Continuous Electron Beam Accelerator Facility Overview

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Outline

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- Beam Requirements
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Jefferson Lab Overview

Core Competencies

- Nuclear Physics Research
- SRF Technology Leadership
- Polarized Electron Sources
- Cryogenics Research and Development
- Accelerator Physics and Diagnostics Development
Jefferson Lab Overview

Quick Facts

- 180 M$ annual operating budget
- 759 Full Time Employees
- 1,385 Active Users
- Produces ~1/3 of US PhDs in Nuclear Physics
- 169 acres and 80 buildings and trailers
Scope of the 12 GeV Upgrade

- Add 5 high performance cryomodules in each linac and their associated LLRF Systems
- Double the capacity of the Central Helium Liquefier
- Upgrade magnets and power supplies for recirculation arcs
- Upgrade Extraction, Instrumentation and Diagnostics, and Safety Systems
- Add new beamlines for Arc 10 and Hall D
- Add new experimental Hall D and upgrade existing Halls
The layout of the injector is the same as the 6 GeV accelerator up to the exit of the First Full Cryomodule.

New components:
- R100 Cryomodule
- 123 MeV Spectrometer
- Matching region shortened
- Chicane length increased
- Synchrotron Light Monitor

Designed to provide 123 MeV CW beam for injection into the North Linac.
CEBAF Injector

- Injector Optics:
  - Segment shown begins at exit of ¼ cryomodule and ends at exit of last chicane dipole.
  - Matching section for measuring emittance and then adjusting quad strengths to match the beam to the entrance of the North Linac.
  - Chicane provides achromatic and isochronous transport of 123 MeV beam to the North Linac.
  - Length of the back leg of the chicane increased by 21 m to accommodate the new Arc 10.
  - Chicane is horizontally dispersion suppressed.
North and South Linacs

- North and South Linac Optics:
  - 9.6 m FODO channel with cryomodules between quadrupoles.
  - Beam injected with large spot size and damps as the beam is accelerated.
  - Skew quads in lattice around C20 and C50 cryomodules to correct for skew moment in cavity fields.
  - C100s have no skew moment.
  - Designed to provide 1090 MeV for a 12 GeV CEBAF
Spreaders and Recombiners

- Spreader/Recombiner layout:
  - Vertically achromatic system designed to accept broad range of multi-pass input parameters for recirculation transport.
  - Final step heights in ½ meter increments above lowest pass.
  - Quads in step control the vertical dispersion.
  - Recombiner is mirror-symmetric to the Spreader.
CEBAF Recirculation Arcs

- Arc layout:
  - Sixteen dipoles for Arc 1 and Arc 2 and thirty-two dipoles for Arc 3-10.
  - The recirculating Pi bends are at a radius of 80 m.
  - Each Arc has 32 quadrupole girders grouped in 4 families to control achromaticity, momentum compaction and the betatron tune.
  - Beam Position Monitors at the entrance of quadrupoles.
  - Horizontal and vertical correctors throughout to control the beam orbit.
1\textsuperscript{st} and 2\textsuperscript{nd} Recirculation Arcs

- Arc 1/2 Optics:
  - Segment begins at start of the Spreader and ends at the exit of the Recombiner.
  - Matching section in Spreader for matching the beam to the Arc.
  - Matching section in Recombiner for matching to the Linac.
  - Quads in vertical steps are used to null the vertical dispersion.
  - Quads near peaks of dispersion function within the Arc are used to null the horizontal dispersion and control $M_{56}$.
  - Enhanced horizontal dispersion in Arcs 1/2 provide better resolution for energy monitoring.
• Arc 3-10 Optics
  – The design optics for the upper Arcs is represented below.
  – Matching section in Spreader for matching the beam to the Arc.
  – Matching section in Recombiner for matching to the Linac.
  – Quads in vertical steps are used to null the vertical dispersion.
  – Quads near peaks of dispersion function within the Arc are used to null the horizontal dispersion and control $M_{56}$.
  – Amplitude of vertical dispersion peaks go down with pass count due to the smaller elevation change.
CEBAF Beam Structure

- Accelerator tuning is always done using low average power beam.
- The 250 ms pulse width at 60 Hz provides a 1.5% duty cycle.
- Nominal pulse height is 4 mA.
- Beam power is 720 W for a 12 GeV beam at this duty factor.
- The 4 ms trailing pulse is for measuring linac BPM orbits and linac arrival time.
- 3 interleaved 499 MHz bunch trains injected into 1497 MHz Linacs
- Future 4-Hall operations will use 249.5 MHz bunch trains
Overall configuration:

- Horizontal extraction systems at 500 MHz for 1st through 4th pass
- Vertical extraction system at 500 MHz for 5th pass
- New horizontal extraction system at 750 MHz for 5th pass
Existing Horizontal RF Separation

- Hall Lasers
  - Hall A: 500 MHz
  - Hall B: 500 MHz
  - Hall C: 500 MHz

- Accelerator Frequency
  - 1500 MHz

- RF Separator Cavity
  - 500 MHz

Separator frequency is 1/3 of the fundamental frequency

Beam to Halls
Recirculated Beams
Halls A, B, C 5th Pass Vertical Separation

Beam

Accelerator Frequency 1500 MHz

RF Separator Cavity 500 MHz

To Halls A, B, C
5th Pass Horizontal RF Separation

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)

RF Separator Cavity
750 MHz

Beam to Halls

A/B/C separator is located downstream

Hall D Beam

Four-Hall Operation!

Hall D laser fills empty buckets at 250 MHz
Extraction System Status

What remains to be done

- Fix Dogleg vacuum chamber in 2\textsuperscript{nd} pass
- Commission second pass horizontal RF and Magnet systems
- Recheck setup of high power phase shifters for 4\textsuperscript{th} pass horizontal system
- Install 5\textsuperscript{th} pass horizontal 750 MHz cavities
- Commission 5th pass horizontal RF and Magnet systems

West Arc Beamlines

1\textsuperscript{st} 750 MHz RF Separator
Installed under 500 MHz Cavities
Diagnostics

- **Bunch Length Monitors**
  - 6 GHz pill box cavities for optimizing longitudinal beam profile in the Injector.
  - Commissioning an interferometer as an online diagnostic

- **Beam Viewers**
  - Insertable flag for monitoring general beam quality. Located in all beamlines for measuring spot evolution. Also used in dispersive locations to phase cavities.

- **Beam Position Monitors**
  - 4-wire M15 and M20 style in all existing beamlines and the new ARC 10. Additional BPMs added to new Spreaders and Recombiners.
  - Stripline style BPMs newly developed for the Hall D beamline.

- **Pathlength Monitors**
  - 499 MHz pill box cavities located at the end of the linacs to measure arrival time of the beam for each pass.

- **Beam profile monitors**
  - Wire Scanners used for matching in the injector, at the entrance of each Arc and in front of the 2 kW beam dumps for Halls A, B, C and D.
  - Synchrotron Light Monitors in Injector, Arc 1, Arc 2, Arc 10, and Hall beamlines.
Existing Diagnostics

Beam Viewers

Antenna-Style Beam Position Monitor

Pathlength Cavity

Beam on Viewer in Chicane

Wire Scanner and Electronics

Wire Scanner Forks

Old Style

New Style
Diagnostics for New Beamlines

- Stripline Beam Position Monitor
- Map of BPM Response from Stretched-Wire Test Stand
- Synchrotron Light Monitor
- Synchrotron Light from 9 GeV Beam in Arc10
30 Hz Differential Orbit Tuning

- Air-core kicker magnets in Arc 1 are used to provide differential orbit data at 30 Hz.
- System uses two kickers in each plane separated by a phase advance of 90 degrees.
- The left figure shows the differential orbits for the y-plane.
- System also used to modulate the energy in the North Linac at 30 Hz to measure/minimize dispersion leakage.
The Courant-Snyder Invariant refers to the invariance of the phase-space beam ellipse as it traverses the accelerator:

$$\epsilon = \beta x^2 + 2 \alpha xx' + \gamma xx^2.$$ 

The 30 Hz beam position data is analyzed to calculate the normalized invariant and compare to model.

Lower left figure shows a reasonably well-tuned result for each of the four kickers.

The same system is used to report the extent of the X-Y coupling errors in the system.
Pathlength Compensation

- Arrival time in linacs depends on distance travelled.
- The pass-pass length of the machine needs to be an integral number of RF wavelengths for peak acceleration.
- Changes in pathlength due to uniform expansion of the tunnel are compensated with changes to the RF frequency of the Master Oscillator.
Pathlength Compensation

- Pathlength optimized after 100 Hz shift in the 1497 MHz Master Oscillator.
- Pathlength chicanes compensate for residual non-uniform changes to the overall machine length.
Magnet Field Quality

- Magnet Measurement Facility Data
  - All dipole and septa magnets measured for field quality.
  - All quad families measured for field quality.
  - Integrated field and dipole gradient data entered into the CEBAF Element Database.
  - Control system gets information from the CEBAF Element Database.
Cryomodule Commissioning

- All 418 SRF cavities were commissioned in advance of beam operations.
  - Measured:
    - Maximum accelerating gradient
    - Cavity $Q_0$s
    - Field emission survey

<table>
<thead>
<tr>
<th>Linac</th>
<th>Type</th>
<th>Ncav</th>
<th>$\langle GMES \rangle$ (MV)</th>
<th>$\text{GMES}_{RMS}$ (MV)</th>
<th>Min-Max (MV)</th>
<th>Egain (MeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inj</td>
<td>C20</td>
<td>10</td>
<td>6.72</td>
<td>0.81</td>
<td>5.86-8.63</td>
<td>33.6</td>
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<tr>
<td>NL</td>
<td>C20</td>
<td>119</td>
<td>7.19</td>
<td>1.64</td>
<td>2.97-11.71</td>
<td>427.6</td>
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<tr>
<td>NL</td>
<td>C50</td>
<td>40</td>
<td>11.03</td>
<td>1.49</td>
<td>6.34-13.45</td>
<td>220.7</td>
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<tr>
<td>NL</td>
<td>C100</td>
<td>38</td>
<td>17.59</td>
<td>2.40</td>
<td>9.80-20.77</td>
<td>467.9</td>
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<tr>
<td>SL</td>
<td>C20</td>
<td>108</td>
<td>7.05</td>
<td>1.40</td>
<td>4.78-10.56</td>
<td>380.7</td>
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<tr>
<td>SL</td>
<td>C50</td>
<td>47</td>
<td>10.06</td>
<td>1.90</td>
<td>6.41-12.36</td>
<td>236.4</td>
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<tr>
<td>SL</td>
<td>C100</td>
<td>40</td>
<td>16.66</td>
<td>2.75</td>
<td>9.70-20.00</td>
<td>466.4</td>
</tr>
</tbody>
</table>
C20 Cavity Performance

C20 Q0 @ Gmaxop

C20 Gmaxop
C50 Cavity Performance

C50 Qo at Gmaxop

C50 Gmaxop
C100 Cavity Performance

C100 $Q_o$ at $E_{\text{max}}$

C100 $E_{\text{max}}$

Cavity Index

MV/m

Cavity Index
Cryomodule Operations

- Optimizing Cavity Phases
  - New software package under development - “Phaser”
    - Dither each cavity phase ±10 degrees
    - Measures the energy response in the Arc Beam Position Monitors
    - Determine phase error from asymmetry of response
    - Should be able to get to less than 0.25 degrees

- Optimizing Cavity Gradients
  - Automated routine to calibrate all cavities relative to one reference cavity
    - Calibrate one high gradient reference cavity relative to the Arc Beam Position Monitors
    - Turn off one cavity and use reference cavity to recover energy in Arc
    - Repeat for all cavities
    - Expect residual errors of a few percent
### Optimizing the SRF Performance

<table>
<thead>
<tr>
<th>Run Period</th>
<th>Dates</th>
<th>Max. 5.5pass Energy</th>
<th>Trip Downtime Goal (% - min/hr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ACC-III</td>
<td>Fall2014</td>
<td>11 GeV</td>
<td>&lt;20% &lt;12</td>
</tr>
<tr>
<td>ACC-IV</td>
<td>Spring2015</td>
<td>11 GeV</td>
<td>&lt;17% &lt;10</td>
</tr>
<tr>
<td>Phy-I</td>
<td>Fall2015</td>
<td>12 GeV</td>
<td>&lt;20% &lt;12</td>
</tr>
<tr>
<td>Phy-II</td>
<td>Spring2016</td>
<td>12 GeV</td>
<td>&lt;17% &lt;10</td>
</tr>
<tr>
<td>Phy-III</td>
<td>Fall2016</td>
<td>12 GeV</td>
<td>&lt;13% &lt;8</td>
</tr>
<tr>
<td>Phy-IV</td>
<td>Spring2017</td>
<td>12 GeV</td>
<td>&lt;12% &lt;7</td>
</tr>
<tr>
<td>Phy-V</td>
<td>Fall2017</td>
<td>12 GeV</td>
<td>&lt;10% &lt;6</td>
</tr>
<tr>
<td>Phy-VI</td>
<td>Spring2018</td>
<td>12 GeV</td>
<td>&lt;10% &lt;6</td>
</tr>
<tr>
<td>Ultimate</td>
<td></td>
<td>12 GeV</td>
<td>&lt;5% &lt;3</td>
</tr>
</tbody>
</table>

### Multiple options for reaching the availability goals over time:

- Improve C20 trip models, maximize gradient/minimize trip rate.
- C50 program, one C50 refurbishment is in progress.
- Build more C100s.
- In-situ Helium Processing to reduce field emission.
Helium Processing

Helium Processing of a CEBAF Cryomodule:
- Introduce helium gas into cavity vacuum space.
- Run RF to clean cavity surfaces.
- Warm up and pump down to remove residual gas.
- Improves high-field Q, reduces x-ray production and greatly reduces incidence of arcing at the cold ceramic window.
Maintaining Gradient

- Coordinated effort to reach 2.2 GeV per pass with acceptable performance for Physics
  - Helium processing
  - C-50 Refurbishment Program
## Beam Physics Requirements

### Beam/beamline requirements @ 11-12 GeV: Initial requirements

<table>
<thead>
<tr>
<th>Hall</th>
<th>Emittance</th>
<th>Energy spread ($\sigma$)</th>
<th>Spot size ($\sigma$)</th>
<th>Halo</th>
<th>Other</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>A</strong></td>
<td>$\varepsilon_x &lt; 10$ nm-rad, $\varepsilon_y &lt; 5$ nm-rad</td>
<td>0.05% (12 GeV) 0.003% (2-4 GeV)</td>
<td>$\sigma_x &lt; 400$ µm $\sigma_y &lt; 200$ µm ($\sigma_y &lt; 100$ µm, (2-4 GeV))</td>
<td>$1 \times 10^{-4}$ Gaussian integral/pedestal integral</td>
<td></td>
</tr>
<tr>
<td><strong>B</strong></td>
<td>$\varepsilon_x &lt; 10$ nm-rad, $\varepsilon_y &lt; 10$ nm-rad</td>
<td>0.1%</td>
<td>$\sigma_x &lt; 400$ µm $\sigma_y &lt; 400$ µm</td>
<td>$2 \times 10^{-4}$ Gaussian integral/pedestal integral</td>
<td>Beam Position Stability &lt; 200 µm Beam Current Stability $\Delta I/I &lt; 5%$</td>
</tr>
<tr>
<td><strong>C</strong></td>
<td>$\varepsilon_x &lt; 10$ nm-rad, $\varepsilon_y &lt; 10$ nm-rad</td>
<td>0.05%</td>
<td>$\sigma_x &lt; 500$ µm $\sigma_y &lt; 500$ µm</td>
<td>$2 \times 10^{-4}$ Gaussian integral/pedestal integral</td>
<td>Beam Position Stability &lt; 500 µm</td>
</tr>
<tr>
<td><strong>D</strong></td>
<td>$\varepsilon_x &lt; 50$ nm-rad, $\varepsilon_y &lt; 10$ nm-rad</td>
<td>&lt;0.5%</td>
<td>At radiator: $\sigma_x &lt; 1550$ µm $\sigma_y &lt; 550$ µm At collimator: $\sigma_x &lt; 540$ µm $\sigma_y &lt; 520$ µm</td>
<td>$1 \times 10^{-4}$ Gaussian integral/pedestal integral</td>
<td>Beam Position Stability &lt; 200 µm 1 nA &lt; Beam Current &lt; 3 µA</td>
</tr>
<tr>
<td>Hall</td>
<td>Emittance</td>
<td>Energy spread (σ)</td>
<td>Spot size (σ)</td>
<td>Halo</td>
<td>Other</td>
</tr>
<tr>
<td>------</td>
<td>-----------</td>
<td>------------------</td>
<td>---------------</td>
<td>------</td>
<td>-------</td>
</tr>
<tr>
<td>A</td>
<td>ε&lt;sub&gt;x&lt;/sub&gt; &lt; 10 nm-rad, ε&lt;sub&gt;y&lt;/sub&gt; &lt; 5 nm-rad</td>
<td>0.05% (12 GeV) 0.003% (2-4 GeV)</td>
<td>σ&lt;sub&gt;x&lt;/sub&gt; &lt; 400 μm σ&lt;sub&gt;y&lt;/sub&gt; &lt; 200 μm (σ&lt;sub&gt;y&lt;/sub&gt; &lt; 100 μm, (2-4 GeV))</td>
<td>1x10&lt;sup&gt;-4&lt;/sup&gt; Gaussian integral/pedestal integral</td>
<td>Parity-Violating Experiments: Charge asymmetry &lt; 0.1 ppm Position difference &lt; 1 nm Angle difference &lt; 10 nrad RMS size difference &lt; 1μm Compton Polarimeter: σ&lt;sub&gt;x&lt;/sub&gt; ~ 50 μm, σ&lt;sub&gt;y&lt;/sub&gt; ~ 50 μm</td>
</tr>
<tr>
<td>B</td>
<td>ε&lt;sub&gt;x&lt;/sub&gt; &lt; 10 nm-rad, ε&lt;sub&gt;y&lt;/sub&gt; &lt; 10 nm-rad</td>
<td>0.1%</td>
<td>σ&lt;sub&gt;x&lt;/sub&gt; &lt; 400 μm σ&lt;sub&gt;y&lt;/sub&gt; &lt; 400 μm</td>
<td>1x10&lt;sup&gt;-4&lt;/sup&gt; Gaussian integral/pedestal integral</td>
<td>Charge asymmetry &lt; 10&lt;sup&gt;-4&lt;/sup&gt; 60 Hz structure &lt; 15% Microscopic duty cycle &gt; 80%</td>
</tr>
<tr>
<td>C</td>
<td>ε&lt;sub&gt;x&lt;/sub&gt; &lt; 10 nm-rad, ε&lt;sub&gt;y&lt;/sub&gt; &lt; 5 nm-rad</td>
<td>0.05% 6 GeV:0.03%</td>
<td>σ&lt;sub&gt;x&lt;/sub&gt; &lt; 400 μm σ&lt;sub&gt;y&lt;/sub&gt; &lt; 200 μm</td>
<td>1x10&lt;sup&gt;-4&lt;/sup&gt; Gaussian integral/pedestal integral</td>
<td>Beam Position Stability &lt; 200 μm Parity-Violating Experiments: Charge asymmetry &lt; 0.1 ppm Position difference &lt; 1 nm Angle difference &lt; 10 nrad RMS size difference &lt; 1μm</td>
</tr>
<tr>
<td>D</td>
<td>ε&lt;sub&gt;x&lt;/sub&gt; = 10 nm-rad, ε&lt;sub&gt;y&lt;/sub&gt; &lt; 5 nm-rad</td>
<td>&lt;0.5%</td>
<td>At radiator: σ&lt;sub&gt;x&lt;/sub&gt; &lt; 1550 μm σ&lt;sub&gt;y&lt;/sub&gt; &lt; 550 μm At collimator: σ&lt;sub&gt;x&lt;/sub&gt; &lt; 540 μm σ&lt;sub&gt;y&lt;/sub&gt; &lt; 520 μm</td>
<td>1x10&lt;sup&gt;-5&lt;/sup&gt; Gaussian integral/pedestal integral</td>
<td>Beam Position Stability &lt; 200 μm Electron Polarization &lt; 1% 1 nA &lt; Beam Current &lt; 3 μA</td>
</tr>
</tbody>
</table>
Achievements to date

- Deliver 2.2 GeV Beam to the 2R dump.
- Commissioned all beamlines except Hall C and the 4T beamline.
- Deliver greater than 10 GeV in 5.5 passes to Hall D.
- Delivered beam for Physics to three halls simultaneously.
Commissioning Milestones

Meeting Beam Size Requirements

First data from Scattered Electrons in Hall A

10.5 GeV Beam to Hall D Ramp

8 Hour Availability for 2.2 GeV Run

Six Beams in the NL for the First Time

Emittance Scan During the Last Run
Next Phase of Beam Operations

- Some of the challenges to refine CEBAF Operations:
  - Optimizing the performance of the SRF Systems.
  - Understanding Synchrotron Radiation Effects.
    - Synchrotron Radiation Compensation Coils.
    - Minimizing emittance growth due to synchrotron radiation losses.
  - Model Development - Reduce amplitude of tuning quads.
    - Emittance measurements at the entrance of each arc.
    - Linear Optics from Closed Orbit (LOCO) – measure body gradients of Spreader, Arc and Recombiner dipoles.
    - RayTrace – measure phase-space pseudo-ellipse using coordinated corrector kicks in x-plane and y-plane. Compare to model of phase-space evolution to look for point sources of model errors.
  - Ramp energy to 12 GeV to Hall D.
    - Dogleg Upgrade.
    - Tunnel Air Conditioning.
Future Run Plans

Winter 2015 Shutdown

• Install the 5\textsuperscript{th} pass 750 MHz RF Separator system.
• Install the 250 MHz drive lasers for the polarized source.

The last two bullets allow for simultaneous operation of Hall A and Hall D at the highest pass and for simultaneous 4-Hall operations.

Spring 2015 Run

• Commission the 750 MHz RF Separators.
• Commission the 250 MHz Drive Laser system.
• Deliver beam for Physics contingent on funding.
Future Run Plans

**Summer 2015 Shutdown**

Major installation work is planned for this shutdown that will enable us to make the push to 12 GeV for the first time. The highlights for the shutdown are:

- Installation of a C50 cryomodule.
- Installation of the tunnel air conditioning.
- Completion of a lab wide upgrade of the power distribution, cooling towers and network.
- Helium processing of SRF cryomodules to reduce field emission and increase the energy reach of the linacs.
Future Run Plans

**Fall 2015 Run**

- Demonstrate 12 GeV capability for the first time.
- Finalize optics setup, energy scaling and procedures.

**Spring 2016 Run**

- Establish beam to Halls B and C in preparation for CLAS12 and SHMS detector checkout.
- Deliver beam in support of Hall B and C detector checkout.
- Support Engineering run in Hall D and Physics in Hall A.
- Deliver beam for Physics contingent on funding.
Last C100 Arriving in Tunnel

Thanks!