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

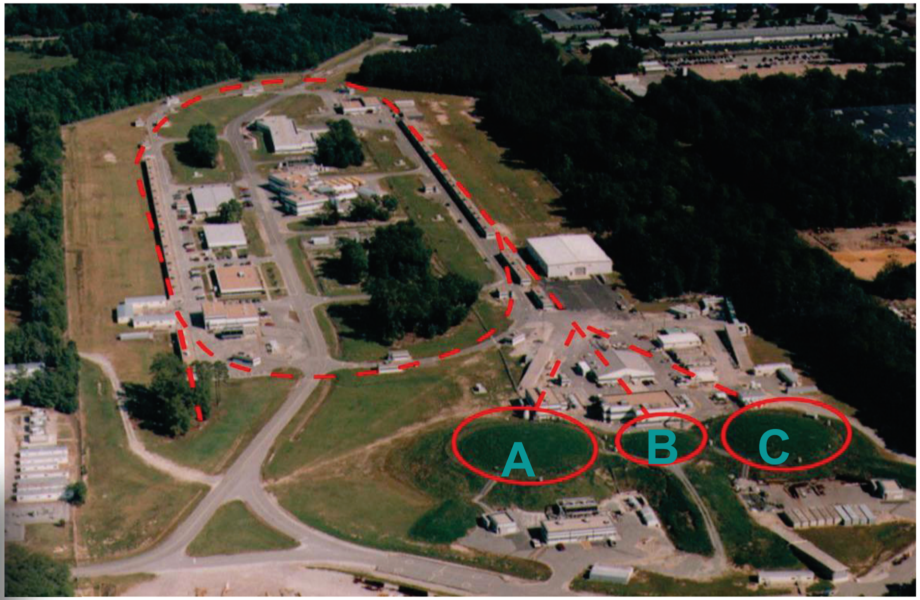
Outline

- Introduction / Scope
- Design
  - Overview & Parameters
- Procurement
  - Planning
  - Execution
  - Lessons Learned
- Production
  - Facilities & Planning
  - Execution
  - Acceptance Testing
  - Lessons Learned
- Installation / Check out & Commissioning
  - Planning
  - Execution
  - Performance
  - Lessons Learned
- Cost & Schedule
  - Lessons Learned
- Summary & Acknowledgements

Introduction to Jefferson Lab

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

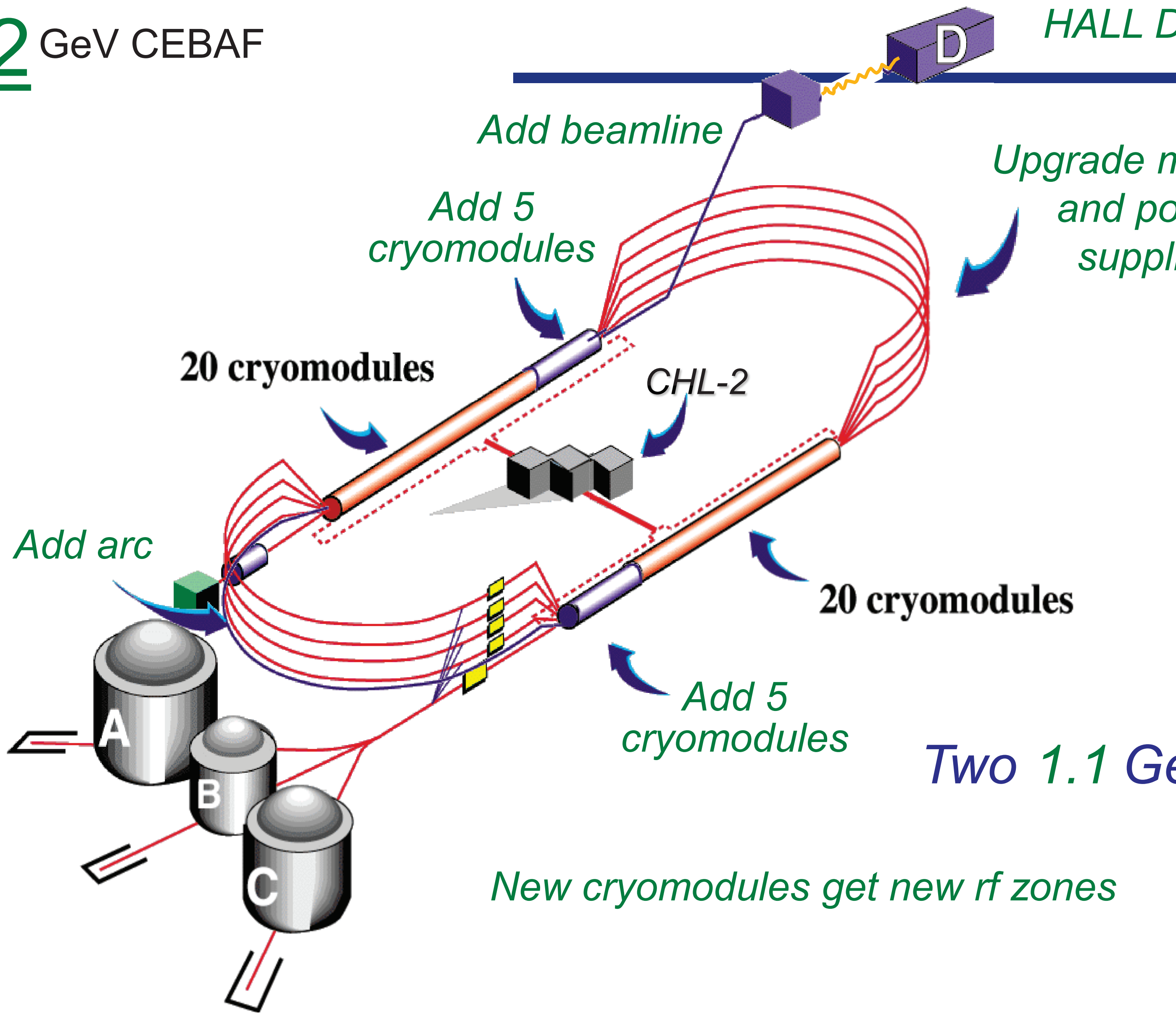
Superconducting electron accelerator provides 100% duty factor beams of unprecedented quality, with high polarization at energies up to 6 GeV



Newport News, VA

Test Lab (SRF) Renovation and Technology & Engineering Development Facility Complete

12 GeV CEBAF



Two 1.1 GeV linacs

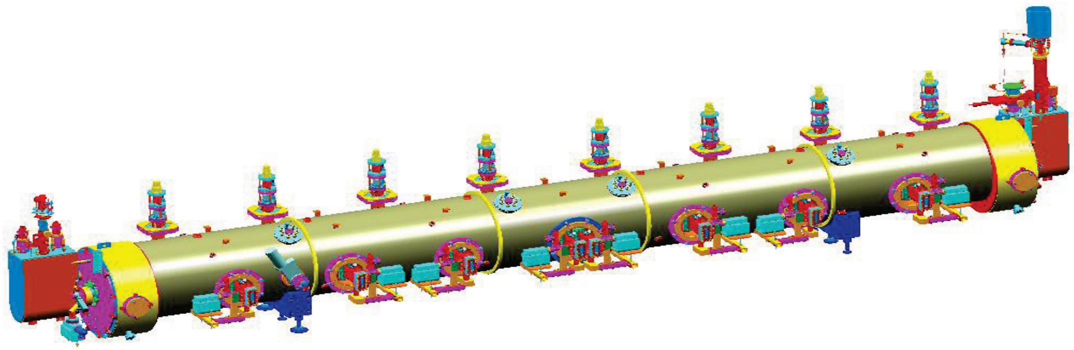
New cryomodules get new rf zones

SCOPE OF 12 GeV UPGRADE

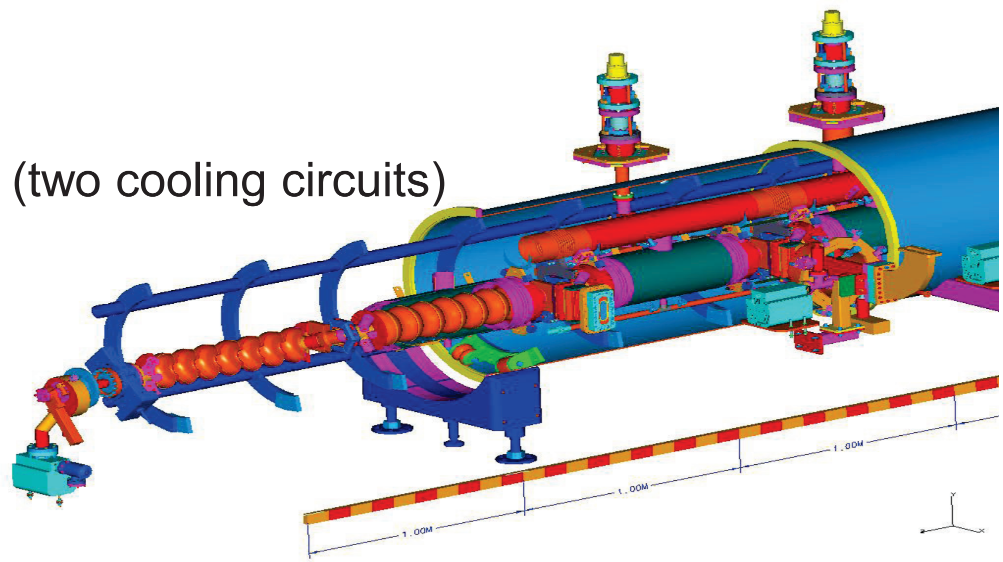
Parameter	Present JLab	Upgraded JLab
Number of Halls	3	4
Number of passes Halls A/B/C	5 (for max energy)	5 (for max energy)
Max Energy to Halls A/B/C	up to ~6 GeV	up to ~11 GeV
Number of passes to Hall D	New Hall	5.5
Energy to Hall D	New Hall	12 GeV
Current – Hall A & C	max ~180 μA combined	max ~85 μA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

Routinely provide beam polarization of ~85% now, same in 12 GeV era

C100 Cryomodule Design



- ➢ 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): ≥ 108 MV

– Corresponds to average cavity gradient of 19.2 MV/m (ensemble average in each linac)

Heat budget: (Interface with Cryogenics)

- 2 K ≤ 300 W
  - Corresponds to cavity Qo 7.2 E9 @ 19.2MV/m
- 50 K ≤ 300 W

Slot Length: 9.8 m

Tuner resolution: ≤ 2 Hz

Fundamental Power Coupler (FPC): 7.5/13 kW (Avg/Pk)

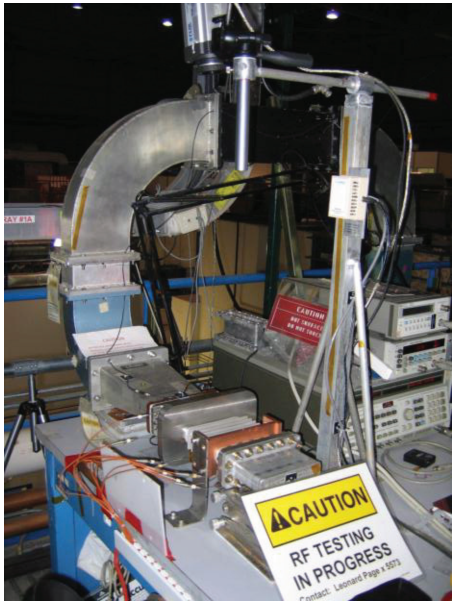
Cryomodule Length (Physical) ~8.5m

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

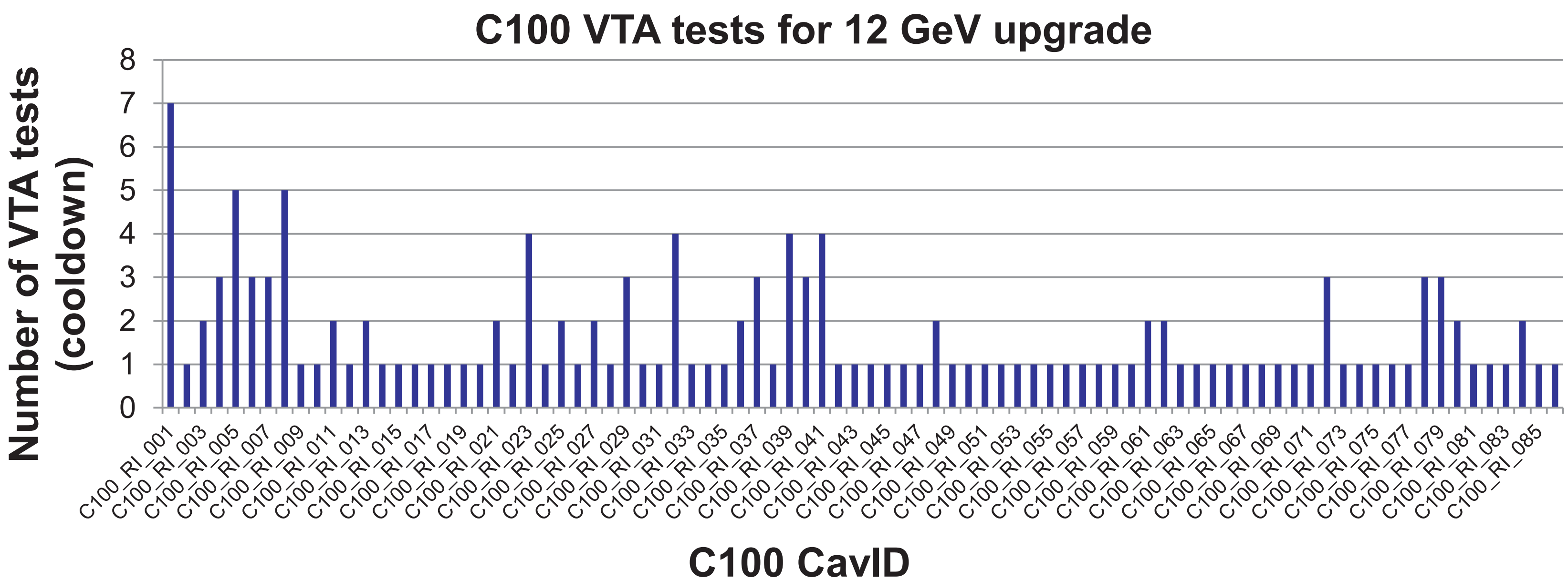
- **Strong Quality Assurance Pays off**
  - Get early start on ‘non-standard’ components
    - Specifications & acceptance criteria must be well documented
      - Acceptance travelers, staff training, feedback to vendor
    - Issues with vendor performance must be communicated promptly
  - Manage resources
    - 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)

Production – Facilities & Planning

- 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**

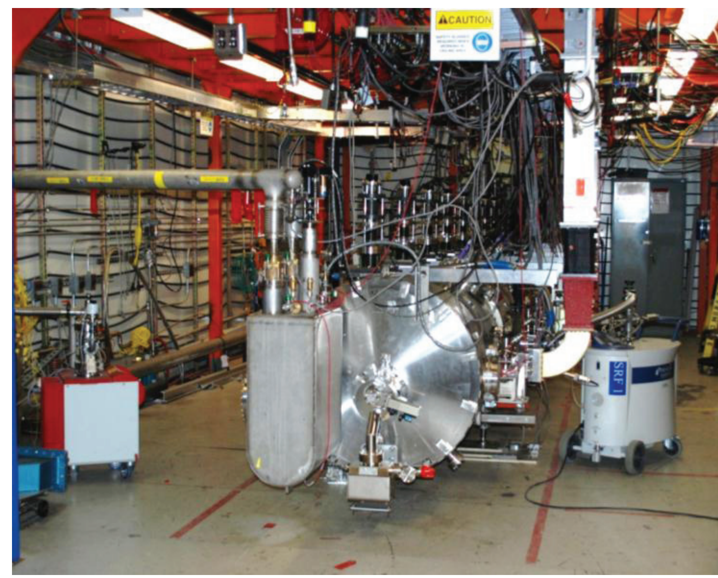


Production – Execution

- **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

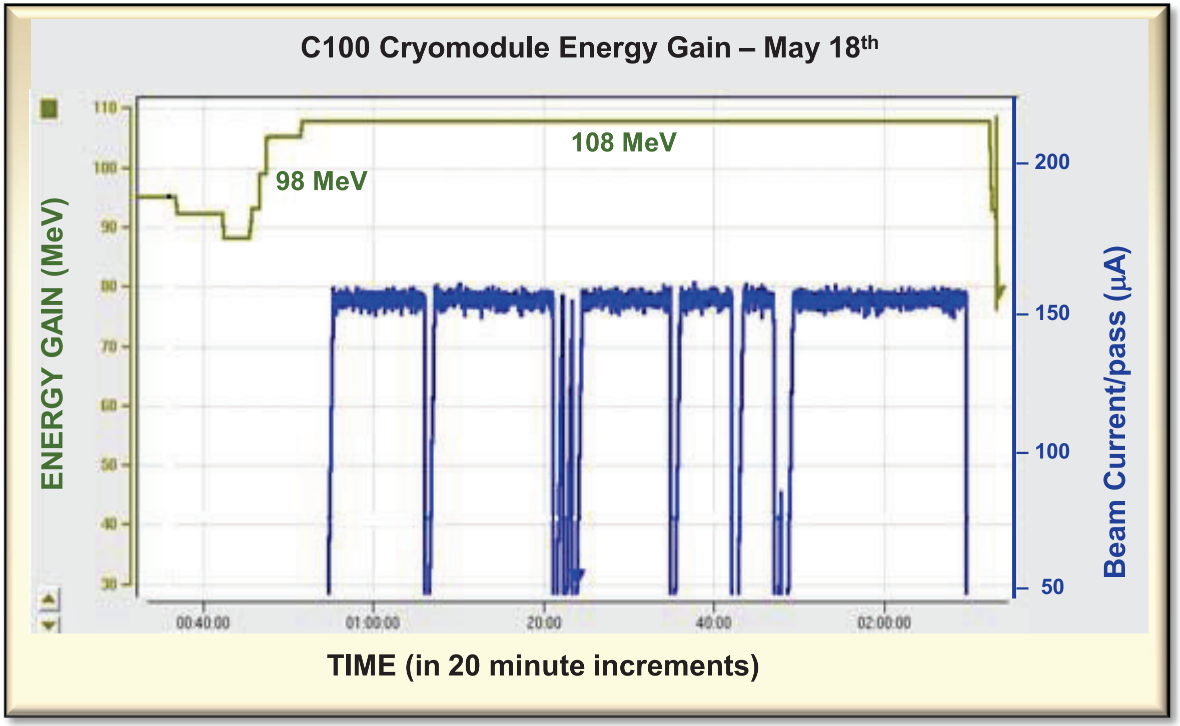
- Coordination (with other 12 GeV upgrade activities)
  - Civil, beam transport, cryogenics, high power-rf, instrumentation, controls & safety
    - Integrate detailed schedule of activities including resources and interdependencies
- Goal – Install two cryomodules into CEBAF ahead of baseline schedule
  - 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.

Installation / Checkout & Commissioning - Execution


- **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

Cryomodule voltage



Beam Current 465 μA

Installation / Checkout & Commissioning - Performance

- Design goals
  - 98 MV/CM
    - Required for 12 GeV operations
  - 108 MV/CM design goal
    - Provide operational margin
  - 19.2 MV/m/cavity
    - Avg Emax = 22.2 MV/m
  - Qo ≥ 7.2 E9 @ 19.2MV/m
    - Avg Qo = 8.1E9

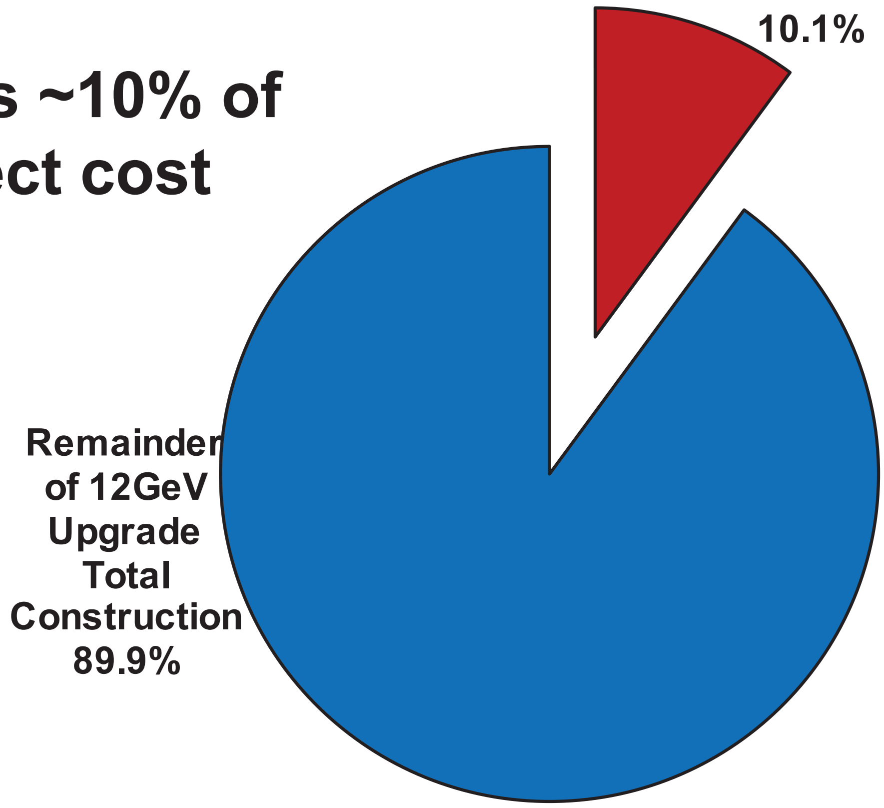
Tunnel Performance (MV)	
C100-01	104
C100-02	110
C100-03	118
C100-04	106
C100-05	110
C100-06	108
C100-07	108
C100-08	In progress
C100-09	114
C100-10	110

Installation / Checkout & Commissioning – Lessons Learned

- **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

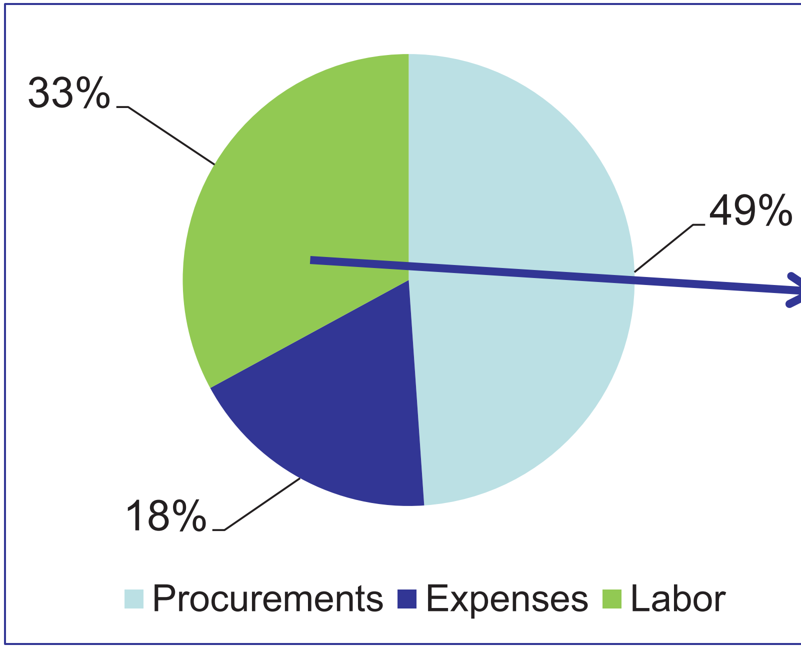
- **C100 CM's ~10% of total project cost**



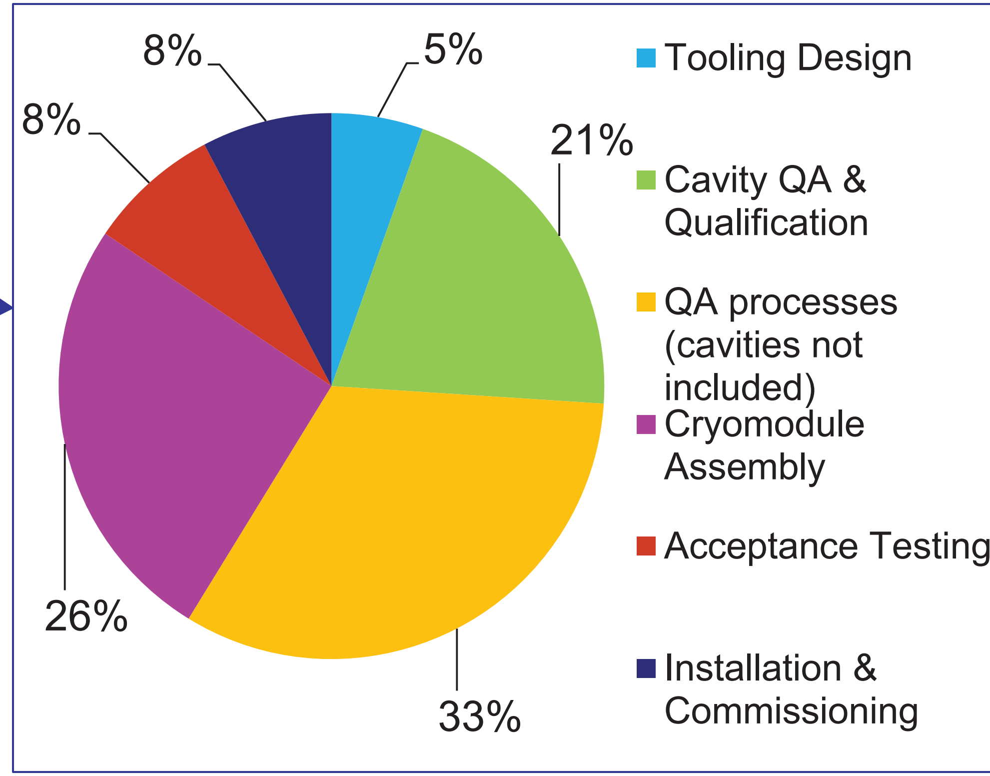
- **Earned Value Management System (EVMS)**
  - **Formal EVMS implemented for 12 GeV project in accordance with DOE Order 413.3B**

Cost & Schedule – Monitoring & Control

Total C100 Cost Breakdown



Labor Breakdown by Process



- **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
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- Frank Marhauser et al., “HOM Damping Sensitivity in SRF cavities,” International Workshop on HOM Damping in SRF Cavities, Cornell University, Ithaca, NY, 11-13 October 2010.
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Jefferson Lab - SRF Cryomodule Production Group