Experience and Challenges with Electron Cooling of Colliding Ion Beams in RHIC

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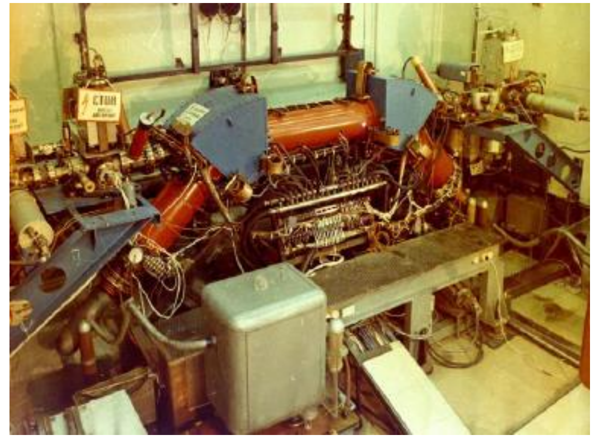
Electron Cooling

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

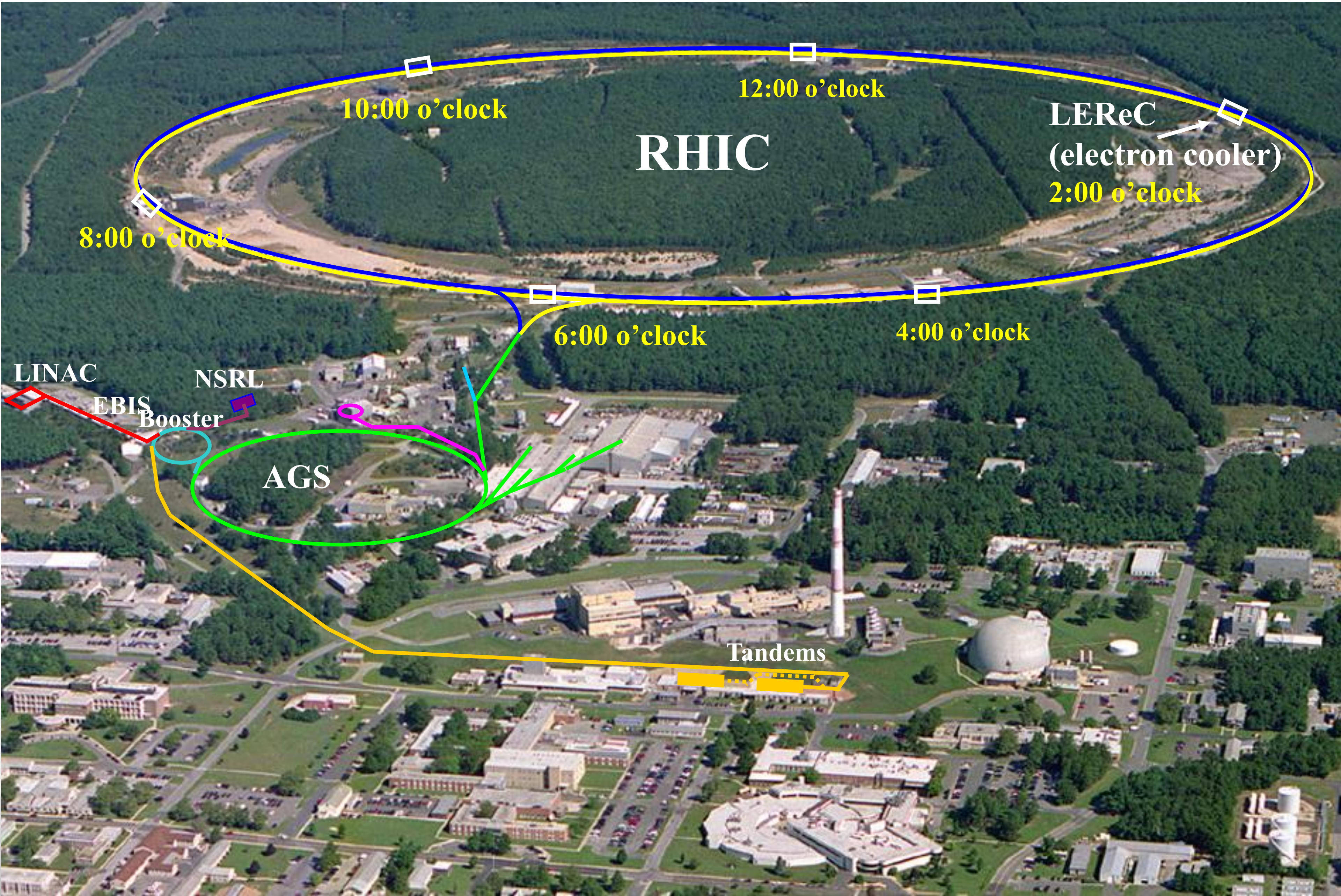


First experimental electron cooling demonstration at NAP-M storage ring (Novosibirsk, Russia, 1974).

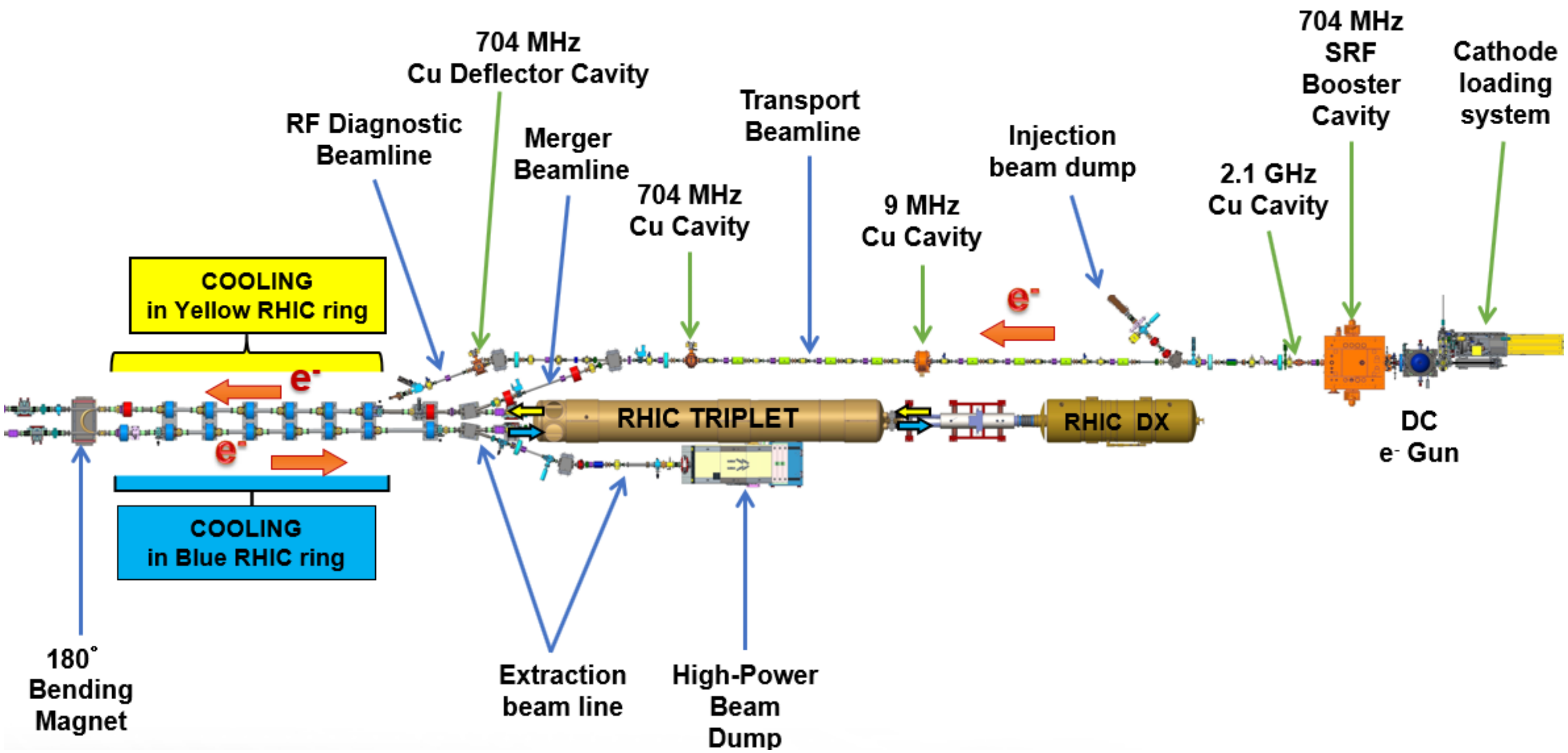
High Voltage DC coolers: **(1974-):** all DC electrostatic accelerators; all use magnetic field to confine electron beam (magnetized cooling). FNAL Recycler cooler: Pelletron electrostatic generator (4MeV electrons), transport of electron beam without continuous magnetic field.

RF acceleration (High Energy approach) **(2019-):** BNL electron cooler LEReC: 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 to cool ion bunches directly at collision energy.

RHIC @ BNL, Long Island, New York

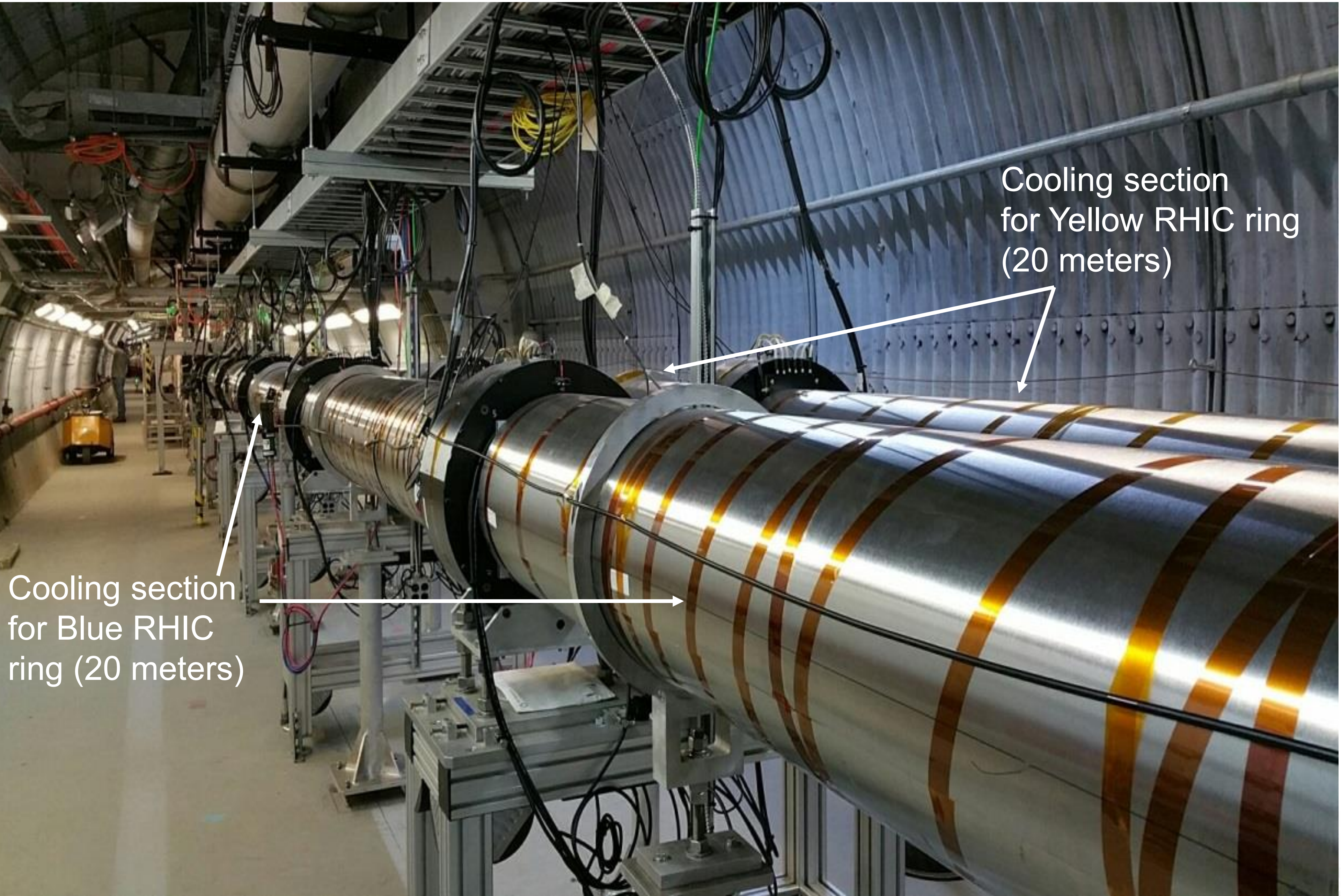


Distinctive features of LEReC



- 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 cooling sections



LEReC electron beam parameters

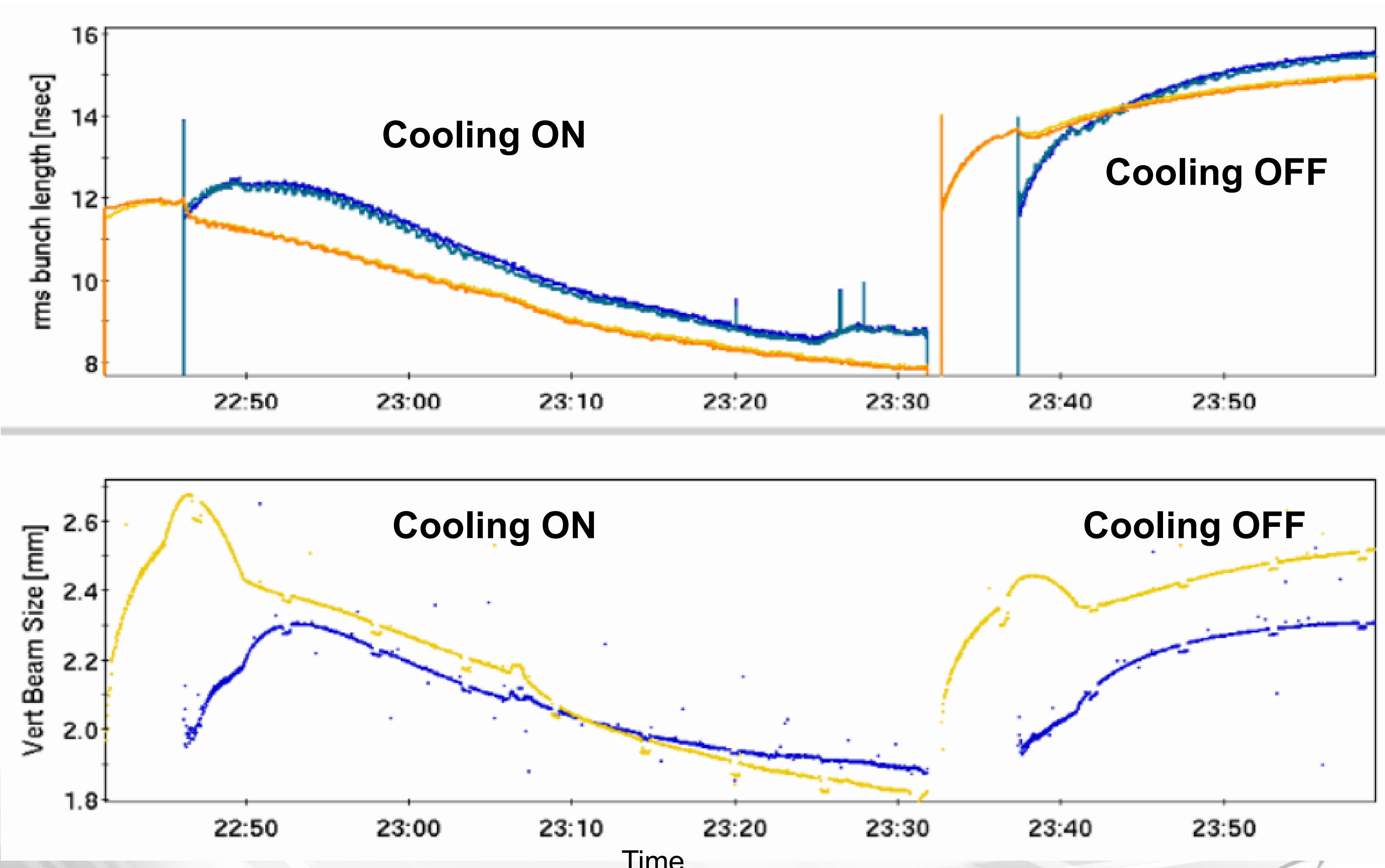
Cooler parameters used for RHIC operations		
Au ions beam energy, GeV/nucleon	3.85	4.6
Electrons kinetic energy, MeV	1.6	2.0
Cooling section length, m	20	20
Electron bunch (704MHz) charge, pC	30-70	50-70
Bunches per macrobunch (9 MHz)	36	30-36
Charge in macrobunch, nC	1-2	1.5-2
RMS normalized emittance, 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).

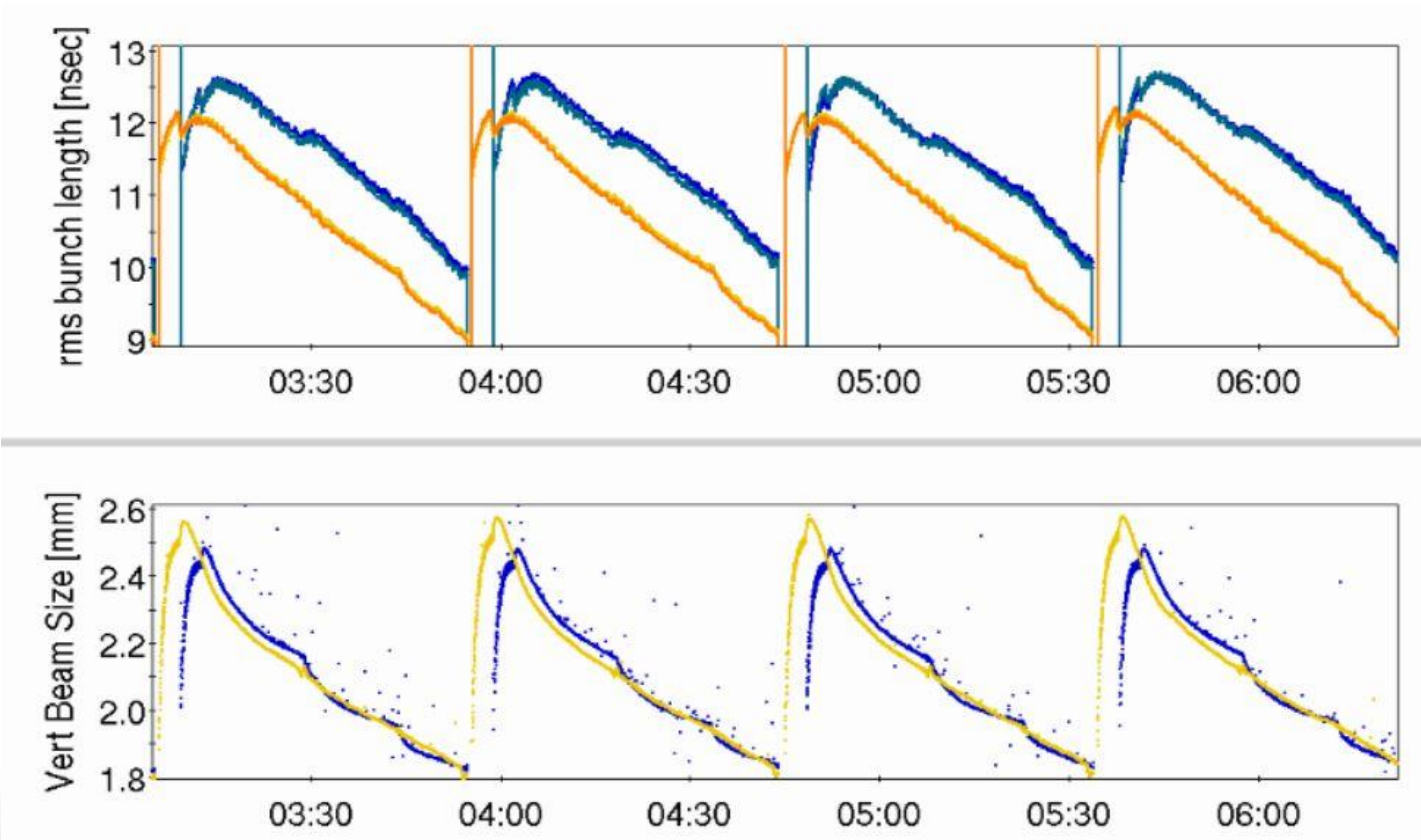
LEReC operational experience

- Stable 24/7 running of high-current electron accelerator and robust cooling was provided over many weeks of collider operation in 2020 and 2021.
- Electron cooling effectively counteracted emittance and bunch length growth due to the Intra-beam scattering. In addition, transverse cooling was optimized to further reduce the ion beam sizes.
- Operational electron current, based on optimization between cooling and other 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).
- Reliable operation was ensured by implementation of laser position feedbacks, intensity feedback, energy feedback, automatic cooling section orbit correction and feedback.
- 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)



Physics stores for Au ions at 4.6 GeV/nucleon (using 2 MeV electrons): rms bunch length (top) and rms beam size (bottom)



Time

Cooling in a collider

Application of electron cooling technique directly at collision energy of hadron beams requires special considerations:

- Control of ion beam distribution under cooling, not to overcool beam core (especially when ion beam space charge is significant)
- Interplay of space-charge and beam-beam effects in hadrons (proper choice of working point)
- 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).

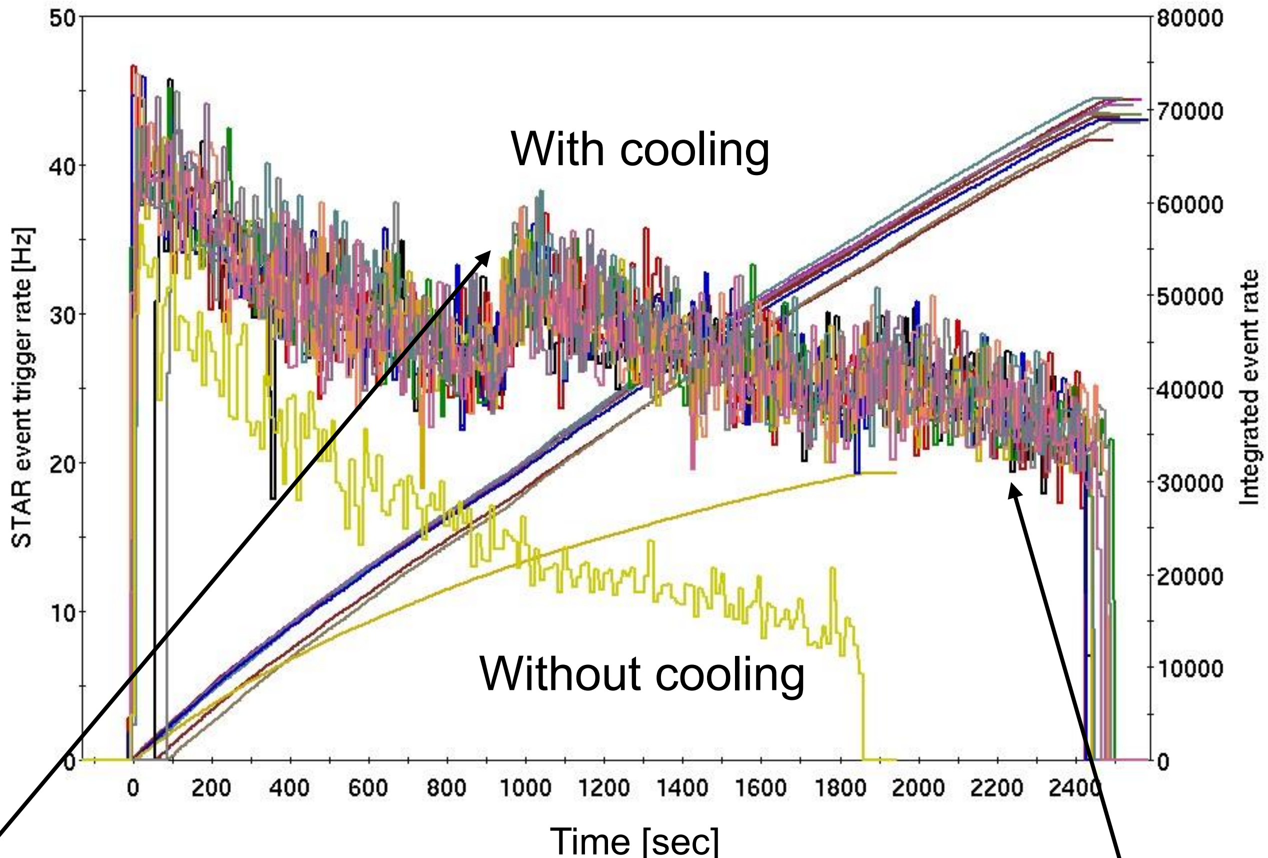
• Providing transverse cooling appeared to be more beneficial for collider operations compared to the longitudinal cooling. This is because longitudinal cooling led to higher peak currents of ions, affecting the ion beam's lifetime due to the space-charge effects.

Cooling optimization for luminosity

Luminosity optimization with cooling included:

- Finding optimum angular spread of electrons in both 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 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.

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

For details of collider performance with electron cooling see: C. Liu et al., Phys. Rev. Accel. Beams, v. 25, 051001 (2022)

Anticipated LEReC challenges (NAPAC’16)

- Production of 3-D high-brightness electron beams ✓
- Transport of such electron beams preserving beam quality ✓
- Operation at several energies; control of electron angles in the cooling section to a very low level for all energies. ✓
- Electron cooling without any help from magnetization: requires very strict control of both longitudinal and transverse electron velocity spread. ✓
- Use the same electron beam to cool ions in two collider rings: preserving beam quality from one cooling section to another. ✓
- Bunched beam electron cooling. ✓

Cooling in a collider:

- Control of ion beam distribution under cooling
- Effects on hadron beam from electrons
- Interplay of space-charge and beam-beam in hadrons
- Cooling and ion beam lifetime

These effects were indeed essential for optimizing luminosity in a collider with electron cooling.

Challenges during RHIC operations

Several challenges which required special attention:

- Effect on electrons from ions: Significant focusing effect on electrons due to the ion's space charge, especially when ion bunch intensity was high.
- 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.
- Loss on recombination: Without continuous longitudinal 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.
- 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 the dominant limiting factor requiring operation at reduced electron currents - stronger cooling does not necessarily lead to highest luminosity.

Cooling studies using LEReC

Starting 2021 LEReC is being used for dedicated experiments:

- Emittance growth of ion beam ("heating") due to interaction with bunched electron beam

S. Seletskiy et al., TUEZ5, this conference

- Coherent excitations of ions and circular attractors

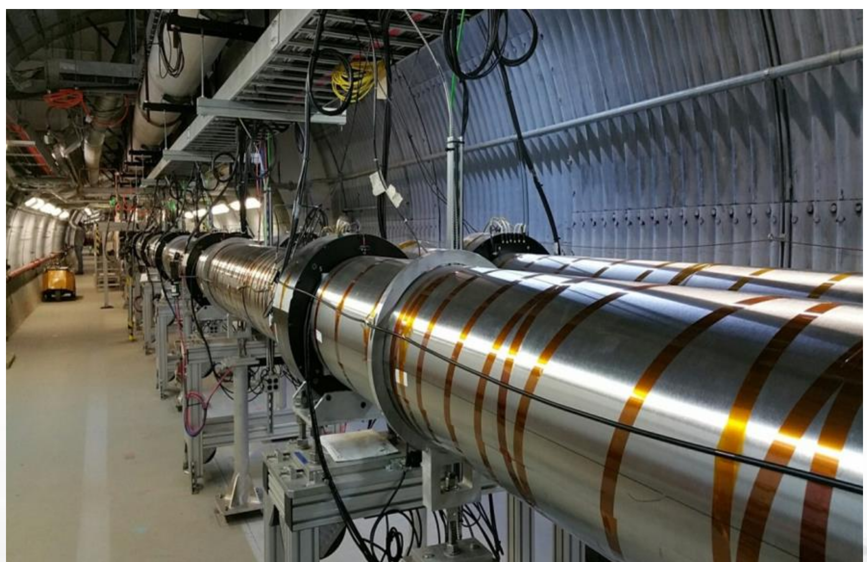
S. Seletskiy et al., COOL21 workshop

- Recombination of ions without continuous magnetic field in cooling section
- Cooling of ion bunch with electron bunches overlapping only small portion of ion bunch
- Dispersive cooling (redistribution of cooling decrements), to provide stronger transverse cooling
- Effects of the presence of the electron beam on the ion beam lifetime

Detailed exploration of these effects is critical for future high-energy coolers.

Summary

- Electron cooling of gold ion beams employing RF-accelerated electron bunches was successfully used to cool ion beams in both collider rings during RHIC operation in 2020 and 2021.
- Despite many challenges of cooling optimization for colliding ion beams, cooling was beneficial for collider operations and provided luminosity improvements for the Beam Energy Scan II Physics program with Au ions.
- LEReC operation for the RHIC Physics program concluded in 2021. Present focus is on cooling studies and high-current accelerator R&D.



Acknowledgement

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Thank you!

Recent 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).
- C. Liu et al., “Gold-gold luminosity increase in RHIC for a beam energy scan with colliding beam energies extending below the nominal injection energy”, Phys. Rev. Accel. Beams, vol. 25, 051001 (2022).