Low Energy RHIC electron Cooling (LEReC):

First Electron Cooling of Hadron Beams Using a Bunched Electron Beam Based on RF Acceleration

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NAPAC2019, Lansing, Michigan, USA

September 2-6, 2019

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LEReC Project Overview

LEReC is world first electron cooler based on the RF acceleration of bunched electron beam

All key elements and experimental demonstrations required for this new approach were successfully achieved:

- ❑ **Building and commissioning of new state of the art electron accelerator ✓**
- ❑ **Produce electron bunches with beam quality suitable for cooling✓**
- ❑ **RF acceleration and transport maintaining required beam quality✓**
- ❑ **Achieve required beam parameters in cooling sections✓**
- ❑ **Commissioning of bunched electron beam cooling✓**
- ❑ **Commissioning of electron cooling in a collider ✓**

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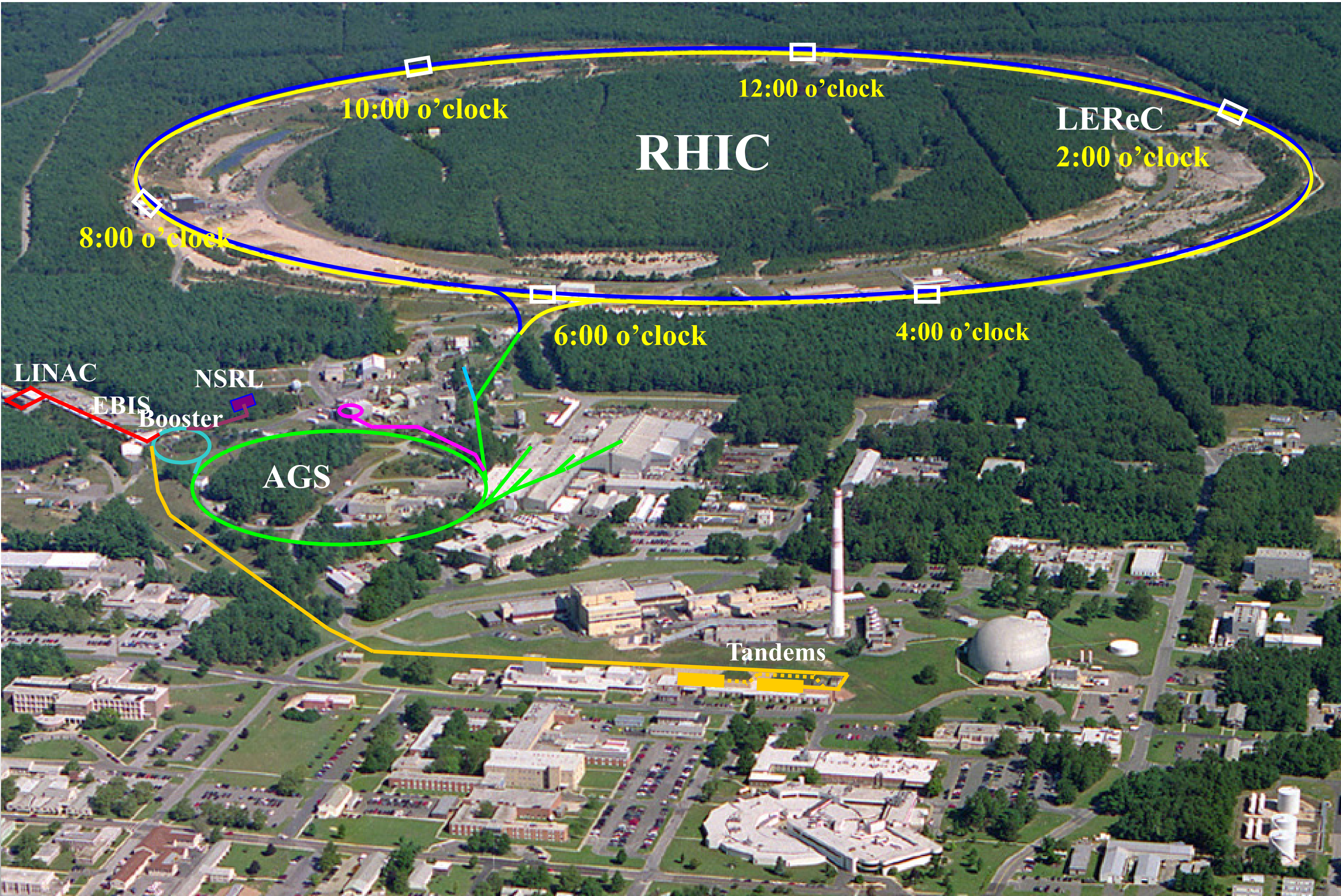
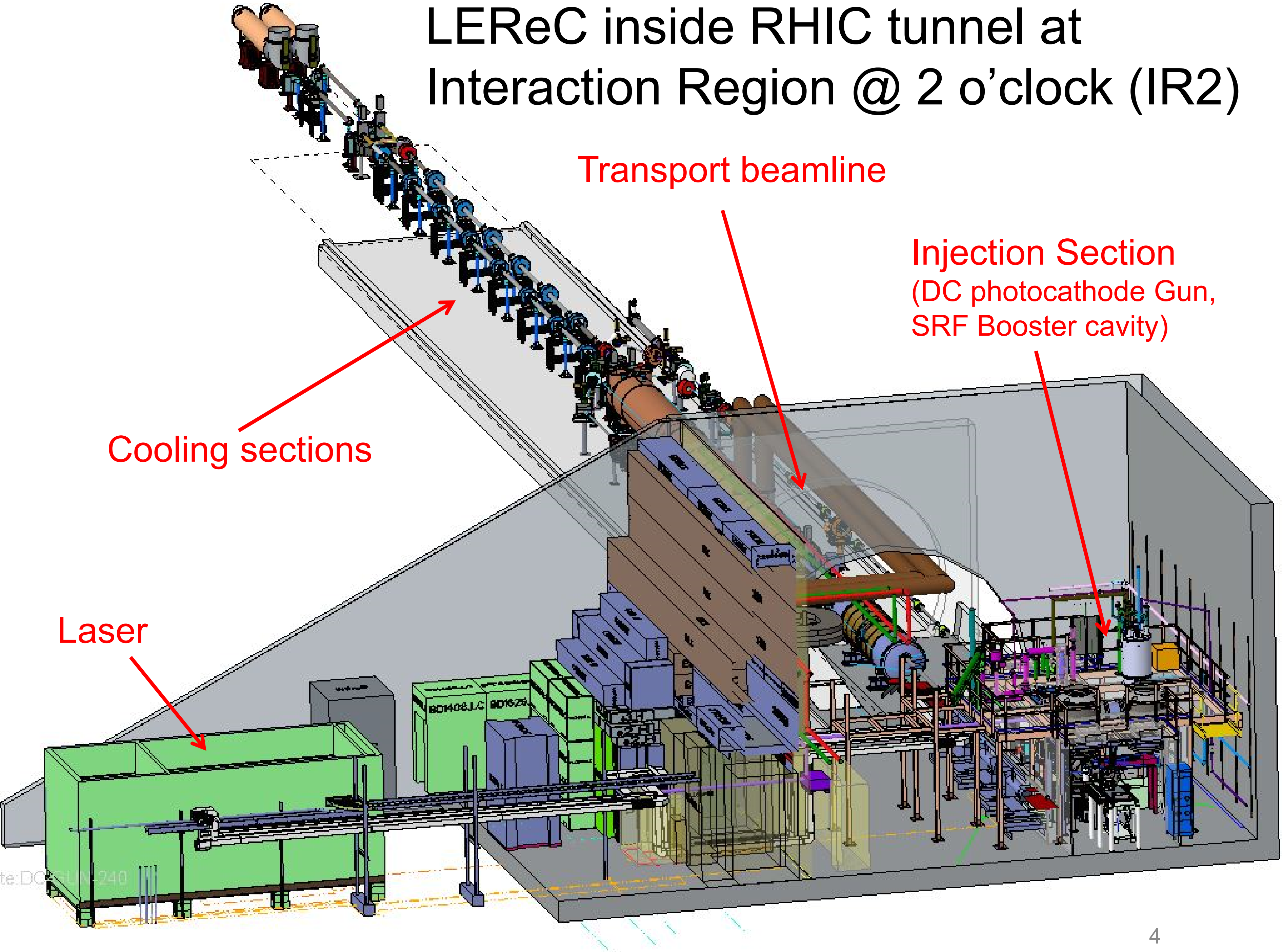
RHIC @ BNL, Long Island, New York

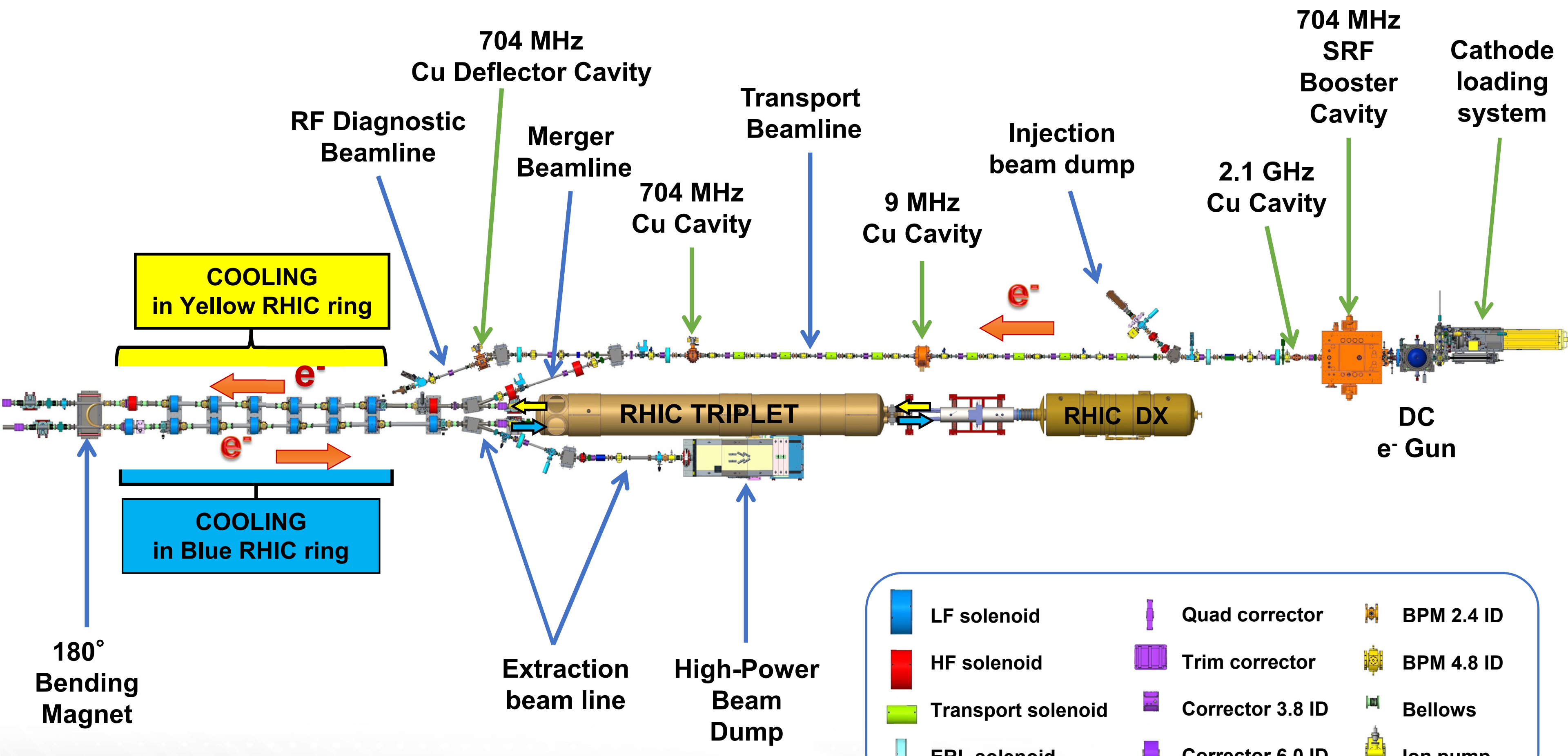


LEReC inside RHIC tunnel at Interaction Region @ 2 o'clock (IR2)



LEReC Accelerator

(100 meters of beamlines with the DC Gun, high-power fiber laser, 5 RF systems, including one SRF, many magnets and instrumentation)



* NOT to scale

LEReC: non-magnetized electron cooling

Non-magnetized friction force:

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

- Non-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.
- LEReC: need to keep total contribution (including from emittances, energy spread, space charge, remnant magnetic fields, etc.) below 150 μrad!

asymptotic for $v_{ion} < \Delta_e$:

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

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

Requirement on electron angles:
For γ=4.1: σ_p=5e-4; θ<150 μrad

LEReC electron beam parameters

Two energies commissioned ✓

Electron beam requirement for cooling			
Kinetic energy, MeV	1.6	2	2.6
Cooling section length, m	20	20	20
Electron bunch (704MHz) charge, pC	130	170	200
Effective charge used for cooling	100	130	150
Bunches per macrobunch (9 MHz)	30	30	24-30
Charge in macrobunch, nC	4	5	5-6
RMS normalized emittance, um	< 2.5	< 2.5	< 2.5
Average current, mA	36	47	45-55
RMS energy spread	< 5e-4	< 5e-4	< 5e-4
RMS angular spread	<150 urad	<150 urad	<150 urad

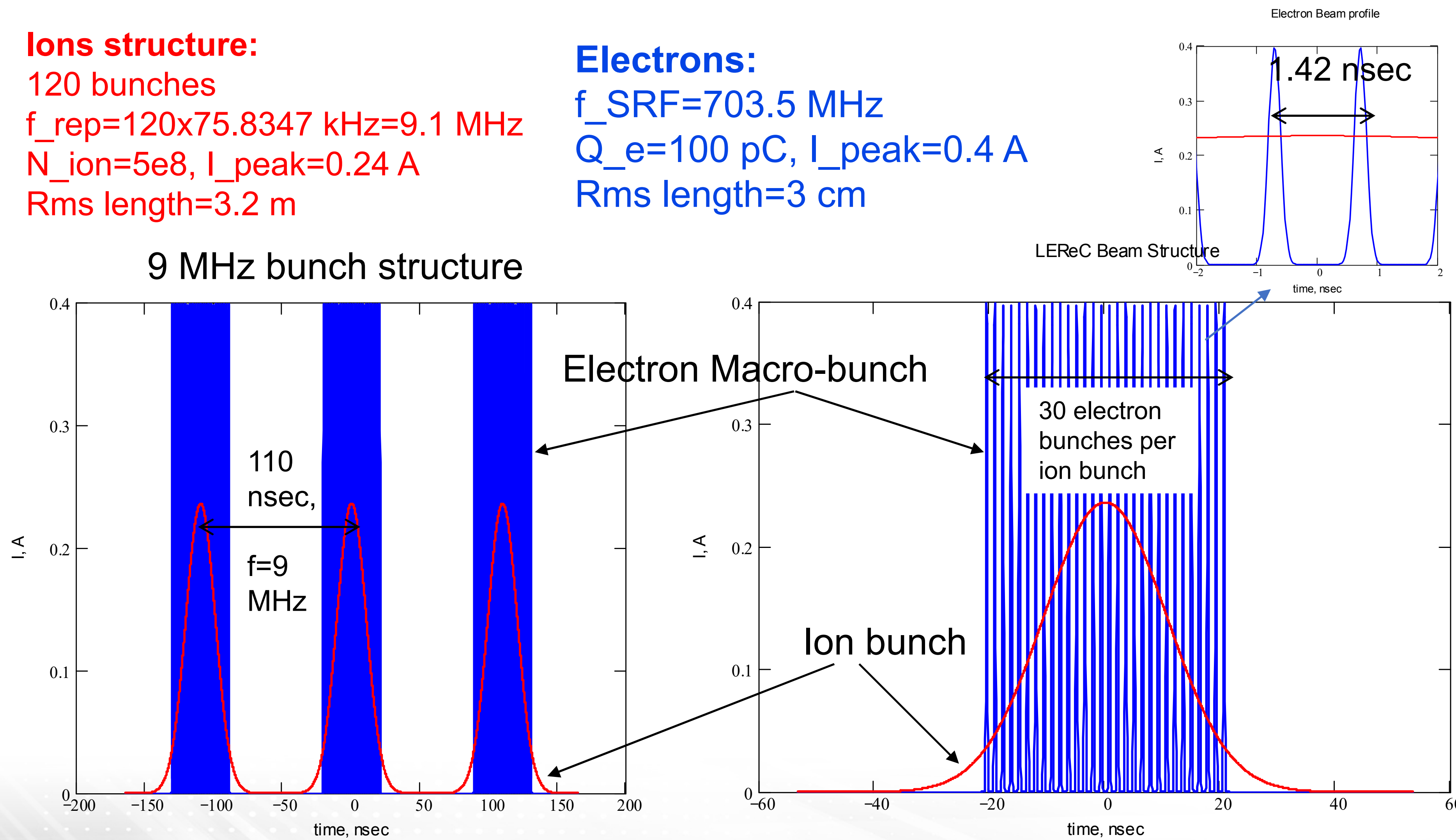
LEReC bunched electron beam cooling

- 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.

LEReC beam structure in cooling section

Ions structure:
120 bunches
f_rep=120x75.8347 kHz=9.1 MHz
N_ion=5e8, 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



Electron beam transport

The use of RF-based approach requires special considerations:

Beam transport of electron bunches without significant degradation of 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:

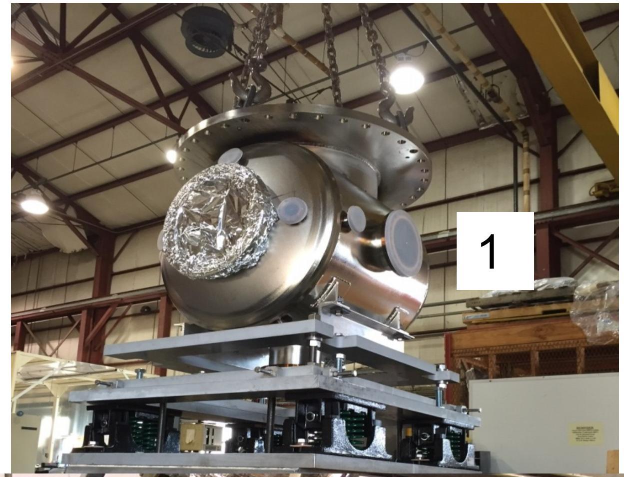
Correction solenoids in the cooling section are used to keep transverse angular spread to a required level.

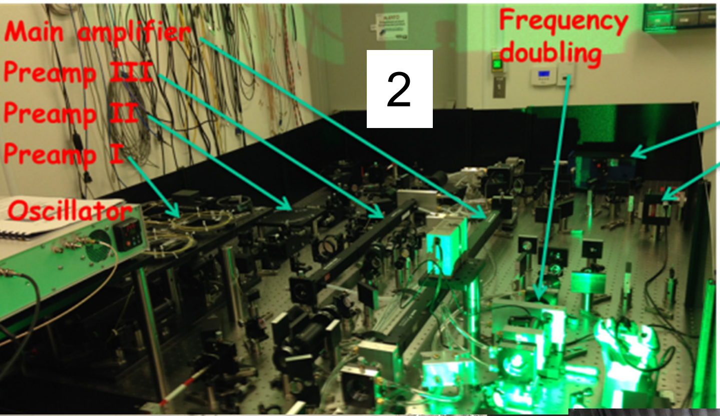
Strict control of electron angles in cooling sections:

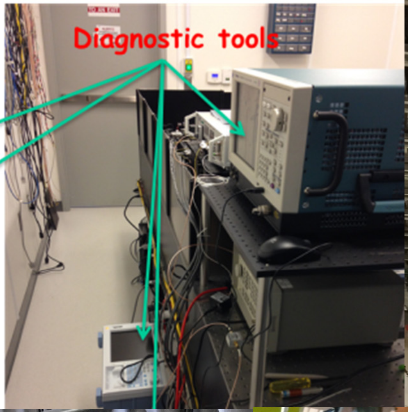
Cooling sections are covered by several layers of Mu-metal shielding.

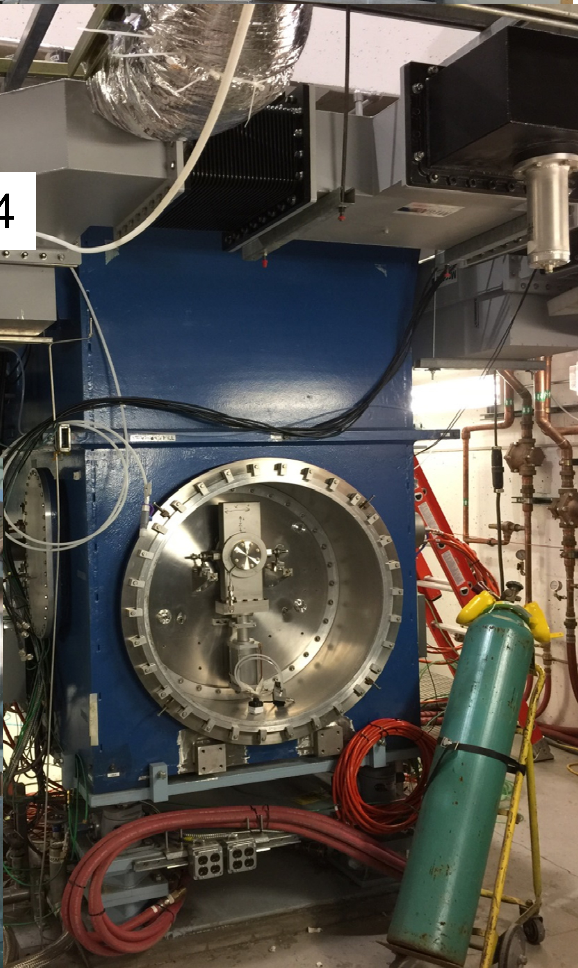
LEReC Critical Technical Systems

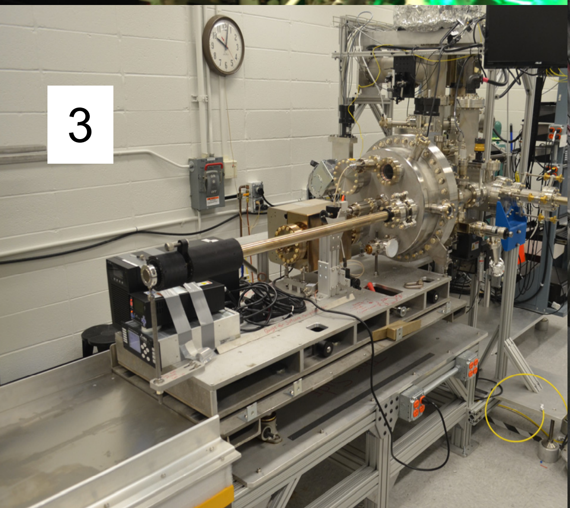
1. High-voltage photocathode electron gun
2. High-power fiber laser, transport and stabilization
3. Cathode production deposition and delivery systems
4. 704 MHz SRF Booster cavity
5. 2.1 GHz and 704 MHz warm RF cavities

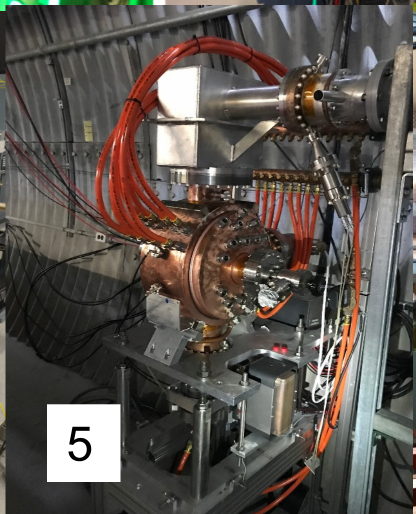


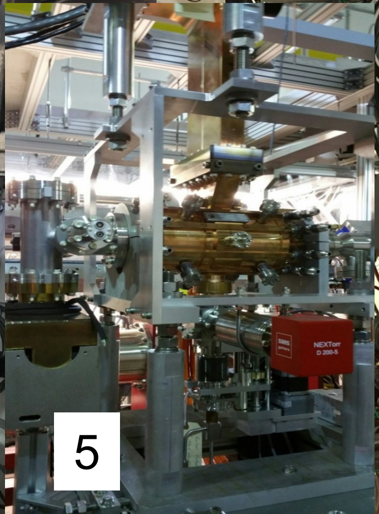










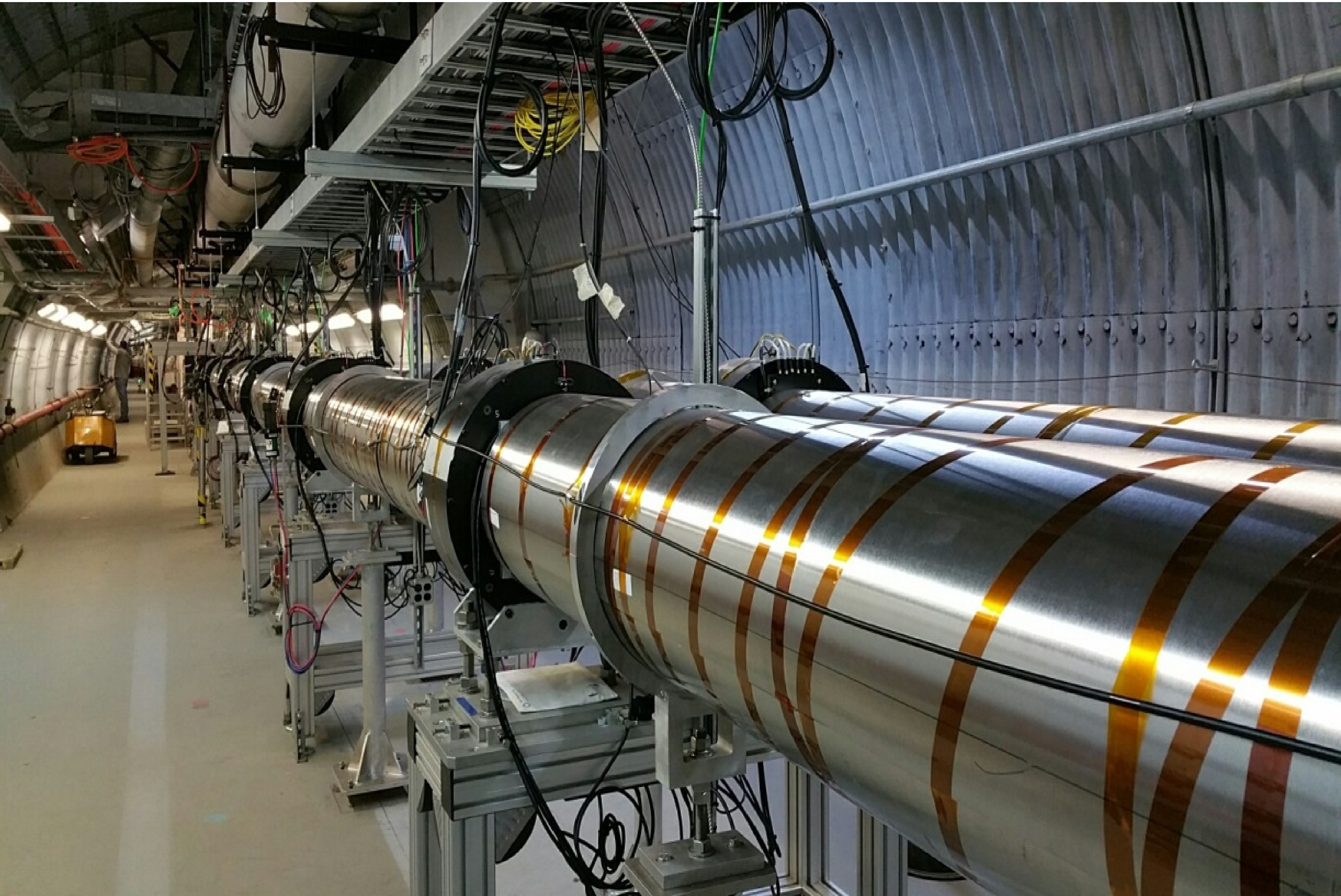


LEReC construction started in 2016

LEReC Gun test beamline (2017)

Full LEReC installation (October 2017)

LEReC cooling sections fully installed (2018)

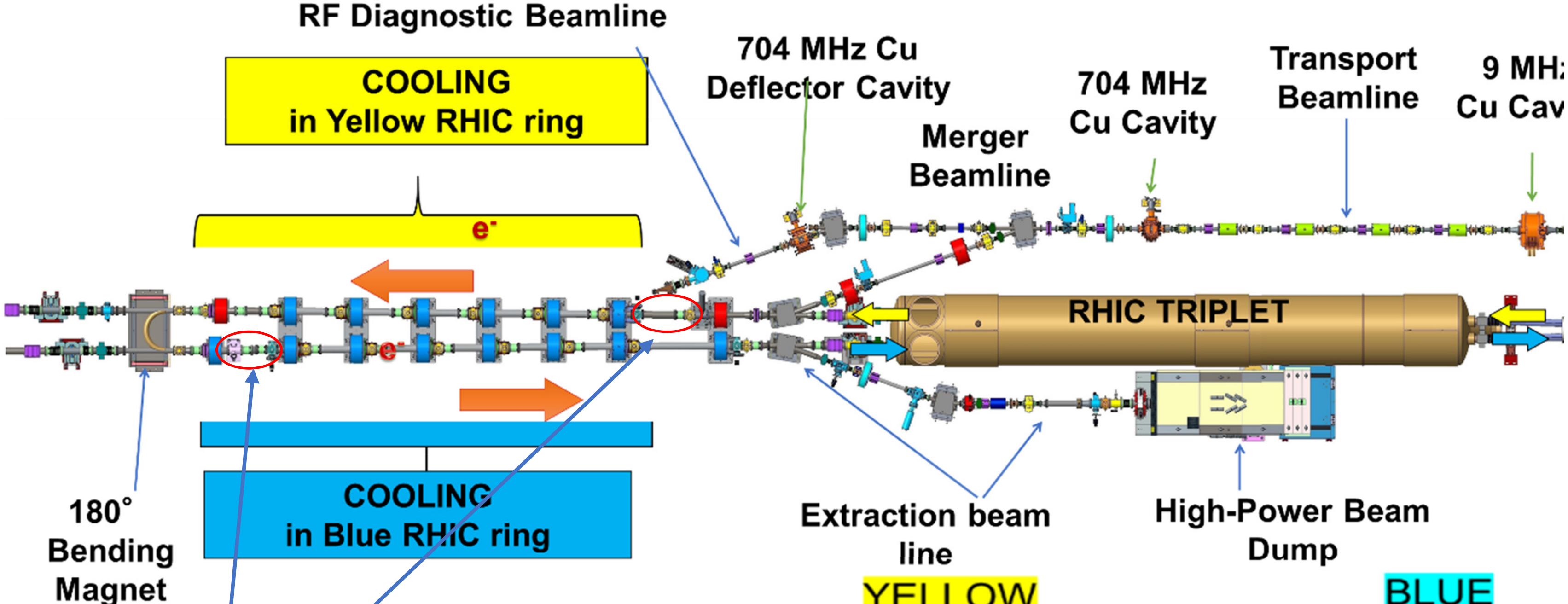


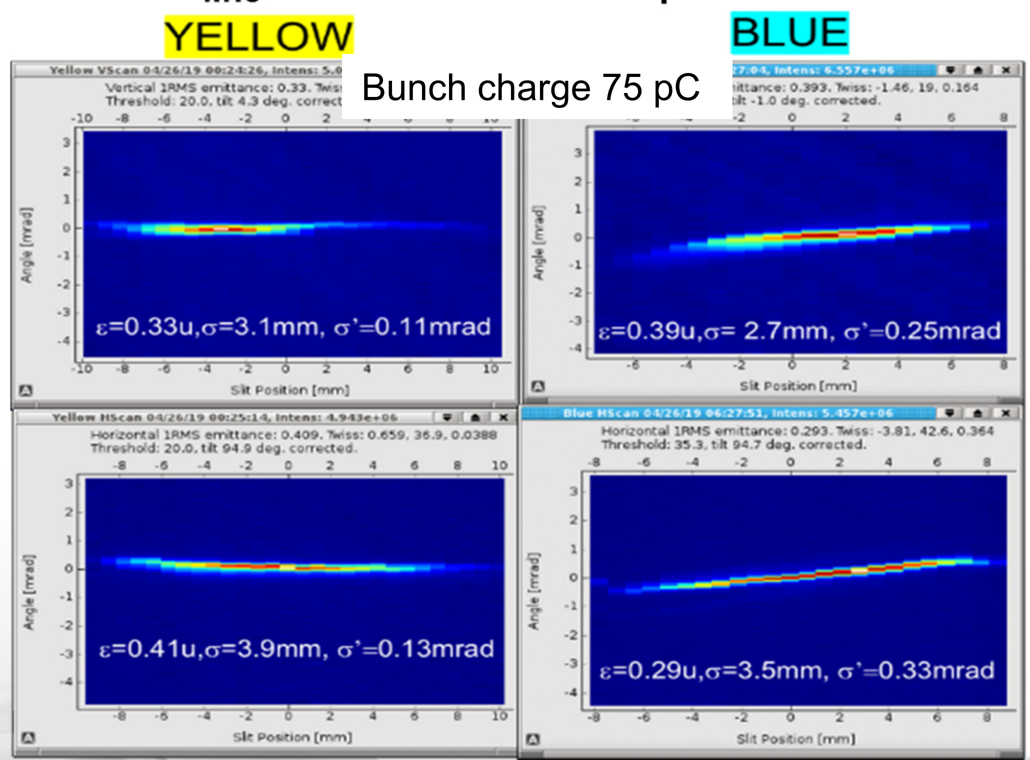
Attainment of "cold" electron beam suitable for cooling

- LEReC is based on the state-of-the-art accelerator physics 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
- Operation of DC gun at high voltages (around 400kV) with high charge and high average current
- RF gymnastics using several RF cavities and stability control
- Energy stability and control
- Instrumentation and controls

Transverse phase-space measurements of electron beam



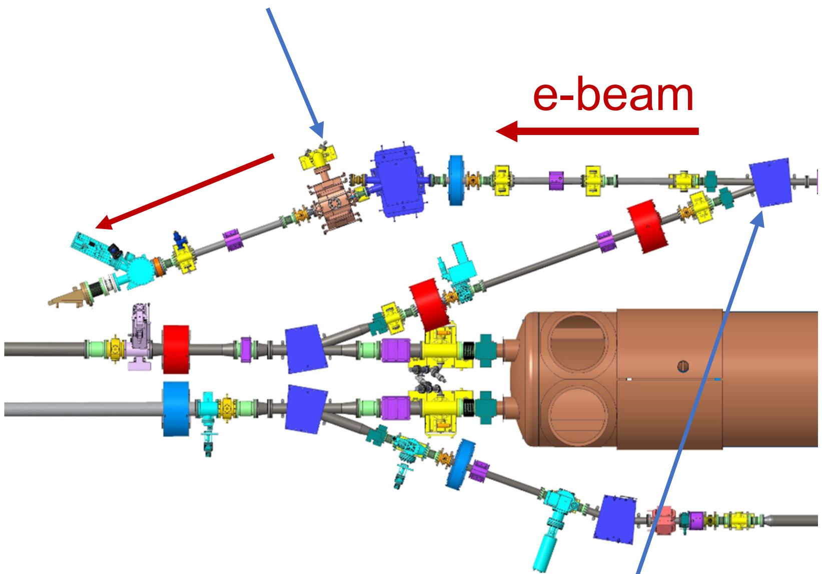


Movable slit and downstream beam profile monitors are installed at the beginning of each cooling section.

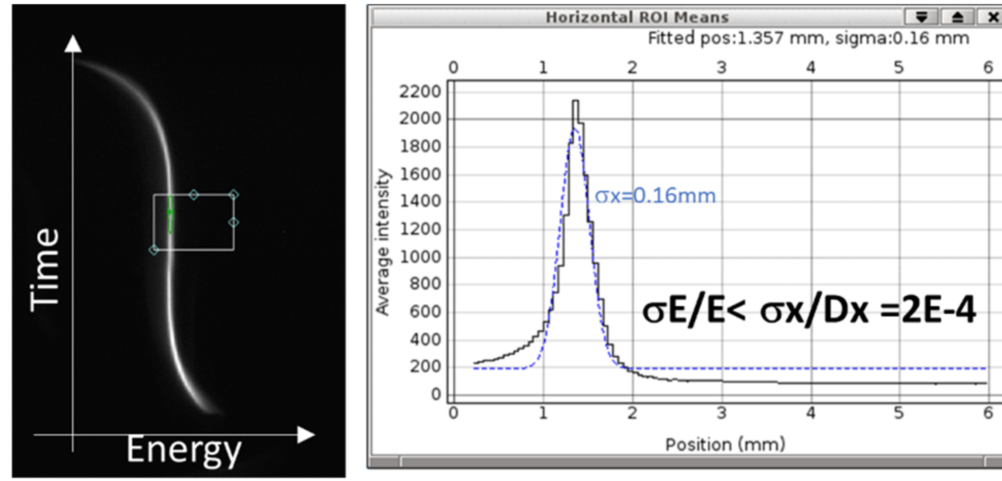
A. Fedotov et al., NAPAC19,

Longitudinal phase-space measurement of electron beam

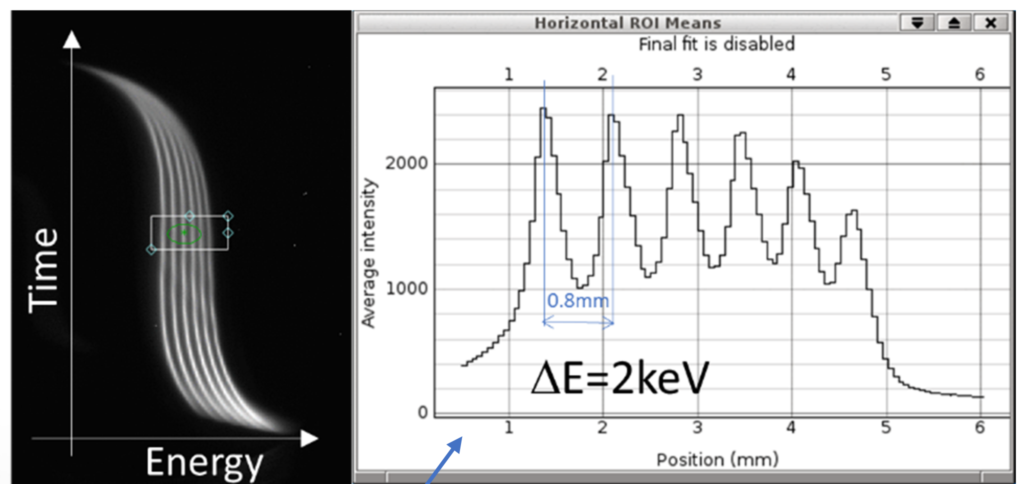
704MHz deflecting cavity



1 macro-bunch of electrons (total charge 3nC)



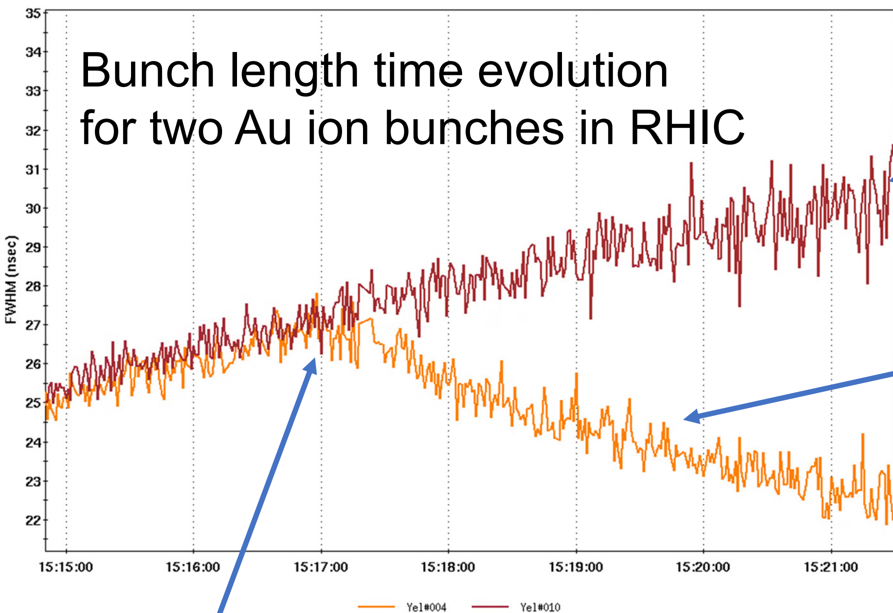
6 macro-bunches, 3 nC each.



- First dogleg merger dipole is off
- Beam goes to RF diagnostic line
- 20 degree dipole produces dispersion
- 704MHz RF deflecting cavity produces time dependent vertical kick

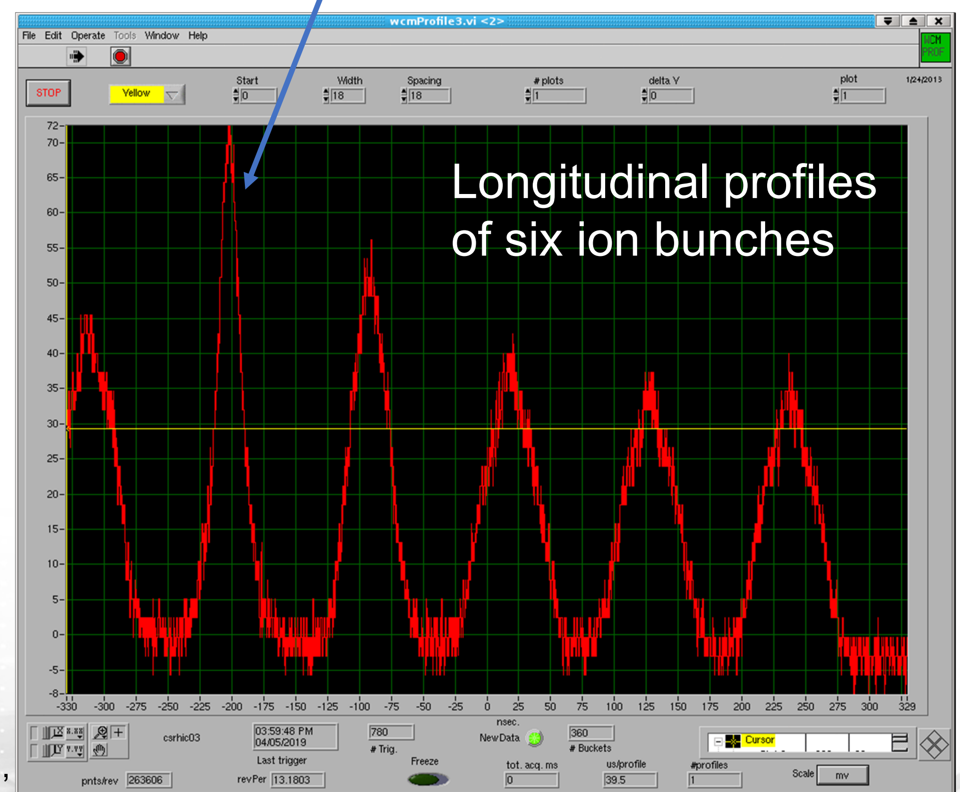
In pulsed mode, subsequent electron macro-bunches have lower energy due to beam loading in RF cavities.

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



Ion bunch #4 which is not being cooled

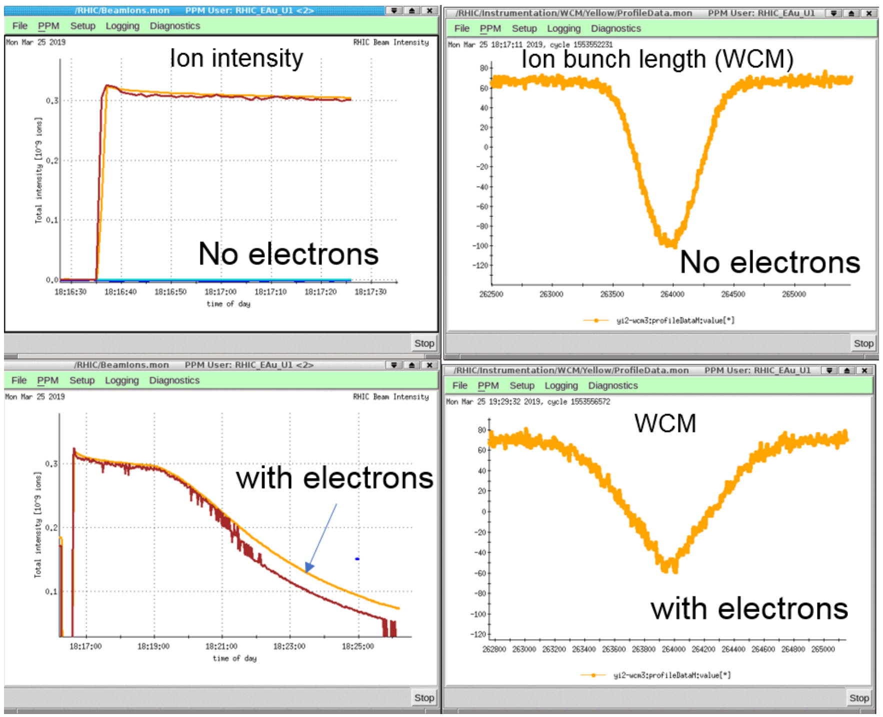
Ion bunch #2 is being cooled



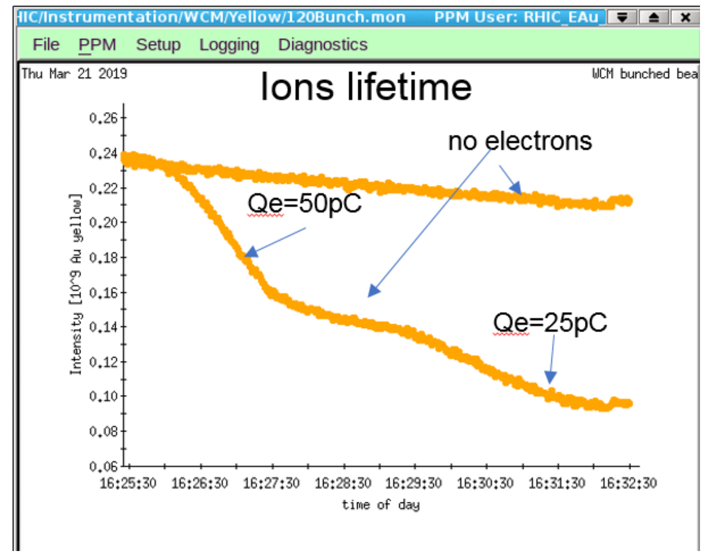
Energy of electrons and ions matched

Effects of electrons on ions: “heating” (March 2019)

- Even before cooling was established we observed strong “heating” effects of electrons on ions (which are space-charge beam-beam kicks from e-beam on ions).

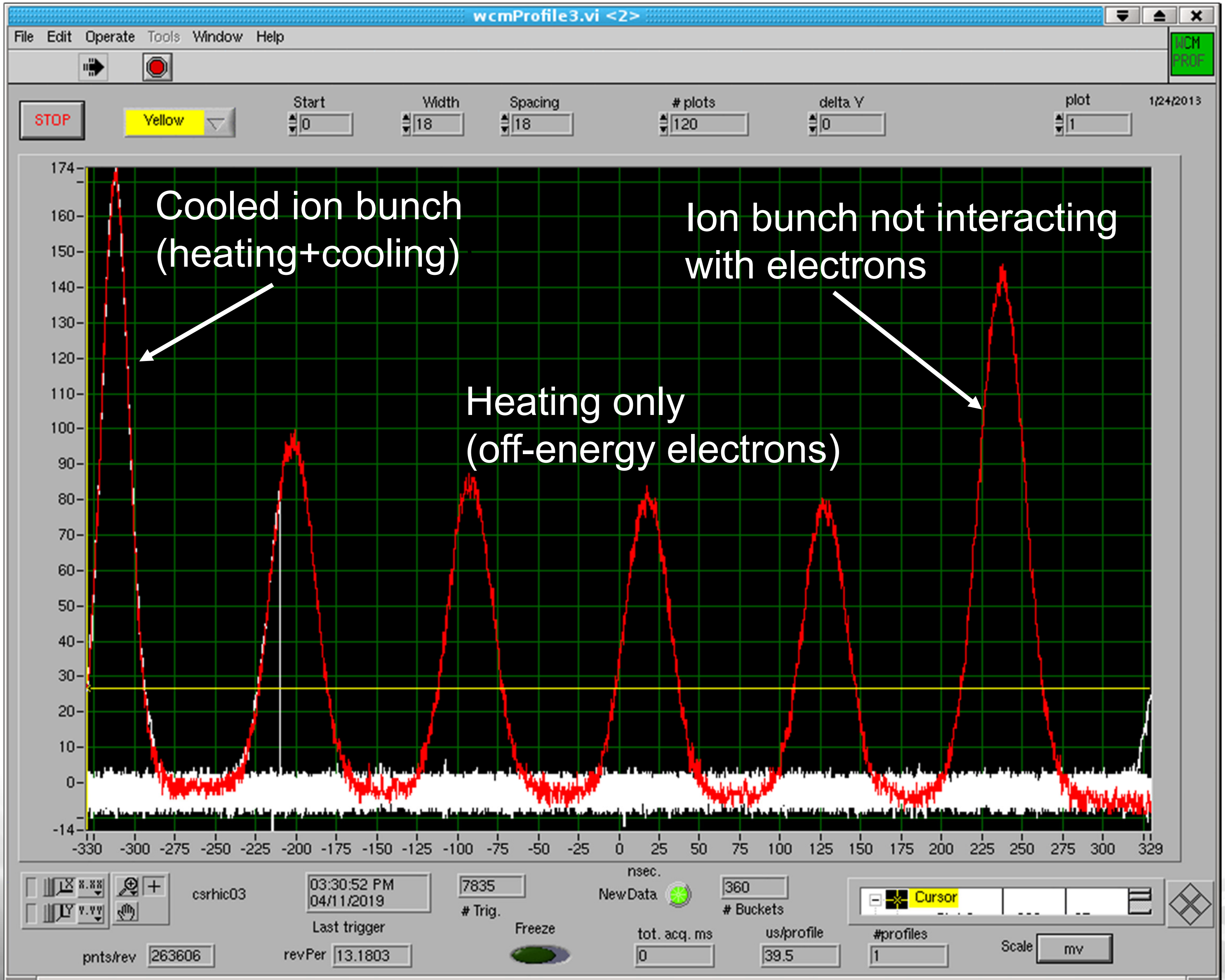


Electrons and ions energies are NOT matched



- These “heating” effects were reduced by going to smaller ion beta-function in cooling section and by finding better working point in tune space.

Yellow RHIC Ring (76kHz mode allowing to cool single ion bunch; 6 ion bunches, 5 electron macro-bunches)



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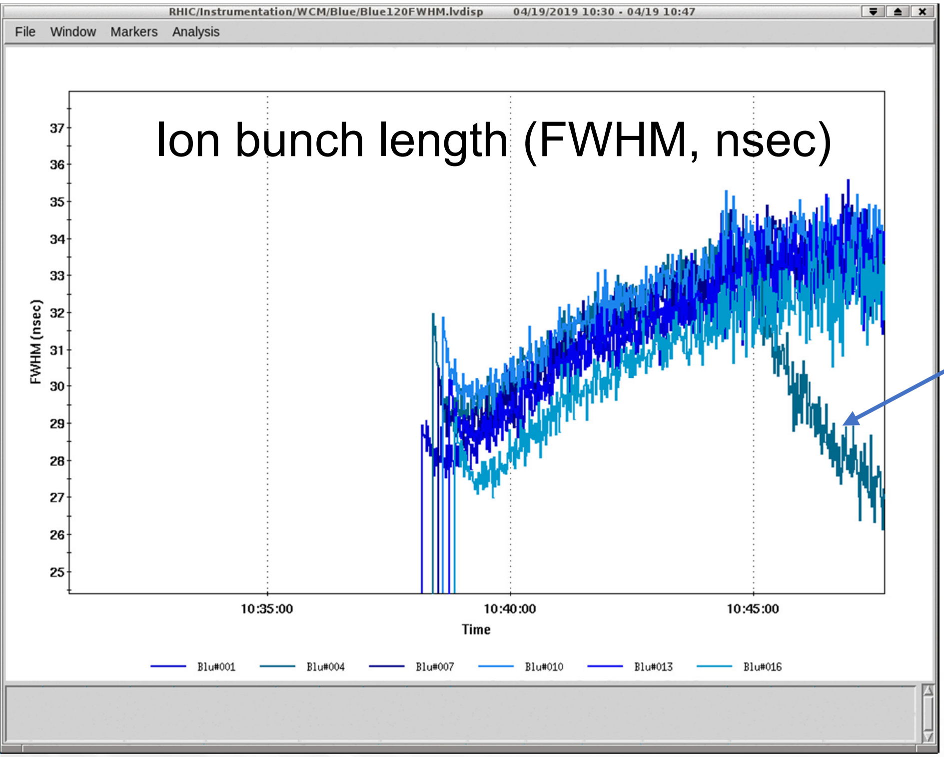
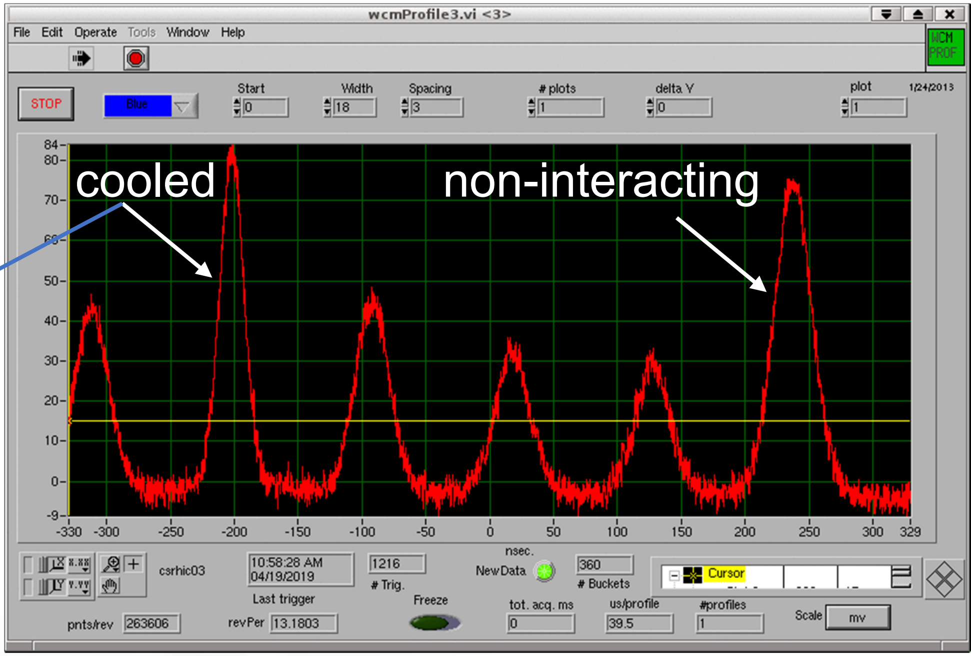
Blue RHIC Ring: first cooling demonstration (April 19, 2019)

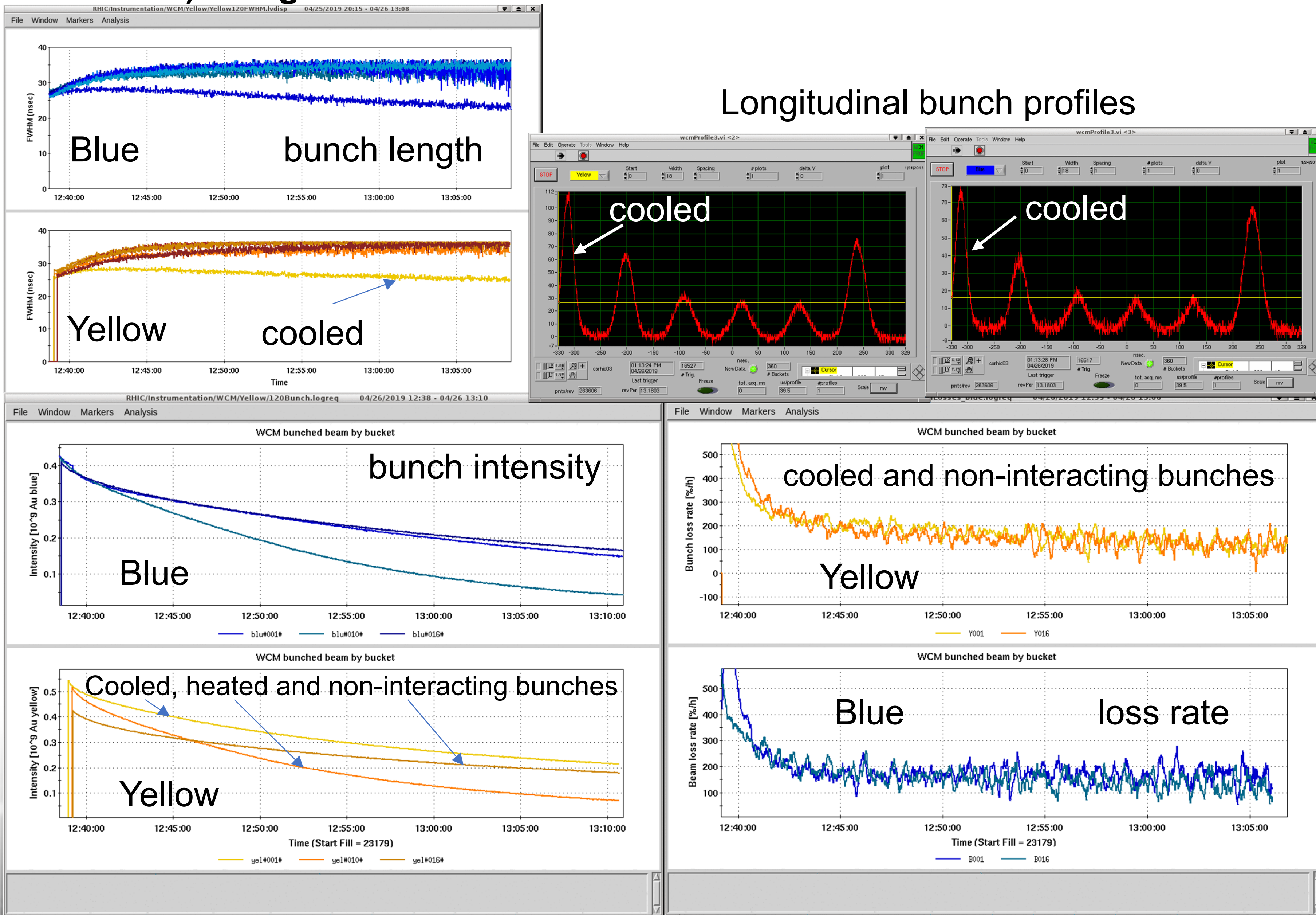
- After RHIC lattice for Au ions and good electron beam optics for Blue cooling section was established, cooling of ions in Blue RHIC Ring was achieved.



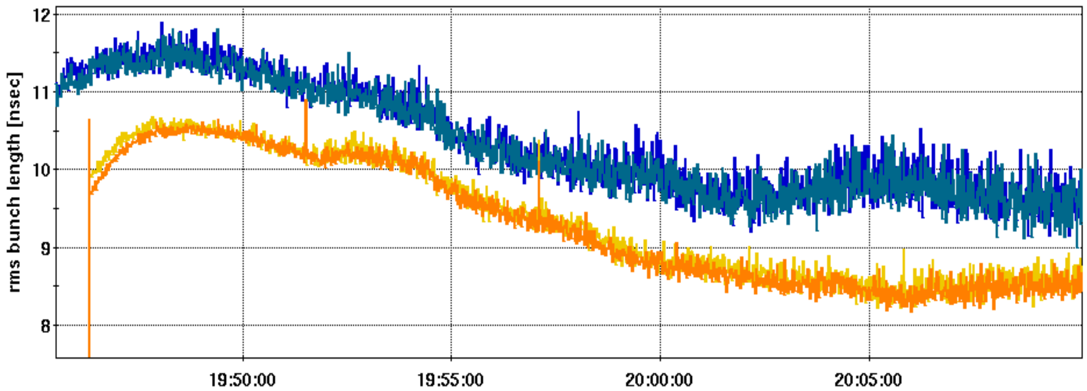
Longitudinal profiles of six ion bunches

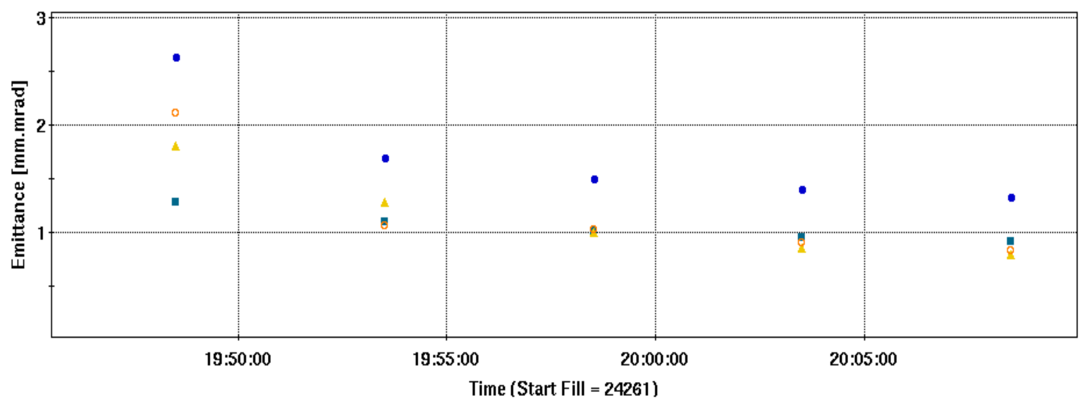


Simultaneous cooling of ion bunches in Yellow and Blue RHIC rings (76kHz mode, 6 ion bunches: bunch #1 is being cooled; bunch #6 does not see electrons) using the same electron beam



Cooling of hadron beams under collisions (RHIC store with 111x111 Au ion bunches) @ 3.85GeV/n using 1.6MeV high-current 9MHz CW electron beam

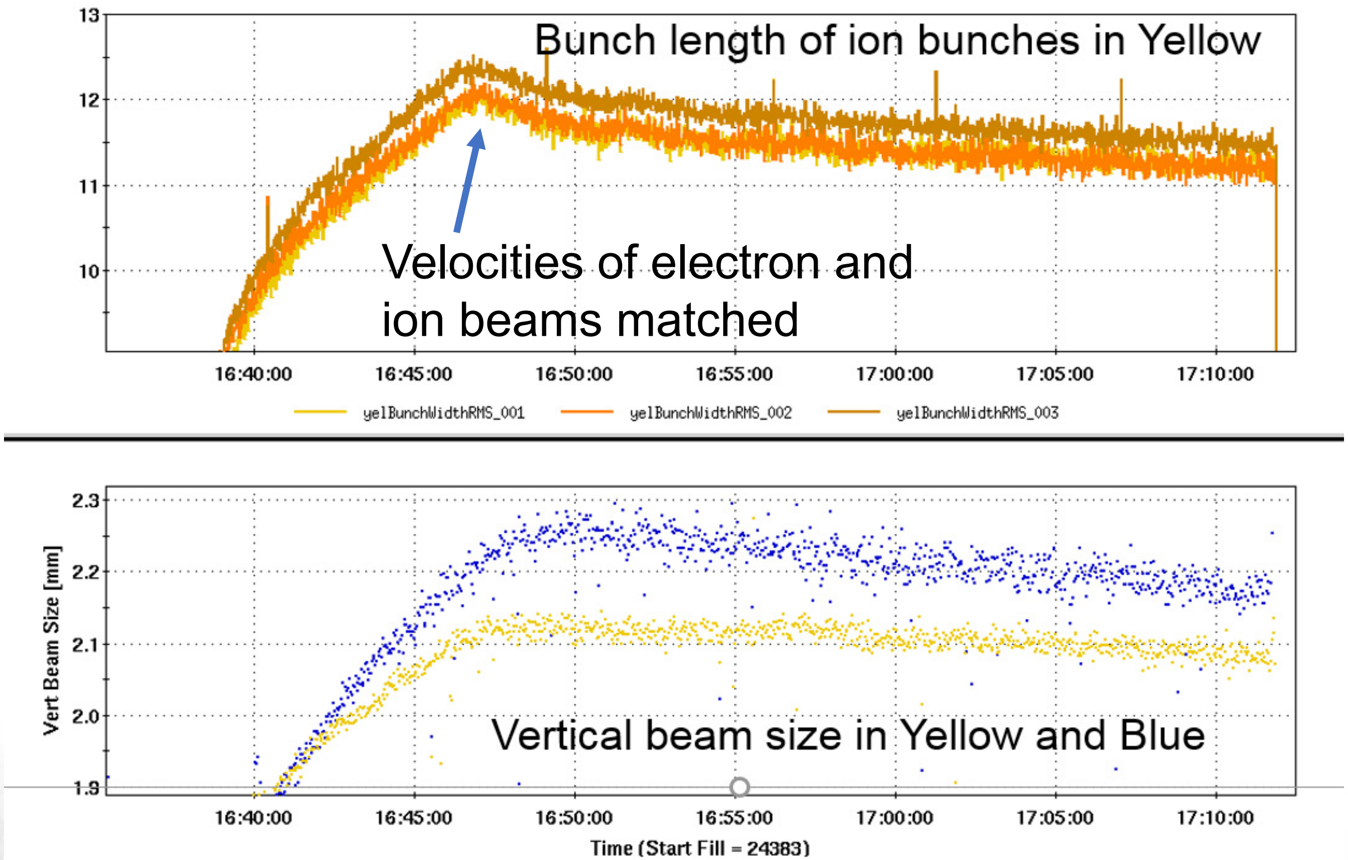




6-D cooling of a 111x111 bunch RHIC store at 3.85 GeV (1.6 MeV electrons, 9 MHz CW current of 15mA).
Top plot - reduction of bunch length. Bottom plot - reduction of transverse beam emittances (two RHIC rings, two planes).

Cooling 4.6GeV/n Au ions using 2MeV high-current 9MHz CW electron beam

Most of the time was spent on commissioning electron cooling using 1.6MeV electron beam. Once everything was commissioned at 1.6MeV it took only several 8-hour shifts to develop electron beam optics for 2MeV beam and go through all commissioning steps to establish cooling of Au ion bunches at 4.6GeV/n in both RHIC rings using high-current 2MeV electron beam.



LEReC roadmap to cooling

- 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 ✓
- Energy matching of electron and ion beams ✓
- First electron cooling demonstration in longitudinal plane✓
- Establishing cooling in 6-D✓
- Matched electron and ion energy in both Yellow and Blue RHIC rings✓
- Achieved cooling in both Yellow and Blue Rings simultaneously using the same electron beam✓
- Demonstrated 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 ✓

Observed issues and limitations

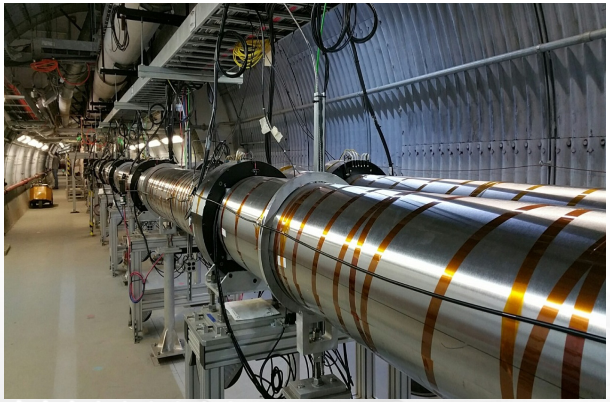
- With no magnetic field in the cooling sections, focusing of electrons by ions was significant. Adjusting the electron beam optics to take this into account was challenging.
- Different focusing on electron bunches distributed at different longitudinal slices of ion bunch.
- Using bunched electron beam for cooling at such a low energy led to emittance growth of ions due to modulated focusing from the electrons (called "heating"). Such heating effects were reduced, but not eliminated, by a proper choice of ion beta-function in the cooling section and of a working point. However, to cope with the heating effects, which had strong dependence on electron beam density, we had to operate at electron currents lower than design values.
- Ion lifetime limitations at low energy in RHIC: physical aperture, dynamics aperture, beam-beam, space charge and IBS.

LEReC project timeline

May 2015:	LEReC project approved for construction
December 2016:	DC gun installed and successfully conditioned in RHIC tunnel
February 2017:	Gun test beamline installed
April-Aug., 2017:	Gun tests with beam
July-Dec., 2017:	Installation of full LEReC accelerator
Jan.-Feb., 2018:	Systems commissioning (RF, SRF, Cryogenics, Instrumentation, Controls, etc.)
March-Sept. 2018:	Commissioning of full LEReC accelerator with e-beam
September 2018:	All project Key Performance Parameters achieved
Oct.-Dec., 2018:	Scheduled upgrades and modifications
Jan.-Feb., 2019:	Restart operation with electron beam
March 2019:	Start commissioning with Au ion beams
April 2019:	First cooling demonstration. Cooling in both RHIC rings using e-bunches at 76kHz frequency.
May 2019:	Simultaneous cooling of many ion bunches using 9MHz CW e-beam
June 2019:	Cooling optimization at 1.6MeV, cooling of beams in collisions (3.85GeV/n ions)
July 2019:	Cooling commissioned at higher electron energy of 2MeV (4.6GeV/n ions)

Summary

- World's first electron cooling of hadron beams based on RF acceleration of electron bunches was successfully demonstrated. Such cooling approach is new and opens the possibility of using this technique to high beam energies.
- Electron cooling using electron beam without any magnetization on the cathode or cooling section, "non-magnetized" cooling, was demonstrated (all previous coolers used magnetization on the cathode).
- First electron cooling in a collider (cooling of ion beams in collisions with various effects impacting beam lifetime)) was achieved by successfully cooling 111 ion bunches in both RHIC rings.
- Cooling was commissioned at electron energy of 1.6MeV (ion energy 3.85GeV/n) and at 2MeV (ion energy of 4.6GeV/n).
- The next step will be to maximize collision rates with cooling in next year's RHIC low-energy collisions.



Acknowledgement

LEReC project greatly benefits 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.

Thank you!

Details can be found in recent LEReC publications:

D. Kayran et al., ”Commissioing of the electron accelerator LEReC for bunched beam cooling”, NAPAC2019, Lansing, Michigan, USA, 2019”

S. Seletskiy *et al.*, ”Precise beam velocity matching for the experimental demonstration of ion cooling with a bunched electron beam.”, NAPAC2019, Lansing, Michigan, USA, 2019

L. Nguyen *et al.,* ”Active pointing stabilization techniques applied to the Low Energy RHIC Electron Cooling laser transport at BNL”, NAPAC2019, Lansing Michigan, USA, 2019

P. Inacker-Mix *et al.,* ”Design of the 2-stage laser transport for the LEReC system”, NAPAC2019, Lansing, Michigan, USA, 2019

D. Kayran *et al.,* ”First results from commissioing of low energy RHIC electron cooler (LEReC)”, IPAC2019, Melbourne, Australia, 2019

M. Gaowei *et al.*, ”Bi-alkali Antimonide Photocathodes for LEReC”, IPAC2019, Melbourne, Australia, 2019

D. Kayran et al., “LEReC Photocathode DC Gun Beam Test Results”, IPAC18, Vancover, Canada, 2018

D. Kayran et al., “First Results of Commissioing of DC Gun for LEReC”, ERL17, CERN, Switzerland, 2017

S. Seletskiy et al., “Status of the BNL LEReC Machine Protection System”, IBIC17, Grand Rapids, USA, 2017

T. Miller at 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

A. Fedotov et al., “Accelerator Physics Design Requirements and Challenges of LEReC”, NAPAC16, Chicago, USA, 2016

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M. Blaskiewicz, “Emittance Growth from Modulated Focusing in Bunched Beam Cooling”, NAPAC16, Chicago, USA, 2016

T. Miller et al., “”LEReC Instrumentation Design and Construction”, IBIC16, Barcelona, Spain, 2016

Z. Sorrell et al., “Beam Position Mointors for LEReC”, IBIC16, Barcelona, Spain, 2016

S. Seletskiy et al., “Conceptual Design of LEReC Fast MPS”, IBIC16, Barcelona, Spain, 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