Low Energy RHIC electron Cooling (LEReC):

Status and Commissioning Progress

Alexei Fedotov

on behalf of the LEReC team

BNL NPP 2019 PAC Meeting

June 10, 2019

BROOKHAVEN NATIONAL LABORATORY

U.S. DEPARTMENT OF ENERGY

LEReC Project Overview

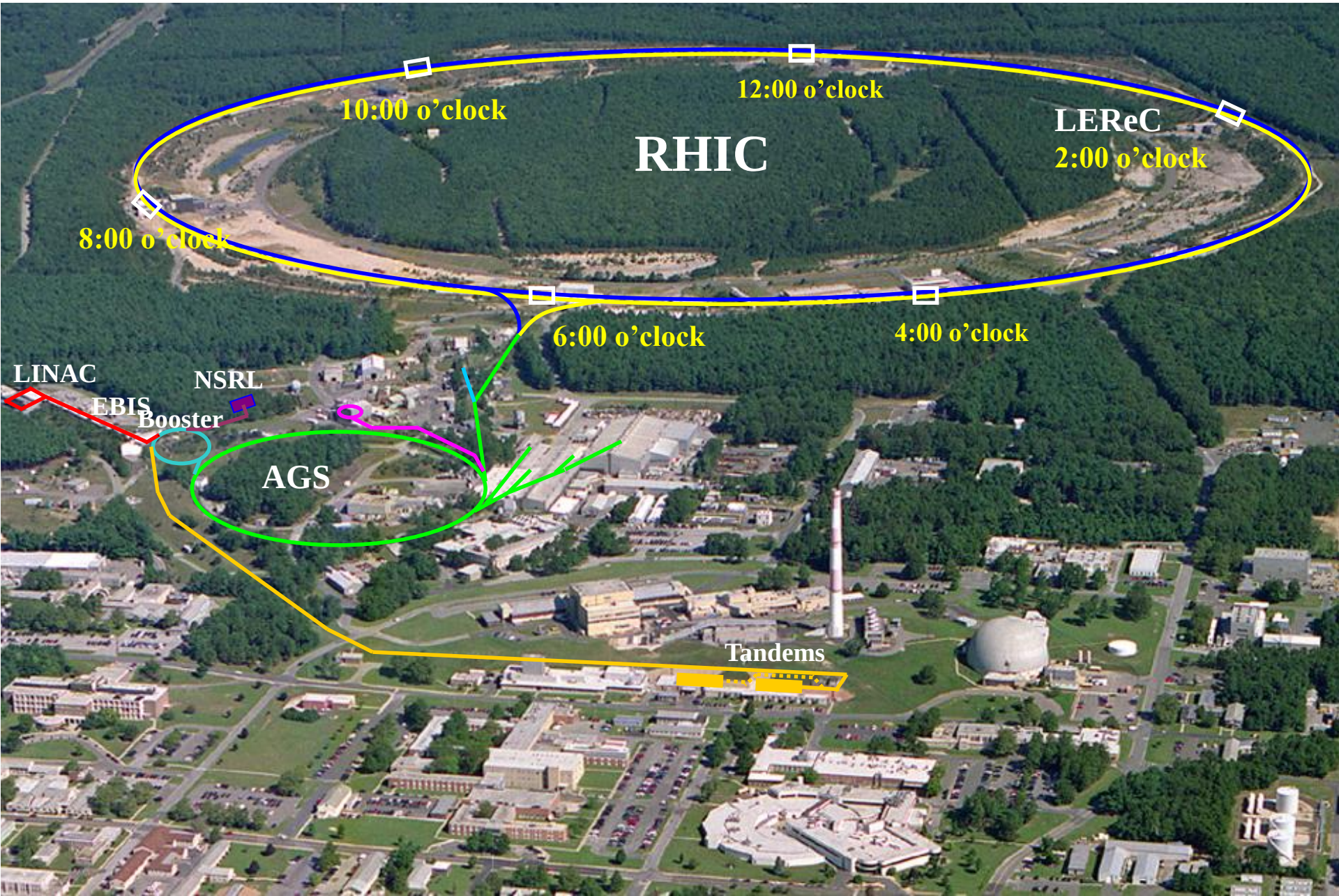
The goal of the LEReC project is to provide luminosity improvement for RHIC operation at low energies to search for the QCD critical point.

LEReC is first RF linac-based electron cooler (bunched beam cooling).

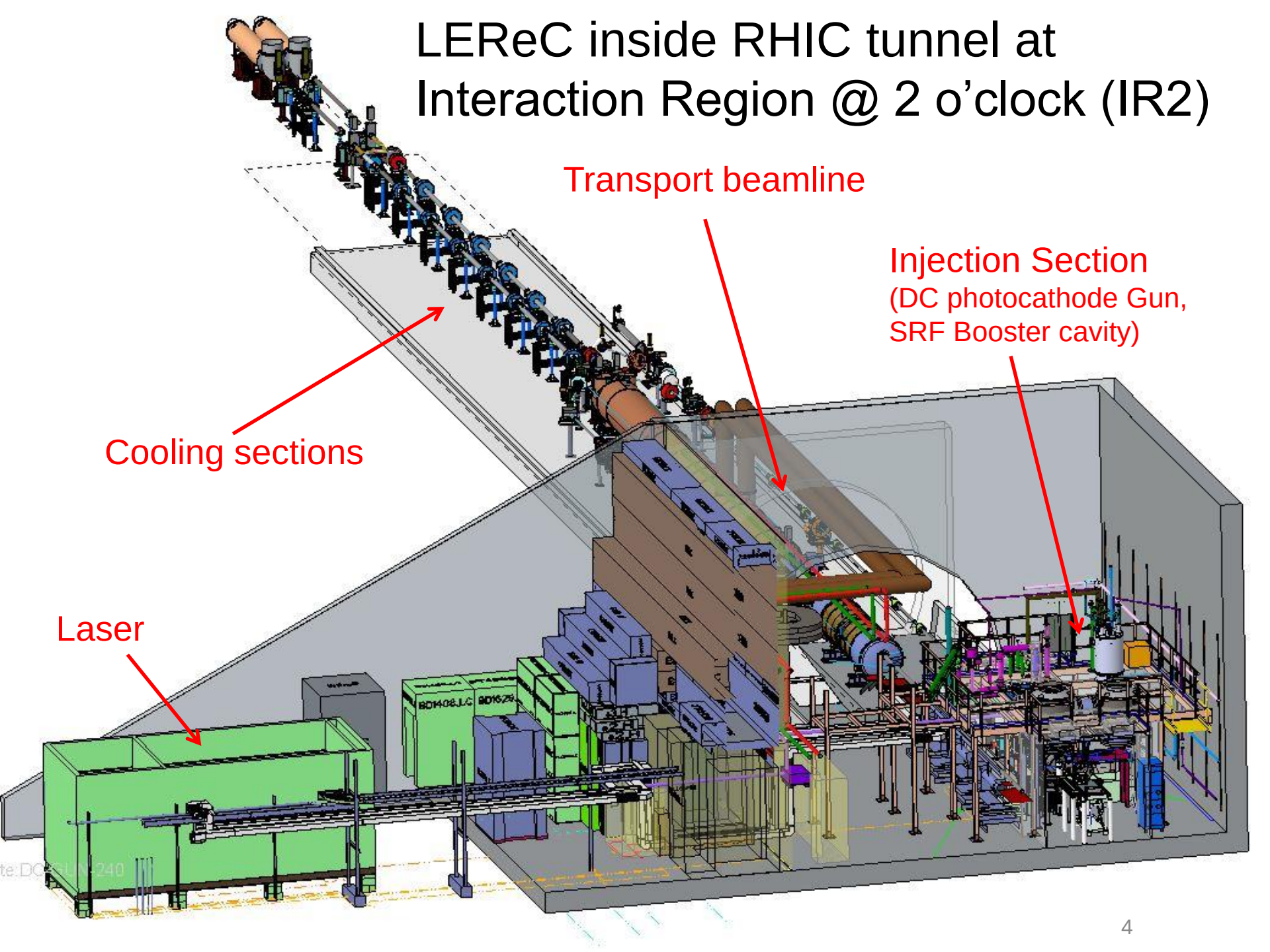
To provide luminosity improvement with such new approach requires:

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

RHIC @ BNL, Long Island, New York

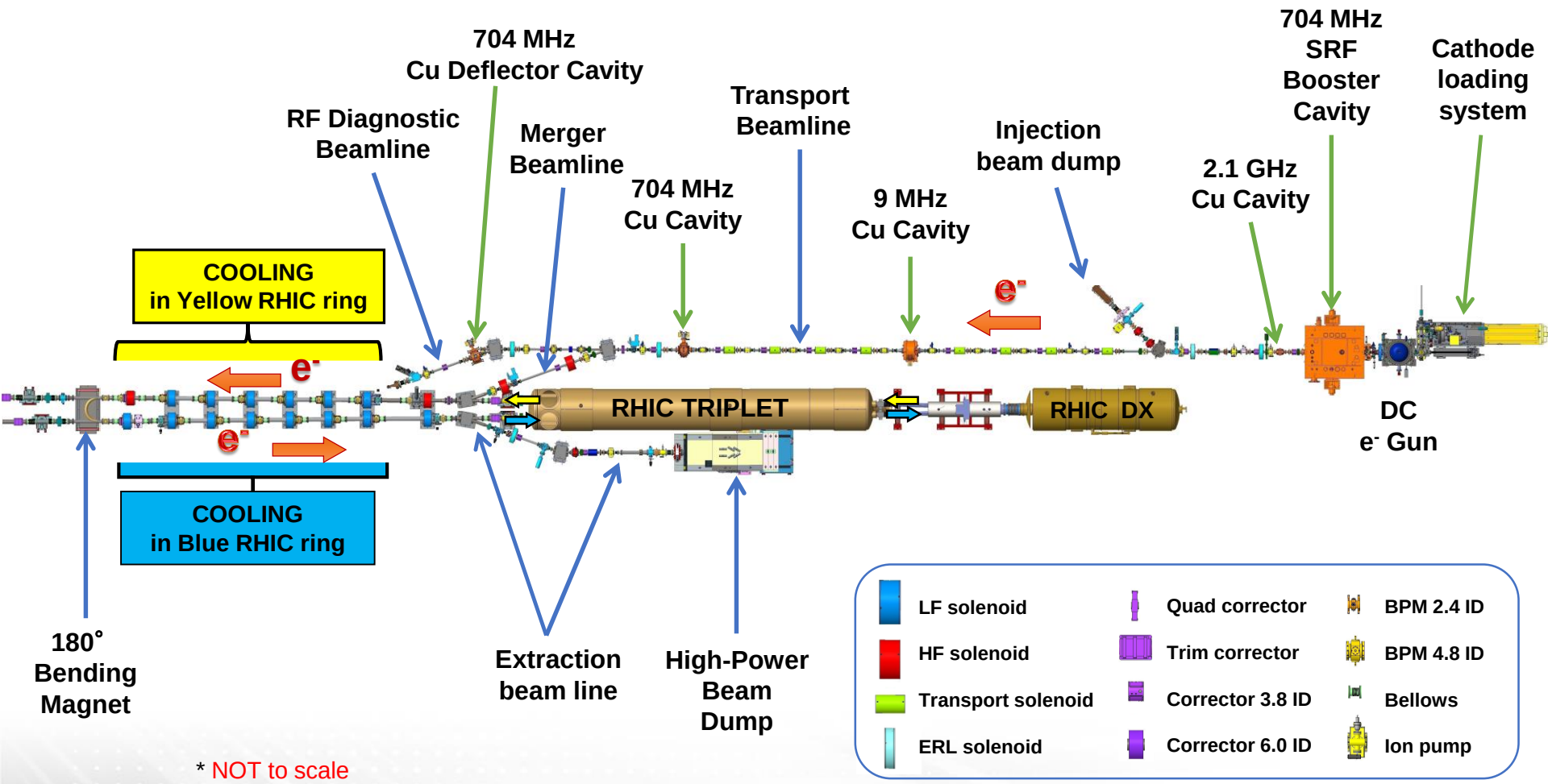


LEReC inside RHIC tunnel at Interaction Region @ 2 o'clock (IR2)



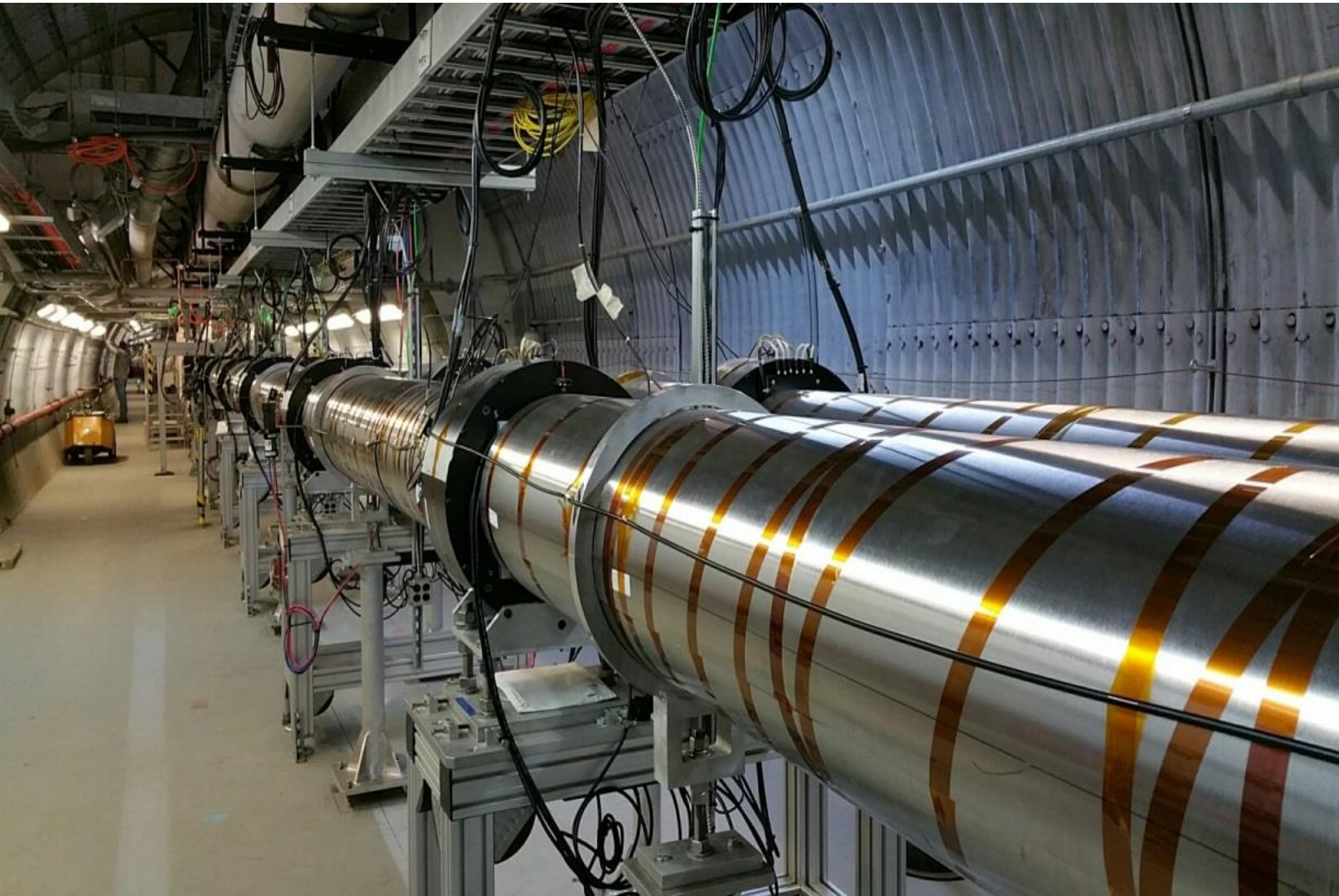
LEReC electron accelerator

(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 cooling sections



LEReC electron beam parameters

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

Bunched beam electron cooling for LEReC

- Electron bunches suitable for cooling are generated by illuminating a multi-alkali (CsK_2Sb) photocathode inside the high-voltage DC Gun with green light using high-power laser (high-brightness in 3D: both emittances and energy spread).

- The 704MHz fiber laser produces required modulations to overlap ion bunches at 9MHz frequency with laser pulse temporal profile shaping using crystal stacking.

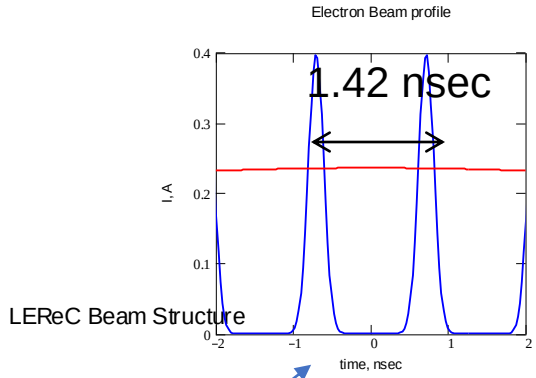
- Such electron bunches are accelerated using 704MHz SRF cavity. RF gymnastics (several RF cavities) is employed to achieve energy spread required for cooling. Electron beams of required quality are delivered to cooling sections.

- Electron bunches overlap only small portion of ion bunch. All ion amplitudes are expected to be cooled as a result of synchrotron oscillations of ions.

LEReC beam structure in cooling section

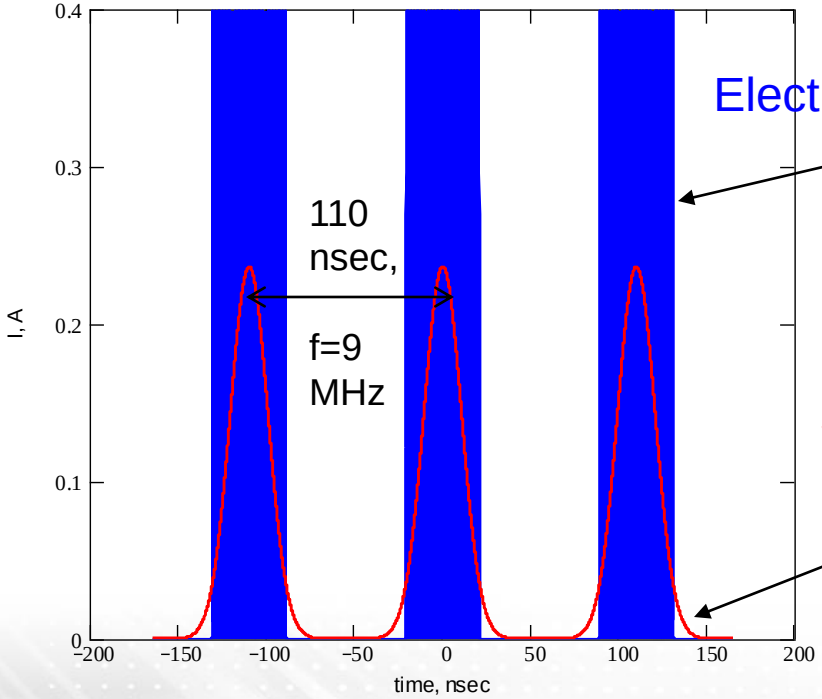
Ions structure:
120 bunches
f_rep=120x75.8347 kHz=9.1 MHz
N_ion=5e8, I_peak=0.24 A
Rms length=3 meters

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



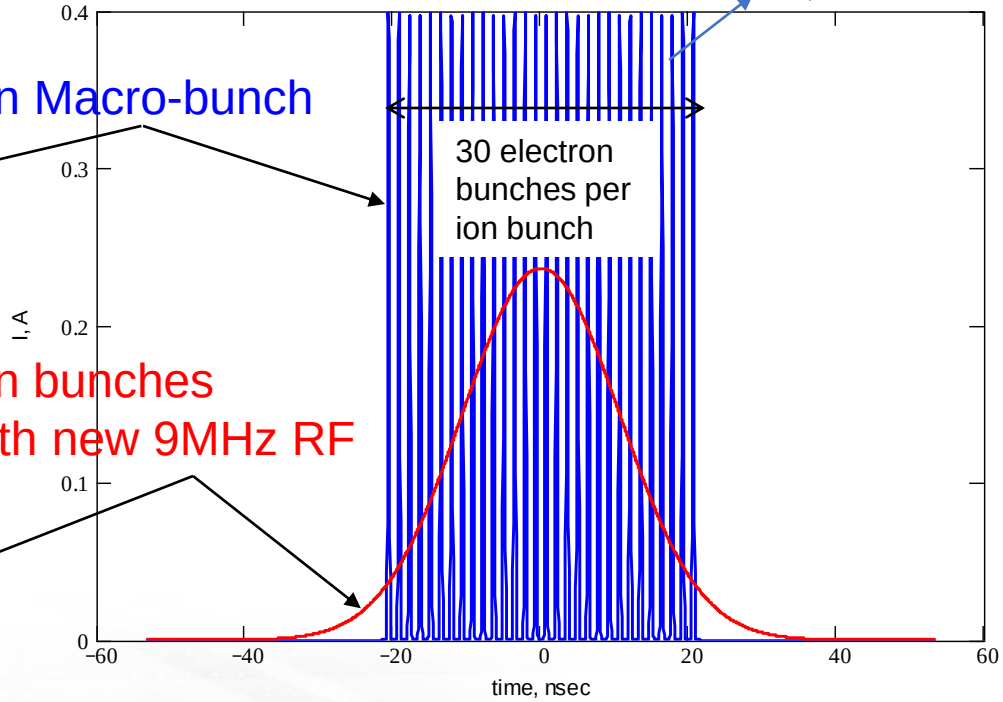
LEReC Beam Structure

9 MHz bunch structure



Electron Macro-bunch

Ion bunches with new 9MHz RF

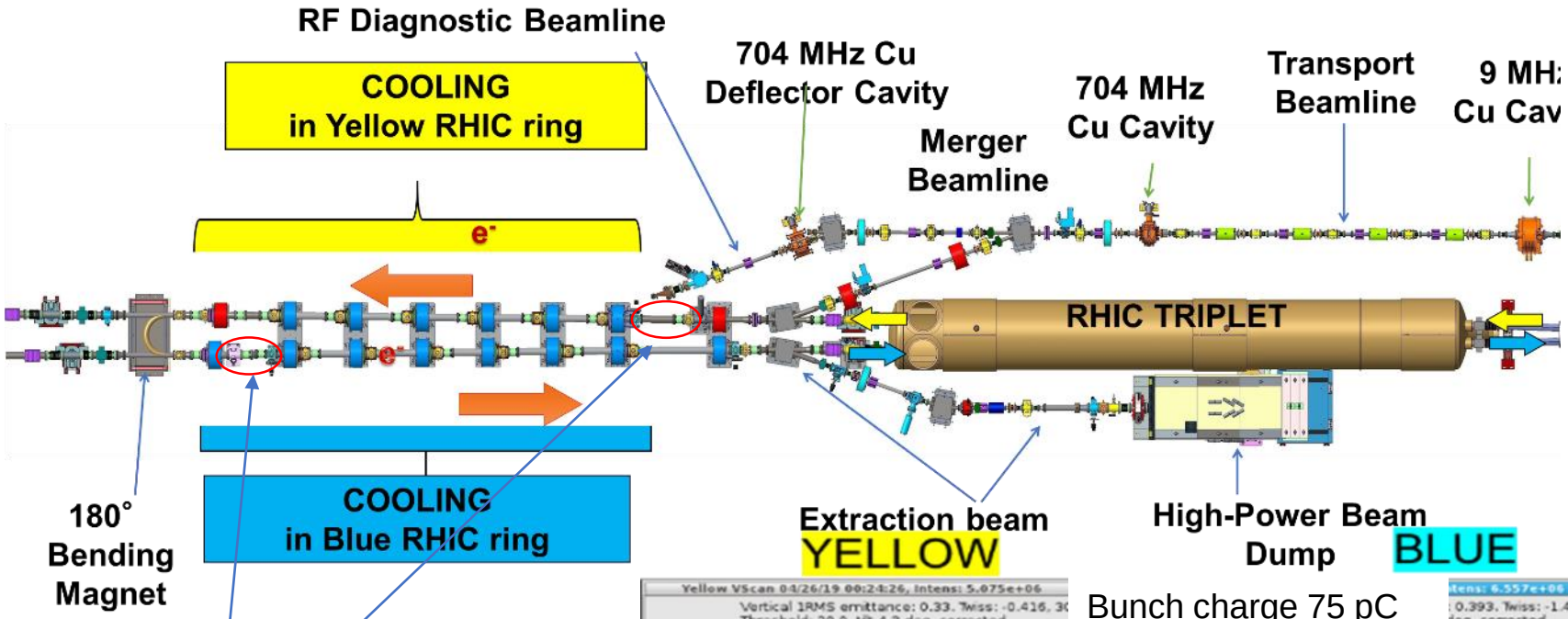


Attainment of “cold” electron beam suitable for cooling

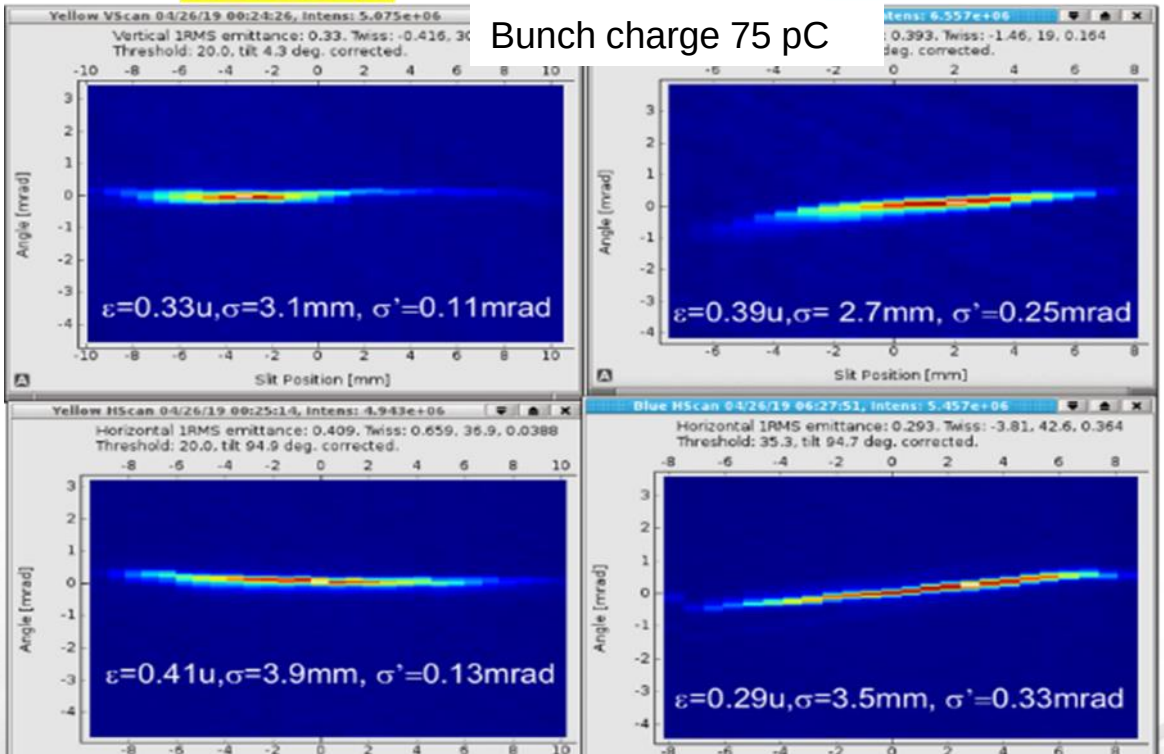
- LEReC is based on the state-of-the-art accelerator physics and technology:

- 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



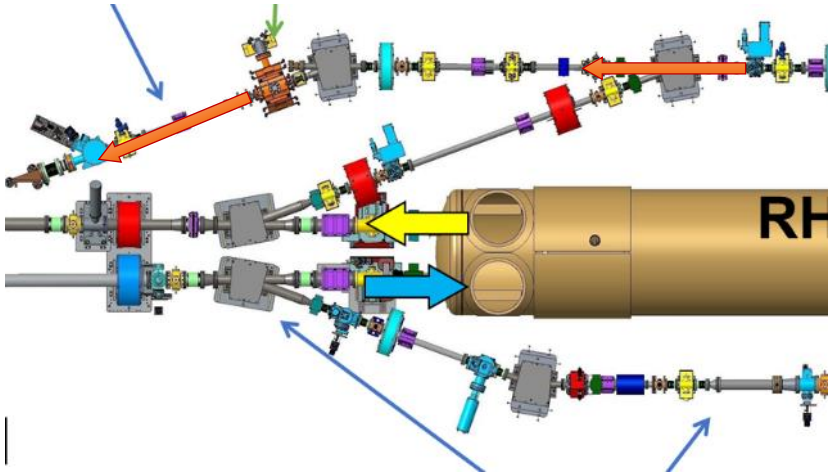
Bunch charge 75 pC



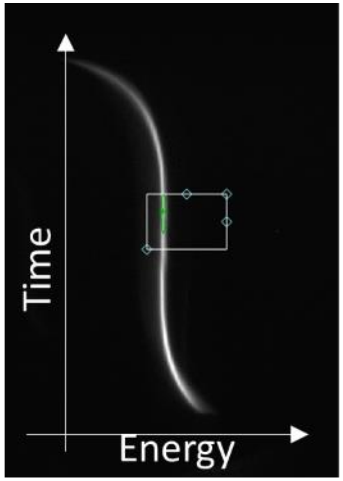
Movable slit and downstream beam profile monitors are installed at the beginning of each cooling section.

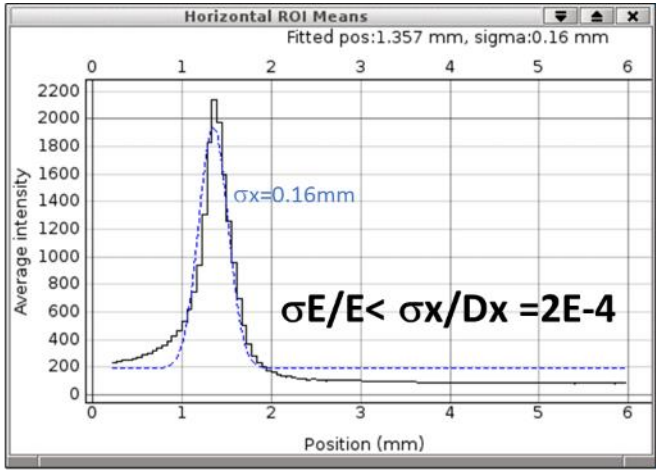
Longitudinal phase space measurement of electron beam

704MHz RF vertically deflecting cavity

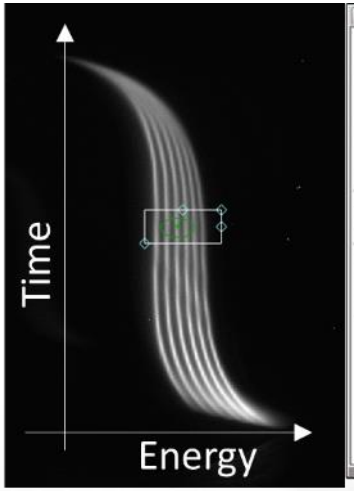


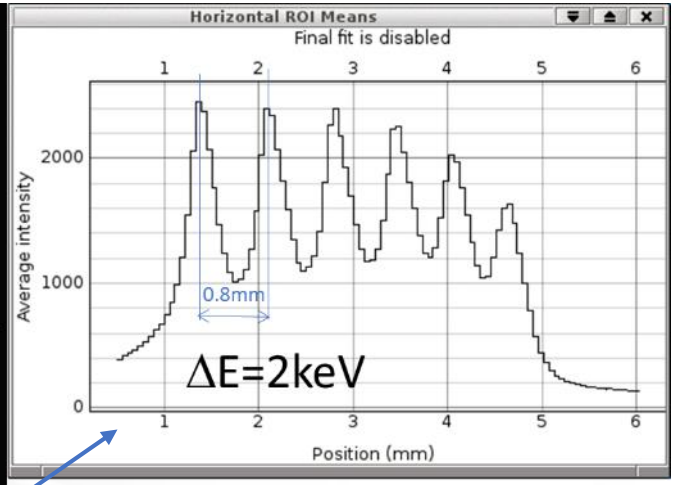
1 macro-bunch of electrons (total charge 3nC)





6 macro-bunches, 3 nC each.

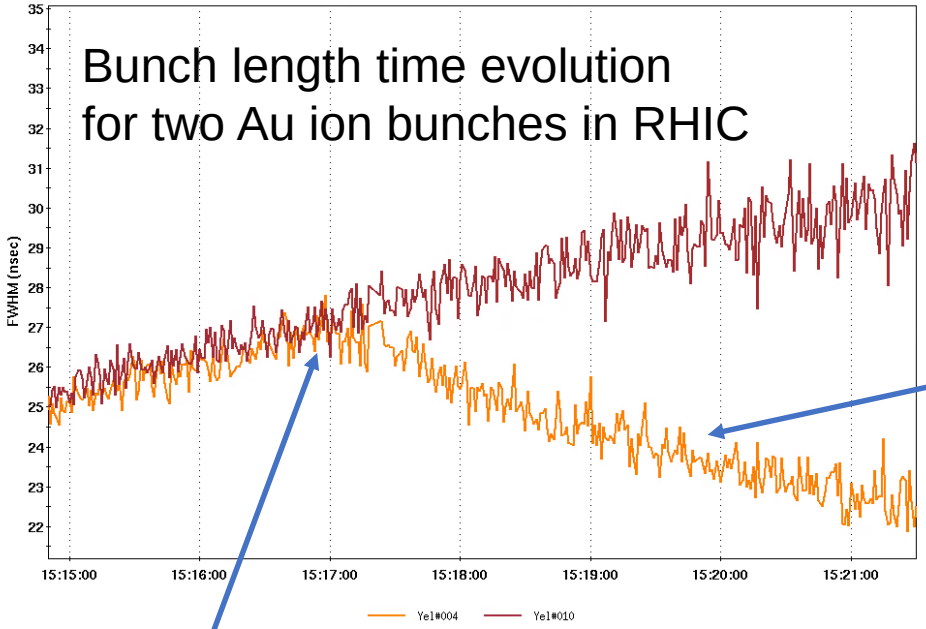




- First dogleg merger dipole is off
- Beam goes to RF diagnostic line
- 20 degree dipole produces dispersion
- Deflecting cavity produces time dependent vertical kick

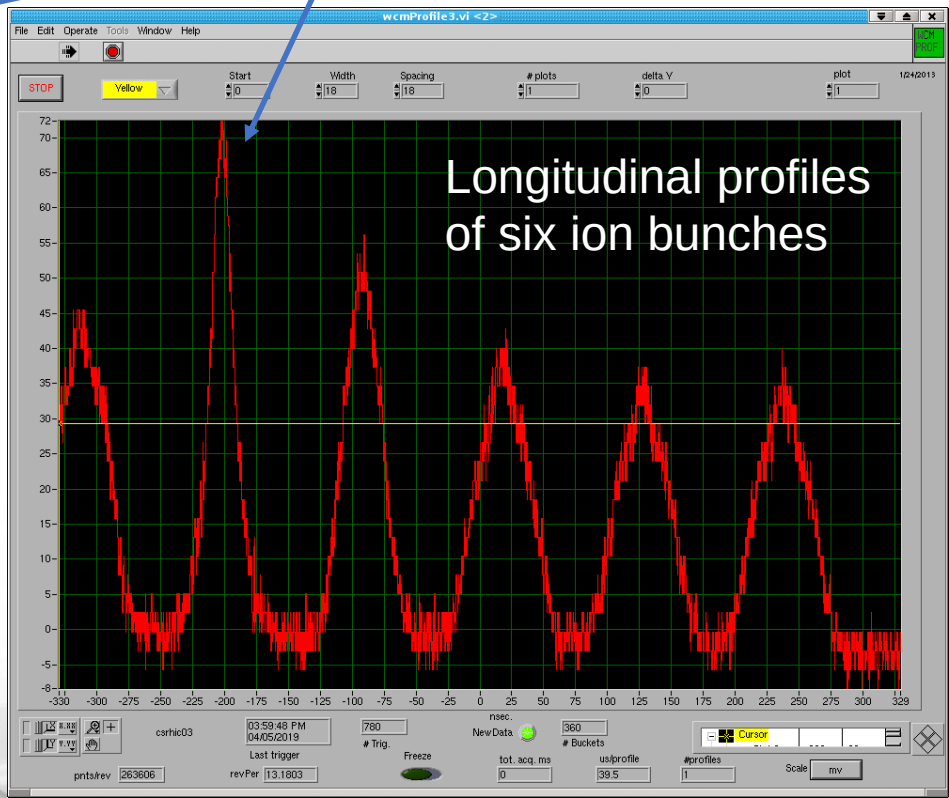
In pulsed mode, subsequent electron macro-bunches have lower energy due to beam loading in RF cavities.

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



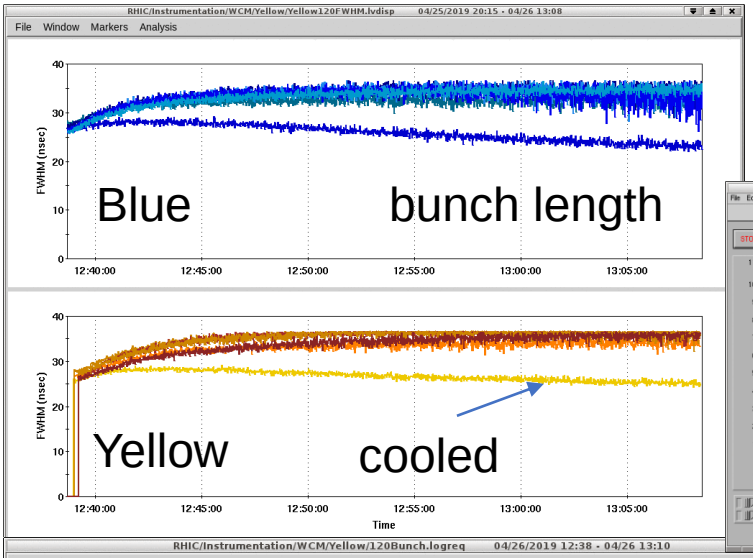
Ion bunch #4 which is not being cooled

Ion bunch #2 is being cooled

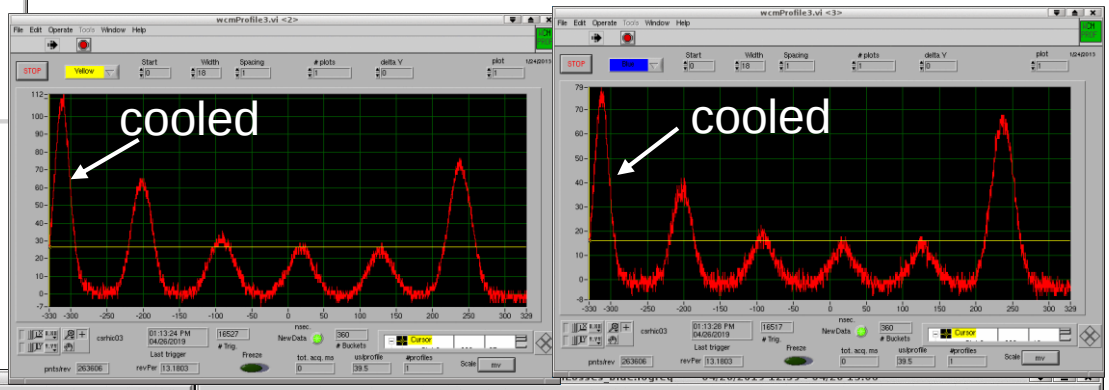


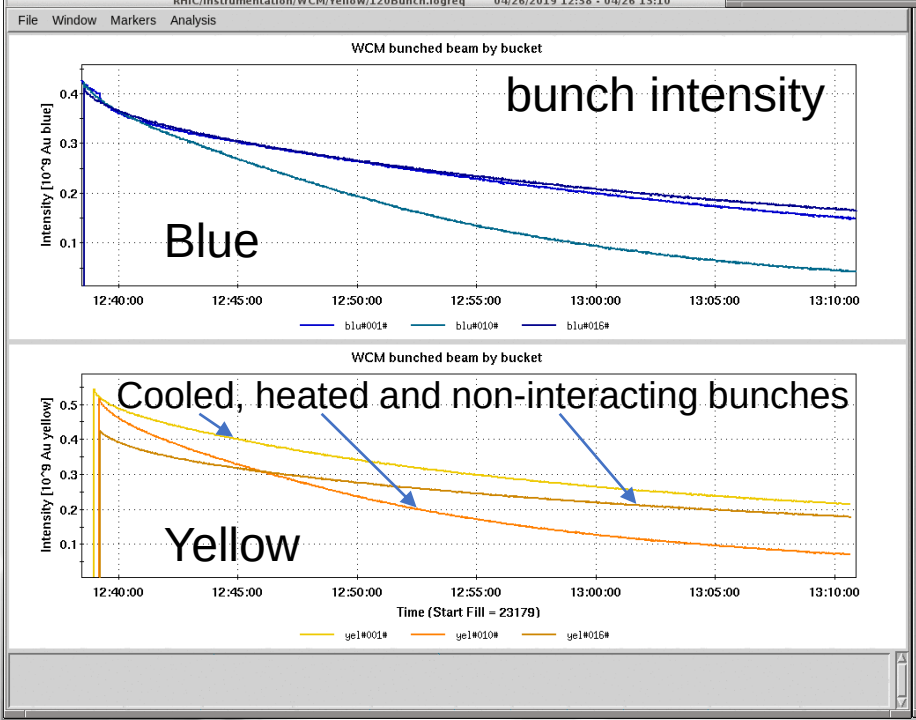
Energy of electrons and ions matched

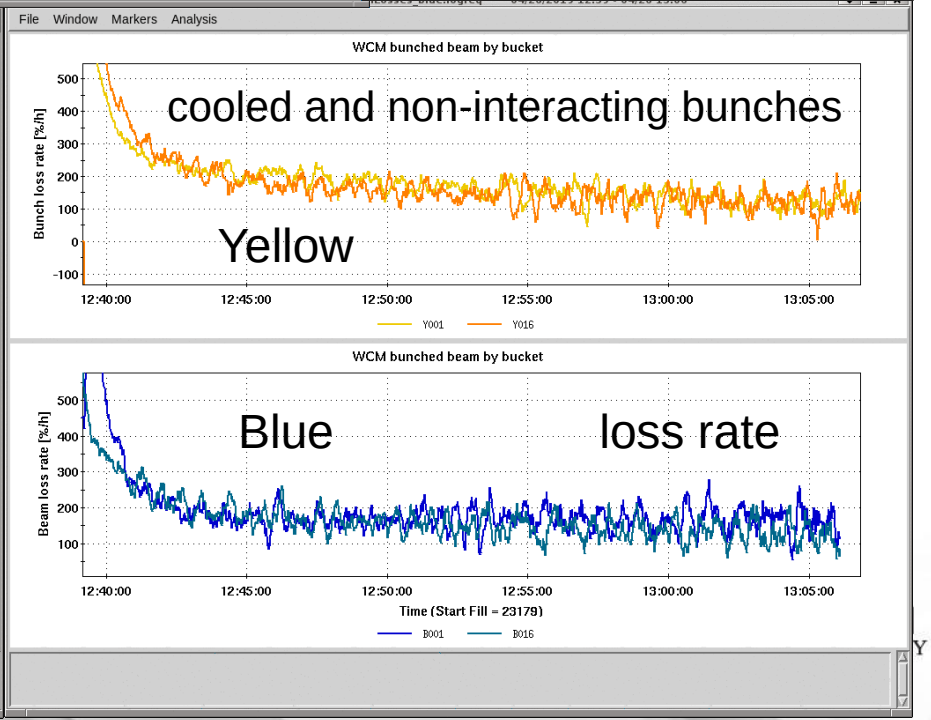
Simultaneous cooling in Yellow and Blue rings (76kHz mode, 6 ions bunches: bunch #1 is being cooled; bunch #6 does not see electrons)



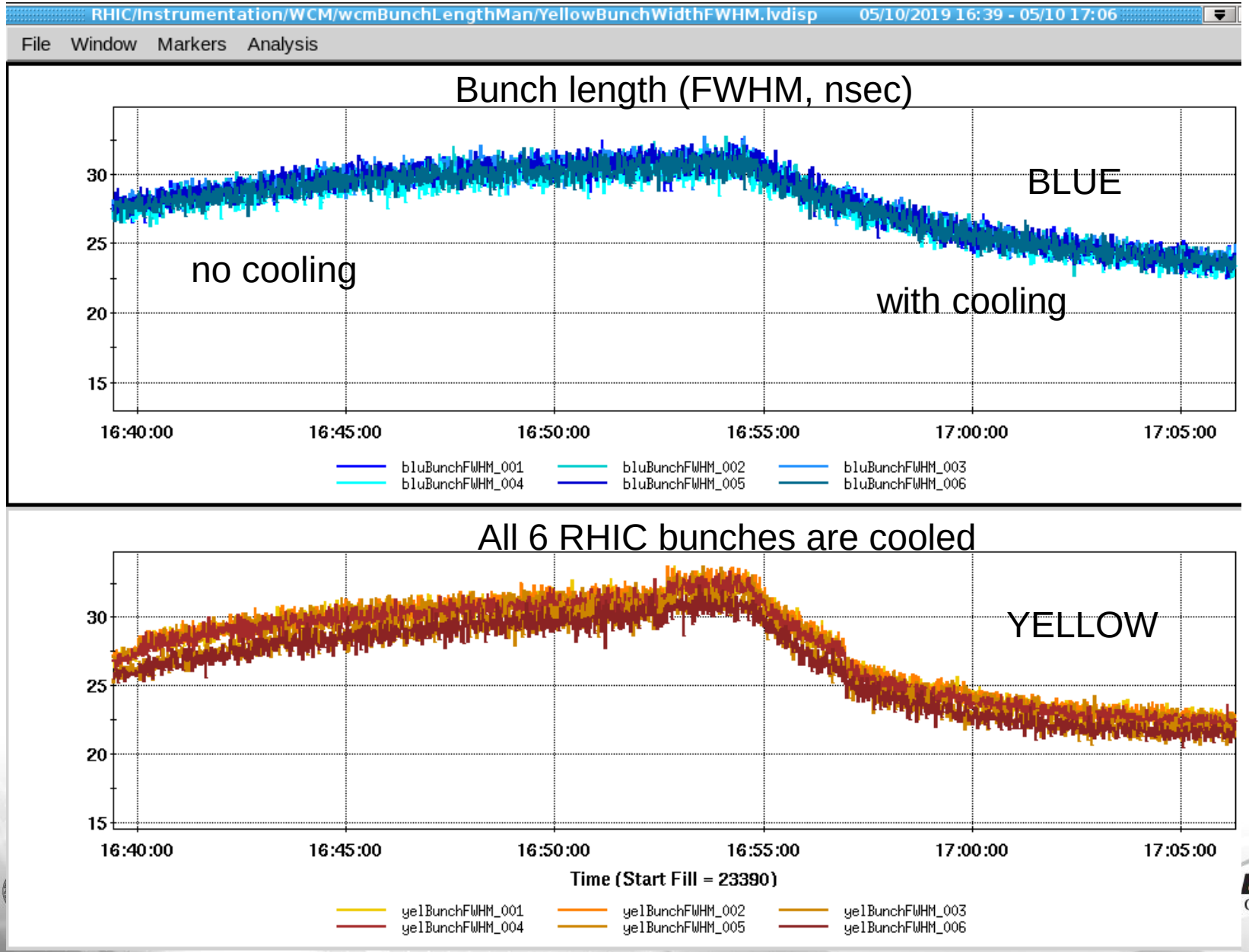
Longitudinal bunch profiles





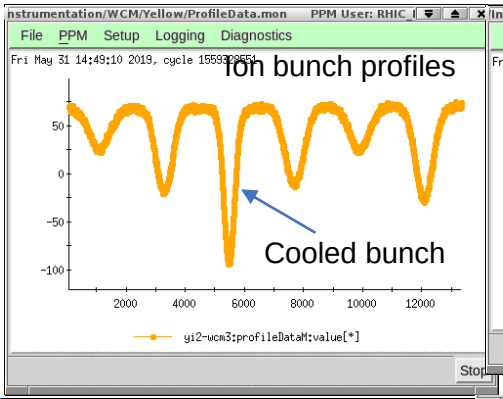


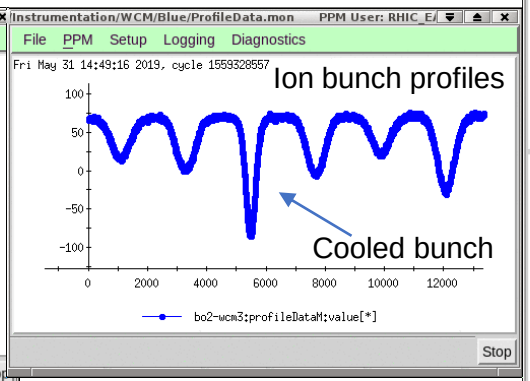
Simultaneous cooling (in Yellow and Blue RHIC rings, 6 bunches in each) using high-current 9 MHz CW electron beam

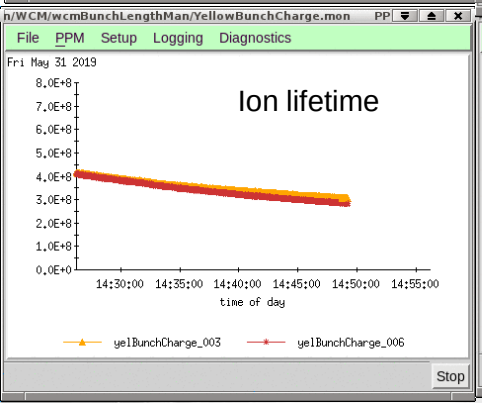


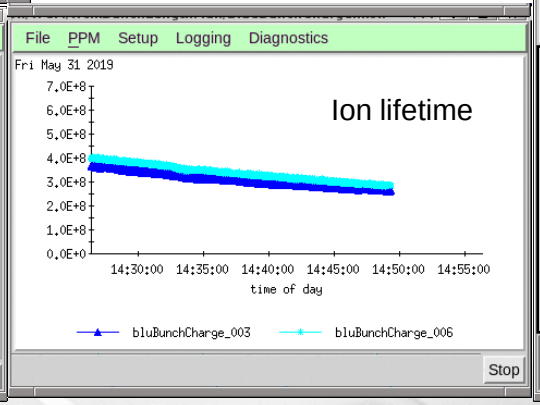
Potential benefits from cooling

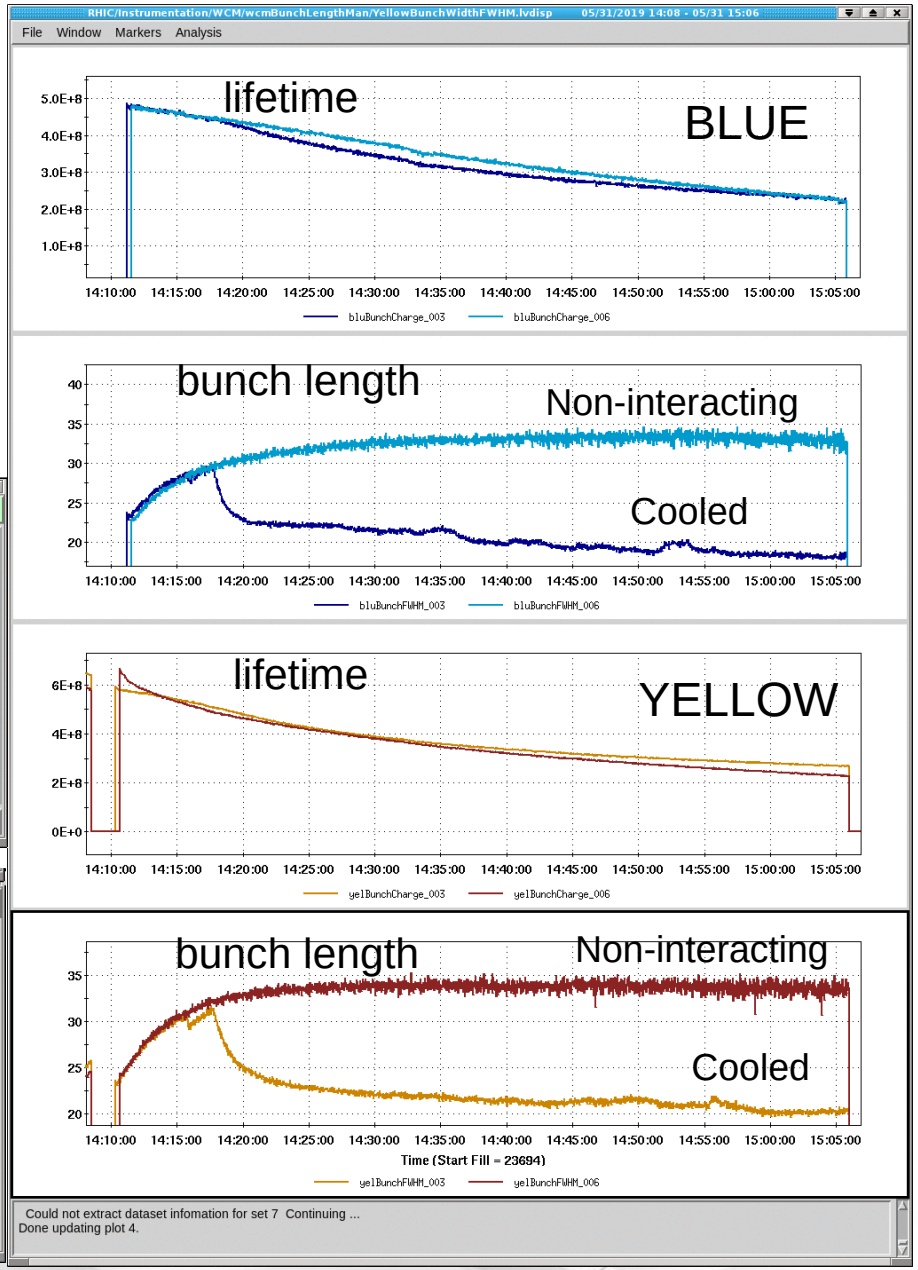
- Cooled bunch is kept shorter, more useful events within trigger window
- Minimize ion beam de-bunching and losses from the RF bucket
- Peak current significantly higher for cooled bunch
- Emittance cooling with possible reduction of beta-function at collisions











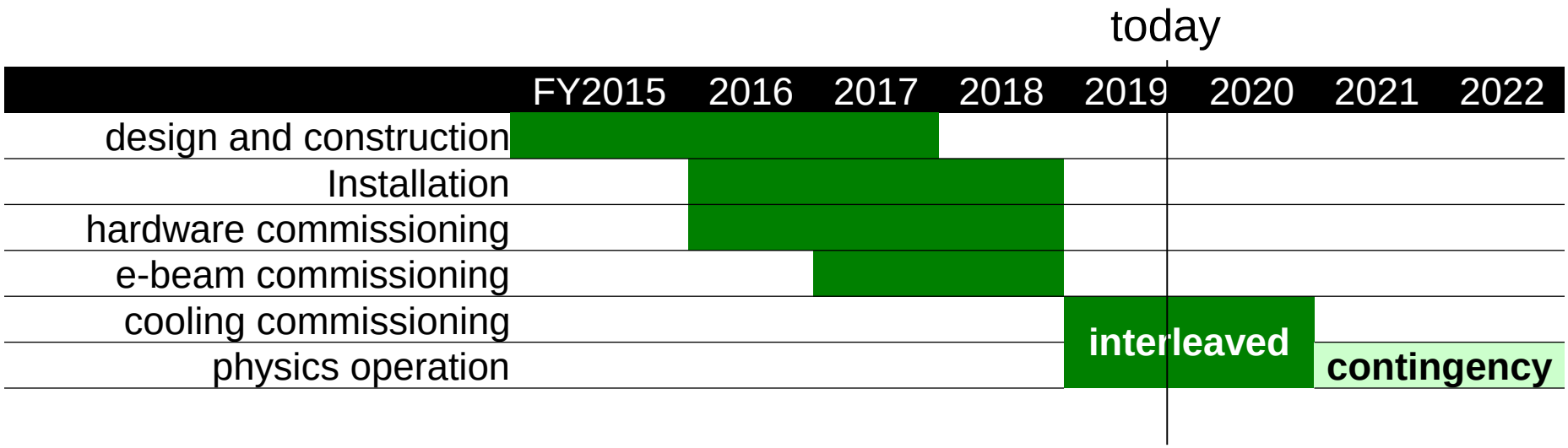
LEReC roadmap to cooling

- 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 ✓

Cooling commissioning milestones:

- Demonstrated first electron cooling using bunched electron beams✓
- Demonstrated cooling in 6-D✓
- Matched electron and ion energy in both Yellow and Blue RHIC rings✓
- Cooling was achieved 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 in both Yellow and Blue RHIC rings simultaneously using CW electron beam ✓

LEReC timeline and integration with RHIC Physics (unchanged, as presented in 2015)



- Installation is complete
- Hardware commissioning is complete
- Commissioning of electron accelerator at 1.6 MeV is complete
- Bunched electron beam cooling commissioned

Present focus is on operational aspects of e-cooling in RHIC

LEReC Physics integration: BES-II required events

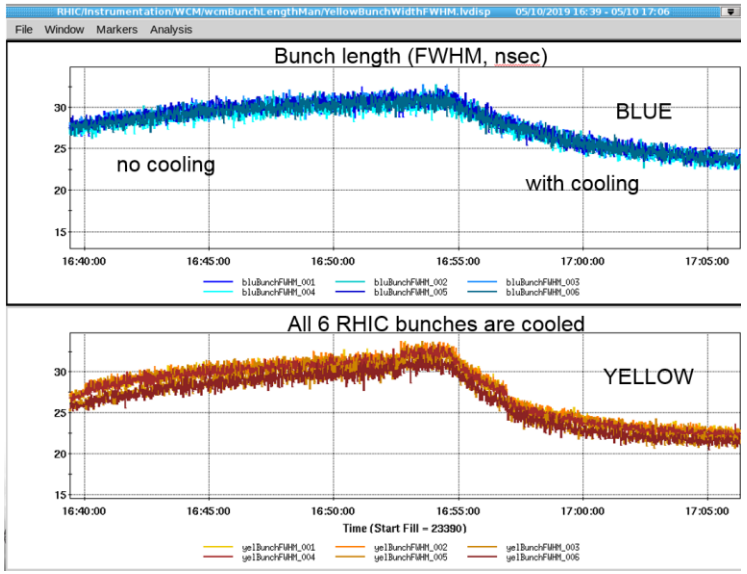
center-of-mass energy $\sqrt{s_{NN}}$	GeV	7.7	9.1	11.5	14.6	19.6
events BES-I, actual	M	4.3		11.7	24	36
events BES-II, **min goal**	M	80	100	150	200	300
events BES-II, **full goal**	M	100	160	230	300	400

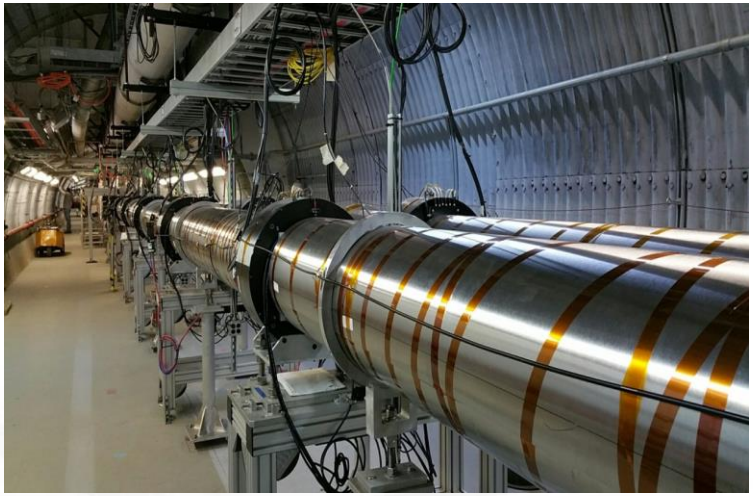
General strategy to maximize integrated luminosity:

- Cooling at the 2 lowest energies, no cooling at the 3 highest energies
- Started BES-II at highest energies (machine ready w/o cooling)
- Interleave cooling commissioning with physics operation
- Finish BES-II at lowest energies (largest gain in L_{avg} and time)

Summary

- We designed, built and commissioned state-of-the-art electron accelerator LEReC which provides beam quality suitable for electron cooling using bunched electron beams.
- Electron cooling using bunched electron beams based on the RF acceleration was successfully demonstrated.
- Such cooling approach is new (previous electron coolers all used DC beams), and opens the possibility of electron cooling at high beam energies.
- Cooling of ion bunches in both RHIC rings simultaneously using the same electron beam was successfully demonstrated.
- An optimization of cooling and effects on ion beam lifetime is in progress.
- The next step will be to show that the cooling enhances collision rates 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!