Low Energy RHIC electron Cooling (LEReC):

Electron Cooling in a Collider

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What is beam cooling?

- Beam cooling is reduction of phase space volume.
- Synonymous to beam temperature (with beam temperature changing over accelerator ring, decreasing temperature by increasing beam size is not cooling).
- Cooling is reduction of beam emittance or energy spread, which equivalently is reduction of random motion of the beam.
- Beam cooling techniques are non-Liouvillian processes - Liouville theorem does not apply

Liouville theorem: conservation of phase-space volume in the absence of dissipative forces

Types of beam cooling

- Radiation damping (Schwinger 1948, Sands 1955, Robinson 1958): energy loss on synchrotron radiation - effective for light particles at high energy
- Electron cooling (Budker, 1966)
- Stochastic cooling (Van der Meer,1968): the statistical fluctuations of the average beam position, caused by the finite number of particles, can be detected with pickup electrodes and a corresponding correction applied.

  Types of stochastic cooling:

  - conventional microwave (GHz-range bandwidth),
  - optical amplifiers (100 THz),
  - coherent electron (use electron beam as an amplifier, THz range)
- Laser cooling (of selected atoms and ions by resonant interaction with laser light)
- Ionization cooling (energy loss while moving in dense targets)

Why to cool beams?

- Synchrotron radiation damping is effectively used in electron and positron storage rings.
- Cooling of ion beams enabled various experiments under conditions unavailable otherwise, including generation and storage of rare nuclei and short-lived isotopes, high-precision measurement of lifetime for radioactive nuclides and of isotope masses, phase-space manipulations, etc.
- For hadron colliders, one is interested to preserve high-brightness of hadron beams by counteracting various diffusion (“heating”) mechanisms for hadron beam such as intra-beam scattering or beam-beam.
- In addition to counteracting beam growth due to various effects, beam emittance can be “cooled” thus increasing phase-space density of colliding beam resulting in higher luminosity (luminosity: event rate/beam size) in a collider.

Beam temperature definitions

Beam temperature refers to the average kinetic energy of particles as measured in the center of mass of the beam.

Longitudinal temperature

$$\frac{1}{2}k_B T_{\|} = \frac{1}{2}mv_{\|}^2 = \frac{1}{2}mc^2\beta^2(\frac{\delta p_{\|}}{p})^2$$

Transverse temperature

$$\frac{1}{2}k_B T_{x,y} = \frac{1}{2}mv_{x,y}^2 = \frac{1}{2}mc^2\beta^2\gamma^2\theta_{x,y}^2$$

Electron cooling principle

- Electron cooling process is thermalization of two component plasma.
- When one co-propagates electrons with the same average velocity as ion beam, in beam rest frame you have two gases with temperatures proportional to their masses: hot ions, cold electrons – ions are cooled.

$$\theta_i = \sqrt{\frac{m_e}{M_i}}\,\theta_e$$

Small angular spread of ions

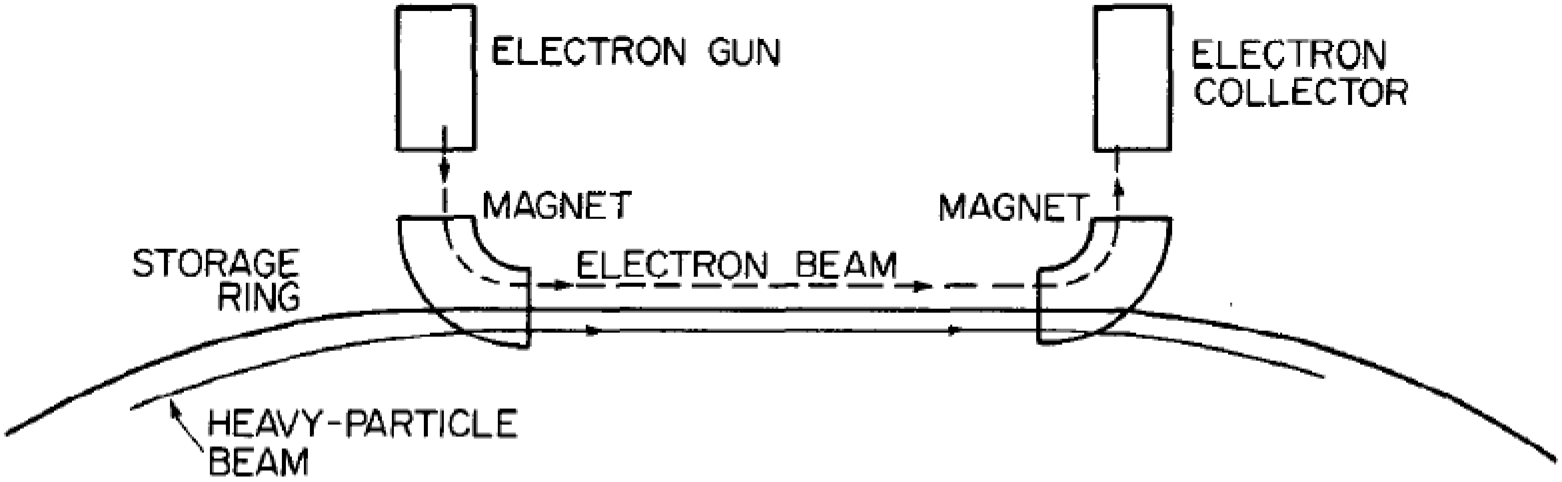
can be potentially obtained

Temperature relaxation formula in two component plasma:

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

This formula was used by Budker for estimates of electron cooling time in 1966.

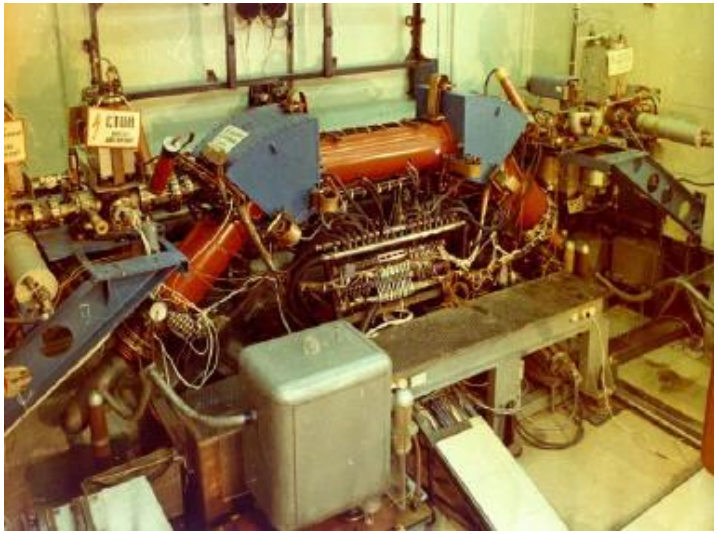
Electron cooling implementation



1. Produce a beam of cold (low emittance) electrons.
2. Co-propagate this electron beam and the ion/proton beam with the same average velocity over some distance (cooling section).
3. Heavy particles scatter off the electrons and energy is transferred to electrons. This energy transfer appears as a friction force acting on the ions. The ions are "cooled".
4. The electrons are renewed.

Electron coolers

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



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

High Voltage DC coolers:

Standard electron coolers (1974-2018): 10’s of coolers were constructed and successfully operated (low energies <300keV)– all DC electrostatic accelerators; all use strong magnetic field to confine electron beam (magnetized cooling). Extended to 2MeV electron energy at COSY.

FNAL Recycler cooler (2005-11) Pelletron electrostatic generator (4MeV electrons) - first relativistic electron cooler. Transport of electron beam without continuous magnetic field.

RF acceleration (High Energy approach):

Electron Cooling in RHIC (LEReC): First RF-linac based electron cooler. Also first cooler without any magnetization of electrons (BNL, 2019).

Friction force (without external magnetic field) acting on an ion moving inside the electron medium

Taking into account finite temperatures of electron beam:

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

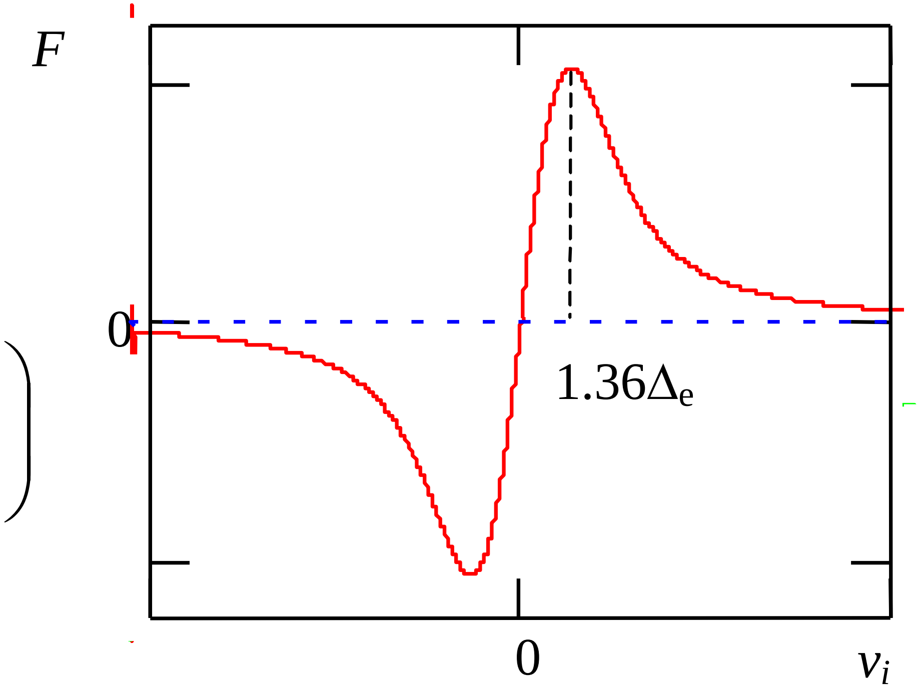
For isotropic Maxwellian velocity distribution of electrons f(v_e) (Chandrasekhar, 1942):

$$f(v_e) = \left(\frac{1}{2\pi}\right)^{3/2} \frac{1}{\Delta_\perp^2 \Delta_\parallel} \exp\left(-\frac{v_\perp^2}{2\Delta_\perp^2} - \frac{v_\parallel^2}{2\Delta_\parallel^2}\right)$$

$$\Delta_\parallel = \Delta_\perp = \Delta_e$$

$$\vec{F}_{NM}(\vec{v}_i) = -\frac{\vec{v}_i}{v_i^3} \frac{4\pi n_e e^4 Z^2 L}{m} \varphi\left(\frac{v_i}{\Delta_e}\right)$$

$$\varphi(x) = \sqrt{\frac{2}{\pi}} \int_0^x e^{-y^2/2} dy - \sqrt{\frac{2}{\pi}} x e^{-x^2/2}$$



Cooling time estimates (based on friction force without magnetic field)

$$\frac{1}{\tau} = -\frac{1}{v_i}\frac{dv_i}{dt} = -\frac{F(v_i)}{p_i}$$

$$\tau_{lab} = \gamma \frac{\tau}{L_{cool}/C} = \gamma \frac{\tau}{\eta}$$

Cooling time in lab frame:

$$\tau \propto \frac{A}{Z^2}\gamma^2 \frac{\theta^3 \gamma^3}{\eta n_e}$$

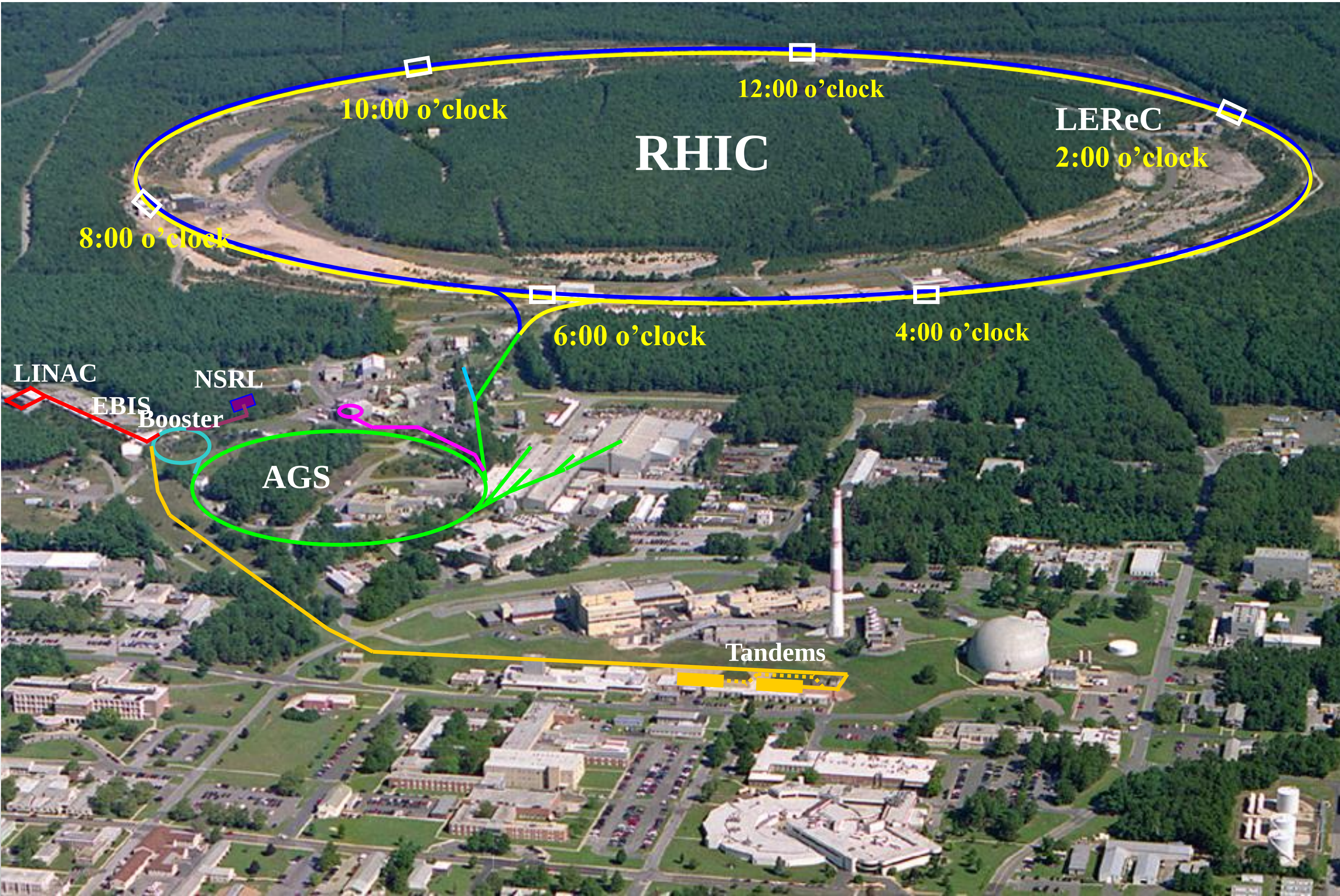
$$v_i > \Delta_e : \qquad \vec{F} = -\frac{4\pi Z^2 e^4 n_e L}{m}\frac{\vec{v}_i}{v_i^3}$$

For dominant transverse

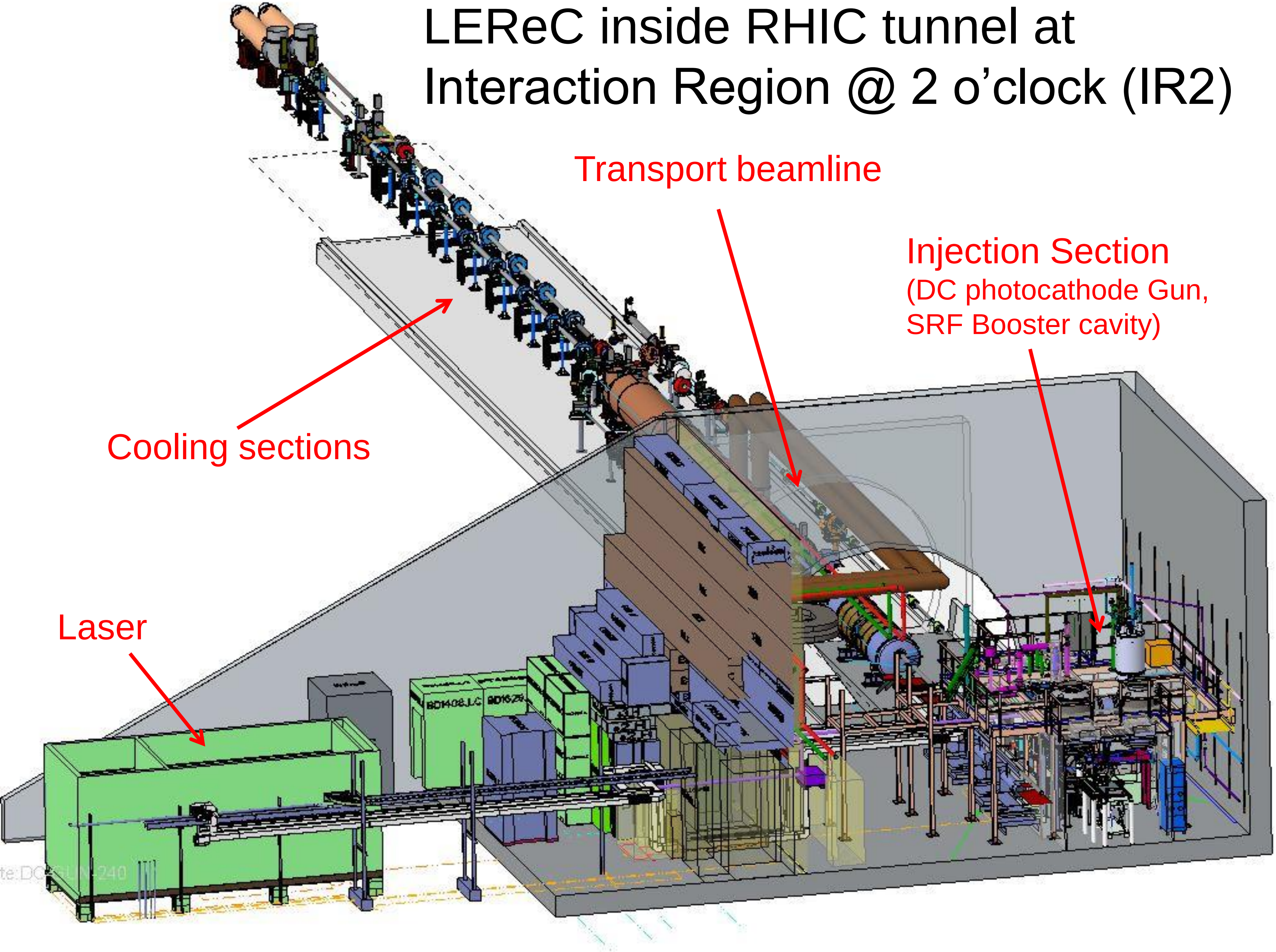
ion velocities:

$$\tau \propto \frac{A}{Z^2}\frac{\gamma^2}{4\pi r_p r_e n_e c\,\eta \Lambda_c}\left(\frac{\gamma \varepsilon_n}{\beta_c}\right)^{3/2}$$

RHIC @ BNL, Long Island, New York



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



Transport beamline

Injection Section
(DC photocathode Gun,
SRF Booster cavity)

Cooling sections

Laser

LEReC – High-energy cooling approach using RF acceleration of electron bunches

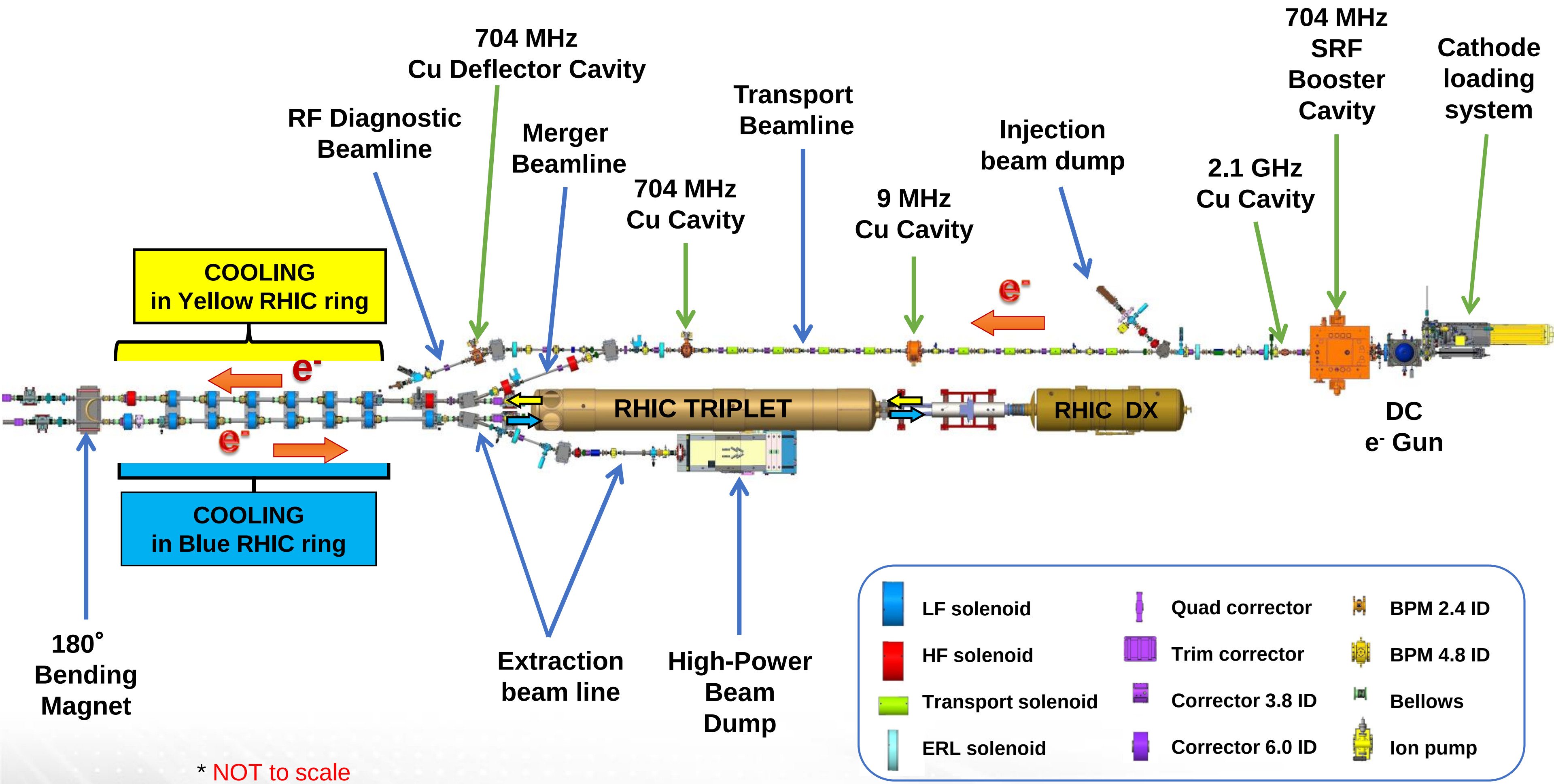
- To cool hadron beam (protons/ions), electron beam has to propagate with the same average velocity as the one of the hadron beam.

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

- To cool 100 GeV protons would require 55MeV electrons, for example.
- RF acceleration is a natural approach to get e-beam to 10s of MeV.
- LEReC is the world's first electron cooler which uses rf-accelerated electron bunches.
- Since the goal of LEReC was to cool Au ions in RHIC at relatively low energy (Beam Energy Scan physics program in search of QCD critical point), electron beam energies of only few MeV were needed. But RF acceleration approach itself is directly scalable to higher energies.

LEReC Accelerator

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



704 MHz SRF Booster Cavity

Cathode loading system

704 MHz Cu Deflector Cavity

RF Diagnostic Beamline

Merger Beamline

Transport Beamline

704 MHz Cu Cavity

Injection beam dump

9 MHz Cu Cavity

2.1 GHz Cu Cavity

COOLING in Yellow RHIC ring

e-

RHIC TRIPLET

RHIC DX

DC e- Gun

COOLING in Blue RHIC ring

180° Bending Magnet

Extraction beam line

High-Power Beam Dump

LF solenoid

HF solenoid

Transport solenoid

ERL solenoid

Quad corrector

Trim corrector

Corrector 3.8 ID

Corrector 6.0 ID

BPM 2.4 ID

BPM 4.8 ID

Bellows

Ion pump

* NOT to scale

Magnetized and non-magnetized cooling

Basic physics is the same. However, strong magnetic field changes collision dynamics which can significantly affect the cooling process.

1. Magnetized cooling: strong magnetic field in the cooling section limits transverse motion of electrons, so that transverse degree of freedom does not take part in the energy exchange. As a result, the efficiency of cooling is determined by the longitudinal velocity spread of electrons.

   In typical low-energy coolers longitudinal velocity spread of electrons is much smaller than transverse, thus allowing to cool ions to much smaller temperatures. Also, strong velocity anisotropy together with magnetic field leads to “fast cooling”.

2. Non-magnetized cooling: No continuous magnetic field in the cooling section - standard collision process. Since there is no magnetic field to suppress transverse velocities of electrons, velocity spread of electrons should be comparable to the velocity spread of ions which needs to be cooled.

LEReC: first electron cooler which uses non-magnetized electron beam: no magnetization on the cathode. As a result, no continuous longitudinal magnetic field in the cooling sections, which significantly simplifies design technically.

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

Cooling was commissioned using 1.6 MeV kinetic energy electron beam to cool Au ions at 3.85 GeV/nucleon total energy and using 2 MeV electron beam to cool ions at 4.6 GeV/nucleon. Cooling operation for physics at 5.75 GeV/nucleon (2.6 MeV electrons) was not needed.

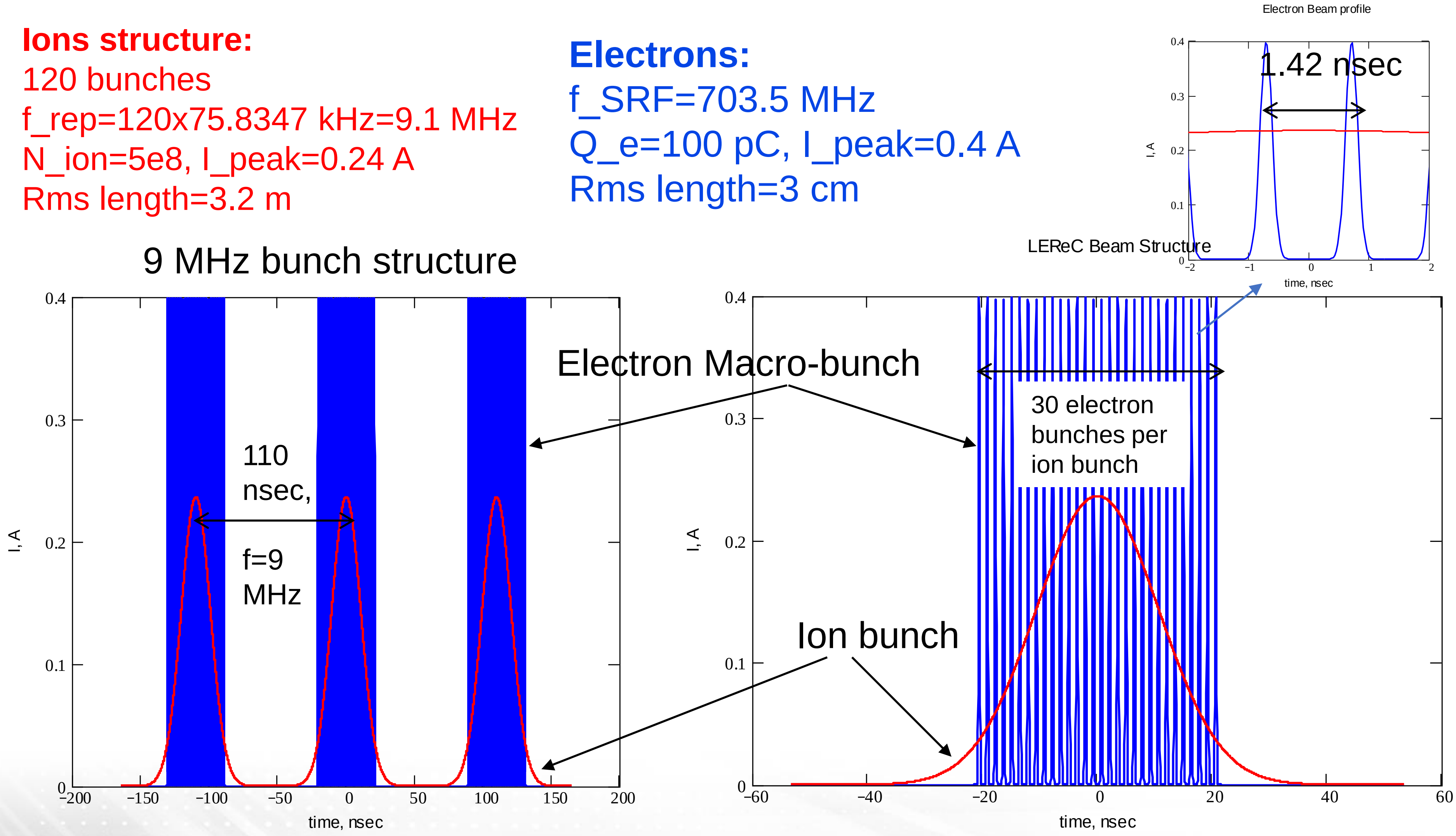
LEReC bunched electron beam cooling

- 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:

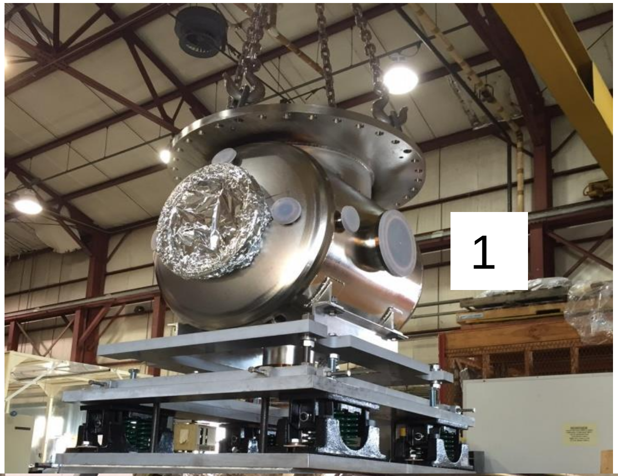
Correction solenoids in the cooling section are used to keep transverse angular spread to a required level.

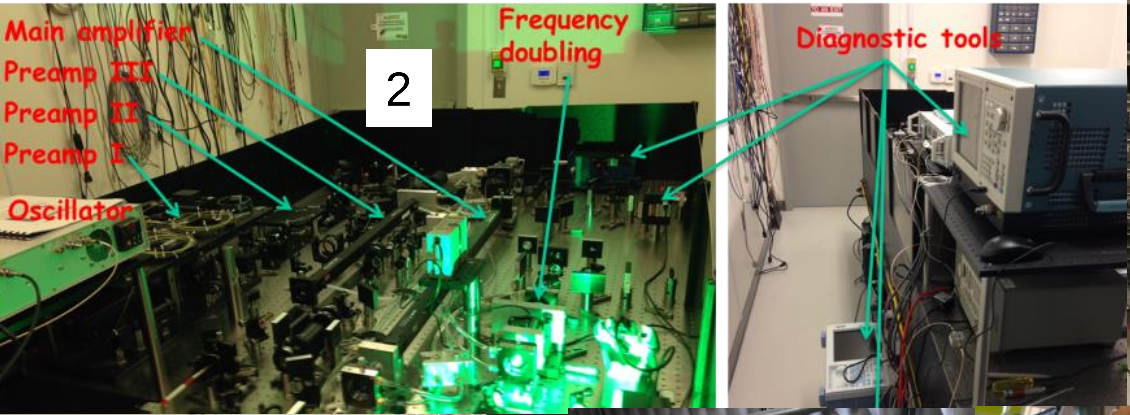
Strict control of electron angles in cooling sections:

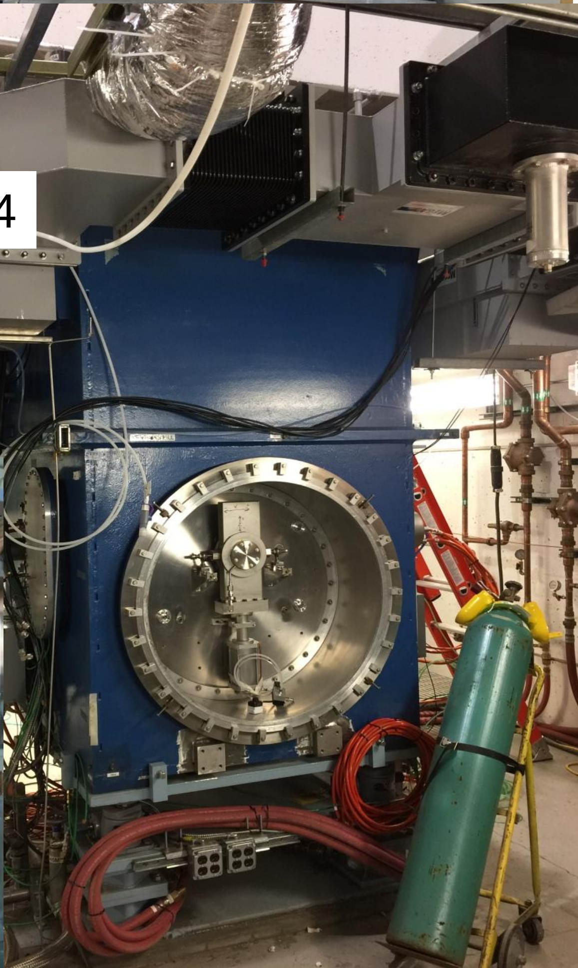
Cooling sections are covered by several layers of Mu-metal shielding.

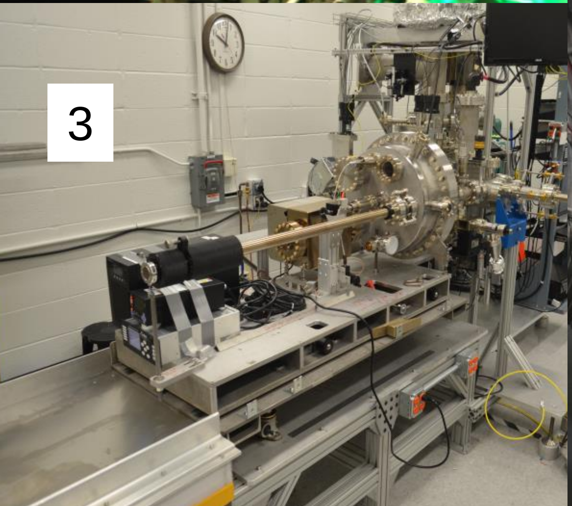
LEReC Critical Technical Systems

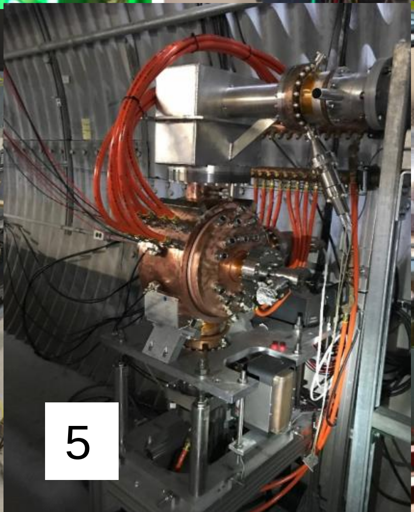
1. High-voltage photocathode electron gun
2. High-power fiber laser, transport and stabilization
3. Cathode production deposition and delivery systems
4. 704 MHz SRF Booster cavity
5. 2.1 GHz and 704 MHz warm RF cavities











LEReC construction started in 2016

LEReC Gun test beamline (2017)


Cathode insertion system


Gun transport section


Injection beamline


Injection beam dump

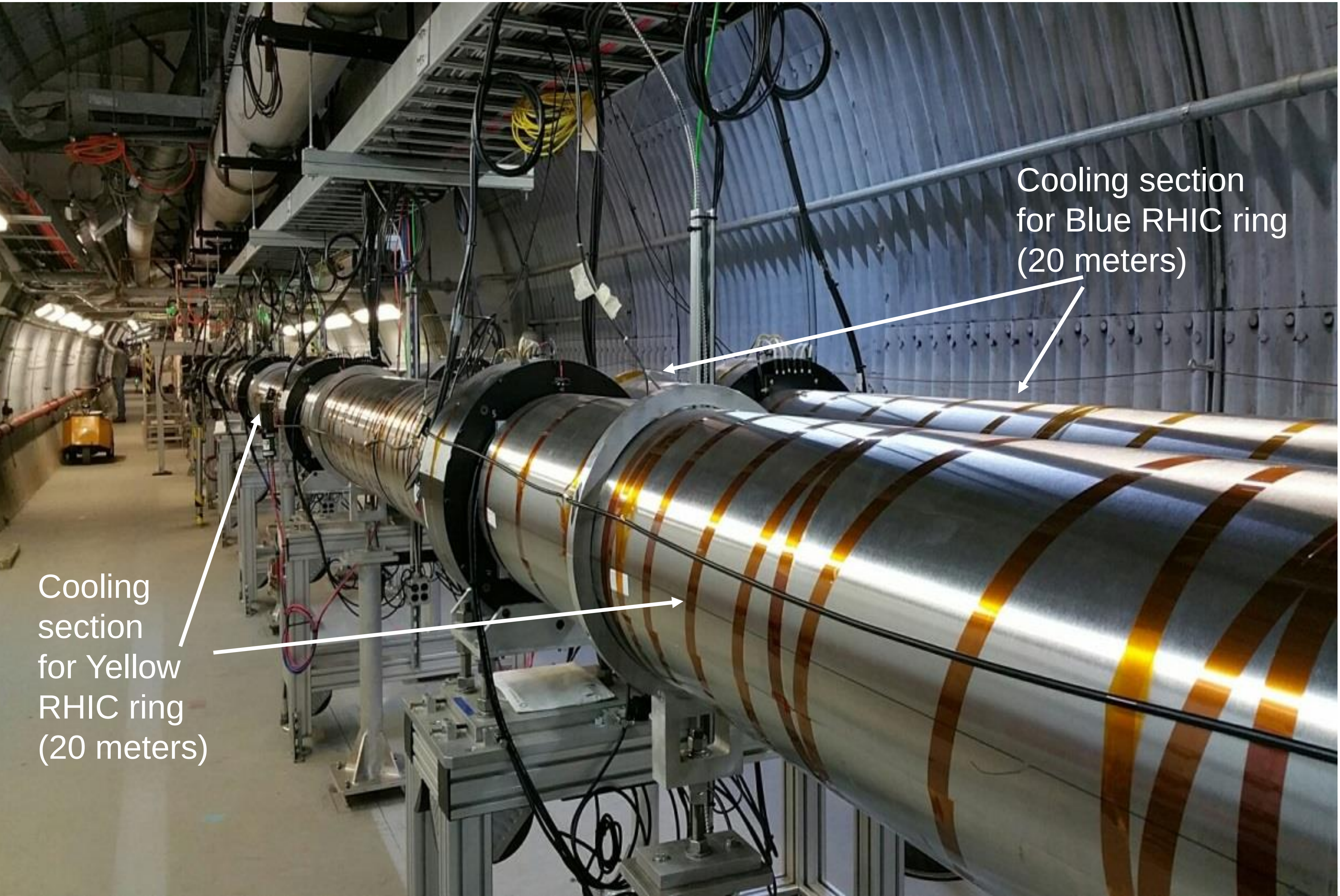
Full LEReC installation (October 2017)

DC Gun

SRF Booster stand

LEReC transport beam line

LEReC cooling sections fully installed (2018)



Cooling section
for Blue RHIC ring
(20 meters)

Cooling
section
for Yellow
RHIC ring
(20 meters)

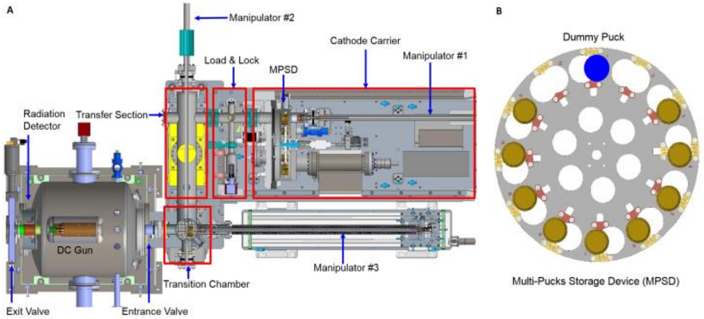
Attainment of “cold” electron beam suitable for cooling

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

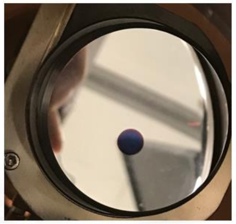
- Photocathodes: production and sophisticated delivery systems
- High power fiber laser, transport and stabilization systems
- Laser beam shaping to produce electron bunches of required quality
- Operation of DC gun at high voltages (around 400kV) with high charge and high average current
- RF gymnastics using several RF cavities and stability control
- Energy stability and control
- Instrumentation and controls

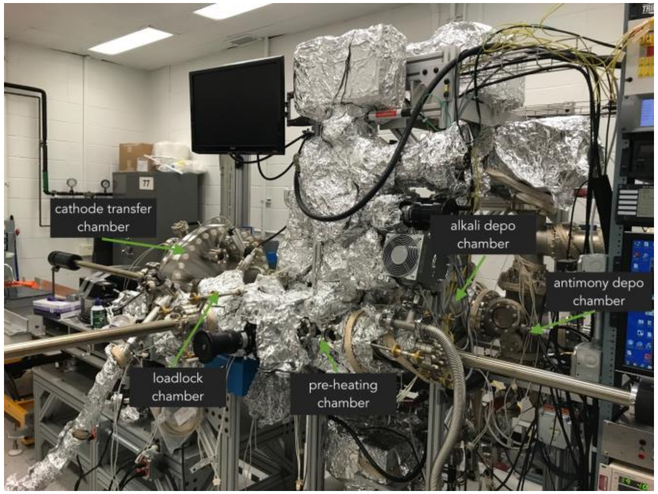
Gun performance

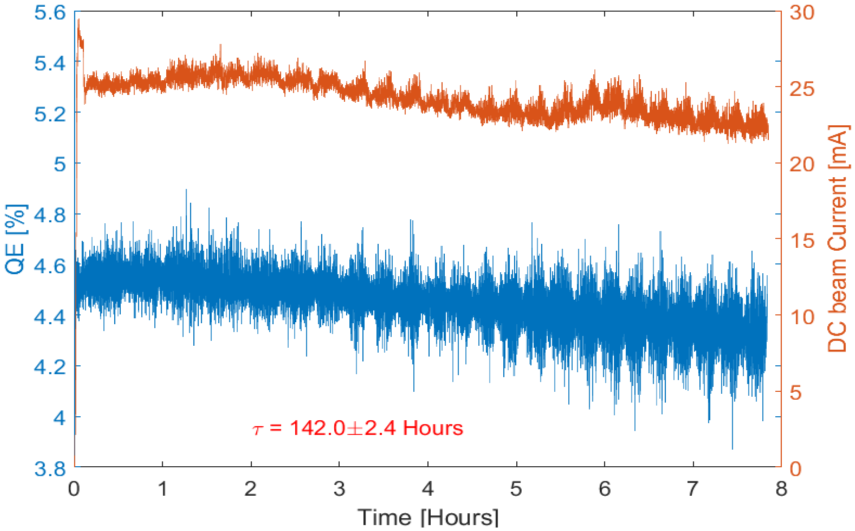
- To support 24/7 operations, cathode production and exchange systems were developed which include two cathode deposition systems and three multi-cathode (up to 12 cathodes) carriers.
- Gun with high QE cathodes (typical initial QE was 8% during 2020 run) and stable laser provided reliable beam operation.



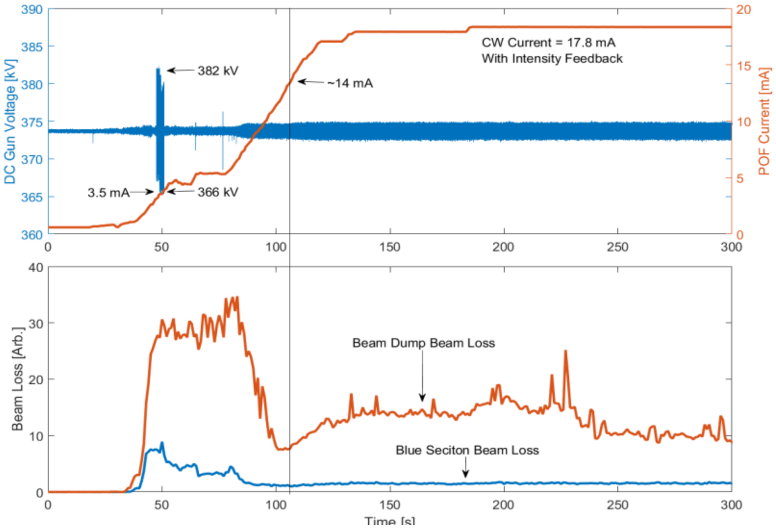
Off center 6mm active area





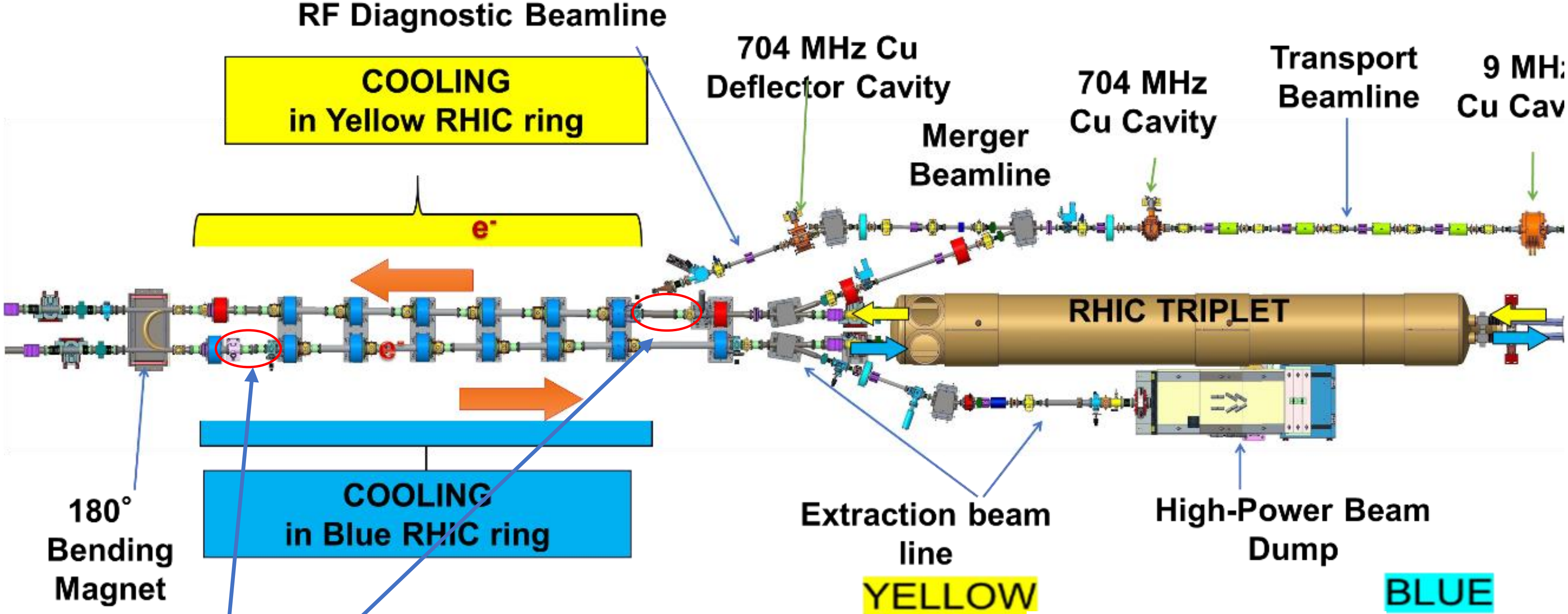


Beam current in CW operation (red line) over 8 hours, and QE (blue line) with a fitted cathode current lifetime of 142 h (2019).



Typical CW beam current ramp-up for cooling optimization.

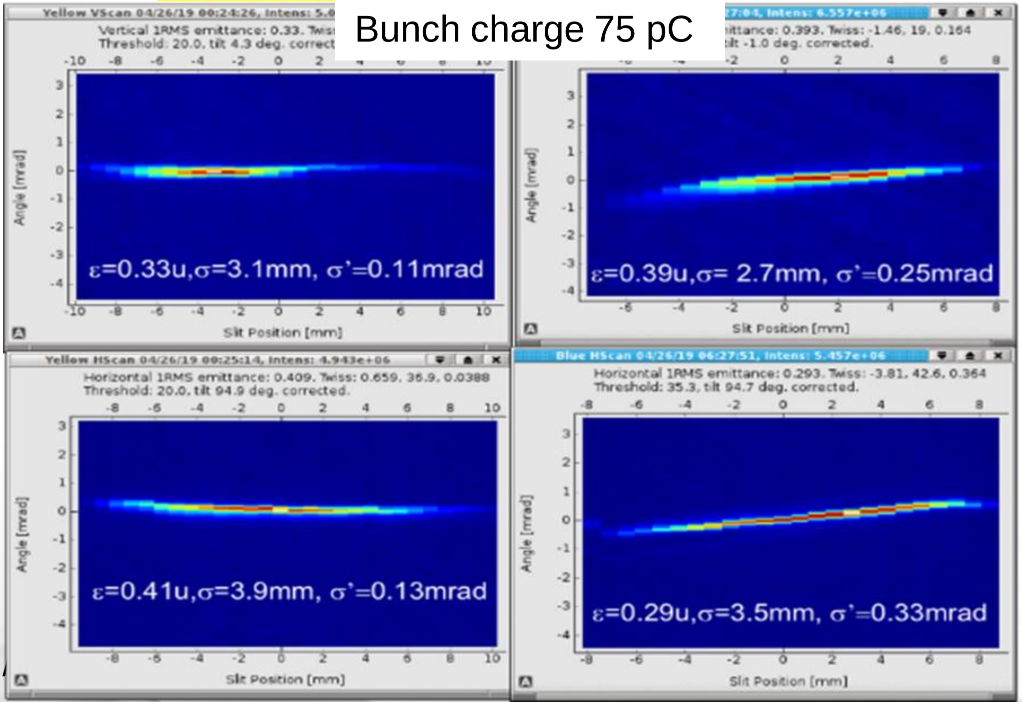
Transverse phase-space measurements of electron beam



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

YELLOW **BLUE**

Bunch charge 75 pC


Yellow VScan 04/26/19 00:24:26, Intens: 5.0
Vertical 1RMS emittance: 0.33. Twis
Threshold: 20.0, tilt 4.3 deg. correct

ε=0.33u,σ=3.1mm, σ'=0.11mrad

27:04, Intens: 6.557e+06
ittance: 0.393. Twiss: -1.46, 19, 0.164
ilt -1.0 deg. corrected.

ε=0.39u,σ= 2.7mm, σ'=0.25mrad

Yellow HScan 04/26/19 00:25:14, Intens: 4.943e+06
Horizontal 1RMS emittance: 0.409. Twiss: 0.659, 36.9, 0.0388
Threshold: 20.0, tilt 94.9 deg. corrected.

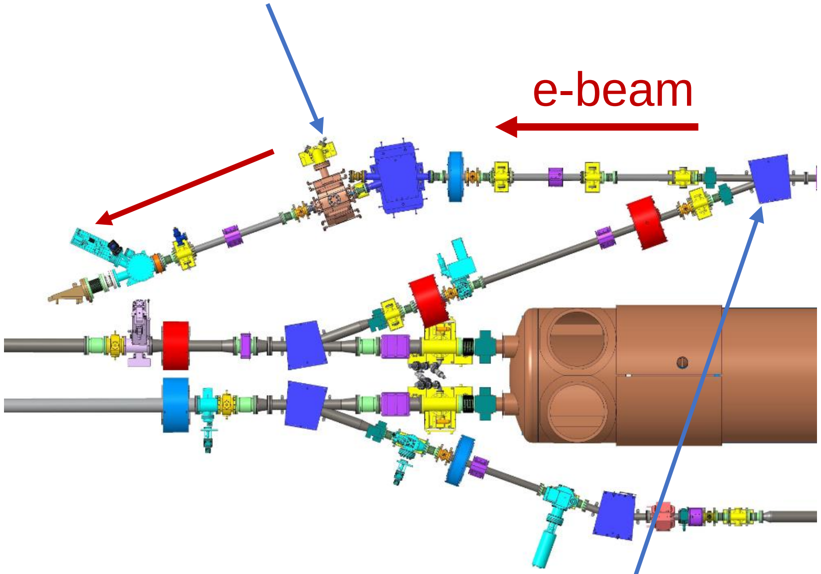
ε=0.41u,σ=3.9mm, σ'=0.13mrad

Blue HScan 04/26/19 06:27:51, Intens: 5.457e+06
Horizontal 1RMS emittance: 0.293. Twiss: -3.81, 42.6, 0.364
Threshold: 35.3, tilt 94.7 deg. corrected.

ε=0.29u,σ=3.5mm, σ'=0.33mrad

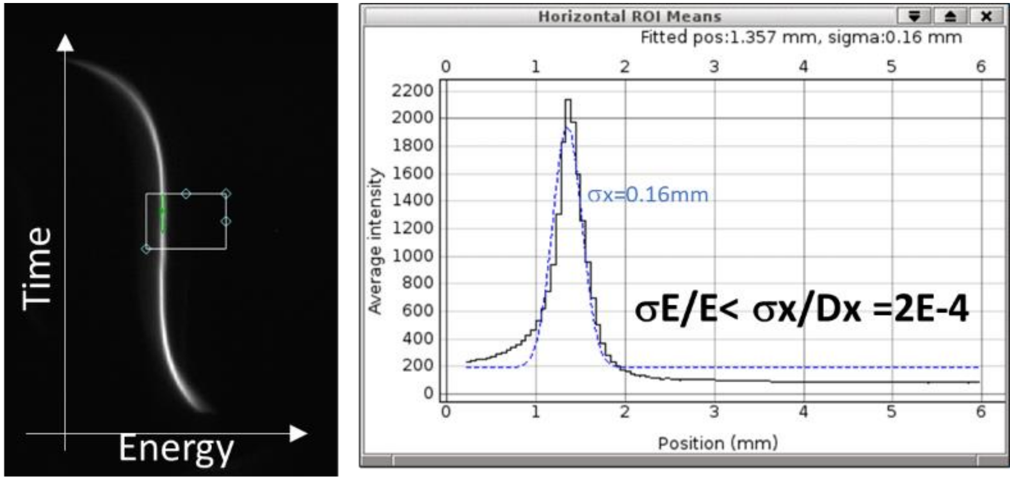
Longitudinal phase-space measurement of electron beam

704MHz deflecting cavity



- 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

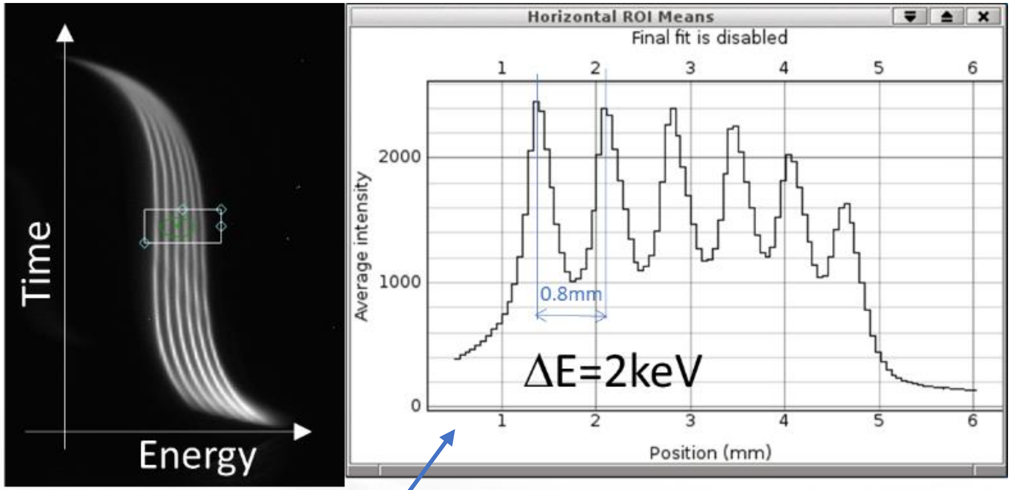
1 macro-bunch of electrons (total charge 3nC)



Fitted pos:1.357 mm, sigma:0.16 mm

σE/E< σx/Dx =2E-4

6 macro-bunches, 3 nC each.

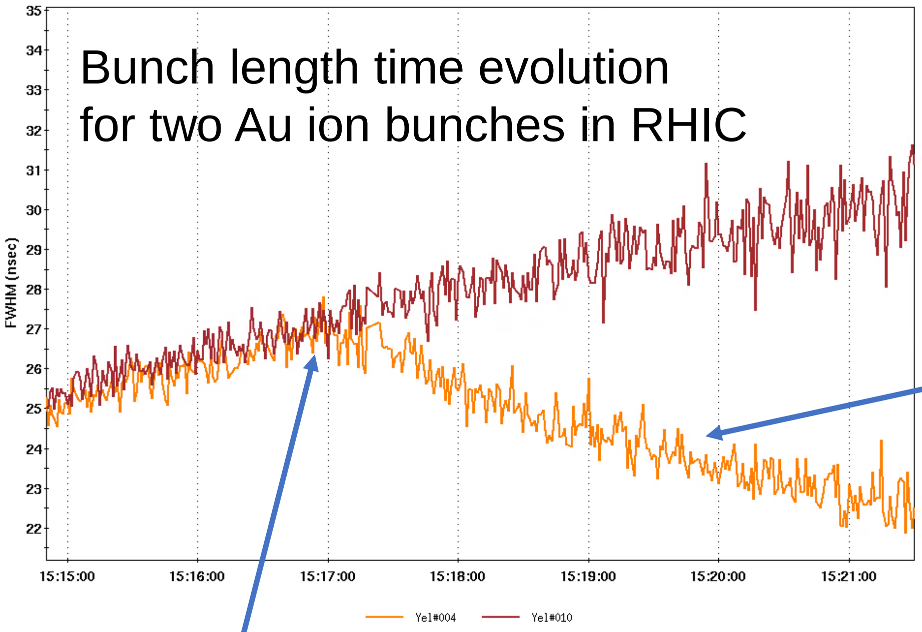


Final fit is disabled

ΔE=2keV

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



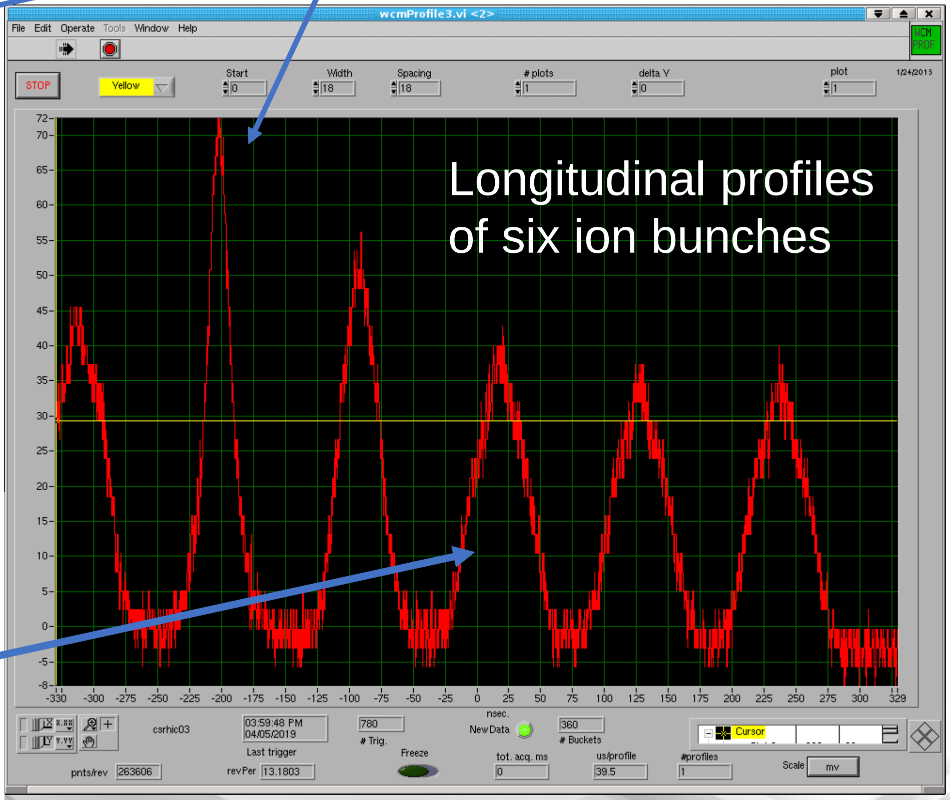
Bunch length time evolution for two Au ion bunches in RHIC

Ion bunch #4 which is not being cooled

Ion bunch #2 is being cooled

Energy of electrons and ions matched

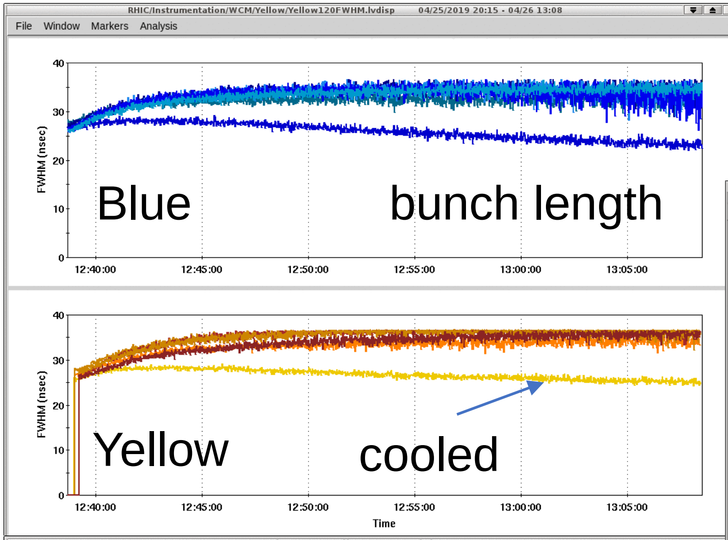
In 76kHz commissioning mode, subsequent electron macro-bunches have lower energy due to beam loading in RF cavities (can match energy/cool effectively single ion bunch).



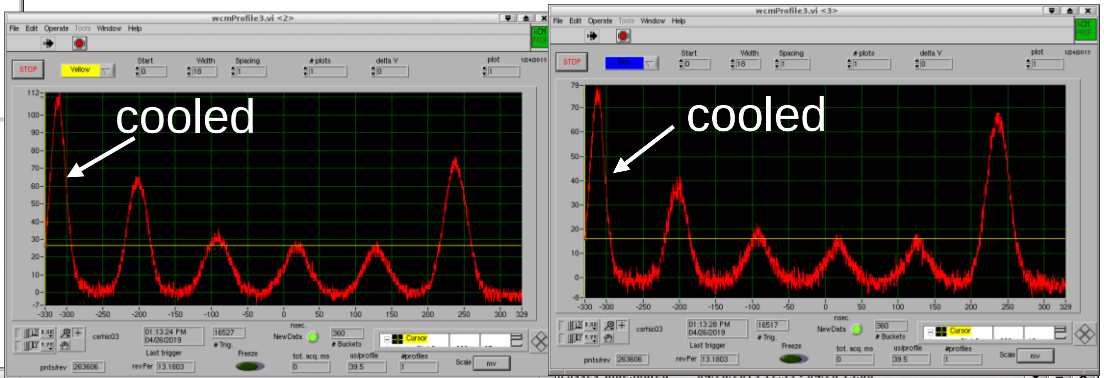
Start 0
Width 18
Spacing 18
plots 1
delta Y 0
plot 1
1/24/2013
csrhic03
Last trigger 03:59:48 PM 04/05/2019
Trig. 780
Freeze
NewData
Buckets 360
tot. acq. ms 0
us/profile 39.5
#profiles 1
pnts/rev 263606
revPer 13.1803
Scale mv

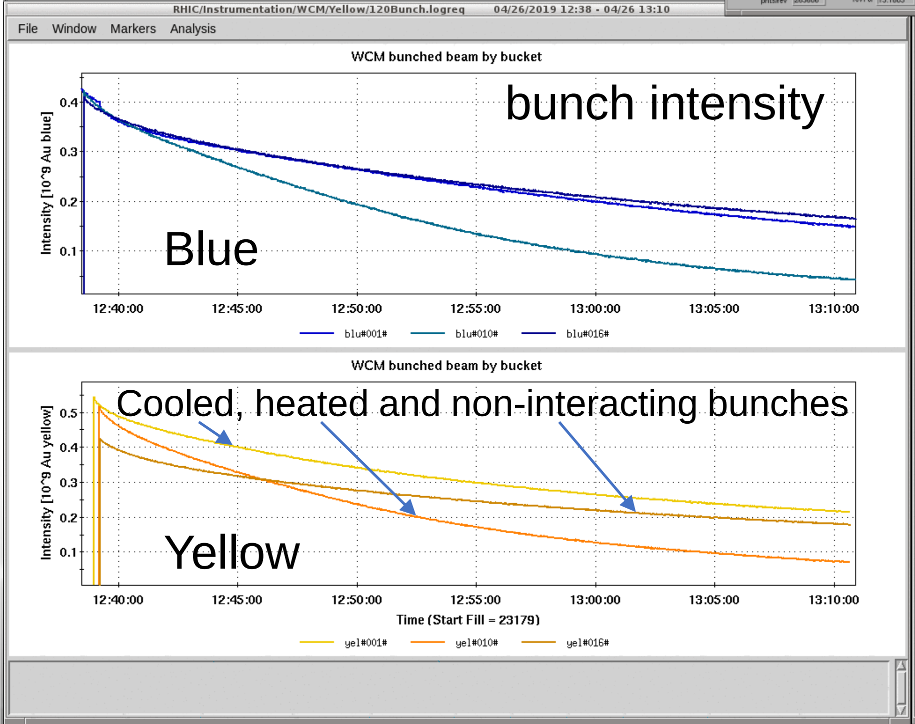
Longitudinal profiles of six ion bunches

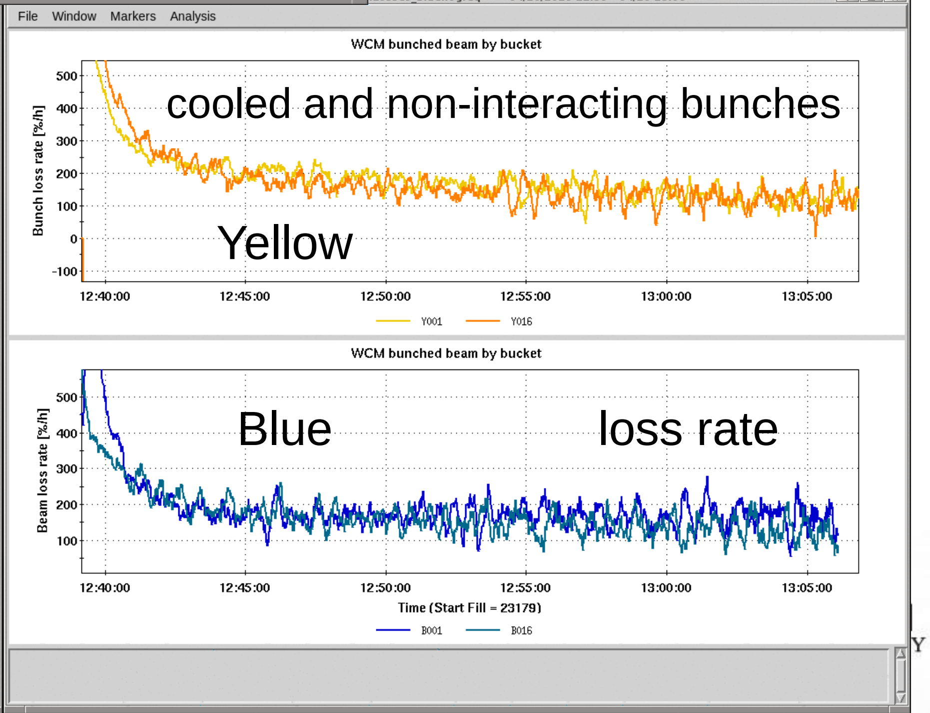
Simultaneous cooling of ion bunches in Yellow and Blue RHIC rings (76kHz mode, 6 ion bunches: bunch #1 is being cooled; bunch #6 does not see electrons) using the same electron beam (2019)



Longitudinal bunch profiles

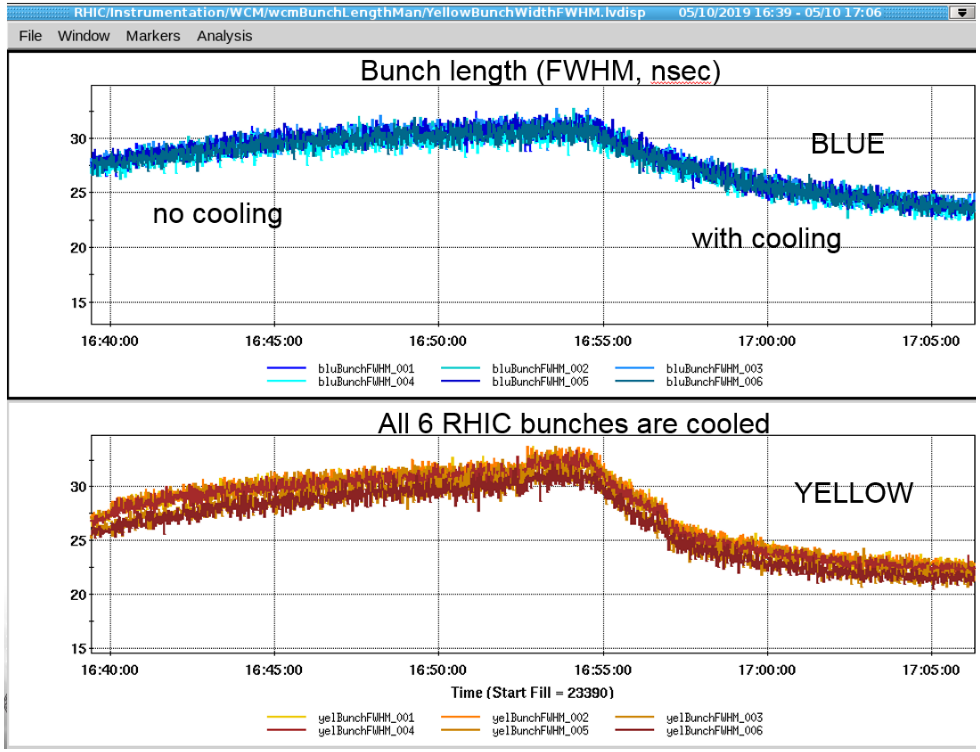


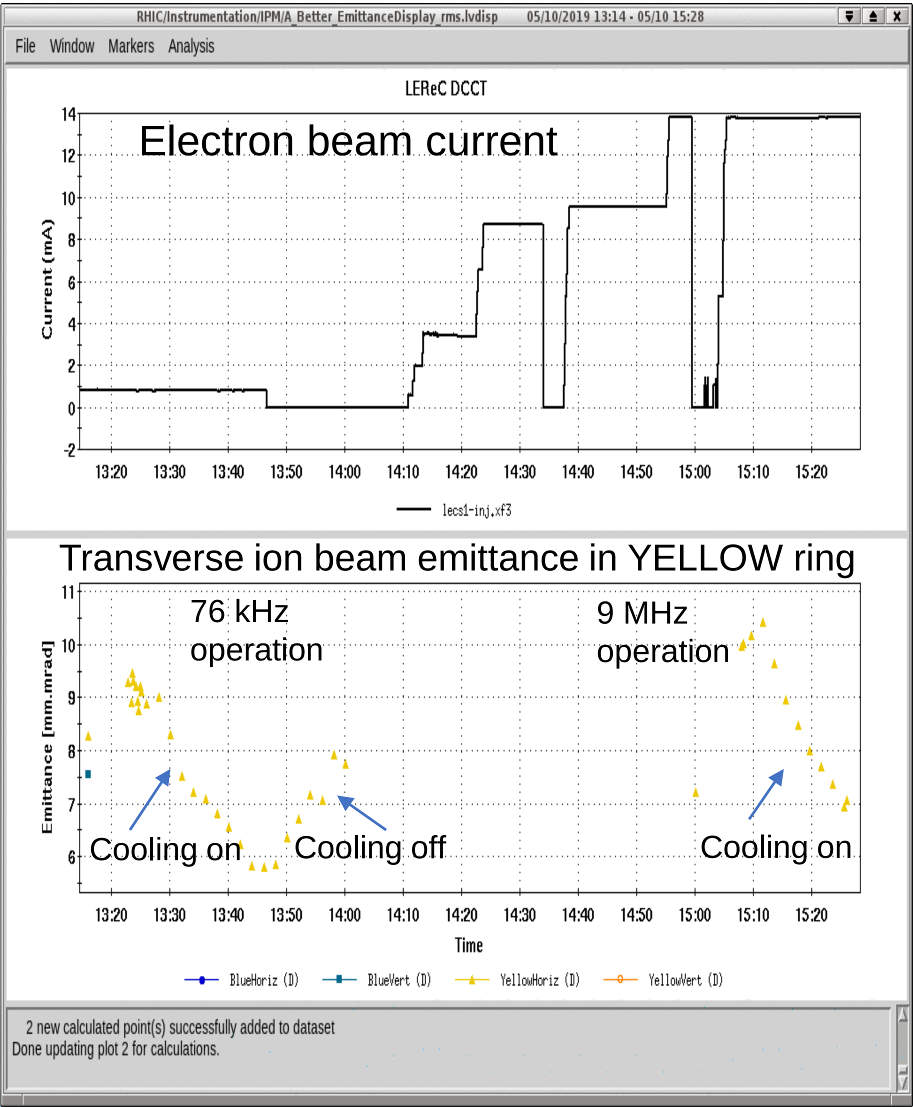




High-current CW electron beam operation and cooling of many ions bunches simultaneously (2019)

- To proceed from cooling single ion bunch using 76kHz electron beam to cooling of many ion bunches required establishing high-current 9MHz electron beam operation through both cooling sections all the way to high-power beam dump.





2 new calculated point(s) successfully added to dataset
Done updating plot 2 for calculations.

Cooling in a collider

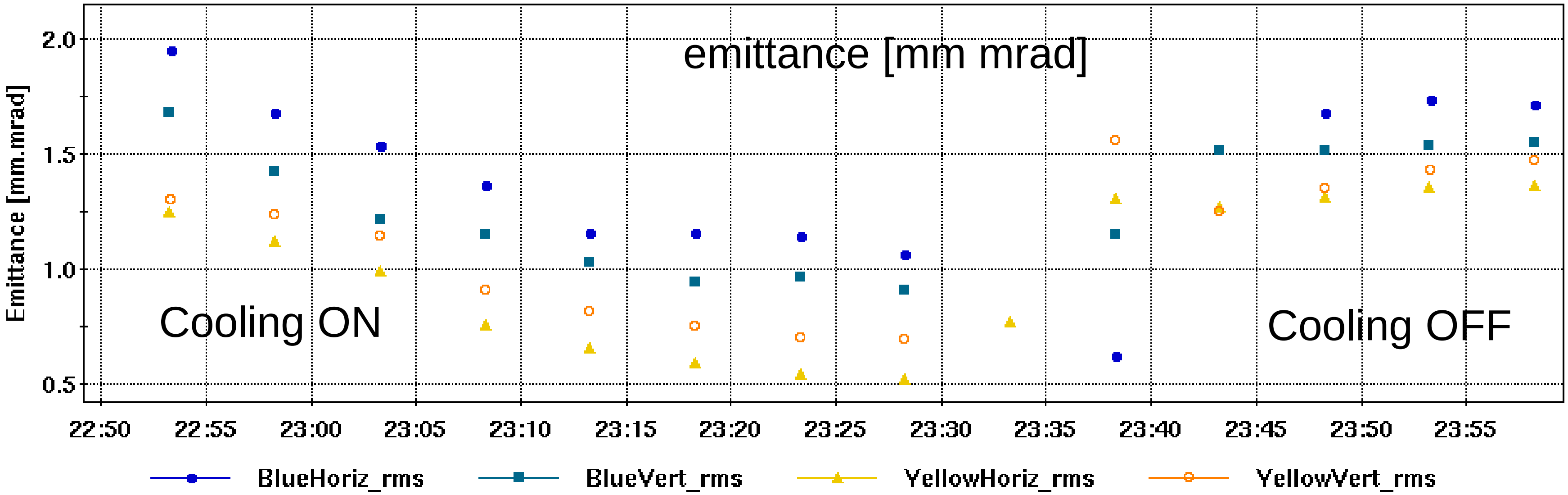
After 6D electron cooling of hadron beams was successfully commissioned in both RHIC rings in 2019, our focus shifted towards operational aspects of cooling of full RHIC stores with ion bunches in collisions.

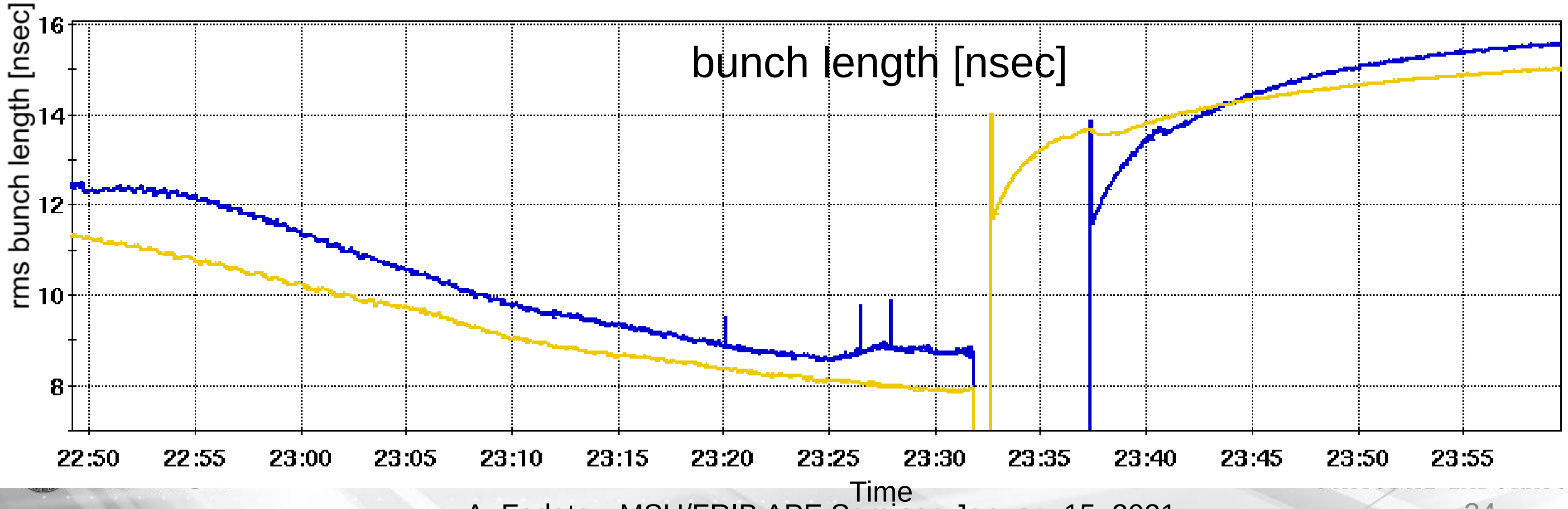
Application of electron cooling technique directly at collision energy of hadron beams brings several challenges, such as:

- 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

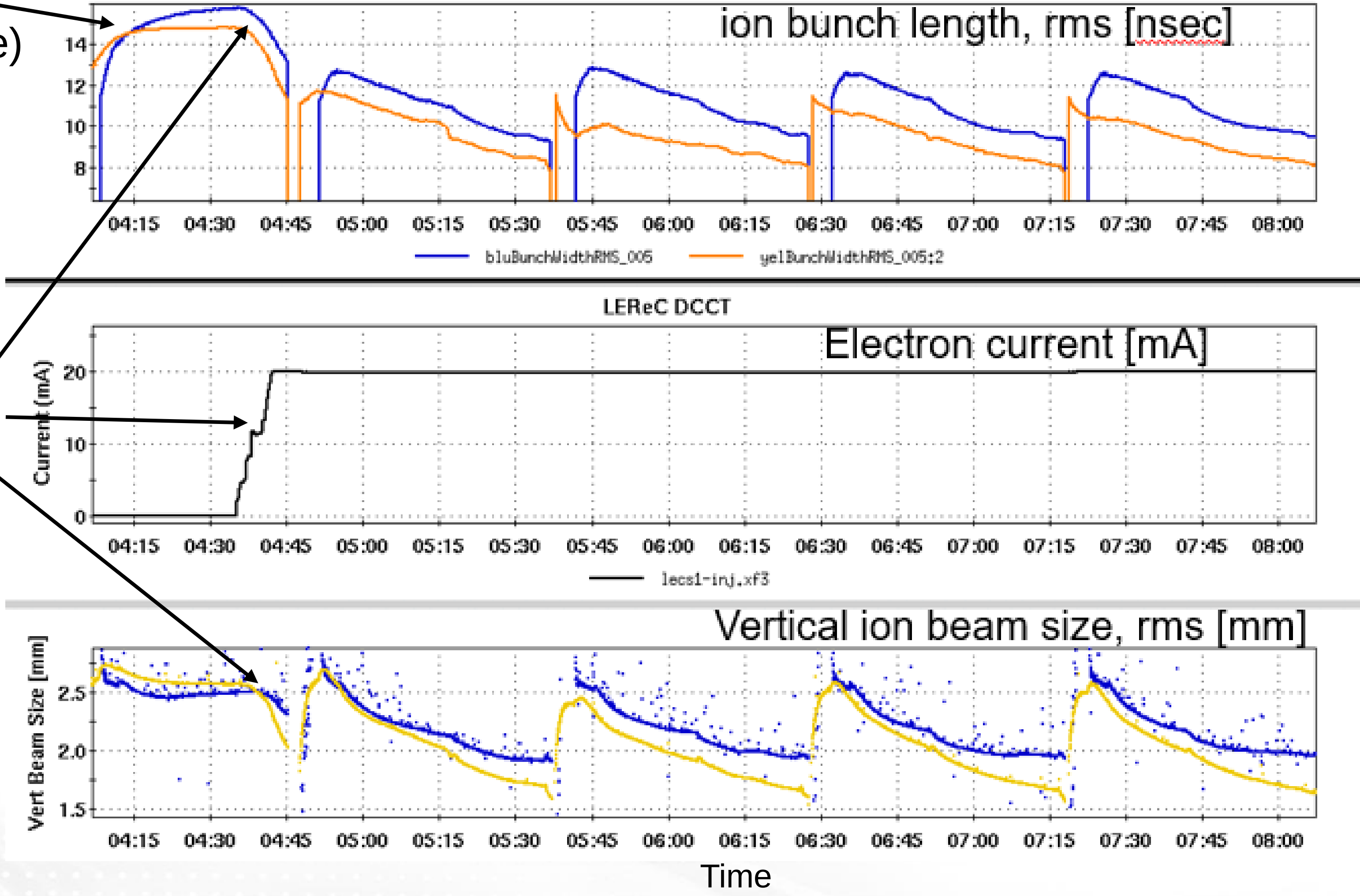
The final optimization was performed during operation for physics by choosing parameters which result in largest luminosity gains (not necessarily higher electron beam current or stronger cooling)

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





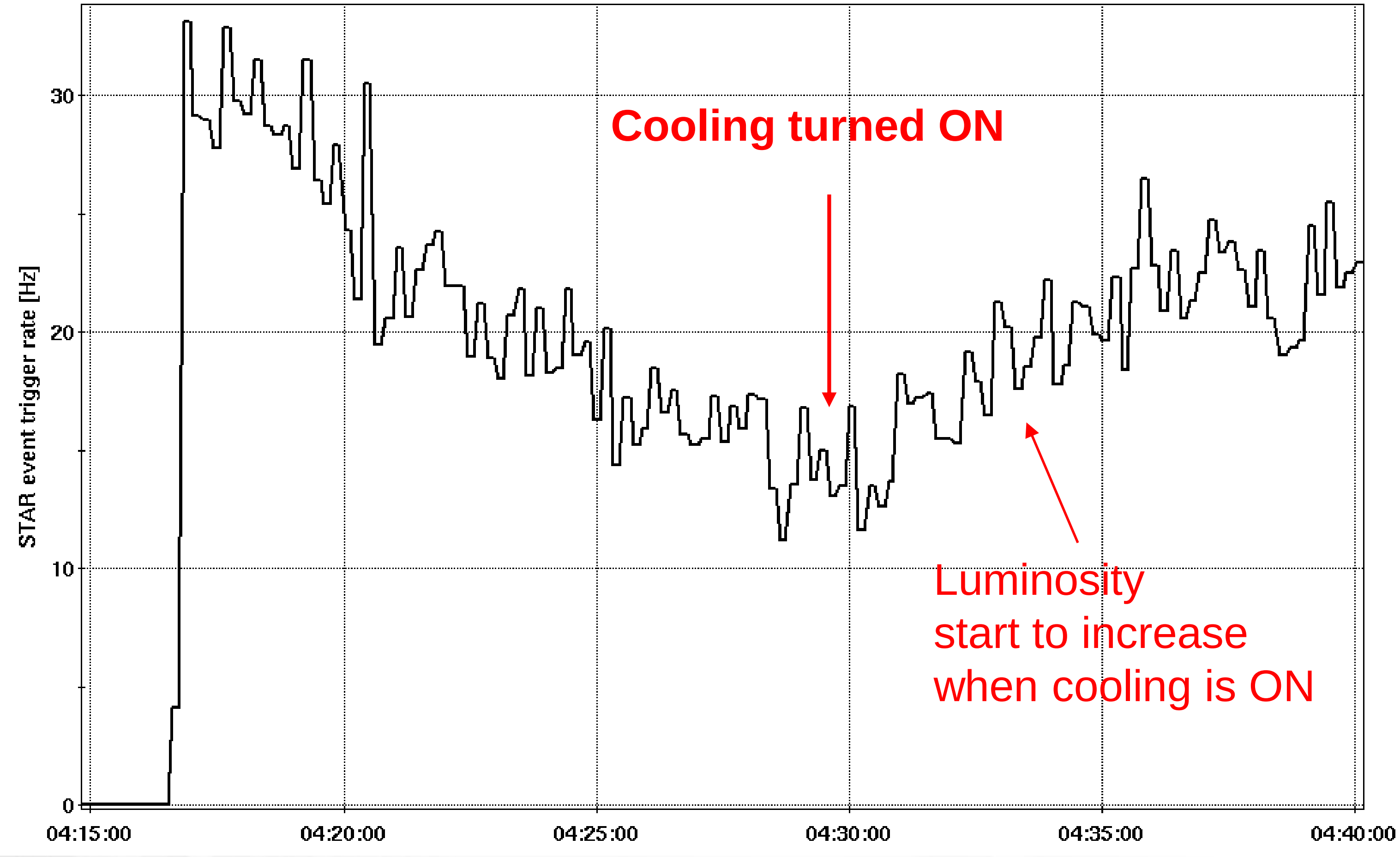
Cooling of hadron beams in Yellow and Blue RHIC rings during physics stores (Au ions at 4.6 GeV/n, 2MeV electrons)



Cooling is off
(during first store)

Cooling starts when electron current is being ramped up.

Physics store with electron beam (cooling) restored later in the store



Cooling turned ON

Luminosity
start to increase
when cooling is ON

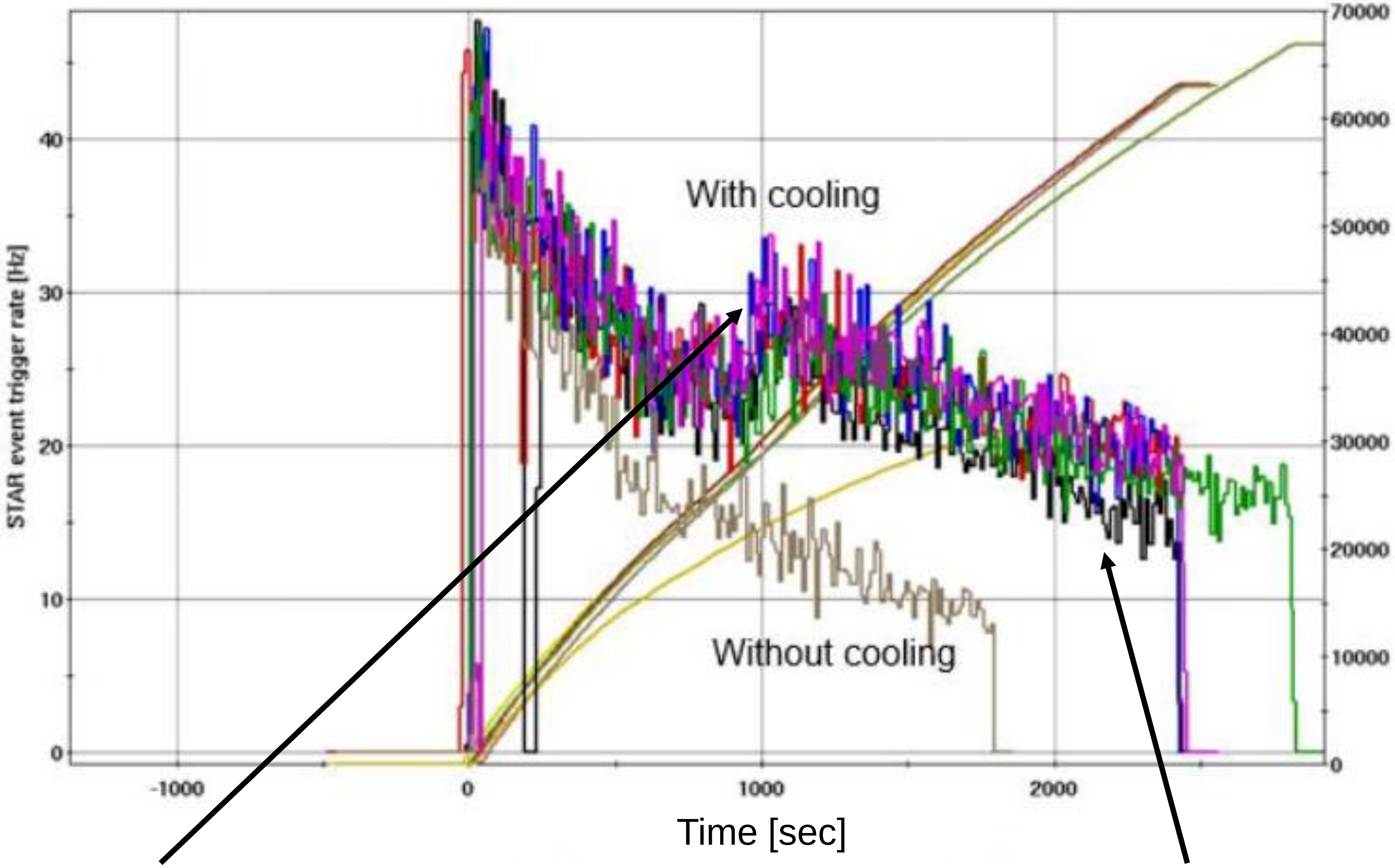
Time

Cooling optimization for luminosity

Luminosity optimization with cooling is ongoing but the following was already successfully tried during physics operation with Au ions at 4.6 GeV/nucleon:

- Finding optimum angular spread of electrons in cooling sections to provide sufficient cooling
- Optimization of electron and ion beam sizes in the cooling sections
- Finding optimum electron current to reduce heating effects on ion beam and still provide sufficient cooling
- Longer stores with cooling
- With cooling counteracting longitudinal IBS and preventing debunching from the RF bucket, ions RF voltage was reduced resulting in smaller momentum spread of ions and improving ion lifetime
- Once good transverse cooling was established dynamic squeeze of ion beta-function at the collision point was implemented

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



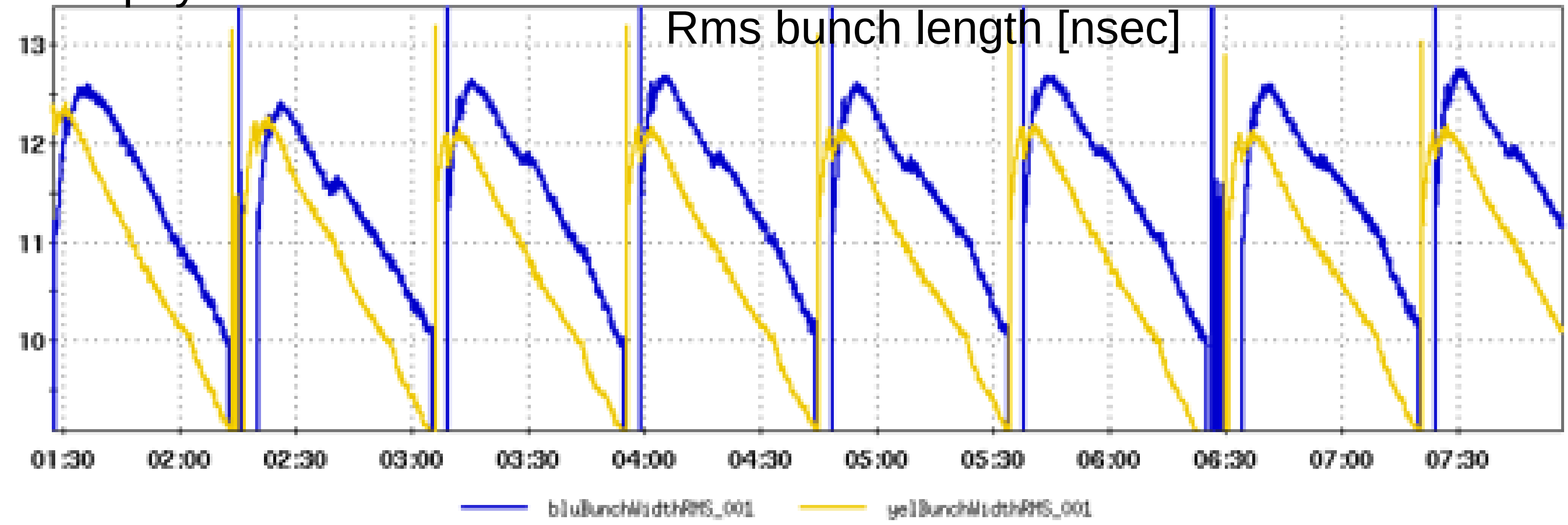
Dynamic squeeze of beta-function at collision point, while transverse beam sizes of ion beams are being cooled

Longer stores with cooling

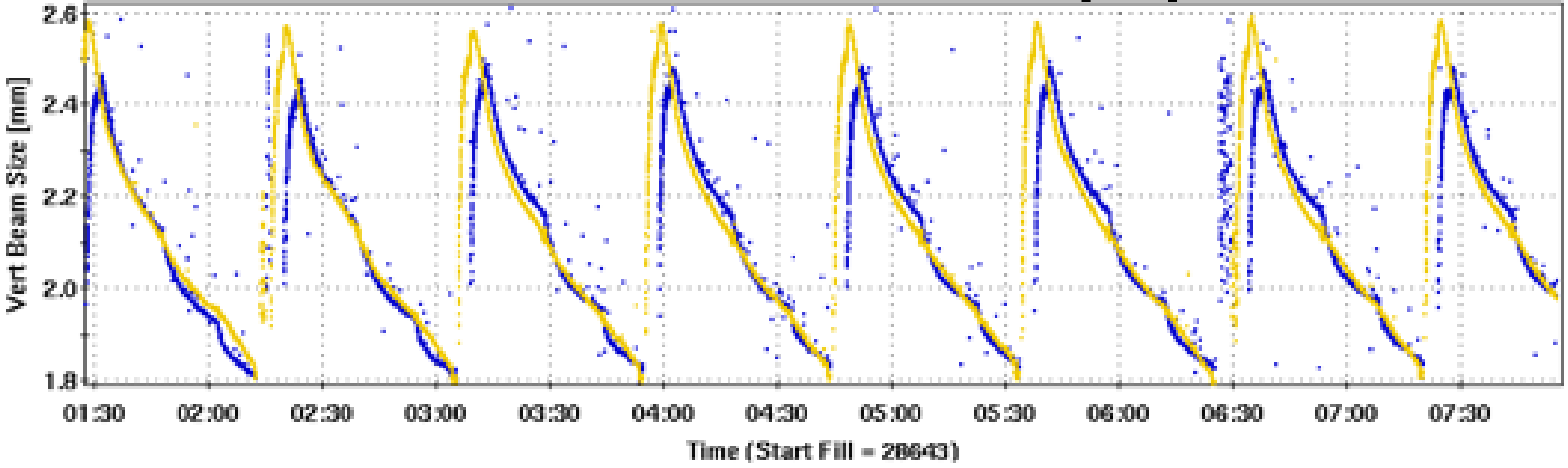
Typical cooling performance (August 26, 2020), 2 MeV electrons, 111x111 Au ion bunches at 4.6GeV/n

Several physics stores

Rms bunch length [nsec]



Vertical beam size [mm]

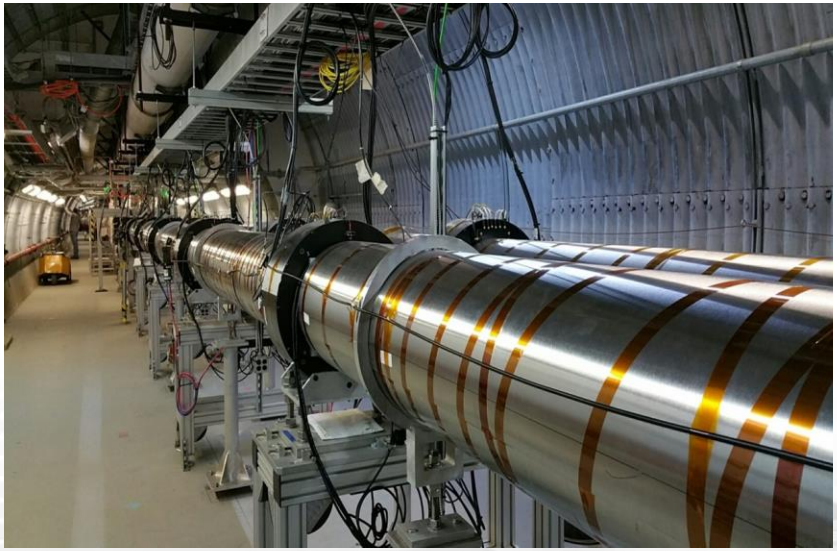


LEReC roadmap to cooling in a collider

- 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 ✓
- 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 ✓

Summary

- LEReC is world’s first electron cooler which uses rf-accelerated electron bunches.
- Electron cooling in a collider was successfully implemented and became fully operational during 2020 RHIC Physics run with Au ions.
- Stable and reliable high-current electron accelerator operation and robust cooling performance during many weeks of Physics running in 2020.
- Luminosity optimization with cooling is ongoing but significant luminosity improvement was already achieved.



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.

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

Thank you!

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).