Upgrade of CEBAF to 12 GeV

Leigh Harwood
(for 12 GeV Accelerator team)
Outline

• Background
• High-level description
• Schedule
• Sub-system descriptions and status
• Summary
CEBAF Science Mission

CEBAF was originally built to establish a deep understanding of the quark/gluon structure of nuclei. (non-perturbative QCD)
The program to date has been highly successful.

Theoretical initiatives identified critical areas with new opportunities for understanding.

– Explanation for quark confinement (exotic meson spectroscopy)
– Tomography of the nucleus with Generalized Parton Distributions
– Valence quark behavior

Investigating these open questions required doubling the CEBAF beam energy
12 GeV Upgrade Project

Scope of the project includes:
- Doubling the accelerator beam energy
- New experimental Hall and beamline
- Upgrades to existing Experimental Halls

The completion of the 12 GeV Upgrade of CEBAF was ranked the highest priority in the 2007 NSAC Long Range Plan.

This priority was re-iterated in an 2013 NSAC report to DOE/NP

The Upgrade is built on an existing facility:
- The vast majority of accelerator and experimental equipment have continued use
6 GeV CEBAF

42 cryomodules (1497 MHz, 9m long)  
8 cavities/cryomodule with individual power and control  
(343 klystrons+controls)

Helium plant: 4.6 kW @ 2K
>2200 magnets with >1800 power supplies
12 GeV CEBAF

- Upgrade magnets and power supplies
- CHL-2 has same capability as CHL-1
- Add beamline

- Add 5 100MV cryomodules
- Add 5 100MV cryomodules
- New cryomodules get new rf zones (80 individually controlled klystrons)

- Two 1.1 GeV linacs

- CHL-2 has same capability as CHL-1
- Add arc
- Add 5.100MV cryomodules
- 20 cryomodules
- 20 cryomodules
Schedule: Long View

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<td>CD4A: Accelerator complete</td>
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Sub-system Descriptions and Status
Cryomodules: Scope & Key Technical Parameters

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

(The following parameters are for each Cryomodule)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Voltage</strong> (Includes 10% reserve):</td>
<td>≥ 98MV (108 MV) (ensemble average in each linac)</td>
</tr>
<tr>
<td>Heat budget: (Interface with Cryogenics)</td>
<td></td>
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<tr>
<td>- 2 K</td>
<td>≤ 300 W</td>
</tr>
<tr>
<td>- 50 K</td>
<td>≤ 300 W</td>
</tr>
<tr>
<td>Slot Length:</td>
<td>9.8 m</td>
</tr>
<tr>
<td>Tuner resolution:</td>
<td>≤ 2 Hz (stepper + PZT)</td>
</tr>
<tr>
<td>Fundamental Power Coupler:</td>
<td>7.5/13 kW (Avg/Pk)</td>
</tr>
<tr>
<td>Higher Order Mode (HOM) damping:</td>
<td></td>
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<tr>
<td>- Transverse (R/Q)Qk</td>
<td>&lt; 2.4 x 10^{10} Ω/m</td>
</tr>
<tr>
<td>- Longitudinal (R/Q)Q</td>
<td>&lt; 6.5 x 10^{11} Ω</td>
</tr>
<tr>
<td>Cryomodule Length (Physical)</td>
<td>~8.5m</td>
</tr>
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</table>
## Cryomodules: Status

<table>
<thead>
<tr>
<th>Checked out in tunnel</th>
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<tbody>
<tr>
<td>#1 104 MV</td>
<td></td>
</tr>
<tr>
<td>#2 110 MV</td>
<td></td>
</tr>
<tr>
<td>#3 118 MV</td>
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<tr>
<td>#4 106 MV</td>
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<td>#5 110 MV</td>
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<td>#6 108 MV</td>
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<td>#7 108 MV</td>
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<td>#8 108 MV</td>
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<tr>
<td>#9 114 MV</td>
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<tr>
<td>#10 110 MV</td>
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</table>

**Avg** 109 MV  
**Avg $Q_0 @ 19.2$ MV** = $8.1 \times 10^9$

**Final C100 installed in linac**

Hogan: WEZAA2
RF: Key Technical Parameters

- Ten new zones of RF power for new accelerating structures:
  - Operating Freq: 1497 MHz
  - Eight cavities per zone
    - Individual low-level controls
    - Cavity $Q_L \geq 2 \times 10^7$
  - Operating Gradients: $>17.5$ MV/m
  - One cavity per klystron

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<thead>
<tr>
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<th>Fast (&lt;1sec)</th>
<th>Slow (&gt;1sec)</th>
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<tbody>
<tr>
<td>Phase Stability (rms)</td>
<td>0.5°</td>
<td>3.0°</td>
</tr>
<tr>
<td>Amplitude (rms)</td>
<td>$4.5 \times 10^{-4}$</td>
<td>NA</td>
</tr>
</tbody>
</table>

**Diagram:**
- EPICS
- Klystron
- LL
- Energy Content (Norm.)
- Cavity de-tuning curve
- Detuning (Hz)
RF details

• Low Level RF
  – Ground-breaking digital solution for cw controls
  – Double-moded
    • Self-Excited Loop (SEL):
      If phase/amplitude control is not needed
      – Permits cavities to be energized and quickly brought onto resonance.
      ⇒ Mitigates the double-valued detuning curve.
    • Generator-Driven Resonator:
      When phase/amplitude control is needed for beam
      Hovater: TUZBA1
      Hoffler: THTB1

• High power RF
  – New 13kW klystron
    – Only 2 cavities/klystrons per high-power amplifier
    ⇒ Improved up time

Installation is complete
RF: Layout

Control racks, PSU’s…

Manifolds

Klystrons

Waveguide components

Cathode power supply

1 zone
RF: LLRF/HPA Control Systems

Field Control Chassis

Cryomodule Interlocks Chassis

High Power Amplifier Control Chassis

Stepper Tuner Control Chassis

Piezo Tuner Amplifier Chassis

Klystron Solenoid Power Supplies
Cryogenics

• Double the capacity of 2K plant: 4.6kW → 9kW
  – New 4.5K helium refrigerator: 4.6kW @ 2.1K, 12kW@35K plus 15 g/s of 4.5K liquefaction
  – Modified the cryogenic distribution system for the interconnection of 10 new C100 cryomodules
  – Note: Leveraged an existing 2K coldbox

• Status
  – 4.5K coldbox has been accepted
  – Distribution system is complete
  – Commissioning on integrated system is underway
Cryogenics (cont’d)

Lower coldbox

Upper coldbox
Beamlines

- Overall length (excluding linacs)
  - Original: 4.3 km
  - Upgrade: 4.9 km
    - New 10th recirculation arc and beamline to new Hall D
- Original layout retained (including dipole & quad locations)
- Almost all magnets were reused
  - Dipoles
    - Beam energy at any location has increased by ~2x, so $\int B dL$ of dipoles much increase by same ratio
    - Solution: Increase the current in the dipoles by 2x
      - Saturation was beaten by adding more return iron
        » Changed “C” dipoles to “H”
  - Quads
    - Most reused w/o change
    - ~100 were shifted to higher-current power supplies
### Beamlines (cont’d)

#### Magnets

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<tr>
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<th>Major (≥1m) dipoles</th>
<th>Quads</th>
<th>Steering dipoles</th>
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<tbody>
<tr>
<td>Original</td>
<td>452</td>
<td>705</td>
<td>750</td>
</tr>
<tr>
<td>Upgrade</td>
<td></td>
<td></td>
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</tr>
<tr>
<td>Unchanged</td>
<td>27</td>
<td>635</td>
<td>750</td>
</tr>
<tr>
<td>Reworked*</td>
<td>425</td>
<td>0</td>
<td>0</td>
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<tr>
<td>New</td>
<td>43</td>
<td>114</td>
<td>64</td>
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*Reworked: disassembled, insulation replaced, iron modified and/or added, coils reconfigured on some magnets, reassembled, QA’ed and field mapped

#### Power supplies

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<th>Power supplies</th>
<th>35-260kW</th>
<th>40-1080kW</th>
<th>10A/20V</th>
<th>20A/70V</th>
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<tbody>
<tr>
<td>Original</td>
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<td>1455</td>
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<tr>
<td>Upgrade</td>
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<td>Reused</td>
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<td>9</td>
<td>1322</td>
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<td>New</td>
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<td>15</td>
<td>240</td>
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Beamlines (cont’d)

- Original
- Removed original
- East Recombiner
- East Arcs
- 12GeV
Extraction: Beam to 3 Halls at Once

- Horizontally deflecting RF cavities (499MHz, copper)
- Horizontally deflecting septa
- Horizontally deflecting dipoles
- Horizontally deflecting Lambertson

Beam Frequency: 1497 MHz

Accelerator Frequency: 500 MHz Horizontal Separators

Plan View

Elevation View
I&C/Safety

• Added diagnostics and machine protection systems for new beamlines
  – New design for beam position monitor electronics was needed because of obsolescence of components for original

• Expanded network and modify control software for new cryomodule/rf zones, magnet power supplies, and CHL expansion

• Modified control software to incorporate new magnet power supplies and new cryomodule/rf zones

• Expanded personnel safety system to cover new Hall D

• Status
  – Ready for beam commissioning
  – Additions for Hall D will complete in FY14
### Schedule: 2009-now

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<th>Activity Name</th>
<th>2009</th>
<th>2010</th>
<th>2011</th>
<th>2012</th>
<th>2013</th>
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<td>Initial use of 12 GeV systems (6 GeV experiments)</td>
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- **FY11 shutdown:** Reworked 7 arcs and installed 2 zones of cryomodules & RF
- **FY12-13 shutdown:** Completed accelerator installation for commissioning
2012: Full Performance of C100 + RF was Demonstrated

This is with beam going to the NP experiments

Total current in linacs: 465 µA

C100 Cryomodule Energy Gain – May 18th, 2012

ENERGY GAIN (MeV)

TIME (in 20 minute increments)

Beam Current/pass (µA)

Cryomodule voltage

98 MeV

108 MeV

Total current in linacs: 465 µA

This is with beam going to the NP experiments
**Costs**

Construction: $119M

- **Power Systems:** 18.7%
- **Beam Transport:** 22.1%
- **Cryogenics:** 26.0%
- **Extraction:** 0.5%
- **Instrumentation & Control Systems:** 6.6%
- **I&C/Safety:**
- **PED:**
- **Commissioning R&D:**
Future

• What’s after 12 GeV?
• The NP community is looking towards an Electron-Ion Collider.  Zhang: TUZAA1
Summary

• An exciting research program in the study of the quark structure of nuclei as well as the fundamental question of quark confinement is possible with a 12GeV cw electron beam.

• The CEBAF accelerator has been upgraded to deliver 12 GeV beam.
  – The core of that upgrade was increasing the total linac voltage by 1.0 GV to a total of 2.2 GV.

• All systems have met their defined goals

Beam commissioning is about to start!