LEReC cooling (with an eye towards the future)

Alexei Fedotov

RHIC Retreat

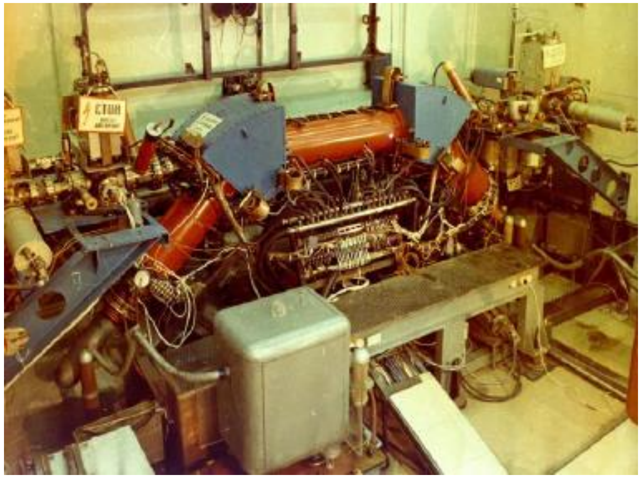
September 16, 2021

Outline

- LEReC performance summary
- LEReC cooling studies (APEX) in 2021
- Future cooling studies
- Future high-current R&D
- Run-22 plans and beyond

Electron coolers

The method of electron cooling was first presented by G.I. Budker (Novosibirsk) at Symposium in Saclay, 1966.

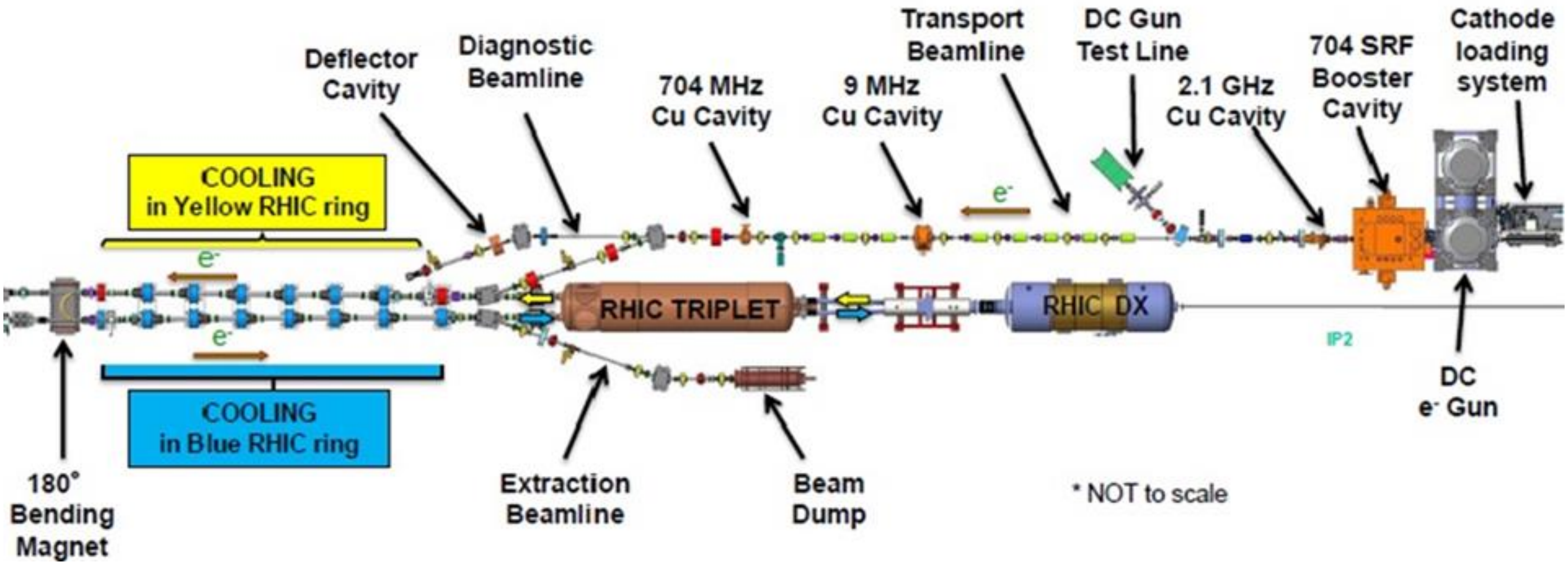


First experimental electron cooling demonstration at NAP-M storage ring (Novosibirsk, Russia, 1974).

High Voltage DC coolers: **(1974 -):** all DC electrostatic accelerators; all use magnetic field to confine electron beam (magnetized cooling).
FNAL Recycler cooler: Pelletron electrostatic generator (4MeV electrons), transport of electron beam without continuous magnetic field.

RF acceleration (High Energy approach): **BNL LEReC electron cooler (2019-21):** **First** RF-linac based electron cooler. Also, **first** cooler without any magnetization of electrons, **first** two-beam electron cooler, **first** electron cooler in a collider.

Distinctive features of LEReC



- LEReC is fully operational electron cooler which:
  - utilizes RF-accelerated electron bunches
  - uses non-magnetized electron beam (there is no magnetization at the cathode and there is no continuous solenoidal field in the cooling section)
- LEReC approach to cooling is directly scalable to high-energies
- LEReC offers unique capability for experimental studies of various cooling topics which are relevant to high-energy coolers

LEReC roadmap to cooling a collider

- Production of 3-D high-brightness electron beams ✓
- RF acceleration and transport of electron bunches maintaining “cold” beam ✓
- Control of various contributions to electron angles in the cooling section to a very low level required for cooling ✓
- Velocity matching of electron and ion beams ✓
- First electron cooling demonstration in longitudinal plane✓
- Establishing cooling in 6-D✓
- Matching electron and ion velocities in both Yellow and Blue RHIC rings✓
- Achieving cooling in both Yellow and Blue Rings simultaneously using the same electron beam✓
- Demonstrating longitudinal and transverse cooling of several ion bunches (high-current 9MHz CW e-beam operation) simultaneously ✓
- Cooling ion bunches in collisions, in both Yellow and Blue RHIC rings using CW electron beam ✓
- Successful operation for RHIC Physics program during 2020-21 ✓

Cooling in a collider

After 6D electron cooling of hadron beams was successfully commissioned in both collider rings in 2019, our focus shifted towards operational aspects of cooling of full RHIC physics stores with ion bunches in collisions.

Application of electron cooling technique directly at collision energy of hadron beams brings several challenges, such as:

- Control of ion beam distribution, not to overcool beam core (especially when ion beam space charge is significant)
- Interplay of space-charge and beam-beam in hadrons
- Effects on hadron beam from electrons ("heating")
- Ion beam lifetime with cooling (as a result of many effects)
- Optimization between cooling process and luminosity improvement

The final optimization was performed during operation for physics by choosing parameters which result in largest luminosity gains (not necessarily higher electron beam current or stronger cooling)

Cooling optimization for luminosity

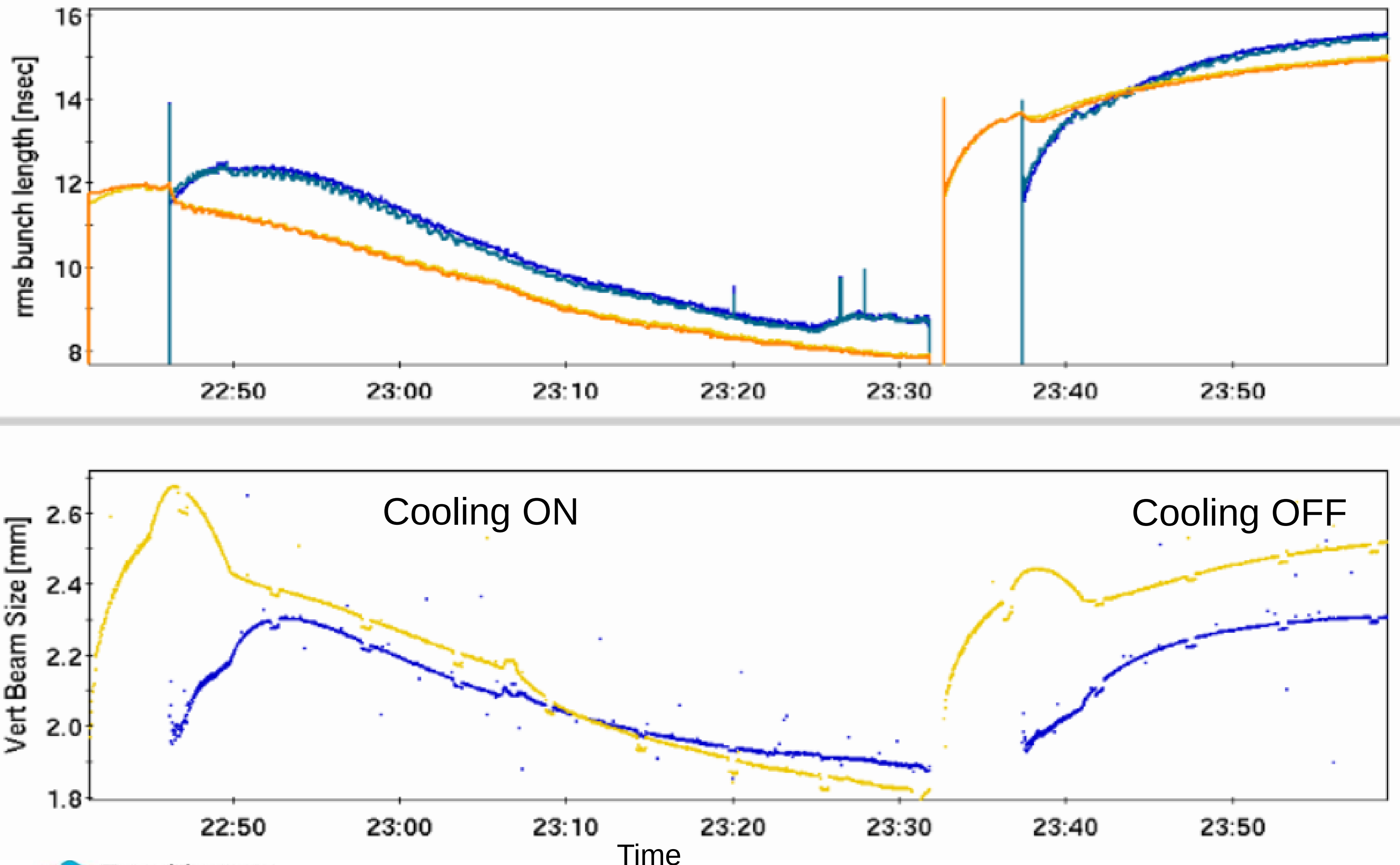
Luminosity optimization with cooling included:

- Finding optimum angular spread of electrons in cooling sections to provide sufficient transverse cooling.
- Optimization of electron and ion beam sizes in the cooling sections.
- Finding optimum working point in tune space for colliding ion beams in the presence of electron beam.
- Finding optimum electron current to reduce effects on ion beam from electrons and at the same time still provide sufficient cooling.
- Longer stores with cooling.
- With cooling counteracting longitudinal IBS and preventing debunching from the RF bucket, the ion's RF voltage could be reduced resulting in smaller momentum spread of ions and improving ion lifetime.
- Once the transverse beam sizes were cooled to small values, the dynamic squeeze of ion beta-function at the collision point was established.

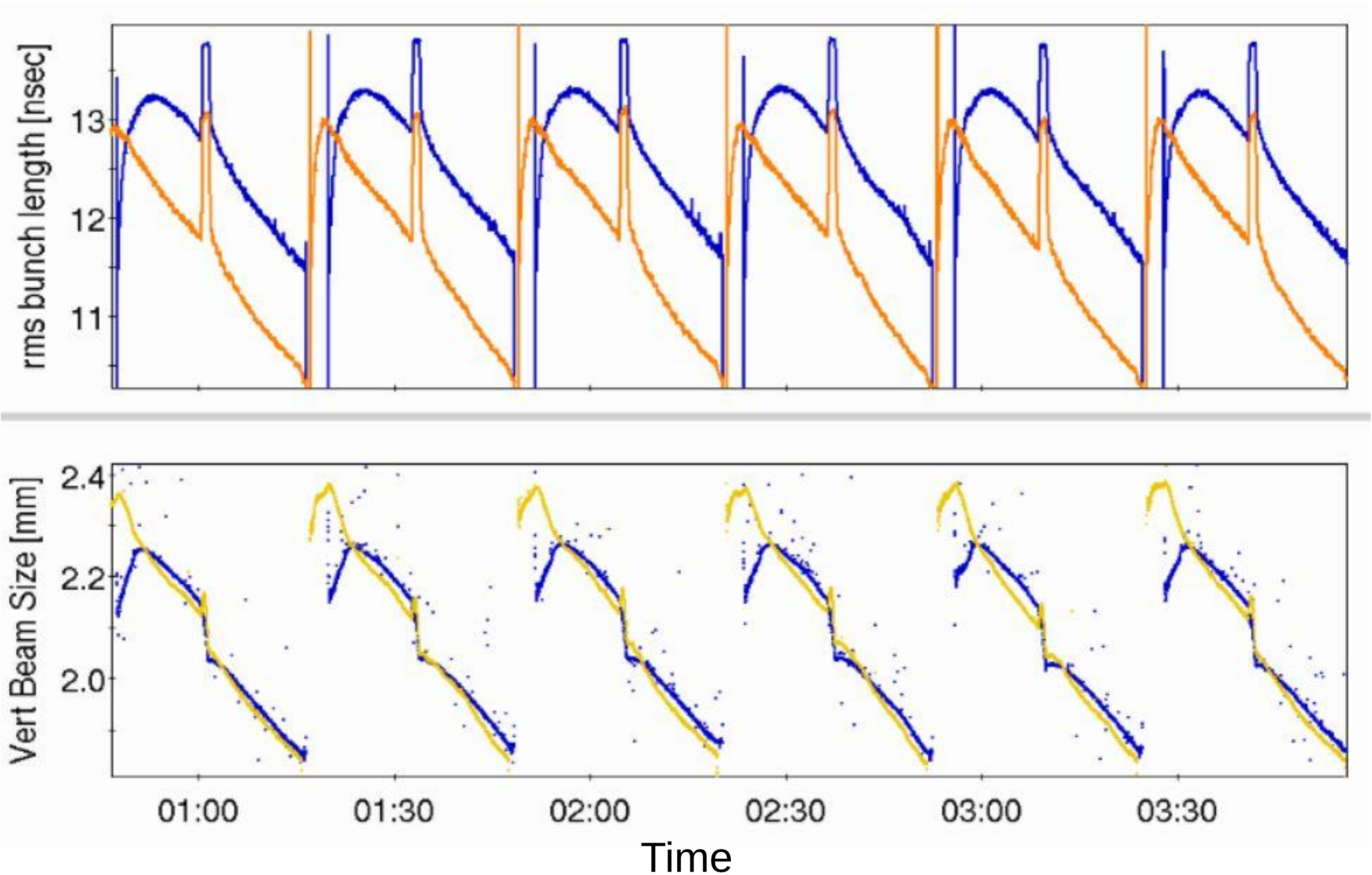
LEReC operational experience

- Stable 24/7 running of high-current electron accelerator and stable cooling was provided over many weeks of collider operation in 2020 and 2021.
- Reliable operation was ensured by implementation of laser position feedbacks, intensity feedback, energy feedback, automatic cooling section orbit correction and feedback.
- Operational electron current based on optimization between cooling and other effects, including ion beam lifetime effects, was: 15-20 mA (for Au ions at 4.6 GeV/n in 2020) and 8-20 mA (for Au ions at 3.85 GeV/n in 2021).
- Very robust photocathodes with initial Quantum Efficiency: 8-9%
- Cathode lifetime: 6-10 days

Physics stores (111x111 ion bunches at 4.6 GeV/n) with and without cooling of ions in Yellow and Blue RHIC rings - rms bunch length (top) and rms beam size (bottom)



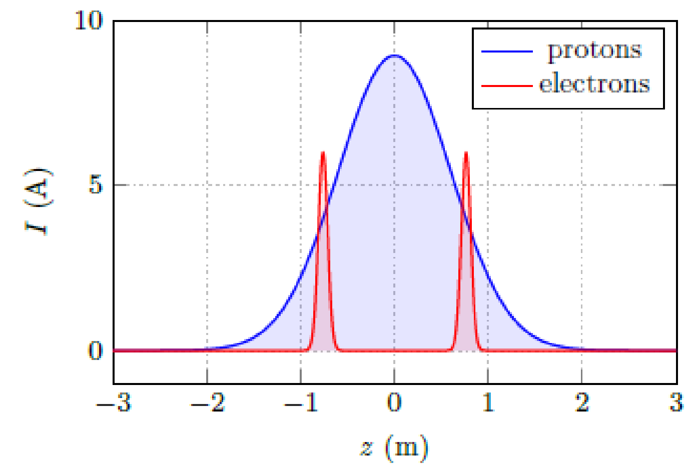
2021 operation for physics (several physics stores), 1.6 MeV electrons, 111x111 Au ion bunches at 3.85 GeV/n, rms bunch length (top) and rms beam size (bottom)



Importance of LEReC cooling studies for future high-energy coolers, including EIC

Electron cooling using bunched electron beams (LEReC-type cooler) is proposed for:

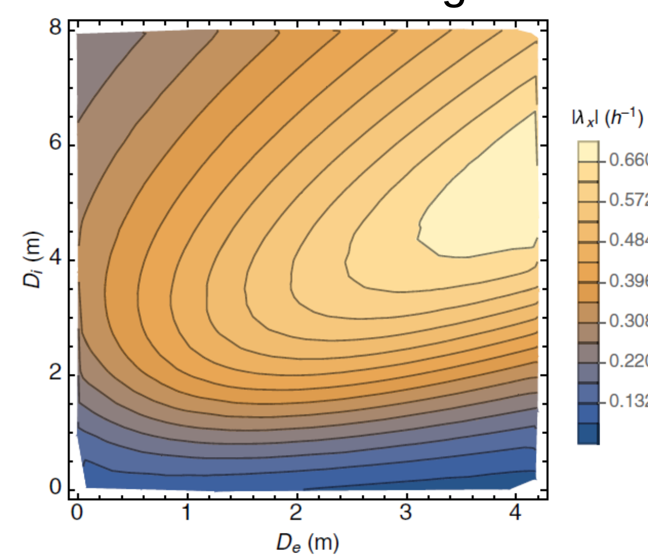
- Pre-cooling of protons at 24GeV for EIC.
- Cooling protons directly at collision energy of 41GeV in EIC.



A. Fedotov, S. Benson et al., "Low energy cooling for EIC", BNL-220686-2020-TECH (2020)

- Cooling of protons at the highest energy of 275GeV using storage ring electron cooler.

Dispersive cooling (275GeV, EIC): Horizontal cooling rate



H. Zhao, J. Kewisch, et al., "Ring-based electron cooler for high energy beam cooling", Phys. Rev. Ac. Beams 24, 043501 (2021)

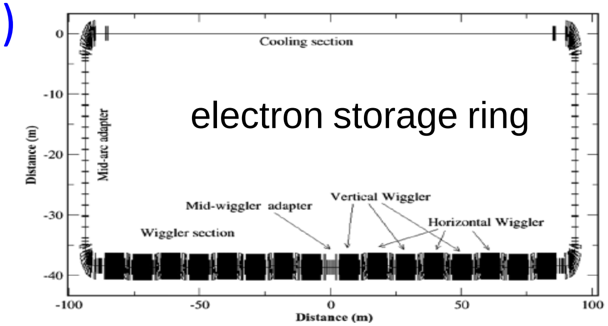


FIG. 2. Layout of the ring cooler.

Brookhaven National Laboratory

Cooling studies directly relevant to EIC coolers

1) Emittance growth of ion beam (“heating”) due to interaction with bunched electron beam
2) Coherent excitations of ions and circular attractors
3) Recombination of ions without continuous magnetic field in cooling section
4) Cooling of ion bunch with electron bunches overlapping only small portion of ion bunch
5) Dispersive cooling (redistribution of cooling decrements), to provide stronger transverse cooling
6) Effects of the presence of the electron beam on the ion beam lifetime

Understanding of these effects is of critical importance for future high-energy coolers.

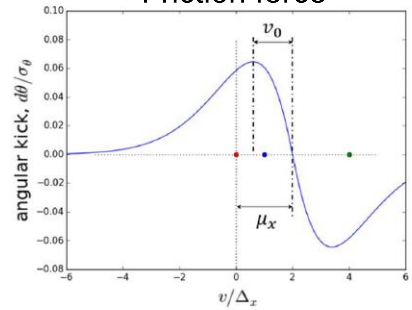
Being a protype for high-energy coolers, LEReC offers unique opportunity to explore these effects in great detail.

The studies above started under APEX program in 2021.

Example of APEX studies: Coherent excitation of ions

A coherent offset in the velocity distribution of the electron bunch shifts the friction force w.r.t. the zero ion's velocity

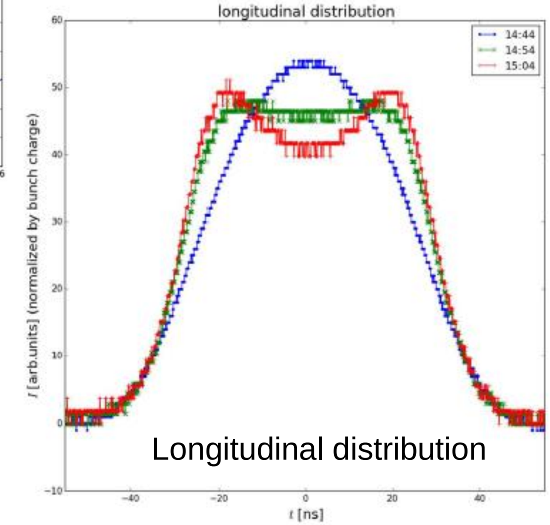
Friction force



$$\vec{F} = -\frac{4\pi n_e e^4 Z^2}{m_e} \int L_C \frac{\vec{v} - \vec{v}_e}{|\vec{v} - \vec{v}_e|^3} f(v_e) d^3 v_e$$

$$f(v_e) = \frac{1}{(2\pi)^{3/2}\Delta_x \Delta_y \Delta_z} \exp - \left(\frac{(v_{ex} - \mu_x)^2}{2\Delta_x^2} + \frac{(v_{ey} - \mu_y)^2}{2\Delta_y^2} + \frac{(v_{ez} - \mu_z)^2}{2\Delta_z^2} \right)$$

APEX measurements

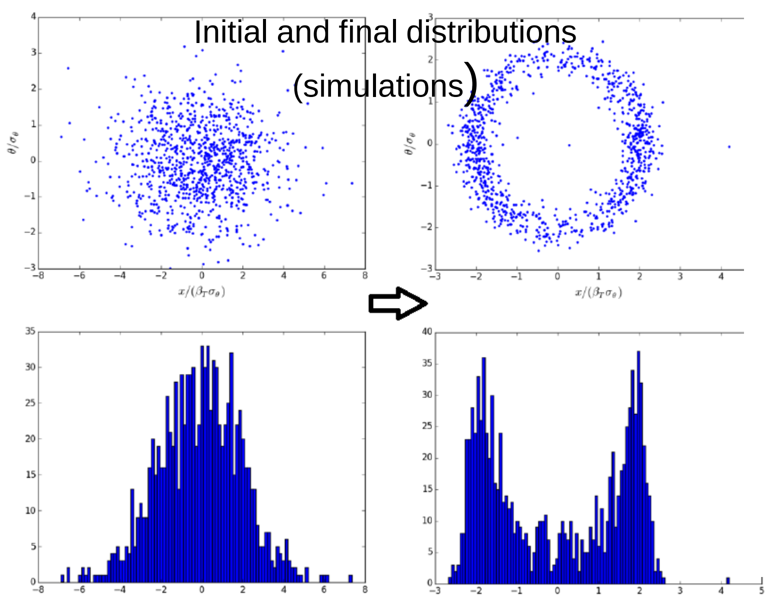


Longitudinal distribution

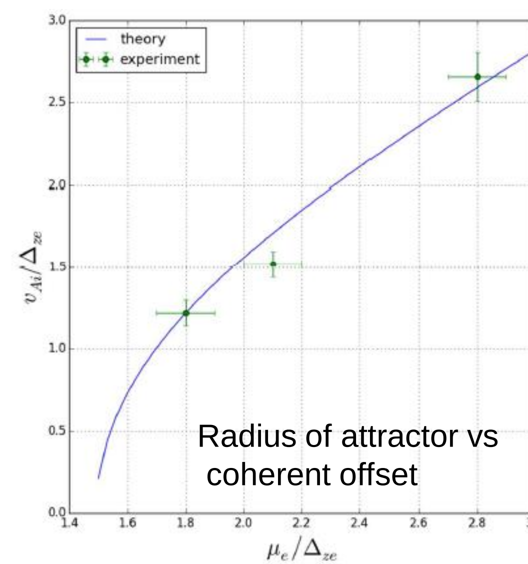
When the coherent shift is larger than the velocity at which the friction force's first derivative is changing sign, then the net force acting on an ion with small amplitude excites the oscillations, resulting in creation of a circular attractor in the phase space.

As a result, small ion amplitudes can increase rather than being damped ("heating").

This effect is also applicable to CeC.



Initial and final distributions (simulations)



Radius of attractor vs coherent offset

Brookhaven National Laboratory

Cooling studies using APEX during 2021 RHIC run

The following APEX studies were performed in 2021:

1) Heating of ions due to interaction with bunched electron beam – significant data was accumulated, but some questions still remain - few more experiments still needed
2) Coherent excitations and circular attractors in electron coolers – attractors were measured in longitudinal plane, good agreement between experiments and theory, completed
3) Recombination of ions without continuous magnetic field in cooling section – no anomalous enhancement (as reported in standard low-energy coolers) was measured, completed
4) Cooling of ion bunch electron bunches overlapping only small portion of ion bunch – started, few more measurements needed
5) Dispersive cooling (redistribution of cooling decrements) – started. Detailed benchmarking of theory (dependance on various parameters) is needed
6) Machine learning for cooling rate optimization - completed

Brookhaven National Laboratory

LEReC Run-22: Planned cooling studies

Cooling studies which are essential for future high-energy coolers, including EIC:

1) **Dispersive cooling** (redistribution of cooling decrements) -started. Detailed benchmarking of theory (exploration of various parameters) is needed. Several APEX sessions: **min 2x8=16 hours**
2) **Heating of ions** due to interaction with bunched electron beam – significant data was already accumulated, but few more experiments still needed: **min 2x4=8 hours**
3) **Short electron macro-bunches:** Cooling of ion bunch electron bunches overlapping only small portion of ion bunch – started, **min 2x4=8 hours**
4) **Lifetime of ions** in the presence of electron bunches, including setup and studies for different working points: **min 2x8 =16 hours**

Total estimate: min request of 48 hours, could be spread over 4 separate APEX sessions (require Au ions at 3.85 or 4.6GeV).

Additional hours may be needed, depending on initial results. Possibly could be done in 2023 if available time during 2022 run will not be sufficient.

Brookhaven National Laboratory

LEReC-based source/accelerator R&D

High-current electron sources is important area of research. They are also required for various cooler designs of the EIC. For example, electron coolers for pre-cooling at low energy in EIC (at 24 GeV and 41 GeV) require stable operation at around 100mA current. Also, the Strong Hadron Cooler (SHC) for EIC requires 100mA source of electrons.

- **High-current source R&D**:

LEReC Gun is designed to operate at high current. Many R&D items critical to high-current source operations could be explored (next slide).

- **Other accelerator studies:**

LEReC accelerator could be used for other R&D studies.

Electron beam dynamics: Micro-bunching, effects of mergers, CSR, beam halo, ion trapping and clearing, as well as effects relevant to space-charge dominated beam transport.

Testing high-current high-power electron beam diagnostics: Various high-power instrumentation devices could be tested in LEReC. Examples of previously considered diagnostics include Beam Induced Fluorescence monitor, BNNT screen and wire scanner.

LEReC-based R&D: High-current source studies

1. Explore Gun operation with high-current: 50, 75, 100mA, possibly higher. Determine limitation of the Gun.
2. Reaching current of 100mA for high Gun voltage of 400kV – this requires 40kW of power which goes above rating of a single inverter (35kW), thus very important R&D is to learn how to use two inverters in parallel. If successful it will allow either for Gun operation at voltages above 400kV or currents above 100mA.
3. Gun and HVPS stability at high currents; long-term stability and what are the issues and limitations. Try to find reasons and remedies for gun trips at high current.
4. Explore what does it take to operate Gun 24/7 with high-current
5. Explore operation with active cathode on center vs cathode off center.
6. Explore large cathode area vs small active area. Explore various laser spot sizes on the cathode.
7. Explore cathode QE at various laser power with and without cathode stalk cooling. For EIC applications, cathode cooling and high laser power on cathode is an important R&D. For LEReC, QE drop by a factor of 4 during operation was compensated by increase in laser power by a factor of 4. For EIC, to cover QE drop from 8 to 2%, would require laser power on the cathode up to 10W, thus cathode cooling.
8. Explore Gun voltage limitations: can one have stable high-current operation at 400kV,425kV. 450kV?
9. Further Gun improvements: Improve the gun vacuum by increase NEG pumps, change Kr line design, develop NEG coated beamline.
10. High-charge high-peak current (beam halo and losses), upgrade of laser system to allow ramping of high-current for fixed electron bunch charge. Otherwise, if electron bunch charge is ramped up at fixed laser frequency, this results in a strong mismatch of beam optics for different bunch charges, and high beam losses.
11. Test multialkali photocathodes using different growth methods such as sputtering. Change the substrate material to get larger crystal multialkali cathode, test cathodes lifetime during high-current operation
12. Other studies…

LEReC Run-22: Planned high-current tests

- **Explore Gun operation at high-current:** 50mA and above. Determine limitation of the Gun. This is needed to plan required Gun upgrades during the 2022 long shutdown.

- Few shifts: 4-6 hour each. Could be done during Maintenance days, need only IR2 to be closed. These tests should be done after all cooling studies (APEX at low energy) are completed (later in Run-22) to minimized possible risks to various accelerator hardware. Schedule during some Maintenance days or during last weeks of the run.

LEReC Run-22 Plan

1. Cooling studies (with Au ions):

Using APEX time (about 48 hours will be requested). Will require setup for Au at 3.85 GeV, electron energy 1.6MeV.

Will be using 28MHz RHIC RF.

2. High-current R&D studies (without ions):

Using Machine Development time, possibly at the end of some Maintenance days or when IP2 is closed while long access to other IP is scheduled. Requires running high-current electron beam through RHIC cooling sections to the high-power beam dump.

LEReC plans for 2022 long shutdown and beyond

Option 1: If, as a result of 2022 cooling studies, it is found that further cooling studies are needed.

This requires keeping LEReC accelerator intact.

Run-23: Cooling studies and high-current R&D.

Option 2: If all essential cooling studies are completed during Run-22.

In such a case, to simplify high-current setup, LEReC can be taken apart and converted into injector for “high-current R&D”. Such conversion allows to decouple high-current tests from RHIC running (no need to run e-beam through RHIC beam pipe). However, with such conversion, all unique features of LEReC as a cooler will no longer be available for future high-energy cooling studies

Converting to simplified injector will require major work in RHIC tunnel:

1. Moving high-power beam dump to injector section (area modifications)
2. Possibly removing SRF and 2.1 GHz RF cavities from present Injector section
3. Major RF and vacuum work during 2022 shutdown.

Summary

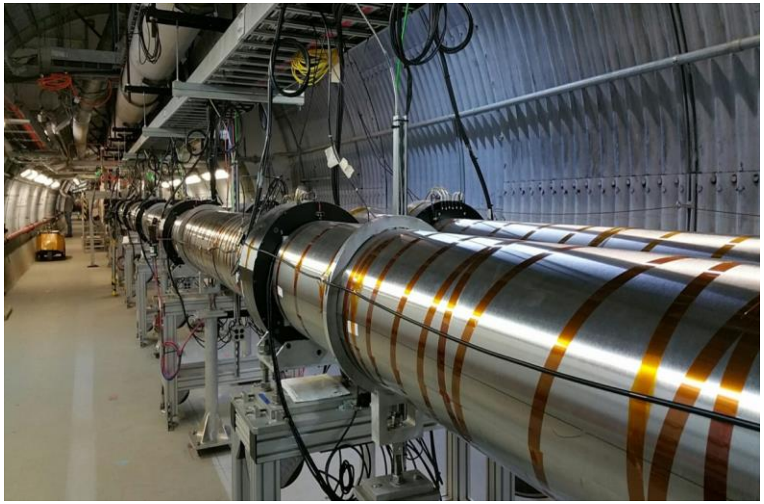
LEReC successfully operated for RHIC physics program in 2020 and 2021, making it the world's first operational electron cooler to cool ions directly at collision energy.

LEReC offers unique opportunity to study various aspects of electron cooling using short electron bunches, as well as effects relevant to the ion beam dynamics.

Several dedicated cooling experiments were already performed in 2021, with more cooling studies planned during Run-22.

The plan is to start high-current accelerator R&D during Run-22.

Planned electron cooling and high-current studies are directly relevant for EIC coolers, both for regular and coherent electron cooling.



Brookhaven National Laboratory

Acknowledgement

LEReC project greatly benefited from help and expertise of many people from various groups of the Collider-Accelerator and other Departments of the BNL.

Special thanks go to LEReC systems experts and to RHIC operators who maintained outstanding performance of LEReC accelerator during RHIC operations.

Work supported by the U.S. Department of Energy.

Thank you!

Brookhaven National Laboratory