Commissioning and Operation of 12 GeV CEBAF

Arne Freyberger

JLAB Accelerator Operations
Outline

• Introduction
  • Jefferson Lab
  • CEBAF

• 12 GeV Upgrade
  • Gradient
  • Cryogenics
  • Magnets

• Beam Commissioning
  • Progress to date
  • Future plans
JLAB Research:

- Experimental, computational and theoretical nuclear physics
- Accelerator Science, SRF technologies and FEL
- Radiation detectors and medical imaging
- Cryogenic technology
CEBAF Timeline

• 1985 CEBAF design changed to use SRF technology
  – First large scale (>40 cryomodules, >320 SRF cavities) implementation of SRF technology
• 1987 **4 GeV** CEBAF green site construction begins
• 1995 CEBAF achieves 4 GeV design energy
• 1996 CEBAF changes its name to Thomas Jefferson National Accelerator Facility (**Jefferson Lab**) 
• 1997 All three halls (A, B & C) beam capable
• 2000 CEBAF reaches **6.07 GeV**
• 2012 CEBAF ceases 6 GeV operations
  – 17 years of experiments
  – 15 years of three hall operation
  – 178 completed experiments
  – 1380 Users (480 users from ~29 foreign countries)
6GeV CEBAF

- Warm magnets, superconducting RF
- Beam bunch on each RF phase (1497MHz)
- One revolution takes 4.2 ms
- Up to 5 recirculation passes: an electron is with us for at most 21 μs

- Linacs transport up to 5 different beam energies simultaneously
- Spreader-Arc-Recombiner transport is globally isochronous
- 1MW CW demonstrated
12GeV Upgrade Physics Case

- Quark confinement
  - Exotic meson spectroscopy
  - Production via linearly polarized high energy photons incident on Hydrogen target
    - Coherent bremsstrahlung of a 12 GeV electron beam incident on a diamond radiator
  - New experimental end-station: Hall-D
- Extend nucleon structure & standard model experimental reach in Halls A, B & C
12GeV CEBAF Timeline

CD: Critical Decision
12GeV Upgrade Overview

- Upgrade injector module
- Recommissioned existing accelerator modules
- Upgraded existing experimental halls
- Added 10th arc, upgraded all existing arcs
- Added 5 accelerating modules
- Recommissioned existing accelerator modules
- Revised all spreaders and recombiners
- Added experimental hall
## Beam Parameters

<table>
<thead>
<tr>
<th></th>
<th>6 GeV</th>
<th>12 GeV</th>
</tr>
</thead>
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<tr>
<td>Max. Energy ABC</td>
<td>6 GeV</td>
<td>11 GeV</td>
</tr>
<tr>
<td>Max. Energy D</td>
<td>NA</td>
<td>12 GeV</td>
</tr>
<tr>
<td>Duty Factor</td>
<td>CW</td>
<td>CW</td>
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<tr>
<td>Max. Beam Power</td>
<td>1 MW</td>
<td>1 MW</td>
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<tr>
<td>Bunch Charge (Min-Max)</td>
<td>0.004 fC – 1.3 pC</td>
<td>0.004 fC – 1.3 pC</td>
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<tr>
<td>Hall Repetition Rate Range</td>
<td>31.2 – 499 MHz</td>
<td>31.2 – 499 MHz</td>
</tr>
<tr>
<td>Nominal Hall Repetition Rate</td>
<td>499 MHz</td>
<td>249.5/499 MHz</td>
</tr>
<tr>
<td>Number of Exp. Halls</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td>Max. Number of Passes</td>
<td>5</td>
<td>5.5</td>
</tr>
<tr>
<td>Emittance (geometric) at full energy</td>
<td>0.1 nm-rad(X)/0.1 nm-rad(Y)</td>
<td>3 nm-rad(X)/1 nm-rad(Y)</td>
</tr>
<tr>
<td>Energy Spread at full energy</td>
<td>0.002%</td>
<td>0.018%</td>
</tr>
<tr>
<td>Polarization</td>
<td>35%(initial), 85%(final)</td>
<td>&gt;85%</td>
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</tbody>
</table>
Doubling the Energy

- 6GeV CEBAF: installed SRF provides 1200 MeV/pass of energy gain.
- Add 10\textsuperscript{th} Arc, maximum number of passes now 5.5 (was 5).
- Add 11 new cryomodules with ~ 100 MeV of energy gain per module
  - 5 new modules per linac
  - 1 new module in the Injector

\[ E_{Hall-D} = 5.5 \text{ passes}(1200 + 1000)\text{MeV/pass} = 12 \text{ GeV} \]

- Each C100 contains 8 7-cell cavities, 1497 MHz, L=0.7 m
- 108 MeV/module (target), 98 MeV/module (required) on average to achieve 12 GeV
- Average target gradient: 19.2 MV/m, average required gradient: 17.5 MV/m.
- Nearly the same form factor as original CEBAF cryomodule
Average Cavity Gradient (per Module)

**Inj./North Linac**

$E_{\text{gain}} = 178 \text{ MeV} / 1335 \text{ MeV}$

**South Linac**

$E_{\text{gain}} = 1325 \text{ MeV}$

17.5 MV/m
Average Cavity $Q_0$ (per module)

Inj. & North Linac

South Linac

THXB1  CEBAF SRF Performance during Initial 12 GeV Commissioning (Rama Bachimanchi)
Cryogenics

**CHL1**
- 4.6 kW @ 2.1 K
- 250 g/s
- 5.5 MW

**CHL2 (12GeV)**
- 4.8 kW @ 2.1 K
- 250 g/s
- 3.8 MW

<table>
<thead>
<tr>
<th>CHL1</th>
<th>1991 – Present</th>
</tr>
</thead>
<tbody>
<tr>
<td>CHL2 (12GeV)</td>
<td>2013 – Present</td>
</tr>
</tbody>
</table>
| 2K Coldbox #1 | 1994 - 2000  
2013 – Present |
| 2K Coldbox #2 | 2000 - Present |
## Accelerator Magnets

<table>
<thead>
<tr>
<th>Count</th>
<th>Description</th>
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<tbody>
<tr>
<td>32</td>
<td>New 4m dipole magnets, Arc-10</td>
</tr>
<tr>
<td>256</td>
<td>Large dipole refurbishments (add steel and/or new coil packs)</td>
</tr>
<tr>
<td>110</td>
<td>Large (&gt;1m) dipole magnets removed and measured</td>
</tr>
<tr>
<td>130</td>
<td>New quadrupole magnets</td>
</tr>
<tr>
<td>120</td>
<td>New corrector magnets</td>
</tr>
</tbody>
</table>

Excitation Curve: BL measurement

Hall probes: Field quality

Stretch Wire System

Stepper Stand
Magnetic Field Measurements

- Excitation curves and measured body gradient entered in database and model
- Shims used to improve field quality beyond specification
- Beam based measurements used to verify and improve the machine model

**QP Quads**

- Spec
- Proto
- 001
- 002
- 003
- 004
- 005
- 006
- 007
- 008

**Spreader/Recombiner Shunt Settings**

**Field Shaping Shim Effects XD5R01 (12GeV Operating Current)**

Specification
12GeV CEBAF Timeline

CD: Critical Decision
The CEBAF Element Database (CED) element definition obtained from varied sources: machine model, magnet measurement, survey and alignment, power supply, control system configuration.

1. The definitive sole oracle for CEBAF configuration.
2. Generates the accelerator model (elegant lattice files).
3. Creates control screens (EPICS).
4. Provides model information for high level applications (orbit & energy locks, beam matching scripts,…).
5. Creates the System checkout (Hot Check Out) lists.
6. And much more.
First Beam Operations

Run I ($E_{\text{linac}} = 1100 \text{ MeV}$)
- 2013-Dec-13 to 2014-Feb-06
- Establish 1-pass beam
- **Program Goal**: Demonstrate 2.2 GeV/pass of energy gain

Run II ($E_{\text{linac}} = 1000 \text{ MeV}$)
- 2014-Mar-07 to 2014-May-11
- Demonstrate full injection energy (123 MeV)
- First multi-pass beams in the 12 GeV era
- **Program Goal**: CW operations to Hall-A, 3-pass beam with $E>6 \text{ GeV}$
- **Program Goal**: 5.5 pass beam to the Hall-D dumplet
Run I and II Progression

1. Run I and II Progression

2. TUPMA040: Commissioning of the 123 MeV Injector for 12 GeV CEBAF (Yan Wang)
Run I & II: Milestones

2.2 GeV/pass
2014-02-05
Beam Arc2 viewer

>6 GeV to Hall A
2014-04-01
Beam profile in A line

5.5 Pass Beam
2014-05-09
Synchrotron Light in Arc10

Availability > 50%

Elastic events in A Spectrometer

6-beams in North Linac
Run III ($E_{\text{linac}} = 909$ MeV)

2014-Oct-08 to 2014-Dec-21
- CW beam, $E>10$ GeV, 5.5 pass beam to Hall-D
- First photons into the new experimental hall
- **Program Goal**: Hall-D detector commissioning
- RF separation (1-4 pass), first simultaneous multiple users in the 12 GeV era

Separated beams on beam viewer

Sustained 3-Hall operations

A-beam (4-pass)

B-beam (1-pass)
Hall D Commissioning

- Hall D: facility for experiments with linearly polarized photon beam
- Main goal: search for gluonic excitations in light meson spectra (GlueX experiment)
- Photon beam line + large acceptance spectrometer for charged particles & photons
- Commissioning with beam Nov. & Dec. 2014

- **Program Goals** demonstrated

Results with preliminary detector calibration and alignment

Neutral particles reconstruction

Charged particles tracking

<table>
<thead>
<tr>
<th>Target location</th>
<th>Z, cm</th>
</tr>
</thead>
<tbody>
<tr>
<td>π° → γγ</td>
<td>70 cm</td>
</tr>
</tbody>
</table>

Event Display

- Electromagnetic calorimeters
- Drift chambers

Spectrometer in solenoidal magnetic field

Results with preliminary detector calibration and alignment

π° → γγ

γγ mass, GeV

Vertex reconstruction

Target location

Z, cm

TUPMA039  First e−/Photon Commissioning Results for the GlueX Experiment/Hall D at CEBAF (Mike McCaughan)
Run IV ($E_{\text{linac}} = 950$ MeV)

2015-Feb-13 to 2015-May-18

- Commission new 249.5 MHz laser/injector configuration
- Commission new 750 MHz 5-pass separators
- Optics tool development: New beam matching process
- Establish baseline emittance and bunch length evolution
- Support ~5wk “early Physics” Operation

Quad Scan: Before match

Quad Scan: After match
RF Separation – Four Halls

Accelerator Frequency 1500 MHz

Hall Lasers
- Hall A: 250 MHz
- Hall B: 250 MHz
- Hall C: 250 MHz
- Hall D: 250 MHz (existing hall lasers run at 500 MHz)

5th Pass RF Separator Cavity 750 MHz

A/B/C separator is located downstream

Beam to Halls

Hall D: 250 MHz (existing hall lasers run at 500 MHz)

New Hall D laser fills empty buckets at 250 MHz

Four-Hall Operation! (D+3)
750MHz Separation

A & D beam separated on 5th pass at 9.6 GeV
Three Hall Program: \( E_{\text{linac}}=500 \text{ MeV} \)

**Hall-A:** Commissioning e- polarimeters

**Hall-B:** Ribbon beam for dark matter search

**Hall-D:** First coherent bremsstrahlung spectrum

\[
A_{\text{Raw}} = \frac{N_+ - N_-}{N_+ + N_-}
\]

Compton Asymmetry

\[
\sigma_x = 294\mu\text{m} \\
\sigma_y = 48\mu\text{m}
\]
12GeV Operations: Future

Summer 2015 (May-18 to Sept-30): Scheduled Accelerator Down
- Helium process all SRF cavities:
  - Goal: 12 GeV operations at high availability.
- Complete tunnel air-condition:
  - Goal: 35 C at 12 GeV magnet settings (max to date 39 C at 10 GeV).
- Complete pathlength chicane upgrade:
  - Goal: pathlength control range comparable to 6GeV CEBAF era.
- Repair 2K cold box
- Upgrade site power distribution for greater availability, redundancy and flexibility.

Run V ($E_{\text{linac}} = 1100$ MeV):
2015-Oct-26 to 2015-Dec-21
- Emittance/energy spread growth studies.
- SRF performance optimization at full energy.
  - Minimize trip rate
  - Minimize recovery time
  - Maximize gradient
- Detector commissioning at full energy.

Run VI ($E_{\text{linac}} = 1100$ MeV):
2016-Jan-28 to 2016-Mar-31
- First Physics runs at 12 GeV energy: Halls A&D
Gradient Maintenance

• C20/C50 performance degradation:
  • 0.21 MV/m – year (~34 MeV/pass - year).
  • Cause of degradation is unknown, actively being investigated.
• C100 insufficient data to date to reliably estimate degradation, if any.

• Commissioning vs. Operations cavity performance:
  • $78\% < \frac{\text{Operational Gradient}}{\text{Commissioning Gradient}} < 94\%$

Helium processing of all cavities planned for Summer 2015
Tracking Performance: Beam Trips

Beam Trip Summary
February 13 - March 25, 2015

<table>
<thead>
<tr>
<th>Category</th>
<th>Trips /Day</th>
<th>Lost Hrs</th>
<th>Mins /Trip</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diagnostics</td>
<td>1.0</td>
<td>0.4</td>
<td>0.6</td>
</tr>
<tr>
<td>Dump (Insert.)</td>
<td>16.4</td>
<td>2.7</td>
<td>0.2</td>
</tr>
<tr>
<td>Dump (Station.)</td>
<td>0.0</td>
<td>0.0</td>
<td>0.1</td>
</tr>
<tr>
<td>Gun/Laser</td>
<td>0.8</td>
<td>1.4</td>
<td>2.8</td>
</tr>
<tr>
<td>MPS (BLM)</td>
<td>24.9</td>
<td>8.9</td>
<td>0.5</td>
</tr>
<tr>
<td>MPS (Multi/Other)</td>
<td>9.4</td>
<td>2.4</td>
<td>0.4</td>
</tr>
<tr>
<td>Magnets</td>
<td>0.1</td>
<td>0.1</td>
<td>1.6</td>
</tr>
<tr>
<td>Multiple/Other</td>
<td>6.5</td>
<td>3.4</td>
<td>0.8</td>
</tr>
<tr>
<td>Unknown/Missing</td>
<td>11.3</td>
<td>4.1</td>
<td>0.5</td>
</tr>
<tr>
<td>Vacuum</td>
<td>0.7</td>
<td>0.5</td>
<td>1.1</td>
</tr>
<tr>
<td>RF (C25/C50)</td>
<td>28.4</td>
<td>6.7</td>
<td>0.4</td>
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<tr>
<td>RF (C100)</td>
<td>6.8</td>
<td>8.6</td>
<td>1.9</td>
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<td>RF (Multi/Other)</td>
<td>5.9</td>
<td>4.5</td>
<td>1.1</td>
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<tr>
<td>RF (Separator)</td>
<td>0.3</td>
<td>0.2</td>
<td>1.0</td>
</tr>
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</table>

**Total:** 112.4 43.8 0.6

- Max Trip Duration: 5 Minutes
- Max Types Per Trip: 10
Summary

- 12GeV Project accelerator deliverable (CD-4A) achieved on 2014-July-30, five months ahead of schedule.
  - 12 GeV CEBAF complete!
- 12GeV Project goals for Hall-D detector commissioning achieved on 2014-Dec-11, ahead of schedule.
  - Hall-B & C commissioning scheduled for Fall 2016 in advance of the 12GeV Project date of Sep. 2017 for CD-4B.
- Accelerator effort continues to build towards robust operations and physics quality beam at the 12 GeV design energy.
  - Continue the model driven, database centric approach to beam operations.
  - Helium processing scheduled for Summer 2015, in support of achieving robust 12 GeV operations in Fall 2015.
  - Detector commissioning progressing, getting ready for Physics data in Fall 2015/Spring 2016.
Acknowledgements

Thanks to:
• External reviewers
• 12GeV Project Management
• JLAB staff from across all divisions and departments

Special thanks to:
• Operations staff
• Accelerator Scientists (CASA, CIS, SRF)

Invited Oral:
• THXB1 CEBAF SRF Performance during Initial 12 GeV Commissioning (Rama Bachimanchi)

Contributed Oral:
• WEBC1 12 GeV CEBAF Transverse Emittance Evolution (Todd Satogata)

Posters:
• MOPWI045 Bunch Length Measurements using a Synchrotron Light Monitor (Mahmoud Ali)
• MOPWI047 Beamline Insertions Manager at Jefferson Lab (Michael Johnson)
• MOPWI048 The CEBAF Element Database and Related Operational Software (Theo Larrieu)
• MOPWI049 edT and Model-based Configuration of 12 GeV CEBAF (Dennis Turner)
• TUPMA039 First e-/Photon Commissioning Results for the GlueX Experiment/Hall D at CEBAF (Mike McCaughan)
• TUPMA040 Commissioning of the 123 MeV Injector for 12 GeV CEBAF (Yan Wang)
• WEPWI026 Vacuum Characterization and Improvement for the Jefferson Lab Polarized Electron Source (Marcy Stutzman)
• WEPWI032 Cavity Design, Fabrication and Commission Performance of a 750MHz, 4-rod Separator for CEBAF 4-Hall Beam Delivery System (Haipeng Wang)
• WEPWI033 Gain-switched Photocathode Drive Lasers with Variable Repetition Rates for High Current Accelerators (Shukui Zhang)
STOP HERE
Doubling the Energy

- 10 + 1 C100 modules installed and commissioned.
- All SRF cavities warmed to 300K during cryo upgrade.
- Every cavity characterized post 2K cool-down
  - $Q_0(E)$
  - $E_{\text{max}}$ (Maximum Gradient)
  - Field Emission onset

<table>
<thead>
<tr>
<th>Linac</th>
<th>Type</th>
<th>N(cavities)</th>
<th>$&lt;E_{\text{max}}\text{OP}&gt;$ (MV/m)</th>
<th>$&lt;Q_0&gt;$</th>
<th>$E_{\text{gain}}$ (MeV)</th>
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<tbody>
<tr>
<td>INJ</td>
<td>C20</td>
<td>10</td>
<td>10.38</td>
<td>4.6e9</td>
<td>52</td>
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<tr>
<td></td>
<td>C100</td>
<td>8</td>
<td>22.58</td>
<td>8.1e9</td>
<td>126</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td><strong>Total $E_{\text{gain}}$</strong> 178</td>
</tr>
<tr>
<td>North Linac</td>
<td>C20</td>
<td>120</td>
<td>8.61</td>
<td>3.9e9</td>
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<td></td>
<td>C50</td>
<td>40</td>
<td>11.72</td>
<td>3.7e9</td>
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<tr>
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<td>20.86</td>
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<td>584</td>
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<td><strong>Total $E_{\text{gain}}$</strong> 1335</td>
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<tr>
<td>South Linac</td>
<td>C20</td>
<td>112</td>
<td>9.09</td>
<td>4.3e9</td>
<td>500</td>
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<td>48</td>
<td>11.55</td>
<td>3.8e9</td>
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<tr>
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<td>C100</td>
<td>40</td>
<td>19.77</td>
<td>7.4e9</td>
<td>554</td>
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<td><strong>Total $E_{\text{gain}}$</strong> 1325</td>
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