CBETA, a 4-turn ERL with FFA arc

Georg Hoffstaetter (Cornell)
Cornell’s synchroton and storage ring CBET
Linacs produce very high bunch quality (narrow, short, low energy spread)

Remaining beam energy is discarded (wasted energy).
Energy Recovery, a Cornell Invention

A Possible Apparatus for Electron Clashing-Beam Experiments (*).

M. Tigner

Laboratory of Nuclear Studies, Cornell University - Ithaca, N. Y.

- Energy Recovery Linacs recapture the beam power in Super-Conducting (SRF) Accelerating structures to accelerate more beam.

- This energy saving allows for unprecedented beam powers from Linacs.

Georg.Hoffstaetter@cornell.edu - May 23, 2018 – DESY
Energy recovery needs continuous beams in SRF structures

- With focus on beam dynamic and SRF, Cornell has been an excellent place for ERL research.
Energy recovery needs continuous beams in SRF structures

- With focus on beam dynamic and SRF, Cornell has been an excellent place for ERL research.
By recovering the Energy of accelerated beams, Energy Recovery Linacs (ERLs) make large beam powers possible that would otherwise be prohibitively expensive.

Linacs produce high beam qualities for scientific experiments and for industrial applications, but their beam power is limited by the available electrical power.

ERLs surpass this power limit: much larger beam currents and beam powers become available because the beam energy is recaptured.

How do ERLs compare to other accelerators?

(a) high currents, like storage rings, because the energy is recovered,

(b) high beam quality (low emittance, bunch length, and energy spread) like linacs, because each bunch traverses it only once,

(c) tolerates beam disruption as each bunch is used only once before it’s discarded.

All these strengths of ERLs are beneficial to EIC cooling!
An ERL for LHeC (e-hadron collisions)
1.7 \times 10^{33} \text{ cm}^{-2} \text{ s}^{-1} \text{ for } \sqrt{s} = 127 \text{ GeV} \ (15.9 \text{ GeV} \text{ e} \uparrow \text{ on } 255 \text{ GeV} \text{ p} \uparrow)

- \times 10 \text{ luminosity with modest improvements (coating of RHIC vacuum chamber)}

- \times 100 \text{ luminosity with shorter bunch spacing (ultimate capability)}
Strong Hadron Cooling for EICs – Boosting the luminosity of JLEIC and eRHIC by at least a factor of 2; and the integrated luminosity even more!

Both JLEIC and eRHIC plan to cool the hadron beam with electrons.

Required beams, e.g. eRHIC pCDR:

Up to 100 mA CW electron beams at up to 150 MeV

Note: 15 MW !

CBETA parameters:
40 mA CW
150 MeV
Note: 6 MW !
Closest beam to an EIC cooler ever!
EIC cooling topics

1) ERL operation for high-power beams
   - Current limits (instabilities and component heating)
   - Startup scenarios
   - Simultaneous beam measurements

2) High-power beam propagation
   - Loss monitoring, component protection, and shielding
   - Intra-beam and rest-gas scattering
   - Beam halo dynamics and halo detection

3) High-brightness beam production
   - CW electron sources and space-charge dynamics
   - Dark currents

4) Low-emittance-growth beam propagation
   - High precision magnets
   - High precision beam dynamics control

Other ERL applications will benefit too
   - High-power FELs
   - Coherent light sources
   - Lithography for chip production
   - Compton backscattering sources
   - High energy colliders, e.g. LHeC
2005 Start of construction of DC photo-emitter gun; to world record current (75mA)


2013 Achieved world record brightness

2014 White paper for CBETA with collaborators at BNL.

2016 Construction funding by NYS begins.

2017 CBETA Design Report

2018 1st beam thorough SRF chain, one separator and one PMA unit.
• CBETA has 150MeV and up to 40mA: 6MW beampower
CBETA has 150MeV and up to 40mA: 6MW beampower

eRHIC cooler ERL has 150MeV and up to 100mA: up to 15mW
The beam power frontier

Home projects of collaborators who joint in recent CBETA running

Georg.Hoffstaetter@cornell.edu - May 23, 2018 – DESY
**2015 NSAC Long Range Plan**

**RECOMMENDATION III**

We recommend a high-energy, high-luminosity polarized Electron Ion Collider as the highest priority for new facility construction following the completion of FRIB.

*The EIC will, for the first time, precisely image gluons in nucleons and nuclei. It will definitively reveal the origin of the nucleon spin and will explore a new Quantum Chromodynamics (QCD) frontier of ultra-dense gluon fields, with the potential to discover a new form of gluon matter predicted to be common to all nuclei. This science will be made possible by the EIC’s unique capabilities for collisions of polarized electrons with polarized protons, polarized light ions, and heavy nuclei at high luminosity.*
CBETA topics to support eRHIC

CBETA study topics important for eRHIC:

1) **FFAG** loops with a factor of 4 in momentum aperture.
   a) Precision, reproducibility, alignment during magnet and girder production.
   b) Stability of magnetic fields in a radiation environment.
   c) Matching and correction of multiple simultaneous orbits.
   d) Matching and correction of multiple simultaneous optics.
   e) Path length control for all orbits.

2) Multi-turn ERL operation with a large number of turns.
   a) HOM damping.
   b) BBU limits.
   c) LLRF control and microphonics.
   d) ERL startup from low-power beam.
   e) Beam parameters of EIC electron coolers
The test ERL in Cornell’s hall LOE CBET

- Cornell DC gun
- 100mA, 6MeV SRF injector (ICM)
- 600kW beam dump
- 100mA, 6-cavity SRF CW Linac (MLC)

Electron Current up to 320mA in the linac
Bunch charge Q of up to 2nC
Bunch repetition rate 1.3GHz/N
Beams of 100mA for 1 turn and 40mA for 4 turns

Cornell-BNL ERL Test Accelerator

42, 78, 114, 150 MeV
Much equipment & infrastructure exists — 32 M$
Major new equipment: — 25 M$ new funding
- 2 splitters (electromagnets & tables)
- FFAF arc permanent magnets
- Diagnostics, power supplies etc.
High Current Beams

Simulations accurately reproduce photocathode performance with no free parameters, and suggest strategies for further improvement.

- Peak current of 75mA (world record)
- NaKSB photocathode
- High rep-rate laser
- DC-Voltage source

Source achievements:
- 2.6 day 1/e lifetime at 65mA
- 8h at 65mA
- With only 5W laser power (20W are available)
- now pushing to 100mA

✓ Source current can meet ERL needs
Normalized rms emittance (horizontal/vertical) 90% beam, E ~ 8 MeV, 2-3 ps
0.23/0.14 mm-mrad

Normalized rms core* emittance (horizontal/vertical) @ core fraction (%)
0.14/0.09 mm-mrad @ 68%
0.24/0.18 mm-mrad @ 61%

ArXiv: 1304.2708

✓ At 5 GeV this gives 20x the world’s highest brightness (Petra-III)
# Key Performance Parameters and Ultimate Performance Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>KPP</th>
<th>UPP (Stretch)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electron beam energy</td>
<td>MeV</td>
<td></td>
<td>150</td>
</tr>
<tr>
<td>Electron bunch charge</td>
<td>pC</td>
<td>123</td>
<td></td>
</tr>
<tr>
<td>Gun current</td>
<td>mA</td>
<td>1</td>
<td>40</td>
</tr>
<tr>
<td>Bunch repetition rate (gun)</td>
<td>MHz</td>
<td></td>
<td>325</td>
</tr>
<tr>
<td>RF frequency</td>
<td>MHz</td>
<td>1300</td>
<td>1300</td>
</tr>
<tr>
<td>Injector energy</td>
<td>MeV</td>
<td>6</td>
<td></td>
</tr>
<tr>
<td>RF operation mode</td>
<td></td>
<td>CW</td>
<td></td>
</tr>
<tr>
<td>Number of ERL turns</td>
<td></td>
<td>1</td>
<td>4</td>
</tr>
<tr>
<td>Energy aperture of arc</td>
<td></td>
<td>2</td>
<td>4</td>
</tr>
</tbody>
</table>
Bunche dynamics in 3D field maps
LOE contained approximately 7,000 square feet of Lab and Shop space
70% of the existing technical-use space was removed for the initial phase
LOE cleaned with CBETA
Installed: DC gun
Installed: DC gun, SRF injector
CBETA in its Hall L0E

Installed: DC gun, SRF injector, mirror diagnostics line
CBETA in its Hall L0E

Installed: DC gun, SRF injector, mirror diagnostics line, ERL cryomodule
Installed: DC gun, SRF injector, mirror diagnostics line, ERL cryomodule
1\textsuperscript{st} splitter of 8
Installed: DC gun, SRF injector, mirror diagnostics line, ERL cryomodule
1\textsuperscript{st} splitter of 8, 1\textsuperscript{st} Fixed Field Alternating-gradient (FFA) girder of 25.
Installation milestones

CERN COURIER

Small accelerator promises big returns

Under construction in the US, the CBETA multi-turn energy-recovery linac will pave the way for accelerators that combine the best of linear and circular machines.

The main linac cryomodule

CERN Courier is now available as a regular digital edition. Click here to read the digital edition.

KEY SUPPLIERS

HuihongFiber

More companies ▷

FEATURED COMPANIES

PHANTONIQ

Digital Edition

CERN Courier is now available as a regular digital edition. Click here to read the digital edition.
5 of 6 cavities had achieved design gradient of 16.2MV/m at 1.8K in MLC.
Cavity#4 is limited by quench so far, no detectable radiation during test.
Enough Voltage for 76MeV per ERL turn (where 36MeV are needed)
Main linac cryomodule (MLC) achieved surface losses ($Q_0$)

- 4 of 6 cavities had achieved design $Q_0$ of 2.0E+10 at 1.8K.
- $Q_0$ of Cavity#6 had severe FE at 16MV/m.
- Enough cooling for 73MV per ERL turn (where 36MeV are needed)
RF Detuning Measurements

Preliminary results:
- Stiffened cavities have ~30Hz detuning, Un-stiffened cavities have ~150Hz detuning.
- Design specs are ~20Hz.
- Detuning spectrum showed large peaks at 60 Hz, 120 Hz.
- Enough Voltage for about 50MeV per ERL turn, if microphonics is not reduced (where 36MeV are needed)
Algorithm is stable! Reduced peak detuning from 30.2Hz to 15.5Hz.

Georg.Hoffstaetter@cornell.edu - May 23, 2018 – DESY
Dipole HOMs on MLC were strongly damped below $Q \sim 10^4$. Consistent with HTC and simulation results.

HTC results were:
• HOM heating: currents are limited to < 40mA in CBETA
• BBU no HOM limits BBU to below 100mA in one turn
Beam break up: a potential limit to ERL currents

Higher Order Modes

\[ V_x(t) = T_{12} \frac{e}{c} \int_{-\infty}^{t} W_x(t - t') V_x(t' - t_r) I(t') dt' \]
Recall... \[ I_{\text{threshold}} \propto \frac{1}{Q_{\text{HOM}}} \]

- Damping circuit easily reduced the Q of the 2106 MHz mode by a factor of 5
  
  *(Above a factor of about 10, the system becomes sensitive to external disturbances)*

- The threshold is increased accordingly: from 2 mA to \(~10\) mA

Magnitude vs. Frequency

Inverse \( Q_{\text{eff}} \) vs. Average Beam Current (mA)
BBU for 1 pass in CBETA

CBETA 1-pass
Cavity shape error: 125 μm

100% of simulations have $I_{th} > 100$ mA
BBU for 4 passes in CBETA

CBETA 4-pass
Cavity shape error: 125 μm
x/y coupling is simulated to increase the threshold significantly

100% of simulations have $I_{th} > 100mA$
86% of simulations have $I_{th} > 40mA$
1-pass ERL with variable phases

$I_{th}$ results can improve significantly

Min = 140 mA
Max = 611 mA
nominal = 342 mA
1-pass ERL with x/y coupling

$I_{th}$ results can improve significantly

Min = 140 mA
Max = 520 mA
nominal = 342 mA
4-path ERL with variable phases

\[ I_{th} \]

Min = 61 mA
Max = 193 mA
Nominal = 69 mA

results can improve
4-path ERL with x/y coupling

$I_{th}$ results can improve

Min = 89 mA
Max = 131 mA
Nominal = 69 mA

**Conclusion:** In 1-path ERLs the benefit from coupling and phase optimization can be significant. In multi-turn ERLs this benefit is much diminished.
Next-order BBU

Don’t forget that there is

(A) Transverse Dipole BBU that is often considered and there are good codes

(B) Longitudinal BBU
- contained in the BMAD simulation code
- It is important because they excite monopole (accelerating) modes with very large Q
- Is minimized by T56=0 for all cavity couplings
- Phase and time-of-flight tricks need to be checked against this instability.

(C) Quadrupole BBU
- Is important because the frequencies of the lowest order Quadrupole modes are below the first higher order dipole modes. Their Q can therefore be extremely large.

(D) Higher-order multipole BBU: Check out the simple scaling formulas in [1]
- Is usually benign if (C) is ok. But it can be important for similar reasons at (C).

Path length: 1-pass ERL

\[ T_1 \cdot f_{rf} = 343 - 0.5 \]
Path length: 2-pass ERL

$T_2 \cdot f_{rf} = 343 - 0.5$

$T_1 \cdot f_{rf} = 343$

Harmonics:
Path length: 3-pass ERL

Harmonics:

\[ T_3 \cdot f_{rf} = 343 - 0.5 \]
\[ T_2 \cdot f_{rf} = 343 \]
\[ T_1 \cdot f_{rf} = 343 \]
Path length: 4-pass ERL

Harmonics:

\[ T_4 \cdot f_{rf} = 343 + 1.5 \]
\[ T_3 \cdot f_{rf} = 343 \]
\[ T_2 \cdot f_{rf} = 343 \]
\[ T_1 \cdot f_{rf} = 343 \]
Orbit Correction of 4 Beams
12 **proof-of-principle magnets** (6 QF, 6 BD) have been built as part of CBETA R&D.

Iron wire shimming has been done on 3 QFs and 6 BDs with good results.
Individual Multipole limits (for < 10% emittance and beam-size growth)

<table>
<thead>
<tr>
<th>b2</th>
<th>37</th>
<th>a2</th>
<th>140</th>
</tr>
</thead>
<tbody>
<tr>
<td>b3</td>
<td>30</td>
<td>a3</td>
<td>90</td>
</tr>
<tr>
<td>b4</td>
<td>26</td>
<td>a4</td>
<td>80</td>
</tr>
<tr>
<td>b5</td>
<td>21</td>
<td>a5</td>
<td>65</td>
</tr>
<tr>
<td>b6</td>
<td>21</td>
<td>a6</td>
<td>63</td>
</tr>
<tr>
<td>b7</td>
<td>19</td>
<td>a7</td>
<td>58</td>
</tr>
<tr>
<td>b8</td>
<td>21</td>
<td>a8</td>
<td>56</td>
</tr>
<tr>
<td>b9</td>
<td>18</td>
<td>a9</td>
<td>53</td>
</tr>
</tbody>
</table>

\[
B_x + iB_y = \frac{b_n + ia_n}{L} (x + iy)^n
\]

\[
b_n = 10^{-4} \frac{GL}{r_0^{n-1}} w_0
\]

Multipole limits:
For < 10% emittance and beam-size growth

\[
\sqrt{\sum_n \left( \frac{b_n}{\text{lim}_{n} b_n} \right)^2 + \left( \frac{a_n}{\text{lim}_{n} a_n} \right)^2} < 0.75
\]
Iron Wire Shimming Improvement

All multipoles of the Halbach magnets can be corrected as required.
First Girder Construction
International interest in CBETA

We are forming a collaboration interested in ERLs for EICs, e.g. coolers.

As a first step, collaborators from 4 labs are participating in the current commissioning run: 3 from HZB/Germany, 2 from Darebury/UK, 3 from JLAB, 5 CBETA members from BNL.
April 18: Beam through the fractional arc!

- Cornell DC gun
- 100mA, 6MeV SRF injector (ICM)
- 600kW beam dump
- 100mA, 6-cavity SRF CW Linac (MLC)

Electron Current up to 320mA in the linac
Bunch charge Q of up to 2nC
Bunch repetition rate 1.3GHz/N
Beams of 100mA for 1 turn and 40mA for 4 turns

Cornell-BNL ERL Test Accelerator

42, 78, 114, 150 MeV

Georg.Hoffstaetter@cornell.edu - May 23, 2018 – DESY
<table>
<thead>
<tr>
<th>#</th>
<th><strong>Milestone</strong> (at the end of months)</th>
<th>Baseline</th>
<th>Actual</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Funding start date</td>
<td></td>
<td>Oct-16</td>
</tr>
<tr>
<td>2</td>
<td>Engineering design documentation complete</td>
<td>Jan-17</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>Prototype girder assembled</td>
<td>Apr-17</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>Magnet production approved</td>
<td>Jun-17</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td><strong>Beam through Main Linac Cryomodule</strong></td>
<td>Aug-17</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>First production hybrid magnet tested</td>
<td>Dec-17</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td><strong>Fractional Arc Test: beam through MLC &amp; girder</strong></td>
<td>Apr-18</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>Girder production run complete</td>
<td>Nov-18</td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>Final assembly &amp; pre-beam commissioning complete</td>
<td>Feb-19</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td><strong>Single pass beam with factor of 2 energy scan</strong></td>
<td>Jun-19</td>
<td></td>
</tr>
<tr>
<td>11</td>
<td><strong>Single pass beam with energy recovery</strong></td>
<td>Oct-19</td>
<td></td>
</tr>
<tr>
<td>12</td>
<td>Four pass beam with energy recovery (low current)</td>
<td>Dec-19</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Project complete</td>
<td>Apr-20</td>
<td></td>
</tr>
</tbody>
</table>
Beam Commissioning

2016

June 2017

August 2019: 1-turn

April 2018: FAT

Push toward 4-turn ERL until April 2020

Georg.Hoffstaetter@cornell.edu - May 23, 2018 – DESY
• Continued commissioning for EIC studies (including electron cooling)
• DarkLight – an experiment to find dark matter particles
• Compact Compton source for hard x-rays – complementing CHESS’ range
• THz laser – complementing CHESS’ range
• Beam for time-resolved electron diffraction from 1-6MeV
• Beam for Plasma Wakefield Acceleration with High Transformer Ratio
• ASML medical isotope cavity testing with beam
• Generic ERL accelerator physics
• Preparations for Perle
• Preparations for LHeC
• High-Power beam dynamics testing
• Permanent magnet and Fixed-Field Alternating-Gradient test bed for future accelerators
If EIC R&D would not come …

- DarkLight – **an experiment to find dark matter particles**

![Diagram of the Darklight detector at JLAB](image)
The Darklight detector will fit around the resonantly extracted CBETA beam, if the movable support is redesigned. Cornell is in contact with the DarkLight collaboration to submit a joint proposal.
Layout of extraction beam line

Extraction line contains:
Extra dipoles to guide the beam
Extra quadrupoles to maintain beam optics
CBB is an NSF funded Science and Technology Center (for 5 years, extendable to 10 years)

CBB Vision:
Better particle beams for applications ranging from giant colliders to table top electron microscopes enabling new opportunities for science and industry.

CBB Mission:
Transform the reach of electron beams by increasing their brightness x100 and reducing the cost and size of key enabling technologies. Transfer the best of these technologies to national labs and industry.
Questions?