Low Energy RHIC electron Cooling (LEReC):

Status and Plans

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on behalf of the LEReC team

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BROOKHAVEN NATIONAL LABORATORY

U.S. DEPARTMENT OF ENERGY

LEReC Project Overview

LEReC project was successfully completed on schedule and on budget, with all project KPPs achieved September 2018.

LEReC is world's first electron cooler based on the RF acceleration of electron bunches (all previous coolers used DC beams). Such cooling approach opens a possibility of using this technique to high beam energies.

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

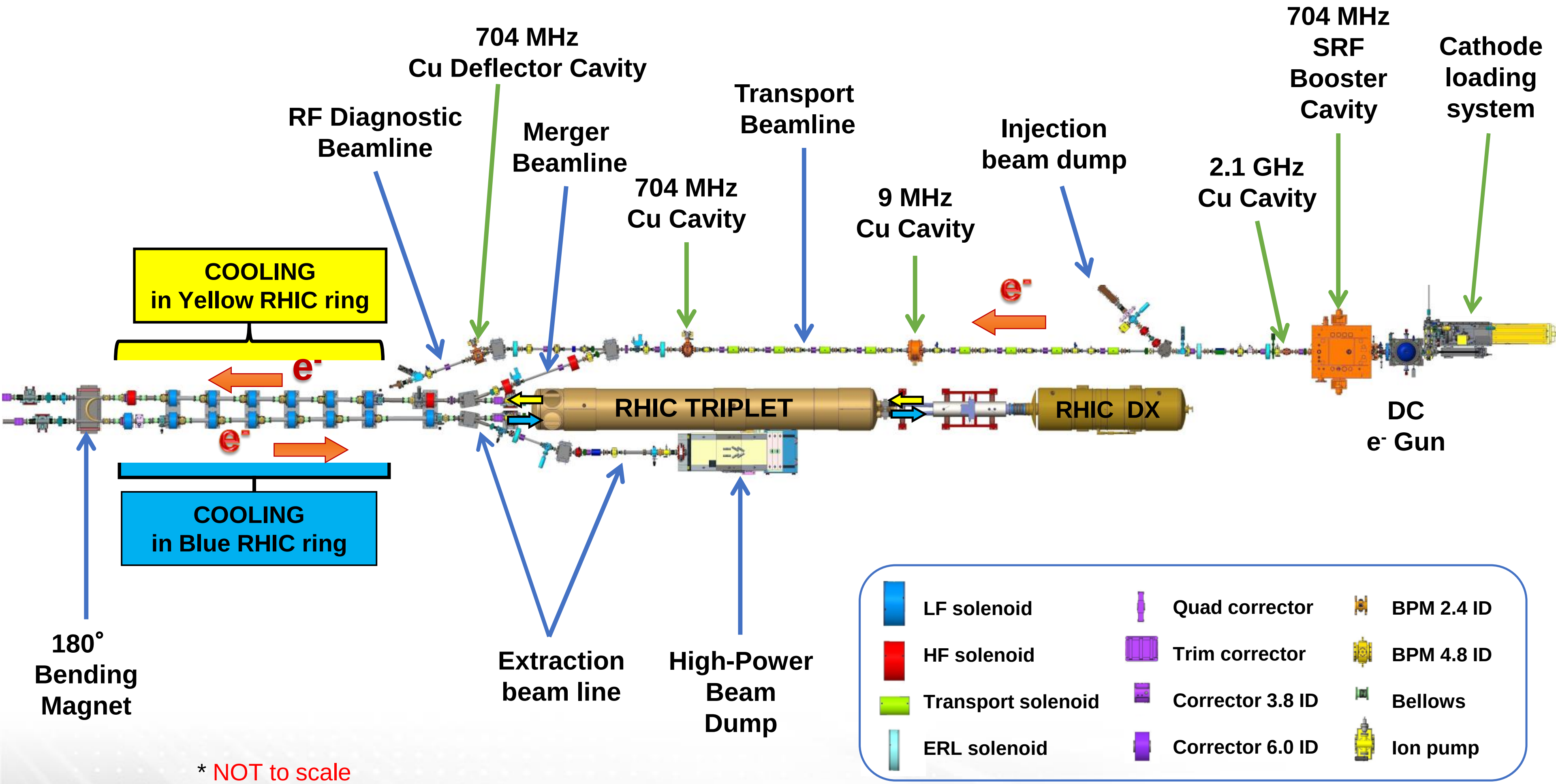
- ❑ **Building and commissioning of new state of the art electron accelerator ✓**
- ❑ **Produce electron bunches with beam quality suitable for cooling✓**
- ❑ **RF acceleration and transport maintaining required beam quality✓**
- ❑ **Achieve required beam parameters in cooling sections✓**
- ❑ **Commissioning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

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 all ion bunches with high-current 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)

LEReC electron 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 electron beam parameters

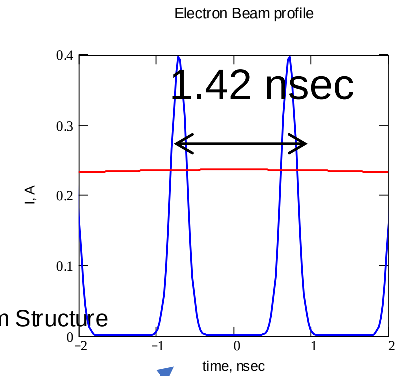
Two energies commissioned ✓

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

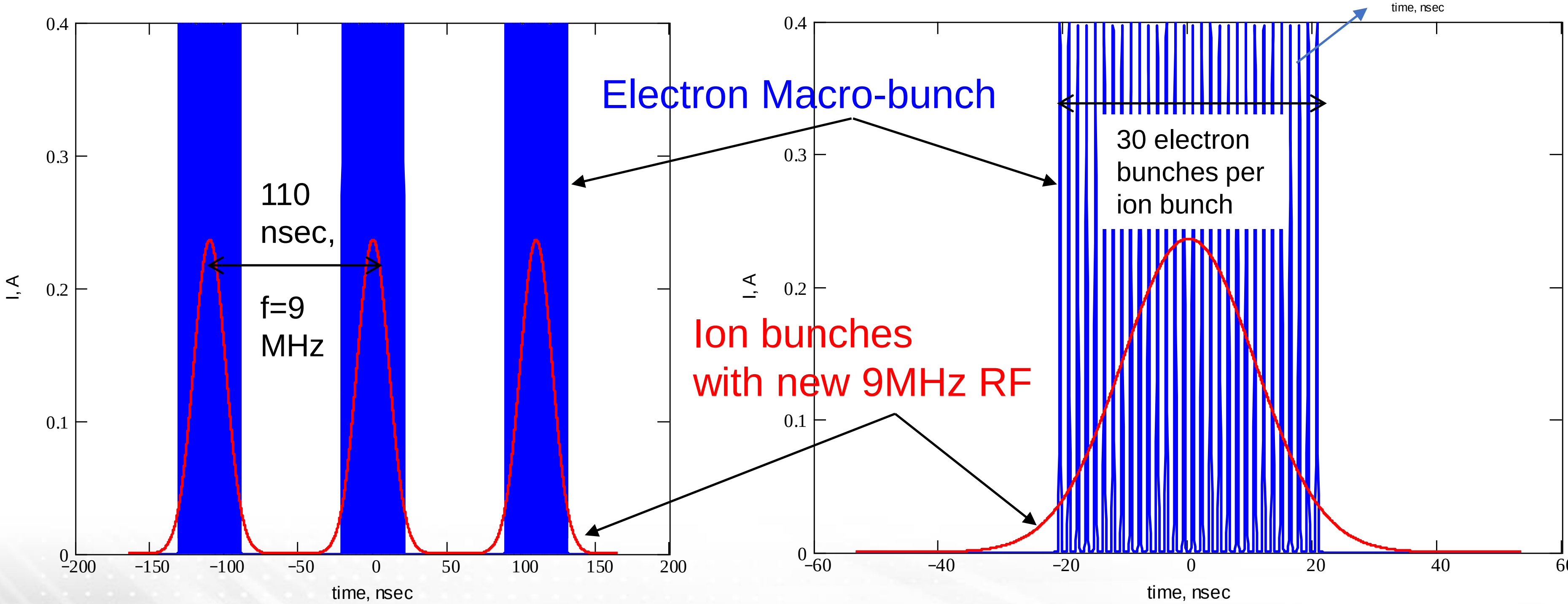
LEReC beam structure in cooling section

Ions structure:
120 bunches
f_rep=120x75.8347 kHz=9.1 MHz
N_ion=5e8, I_peak=0.24 A
Rms length=3 meters

Electrons:
f_SRF=704 MHz
Q_e=100 pC, I_peak=0.4 A
Rms length=3 cm

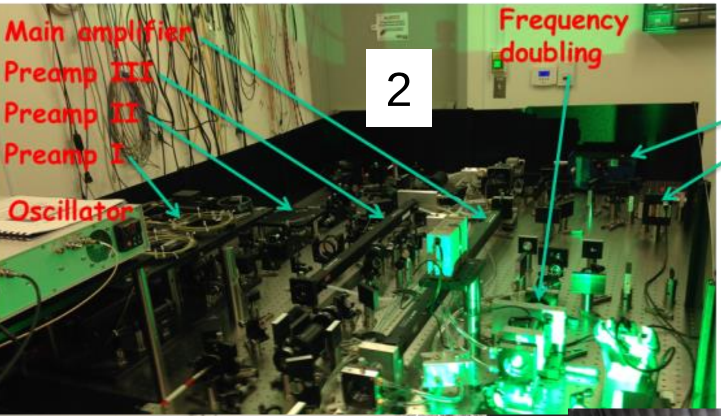


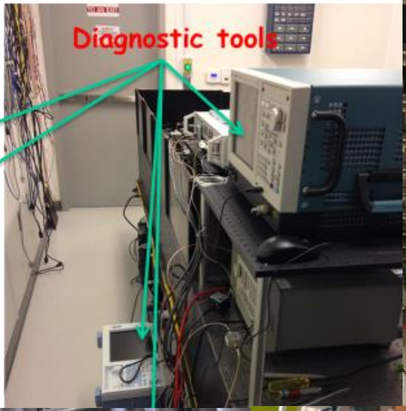
9 MHz bunch structure

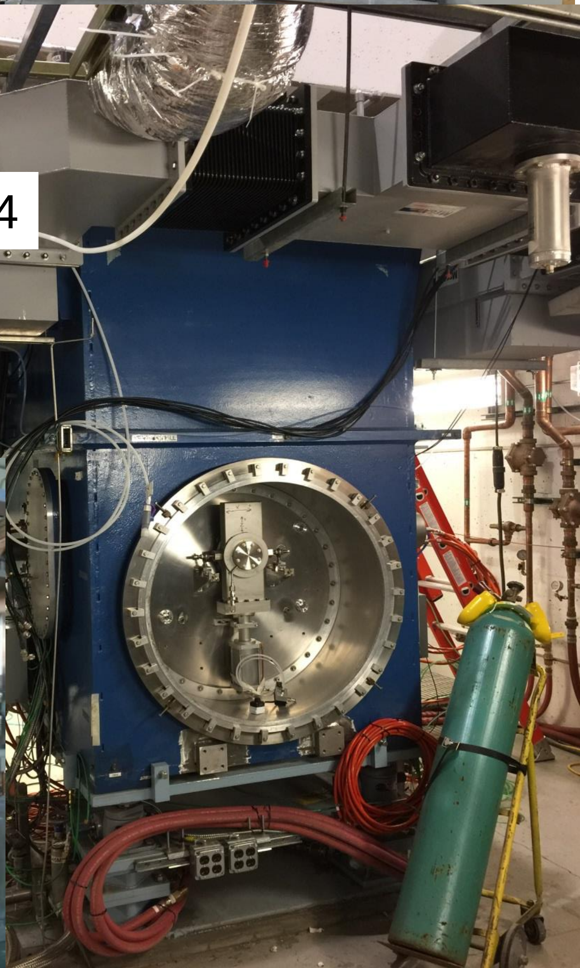


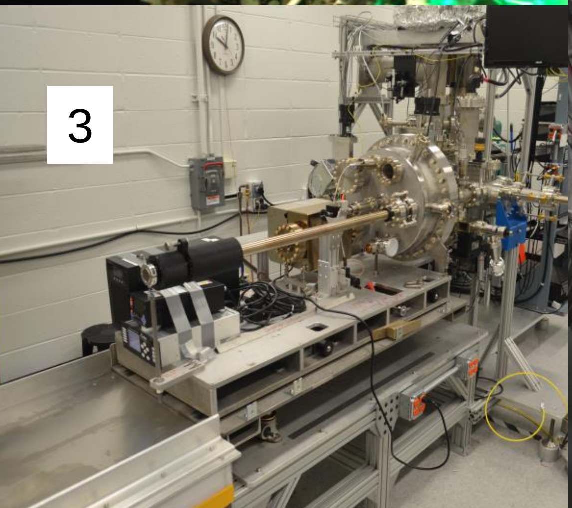
LEReC Critical Technical Systems

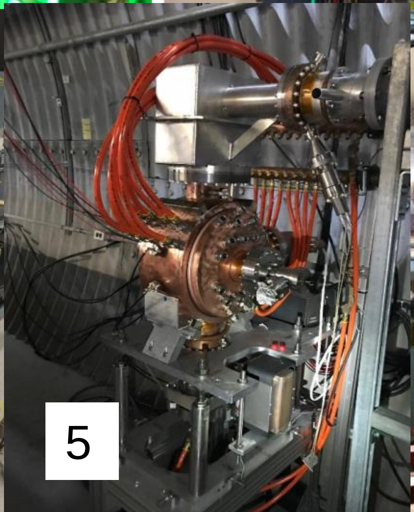
1. High-voltage photocathode electron gun
2. High-power fiber laser, transport and stabilization
3. Cathode production deposition and delivery systems
4. 704 MHz SRF Booster cavity
5. 2.1 GHz and 704 MHz warm RF cavities

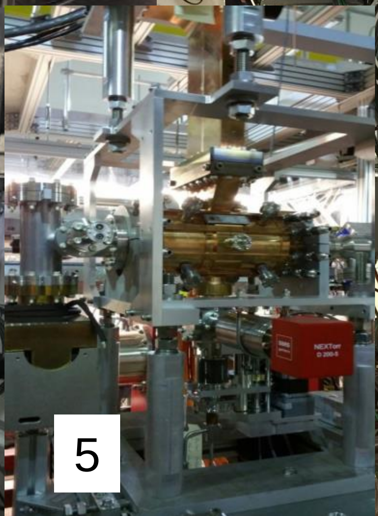




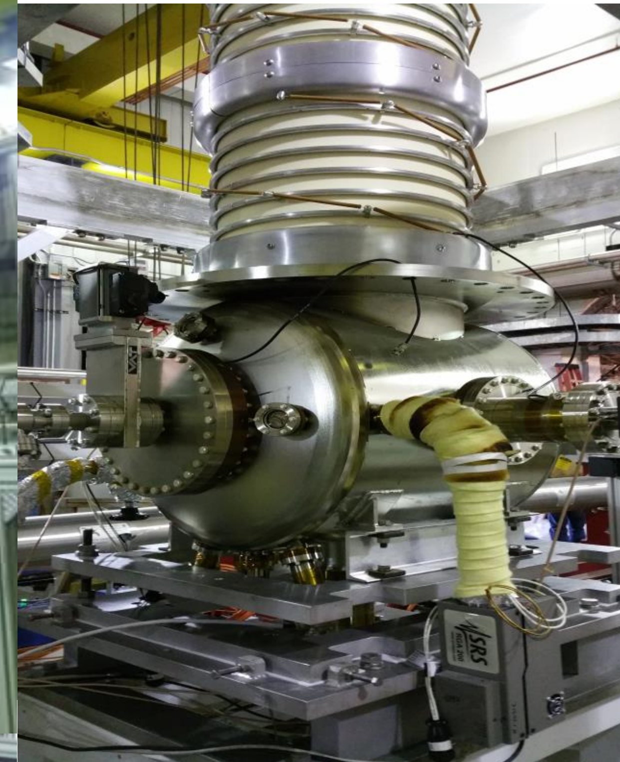




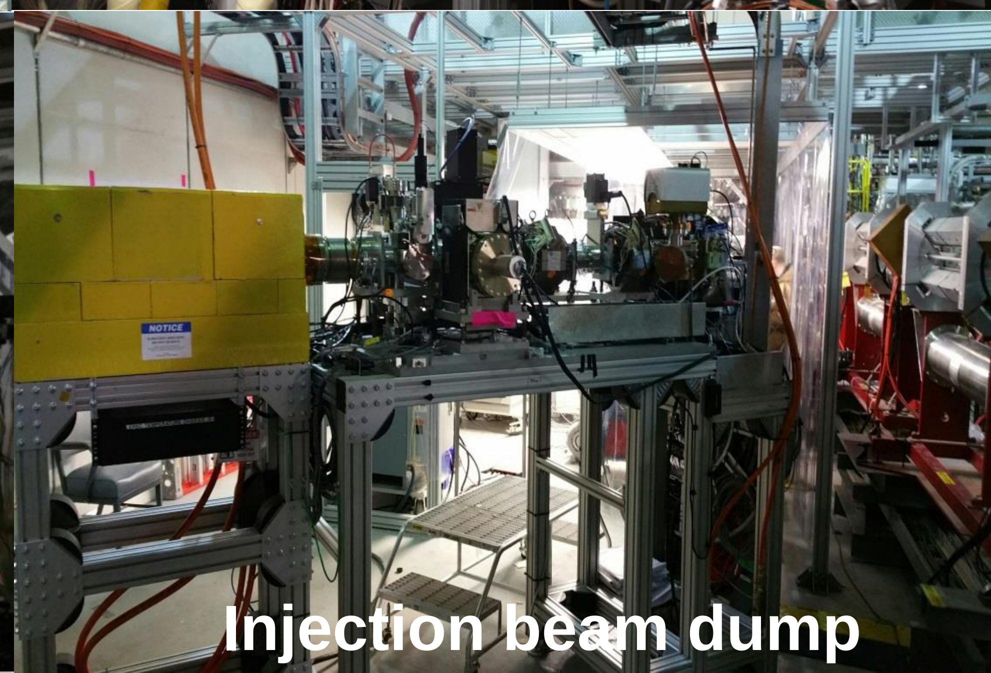




LEReC construction started in 2016

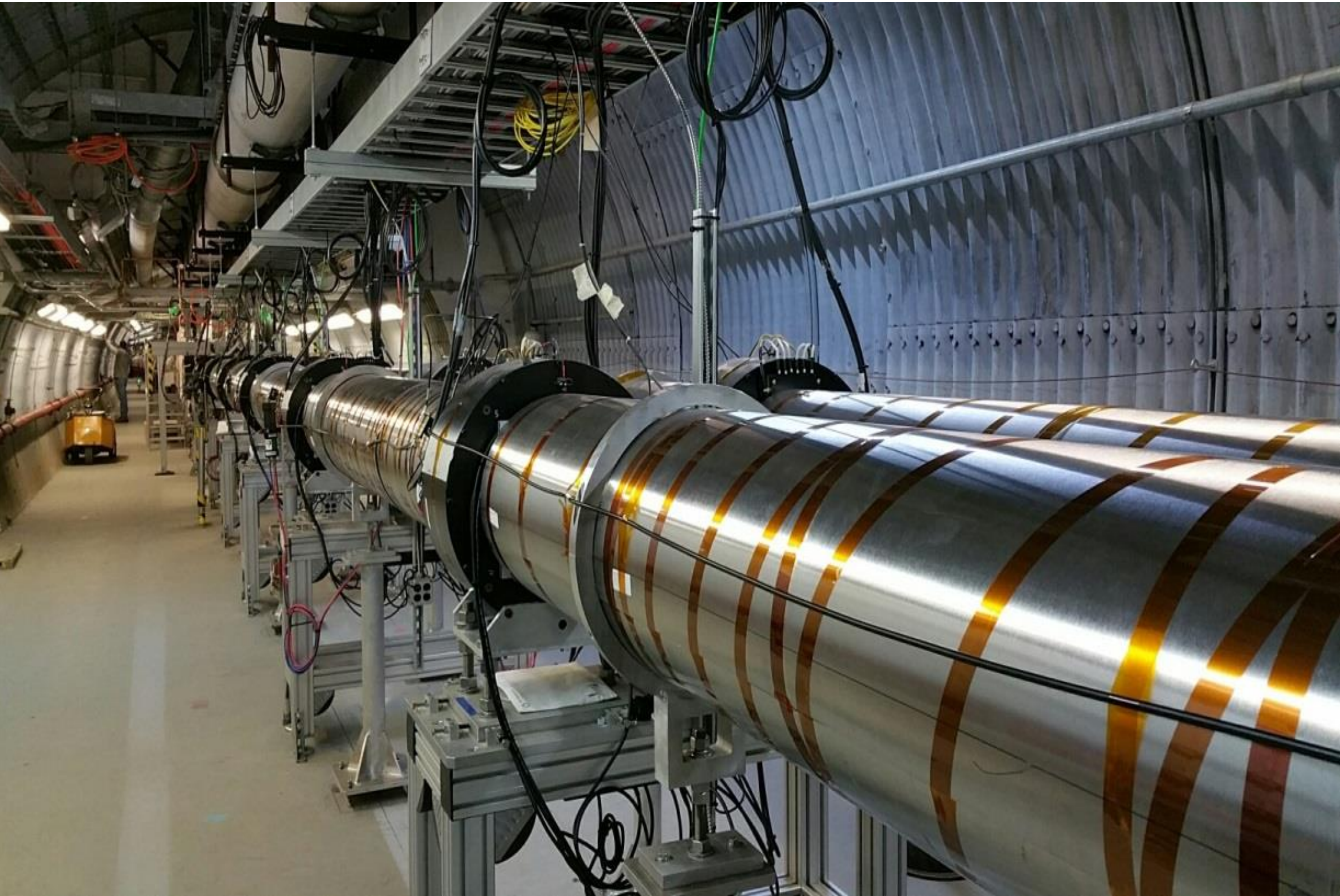


LEReC Gun test beamline (2017)



Full LEReC installation (October 2017)

LEReC cooling sections fully installed (2018)

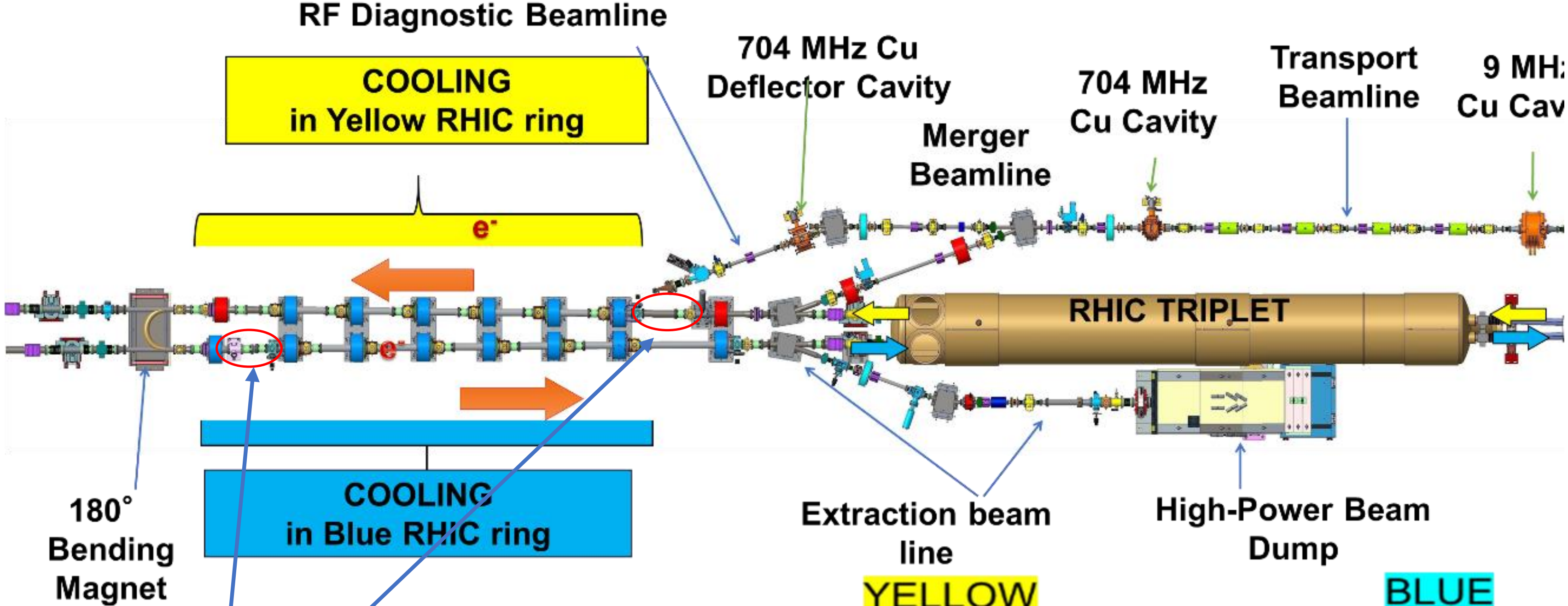


Attainment of "cold" electron beam suitable for cooling

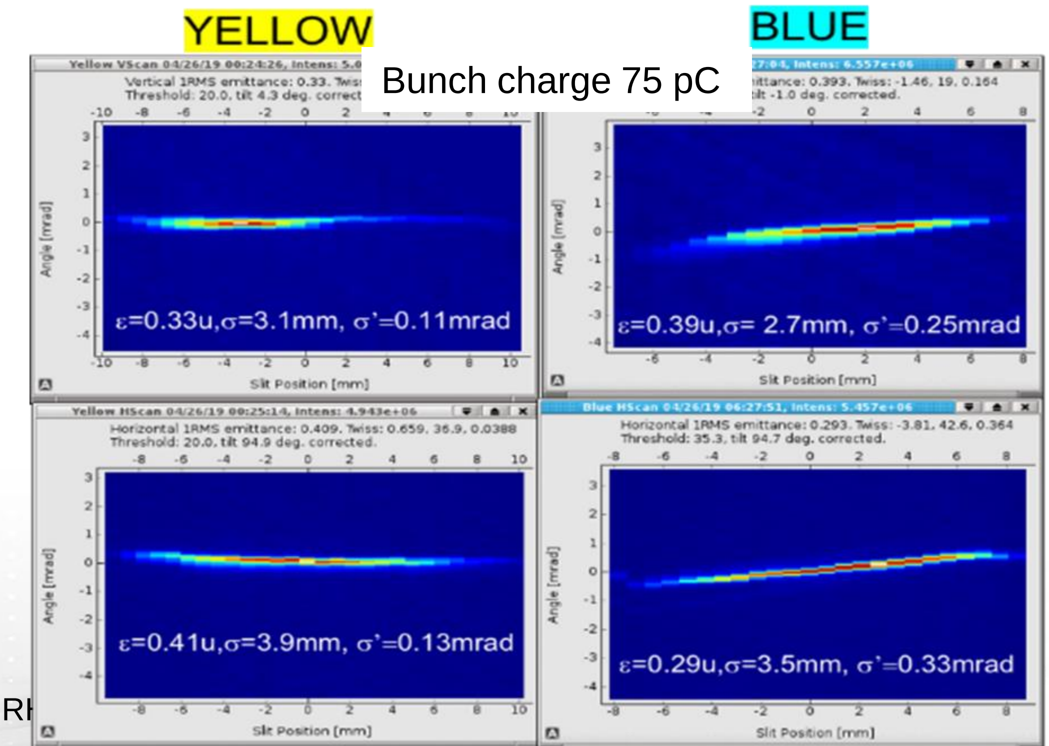
- LEReC is based on the state-of-the-art accelerator physics and technology:

- Photocathodes: production and 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

Transverse phase-space measurements of electron beam

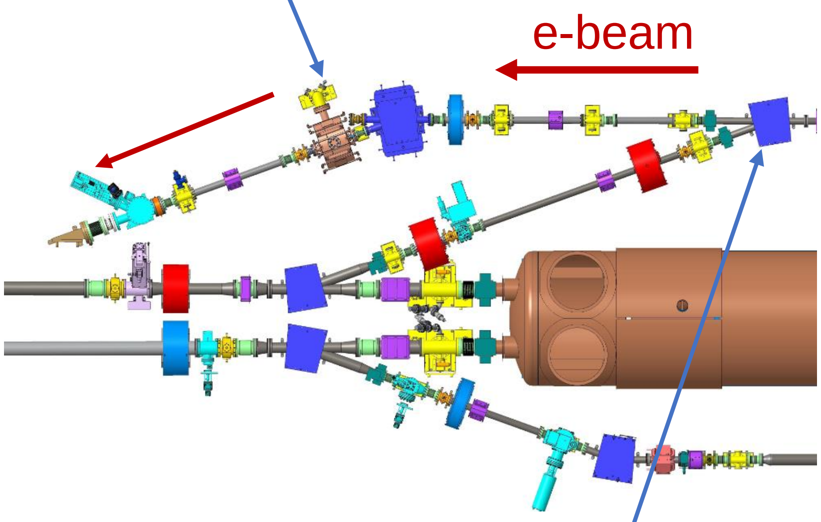


Movable slit and downstream beam profile monitors are installed at the beginning of each cooling section.

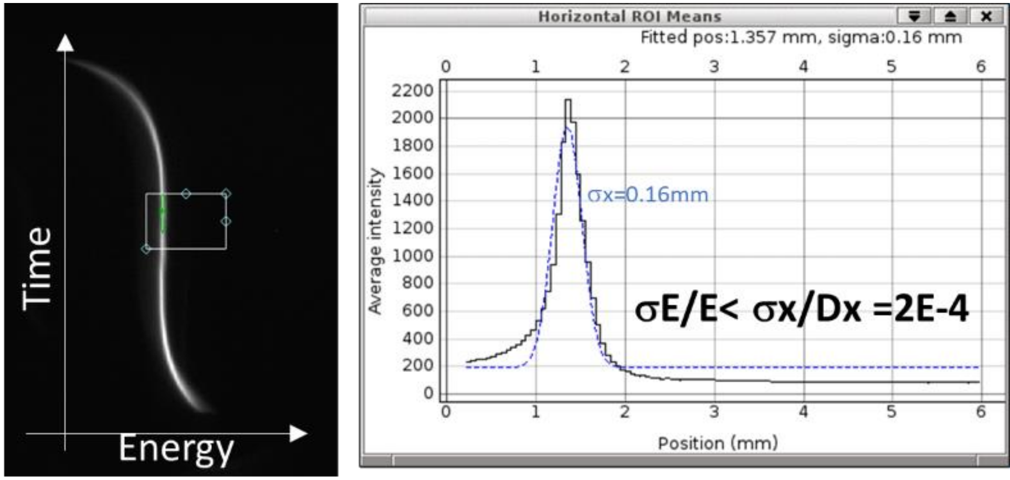


Longitudinal phase-space measurement of electron beam

704MHz deflecting cavity

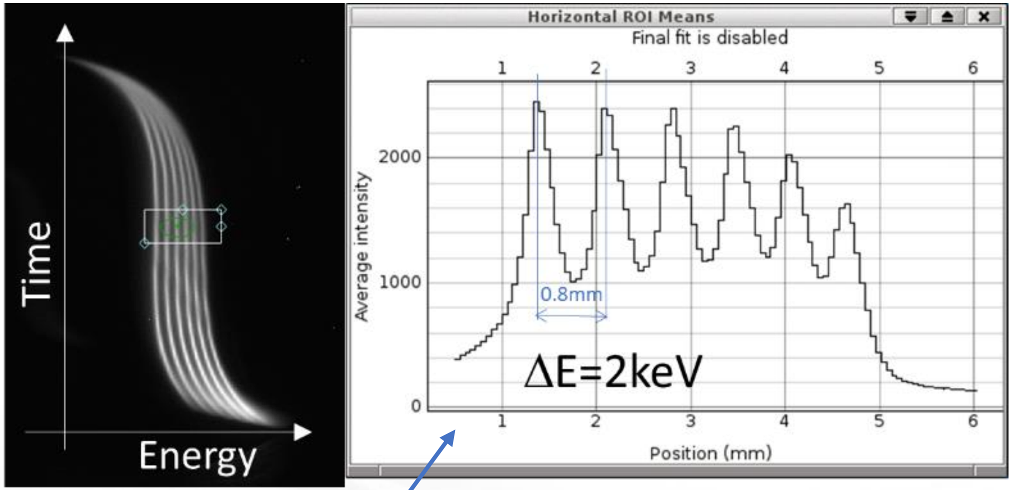


1 macro-bunch of electrons (total charge 3nC)



- 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

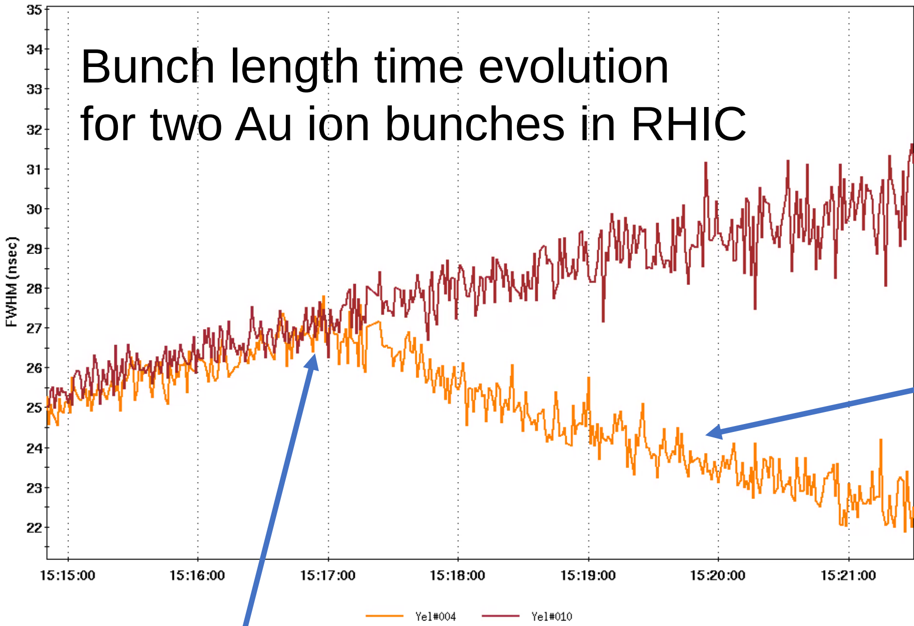
6 macro-bunches, 3 nC each.



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

Bunch length time evolution for two Au ion bunches in RHIC

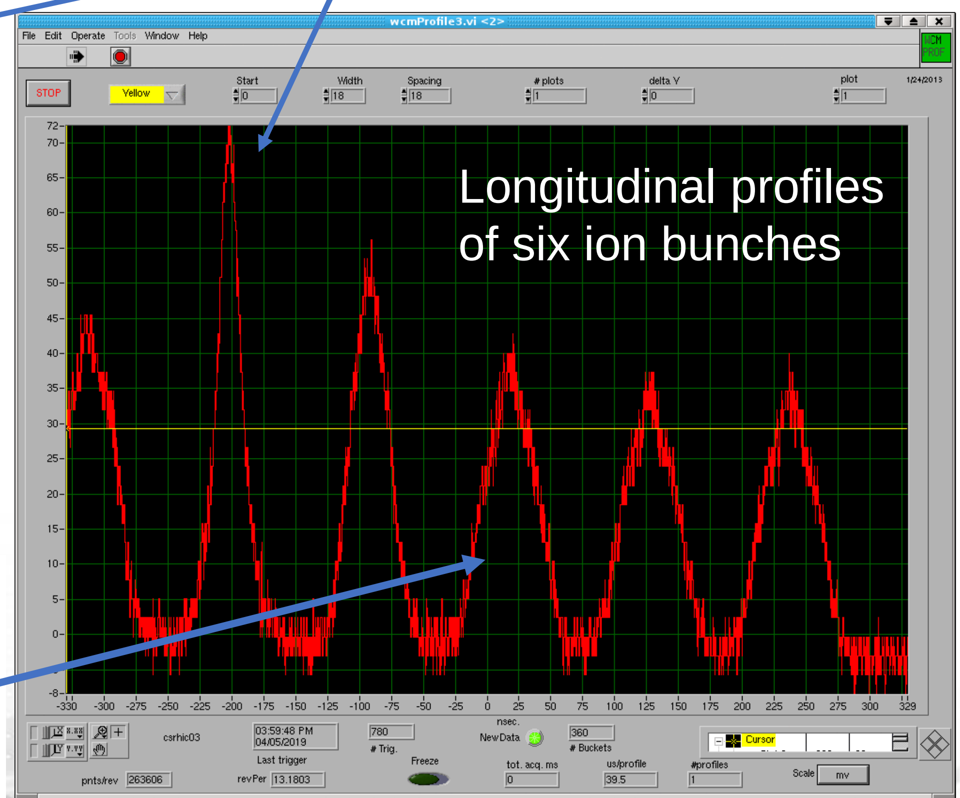


Ion bunch #4 which is not being cooled

Ion bunch #2 is being cooled

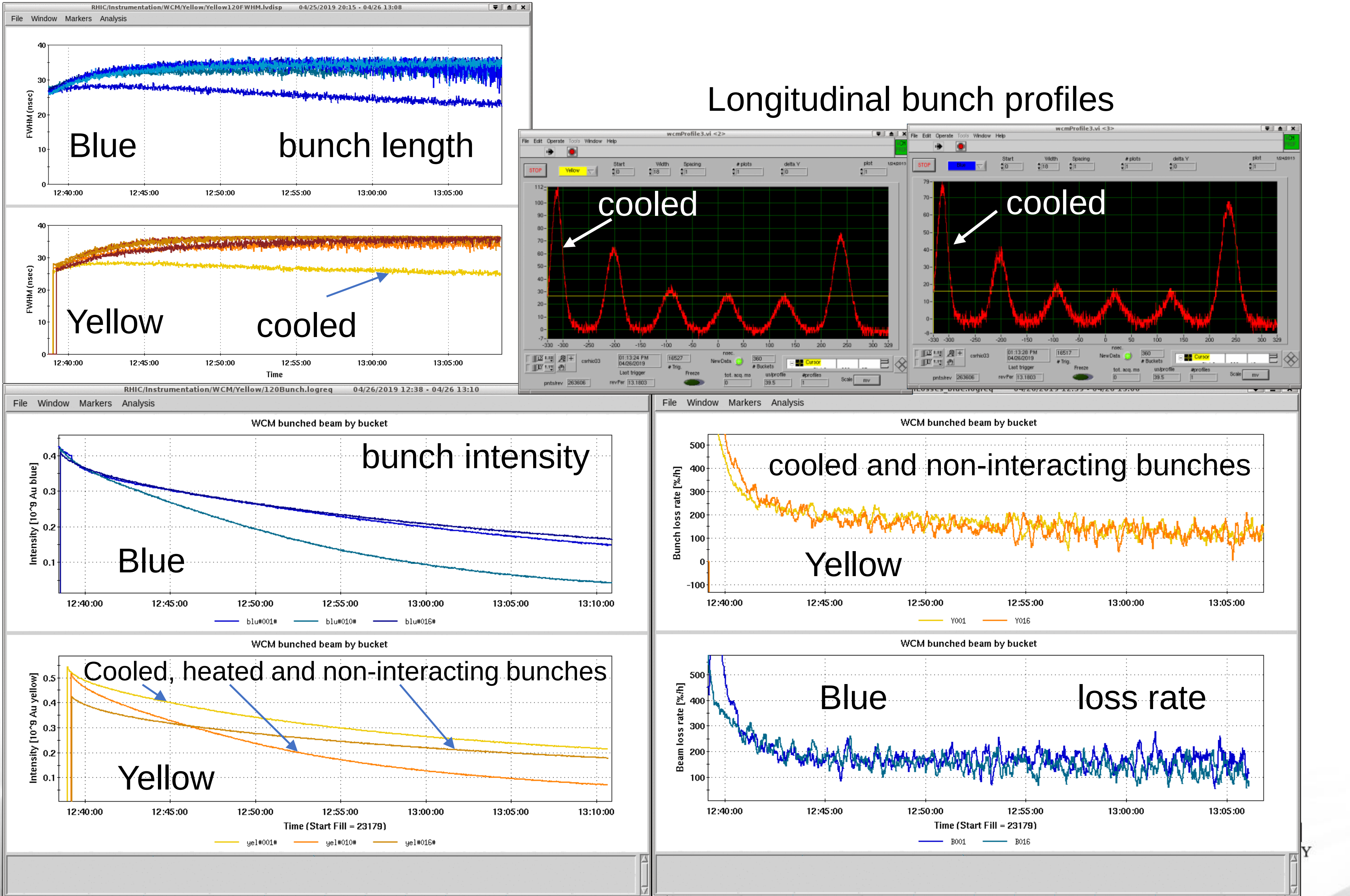
Energy of electrons and ions matched

Longitudinal profiles of six ion bunches

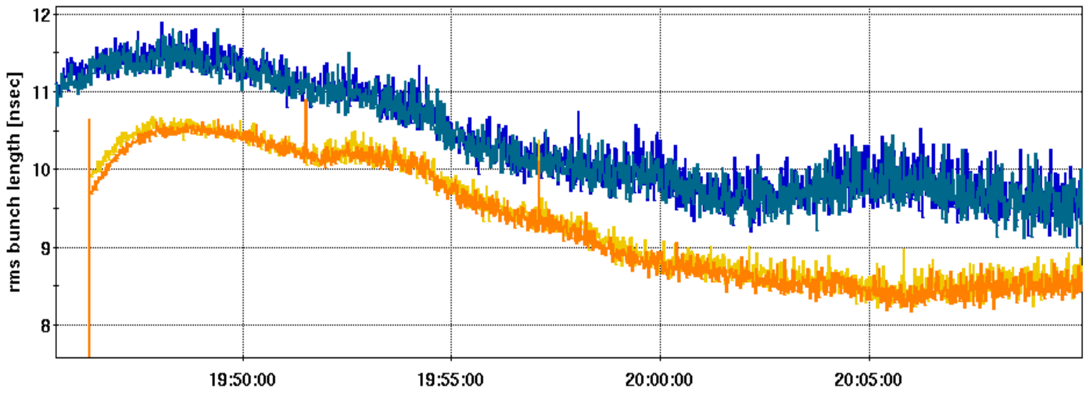


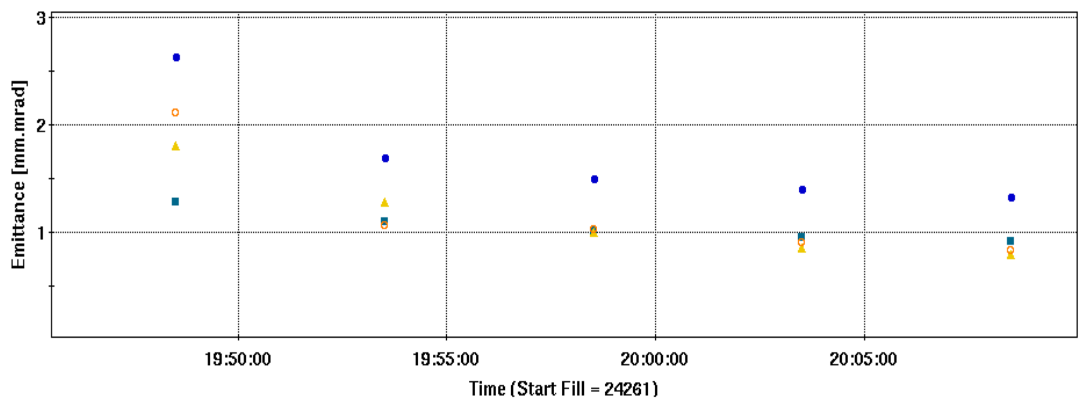
In 76kHz mode, subsequent electron macro-bunches have lower energy due to beam loading in RF cavities (can match energy/cool effectively single ion bunch).

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



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

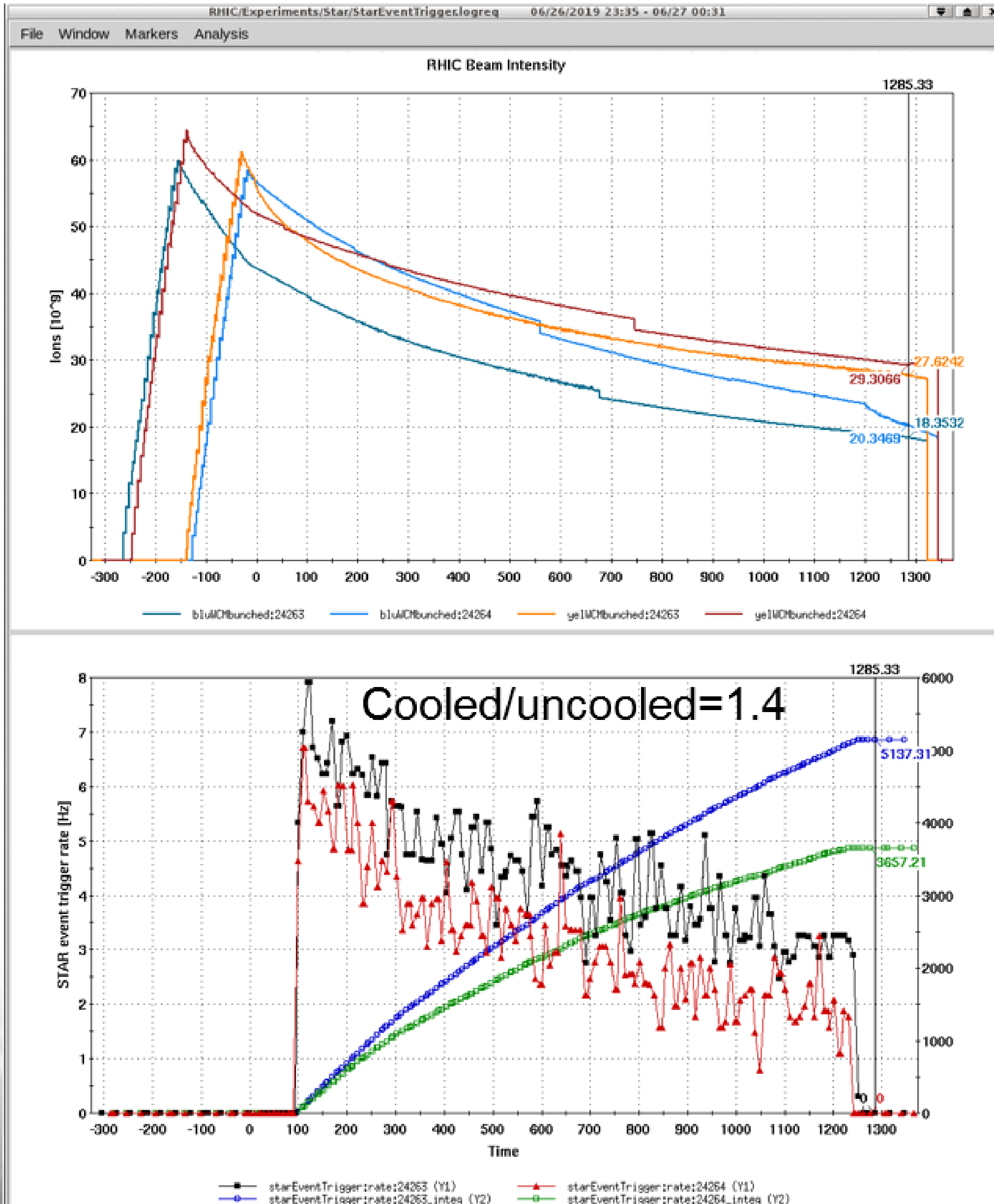




6-D cooling of a 111x111 bunch RHIC store at 3.85 GeV (1.6 MeV electrons, 9 MHz CW current of 15mA).
Top plot - reduction of bunch length. Bottom plot - reduction of transverse beam emittances (two RHIC rings, two planes).

Cooling of 111x111 ion bunches at 3.85GeV (1.6MeV 9MHz CW electrons)

Cooled vs uncooled store (+/-0.7m trigger)



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

Luminosity improvement in test stores with longitudinal cooling.

Better luminosity improvement requires:

1. Collecting data with longer vertex cut
2. Establishing good transverse cooling and dynamic squeeze of beta*

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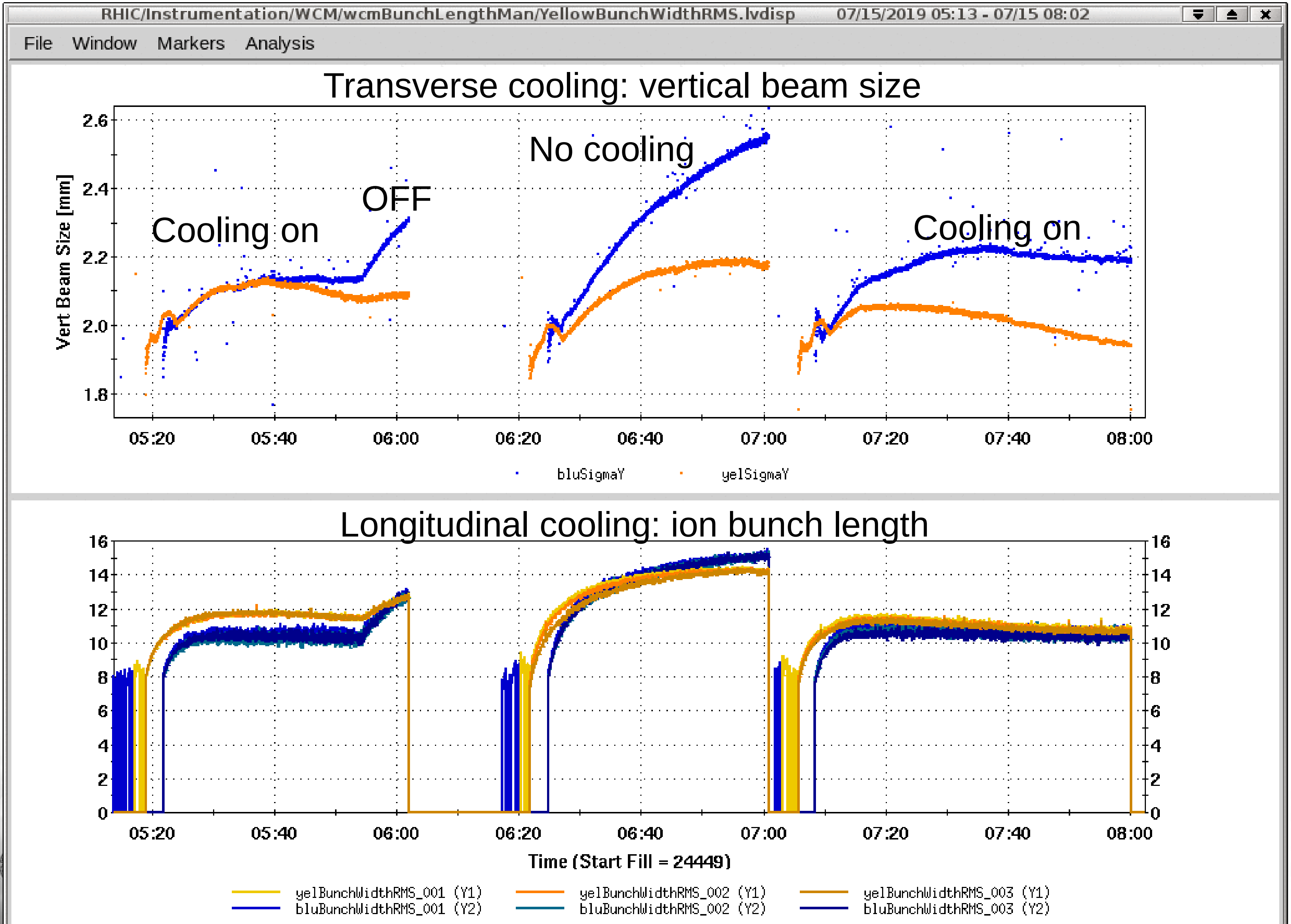
Cooling using 2MeV electron beam (ions at 4.6GeV/n)



LEReC roadmap to cooling

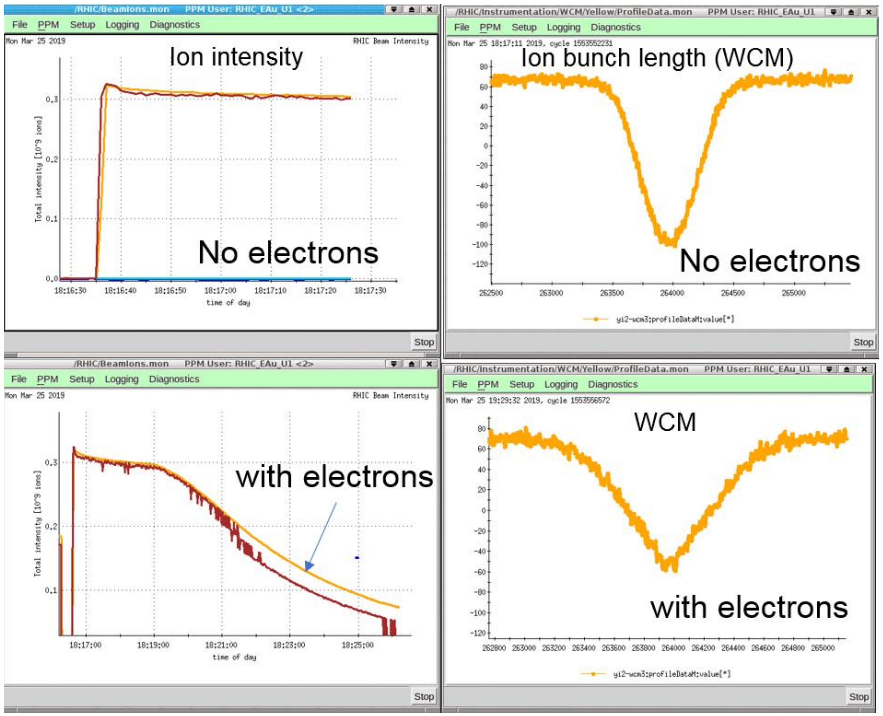
- Production of 3-D high-brightness electron beams ✓
- RF acceleration and transport of electron bunches maintaining “cold” beam ✓
- Control of various contributions to electron angles in the cooling section to a very low level required for cooling ✓
- Energy matching of electron and ion beams ✓
- First 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

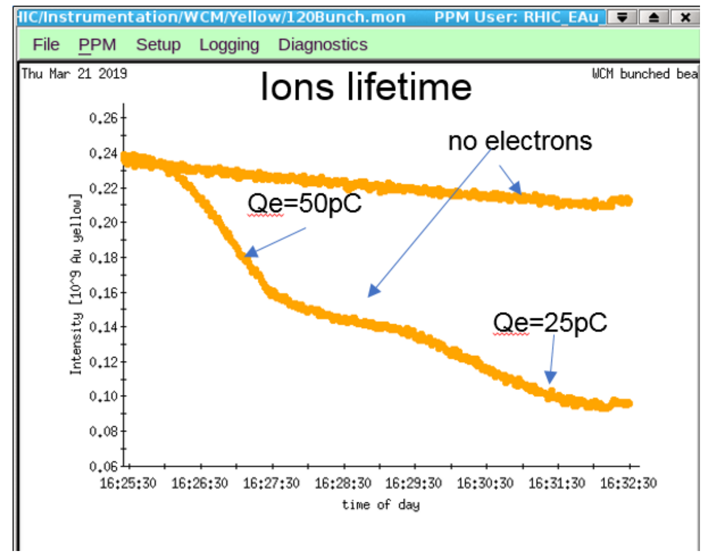
- With no magnetic field in the cooling sections, focusing of electrons by ions was significant. Adjusting the electron beam optics to take this into account was challenging.
- Different focusing on electron bunches distributed at different longitudinal slices of ion bunch.
- Using bunched electron beam 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.

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).

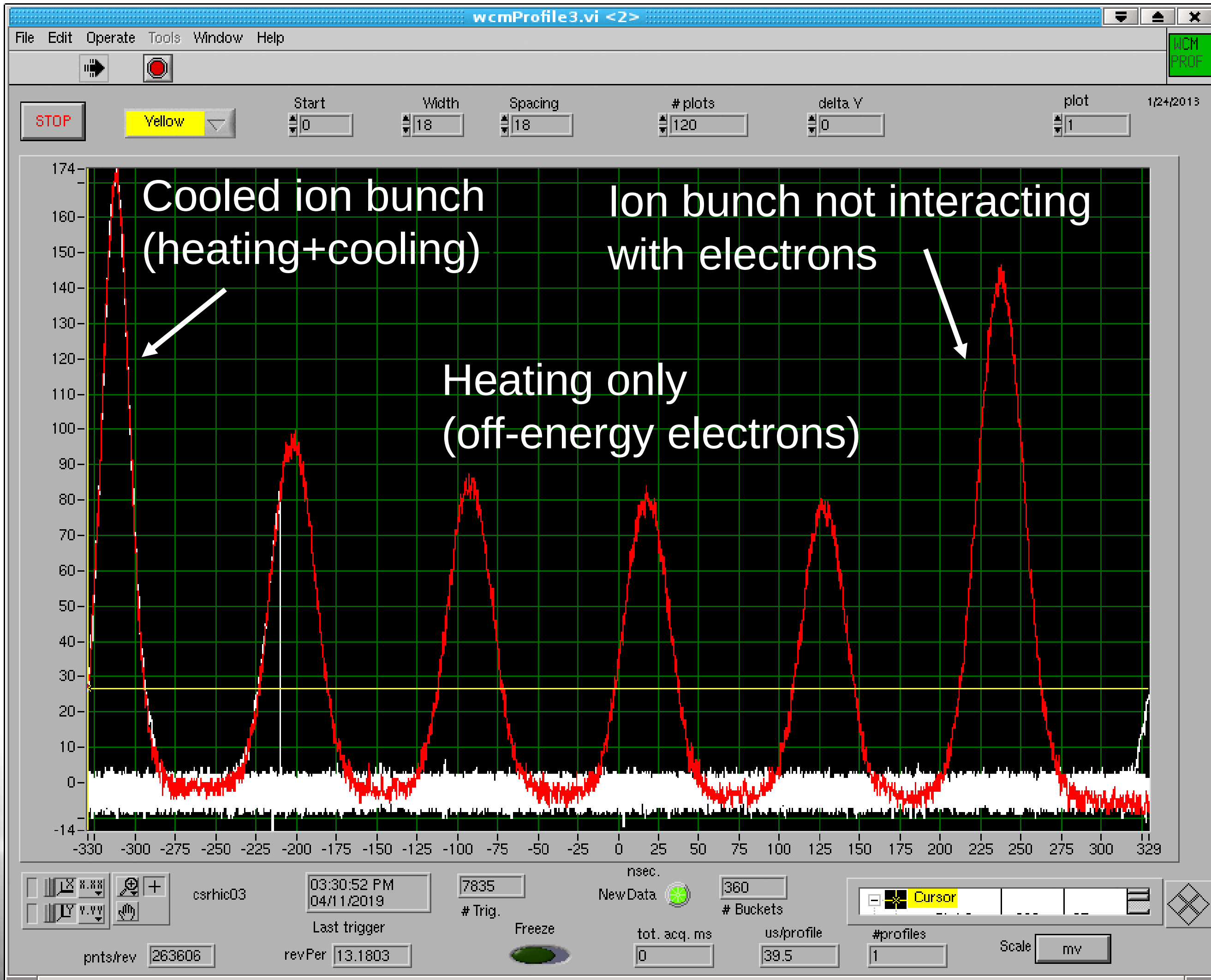


Electrons and ions energies are NOT matched



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

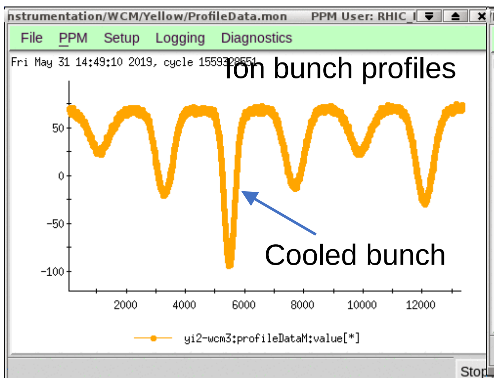
Yellow RHIC Ring (76kHz mode allowing to cool single ion bunch; 6 ion bunches, 5 electron macro-bunches)

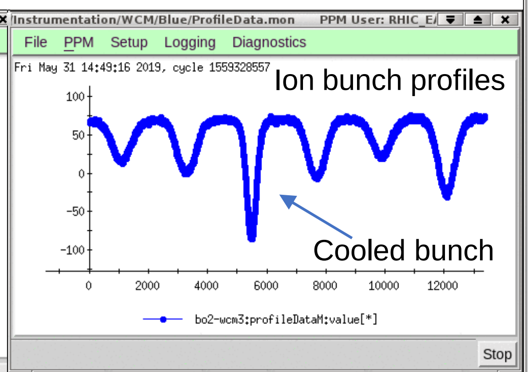


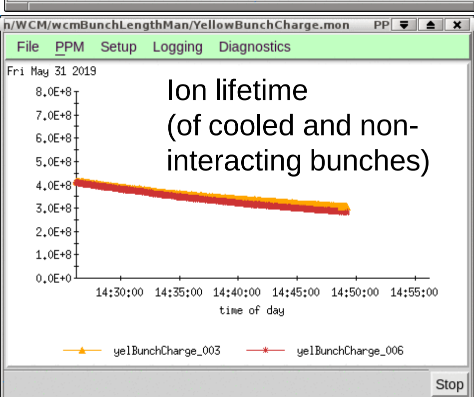
Heating effects were reduced, but not eliminated,
by a proper choice of ion beta-function in the cooling section and of a working point.
We were able to counteract heating with cooling (see bunch #1, as an example).

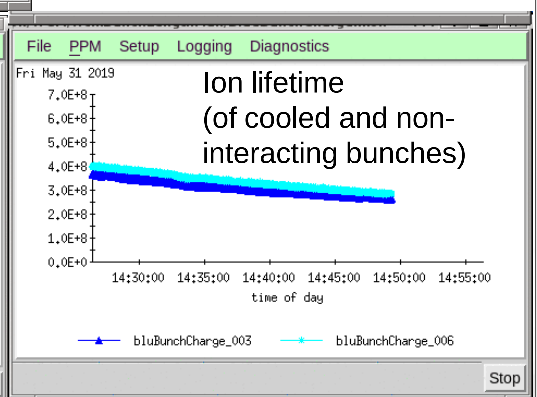
Potential benefits from cooling

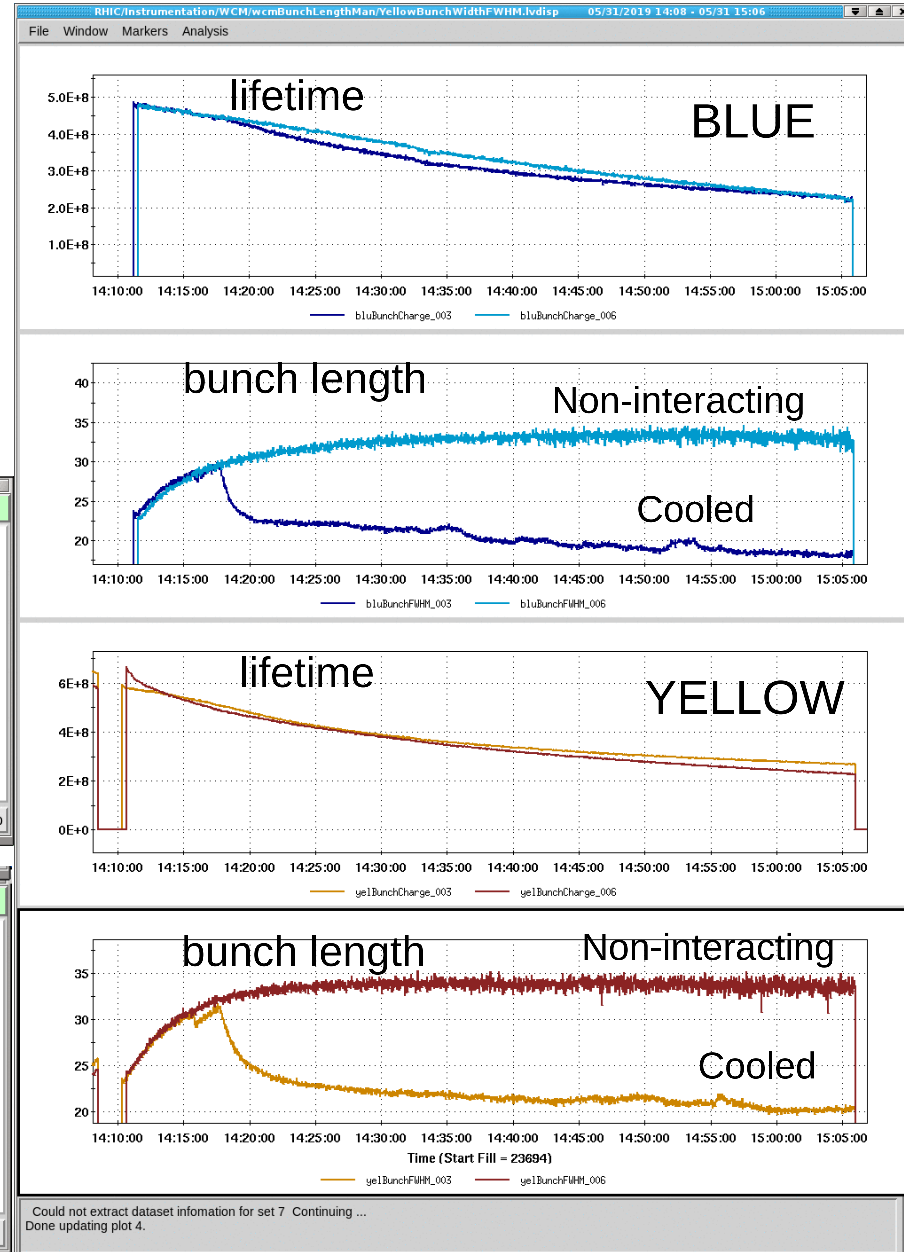
- Cooled bunch is kept shorter, more useful events within trigger window
- Minimize ion beam de-bunching and losses from the RF bucket
- Peak current significantly higher for cooled bunch
- Allows longer stores
- Transverse cooling can help with reduction of beta*











LEReC transition to operations by MCR

- In 2018-2019 LEReC was in commissioning mode.
- During 2019 commissioning already started transition to Ops:
  - Various LEReC systems ran successfully 24/7 during 7-month period.
  - Tapes and procedures for various systems were developed and already used by MCR operators.
  - MCR already developed tape to ramp up bunch charge and used it successfully when LEReC e-beam was left to run overnight.

What remains to be done:

- Finish commissioning and optimization and freeze e-beam parameters and lattice which works best for cooling
- Implement energy and orbit feedbacks
- Covert useful commissioning scripts to Ops applications
- Update tapes and procedures
- Update training of operators on LEReC Ops

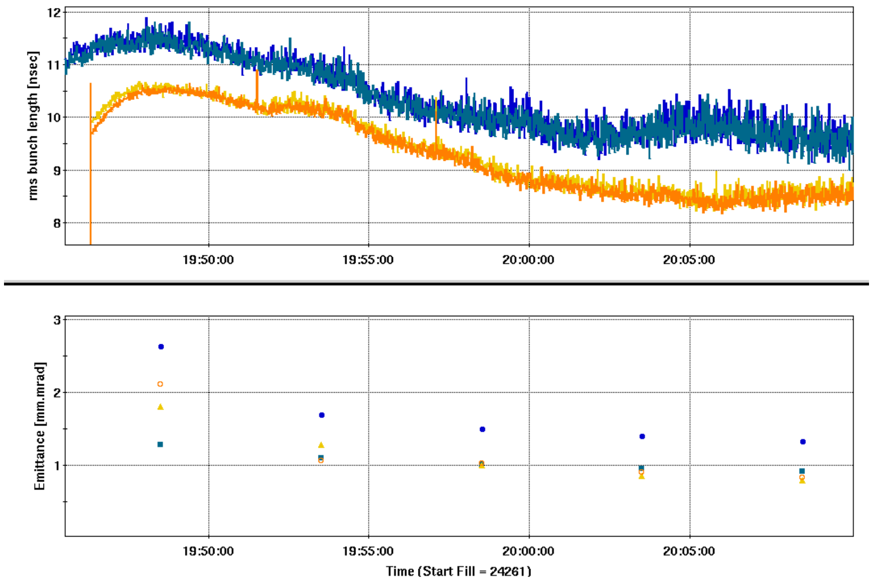
Nine LEReC shift leaders are available to provide further training of MCR operators and assist with LEReC running.

LEReC upcoming plans

November, 2019:	Gun conditioning
December, 2019:	Once SRF booster is at 2K, restart ops with electron beam
Dec.'19-Feb.'20:	Cooling optimization for 4.6GeV/n ions (2MeV electrons): 2 weeks of dedicated time – interleaved with Physics running at 5.75GeV.
March - June, 2020:	Physics run with cooling at 4.6GeV/n (2MeV electrons). Transition to running LEReC by MCR.
March - June, 2020:	Cooling optimization for 3.85GeV/n ions (1.6MeV electrons): 2 weeks of dedicated time – interleaved with Physics running at 4.6GeV.
2021	Physics run with cooling at 3.85GeV/n (1.6MeV electrons).

LEReC summary

- LEReC project was completed on budget and on schedule.
- All commissioning milestones were successfully achieved.
- World's first electron cooling of hadron beams based on RF acceleration of electron bunches was demonstrated. Such cooling approach is new (all previous coolers used DC beam) 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.
- Cooling was commissioned at electron energy of 1.6MeV (ion energy 3.85GeV/n) and at 2MeV (ion energy of 4.6GeV/n)
- 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.
- The next step will be to maximize collision rates with cooling in next year's RHIC low-energy collisions.



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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!