Outline

• CEBAF Overview and the 12 GeV Upgrade

• Optical Design and 12 GeV Expectations

• Commissioning: Optics Matching and Operations Emittance Measurements

• CSR Suppression Experiment

• Conclusions
Scope of 12 GeV Upgrade

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

The upgrade is designed to build on existing facility: vast majority of accelerator and experimental equipment have continued use.

Scope of the upgrade includes:
- Doubling the accelerator beam energy
- Doubling the injector energy
- New experimental Hall and beam-lines
- Upgrades to existing Experimental Halls

MOXGB2 (A. Freyberger, 12 GeV Commissioning/Ops)
THXB1 (R. Bachimanchi, 12 GeV SRF Performance)
# 6 GeV to 12 GeV Parameters

<table>
<thead>
<tr>
<th></th>
<th>6 GeV Operations</th>
<th>12 GeV Design/Requirements</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy to Halls A,B,C / D</td>
<td>6 GeV</td>
<td>11 GeV / 12 GeV</td>
</tr>
<tr>
<td>Number of passes for Halls A,B,C / D</td>
<td>5</td>
<td>5 / 5.5 (add a tenth arc)</td>
</tr>
<tr>
<td>Duty Factor</td>
<td>CW, 499 MHz</td>
<td>CW 499 MHz, 250 MHz</td>
</tr>
<tr>
<td>Max. Current to Halls A+ C / B</td>
<td>200 µA / 5 µA</td>
<td></td>
</tr>
<tr>
<td>Max. Current to Halls A+C / B+D</td>
<td>85 µA / 5 µA</td>
<td></td>
</tr>
<tr>
<td>Bunch charge</td>
<td>&lt; 0.41 pC</td>
<td>&lt; 0.36 pC</td>
</tr>
<tr>
<td><strong>Emittance at max. energy</strong></td>
<td><strong>(geometric, rms): x, y</strong></td>
<td><strong>(geometric, rms): x, y</strong></td>
</tr>
<tr>
<td></td>
<td>1 nm-rad, 1 nm-rad</td>
<td>10 nm-rad, 2 nm-rad</td>
</tr>
<tr>
<td>Energy spread at max. energy</td>
<td>2.5 x 10⁻⁵</td>
<td>5 x 10⁻⁴ / 5 x 10⁻³</td>
</tr>
<tr>
<td>Bunch length (rms)</td>
<td>0.2 ps</td>
<td>~1 ps</td>
</tr>
<tr>
<td>Polarization</td>
<td>80%</td>
<td>80%</td>
</tr>
</tbody>
</table>
CEBAF Detail Schematic
CEBAF Detail Schematic
CEBAF Detail Schematic
Synchrotron Radiation Emittance Growth

\[ \Delta \epsilon \approx 2 \times 10^{-27} \left( \frac{\gamma^5}{\rho[m]^2} \right) \langle \mathcal{H} \rangle \]

\[ \sigma_E^2 \approx 1.2 \times 10^{-33} \text{ GeV}^2 \left( \frac{\gamma^7}{\rho[m]^2} \right) \]

- Arc focusing very flexible: separate power supplies for all 32 arc quads
- Traditional CEBAF FODO cells \( \rightarrow \) DBA cells in higher arcs
- 30-40% reduction in \( \langle \mathcal{H} \rangle \)
  - Tradeoffs in \( M_{56} \), matching

**Arc 10 DBA optics**
Transverse Emittance Evolution

<table>
<thead>
<tr>
<th>Region</th>
<th>$\frac{\delta p}{p}$ [x10^{-3}]</th>
<th>$\epsilon_x$ [nm]</th>
<th>$\epsilon_y$ [nm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chicane</td>
<td>0.5</td>
<td>4.00</td>
<td>4.00</td>
</tr>
<tr>
<td>Arc 1</td>
<td>0.05</td>
<td>0.41</td>
<td>0.41</td>
</tr>
<tr>
<td>Arc 2</td>
<td>0.03</td>
<td>0.26</td>
<td>0.23</td>
</tr>
<tr>
<td>Arc 3</td>
<td>0.035</td>
<td>0.22</td>
<td>0.21</td>
</tr>
<tr>
<td>Arc 4</td>
<td>0.044</td>
<td>0.21</td>
<td>0.24</td>
</tr>
<tr>
<td>Arc 5</td>
<td>0.060</td>
<td>0.33</td>
<td>0.25</td>
</tr>
<tr>
<td>Arc 6</td>
<td>0.090</td>
<td>0.58</td>
<td>0.31</td>
</tr>
<tr>
<td>Arc 7</td>
<td>0.104</td>
<td>0.79</td>
<td>0.44</td>
</tr>
<tr>
<td>Arc 8</td>
<td>0.133</td>
<td>1.21</td>
<td>0.57</td>
</tr>
<tr>
<td>Arc 9</td>
<td>0.167</td>
<td>2.09</td>
<td>0.64</td>
</tr>
<tr>
<td>Arc 10</td>
<td>0.194</td>
<td>2.97</td>
<td>0.95</td>
</tr>
<tr>
<td>Hall D</td>
<td>0.18</td>
<td>2.70</td>
<td>1.03</td>
</tr>
</tbody>
</table>

(Nearly) end to end elegant simulations with mitigation

Adiabatic damping dominated

Arcs 6-10 with optics reconfigured from FODO to DBA

Synchrotron radiation dominated

Emittances are geometric
All quantities are rms from Y. Roblin
Emittance/Optics Campaign Strategy

• **Incorporate into 12 GeV optics commissioning**
  – Measure in all (available) matching regions
  – Single quad ➔ single wire scanner measurements
  – Improve automation, model integration in 6 GeV tools
    • Measurement/match: 6-8 hours (expert) ➔ 1 hour (operators)

• **Additional benefits**
  – Matching more systematic and consistent through CEBAF
    • Driven by elegant CED/online model
  – Faster matching can be performed more routinely
  – “Parasitic” beam emittance data from every scan/rematch

• **Note following data is for 11 GeV CEBAF commissioning**
  – Full 12 GeV commissioning in Fall 2015
**Model-Based Optics Rematch**

All data plotted is the projected beam ellipse in \((x,x')\) at start of an upstream scanned quad

This data is for Arc 9 spreader

**Blue and green ellipses are online model prediction**

**Red is measurement**

Discrepancy in horizontal after match is only due to measured beam emittance being larger from expected design value

\(\varepsilon_x = 2.6\ \text{nm-rad} \)

\(\varepsilon_y = 1.9\ \text{nm-rad} \)

\(\varepsilon_x = 3.0\ \text{nm-rad} \)

\(\varepsilon_y = 1.9\ \text{nm-rad} \)
Model-Based Optics Rematch

All data plotted is $(\text{measured beam } \sigma_{\text{rms}})^2$ vs $(\text{set quadrupole KL})$

Before match, as found

<table>
<thead>
<tr>
<th></th>
<th>KL [m$^{-1}$]</th>
<th>$\sigma_x^2$ [$\mu$m$^2$]</th>
<th>Horizontal</th>
<th>$\varepsilon_x=2.6$ nm-rad</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Model</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Measurement</td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.95</td>
<td>1.8x10$^6$</td>
<td>1.4x10$^6$</td>
<td>2.0x10$^6$</td>
</tr>
<tr>
<td></td>
<td>0.40</td>
<td>2.2x10$^5$</td>
<td>2.0x10$^5$</td>
<td>1.5x10$^5$</td>
</tr>
</tbody>
</table>

After match

<table>
<thead>
<tr>
<th></th>
<th>KL [m$^{-1}$]</th>
<th>$\sigma_x^2$ [$\mu$m$^2$]</th>
<th>Vertical</th>
<th>$\varepsilon_y=1.9$ nm-rad</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Model</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Measurement</td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.95</td>
<td>2.2x10$^5$</td>
<td>1.7x10$^5$</td>
<td>1.9x10$^5$</td>
</tr>
<tr>
<td></td>
<td>0.40</td>
<td>9.0x10$^5$</td>
<td>8.5x10$^5$</td>
<td>6.0x10$^5$</td>
</tr>
</tbody>
</table>

Blue data is model prediction

Red data is measurement

Discrepancy in horizontal after match is only due to measured beam emittance being larger from expected design value

Discrepancy in horizontal after match is only due to measured beam emittance being larger from expected design value
### Spring 2015 Measurements

<table>
<thead>
<tr>
<th>Location</th>
<th>Design $\varepsilon_x$</th>
<th>Meas $\varepsilon_x$</th>
<th>Design $\varepsilon_y$</th>
<th>Meas $\varepsilon_y$</th>
</tr>
</thead>
<tbody>
<tr>
<td>123 MeV</td>
<td>4.0</td>
<td>2.5±0.9</td>
<td>4.0</td>
<td>1.9±0.6</td>
</tr>
<tr>
<td>Arc 1</td>
<td>0.41</td>
<td>0.43±0.04</td>
<td>0.41</td>
<td>0.32±0.05</td>
</tr>
<tr>
<td>Arc 2</td>
<td>0.26</td>
<td>0.50±0.10</td>
<td>0.23</td>
<td>0.31±0.10</td>
</tr>
<tr>
<td>Arc 3</td>
<td>0.22</td>
<td>0.63±0.05</td>
<td>0.21</td>
<td>0.72±0.07</td>
</tr>
<tr>
<td>Arc 4</td>
<td>0.21</td>
<td>0.81±0.07</td>
<td>0.24</td>
<td>0.65±0.10</td>
</tr>
<tr>
<td>Arc 5</td>
<td>0.33</td>
<td>--</td>
<td>0.25</td>
<td>--</td>
</tr>
<tr>
<td>Arc 6</td>
<td>0.58</td>
<td>0.48±0.05</td>
<td>0.31</td>
<td>0.66±0.04</td>
</tr>
<tr>
<td>Arc 8</td>
<td>1.21</td>
<td>1.1±0.1</td>
<td>0.57</td>
<td>1.0±0.1</td>
</tr>
<tr>
<td>Arc 9</td>
<td>2.09</td>
<td>3.1±0.2</td>
<td>0.64</td>
<td>1.9±0.3</td>
</tr>
<tr>
<td>Arc 10</td>
<td>2.97</td>
<td>2.4±0.3</td>
<td>0.95</td>
<td>1.7±0.4</td>
</tr>
</tbody>
</table>

Wire scanner not installed in Arc 7 in spring 2015; reinstall for fall 2015

Wire scanner in Arc 5 in disrepair, to be repaired summer 2015
Future Plans

• Fall 2015: Full CEBAF 12 GeV commissioning
  – Evaluation of full impact of SR on transverse emittances
  – Improved matching procedures
  – Investigate/compare beams for different halls/lasers
  – Investigate/measure/reduce systematic errors

• Longer term improvements
  – Parasitic emittance monitoring with sync light monitors
  – Wire scanners ➔ large dynamic range YAG viewers / CTR
  – Iteration of model-driven machine
    • Optics measurements with LOCO, rayTrace
CSR Suppression Experiment

• 12 GeV CEBAF is a natural CSR/ISR test bed
  – Yves Roblin heading LDRD project to evaluate feasibility

• Jefferson Lab MEIC concept
  – includes e-cooling from a high-power ERL (55 MeV, 200 mA)
  – recirculated beam quality critical: control CSR, $\mu$BI

• Leverage…
  – CSR emittance growth compensation lattice design
    • Recent ideas of diMitri/Cornacchia/Douglas/Borland

  – “High-current” gun (350 kV, 50-100 pC), compression to 0.5 ps
  – Extremes of ISR/CSR-driven emittance growth, energy spread

TUJB3 (F. Lin et al., MEIC)
TUPMA034 (D. Douglas et al., CSR/ISR Control)
MOPMA025 (C.-Y. Tsai et al., CSR uB Transients)
Conclusions

- 12 GeV CEBAF transverse emittance dominated by synchrotron radiation in higher-pass arcs
  - (Somewhat) mitigated with FODO ➔ DBA optics

- Optics matching and emittance program combined
  - Becoming efficient and mature
  - Excellent tool development

- Measurements, theory, simulations are consistent
  - Within factor of 2
  - 10.5 GeV data shows we are meeting program goals
  - Full 12 GeV commissioning in Fall 2015

- CSR mitigation experiments being developed
Thanks!

• Thank you to…
  – The CEBAF model team
  – The CEBAF beam transport “BTeam”
  – Yves Roblin, Dennis Turner, Arne Freyberger, Mike Spata, Mike Tiefenback, Alex Bogacz, Joe Grames, Chris Tennant, and REU student Charlie McIntyre (Reed College)
  – … and to you!