
<td>7.3</td>
<td>7.0 typ</td>
<td>V DC</td>
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<tr>
<td>Modulating anode</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td></td>
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<tr>
<td>Isolated collector</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td></td>
</tr>
<tr>
<td>Cavities</td>
<td>4</td>
<td>5</td>
<td>5</td>
<td></td>
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<tr>
<td>Focus</td>
<td>PM</td>
<td>EM</td>
<td>~900</td>
<td>Watts</td>
</tr>
</tbody>
</table>
Klystron

- Model L1433 by L-3
- Water-cooled window
- Cavities 4 & 5 water-cooled
- Robust tuning mechanism
13 kW Curve
Layout

Control racks, PSU’s...

Manifolds

Klystrons

Waveguide components

Cathode power supply

1 zone
RF Zone
Hose City - Set of Klystrons
HPA Module (4 per zone)

HPA w/klystron (left), card cage inside (front & rear)
Klystron Installation

- Gantry crane assembled in quad
- Solenoid is bolted to mounting plate
- Portable lift used to insert klystron into solenoid
- WG transition attached to klystron
- Crane picks up assembly
- Jack screws adjusted for precise waveguide mating
- Replacement installs similar, but transition may be unplugged first
- Klystron only extracted
225KW DC Power Supply (NWL)

- As before, each powers 8 klystrons (considered 1 to 40)
- Resonant mode switcher (15-20 KHz)
- Adjustable to -15kV @ 3.75A
- 4 separate supplies, each feeding 2 klystrons
  - Minimizes klystrons off on failure
  - Currently controlled as a unit (15A total)
- Originally designed for electrostatic precipitators (higher volts/lower amps in oil) 1000+ units in the field
- Designed to withstand load faults
- Lower stored energy than T-R, fast turn off on fault, resistor limited output
- Passes wire test w/o crowbar
HV Deck (4 per supply, on rollers)

Rear View / Cooling
HV PS Details

• Voltage/current to match klystrons
• 0.1% p-p ripple (as before)
• Soft current limiting
• Arc detection (DC O/L)
• Built-in self test functions, good displays
  – Currents, voltages, temps, duty factor, counters, etc.
• Redundant interlocks, internal/external
• Similar interface as existing systems – discrete
• Local operation possible (used mostly for testing)
NWL Display/Control
Notes

- Not all signals are not reported (I/O limits for DSP board)
  - The standard controller had insufficient inputs
- Fully air-cooled - this may require some ducting based on initial experience (insufficient A/C)
- Water or air cooling permitted (no interest on using water)
  - New requirements for systems pressurized over >15 psi would have to be met
  - Heat sinks could have been water-cooled (about half of heat load)
Waveguide

- 1-5/8” coax to WR650 transition w/mono coupler (KRRP)
- Offset (klystron/WG penetration centers don’t match)
- Isolator
- Reflectometer coupler
- 3-stub tuner
- 16ft waveguide through penetration
- Sweeps, flexes, offsets, misc. straight pieces
- HOM filter or full to reduced height transition

Vendors
- Ferrite Co. for isolator
- MCI for standard (except for size red./full transition)
- CML for HOM / MEGA for red./full transition
WR650 Isolator

- Ferrite Company
- Model LC3-535, (RH / LH)
- Fc: 1497 MHz, 6 MHz BW
- Power: 13 kW CW, full reflection
- Isolation: 21 dB min (spec)
- Field adjusted for close spacing
- Certified for pressure (required)
- Load has additional window
  - Keep water out of waveguide
- *Magnets & match being adjusted to improve performance*
Water

- 1 manifolds/zone, each supplies needs of 4 klystrons/circulators
- One flow meter per manifold
- Fixed orifices/adapters to set flow
- To reduce flow requirements
  - 2 collectors in series (8 gpm)
  - 2 circulator loads in series (7 gpm)
  - Klystron body/window, circulator body, solenoid all parallel paths
  - ~110 gpm per zone (95F/35C)
HPA Controller

- FPGA with PC-104 to EPICS (replaces CAMAC, LLRF)
- Monitors all klystron and HV signals
- First fault detection
- Ring buffer for fast signal capture (1 ms rate)
  - Normal archiver data sampled at 1 second rate
- Designed with lots of I/O - not all used
  - 128 A/D channels (klystron & other signals)
  - 32 D/A channels (filament, mod anode, HV set)
  - 48 relay out (various power, HV, solenoid control)
  - 32 TTL in (digital cathode current, heater voltage)
  - 16 fiber (handshake with LLRF)
  - 48 isolated inputs for status read backs
EPICS HPA Screen

- Controls
- Status
- Set points
  - Fil, MA, HV
- Trip levels
  - All
- First fault
- Ring buffers
- Temperatures
- Diagnostics
Current Status (April 2012...)

- Klystrons: 66 of 84 received, 32 installed
- HV Power Supplies: 10 of 10 received & installed
- WG Isolators: 84 received, 40 installed
- Waveguide: all in house. 2 zones waveguide fully installed. Remainder in progress.
- HOM filter: first article at vendor test (late)
- HPA cabinets: all installed, half are populated
- Solenoid power supplies: all in house
  - First contract cancelled. Cheap but never arrived.
- Filament & Mod anode PSU’s tested; half installed
- Interface boards: half installed
- Zones commissioned: 2 (+2 additional summer 2012)
Schedule (not updated)

- 6 month down
- 12 month down

- Installation task
- Commissioning task with cryomodule

- 12GeV
Performance So Far

- Two zones operational and integrated into accelerator operations (since fall 2011)
- Achieved >100 MV/m (target)
- Recovery from trips automated for faster recovery
- Technical issues
  - Circulator isolation on some units (being worked)
  - Full 1power in all positions (being worked)
  - HVPS exhaust heat may need to be addressed
Questions ?
### Major Procurements (totals)

<table>
<thead>
<tr>
<th>Item</th>
<th>Cost</th>
<th>Quantity/Specs</th>
<th>Vendor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Klystrons</td>
<td>$3.5M</td>
<td>84 w/sol</td>
<td>L-3</td>
</tr>
<tr>
<td>CPS (HV)</td>
<td>$1.2M</td>
<td>10 units</td>
<td>NWL</td>
</tr>
<tr>
<td>Isolators</td>
<td>$605k</td>
<td>84 units</td>
<td>Ferrite Co.</td>
</tr>
<tr>
<td>Waveguide</td>
<td>$500k</td>
<td>various</td>
<td>MCI/Mega</td>
</tr>
<tr>
<td>HOM filters</td>
<td>$187k</td>
<td>26</td>
<td>CML</td>
</tr>
<tr>
<td>Solenoid PS</td>
<td>$115k</td>
<td>84 units</td>
<td>Sorensen</td>
</tr>
</tbody>
</table>
Waveguide Installation
Waveguide
FPGA Board

PC-104 board not shown
EPICS: LLRF Screen (1 channel)
Test Stands

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1st Article at L-3