CBETA, a 4-turn ERL with FFAG arc

FFAG workshop 09/08/2017

Georg Hoffstaetter (Cornell)
Cornell’s synchrotron and storage ring CBET

Cornell Laboratory for Accelerator-based Sciences and Education (CLASSE)
1932: Brasch and Lange use potential from lightening, in the Swiss Alps, Lange is fatally electrocuted

1934: Livingston builds the first Cyclotron away from Berkely (2MeV protons) at Cornell (in room B54)

1949: Wilson et al. at Cornell are first to store beam in a synchtotron (later 300MeV, magnet of 80 Tons)

1954: Wilson et al. build first synchrotron with strong focusing for 1.1GeV electrons at Cornell, 4cm beam pipe height, only 16 Tons of magnets.

1979: 5GeV electron positron collider CESR (designed for 8GeV)

Currently:
- CESR operation and optimization for the CLEO experiment
- CESR operation and optimization for CHESS
- ERL prototyping facility (ERL e-source and injector linac)
- ERL and CESR upgrade to an ERL
- ILC design, simulations, damping ring studies with CESR
Cornell accelerators:

Cornell is a world leader in accelerators
Superconducting acceleration.
Bright electron sources. World record high current, low emittance.
Multi-turn FFAG ERL. A new accelerator paradigm.

Cornell’s academic program in accelerator science is the strongest in the U.S.
Most faculty, most PhD’s, most high-impact accomplishments.
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.
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.
1.7 \times 10^{33} \text{ cm}^{-2} \text{ s}^{-1} \text{ for } \sqrt{s} = 127 \text{ GeV} (15.9 \text{ GeV} e \uparrow \text{ on } 255 \text{ GeV} p \uparrow )

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

\times 100 \text{ luminosity with shorter bunch spacing (ultimate capability)}
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.
80% polarized electrons: 6.6 – 21.2 GeV

Center-of-mass energy range: 30 – 145 GeV
Full electron polarization at all energies
Full proton and He-3 polarization with six Siberian snakes
Any polarization direction in electron-hadron collisions:

Luminosity: $10^{33} – 10^{34}$ cm$^{-2}$ s$^{-1}$

Light ions (d, Si, Cu)
Heavy ions (Au, U)
10 - 100 (110*) GeV/u
Pol. light ions (He-3)
17 - 167 (184*) GeV/u
The baseline design of eRHIC has been a linac-ring collider to boost the luminosity to into the $10^{34}$ regime, based on a 12-turn ERL with 2 permanent magnet FFAG return loops.

About 6 months ago the baseline design changed to a ring-ring collider. Luminosities in the region $10^{33}$ to $10^{34}$ regime are possible, depending on details. To provide all helicity combinations for collisions, a recirculating linac injector is chosen. 12-turn recirculation with 2 FFAG return loops is a cost-saving option.

If polarization can survive acceleration in a spin-optimized rapid cycling synchrotron, a ring as injector would be a cost-saving alternative. As an option for electron cooling, an ERL is then still an important topic of study.
eRHIC uses two FFAG beamlines to do multiple recirculations. (FFAG-I: 1.7-5.0 GeV, FFAG-II: 6.7-18.3 GeV, 20 GeV)

- All sections of a FFAG beamline is formed using a same FODO cell. Required bending in different sections is arranged by proper selection of the offsets between cell magnets (or, alternatively, with dipole field correctors).

- Permanent magnets can be used for the FFAG beamline magnets (no need for power supplies/cables and cooling)

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Each of two eRHIC FFAGs contain 1066 FFAG cells
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.
The test ERL in Cornell’s hall LOE

- 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
The test ERL in Cornell’s hall LOE

- Cornell DC gun
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- 600 kW beam dump
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Existing components at Cornell

Electron Current: up to 320 mA in the linac
Bunch charge Q: up to 2 nC
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Beams of 100 mA for 1 turn and 40 mA for 4 turns

Cornell-BNL ERL Test Accelerator

42, 78, 114, 150 MeV

Construction start: October 2016
• DC photo-emitter electron source with highest current (75mA)
• SRF injector linac with up to 0.5MW, 12MeV, larges bunch brightness for high current
• Full 6-D beam diagnostics for low-emittance studies.
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%

0.51/0.29 mm-mrad

0.24/0.18 mm-mrad @ 61%

ArXiv: 1304.2708

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

Georg.Hoffstaetter@cornell.edu - September 8, 2017 – FFAG workshop, Cornell
MLC construction at Cornell

- 1.3GHz, 6 cavities, 7 cells, a SiC beampipe HOM absorber next to each cavity.
- 5 kW solid-state amplifiers for each coupler (capable of 10kW)
### Key Performance Parameters and Ultimate Performance Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>KPP</th>
<th>UPP (Stretch)</th>
</tr>
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<tbody>
<tr>
<td>Electron beam energy</td>
<td>MeV</td>
<td></td>
<td>150</td>
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<tr>
<td>Electron bunch charge</td>
<td>pC</td>
<td>123</td>
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<tr>
<td>Gun current</td>
<td>mA</td>
<td>1</td>
<td>40</td>
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<tr>
<td>Bunch repetition rate (gun)</td>
<td>MHz</td>
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<tr>
<td>RF frequency</td>
<td>MHz</td>
<td>1300</td>
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<tr>
<td>Injector energy</td>
<td>MeV</td>
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<tr>
<td>RF operation mode</td>
<td></td>
<td></td>
<td>CW</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>
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</tbody>
</table>
Background for CDR

Wrote PDDR for hard X-ray ERL at Cornell in 2012.

Start of CBETA July 2014 White paper December 2014

Defined CBETA in a white paper in December 2014.

CDR for CBETA in with Hybrid permanent magnets in July 2016.

Secured funding October 2016

Passed design and finance review, January 2017

DR for CBETA with Halbach magnets in February 2017

Prototype FFAG girder, April 2017

1st beam through MLC, May 2017
Existing & new equipment

Much equipment & infrastructure exists — 32 M$

Major new equipment: — 25 M$ new funding

- 2 splitters (electromagnets & tables)
- FFAG arc permanent magnets
- Diagnostics, power supplies etc.
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
The gun and ICM were tested with beam
LOE with space for the return loop

Before and After of the Vacuum Lab in Wilson Laboratory
2019 Layout
Bunche dynamics in 3D field maps
RF sources
Main linac cryomodule (MLC) achieved accelerating gradients

- 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)
5 kW RF power gives sufficient overhead for 8MV/m cavity operation with up to 90 Hz peak detuning (50 Hz if $Q_L$ is not adjusted)
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)
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
Current limits from HOMs

Algorithm is stable! Reduced peak detuning from 30.2Hz to 15.5Hz.
Girder Types and Positions

Integrated H2O manifold
Flexible component mounting

Cable tray
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.
Iron Wire Shimming Improvement

Factor of ~4 reduction regardless of starting value

2nd iteration improved further in previous R&D:
29.62 → 6.69 → 1.94
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>
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<tr>
<td>b3</td>
<td>30</td>
<td>a3</td>
<td>90</td>
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<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>
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<td>b7</td>
<td>19</td>
<td>a7</td>
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<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>

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

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

Multipole limits:

For < 10% emittance and beam-size growth

\[
\sqrt{\sum_n \left(\frac{b_n}{\text{lim}_{n} b_n}\right)^2 + \left(\frac{a_n}{\text{lim}_{n} a_n}\right)^2} < 0.75
\]
First Girder Construction
Beam through accelerator test

- 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
FFAG test with beam

Scaled down Halbach FFAG with beam at BNL’s ATF

Courtesy Stephen Brooks
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1<sup>st</sup> beam through MLC, May 2017
The path is free for CBETA

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

2016

June 2017

August 2019: 1-turn

April 2018: FAT

Push toward 4-turn ERL until April 2020
Preparations for the FAT

- Tables are designed.
- Dipoles and Quadrupoles are ordered, power supplies are ordered.
- Common magnets are designed and about to be ordered.
- All but one FFAG quad are built.
- Space is nearly cleared out.
- Much infrastructure preparation remains, e.g. wholes in the east wall and placement of beam stop and FFAG table.
- The next major milestone April 30 seems achievable.
Questions?