RF-based Electron Cooling (LEReC)

Alexei Fedotov on behalf of the LEReC team
Brookhaven National Laboratory

RHICfest, BNL

9-10 July 2026

Brookhaven National Laboratory
U.S. DEPARTMENT of ENERGY

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Electron cooling

Electron Cooling (EC) process is thermalization of two component plasma.

When electrons are co-propagating with the same average velocity as ion beam, in beam rest frame one has two gases with temperatures proportional to their masses: ions - hot, electrons – cold. As a result, ions are cooled.

Temperature relaxation formula in two component plasma:

$$\tau = \frac{3}{8\sqrt{2\pi}n_e Q^2 r_e r_i c L_C}\left(\frac{k_B T_e}{m_e c^2} + \frac{k_B T_i}{m_i c^2}\right)^{3/2}$$

Formal publication of EC method with its practical application:

G.I. Budker: "An effective method of damping particle oscillations in proton and antiproton storage rings", Atomnaya Energia, Vol. 22, No.5, p. 346, May 1967.

Rough estimate:

H. Hereward: "Artificial damping in the CERN proton storage rings", MPS/Int DL-66-7 Tech Note, 23 September 1966.

From Hereward paper: "In this connexion another possibility, suggested by Budker, is a stream of electrons with the same velocity as average proton.. " (for high-energy application, 12 MeV electrons).

Physics Today, 1977:

The electron-cooling idea was first proposed by Lyman Spitzer (Princeton University) about 20 years ago. At that time C. Tsao and Gerard K. O'Neill (Princeton University) did a theoretical analysis, and verified that the idea should work. In 1966 Gersh I. Budker (Novosibirsk) independently developed the electron-cooling idea, reporting on it that year at the Paris particle-accelerator conference. He and Alexander Skrinsky (Novosobirsk) then proposed building a proton–antiproton colliding-beam device using electron cooling (PHYSICS TODAY, August 1969, page 62).

First report by Budker on Electron Cooling work in Novosibirsk at the International Symposium on Electron and Positron Storage Rings, Saclay, 26-30 September 1966:

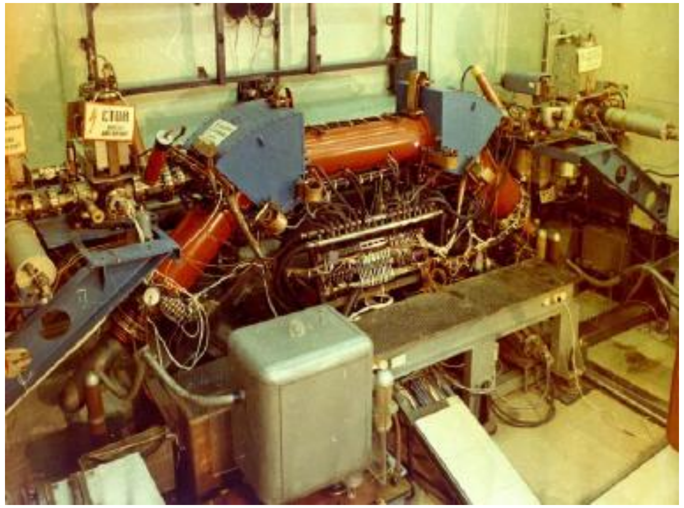
STATUS REPORT OF WORKS ON STORAGE RINGS AT NOVOSIBIRSK

SHORT SUMMARY OF THE TALK GIVEN BY :

G.I. BUDKER

Lack of radiation damping for heavy particles somewhat complicates their accumulation. We are working out in our Institute a method of artificial damping through interaction between the proton beam and an electron beam. In discussions with prof. O'Neill, I found out that they also contemplated such a method several years ago, and named it "electron cooling".

Electron Cooling implementation



To demonstrate electron cooling concept experimentally, a special proton storage ring NAP-M ("Model of Antiprotons Accumulation") and a system producing required electron beam was built in Novosibirsk.

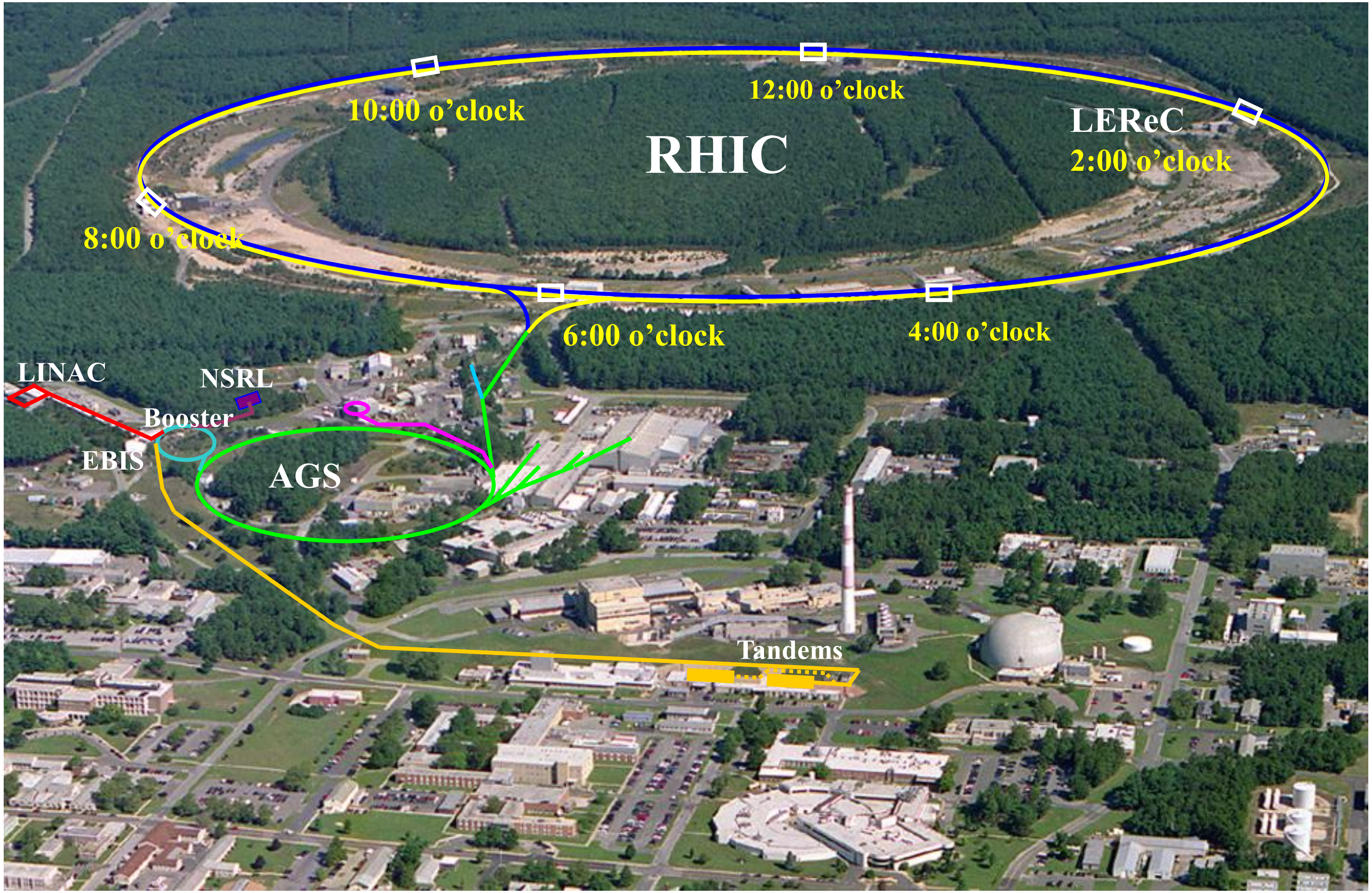
First experimental demonstration of electron cooling at NAP-M storage ring, cooling of 65MeV protons using 35keV electrons (Novosibirsk, 1974).

High Voltage DC coolers: **(1974-):** all DC electrostatic accelerators; all use magnetic field to confine electron beam (magnetized cooling). **FNAL cooler (2005-11):** Extension to relativistic energies (4.3MeV electrons), transport of electron beam without continuous magnetic field.

RF acceleration (High Energy approach): **BNL LEReC electron cooler (2019-25):** First RF-based electron cooler (concept directly extendable to higher energies). LEReC does not use any magnetization of electrons. LEReC was successfully used for RHIC operations in 2020-21 to provide 3D cooling of ion bunches directly at collision energy. Observation of Electron Cooling at highest to date energy (9.5MeV electrons) with CeC accelerator (2026).

A. V. Fedotov et al. "Experimental Demonstration of Hadron Beam Cooling Using Radio-Frequency Accelerated Electron Bunches", Phys. Rev. Lett. 124, 084801 (2020)

RHIC @ BNL, Long Island, New York



RF-based Electron Cooling

To cool hadron beam (protons/ions), electron beam has to propagate with the same average velocity as the one of the hadron beam.

$$E_e = \left(\frac{m_e}{M_i}\right) E_i$$

For example, to cool 100 GeV protons would require 54MeV electrons.

RF acceleration is a natural approach to get e-beam to 10s of MeV.

Low-Energy RHIC Electron Cooler (LEReC) was the world's first electron cooler which used RF-accelerated electron bunches.

Since the goal of LEReC was to cool Au ions for RHIC operation at very low energy (Beam Energy Scan physics program in search of QCD critical point), electron beam kinetic energies of only 1.6 and 2MeV were needed. But RF acceleration approach itself is directly scalable to higher energies.

Electron Cooling at highest to date energy (Ek=9.5MeV), utilizing RF-accelerated electron bunches, was recently observed in RHIC using CeC accelerator (2026).

LEReC history

RF-based Electron Cooling framework was developed for the proposed RHIC-II upgrade (I. Ben-Zvi et al.), which required 54MeV electrons (2000-2007).

Non-magnetized electron cooling approach for RHIC-II was developed 2005-2007, presentations starting with "Cooling dynamics studies and scenarios for the RHIC cooler", PAC'05 Conference, Knoxville, TN, May 2005.

Low-Energy RHIC Electron Cooler (LEReC):

Can We Discover the QCD Critical Point at RHIC?

March 2006 workshop @BNL

Electron Cooling in RHIC at Low Energies
A. Fedotov 93

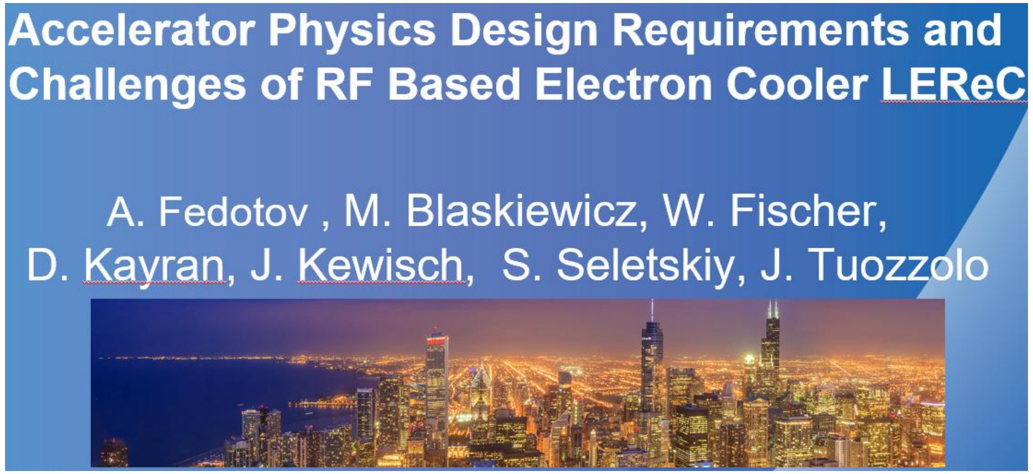
"Electron cooling simulations for low-energy RHIC operation", COOL'07 Workshop, Germany, 2007.

LEReC concept and technology (DC vs RF acceleration, SRF gun vs DC gun) evolved over the years…

LEReC RF-based approach was chosen, 2012:

"Bunched beam electron cooler for low-energy RHIC operation", NAPAC 2013 Conference, Pasadena, CA, 2013.

Final LEReC Accelerator Physics design, NAPAC'16 Conference, Chicago, IL, 2016:



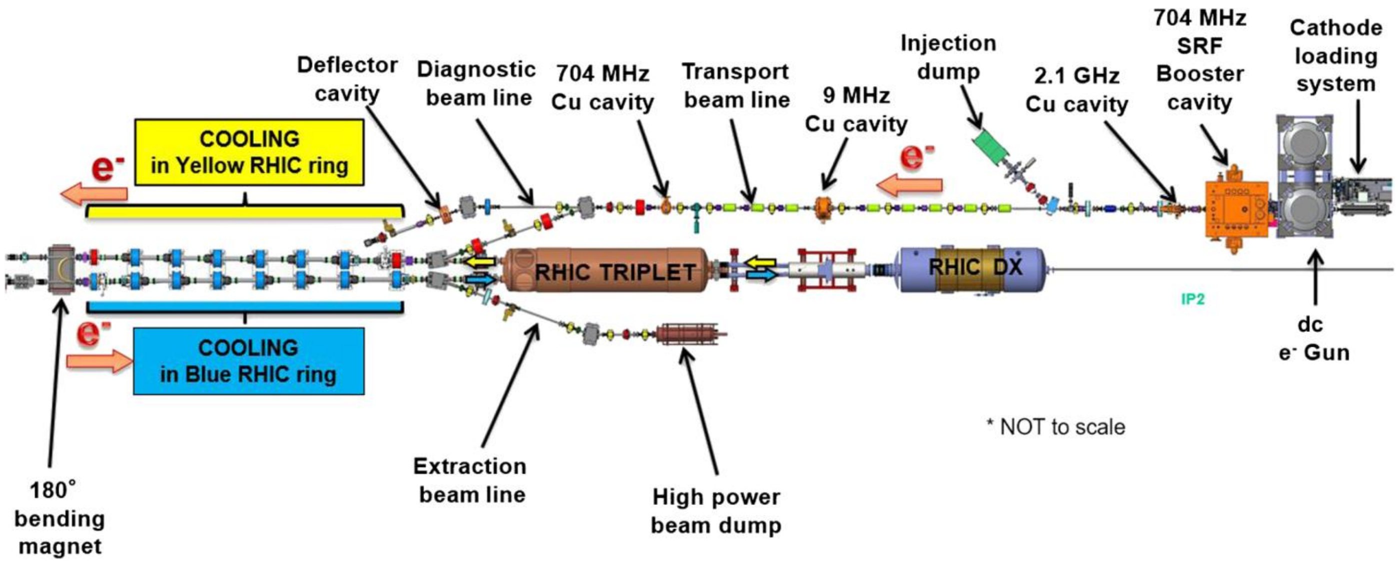
LEReC project timeline

May 2015:	**LEReC project approved for construction**
December 2016:	DC gun (built by Cornell University) successfully conditioned in RHIC tunnel
February 2017:	Gun test beamline installed
April-Aug, 2017:	**Gun tests with electron beam**
July-Dec, 2017:	Installation of full LEReC accelerator (RF, etc.)
March-Sep, 2018:	**Commissioning of full LEReC accelerator with electron beam**
September 2018:	All required electron beam parameters achieved
March 2019:	**Start of cooling commissioning with Au ion beams**
April 5, 2019:	**First cooling demonstration**
April 2019:	Cooling in both RHIC rings using electron bunches at 76 kHz frequency.
May 2019:	Simultaneous cooling of many ion bunches using 9 MHz CW e-beam
June 2019:	Cooling commissioning of beams in collisions (1.6MeV electrons, 3.85 GeV/n ions)
July 2019:	Cooling commissioning at higher electron energy (2MeV electrons, 4.6 GeV/n ions)
2020:	**LEReC transferred to RHIC operations**

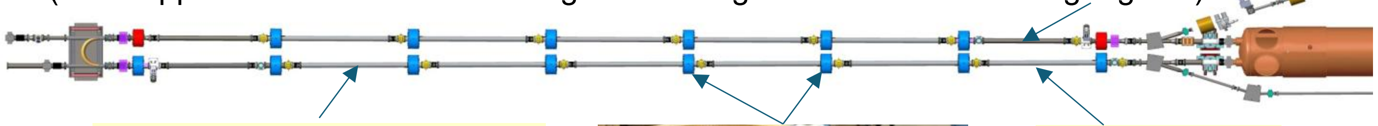
LEReC E-cooling innovations

Key innovations:

- **RF-accelerated** electron bunches
- **Non-magnetized electron beam** (there is no magnetization at the cathode and there is no continuous solenoidal field in the cooling section)
- 3D **cooling** of ion bunches **in two RHIC rings simultaneously using the same electron beam**
- First application of **electron cooling** directly **for colliding ion beams**

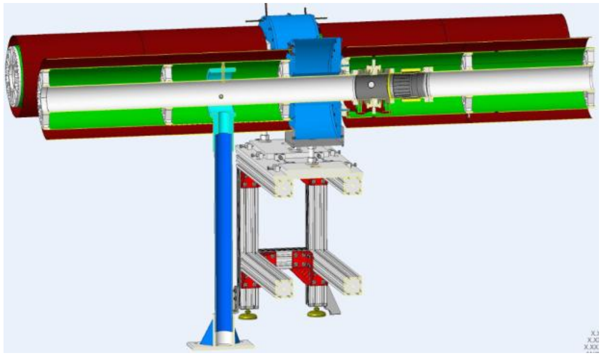


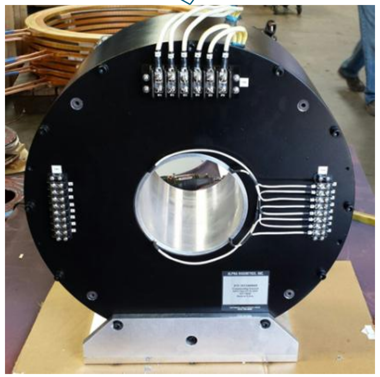
Cooling sections
(with suppressed transverse and longitudinal magnetic field in the cooling regions)



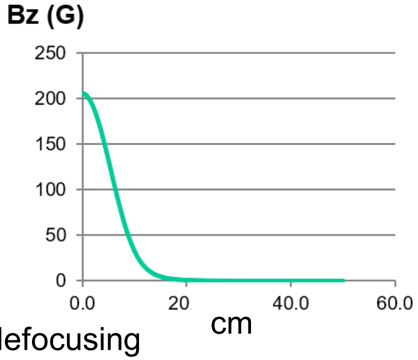
$\int B_{\perp}(z)dz \leq 1.0\ G \cdot cm$

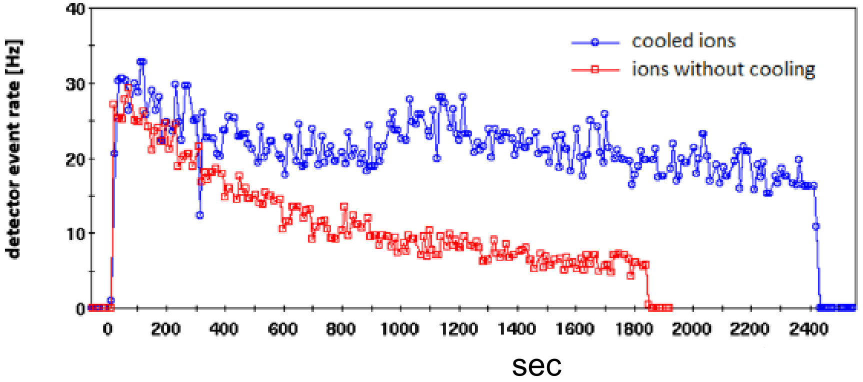
$B_z < 1G$





Correction solenoids to compensate space-charge defocusing

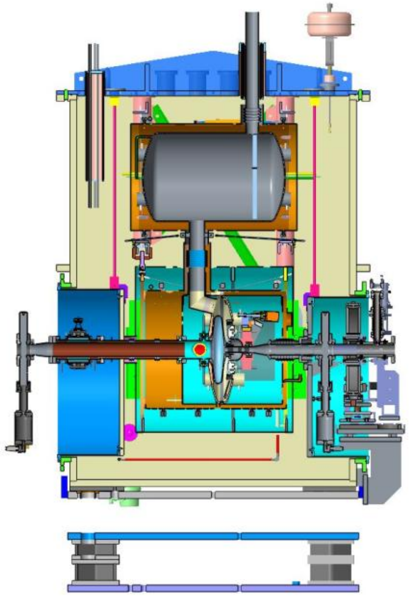


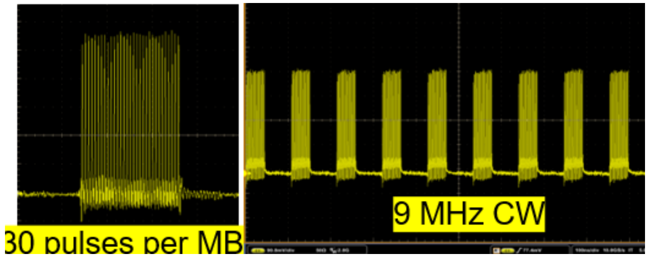


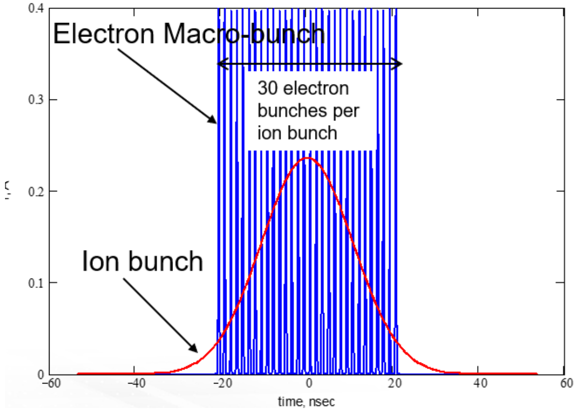
Alexei Fedotov

LEReC RF-based Electron Cooling

- In order to be accelerated to high energy by the RF cavities electron beam has to be bunched.
- Bunches are generated by illuminating a photocathode inside the high-voltage Gun with green light laser (high-brightness in 3D: both emittances and energy spread). Electron beam properties resulting from acceleration of bunched beam are different from those obtained in standard DC beam coolers.
- The 704MHz high-power fiber laser produces required modulations to overlap ion bunches at 9MHz frequency with laser pulse temporal profile shaping using crystal stacking.
- RF gymnastics (several RF cavities) is employed to accelerate electron beam and to achieve energy spread required for cooling. Electron beams of required quality are delivered to cooling sections.
- Electron bunches overlap only small portion of ion bunch. All ion amplitudes are cooled as a result of synchrotron oscillations of ions.

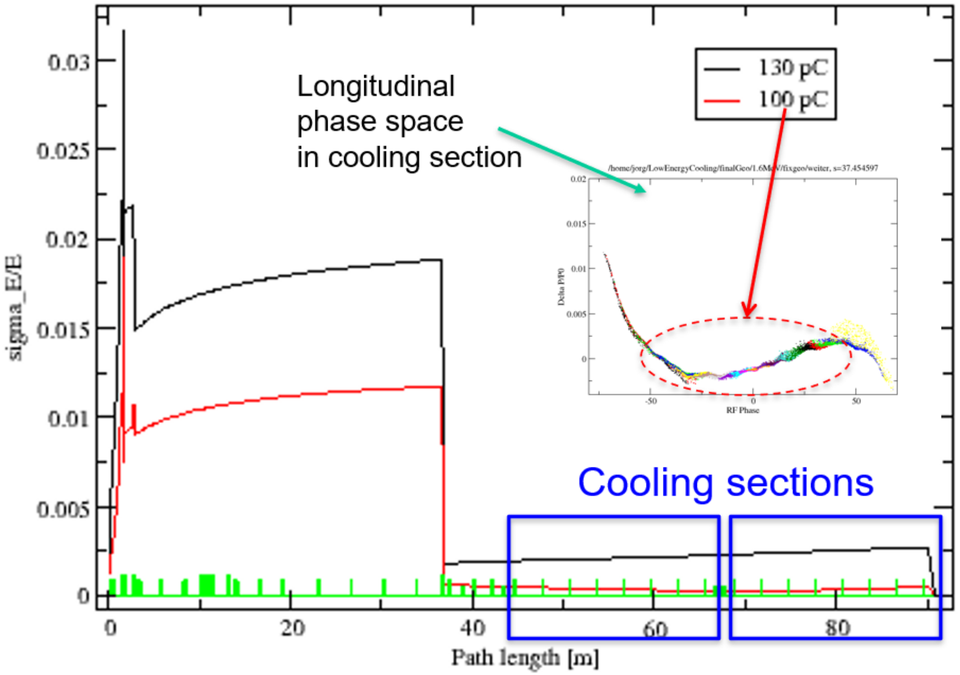


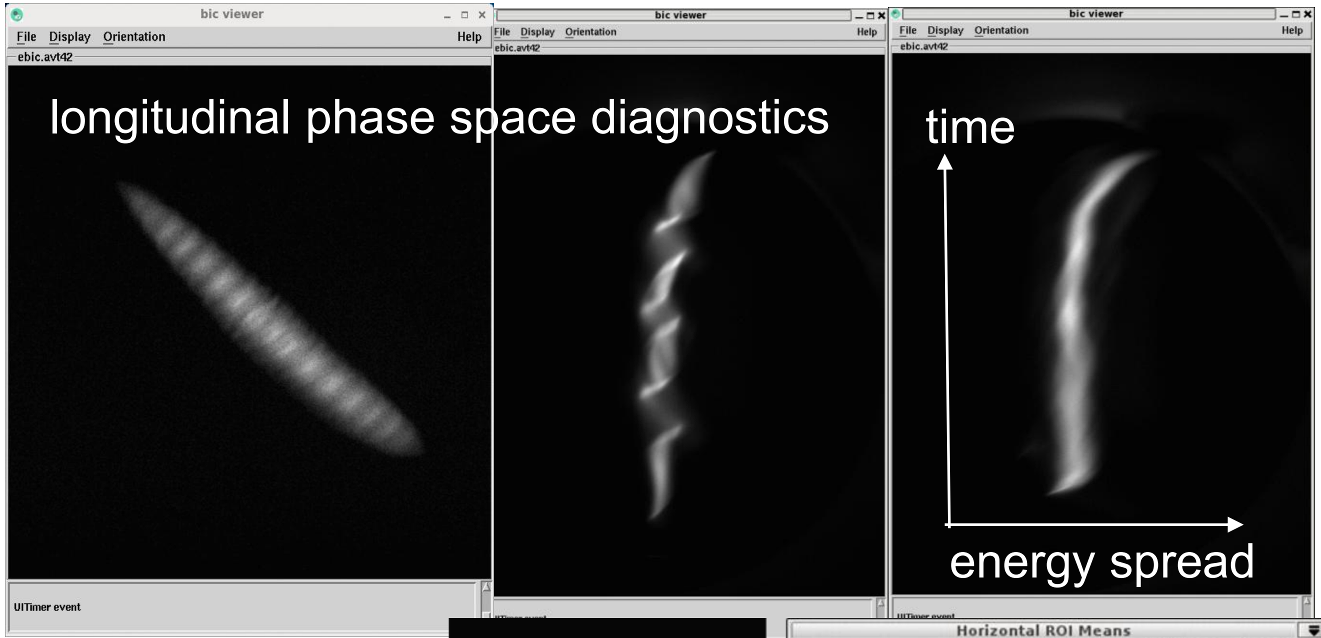




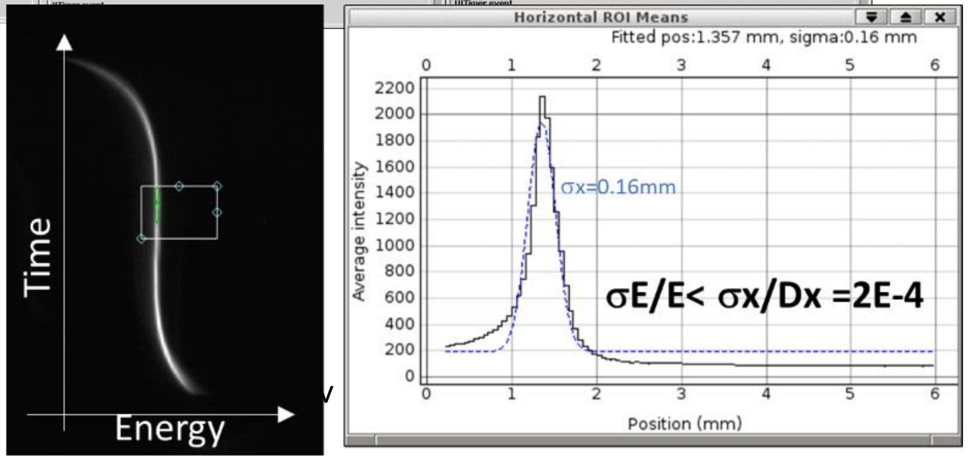
Longitudinal phase space RF gymnastics

- 704 MHz SRF cavity is used for accelerate and create energy chirp for bunch stretching
- 3rd harmonic of the 704 MHz (2.1GHz) RF is used to remove non-linear energy spread introduced by the RF curvature
- After bunches are stretched another 704 MHz NCRF cavity is used to remove energy chirp
- 9 MHz RF cavity is being employed to remove bunch-by-bunch energy variation within the 30-bunch train





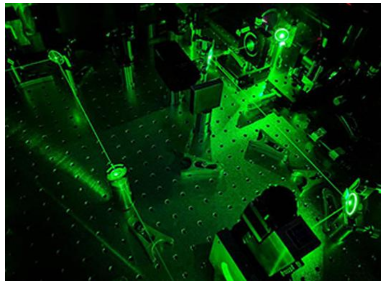
Optimized energy spread:

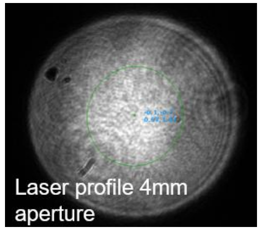


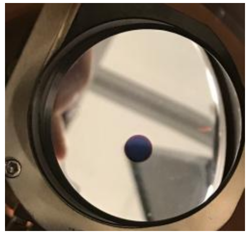
Accelerator Science and Technology

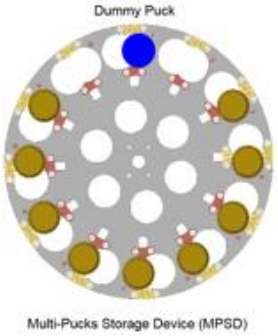
LEReC is based on the state-of-the-art accelerator science and technology:

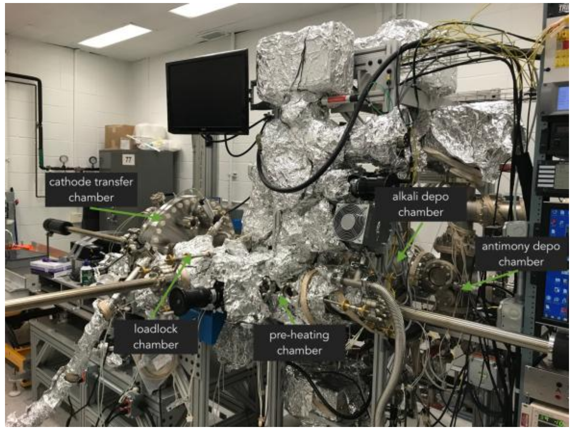
- Photocathodes: production and sophisticated delivery systems
- High power fiber laser, transport and stabilization systems
- Laser beam shaping to produce electron bunches of required quality
- Laser intensity feedback
- Operation of high-voltage photocathode electron gun and high-voltage power supply at high average current
- Several RF cavities and stability control
- Energy stability and control
- Instrumentation and controls

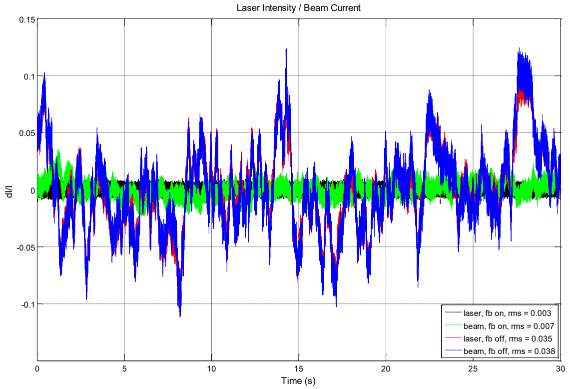


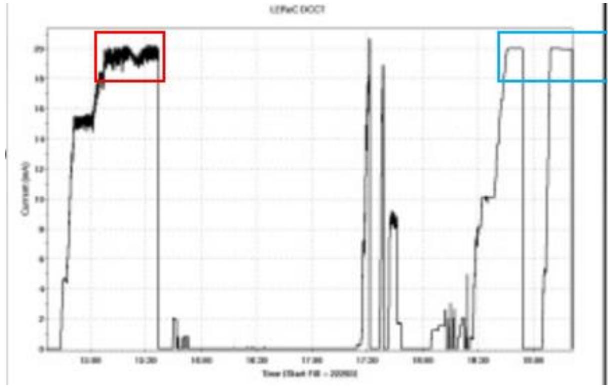






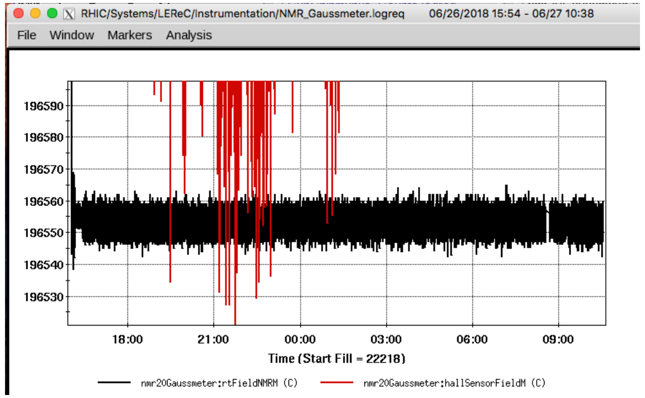


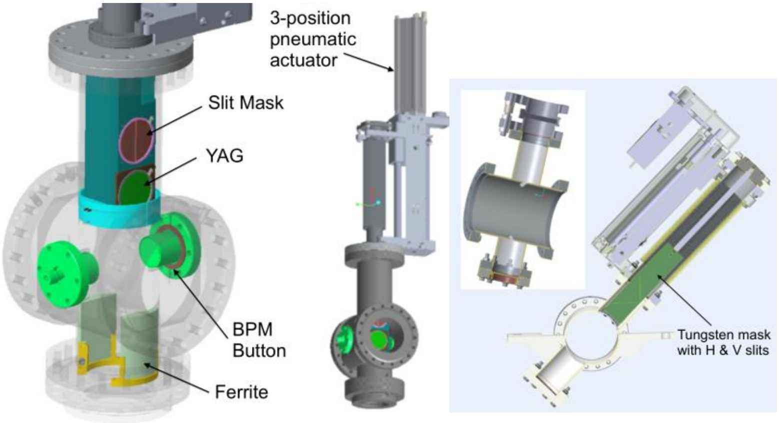




NMR probe:

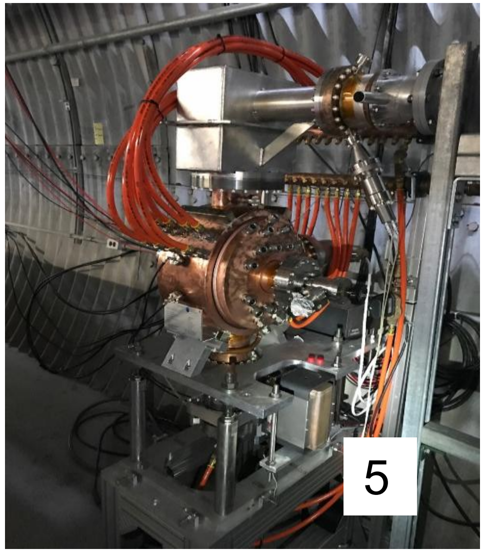
15mG measurement stability @ ~200Gauss (0.7×10^{-4})

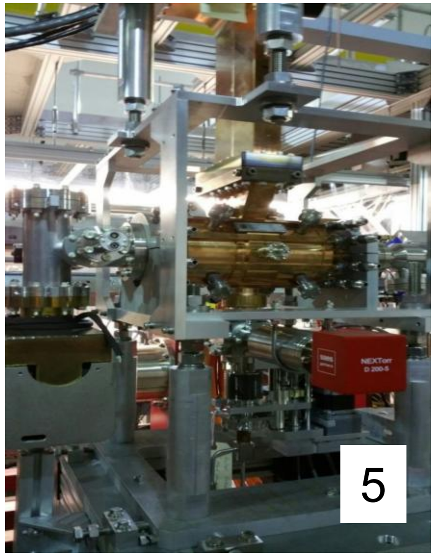


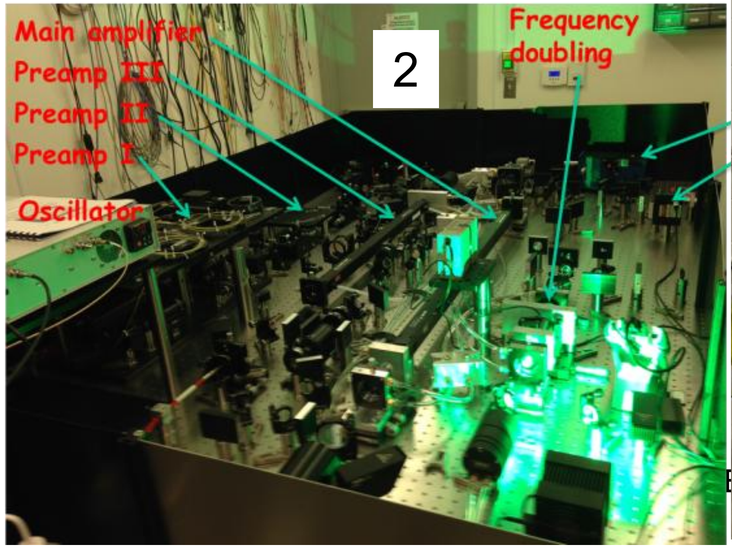


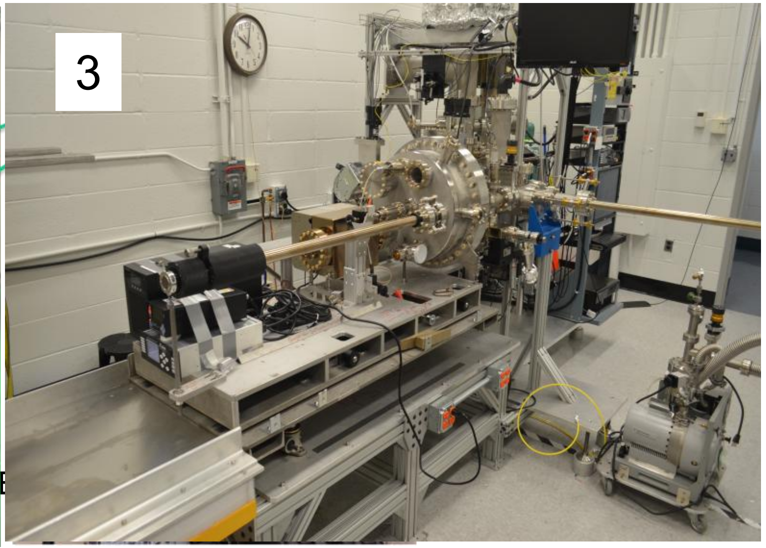
LEReC Critical Technical Systems

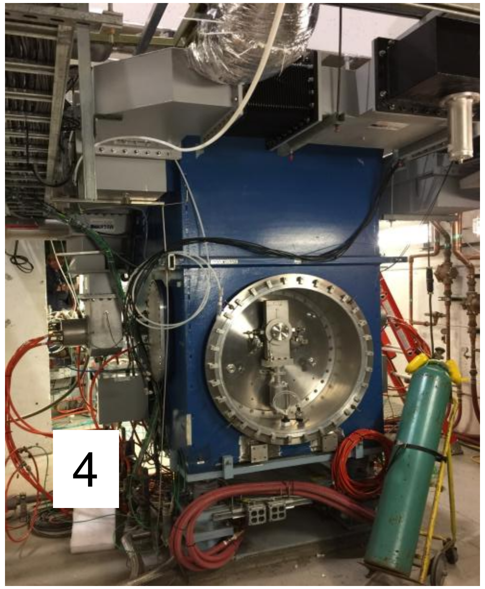
1. High-voltage electron gun and power supply
2. High-power fiber laser, transport and stabilization
3. Cathode production deposition and delivery systems
4. 704 MHz SRF Booster cavity
5. 2.1 GHz and 704 MHz NCRF cavities

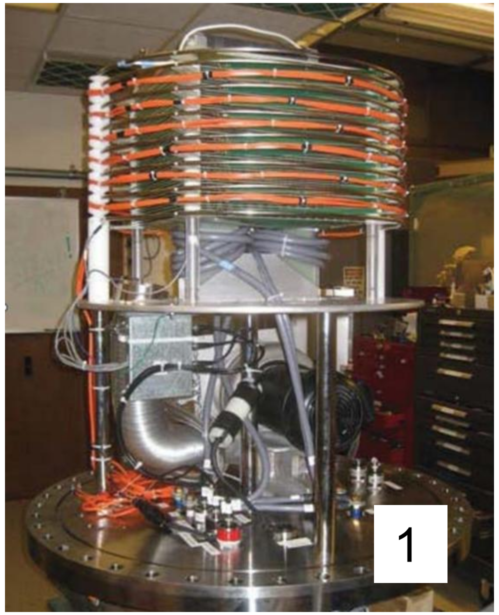






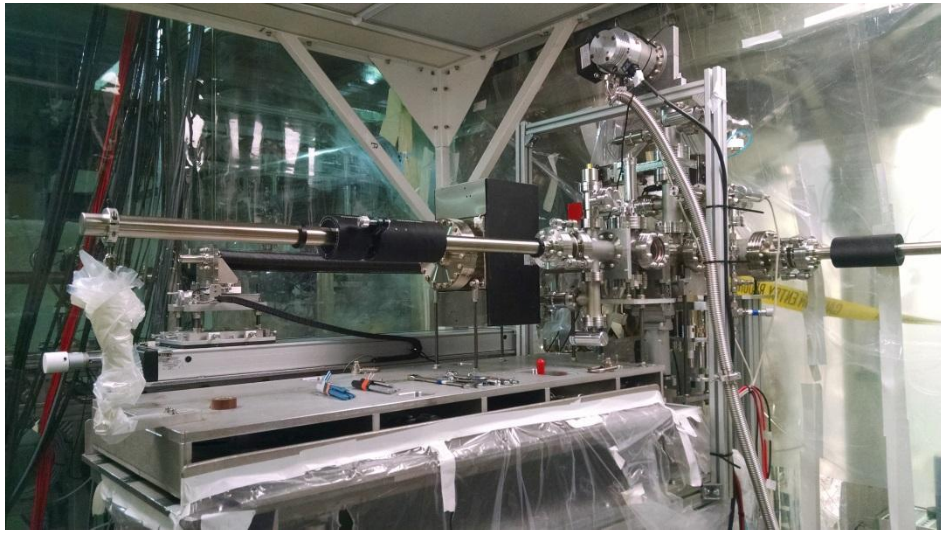




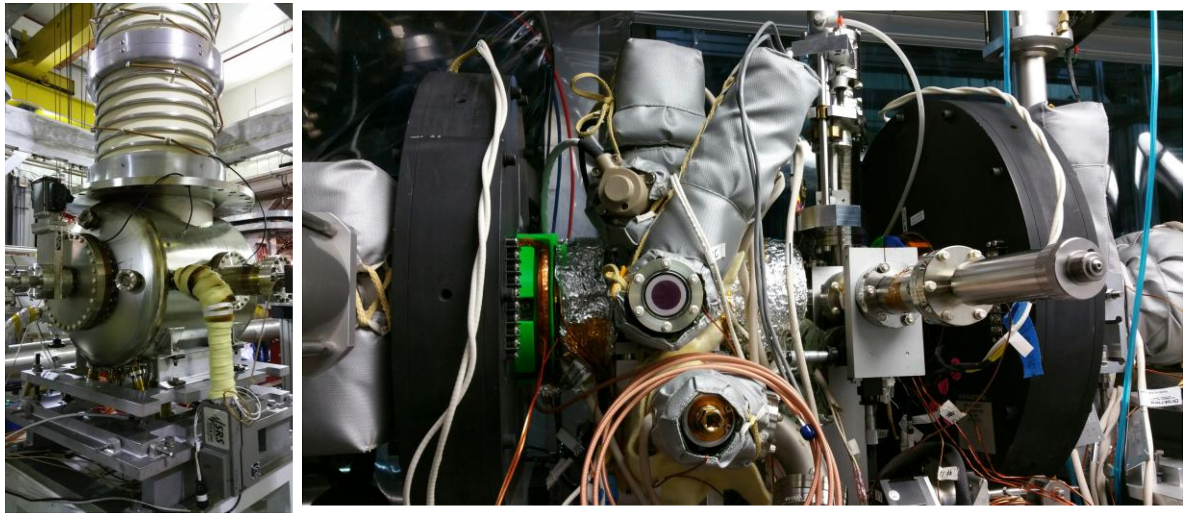


LEReC Gun test beamline
(installation completed in RHIC IR2, February 2017)

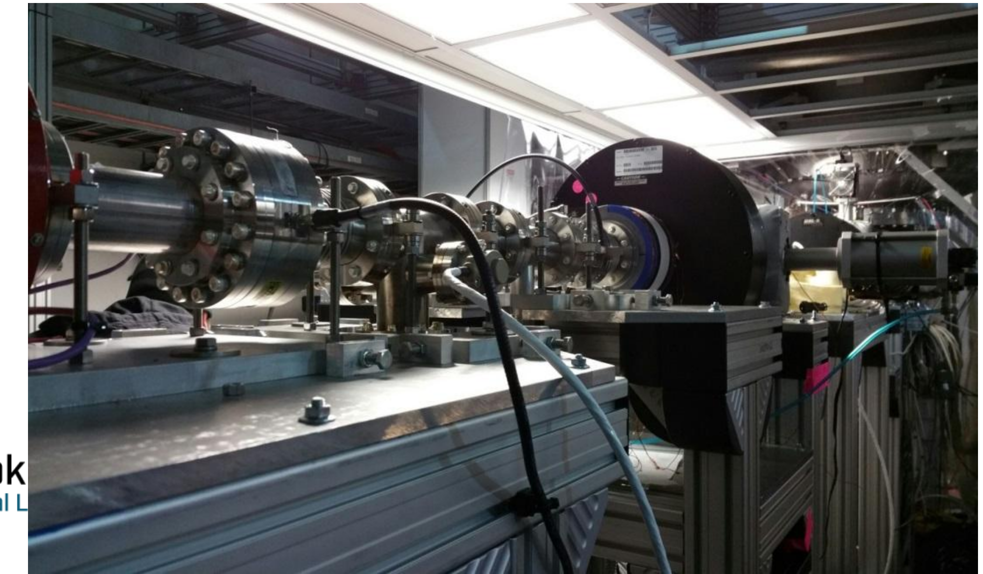
Cathode insertion system



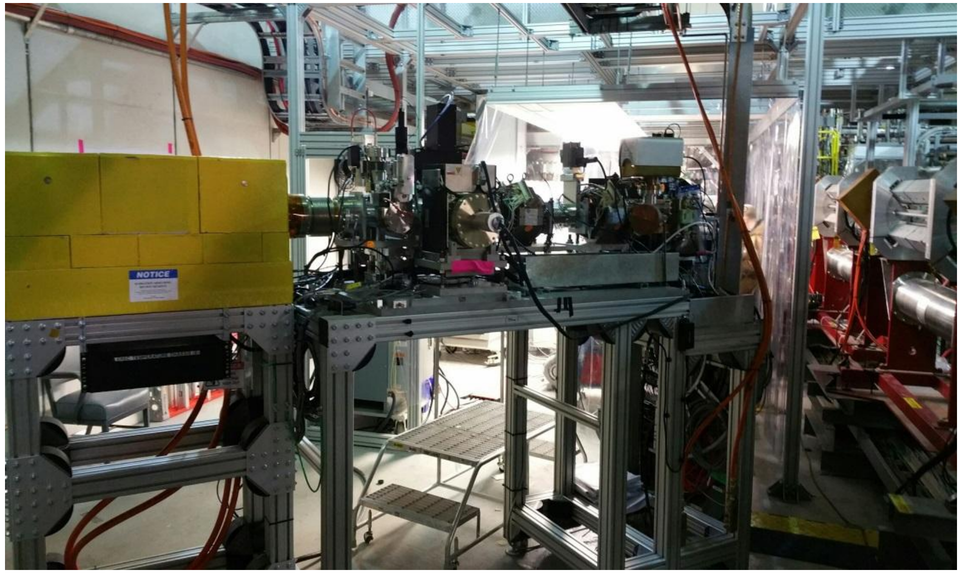
Gun and gun transport section



Transport beamline

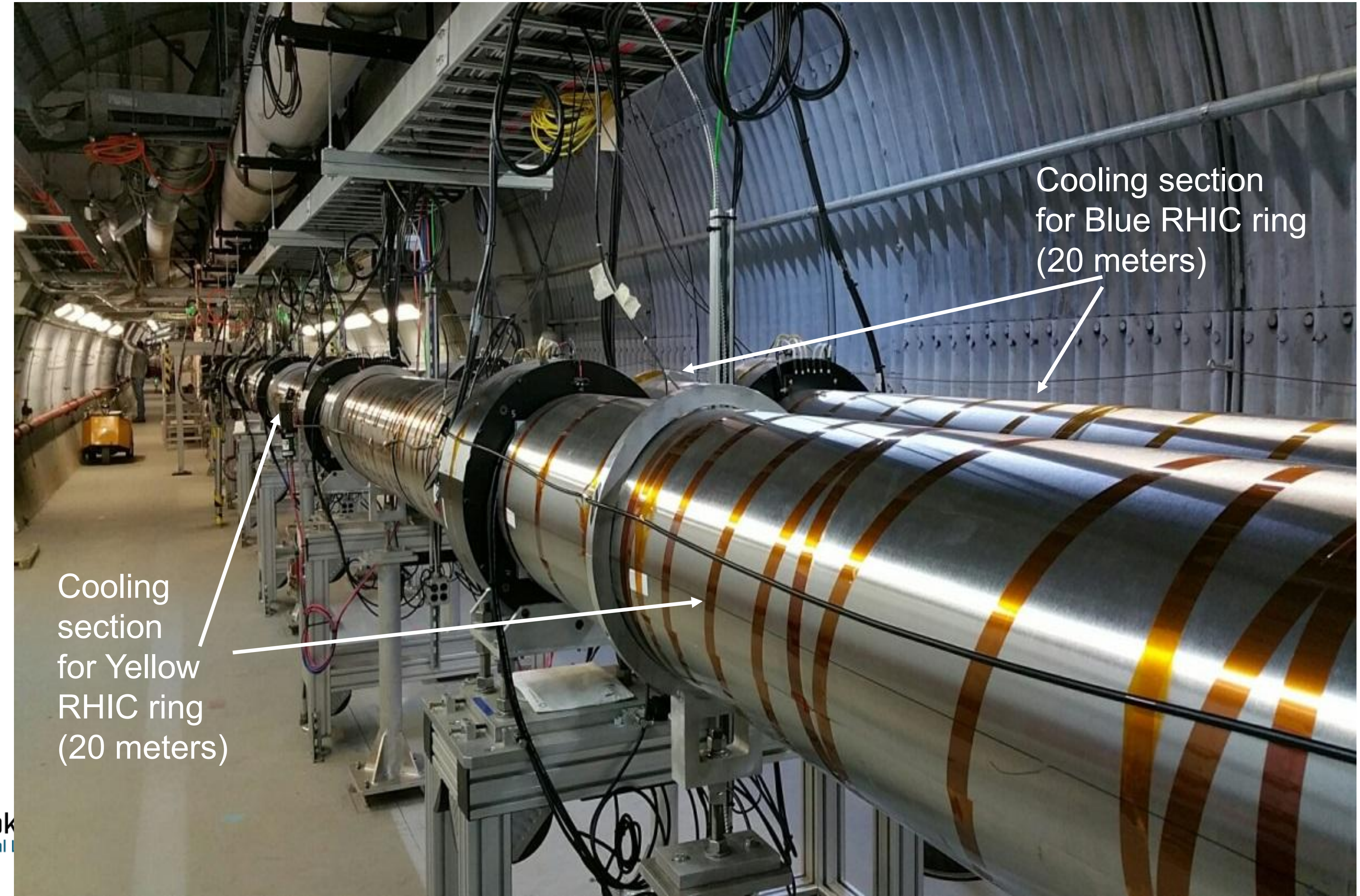


Extraction line and low-power beam dump

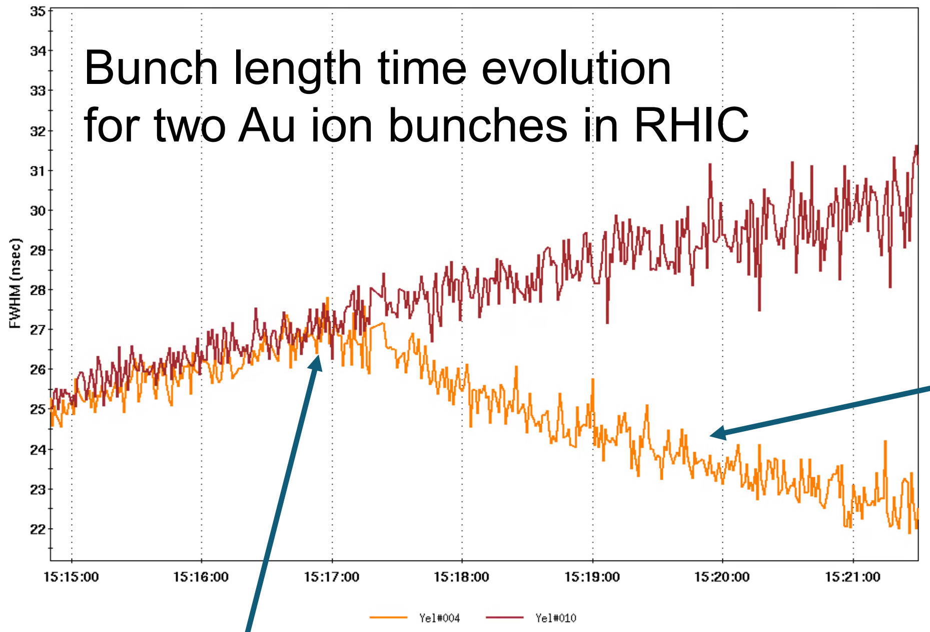


Installation of full LEReC accelerator (October 2017)

LEReC cooling sections fully installed (2018)



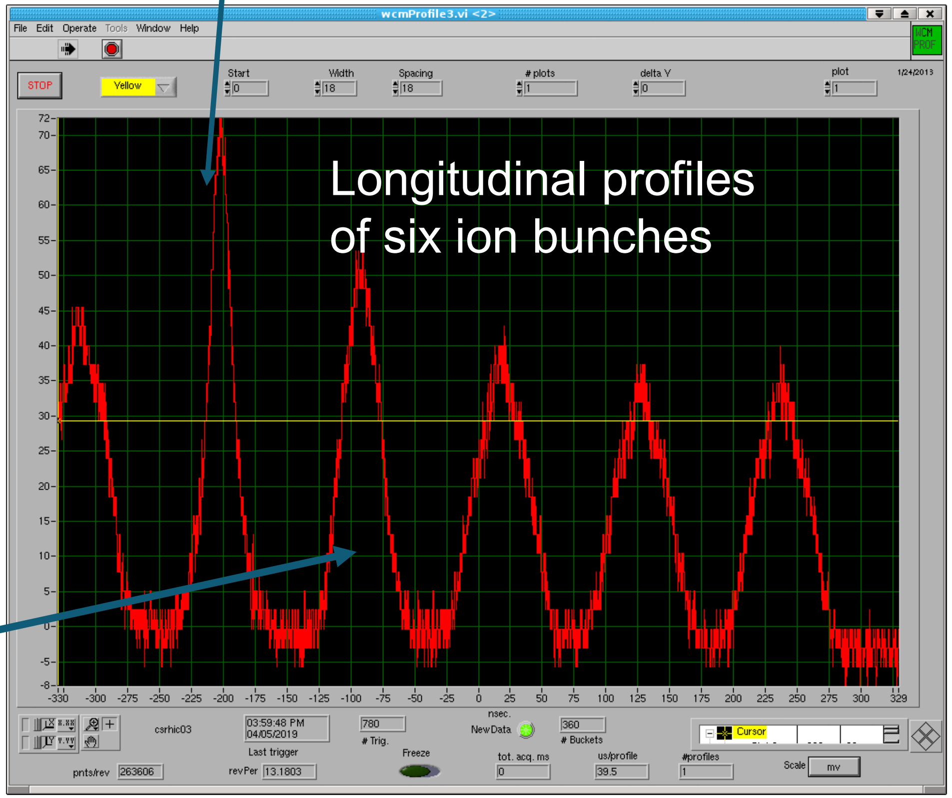
LEReC: First observation of electron cooling - April 5, 2019



Ion bunch #4 which is not being cooled

Ion bunch #2 is being cooled

Energy of electrons and ions matched



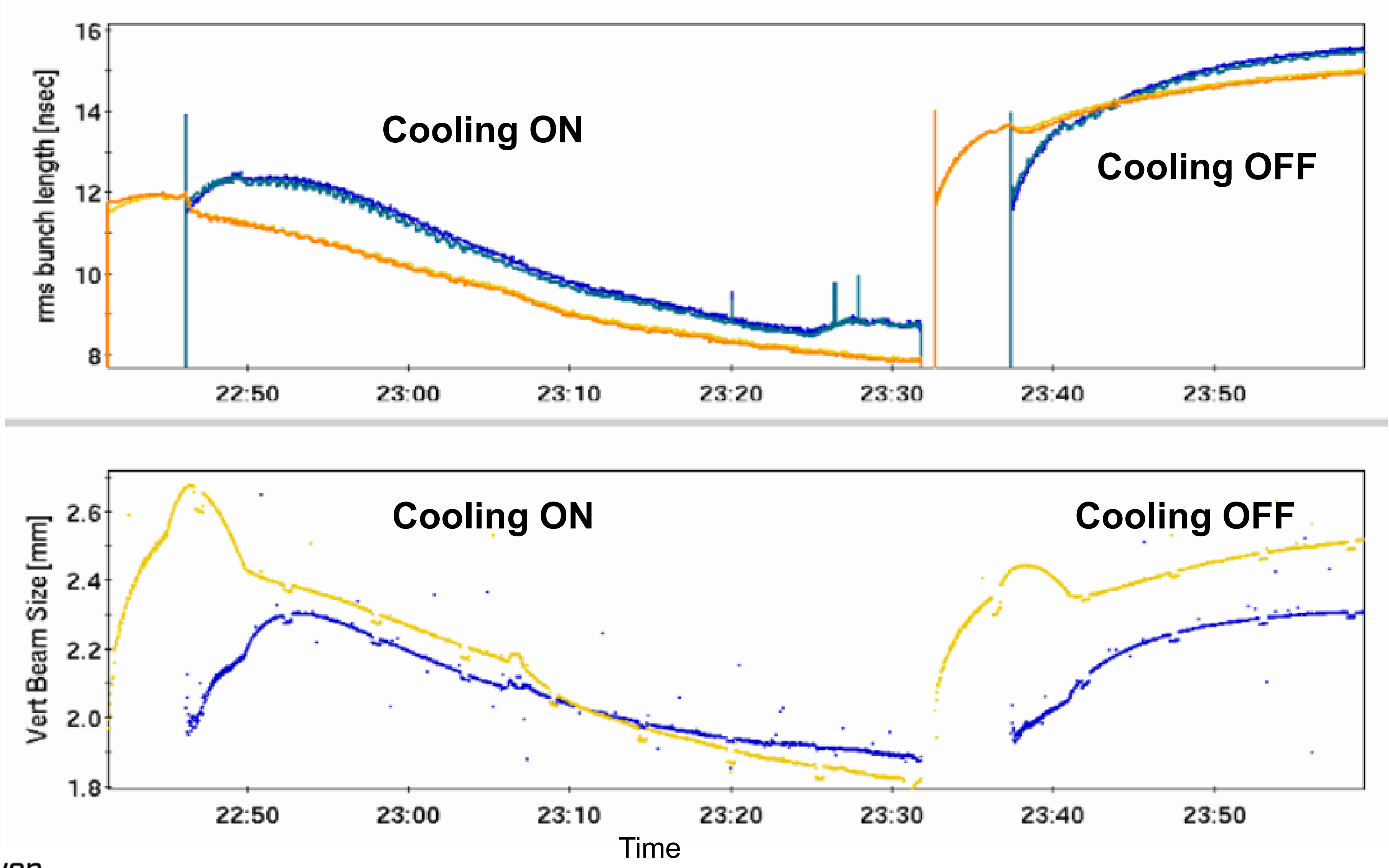
In 76kHz commissioning mode, subsequent electron macro-bunches have lower energy due to beam loading in RF cavities (can match energy/cool effectively single ion bunch).

Brook National

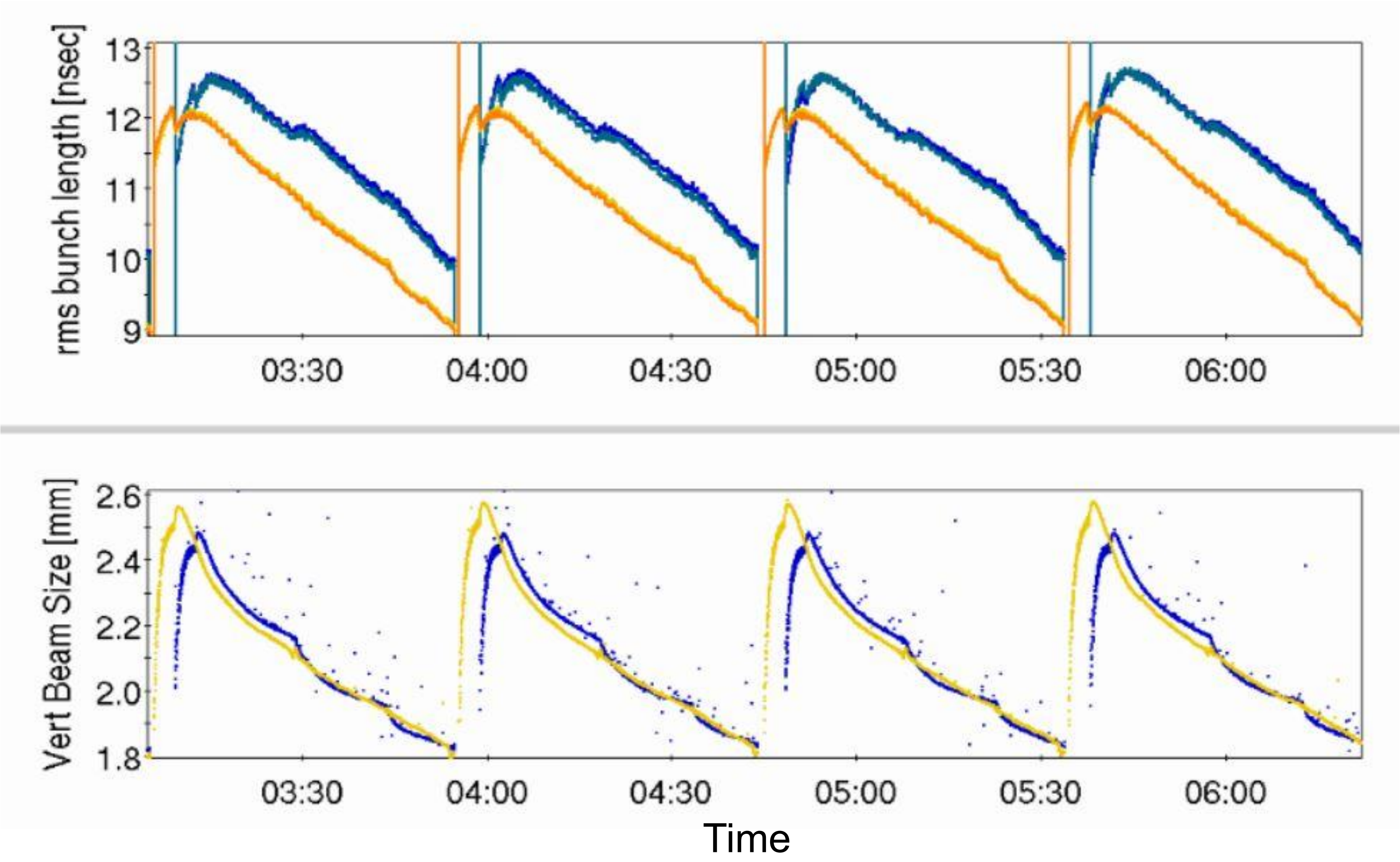
First electron cooling observation, RHIC MCR – April 5, 2019

People left to right (not all present in MCR shown):
S. Seletskiy, K. Mernick, A. Fedotov (in front), M. Blaskiewicz, I. Pinayev, H. Zhao (behind I.P.), G. Wang, V. Ptitsyn…

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)



3-D cooling of colliding Au ion bunches in two RHIC rings simultaneously using
the same electron beam.

LEReC roadmap to operational RF-based electron cooling in a collider

Production and delivery of required electron beam:

- Production of 3-D high-brightness electron beams ✓
- RF acceleration and transport of electron bunches maintaining "cold" e-beam ✓

Cooling demonstrations:

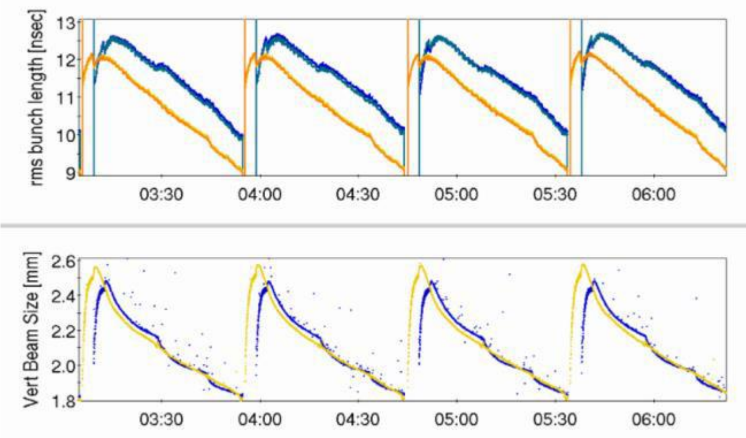
- Energy matching of electron and ion beams ✓
- First electron cooling demonstration in longitudinal plane✓
- Control of various contributions to electron angles in the cooling section to a very low level required for non-magnetized electron cooling ✓
- Demonstration of cooling in 3-D✓

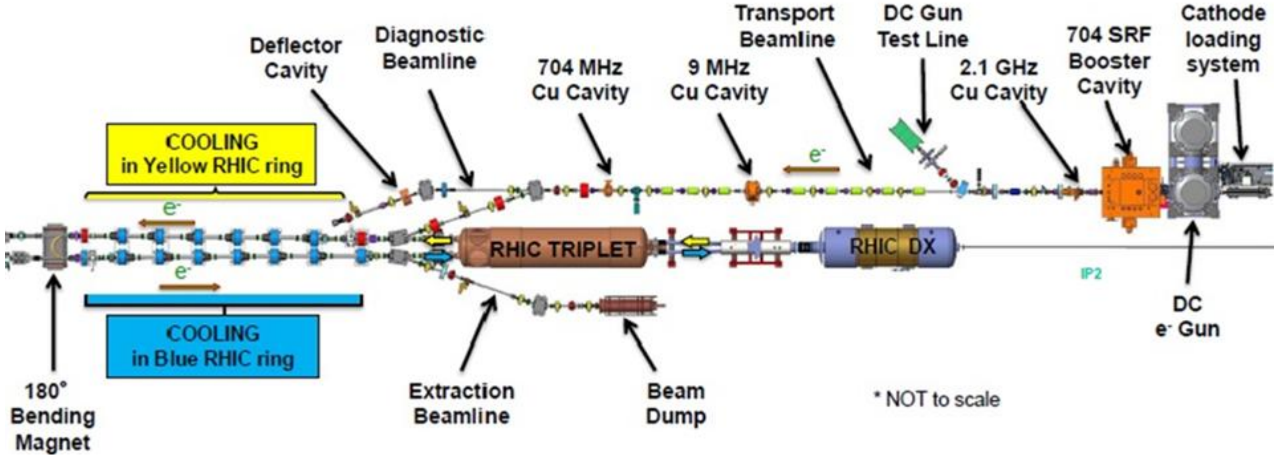
From demonstration to operational RF-based cooler in a collider:

- Establishing stable high-current operation of electron accelerator ✓
- Establishing 3D cooling of many ion bunches (high-current 9MHz CW e-beam operation) simultaneously ✓
- Cooling ion bunches in collisions, in both Yellow and Blue RHIC rings ✓

RF-based Electron cooling at RHIC and EIC

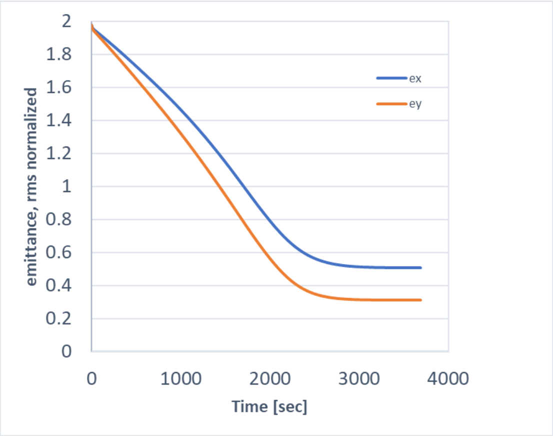
- **LEReC @RHIC** is a fully-operational electron cooler which utilizes RF-accelerated electron bunches (2 MeV electron kinetic energy).

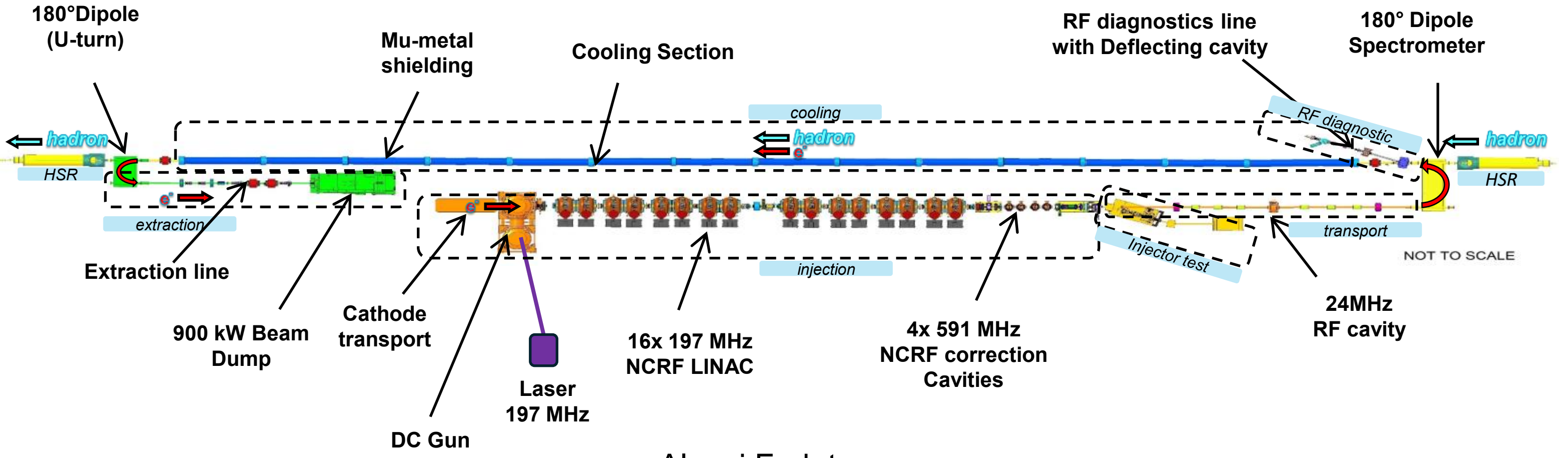




Operational 3D cooling of Au ions during RHIC Run 2020.

- **Low-Energy Cooler (LEC) @ EIC** uses LEReC approach with electron energy extended to 12.5 MeV

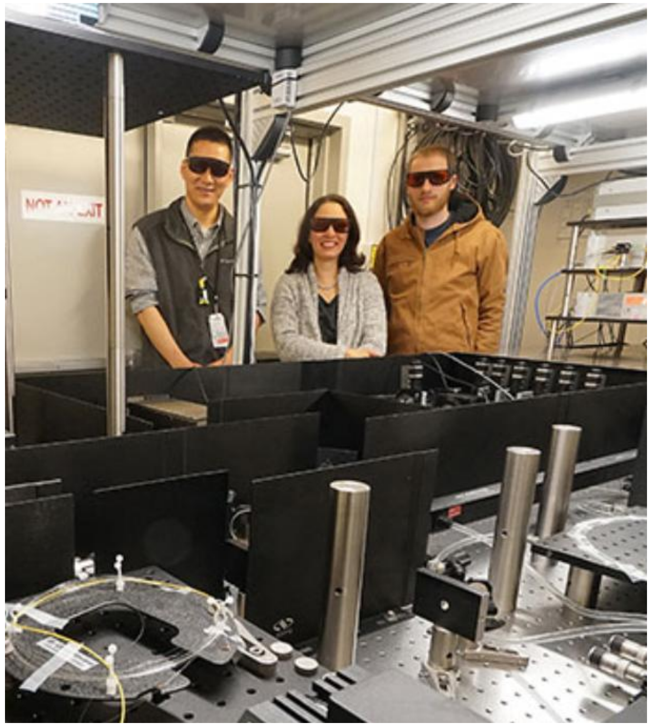


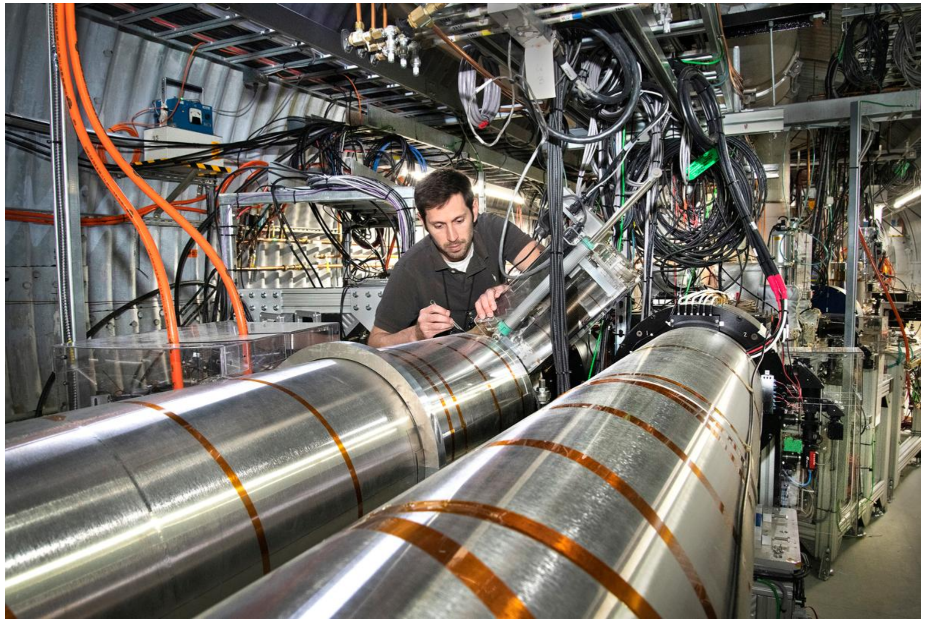


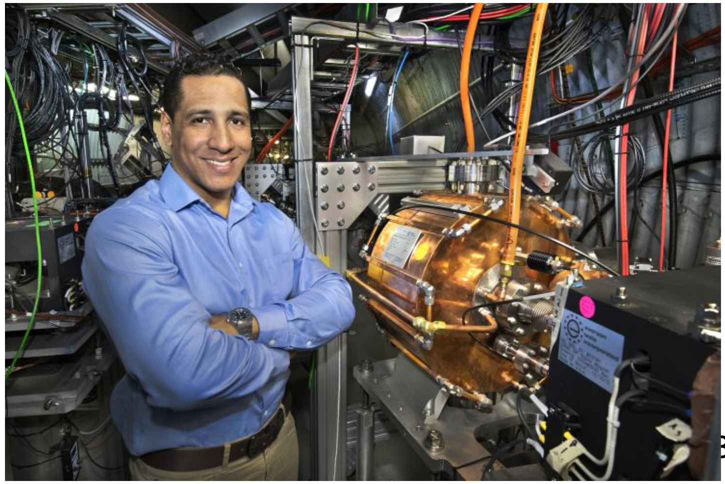
Cooling simulations of protons at γ=25.

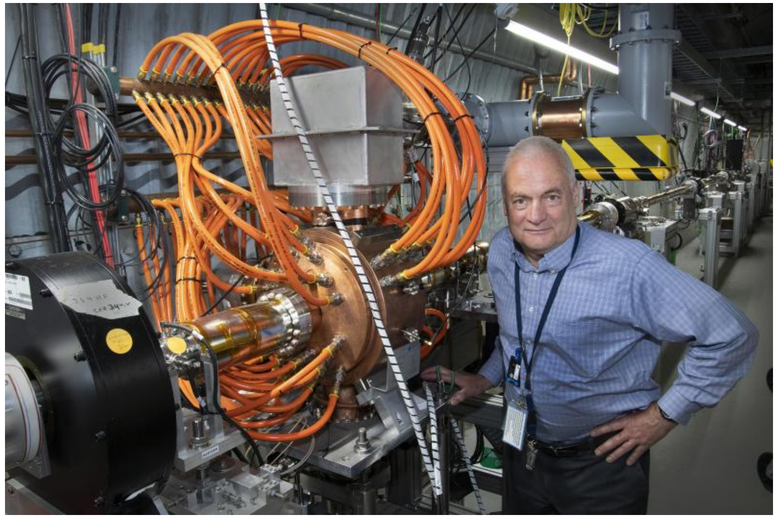
Alexei Fedotov

Making LEReC work









LEReC Team

Making the world's first RF-based Electron Cooling operational became possible due to help and expertise of many people from various groups of the Collider-Accelerator and other Departments of the BNL.

Thank you!