CBETA, the 4-Turn SRF ERL with Single Return Loop

IPAC18, 1 May 2018

Georg Hoffstaetter (Cornell)

For the CBETA-collaboration team
Energy recovery needs continuously fields in the RF structure

- Normal conducting high field cavities can get too hot.
- Superconducting cavities used to have too low fields.
Energy recovery needs continuously fields in the RF structure

- Normal conducting high field cavities can get too hot.
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The Regime of ERLs

ERLs store the energy in SRF cavities, but they do not the beam.

They can have

(a) **high currents**, like storage rings, b/c the energy is recovered,
(b) **high beam quality** (low emittance, bunch length, and energy spread) like linacs, b/c each bunch traverses it only once,
(c) **higher luminosity** than ring colliders, b/c bunches can be damaged more by the beam beam force.

Their current is not limited by the available power, as in linacs, but by
(a) HOM heating
(b) HOM-driven Beam-Brakeup Instability
Strong Hadron Cooling for EICs

Both EIC projects, the one at BNL and the one at JLAB, plan to cool the hadron beam with electrons.

Required beams:

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

**Note:** **15MW**!
Advantageous over an electron ring in the LHC tunnel:

- Less downtime of the LHC rings
- Less damage to electrons from the beam beam force => more luminosity
- Less synchrotron radiation than a ring on the same track.
2005 Start of construction of DC photo-emitter gun; to 75mA.

2006 Start of construction of Injector Cryo-Module (ICM); to 500kW CW.

2009 Start of commissioning of ERL injector; to 0.3 micron for bunch charges of 100mA beam.


2014 White paper for CBETA with collaborators at BNL.

2016 Secured funding by NYS.

2017/05 1st beam through SRF

2017/06 DR for CBETA as 4-turn SRF ERL and permanent magnet array (PMA) with Halbachs.

2018 1st beam thorough SRF chain, one separator and one PMA unit.

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CBETA has 150MeV and up to 40mA: 6MW beampower
• 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

42, 78, 114, 150 MeV
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
L0E cleaned with CBETA
Installed: DC gun
CBETA in its Hall L0E

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

Installed: DC gun, SRF injector, mirror diagnostics line, ERL cryomodule

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

- 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

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

✓ Source current can meet ERL needs
Beam Brightness

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%

At 5 GeV this gives 20x the world’s highest brightness (Petra-III)

ArXiv: 1304.2708
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 (Q0)

- 4 of 6 cavities had achieved design Q0 of 2.0E+10 at 1.8K.
- Q0 of Cavity#6 had severe FE at 16MV/m.
- Enough cooling for 73MV per ERL turn (where 36MeV are needed)

Readout 15 May 2018

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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 by about a factor of 2.
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.
Multipole tolerances in the FFAG

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>

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

\[ b_n = \left[ 10^{-4} \frac{GL}{r_0^{n-1}} \right] u_0 \]

Multipole limits:

For <10% emittance and beam-size growth

\[ \sqrt{\sum_n \left( \frac{b_n}{\lim b_n} \right)^2 + \left( \frac{a_n}{\lim a_n} \right)^2} < 0.75 \]
All multipoles of the Halbach magnets can be corrected as required.
First Girder Construction
<table>
<thead>
<tr>
<th>#</th>
<th>Milestone (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>
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<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>
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<tr>
<td>5</td>
<td>Beam through Main Linac Cryomodule</td>
<td>Aug-17</td>
<td></td>
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<tr>
<td>6</td>
<td>First production hybrid magnet tested</td>
<td>Dec-17</td>
<td></td>
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<tr>
<td>7</td>
<td>Fractional Arc Test: beam through MLC &amp; girder</td>
<td>Apr-18</td>
<td></td>
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<tr>
<td>8</td>
<td>Girder production run complete</td>
<td>Nov-18</td>
<td></td>
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<tr>
<td>9</td>
<td>Final assembly &amp; pre-beam commissioning complete</td>
<td>Feb-19</td>
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<tr>
<td>10</td>
<td>Single pass beam with factor of 2 energy scan</td>
<td>Jun-19</td>
<td></td>
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<tr>
<td>11</td>
<td>Single pass beam with energy recovery</td>
<td>Oct-19</td>
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<td>12</td>
<td>Four pass beam with energy recovery (low current)</td>
<td>Dec-19</td>
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<tr>
<td></td>
<td>Project complete</td>
<td>Apr-20</td>
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Interest in commissioning

We are forming a collaboration interested in CBETA or generic ERL research.

As a first step, visitors from 4 labs are participating in the current commissioning run: 3 from HZB/Germany, 2 from Darebury/UK, 3 from JLAB, 5 from BNL.

1st set of international visitors for Commissioning (r to l): D. Kelliher & J. Jones (Daresbury), B. Kuske & J. Völker (HZB).

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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

42, 78, 114, 150 MeV
Dipole HOMs on MLC were strongly damped below $\mathcal{Q} \sim 10^4$. 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
New current limit

Beam break up: a potential limit to ERL currents

Higher Order Modes

\[ V_x(t) = T_{12} \frac{e}{c} \int_{-\infty}^{t} W_x(t - t')V_x(t' - t_r)I(t')dt' \]
BBU for 1 pass in CBETA

CBETA 1-pass
Cavity shape error: 125 μm

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

CBETA 4-pass
Cavity shape error: $125 \, \mu m$

x/y coupling is simulated to increase the threshold significantly

100\% of simulations have $I_{th} > 100mA$

86\% of simulations have $I_{th} > 40mA$
4-path ERL with variable phases

\[ I_{th} \]

\[ \begin{align*}
\text{Min} &= 61 \text{ mA} \\
\text{Max} &= 193 \text{ mA} \\
\text{Nominal} &= 69 \text{ mA}
\end{align*} \]

\[ I_{th} \text{ results can improve} \]
4-path ERL with x/y coupling

Results can improve

$\min = 89 \text{ mA}$
$\max = 131 \text{ mA}$
$\text{Nominal} = 69 \text{ mA}$

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

2016
Beam Commissioning

2016

June 2017
Beam Commissioning

2016

June 2017

April 2018: FAT

Push toward 4-tunr ERL until April 2020

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Beam Commissioning

2016

June 2017

August 2019: 1-turn

April 2018: FAT

Push toward 4-turn ERL until April 2020

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Questions?