ER@CEBAF

A High-Energy, Multiple-Pass, Energy Recovery Experiment at CEBAF

On behalf of the JLab-BNL ER@CEBAF collaboration:


François Méot, Brookhaven National Laboratory
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1 CONTEXT OF THIS PROJECT

WEPMW027: “The ERL-based Design of Electron-Hadron-Collider eRHIC”
WEPMW044: “Start-to-End Simulation of eRHIC ERL”

1.1 eRHIC Electron-Ion Collider

• EIC is next high priority large facility in the 2015 DOE NP Long Range Plan
• BNL develops a linac-ring scheme - based on the existing RHIC collider, - and on a 20 GeV energy recovery linac.

<table>
<thead>
<tr>
<th>eRHIC EIC - in short</th>
</tr>
</thead>
<tbody>
<tr>
<td>Luminosity [/cm²/s]</td>
</tr>
<tr>
<td>Center-of-mass energy [GeV]</td>
</tr>
<tr>
<td>Species</td>
</tr>
<tr>
<td>Energy, max. [GeV, GeV/u]</td>
</tr>
<tr>
<td>Beam current, max. [mA]</td>
</tr>
<tr>
<td>Polarization [%]</td>
</tr>
</tbody>
</table>

Advantages of ERL method:

• high brightness e-bunches, undergo single collision, then ER’ed,
• high beam power with reduced RF drive power,
• yet - beam current on lower side, thus - SR power loss as well,
• low energy, low power beam dump,
• wall-plug efficiency (a necessity, given e-beams of 100s of MW).
1.2 Objective of ER@CEBAF: EIC R&D

- We want to do big, pioneering science:
  - multi-GeV, multiple-pass energy recovery

- Goal: perform a practical study of bunch phase space preservation

- Which - in passing - also means commissioning and operation of a large-scale superconducting recirculating linac in energy recovery mode

Further:

- Evaluate the limitations and ultimate performance, anticipate on difficulties in relation with eRHIC ERL R&D

- Anticipate on eRHIC ERL operation: provide guidance, learn, form people
## CEBAF 12 GeV RLA

<table>
<thead>
<tr>
<th>Parameters</th>
<th>CEBAF</th>
<th>eRHIC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy [GeV]</td>
<td>12</td>
<td>3.3 - 20</td>
</tr>
<tr>
<td>Beam current [mA]</td>
<td>$\lesssim 0.1$</td>
<td>26 - 50</td>
</tr>
<tr>
<td>Beam power [MW]</td>
<td>$\begin{cases} 1 \text{ (a)} \ \text{up to 400} \end{cases}$</td>
<td>$\begin{cases} 2.5 \text{ (a)} \ \text{up to 400} \end{cases}$</td>
</tr>
<tr>
<td>SR loss [MW]</td>
<td>0.008</td>
<td>2.5</td>
</tr>
<tr>
<td>Numb. of linacs</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>Linac energy [GeV]</td>
<td>1.09</td>
<td>1.67</td>
</tr>
<tr>
<td>Linac passes</td>
<td>$\leq 11$</td>
<td>$\leq 12$</td>
</tr>
</tbody>
</table>

**Bunch:**
- Bunch freq. [MHz]            | 31-1497 | 9.4    |
- ppb, max. $[10^{10}]$        | $10^{-4}$ | 1.7 - 3.3 |
- $rms \epsilon_{x,y,norm.} [\pi \mu m]$ | 3       | 10 - 70 |
- $rms$ length [mm]             | 0.09-0.15 | 3       |
- $rms \Delta E/E$             | $< 10^{-4}$ | $< 10^{-3}$ |

**Linac:**
- Length [m]                    | 250    | 176        |
- RF freq. [MHz]                | 1497   | 647        |
- Numb. of cavities/linac       | 200    | 80         |
- Cavity type                   | 5- & 7-cell | 5-cell     |
- Gradient [MV/m]               | 7 - 20 | 18         |

(a) Practical constraint
3 ENERGY RECOVERY AT JLAB

- CEBAF is the only installation that allows multiple-pass, multi-GeV ER.

- Other installations are limited
  - in energy
  - or in the number of passes

<table>
<thead>
<tr>
<th>Facilities</th>
<th>CEBAF-ER</th>
<th>JLab FEL</th>
<th>BINP</th>
<th>KEK</th>
</tr>
</thead>
<tbody>
<tr>
<td>Linac E [MeV]</td>
<td>1000</td>
<td>165</td>
<td>135</td>
<td>10</td>
</tr>
<tr>
<td>Numb. passes</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>4</td>
</tr>
<tr>
<td>ER’ed curr. [mA]</td>
<td>0.08</td>
<td>9</td>
<td>2.5</td>
<td>30</td>
</tr>
</tbody>
</table>

- JLab has a long expertise in design, commissioning, operation of multiple ERLs:
  - CEBAF Front-End Test (1992, 42.8 MeV, 31 µA CW beam, 100% ER’ed)
  - CEBAF-ER experiment (2003, 1 GeV, 80 µA, CW)
  - JLab FEL, since 1997 : IR Demo, IR Upgrade, UV FEL, Darklight
CEBAF-ER experiment, 2003

- It demonstrated 1-pass up/1-pass down, 1 GeV energy recovery, CW beam,

- Measurements included (at injector, arcs, dump) transverse emittances, momentum spread, halo. Included RF system response to ER.

[Details: C. Tennant, Studies of ERLs at Jefferson Laboratory, PhD Dissertation, JLab, 2006.]
• HIGH ENERGY: up to 7+ GeV

• MULTIPLE-PASS: 1 up + 1 down, 3 up + 3 down, 5 up + 5 down

• Experiments can start with 1-pass up/1-pass down (similar to 2003 CEBAF-ER), to test procedures, equipments, diagnostics, verify beam, etc.

• Then increase number of turns, up to 5 up/5 down, at low energy enough that SR does not harm (400~500 MV/linac)

• Then push energy to 7+ GeV

*Limitation momentum acceptance in Arc 1, $\frac{\Delta p}{p} \approx 2 - 3 \times 10^{-3}$ (beam up and beam down have different energies due to SR loss)*
4.1 Hardware modifications to CEBAF

- (1/2) Phase chicane at entrance of Arc 10 ($\delta l = \lambda/2$)
  - Design complete

‘Dogleg’ Chicane - Arc A Optics

A. Bogacz  
JLab

C. Dubbe  
JLab
(2/2) Extraction line and dump

- Design complete

Chicane and dump are both transparent to CEBAF Nuclear Physics program.

Leaving them in place will allow more, long-term, ER R&D
4.2 Dedicated optics

- (1/3) Linacs

  - Constraints:
    - limiting beta functions as energy increases
    - and along each linac pass (minimize $< \beta/E >_{\text{linac}}$)
  
- Optimal: $60^\circ$ FODO-like

Example: 750 MeV/pass

A. Bogacz - JLab
• (2/3) Spreaders/recombiners

- They ensure match between linacs and arcs.

- Arc sextupoles are not used in normal operation. They can be included for ER experiment if necessary (e.g., 2nd order path length, chromatic aberrations)
• (3/3) Longitudinal optics

• ISR will degrade the beam energy spread and cause energy loss;
  - this must be allowed for by the longitudinal match
  - phases and momentum compactions must be adjusted to insure that the beam stays within the machine momentum aperture during recovery:
    - energies must be matched during transport through corresponding recirculation arcs
    - energy spread must be compressed

• CEBAF transport system provides phase (path length) and compaction ($M_{56}$ trim) knobs providing appropriate controls
### Parameter list

#### MACHINE/LATTICE

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$f_{RF}$</td>
<td>1497 MHz</td>
<td>Standard CEBAF RF frequency</td>
</tr>
<tr>
<td>$\lambda_{RF}$</td>
<td>20 cm</td>
<td>Standard CEBAF RF wavelength</td>
</tr>
<tr>
<td>$E_{linac}$</td>
<td>700 MeV</td>
<td>Energy gain per linac pass</td>
</tr>
<tr>
<td>$E_{inj}$</td>
<td>79 MeV</td>
<td>$= E_{linac} \times 123/1090$</td>
</tr>
<tr>
<td>$N$ passes</td>
<td>1, 3, 5</td>
<td>Number of passes</td>
</tr>
<tr>
<td>$\phi$ FODO, linacs</td>
<td>60 deg</td>
<td>Phase advance per cell</td>
</tr>
<tr>
<td>$M_{56}$ (Arc A)</td>
<td>80-90 cm</td>
<td>M56 compression of Arc A</td>
</tr>
<tr>
<td>$M_{56}$ (other arcs)</td>
<td>0 cm</td>
<td>M56 compression of other arcs</td>
</tr>
<tr>
<td>Extraction angle</td>
<td>8 deg</td>
<td>Angle to dump line (3)</td>
</tr>
<tr>
<td>Dump power</td>
<td>20 kW</td>
<td>Max. ER’ed beam power</td>
</tr>
<tr>
<td>$\Delta \phi$ MOmod$^4$</td>
<td>0.25 deg</td>
<td>Pathlength control tolerance</td>
</tr>
</tbody>
</table>

1. Master Oscillator modulation feedback that provides pathlength/phase control for main RF. 0.1 degree with new electronics.

#### BEAM

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$f_{beam}$, CW</td>
<td>31 - 499 MHz</td>
<td>CW bunch repetition frequency</td>
</tr>
<tr>
<td>$f_{beam}$, tune (1)</td>
<td>7.485 MHz</td>
<td>Tune bunch repetition frequency</td>
</tr>
<tr>
<td>$I_{beam}$, max. CW</td>
<td>100 $\mu$A</td>
<td>Maximum CW beam current</td>
</tr>
<tr>
<td>$q_{bunch}$, max. CW</td>
<td>0.2 pC</td>
<td>Bunch charge at 100 $\mu$A CW</td>
</tr>
<tr>
<td>$\sigma_l$</td>
<td>90 - 150 $\mu$m</td>
<td>Bunch length (high energy)</td>
</tr>
<tr>
<td>$\sigma_t$</td>
<td>300 - 500 fs</td>
<td>Transverse $rms$, at injection</td>
</tr>
<tr>
<td>$\epsilon_{x,y}$ geom., inj.</td>
<td>$\sim 10^{-8}$ m</td>
<td>Energy spread at injector</td>
</tr>
<tr>
<td>$dp/p_{inj}$</td>
<td>??</td>
<td>ER’ed bunch, 5 pass up/down</td>
</tr>
<tr>
<td>$\epsilon_{x,y}$ geom., extr.</td>
<td>$O(10^{-8})$ m</td>
<td>Energy spread at extraction</td>
</tr>
</tbody>
</table>

1. Tune mode beam: \{250 $\mu$s macro-pulse filled, 100 $\mu$s off, 4 $\mu$s macro-pulse filled, then off\} repeating at 60 Hz (16.67 ms). 4 $\mu$s trailing pulse used for linac BPM orbits and linac arrival time cavities.
4.4 Measurements foreseen

- The ultimate goal of the measurements is, characterizing the bunch at all steps in the ER process all the way from injection to dump line: similar to 2003’s CEBAF-ER, in many more locations

- In particular, transverse emittances can be characterized at all energies (up, down) by extraction to Halls’ line, using RF separators

- Will study RF system response to ER regime

- A host of open topics:
  - Increase beam current beyond 0.1 mA. How far / what limitations?
  - 6D tomography at the dump
  ...

- Beyond EIC ER R&D, additional possibilities of experiments are contemplated:
  - BBU
  - halo
  - polarization transport to 12 GeV (SR effects, RF compensation)
  - multiple-beam diagnostics instrumentation
  ...
Red markers: previous demonstrations of ER
Green markers: ERLs in operation (2014)
[C. Tennant, Energy Recovery Linacs, in “Challenges and Goals for Accelerators in the XXI Century”, World scientif c]