Electron Cooling of Colliding Ion Beams in RHIC: status and perspectives

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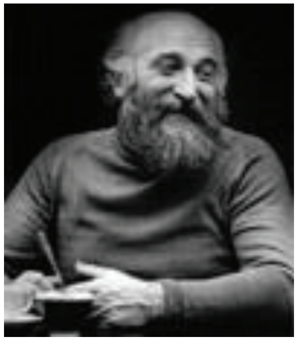
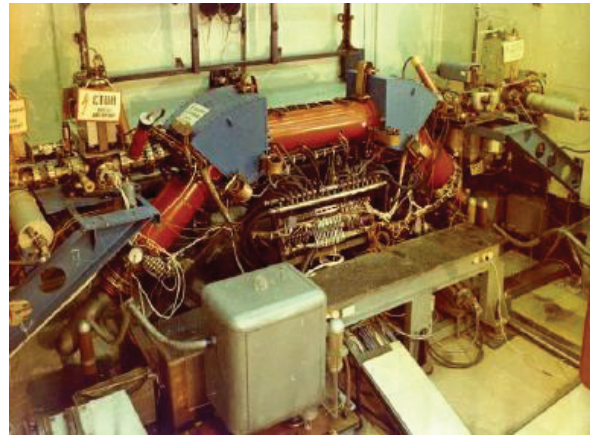
Electron Cooling



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

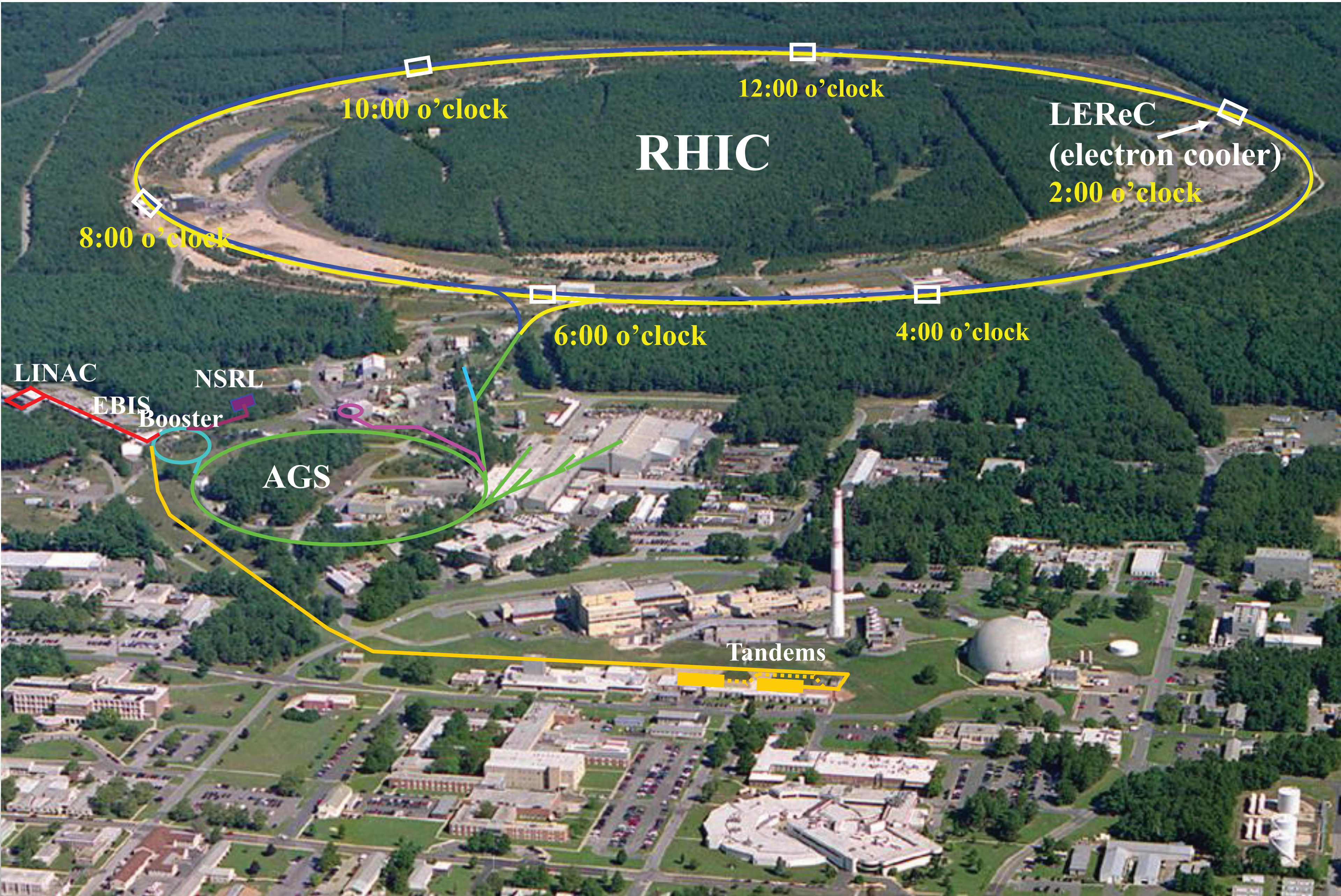


First experimental electron cooling demonstration at NAP-M storage ring (Novosibirsk, Russia, 1974).

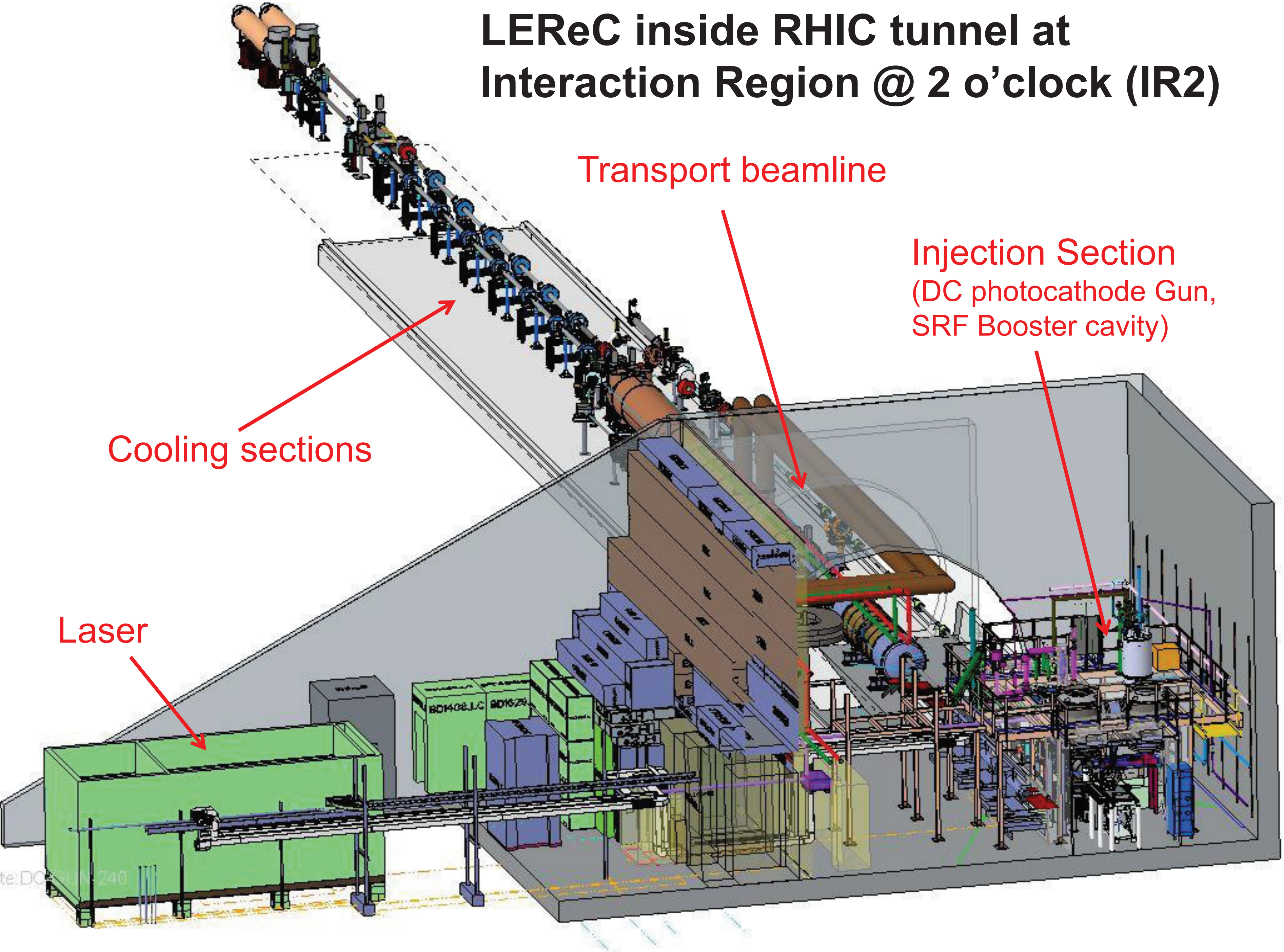
High Voltage DC coolers: **(1974-):** all DC electrostatic accelerators; all use magnetic field to confine electron beam (magnetized cooling). FNAL Recycler cooler: Pelletron electrostatic generator (4MeV electrons), transport of electron beam without continuous magnetic field.

RF acceleration (High Energy approach): **BNL LEReC electron cooler (2019-21):** First RF-linac based electron cooler. LEReC does not use any magnetization of electrons. The same electron beam is used twice to cool Au ions in both collider rings. LEReC was successfully used for RHIC operations in 2020-21 to cool ion bunches directly at collision energy.

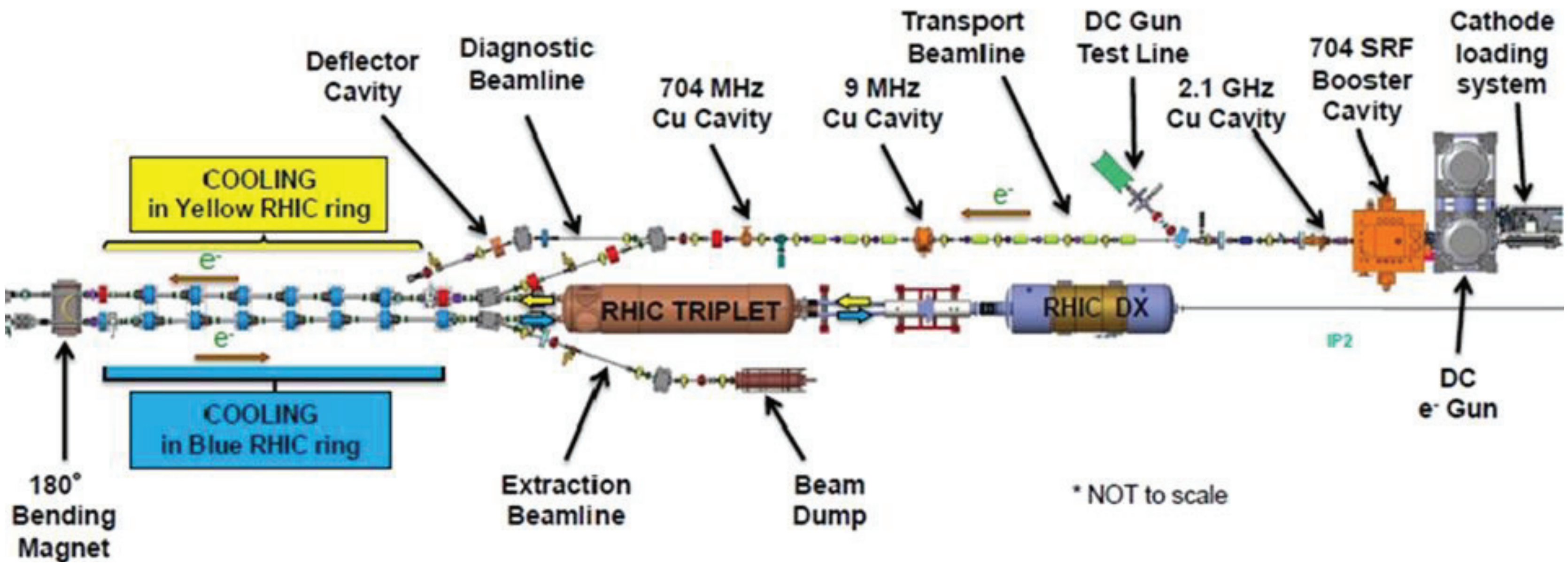
RHIC @ BNL, Long Island, New York



LEReC inside RHIC tunnel at Interaction Region @ 2 o'clock (IR2)



Distinctive features of LEReC

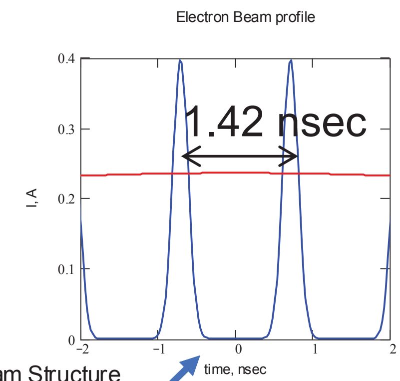


- LEReC is fully operational electron cooler which:
  - utilizes RF-accelerated electron bunches
  - uses non-magnetized electron beam (there is no magnetization at the cathode and no continuous solenoidal field in the cooling section)
  - after cooling ions in one RHIC ring (“Yellow”) the same electron beam is used one more time to cool ions in the other RHIC ring (“Blue”)
- LEReC approach is directly scalable to high energies (10’s of MeV)

LEReC beam structure in cooling section

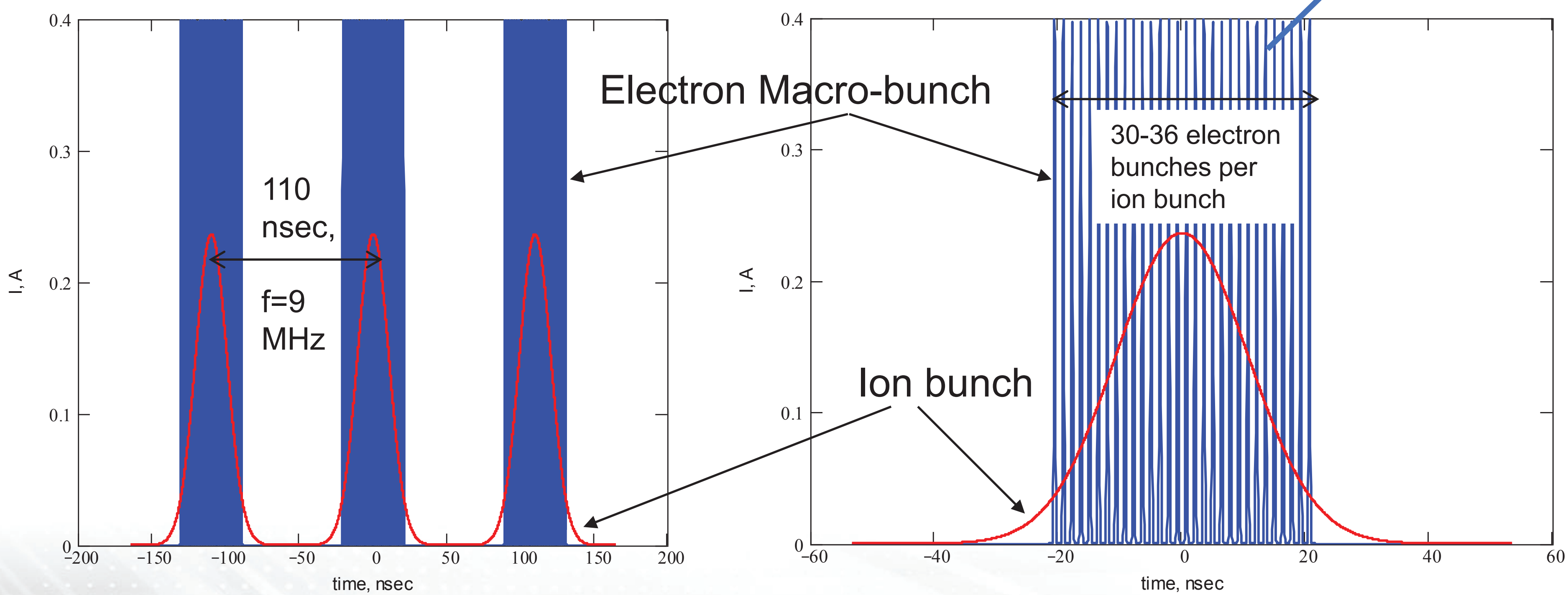
Ions structure:
120 bunches
f_rep=9.1 MHz
N_ion=5e8, I_peak=0.24 A
Rms length=3.2 m

Electrons:
f_SRF=704 MHz
Q_e=100 pC, I_peak=0.4 A
Rms length=3 cm

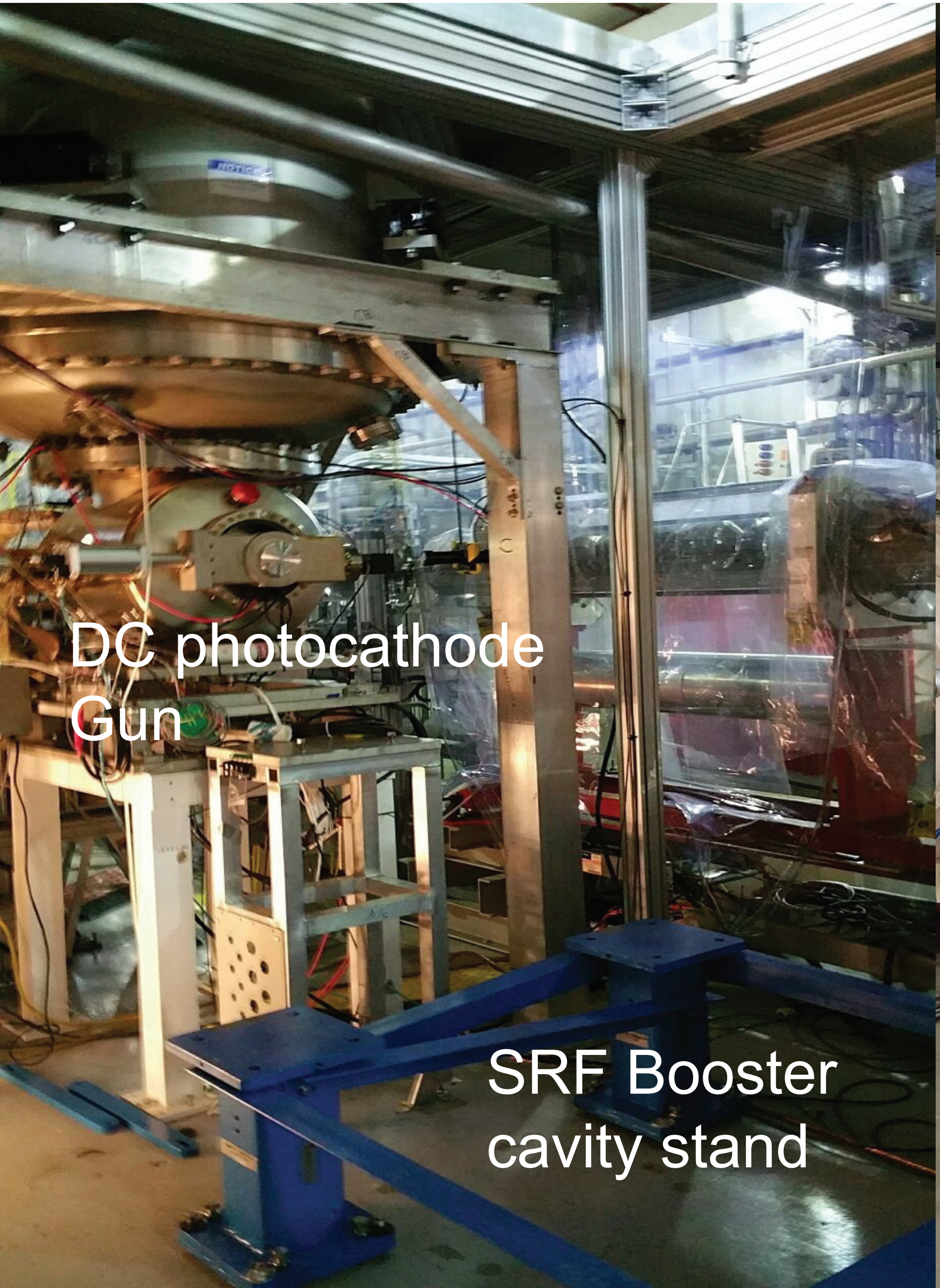


9 MHz bunch structure

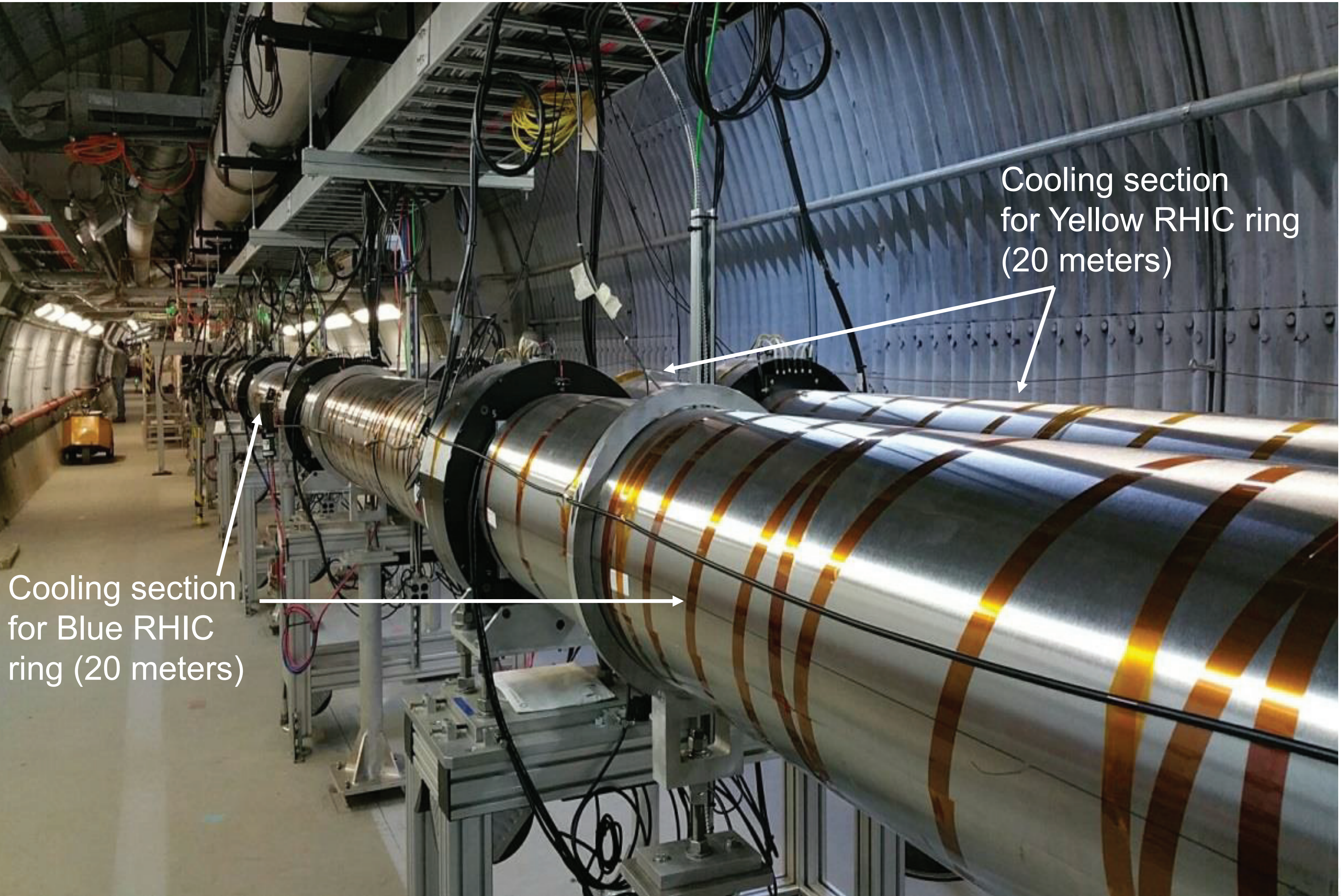
LEReC Beam Structure



LEReC installation (October 2017)



LEReC cooling sections fully installed (2018)



LEReC roadmap to electron cooling of colliding ion bunches in RHIC

- 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 (<150urad) required for cooling ✓
- Velocity matching (<1e-4) of electron and ion beams ✓
- First electron cooling demonstration in longitudinal plane (April 2019)✓
- 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:

- Effects on hadron beam from electrons (“heating”)
- Ion beam lifetime with cooling (as a result of many effects)
- 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 effects in hadrons
- 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)

LEReC electron beam parameters

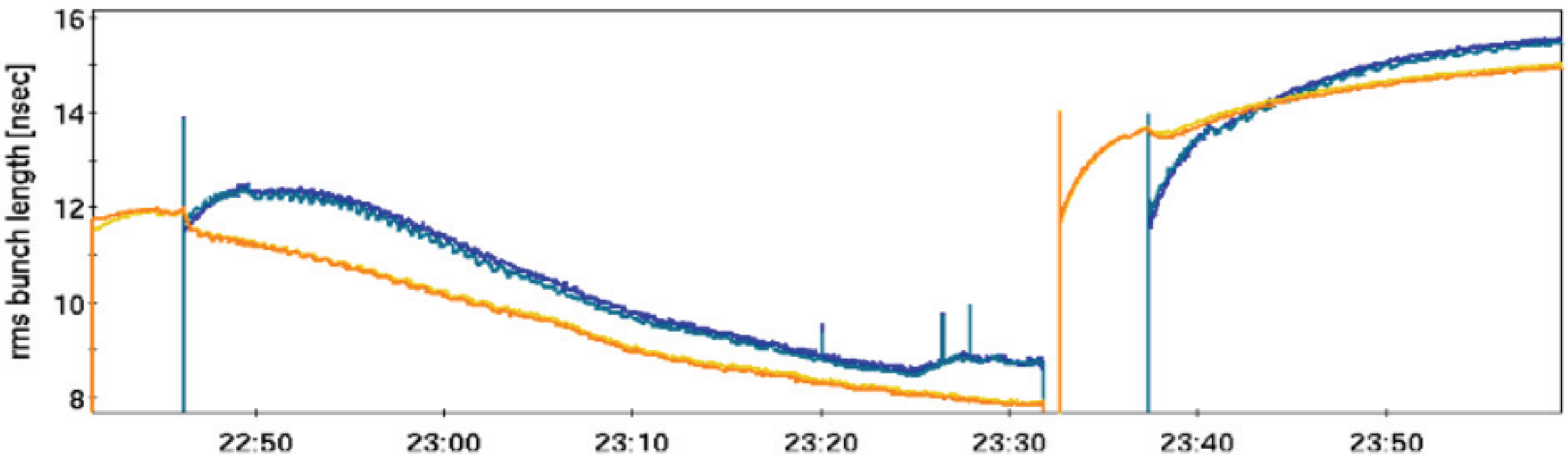
Cooler parameters used for RHIC operations		
Au ions beam energy, GeV/nucleon	3.85	4.6
Electrons kinetic energy, MeV	1.6	2.0
Cooling section length, m	20	20
Electron bunch (704MHz) charge, pC	30-70	50-70
Bunches per macrobunch (9 MHz)	36	30-36
Charge in macrobunch, nC	1-2	1.5-2
RMS normalized emittance, um	< 2.5	< 2.5
Average current, mA	8-20	15-20
RMS energy spread	< 4e-4	< 4e-4
RMS angular spread	<150 urad	<150 urad

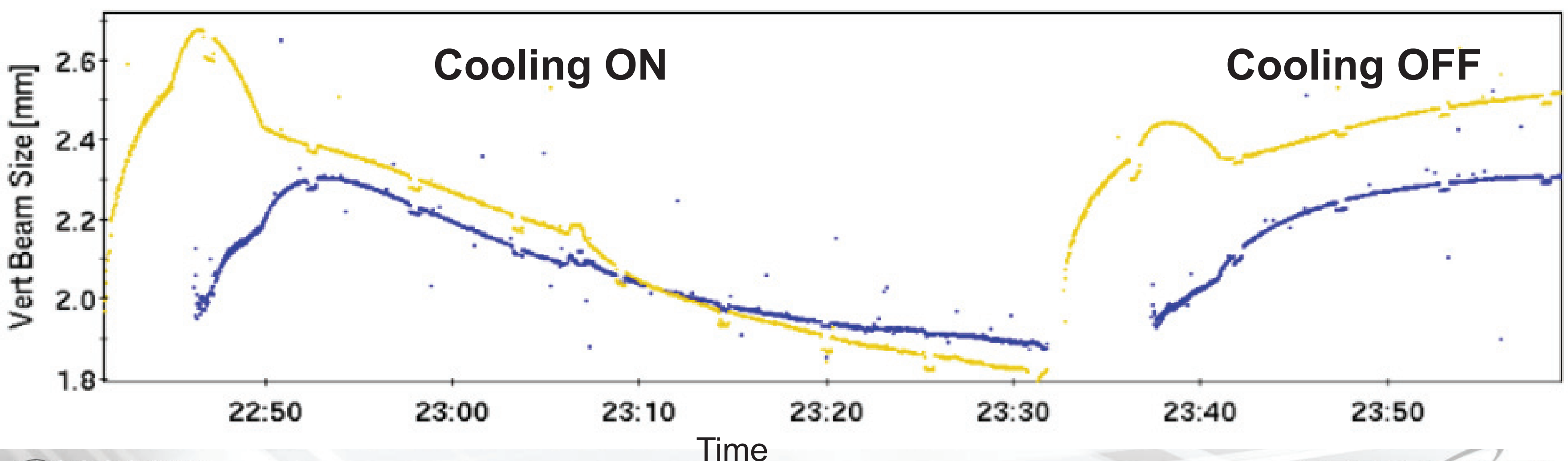
LEReC operated for RHIC physics program using 1.6 and 2 MeV electron beam (LEReC was designed to operate with 1.6, 2.0 and 2.6 MeV electrons. Operation with 2.6 MeV electrons was not needed due to sufficient collider luminosity at that energy).

LEReC operational experience

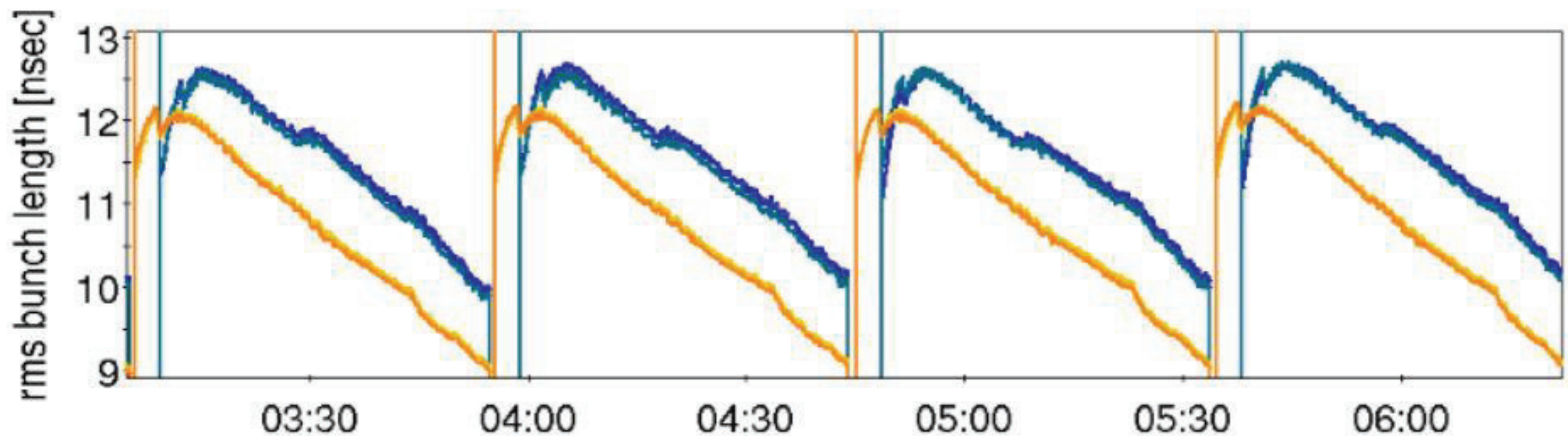
- Stable 24/7 running of high-current electron accelerator and stable cooling was provided over many weeks of collider operation in 2020 and 2021.
- Reliable operation was ensured by implementation of laser position feedbacks, intensity feedback, energy feedback, automatic cooling section orbit correction 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).
- Robust photocathodes (K_2CsSb) with initial Quantum Efficiency: 8-9%
- Typical cathode exchange: once every two weeks

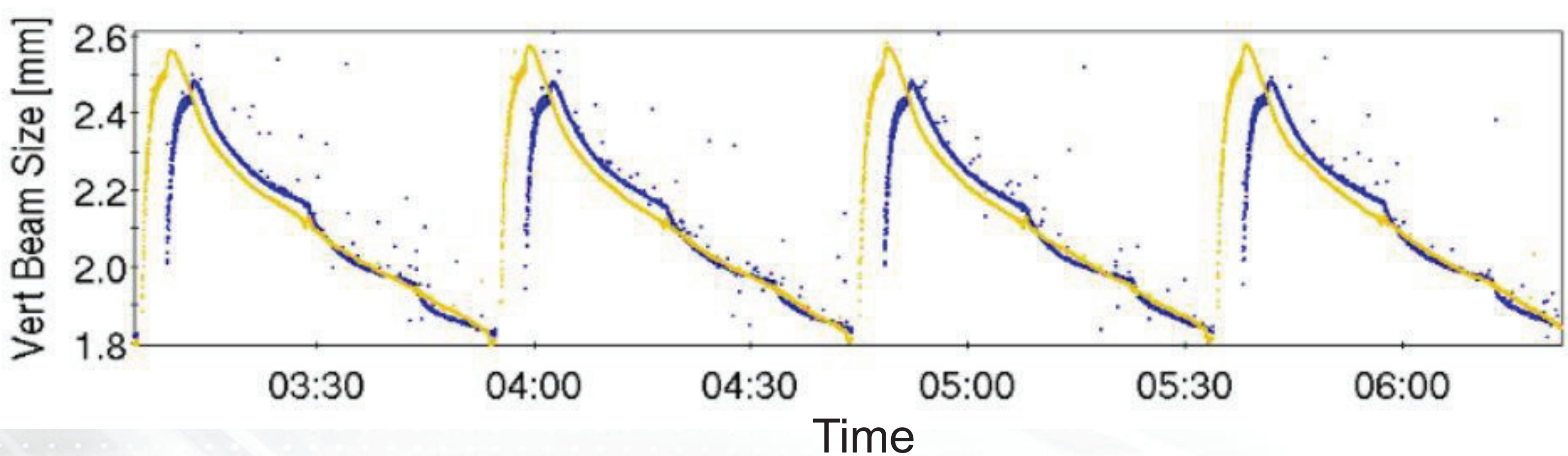
Physics stores with and without cooling of ions in Yellow and Blue RHIC rings - rms bunch length (top) and rms beam size (bottom)



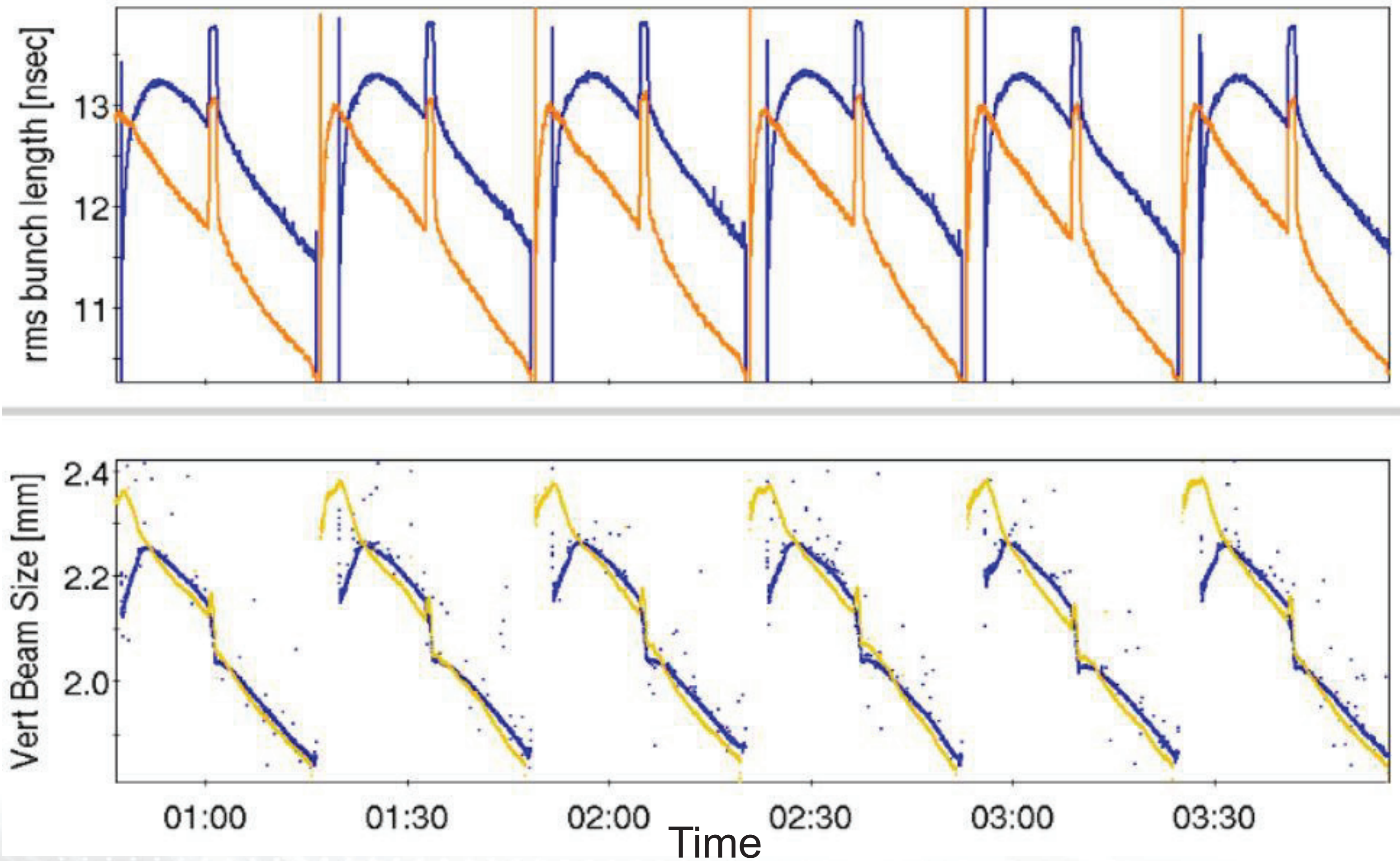


2020 operation for physics (several physics stores) 2 MeV electrons, 111x111 Au ion bunches at 4.6 GeV/n, rms bunch length (top) and rms beam size (bottom)





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)



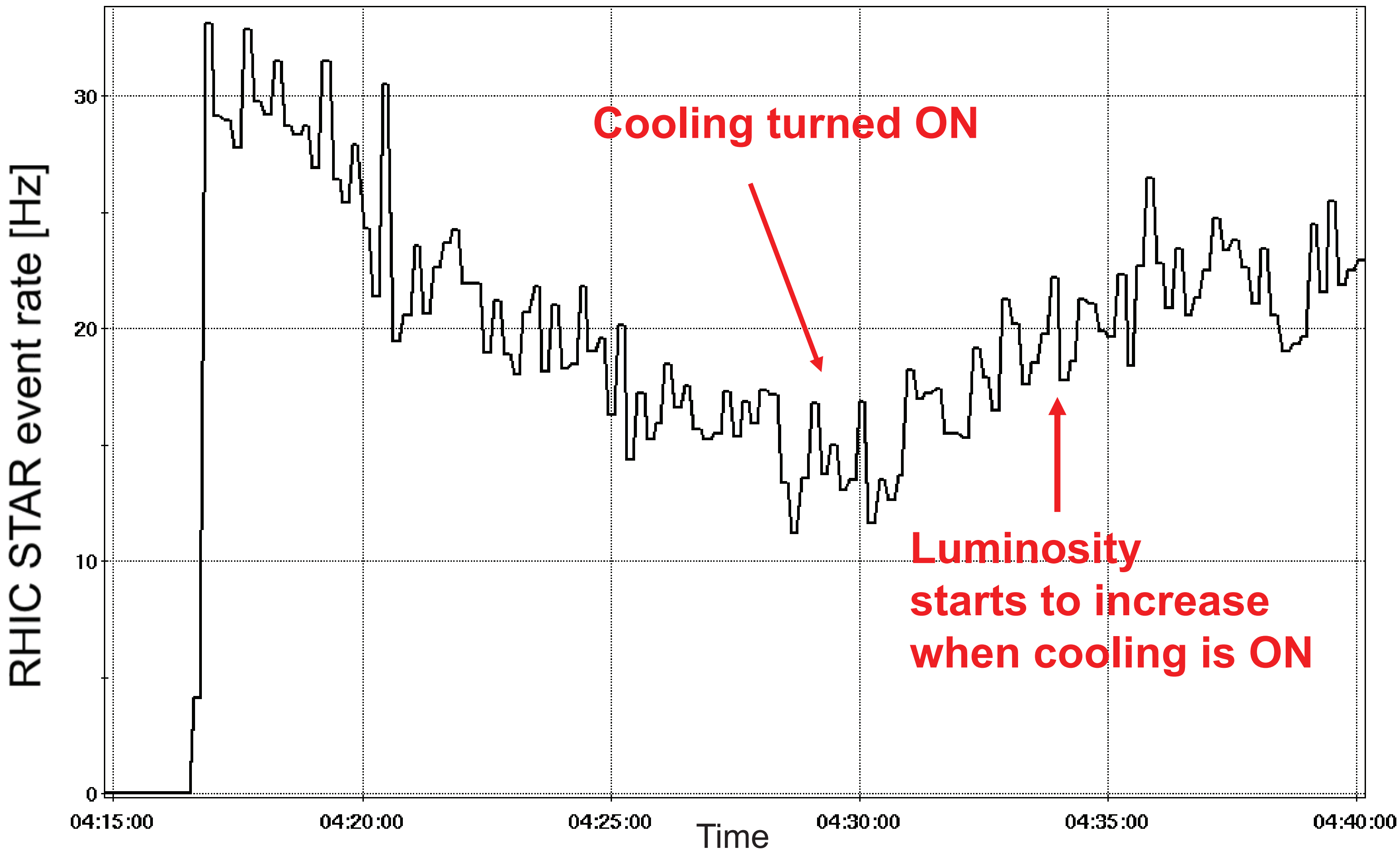
Spikes in bunch length are due to ion-beam RF manipulation to alleviate space-charge effects during the beta-squeeze.

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 beam 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 was 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.

Effects of cooling on luminosity



In addition to counteracting IBS, cooling of ion beam sizes results in luminosity increase.

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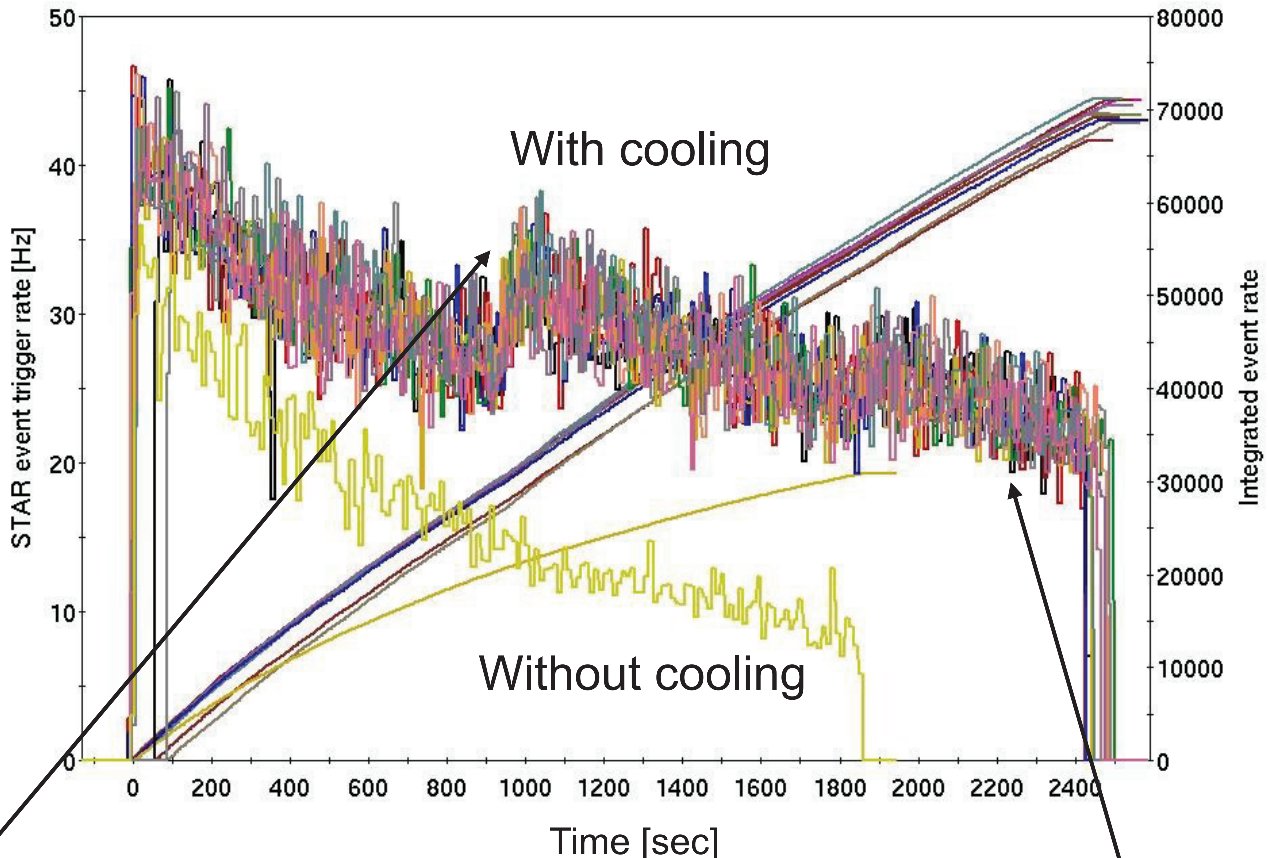
Several physics stores at 4.6 GeV/nucleon with cooling (2MeV): vertical axis: events rate [Hz] within +/-0.7m (left); store integrals (right)



Dynamic squeeze of beta-function at collision point, while transverse beam sizes of ion beams are being cooled

Longer stores with cooling

Gains in integrated luminosity from cooling:
2020 (4.6 GeV/n): about factor of 2
2021 (3.85 GeV/n): 30-50%

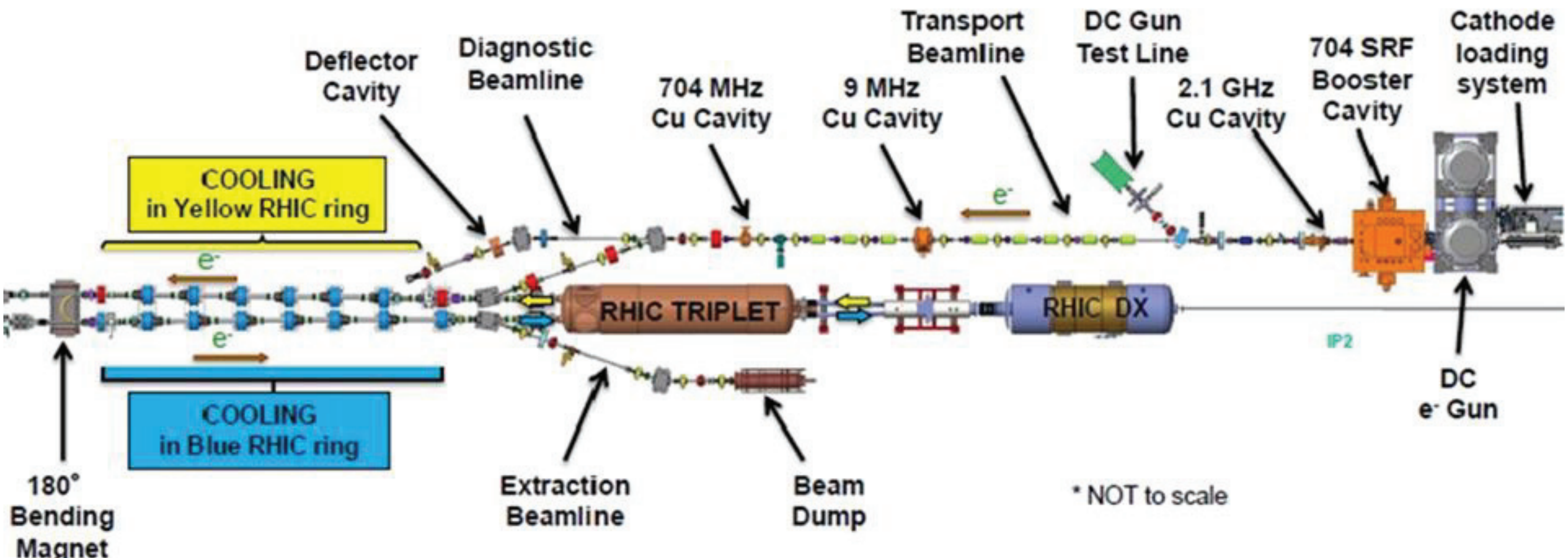
LEReC cooling challenges during RHIC operations

Optimization of collider operations with electron cooling for highest luminosity required compromise between various effects.

Few examples are listed below:

- Effect on electrons from ions: High ion bunch intensity, which typically is the most important parameter to increase luminosity, had significant effect on electrons due to the ion's space charge.
- Additional diffusion mechanism from electrons: With LEReC cooling provided by short electron bunches, there was additional growth of transverse beam size of ions caused by electrons (which we called "heating"). Such heating was counteracted by cooling and was not a limiting factor for performance.
- Lifetime of ions: Besides heating, ions lifetime suffered due to the presence of electron beam, this was especially true for working point close to an integer. This was a limiting factor requiring operation at electron current smaller than the value which provided strongest cooling: stronger cooling does not necessarily lead to highest luminosity.
- Loss on recombination: Without continuous magnetic field in the cooling section and small temperatures of electron beam, loss of ions due to radiative recombination was noticeable (in typical low-energy coolers magnetic field allows to suppress recombination loss with large transverse temperatures). This could partially be mitigated by introducing a small average velocity offset between electrons and ions.

LEReC cooling studies



- LEReC operations for RHIC physics program (Beam Energy Scan II) concluded in 2021. For details of RHIC operations with cooling see:
  C. Liu et al., "RHIC Beam Energy Scan Operation with Electron cooling in 2020", Proceedings of IPAC21, May 2021.
  A. Fedotov et al., "Operational Electron Cooling in RHIC", IPAC21.

- Starting June 2021 LEReC is being used for dedicated experimental studies of various cooling topics.

Cooling studies using LEReC

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.

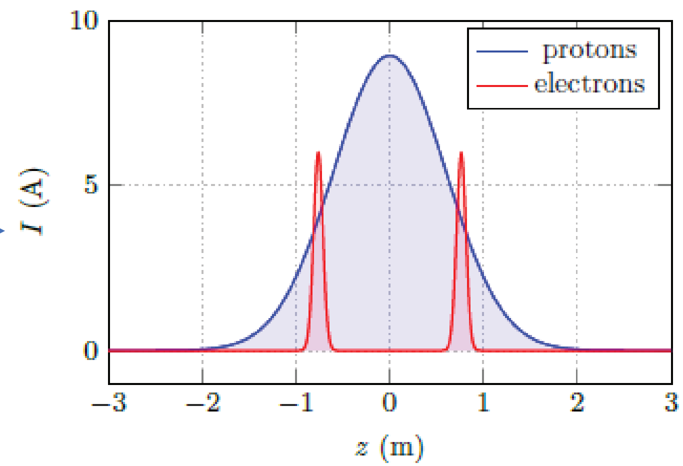
Being a protype for high-energy coolers, LEReC offers unique opportunity to explore these effects in great detail.

The studies above started under Accelerator Physics Experiments (APEX) program in 2021.

High-energy cooling studies, including for EIC

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

- Pre-cooling of protons at 24GeV for EIC (13 MeV electron cooler)
- Cooling protons directly at collision energy of 41GeV in EIC (22 MeV electron cooler)

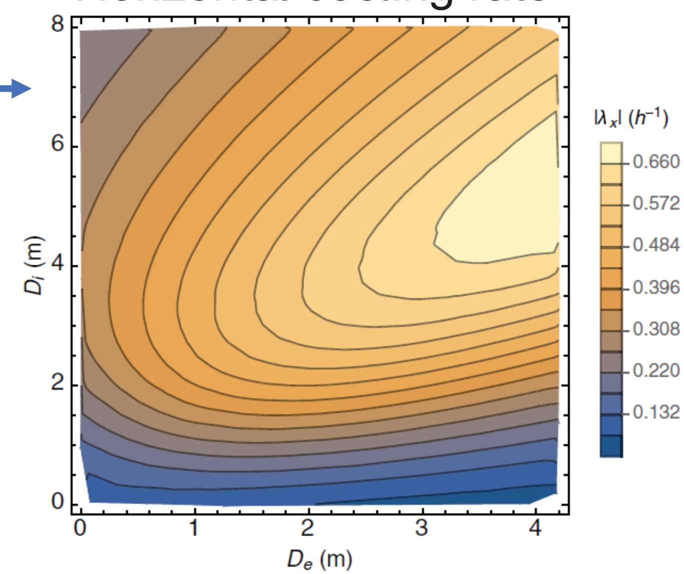


A. Fedotov, S. Benson et al., "Low energy cooling for EIC", BNL-220686-2020-TECH (2020)

Dispersive cooling (275GeV, EIC):

Horizontal cooling rate

- Cooling of protons at the highest energy of 275GeV using storage ring electron cooler (150 MeV)



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

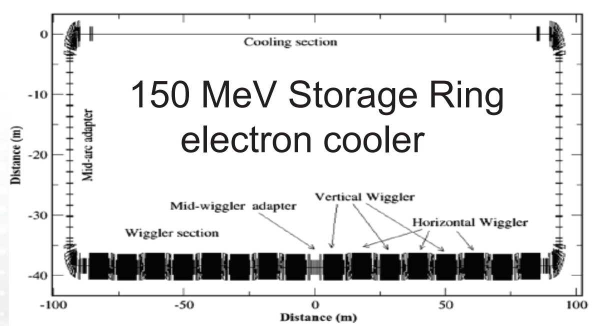


FIG. 2. Layout of the ring cooler.

LEReC electron source and 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, proposed 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 and are planned.

- **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 Run-22 Plan and beyond

2022 (short RHIC physics run: November’21-April’22):

- Cooling studies (with Au ions):

Continue cooling studies using Accelerator Physics Experiments time.

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

Explore Gun operation at high current (50mA and above) in present LEReC configuration.

April - December 2022:

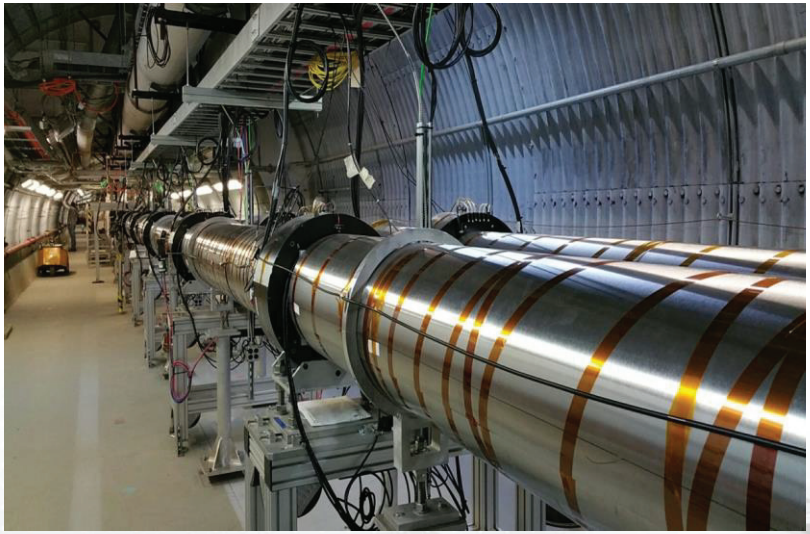
Long RHIC shutdown, no LEReC operations.

2023:

- Further high-current R&D studies (possibly, remaining cooling studies)

Summary

- LEReC is the world's first electron cooler which uses rf-accelerated electron bunches. It is also the first cooler which does not use any magnetization of the electron beam. The same electron beam is used twice to cool Au ions in both collider rings.
- Electron cooling in RHIC was fully operational and provided luminosity improvements for the Beam Energy Scan II Physics program with Au ions in 2020 and 2021.
- LEReC operation for the RHIC Physics program concluded in 2021. The focus now is being shifted towards cooling studies and high-current R&D.



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.

As well as FNAL, ANL, JLAB and Cornell University.

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!

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Recent LEReC peer-reviewed publications

- A. Fedotov et al., ” Experimental demonstration of hadron beam cooling using radio-frequency accelerated electron bunches”, Physical Review Letters 124, 084801 (2020).
- D. Kayran et al., ” High-brightness electron beams for linac-based bunched beam electron cooling”, Phys. Rev. Accel. Beams 23, 021003 (2020).
- S. Seletskiy et al., ” Accurate setting of electron energy for demonstration of first hadron beam cooling with rf-accelerated electron bunches”, Phys. Rev. Accel. Beams 21, 111004 (2019).
- X. Gu et al., ”Stable operation of a high-voltage high-current dc photoemission gun for the bunched beam electron cooler in RHIC”, Phys. Rev. Accel. Beams 23, 013401 (2020).
- H. Zhao et al., ”Cooling simulation and experimental benchmarking for an rf-based electron cooler”, Phys. Rev. Accel. Beams 23, 074201 (2020).
- S. Seletskiy et al., ”Obtaining transverse cooling with non-magnetized electron beam”, Phys. Rev. Accel. Beams 23, 110101 (2020).