Low Energy RHIC electron Cooling (LEReC) Project Status

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for the LEReC team
Electron cooling studies for RHIC

- For high energies (from a few to several tens of MeV) RF-based acceleration and bunched electron beam cooling appears to be an attractive approach.

- **Past:** RHIC-II (feasibility study 2001-07): Detailed study was performed for 55 MeV electron cooler. Various aspects of both magnetized and non-magnetized cooling approaches were studied.

- **Future:** eRHIC (under consideration): Various stages and configurations require some sort of high-energy cooling.

- **Present:** LEReC (under construction): Although required energies of electron beam (few MeV) are not very high, an approach based on RF acceleration of electron beams was chosen. As such, it is also a prototype of high-energy cooler.
The purpose of the LEReC is to provide luminosity improvement for RHIC operation at low energies to search for the QCD critical point (Beam Energy Scan Phase-II physics program).

LEReC will be RF linac-based electron cooler (bunched beam cooling).

To provide luminosity improvement with such approach requires:

- Building and commissioning of new state of the art electron accelerator
- Produce electron beam with beam quality suitable for cooling
- Transport with RF acceleration maintaining required beam quality
- Commissioning of bunched beam electron cooling
- Commissioning of electron cooling in a collider
3D LEReC layout in RHIC tunnel at Interaction Region @ 2 o’clock (IR2)

- Injection Section
  - (DC photocathode Gun, SRF Booster cavity and test beamline)

- Transport beamline

- Cooling sections

- Laser

- Laser transport beamline
# LEReC electron beam parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Requirement 1</th>
<th>Requirement 2</th>
<th>Requirement 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kinetic energy, MeV</td>
<td>1.6*</td>
<td>2</td>
<td>2.6</td>
</tr>
<tr>
<td>Cooling section length, m</td>
<td>20</td>
<td>20</td>
<td>20</td>
</tr>
<tr>
<td>Electron bunch (704 MHz) charge, pC</td>
<td>130</td>
<td>170</td>
<td>200</td>
</tr>
<tr>
<td>Effective charge used for cooling</td>
<td>100</td>
<td>130</td>
<td>150</td>
</tr>
<tr>
<td>Bunches per macrobunch (9 MHz)</td>
<td>30</td>
<td>30</td>
<td>24-30</td>
</tr>
<tr>
<td>Charge in macrobunch, nC</td>
<td>4</td>
<td>5</td>
<td>5-6</td>
</tr>
<tr>
<td>RMS normalized emittance, um</td>
<td>&lt; 2.5</td>
<td>&lt; 2.5</td>
<td>&lt; 2.5</td>
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<tr>
<td>Average current, mA</td>
<td>36</td>
<td>47</td>
<td>45-55</td>
</tr>
<tr>
<td>RMS energy spread</td>
<td>&lt; 5e-4</td>
<td>&lt; 5e-4</td>
<td>&lt; 5e-4</td>
</tr>
<tr>
<td>RMS angular spread</td>
<td>&lt;150 urad</td>
<td>&lt;150 urad</td>
<td>&lt;150 urad</td>
</tr>
</tbody>
</table>

*CW mode at 704 MHz without macrobunches is also being considered (with even higher average current up to 85 mA)
LEReC: un-magnetized electron cooling

Un-magnetized cooling:
very strong dependence on relative angles between electrons and ions.

Requires strict control of both transverse angular spread and energy spread of electrons in the cooling section.

This will be the first cooling without any magnetization.

Un-magnetized friction force:

\[ \vec{F} = -\frac{4\pi n_e e^4 Z^2}{m} \int \ln \left( \frac{\rho_{\text{max}}}{\rho_{\text{min}}} \right) \frac{\vec{V} - \vec{v}_e}{|\vec{V} - \vec{v}_e|^3} f(v_e) d^3 v_e \]

asympotic for \( v_{\text{ion}} < \Delta_e \):

\[ \vec{F} = -\frac{4\pi Z^2 e^4 n_e L}{m \Delta_e^3} \vec{v}_i \]

\[ \vec{F} = -\frac{4\pi Z^2 e^4 n_e L}{m} \frac{\vec{v}_i}{\beta^3 c^3 (\gamma\theta)^2 + \sigma_p^2}^{3/2} \]

Requirement on electron angles:
For \( \gamma=4.1 \): \( \sigma_p=5\times10^{-4} \); \( \theta<150 \text{ \mu rad} \)
Bunched beam electron cooling for LEReC

• Produce electron bunches suitable for cooling by illuminating a multi-alkali (CsK₂Sb or NaK₂Sb) photocathode inside the Gun with green light using high-power laser (high-brightness in 3D: both emittance and energy spread).

• The 704 MHz fiber laser will produce bunch trains with individual electron bunches of about 80 ps full length.

• Accelerate such bunches with RF and maintain beam quality.

• Deliver and maintain beam quality in cooling sections.

• Electron bunch overlaps only small portion of ion bunch. All amplitudes are being cooled as a result of synchrotron oscillations.
LEReC beam structure in cooling section
Example for $\gamma = 4.1$ ($E_{ke} = 1.6$ MeV)

**Ions structure:**
- 120 bunches
- $f_{rep} = 120 \times 75.8347$ kHz = 9.1 MHz
- $N_{ion} = 5 \times 10^8$, $I_{peak} = 0.24$ A
- Rms length = 3.2 m

**Electrons:**
- $f_{SRF} = 703.5$ MHz
- $Q_e = 100$ pC, $I_{peak} = 0.4$ A
- Rms length = 3 cm

9 MHz bunch structure

Electron Macro-bunch

Ion bunch

30 electron bunches per ion bunch

1.42 nsec

110 nsec, $f = 9$ MHz
RF gymnastics

• The 704 MHz SRF booster cavity will not only accelerate the electrons but also introduce an energy chirp which causes ballistic stretching of the bunch as it drifts through the transport beam line.

• Additional 704 MHz warm cavity removes the energy chirp before electron and ion beams are merged in the cooling section.

• Warm cavity operating at 2.1 GHz (3rd harmonic of 704 MHz, located next to the SRF booster) removes the curvature of the bunch shape in longitudinal phase space.

• 9 MHz warm RF cavity is being employed to remove bunch-by-bunch energy variation within the 30 bunch train (macro-bunch) caused by beam loading in the RF cavities.
COOLING in Blue RHIC ring

COOLING in Yellow RHIC ring

180° Bending Magnet

20° Bending Magnets

High-Power Beam Dump

RF Diagnostic Beamline

Merger Beamline

Transport Beamline

DC Gun Beamline

704 MHz Cu Cavity

9 MHz Cu Cavity

45° Bending Magnets

704 MHz SRF Booster Cavity

2.1 GHz Cu Cavity

Cathode loading system

704 MHz Cu Deflector Cavity

45° Bending Magnet

RF Diagnostic

Beamline

BPM 2.4 ID

BPM 4.8 ID

Bellows

Ion pump

Quad corrector

Trim corrector

Corrector 3.8 ID

Corrector 6.0 ID

* NOT to scale
Electron beam transport

The use of RF-based approach requires careful considerations:
Beam transport of electron bunches without significant degradation of beam emittance and energy spread, especially at low energies.

Impedance and wakefields from beam transport elements:
Accurate simulations of the wake fields including diagnostics elements showed that electron beam is very sensitive to the wake fields. Many instrumentation devices were redesigned to minimize effect of the wake fields. The dominant contribution comes from the RF cavities. The 704 MHz and 2.1GHz warm RF cavities had to be redesigned to minimize effects of the HOMs.

Longitudinal space charge:
Requires stretching electron beam bunches to keep energy spread growth to an acceptable level. Warm RF cavities are used for energy spread correction.

Transverse space charge:
Correction solenoids in the cooling section are used to keep transverse angular spread to a required level.

Strict control of electron angles in cooling sections:
Cooling sections are covered by several layers of Mu-metal shielding.
We found that these effects are most difficult to control < 2 MeV.
Production of bunched electron beam suitable for cooling

- LEReC is based on the State of the Art physics and technology:
  - Photocathodes: both production and delivery system to support 24/7 operation at high current
  - High power fiber laser
  - Laser beam shaping
  - Operation of HV DC gun (400-500kV) with high charge and high average current
  - RF gymnastics and stability control

Most of this expertise is directly applicable to EIC.
LEReC Critical Technical Systems

1. DC photocathode electron gun and HV PS.
2. High-power fiber laser system and transport
3. Cathode production deposition and delivery systems
4. SRF Booster cavity
5. 2.1 GHz and 704 MHz warm RF cavities
LEReC accelerator (100 meters of beamlines with the DC Gun, 5 RF systems, many magnets and instrumentation devices)

63.9 m to IP2

* NOT to scale

EIC Collaboration Meeting, BNL, October 10-12, 2017
LEReC Injection section (zoom in), 2018

- Beam Dump
- Halo Monitors
- Profile Monitor
- BPM
- Quadrupole
- Solenoid
- H/V Corrector
- DCCT & ICT
- Emittance Slit
- BPM
- 2.1 GHz Cavity
- e-beam direction
- 704 MHz SRF Cavity
- 7 m

Cathode Insertion
Cathode Suitcase
DC e⁻ Gun

BROOKHAVEN NATIONAL LABORATORY

Office of Science
U.S. DEPARTMENT OF ENERGY

EIC Collaboration Meeting, BNL, October 10-12, 2017
Gun Test setup 2017
(no RF components in beam line)

2.1 GHz warm cavity:
The cavity was installed outside of beamline to decouple its commissioning from the DC gun commissioning.

7 m
LEReC Gun Test beamline under construction (November 2016)
LEReC DC Gun test beamline
(installation complete in RHIC IR2, February 2017)

Cathode insertion system

Gun transport section

Transport beamline

Extraction line and beam dump
First photocurrent (DC) observed (April 18, 2017)

- Photo cathode visible light image before installation
- Cathode camera image with LED lamp on
- Photocurrent image result of LED (beam profile monitor)

Diagram showing the layout of the equipment with labels for Profile monitor/FC, BPMs, Solenoids, XY Correctors, and cathode.
Pulsed beam operation (June 16, 2017)

- 4 laser pulses at 1Hz
- 9 MHz laser pulses
- Faraday Cup signal

Charge per Macro-bunch 4nC (30 electron bunches), single bunch charge 130 pC
First CW operation (August 1, 2017)

Gun and Dump Fast Current Transformer signal

Gap in laser pulses
LEReC DC Gun Tests Highlights

- **December 2016**: DC Gun was conditioned to 455kV with stable operation at 400kV, which is design goal.
- **April 18, 2017**: first electron beam (DC)
- **May 5**: First pulsed electron beam using high-power green laser; beam propagated all the way to the beam dump
- **June 16**: Delivered cathode with design QE value (>1%) inside the gun
- **June 16**: Demonstrated LEReC design electron bunch charge (130pC/laser pulse; 4nC per macro-bunch)
- **August 1**: First CW operation (at 9MHz)
- **August 1**: Achieved 1mA CW current
- **August 11**: Achieved 10mA CW current
2.1 GHz warm RF cavity
(installed and tested at high power)

RF tested to 220 kV in CW mode (design value 250kV)
704 MHz warm RF cavity (installed and tested at high power)

RF tested to 250kV (design value 400kV, will need 250kV for operation)
LEReC SRF booster cavity

SRF Booster cavity assembled and RF tests started in June, 2017:

- The general behavior of the cavity has been excellent.
- Based on the FPC Qext calibration and forward power achieved CW voltage is 2.2MV (maximum required for LEReC).
- The downstream HOM damper insert installed, additional cavity tests are being performed to verify RF performance.

Cavity string assembly in clean room

Cavity inside cryostat
Present Installation (October 2017)
**LEReC project timeline**

May 2015: Project approved by DOE for construction
January 2016: Cooling section magnets installed
April 2016: Laser assembled
September 2016: DC gun assembled at Cornell University
October 2016: DC gun delivered to BNL
November 2016: Approval from DOE for DC Gun Tests received
December 2016: DC gun successfully conditioned in RHIC IR2
February 2017: Gun Test beamline and laser transport installed in RHIC
April-Aug. 2017: Gun tests/commissioning with beam
July-Dec. 2017: Installation of remaining components
Dec.’17-Feb. 2018: Systems commissioning (RF, SRF, Cryogenics, etc.)
March 2018: Start commissioning of full LEReC accelerator with e-beam
September 2018: Demonstrate electron beam parameters needed to start commissioning of cooling process
2019: Commissioning of cooling with Au ion beams during RHIC Run-19.
LEReC as testbed of high-energy cooling

• Production of 3-D high-brightness electron beams.
• RF-based electron cooler.
• Transport of such electron bunches maintaining “cold” beam.
• Control of electron angles in the cooling section to a very low level required for cooling.
• Preserving beam quality from one cooling section to another.
• Various aspects of bunched beam electron cooling.

Electron cooling in a collider:
- Control of ion beam distribution, not to overcool beam core.
- Effects on hadron beam.
- Interplay of space-charge and beam-beam in hadrons.
- Cooling and beam lifetime (as a result of many effects).
Summary

- LEReC will be first electron cooler based on the RF acceleration of electron beam. As such, it is also a prototype of future high-energy electron coolers.
- It will be the first application of electron cooling in a collider.
- Project is in full construction and commissioning phase.
- Injection section (without SRF booster) and laser transport successfully commissioned in 2017.
- Final installation is underway.
- Commissioning with electron beam of full LEReC accelerator will start in 2018.
Acknowledgement

LEReC project greatly benefits from help and expertise of many people:


with numerous help from many others from various groups of the Collider-Accelerator and other Departments of the BNL. As well as FNAL, ANL, JLAB, SLAC and Cornell University.
Details can be found in recent LEReC publications:

S. Seletskiy et al., “Status of the BNL LEReC Machine Protection System”, IBIC17, Grand Rapids, USA, 2017
T. Miller et al., “Low Field NMR Probe Commissioning for LEReC Spectrometer”, IBIC17, Grand Rapids, USA, 2017
J. Kewisch et al., “Tracking of Electrons Created at Wrong RF Phases in LEReC”, IPAC17, Copenhagen, Denmark, 2017
S. Seletskiy et al., “Dependence of LEReC energy spread on laser modulation”, IPAC17, Copenhagen, Denmark, 2017
S. Seletskiy et al., “Alignment of Electron and Ion Beam trajectories in LEReC”, IPAC17, Copenhagen, Denmark, 2017
Z. Zhao et al., “Generation of 180 W average green power from fiber laser”, Optics Express 8138, Vol. 25, No. 7, 2017
D. Kayran et al., “DC Photogun Test for LEReC”, NAPAC16, Chicago, USA, 2016
S. Seletskiy et al., “Magnetic Sheilding of LEReC Cooling Section”, NAPAC16, Chicago, USA, 2016
M. Blaskiewicz, “Emittance Growth from Modulated Focusing in Bunched Beam Cooling”, NAPAC16, Chicago, USA, 2016
S. Seletskiy et al., “Study of YAG Exposure Time for LEReC RF Diagnostic Beamline”, IBIC16, Barcelona, Spain, 2016
J.C. Brutus et al., “Mechanical Design of Normal Conducting RF cavities of LEReC”, IPAC16, Busan, Korea, 2016
F. Carlier et al., “Radiation Recombination Detection for LEReC”, IPAC16, Busan, Korea, 2016
Binping Xiao et al., “RF design of Normal Conducting cavities for LEReC”, IPAC16, Busan, Korea, 2016
Binping Xiao et al., “HOM Consideration of 704MHz and 2.1GHz cavities for LEReC”, IPAC16, Busan, Korea, 2016

and references therein to previous publications.