Low Energy RHIC electron Cooling (LEReC):

Cooling commissioning results and challenges of RF-based electron cooler LEReC

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on behalf of the LEReC team

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U.S. DEPARTMENT OF ENERGY

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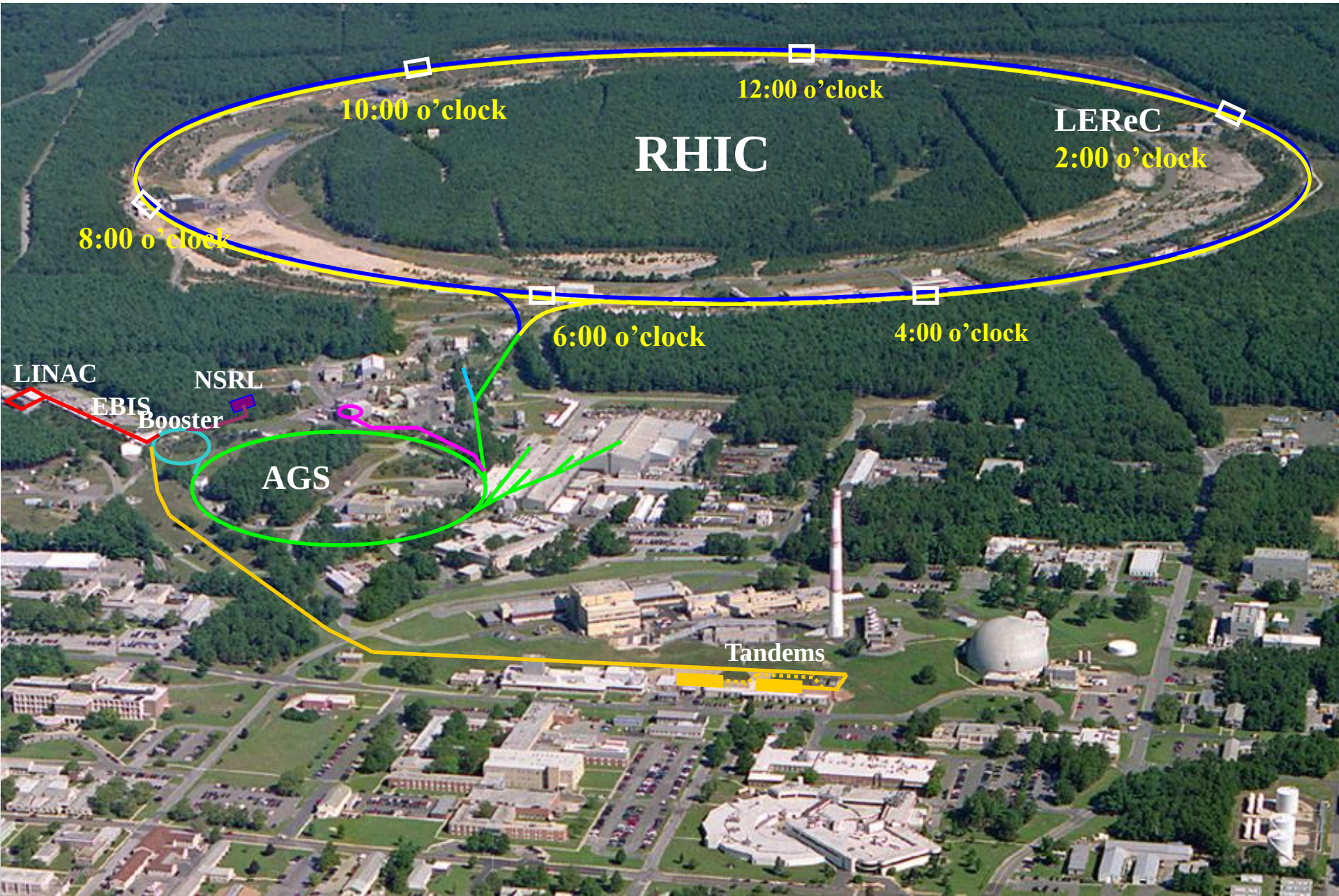
LEReC Project Overview

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:

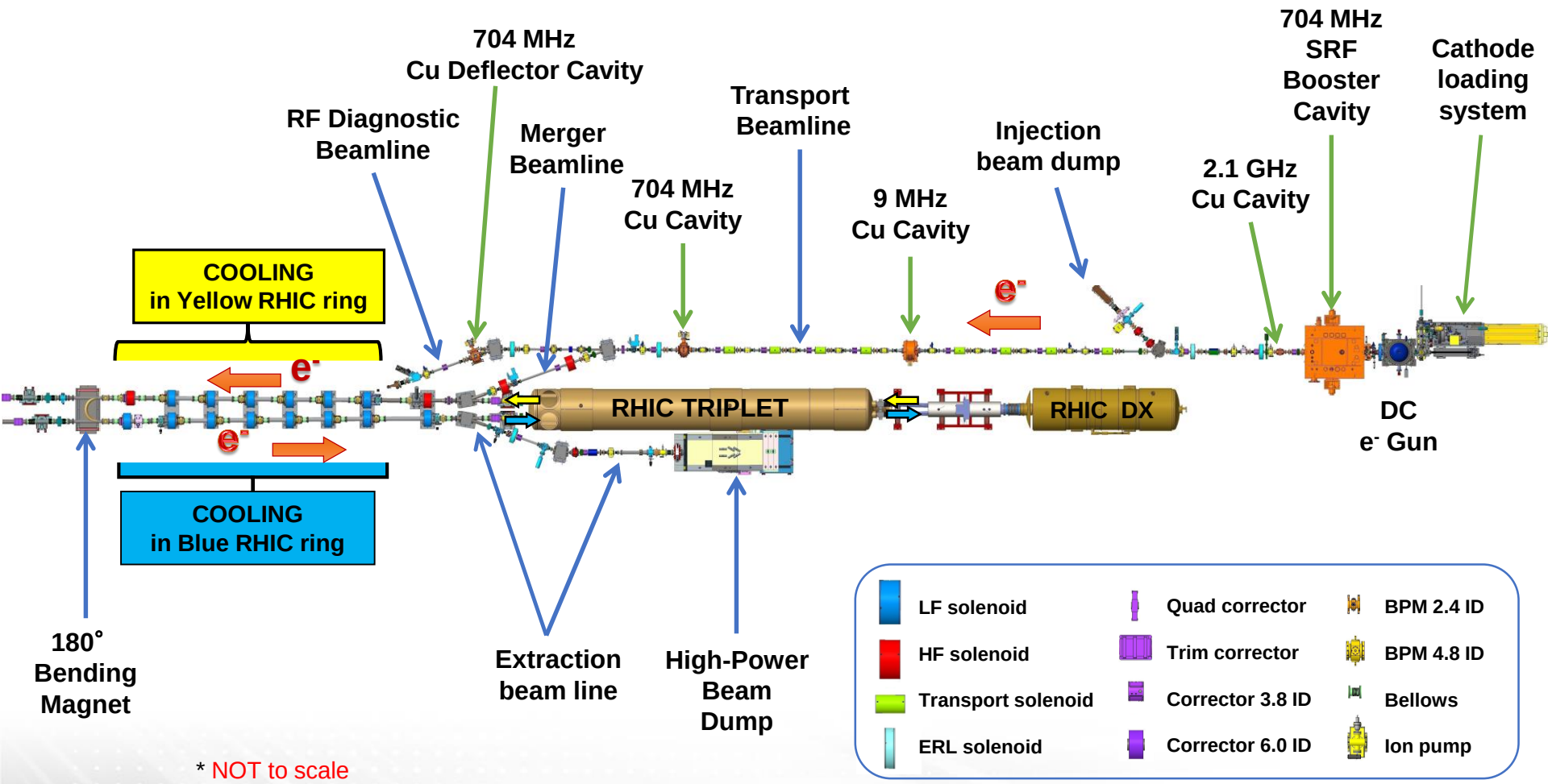
- ❑ **Building and commissioning of new state of the art electron accelerator ✓**
- ❑ **Produce electron bunches with beam quality suitable for cooling✓**
- ❑ **RF acceleration and transport maintaining required beam quality✓**
- ❑ **Achieve required beam parameters in cooling sections✓**
- ❑ **Commissioning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

RHIC @ BNL, Long Island, New York



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:

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

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

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

- 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 emittance, space charge, remnant magnetic fields, etc.) below 150 μrad.

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

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

LEReC electron beam parameters

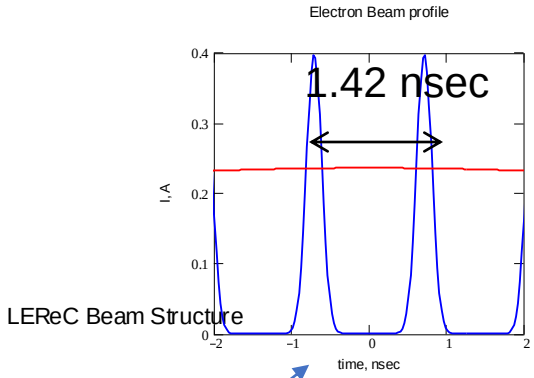
Two energies commissioned ✓

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 beam structure in cooling section

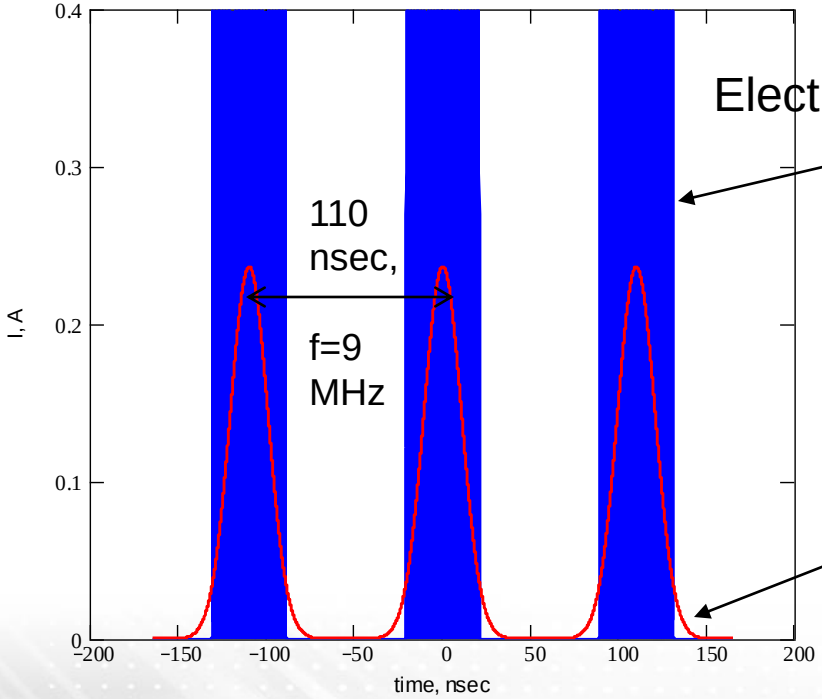
Ions structure:
120 bunches
f_rep=120x75.8347 kHz=9.1 MHz
N_ion=5e8, I_peak=0.24 A
Rms length=3.2 m

Electrons:
f_SRF=703.5 MHz
Q_e=100 pC, I_peak=0.4 A
Rms length=3 cm

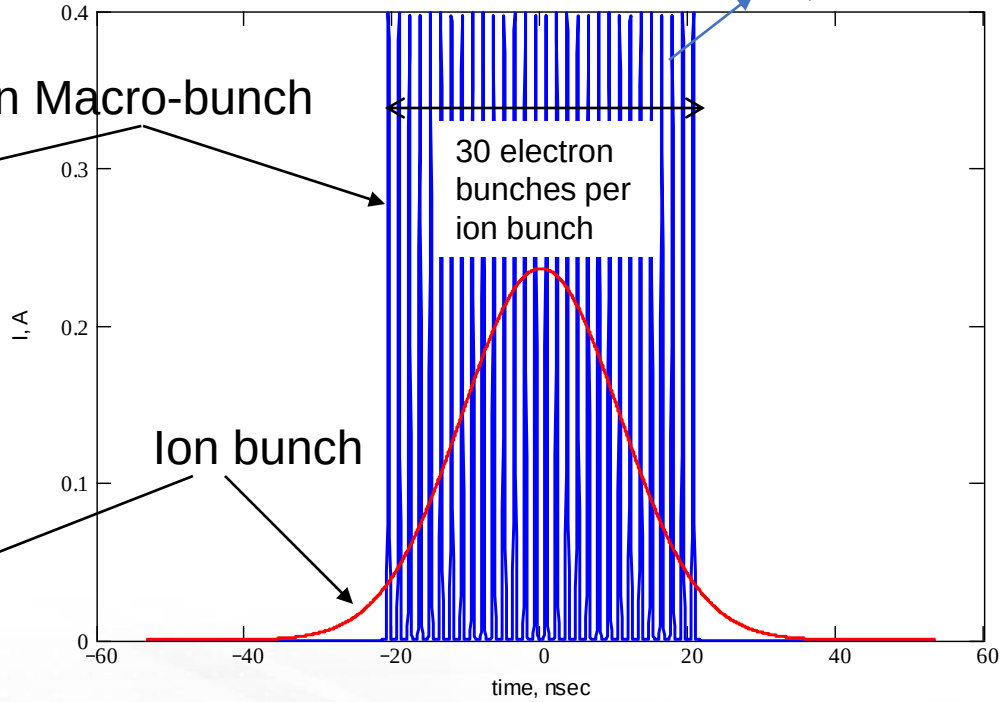


LEReC Beam Structure

9 MHz bunch structure



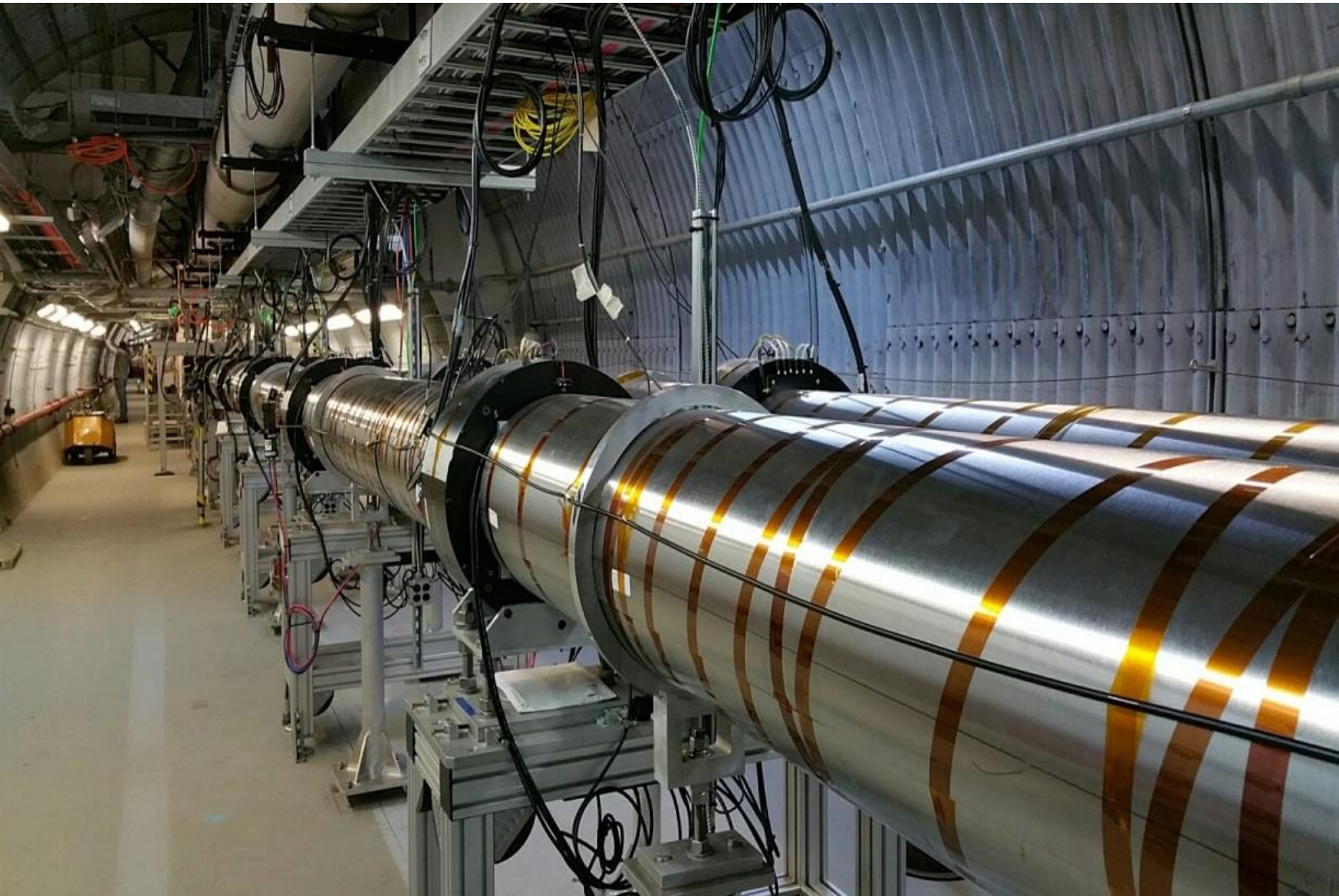
Electron Macro-bunch



LEReC construction started in 2016

Full LEReC installation (October 2017)

LEReC cooling sections fully installed (2018)



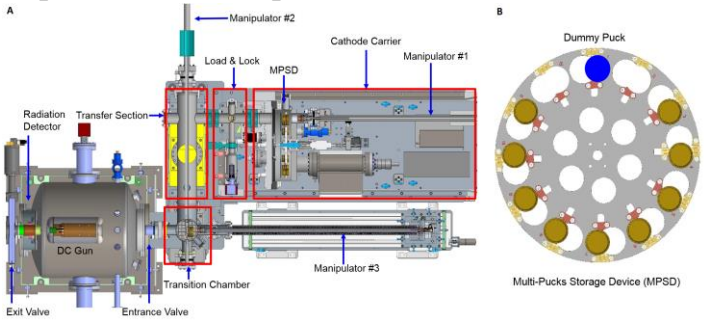
Attainment of “cold” electron beam suitable for cooling

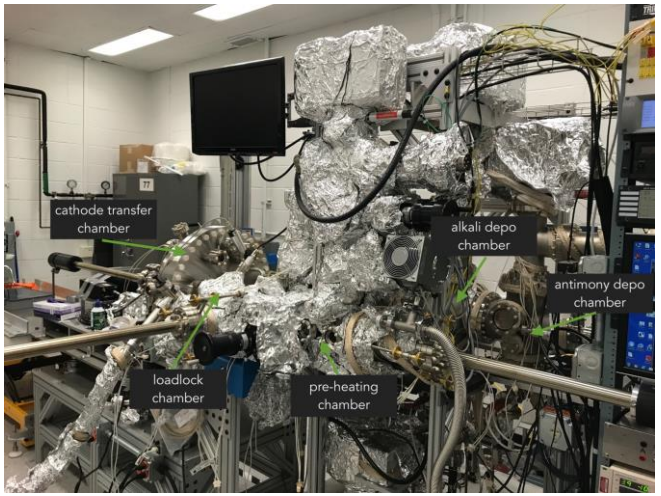
- LEReC is based on the state-of-the-art accelerator physics and technology:

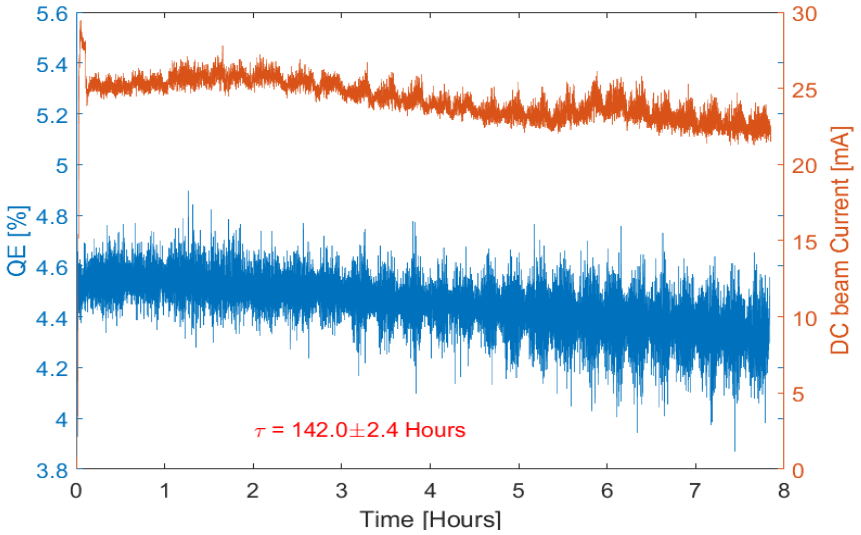
- Photocathodes: production and delivery system
- High power fiber laser and transport
- Laser beam shaping to produce electron bunches of required quality
- Operation of DC gun at high voltages (around 400kV) with high charge and high average current
- RF gymnastics using several RF cavities and stability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

Gun performance

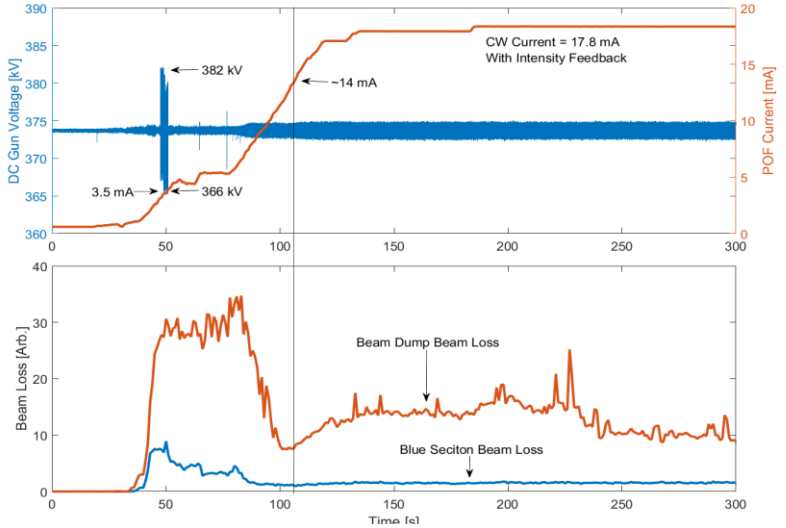
- To support 24/7 operations, cathode production and exchange systems were developed which include two cathode deposition systems, three multi-cathode (up to 12 cathodes) carriers, and a mechanism allowing for cathode exchange in RHIC tunnel in less than 1 hour.
- DC gun with high QE cathodes and stable laser provided reliable beam operation over a period of 7 months.





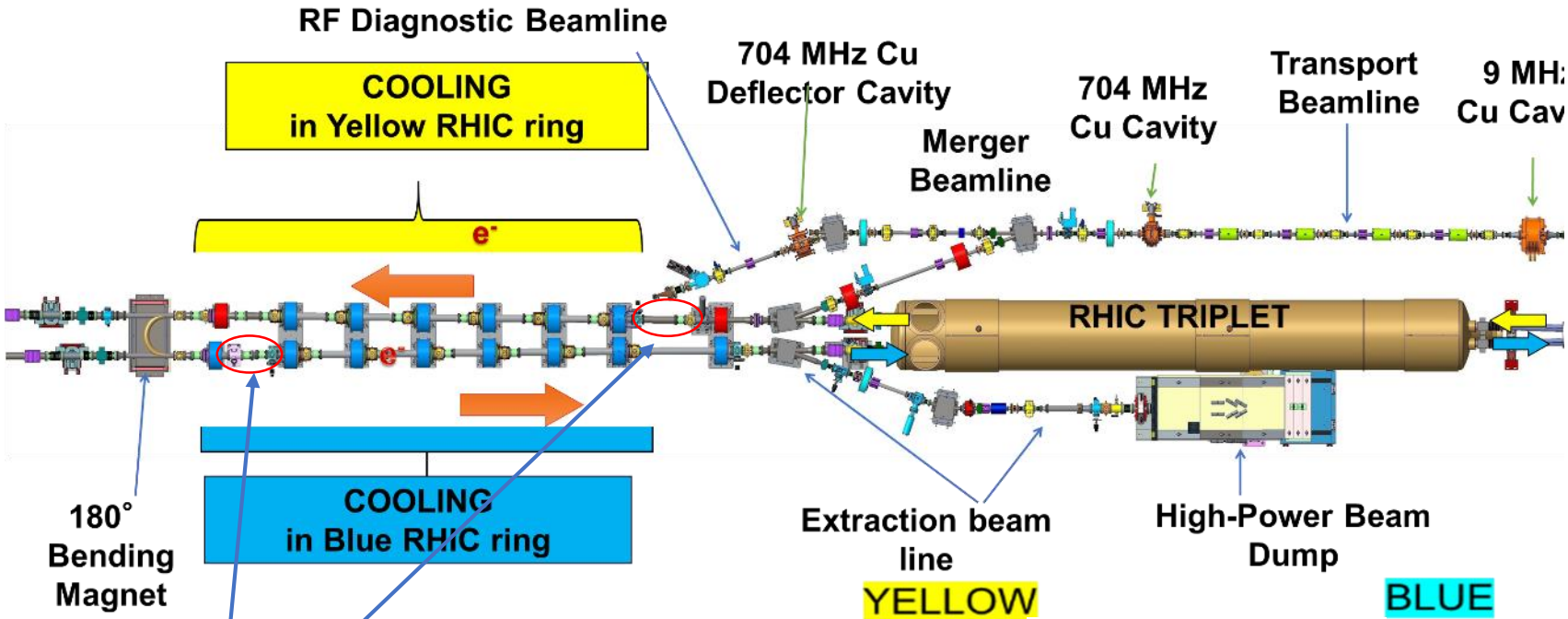


Beam current in CW operation (red line) over 8 hours, and QE (blue line) with a fitted cathode current lifetime of 142 h.



Typical CW beam current ramp-up for cooling optimization.

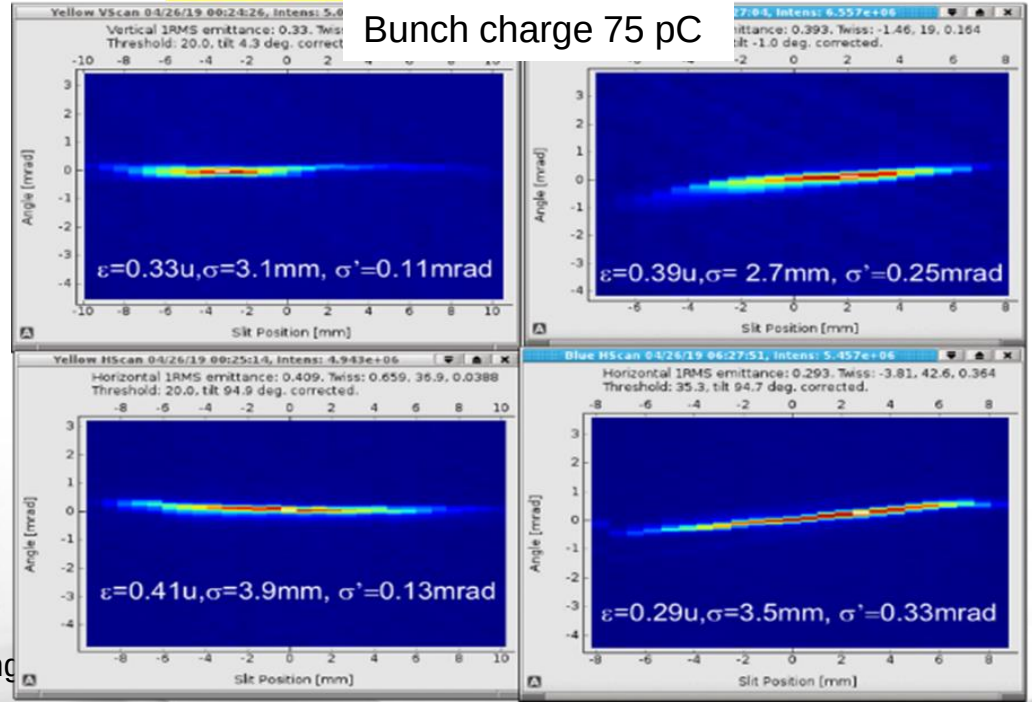
Transverse phase-space measurements of electron beam



YELLOW

BLUE

Bunch charge 75 pC

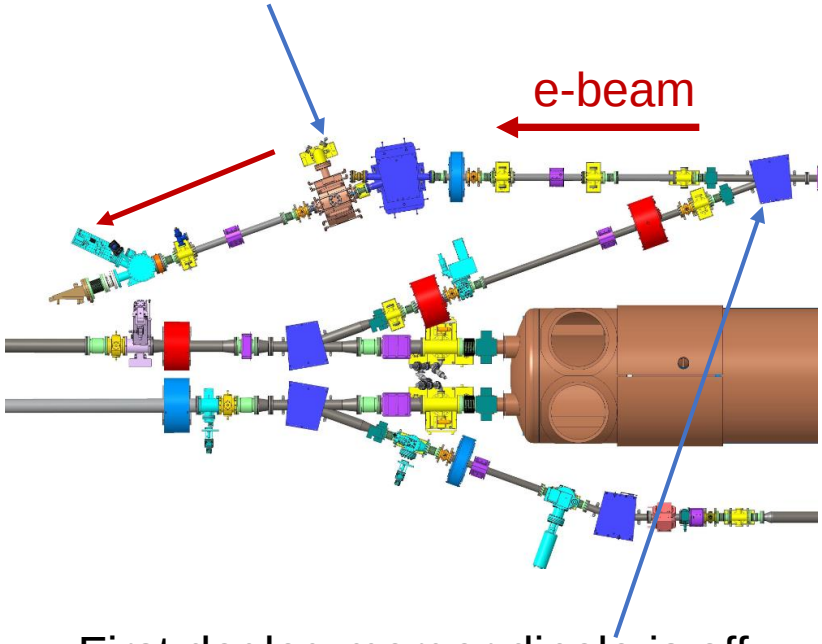


Movable slit and downstream beam profile monitors are installed at the beginning of each cooling section.

Achieved rms normalized emittances in cooling sections < 2 μm
(requirement: 2.5 μm)

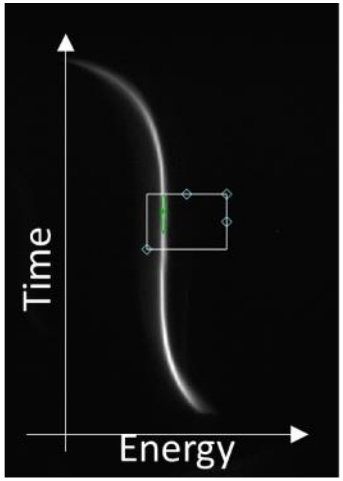
Longitudinal phase-space measurement of electron beam

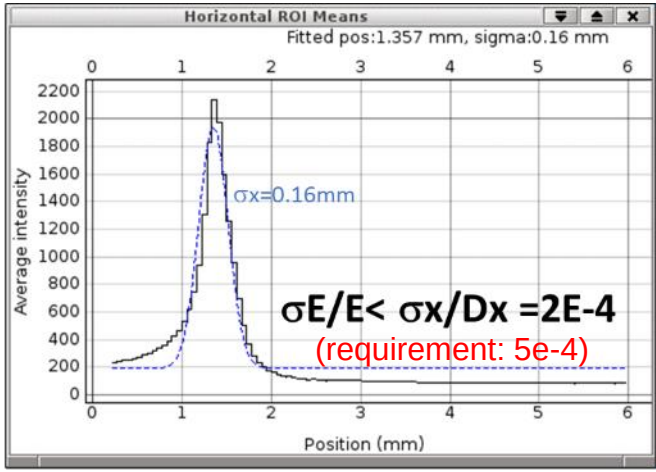
704MHz deflecting cavity



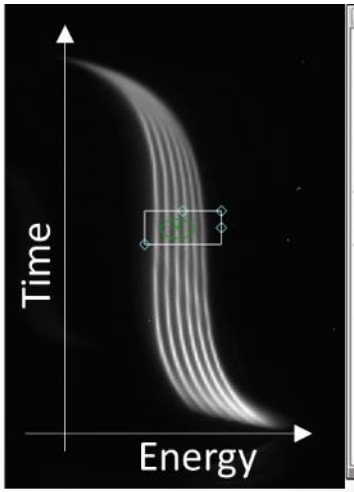
- First dogleg merger dipole is off
- Beam goes to RF diagnostic line
- 20 degree dipole produces dispersion
- 704MHz RF deflecting cavity produces time dependent vertical kick

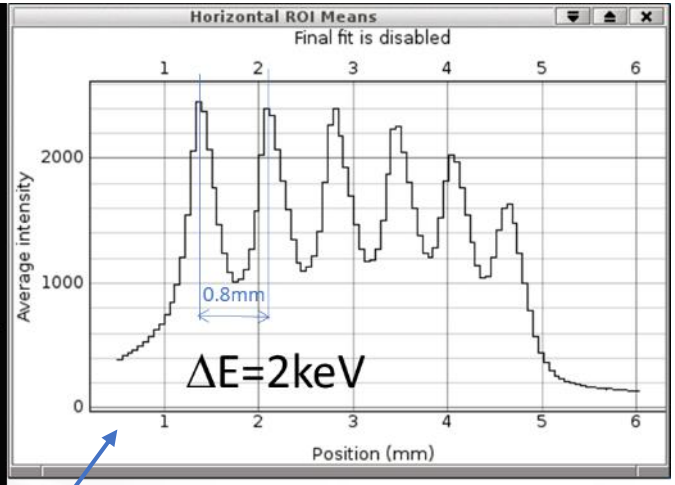
1 macro-bunch of electrons (total charge 3nC)





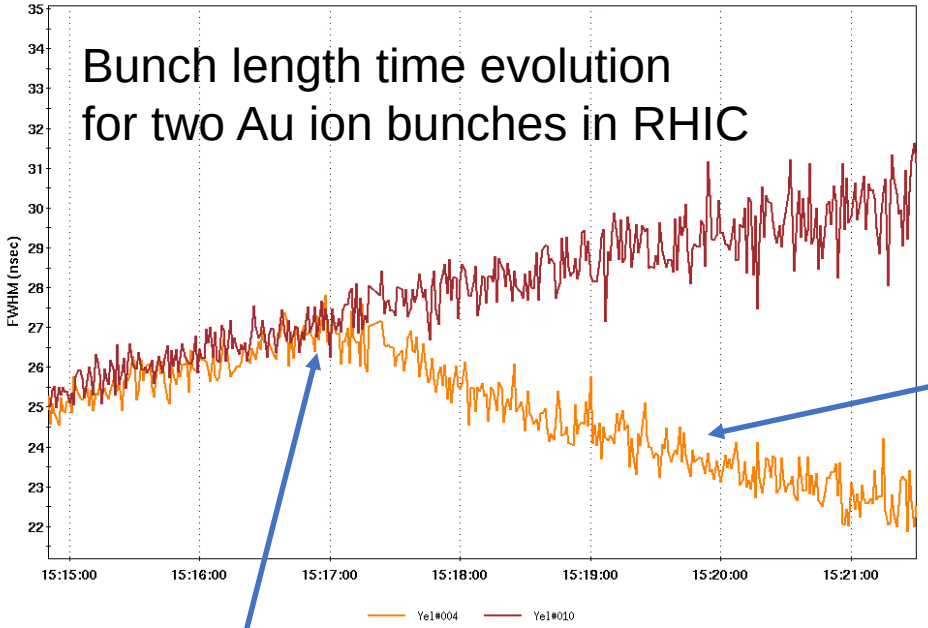
6 macro-bunches, 3 nC each.





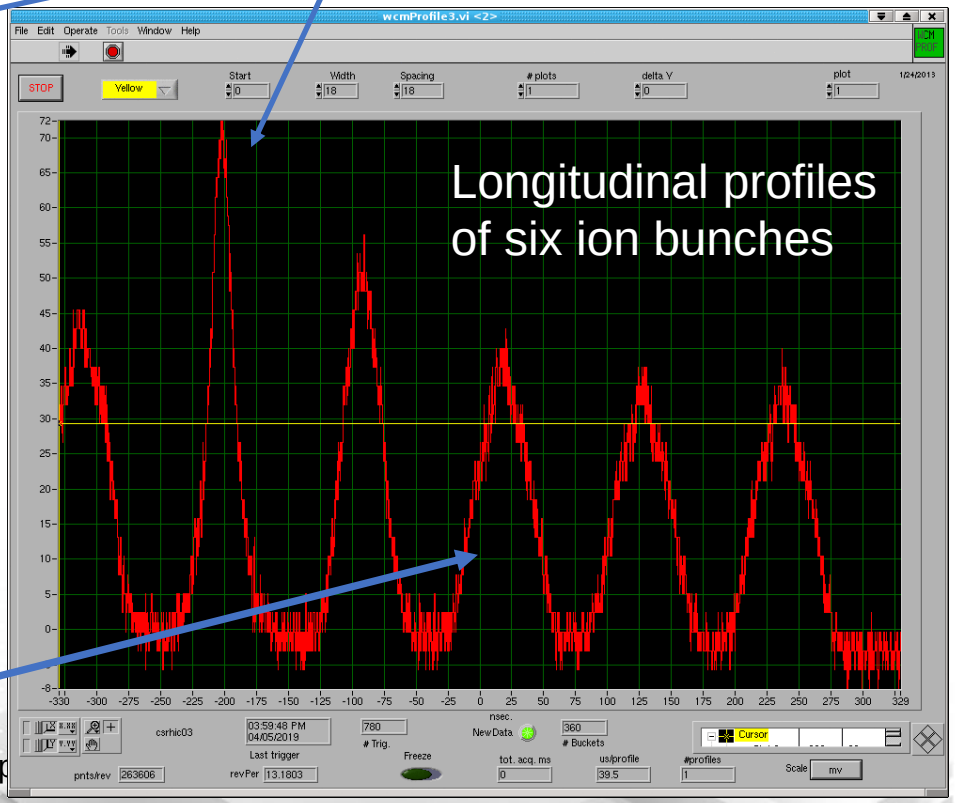
In pulsed mode, subsequent electron macro-bunches have lower energy due to beam loading in RF cavities.

LEReC: First observation of electron cooling using bunched electron beam, April 5, 2019



Ion bunch #4 which is not being cooled

Ion bunch #2 is being cooled

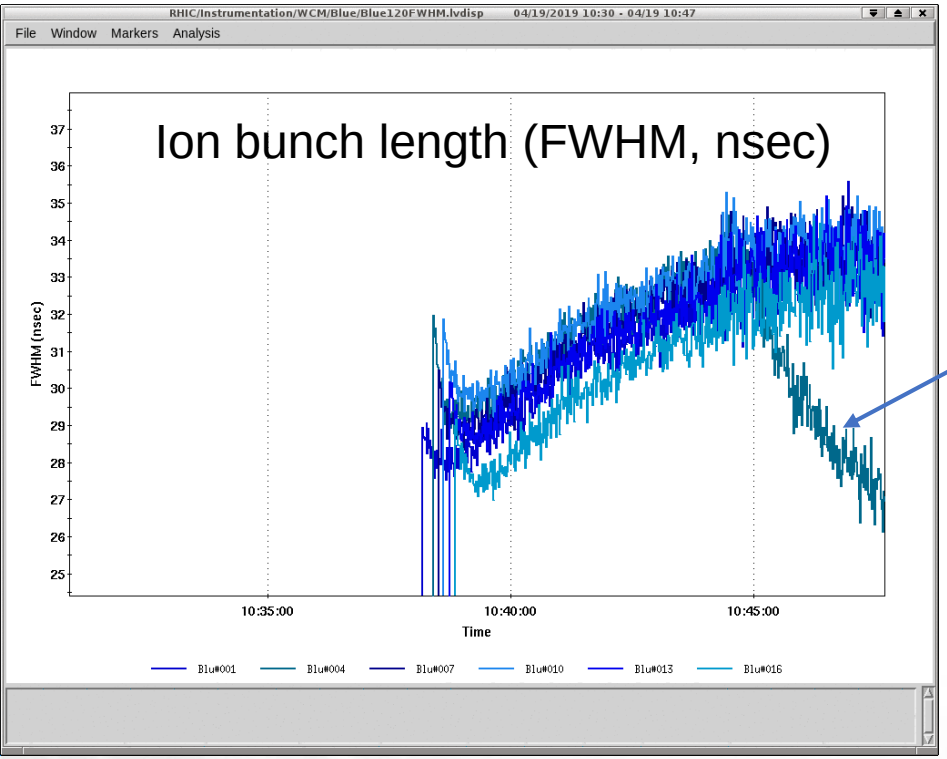


Energy of electrons and ions matched

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

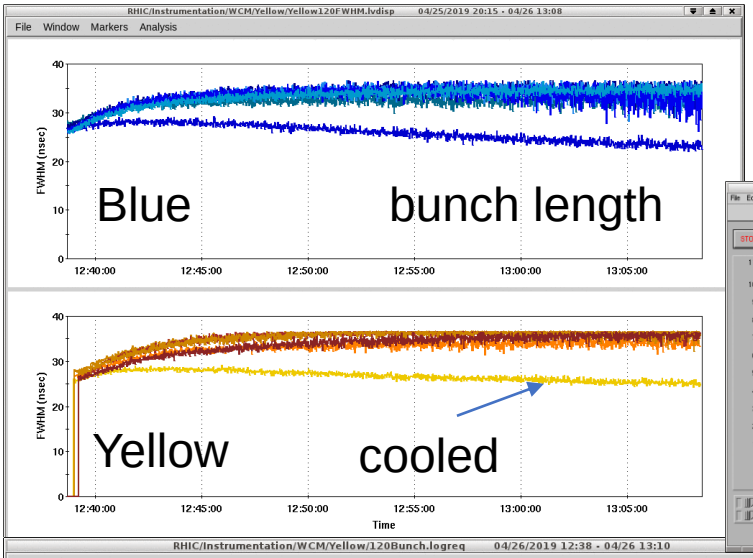
First cooling in Blue RHIC Ring (April 19, 2019)

- 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.

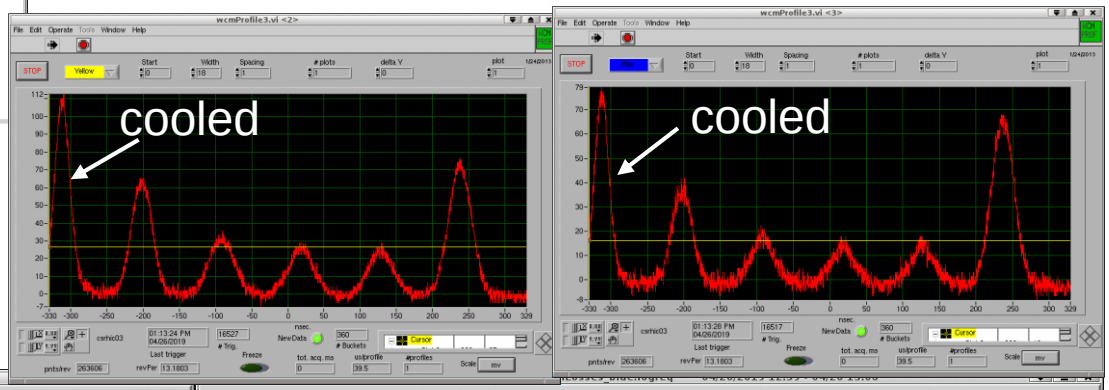


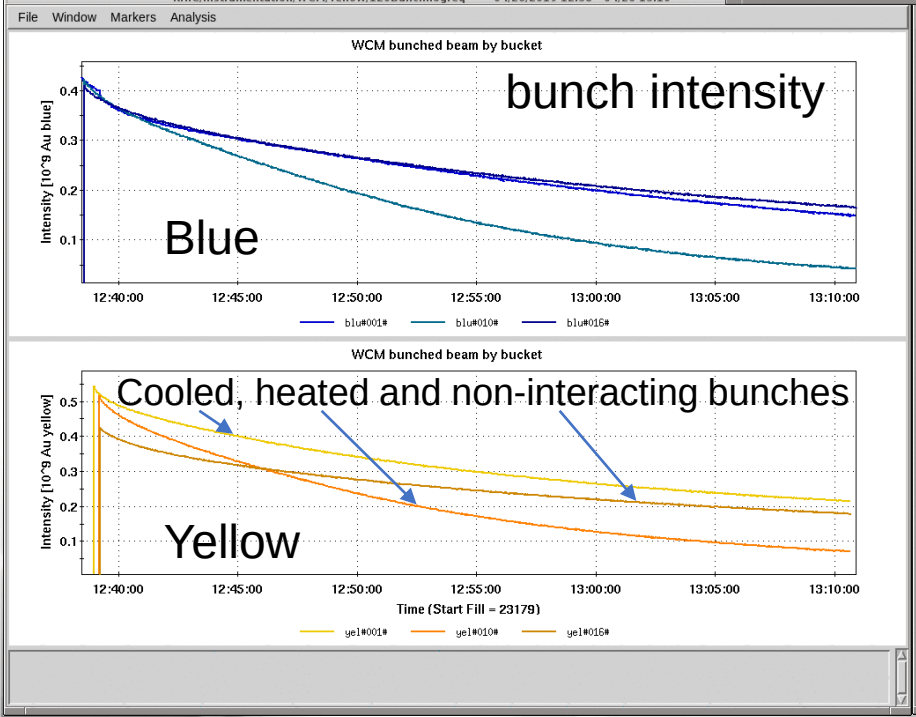
Longitudinal profiles of six ion bunches

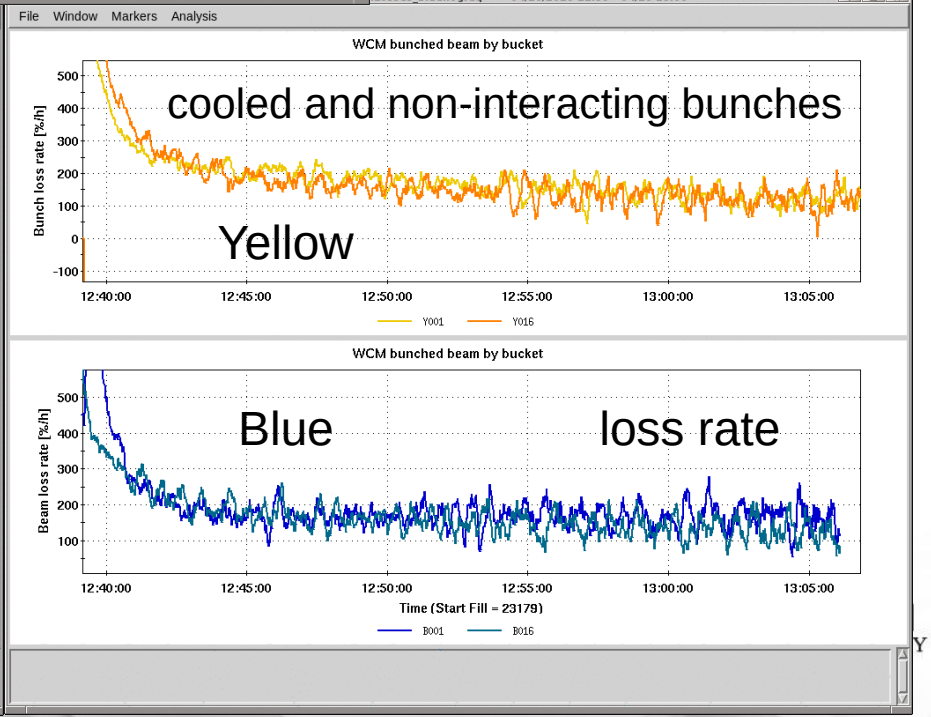
Simultaneous cooling in both Yellow and Blue RHIC rings using the same electron beam (76kHz mode, 6 ion bunches: bunch #1 is being cooled; bunch #6 does not see electrons)



Longitudinal bunch profiles

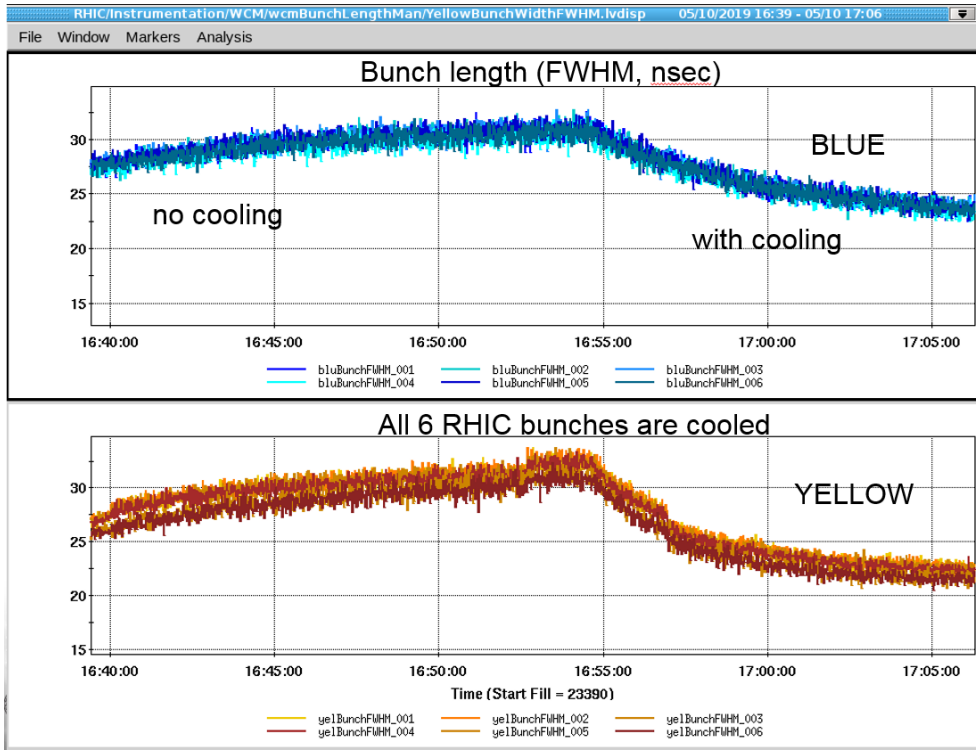


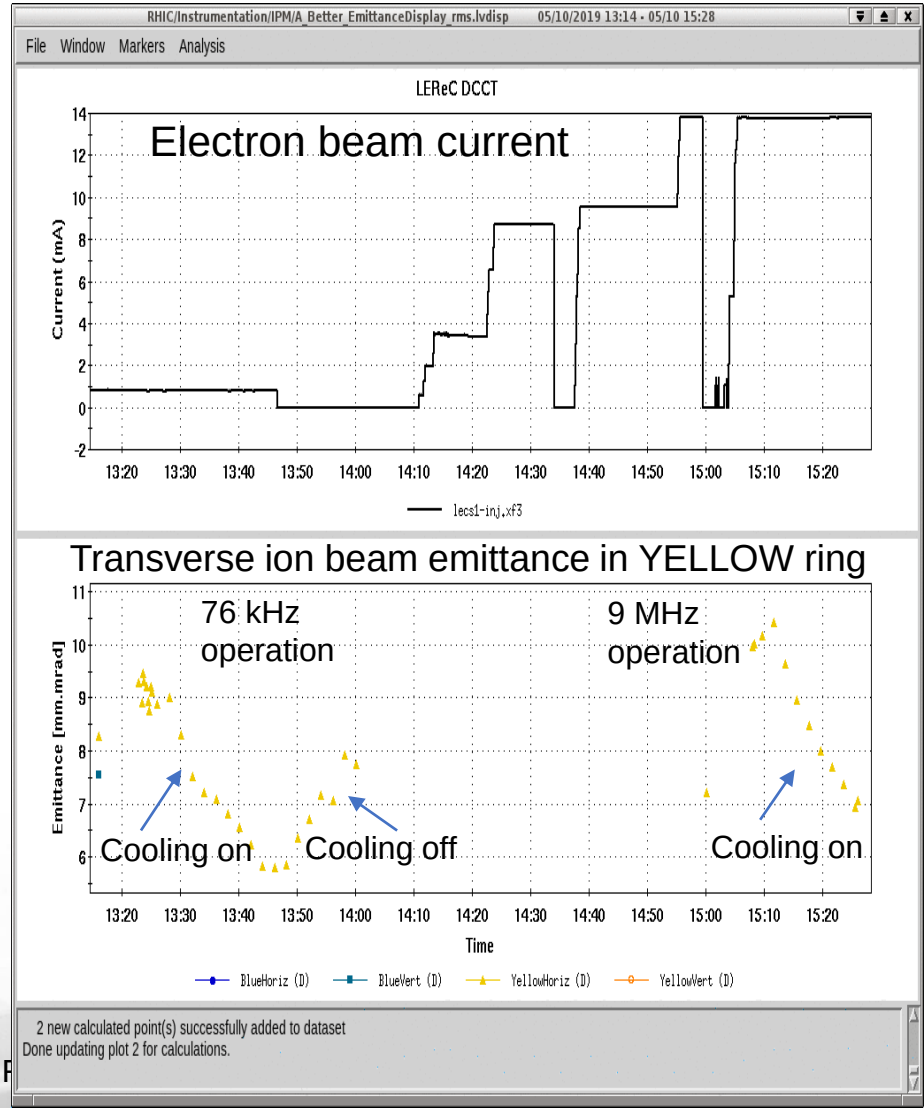




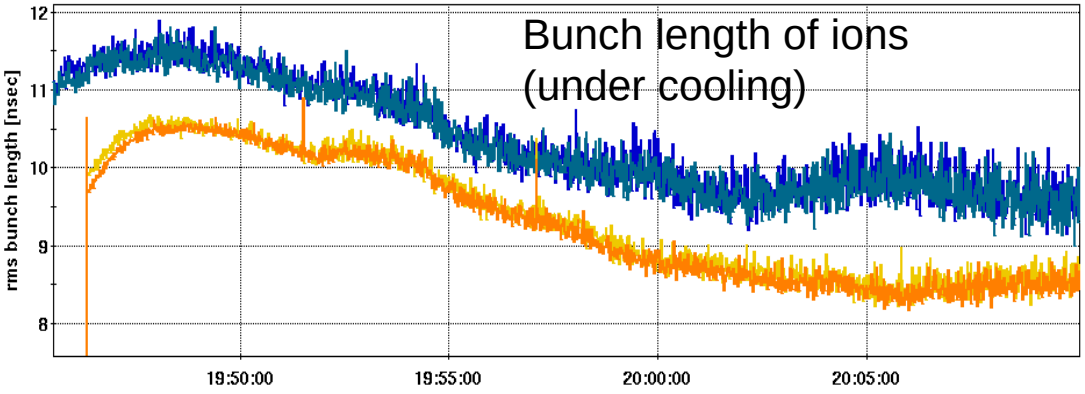
High-current CW electron beam operation and cooling of many ions bunches simultaneously

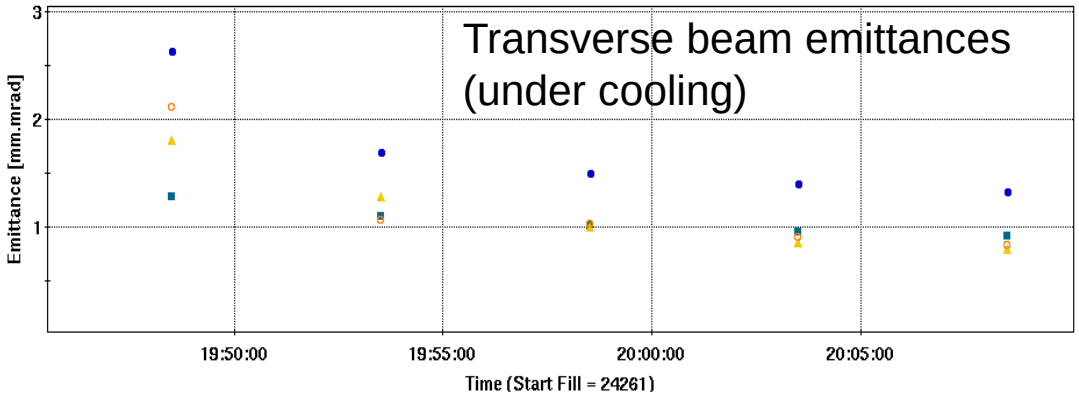
- To proceed from cooling single ion bunch using 76kHz electron beam to cooling of many ion bunches required establishing high-current 9MHz electron beam operation through both cooling sections all the way to high-power beam dump.





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





Electron cooling in a collider:
Cooling of hadron beams in collisions

6-D cooling of a 111x111 bunch RHIC store at 3.85 GeV (1.6 MeV electrons, 9 MHz CW current of 15mA).

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.

See talk by S. Seletskiy in WG1

- Ion lifetime limitations at low energy in RHIC: physical aperture, dynamics aperture, beam-beam, space charge and IBS.

LEReC challenges

- Production of high-brightness (in 3-D) electron beam
- Transport of such electron beams preserving beam quality
- Careful design of each beam transport element due to effects of wake fields on energy spread
- RF gymnastics with precise control and stability
- High-current beam operation
- Electron beam quality during high-current operation
- Control of electron angles in the cooling section to a very low level
- Electron cooling without any help from magnetization
- 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

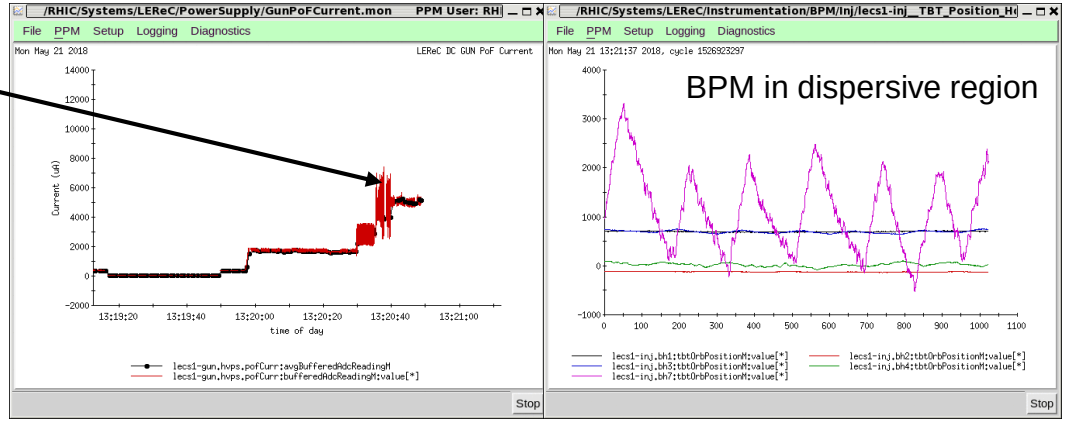
Cooling in a collider:

- Control of ion beam distribution, not to overcool beam core
- Effects on hadron beam
- Interplay of space-charge and beam-beam in hadrons
- Cooling and beam lifetime (as a result of many effects)

Technical challenges during commissioning

As with any new machine, we had our share of problems which had to be addressed as we moved forward:

- Gun HVPS instabilities
- Gun trips at high current
- Gun performance after the trips which required re-conditioning
- Laser power and stability
- RF reliability
- Effect of RF noise on instrumentation electronics (BPMs, FCTs)
- Electronics survival in radiation environment inside RHIC tunnel
- High power beam dump and vacuum issues due to heating/cooling of dump flange



Technical issues which were addressed prior to cooling demonstration

- Gun HVPS controls chassis was modified, which allowed to operate at high currents for high Gun voltages >350kV. Remaining instabilities are rather weak and only at low currents.
- Gun voltage ripple was measured and met the specs.
- Stable long-term Gun runs at 30mA with small active cathode area off center.
- Stable production of cathodes with high QE and good lifetime during high-current operation
- 2.1GHz RF amplifier upgraded to deliver full design power.
- All instrumentation successfully commissioned
- MPS logic was improved to add additional layers of protection.
- Laser intensity feedback implemented.
- Long term 24/7 stability tests of laser, RF and Gun performed.

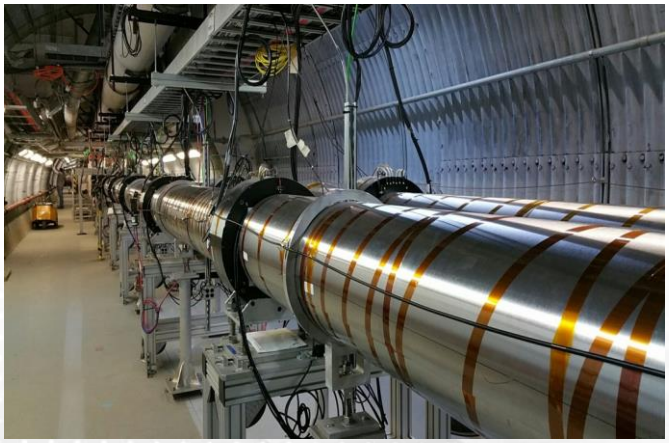
LEReC is also a testbed of high-energy cooling

- **Production of high-brightness electron beams in 3-D**
- **RF-based (bunched beam) electron cooler**
- **Transport of such electron bunches maintaining "cold" beam**
- **Control of electron angles in the cooling section to a very low level required for cooling**
- **Various aspects of bunched beam electron cooling**
- **High-current operational aspects**
- **Electron cooling in a collider:**
  - **Effects on hadron beam.**
  - **Interplay of space-charge and beam-beam in hadrons.**
  - **Cooling and beam lifetime (as a result of many effects).**

All of these are essential elements for high-energy cooling.

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).
- Many challenges associated with this new approach were overcome but some remain.



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!

A. Fedotov et al., ”First electron cooling of hadron beams using a bunched electron beam”, NAPAC2019, Lansing, Michigan, USA, 2019

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