Overview and Lessons Learned of the Jefferson Lab Cryomodule Production for the CEBAF 12 GeV Upgrade
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Introduction to Jefferson Lab

>1200 active member international user community engaged in exploring quark-gluon structure of matter

Superconducting electron accelerator provides 100% duty factor beams of unprecedented quality, with high polarization at energies up to 6 GeV

Test Lab (SRF) Renovation and Technology & Engineering Development Facility Complete
Two 0.6 GeV linacs

Add arc

Add 5 cryomodules

20 cryomodules

New cryomodules get new rf zones

Add beamline

Add 5 cryomodules

20 cryomodules

Upgrade magnets and power supplies

HALL D

12 GeV CEBAF

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**SCOPE OF 12 GeV UPGRADE**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Present JLab</th>
<th>Upgraded JLab</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of Halls</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td>Number of passes Halls A/B/C</td>
<td>5 (for max energy)</td>
<td>5 (for max energy)</td>
</tr>
<tr>
<td>Max Energy to Halls A/B/C</td>
<td>up to ~6 GeV</td>
<td>up to ~11 GeV</td>
</tr>
<tr>
<td>Number of passes to Hall D</td>
<td>New Hall</td>
<td>5.5</td>
</tr>
<tr>
<td>Energy to Hall D</td>
<td>New Hall</td>
<td>12 GeV</td>
</tr>
<tr>
<td>Current – Hall A &amp; C</td>
<td>max ~180 µA combined</td>
<td>max ~85 µA combined (higher at lower energy)</td>
</tr>
<tr>
<td>Current – Hall B &amp; D</td>
<td>(B) Up to 5 µA max</td>
<td>(B, D) Up to ~5 µA max each</td>
</tr>
<tr>
<td>Central Helium Liquefier (CHL)</td>
<td>4.5 kW</td>
<td>9 kW</td>
</tr>
<tr>
<td># of cryomodules in LINACS</td>
<td>40</td>
<td>50</td>
</tr>
<tr>
<td>Accelerator energy per pass</td>
<td>1.2 GeV</td>
<td>2.2 GeV</td>
</tr>
</tbody>
</table>

*Routinely provide beam polarization of ~85% now, same in 12 GeV era*
- Eight-seven cell SRF cavities (2K - nominal operating temp)
- Eight individual helium vessels (stainless steel)
- Waveguide power couplers (double warm rf-windows)
- Cavity tuners
  - Cold scissor jack
  - Warm drive components
- Supply/Return cryogenic end-caps (two cooling circuits)
  - 2K primary & 50K shield
Cryomodule Scope & Key Technical Parameters

- **Scope:** Develop, Design, Fabricate, Install and Check-out 10 Cryomodules (5 new cryomodules per linac)

(Note: The following parameters are for each Cryomodule)

**Voltage** (Includes 10% reserve): \( \geq 108 \text{ MV} \)
- Corresponds to average cavity gradient of 19.2 MV/m (ensemble average in each linac)

**Heat budget:** (Interface with Cryogenics)
- 2 K \( \leq 300 \text{ W} \)
  - Corresponds to cavity Qo 7.2 E9 @ 19.2MV/m
- 50 K \( \leq 300 \text{ W} \)

**Slot Length:** 9.8 m
**Tuner resolution:** \( \leq 2 \text{ Hz} \)

**Fundamental Power Coupler (FPC):** 7.5/13 kW (Avg/Pk)
**Cryomodule Length (Physical):** \( \sim 8.5 \text{ m} \)
Procurement - Planning

• Industry to produce components (build to print)
  – Develop advanced procurement plan
  – Specifications, drawings, acceptance criteria, schedule
  – Bid/Award process
    • Stock components
    • Low price technically acceptable
    • Best Value (consideration for experience)
  – Acceptance criterion
  – Delivery schedule
  – Production Schedule
Procurement - Execution

- **Manufacturing and Acceptance**
  - Criterion developed & defined prior to award
  - Vendor visits during production improves communication
  - First Article delivery schedule is critical
    - Validate production process before all components made

- QA/QC all components prior to release for use in cryomodule production
Procurement – Lessons Learned

• Strong Quality Assurance Pays off
  – Get early start on ‘non-standard’ components
    • Specifications & acceptance criteria must be well documented
      – Acceptance travelers, staff training, feedback to vendor
    • Issues with vendor performance must be communicated promptly
  – Manage resources
    • Resources must be in place prior to delivery of first article
    • Staffing: Availability, allocation, training, skill sets, etc.
    • Facilities: Process control, priority access, maintenance
  – Maintain Detailed Documentation
    • All procedures must be vetted prior to release
    • Establish robust QC; traveler system - (receiving inspections, process control, testing results, database management)
• Pre-production

  – Inventory management
    • Logistics:
      – Space, access, equipment, staffing
  – Scheduled mockup activities
    • Exercise tooling (ensure fit & function)
    • Work through assembly procedures
    • Identify/resolve any interference issues
    • Opportunity to vet assembly travelers
Production – Execution

- Production
  - Cavity qualification
    - Qualified in He vessel in VTA
    - 65% qualified on first test
  - Cavity string assembly
    - Assembly in cleanroom

C100 VTA tests for 12 GeV upgrade
Production – Execution

• Production (in-process quality checks)
  – Cold mass assembly
    • Mag shielding, Headers, tuners, instrumentation, MLI
  – Space frame assembly
    • Alignment, Thermal & Mag shielding, MLI
Production – Acceptance Testing

• Production
  – Final assembly
    • Complete warm checkout of all subsystems.
  – Acceptance testing
    • Cryomodule is slow cooled down to 4K (pumped down 2K)
      – Instrumentation checkout
    • Low power measurements
      – Tuner operation, cavity frequencies, HOM damping, heater control
    • High power measurements
      – Emax, Qo, Heat loads, Lorentz
Production – Lessons Learned

• Have Focused Response to ‘unplanned’ Issues
  – High permeability in He vessel heads
    • Spuncast head manufacturer added carbon steel to process
      – Manufacturer contacted; new (C-free) process implemented
      – Replacement heads manufactured from 316 SS
  – Cryogenic electrical feed-through (F-T) leaks
    • Failed after QA acceptance testing
      – Replaced: Based on previous experience, F-T’s located behind access panels.
  – Microphonic response higher than planned
    • Cold tuner modified to add stiffness to system.
  – Individual cavity heater control needed for operations
    • LLRF controls modified to accommodate
      – Based on previous experience, individual heaters installed
Installation / Checkout & Commissioning - Planning

• Coordination (with other 12 GeV upgrade activities)
  – Civil, beam transport, cryogenics, high power-rf, instrumentation, controls & safety
    • Integrate detailed schedule of activities including resources and interdependencies

• Goal – Install two cryomodules into CEBAF ahead of baseline schedule
  – Opportunity to operate cryomodules with beam and demonstrate performance goals.
    • Close coordination with physics program to integrate new digital LLRF control system designed for C100 cryomodules.
• Following acceptance testing
  – Cryomodule transported from Test Lab to CEBAF tunnel
  – Installation into designated zone
    • Complete integration with all other accelerator systems
    • Beamline, cryogenics, high-power-rf & rf control & safety systems
Full Performance of C100 & RF Demonstrated

C100 Cryomodule Energy Gain – May 18th

Beam Current 465 μA

Cryomodule voltage

Beam Current /g80

Energy gain (MeV)

TIME (in 20 minute increments)
**Design goals**

- **98 MV/CM**
  - Required for 12 GeV operations

- **108 MV/CM design goal**
  - Provide operational margin

- **19.2 MV/m/cavity**
  - Avg $E_{\text{max}} = 22.2 \text{ MV/m}$

- **Qo $\geq 7.2 \times 10^9$ @ 19.2 MV/m**
  - Avg Qo = $8.1 \times 10^9$

<table>
<thead>
<tr>
<th>Tunnel Performance (MV)</th>
<th></th>
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<tbody>
<tr>
<td>C100-01</td>
<td>104</td>
</tr>
<tr>
<td>C100-02</td>
<td>110</td>
</tr>
<tr>
<td>C100-03</td>
<td>118</td>
</tr>
<tr>
<td>C100-04</td>
<td>106</td>
</tr>
<tr>
<td>C100-05</td>
<td>110</td>
</tr>
<tr>
<td>C100-06</td>
<td>108</td>
</tr>
<tr>
<td>C100-07</td>
<td>108</td>
</tr>
<tr>
<td>C100-08</td>
<td>In progress</td>
</tr>
<tr>
<td>C100-09</td>
<td>114</td>
</tr>
<tr>
<td>C100-10</td>
<td>110</td>
</tr>
</tbody>
</table>
• Good communication & cross functional coordination is critical to success
  – Baseline design performance goal achieved
  – Design goal of 10% margin not achieved on all cryomodules
    • These activities are still in progress
      – Preliminary lessons learned
        » Improvements made to process/configuration control
        » Upgrades to testing hardware & software beneficial
Cost & Schedule – Planning

- C100 CM’s ~10% of total project cost

- Earned Value Management System (EVMS)
  - Formal EVMS implemented for 12 GeV project in accordance with DOE Order 413.3B
Cost & Schedule – Monitoring & Control

Total C100 Cost Breakdown

- 33% Procurements
- 18% Expenses
- 49% Labor

Labor Breakdown by Process

- 21% Tooling Design
- 26% Cavity QA & Qualification
- 33% QA processes (cavities not included)
- 8% Cryomodule Assembly
- 5% Acceptance Testing
- 8% Installation & Commissioning

• EVMS data
  - Procurements were the dominate cost for the C100 CM’s
  - Labor costs dominated by QA, cavity processing & cryomodule assembly
Cost & Schedule – Monitoring & Control

• EVMS – ‘Touch labor’
  – Quality Control
    • Component receiving inspections
      – Several hundred individual component inspections
    • Documentation (travelers, database management, etc.)
    • Inventory control
      – 1000’s of parts inventoried, tracked & released for production
  – Cavity QA & qualification
    • Cavity receiving inspection, chemical cleaning, testing and assembly
  – Cryomodule assembly
    • Cold mass, space frame & final assembly
Cost & Schedule – Lessons Learned

• Cost
  – Procurement
    • Work with vendors to identify cost drivers and minimize NRE & schedule delays
    • Take advantage of quantity discounts were possible
    • Minimize custom components/maximize common parts
  – Labor
    • QA: Develop capable vendors prior to request for quotes
    • Processing & Assembly:
      – Automate processes and redundancy
      – Minimize touch labor

• Schedule
  – Good communication critical
    • With vendors, safety, facility and technical and PM staff
Summary

• Planning
  – Prototyping
    • Develop/finalize component specifications & acceptance criteria
    • Identify/resolve any potential performance issues
    • Thoroughly vet processes, procedures, tooling and staffing needs
    • Develop sound basis for full production planning

• Execution, Monitoring and Controlling
  – Utilize formal database management
    • Receiving inspections, assembly travelers, cost & schedule
    • Establish baseline, monitor progress & promptly identify cost issues
  – Work the plan
    • Communicate progress to all stakeholders on a regular basis
Acknowledgements

• Andrew Burrill et al., “Production and Testing Experience with the SRF Cavities for the CEBAF 12 GeV Upgrade,” IPAC2011, San Sebastian, Spain, September 2011, MOOCA01

• Leigh Harwood, “The JLab 12 GeV energy Upgrade of CEBAF”, NA-PAC13, Pasadena, CA MOZAA1

• V. Ganni et al, “Commissioning of Helium Refrigeration System at JLab for 12 GeV Upgrade”, CEC-ICMC 2013, Anchorage, AK


• Andrew Burrill et al., “SRF Cavity Performance Overview for the 12 GeV Upgrade,” IPAC 2012, New Orleans, LA., WEPPC089

• Michael Drury et al., “CEBAF Upgrade: Cryomodule Performance and Lessons Learned,” SRF 2013, Paris, France, THIOB01