

Low Energy RHIC Electron Cooling (LEReC) Report

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On behalf of LEReC team

RHIC and AGS Users' Meeting

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BROOKHAVEN
NATIONAL LABORATORY

 U.S. DEPARTMENT OF
ENERGY

LEReC Project Goals

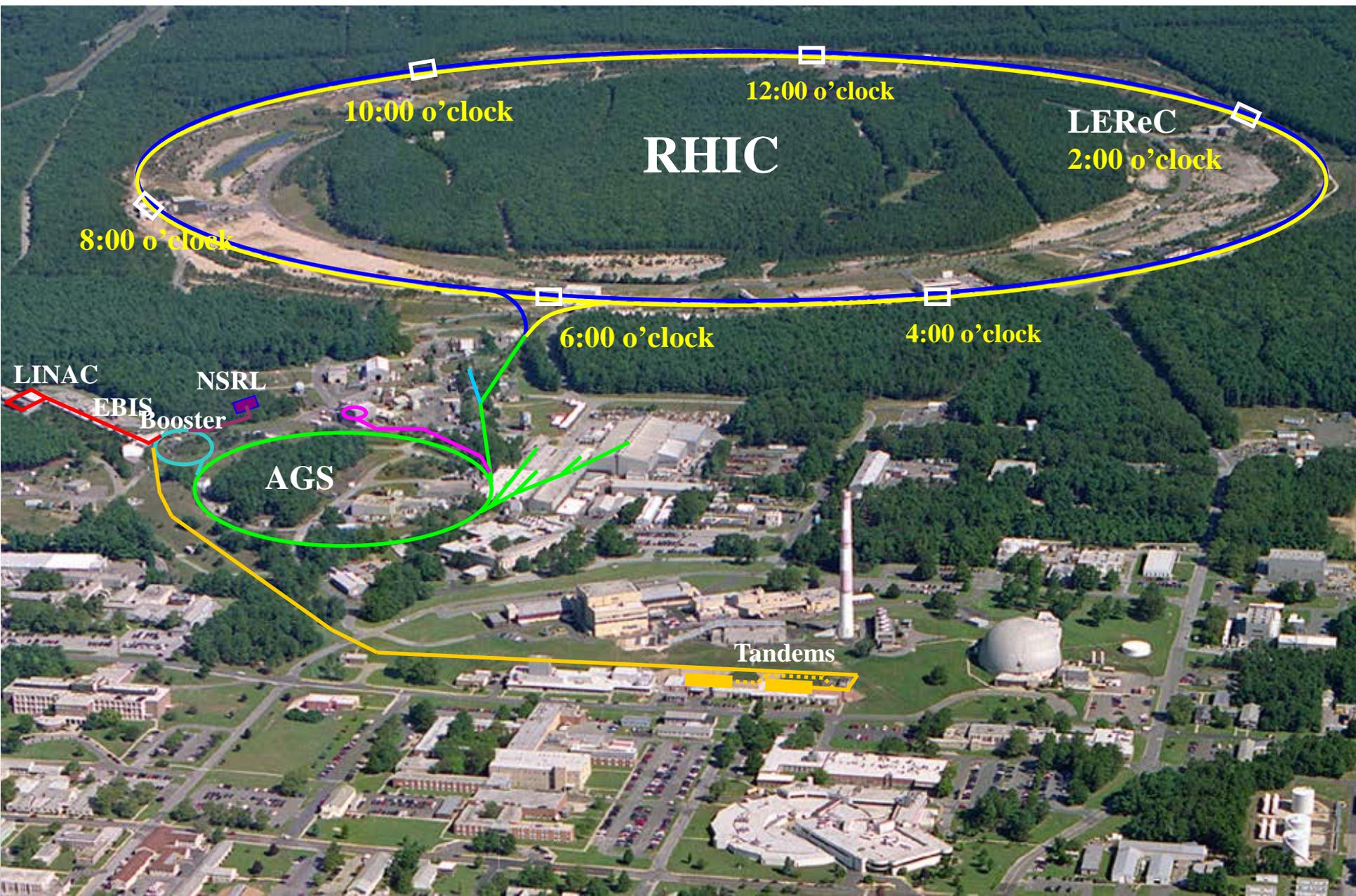
The goal of the LEReC project is to provide luminosity improvement for RHIC operation at low energies to search for a QCD critical point (Beam Energy Scan Phase-II physics program).

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

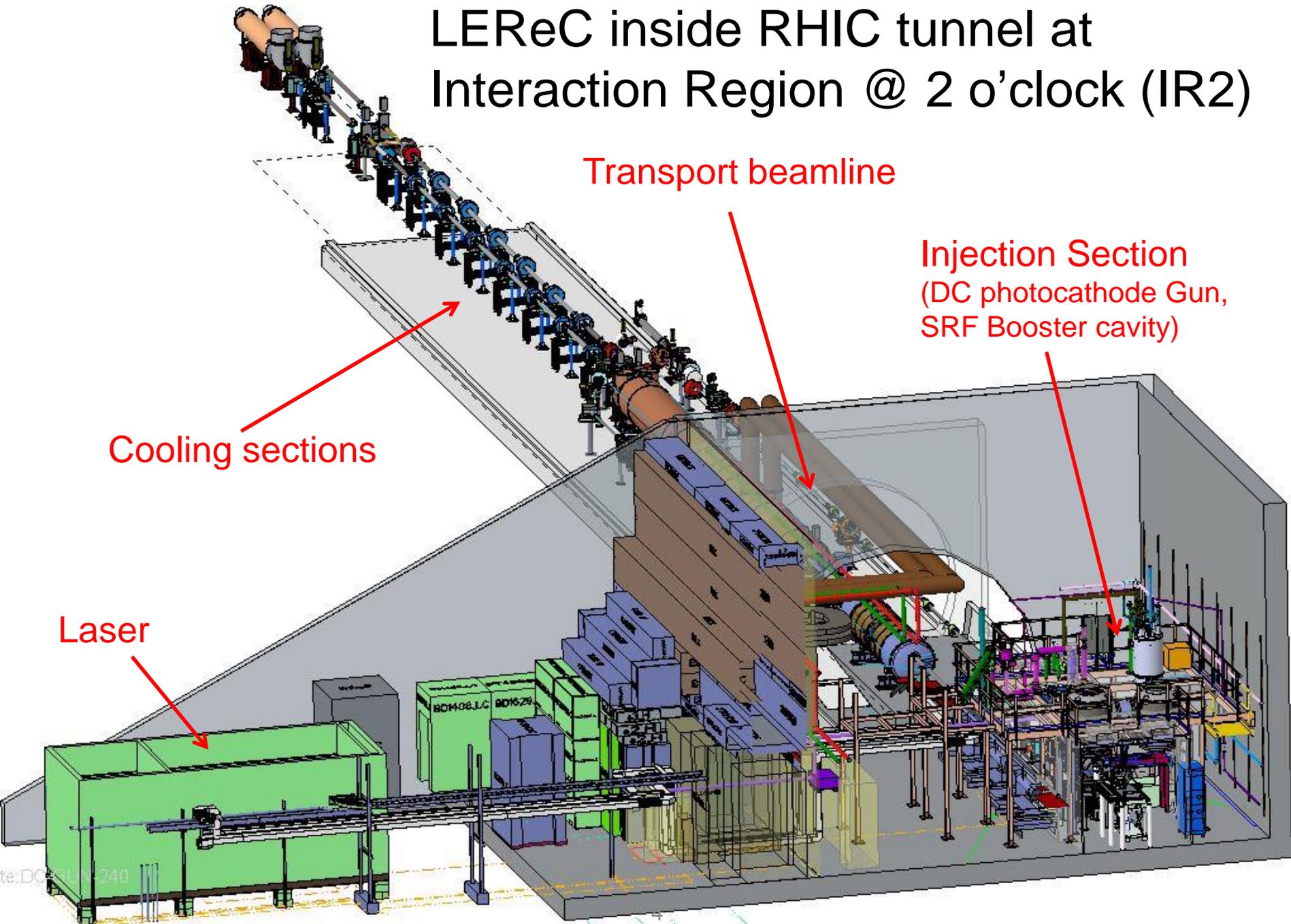
To provide luminosity improvement with such approach requires:

- 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

RHIC @ BNL, Long Island, New York

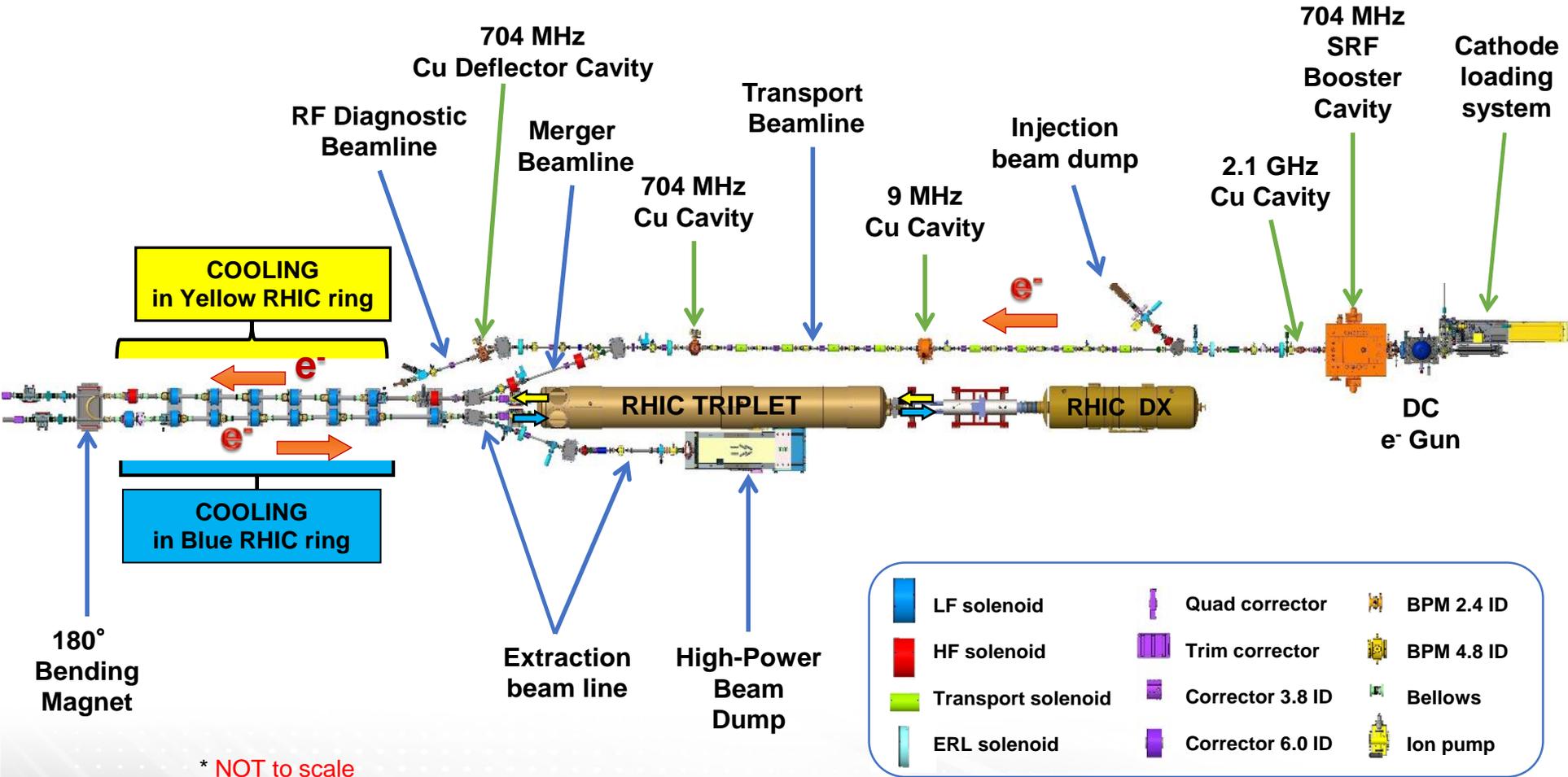


LEReC inside RHIC tunnel at Interaction Region @ 2 o'clock (IR2)



LEReC Accelerator

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



Stages of LEReC Commissioning

- **Phase 1: DC Gun tests**
(April-August 2017): DC Gun tests in temporary configuration
(January-February 2018): DC Gun tests in final configuration
- **Phase 2 (March-September 2018): Full LEReC commissioning**
Goals: Meet all required KPPs. Achieve high-current operation of accelerator. Achieve electron beam parameters suitable for cooling.
- **Phase 3 (2018-2019): Transition to operations**
Goals: Achieve required stability (energy, orbit) of electron beam. Develop necessary stability, ripple, intensity, orbit feedbacks. Commissioning of LEReC for operation at higher energies.
- **Phase 4 (2019-2020): Commissioning of cooling – requires Au ions at the same energy.**

LEReC electron beam parameters

Electron beam requirement for cooling				Measured*
Kinetic energy, MeV	1.6*	2	2.6	1.6, 2.0
Laser pulse duration, psec	40	40	40	40
Bunch duration in cool. sect, psec	400	400	20	400
Electron bunch (704MHz) charge, pC	130	170	200	50-200
Bunches per macrobunch (9 MHz)	30	30	24-30	30
Charge in macrobunch, nC	4	5	5-6	1-6
RMS normalized emittance, um	< 2.5	< 2.5	< 2.5	1.6-2
Average current, mA	36	47	45-55	14-30
RMS energy spread	< 5e-4	< 5e-4	< 5e-4	<2e-4
RMS angular spread in cooling section	<150 urad	<150 urad	<150 urad	100-200 urad

2019 test RUN

Bunched beam electron cooling for LEReC

- Produce electron bunches suitable for cooling by illuminating a multi-alkali photocathode inside the Gun with green light using high-power laser (high-brightness in 3D: both emittance and energy spread).
- The 704 MHz fiber laser produces required modulations to overlap ion bunches at 9 MHz frequency with laser pulse temporal profile shaping using crystal stacking.
- Accelerate such bunches with RF and use RF gymnastics (several RF cavities) to achieve energy spread required for cooling. Deliver and maintain beam quality in both cooling sections.
- Electron bunch overlaps only small portion of ion bunch. All amplitudes are being cooled as a result of synchrotron oscillations.

LEReC beam structure used in cooling section

Ions structure:

120 bunches

$f_{\text{rep}} = 120 \times 75.8347 \text{ kHz} = 9.1 \text{ MHz}$

$N_{\text{ion}} = 6e8$, $I_{\text{peak}} = 0.25 \text{ A}$

Rms length = 12 nsec

$N_{\text{ion}} = 6e8$

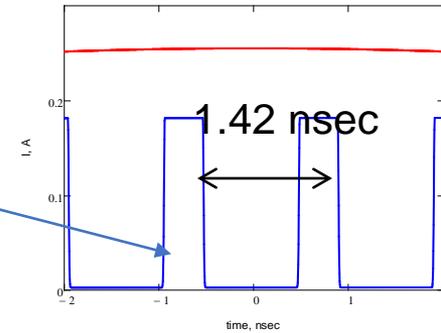
Electron bunches:

$f_{\text{SRF}} = 703.5 \text{ MHz}$

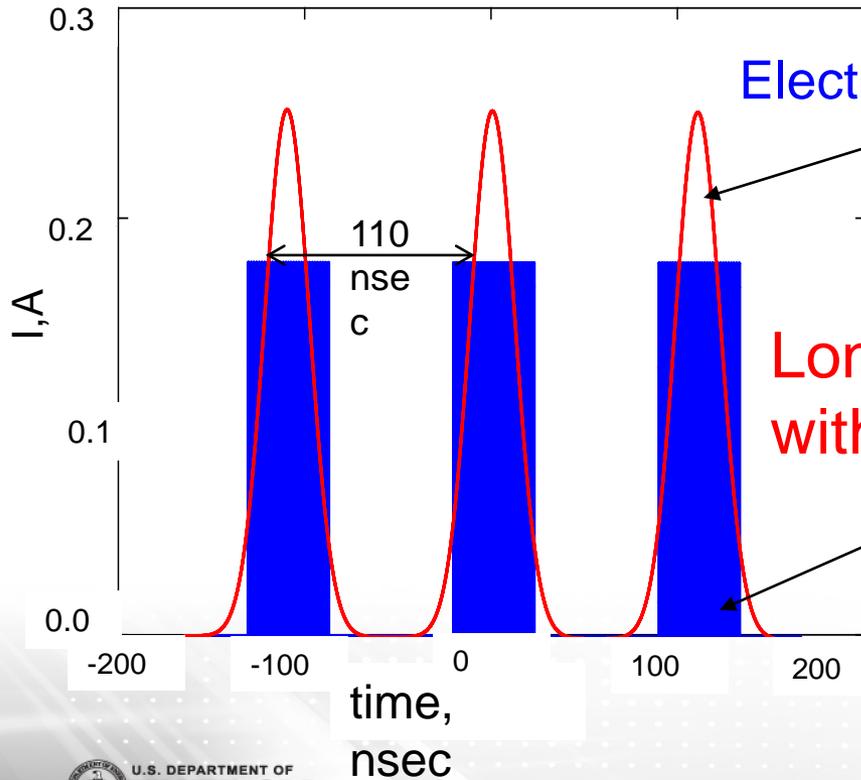
$Q_e = 75 \text{ pC}$, $I_{\text{peak}} = 0.18 \text{ A}$

FWHM = 400 psec

Electron Beam profile



9 MHz bunch structure

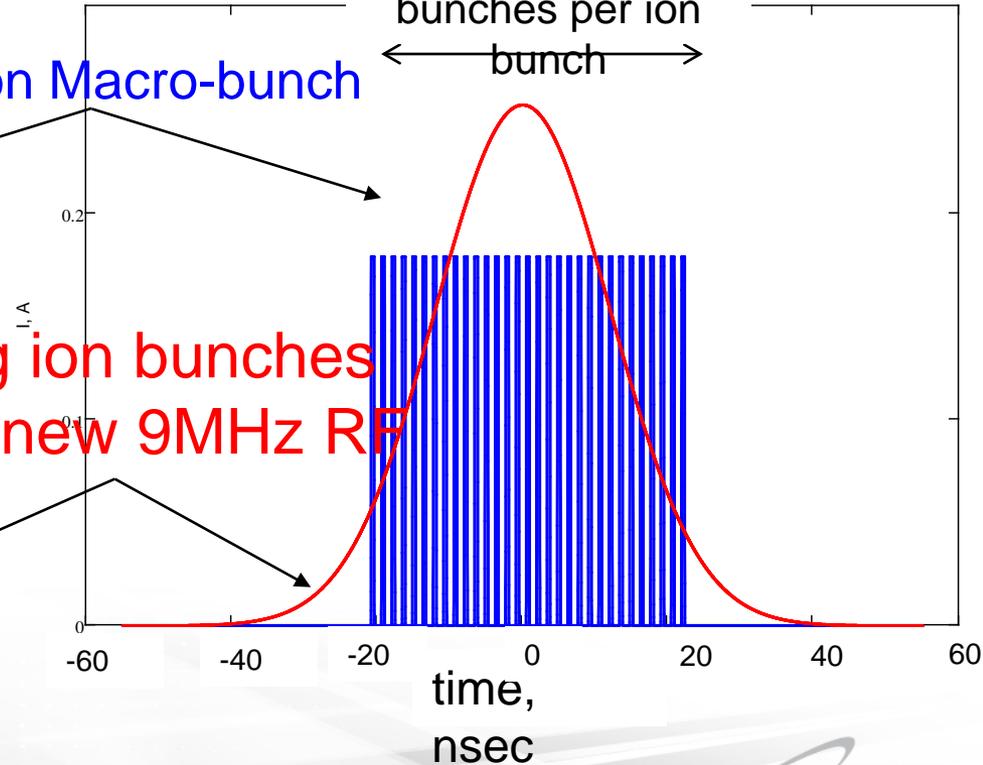


30 electron bunches per ion bunch

Electron Macro-bunch

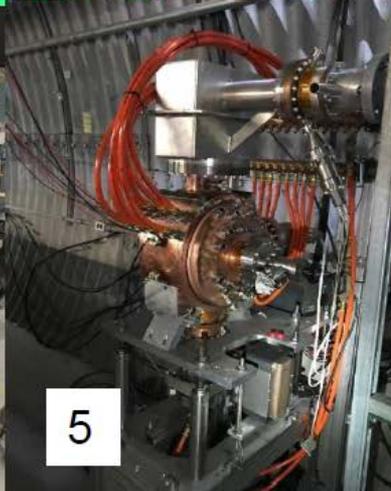
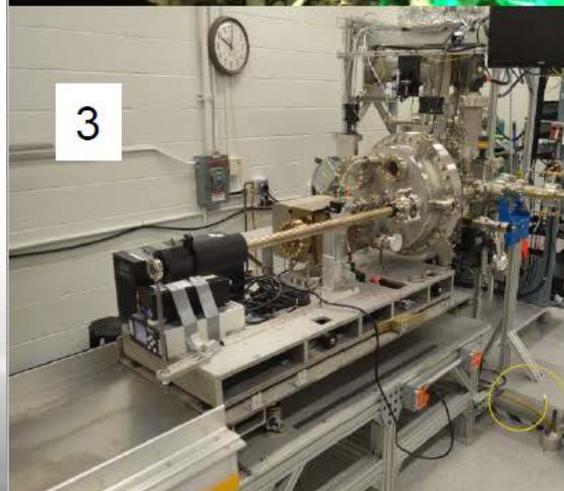
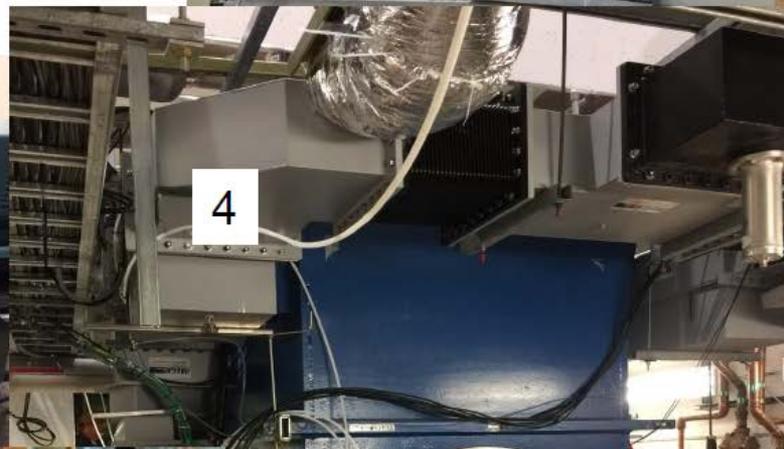
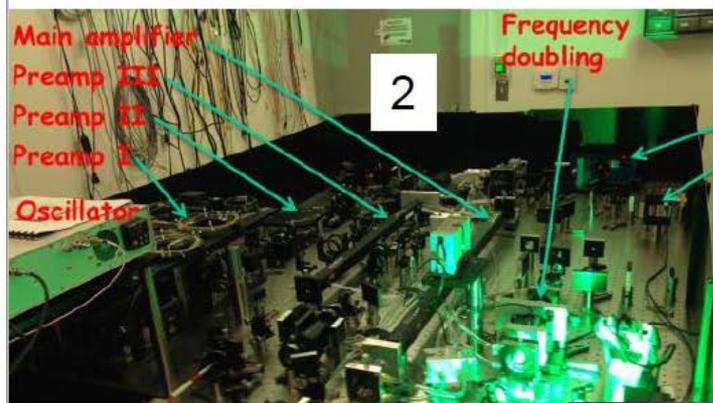
← bunch →

Long ion bunches with new 9MHz RF



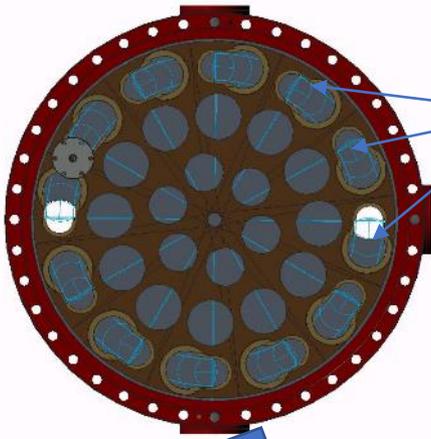
LEReC Critical Technical Systems

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

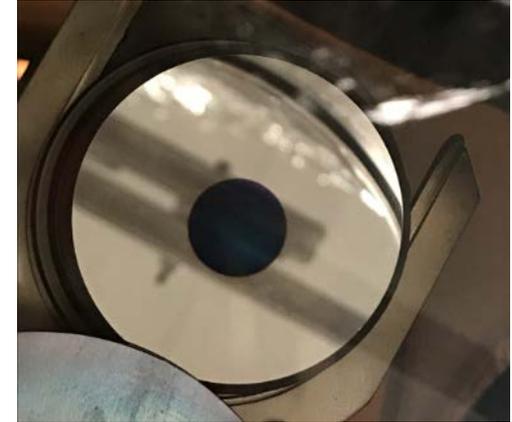


Photocathode production (in instrumentation building)

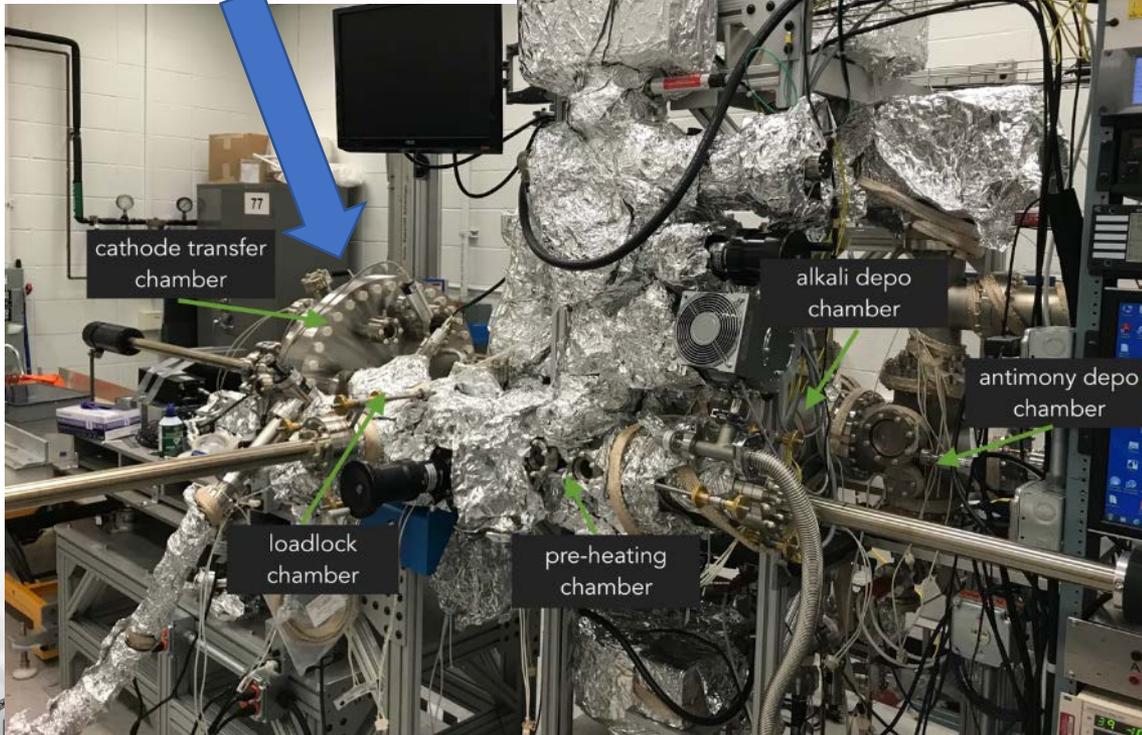
On center 12mm active area
Used 2017-18 commissioning



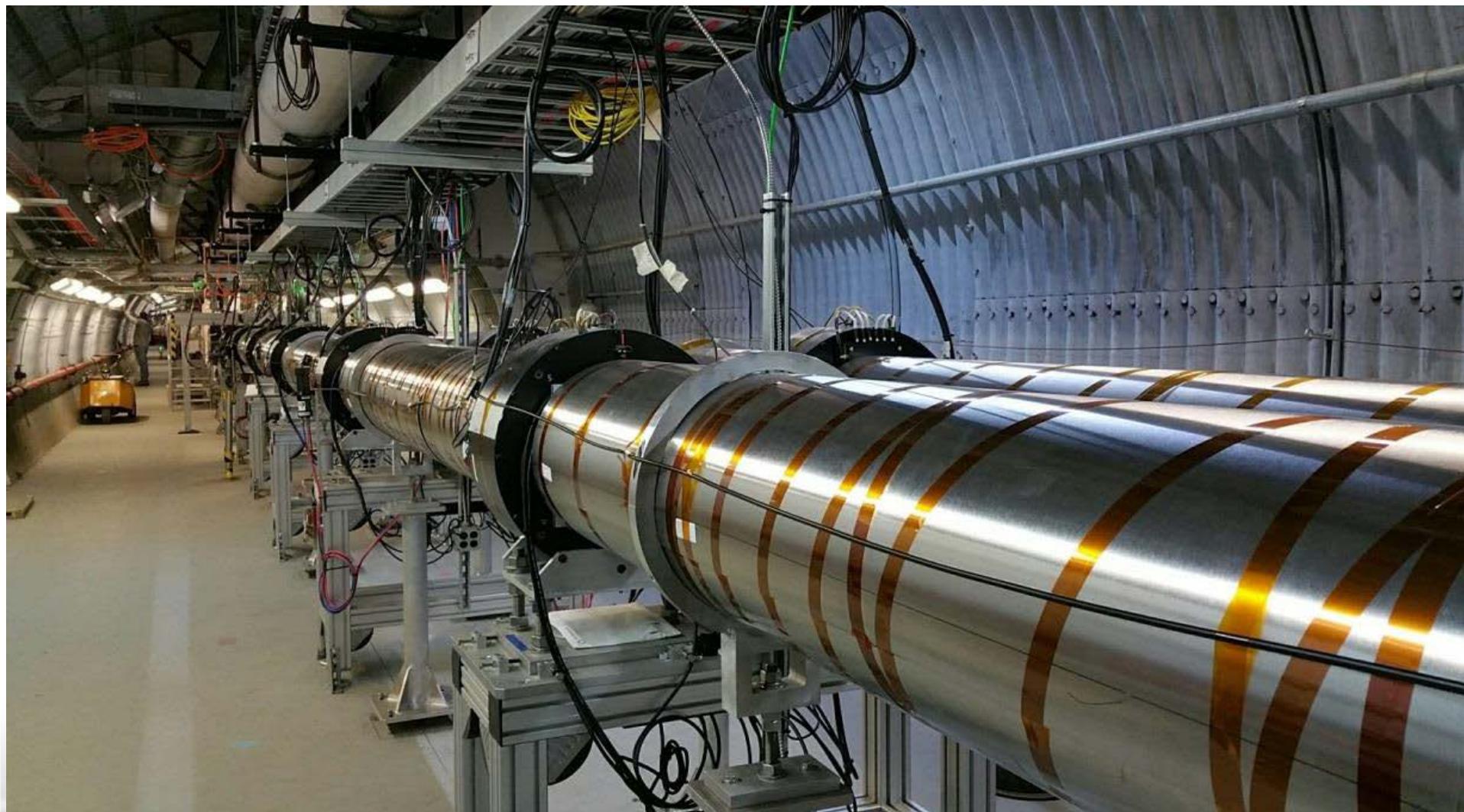
Cathode transfer camera
can hold up to 12 cathodes



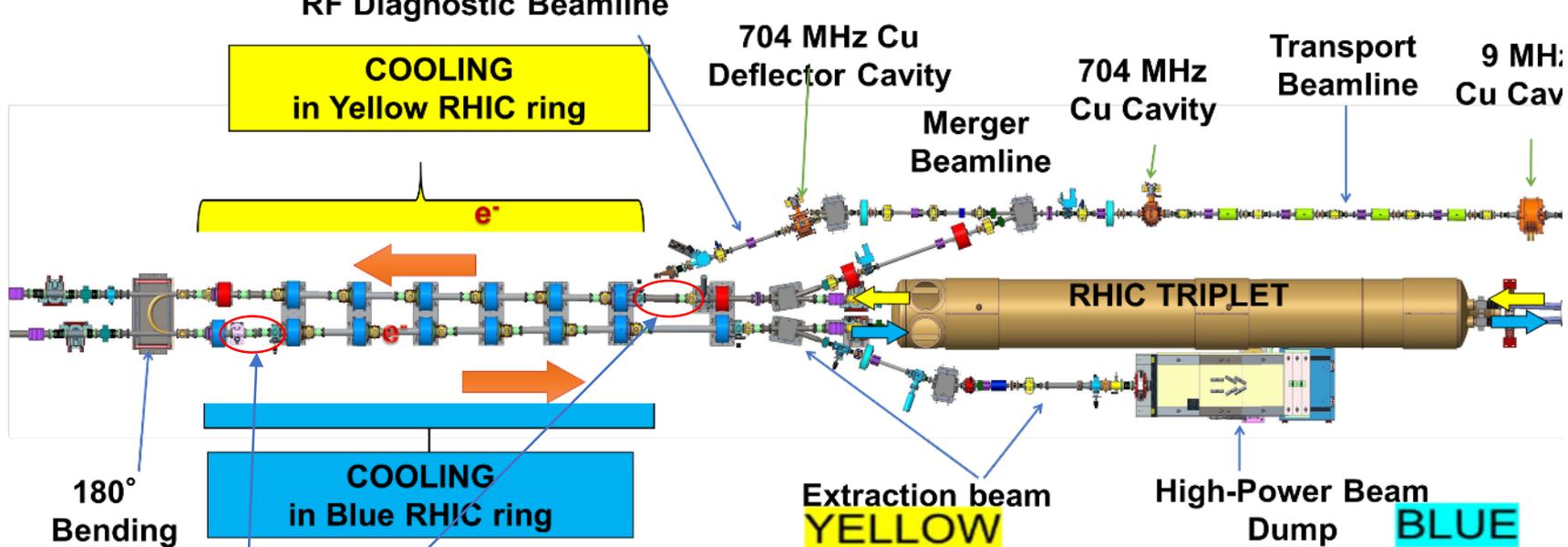
Off center 6mm active area
Used during 2019



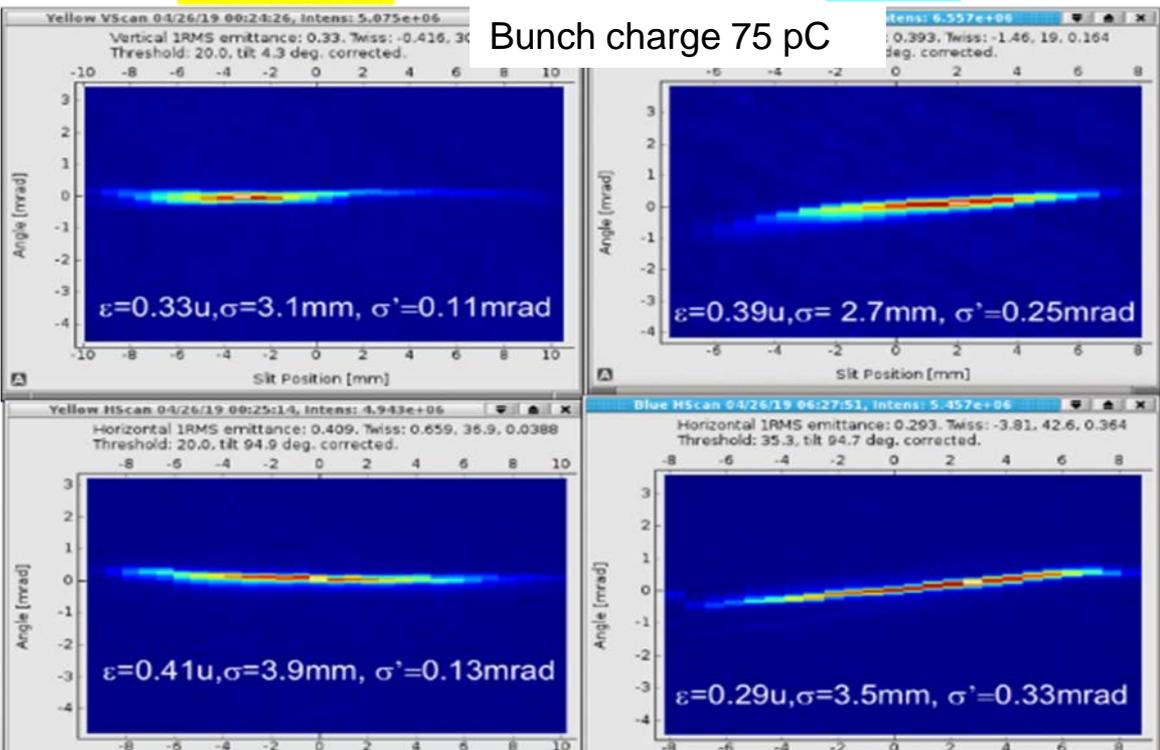
LEReC cooling section fully installed (2018)



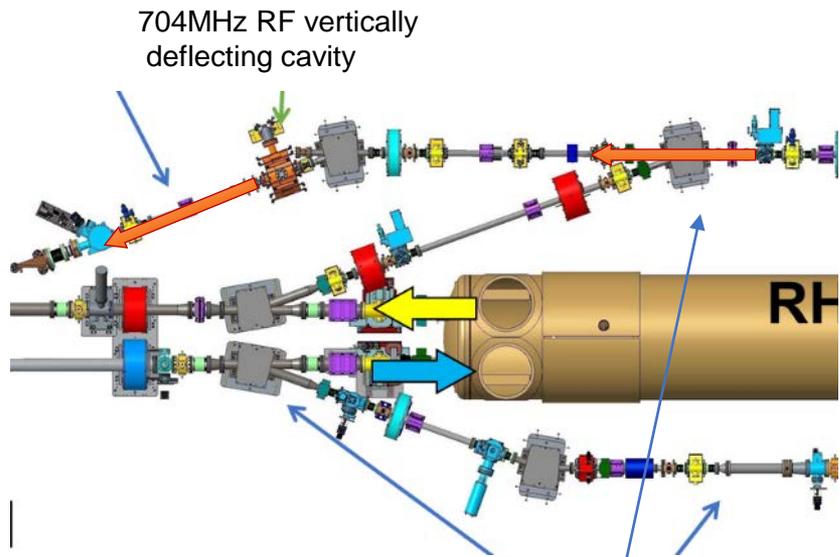
Transverse beam quality in cooling sections without ions



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

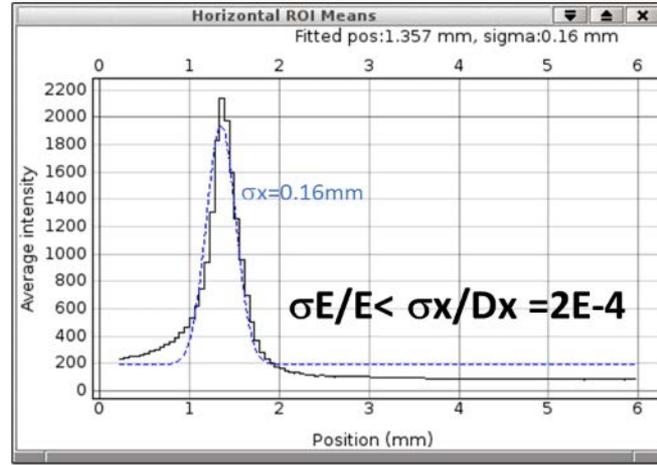
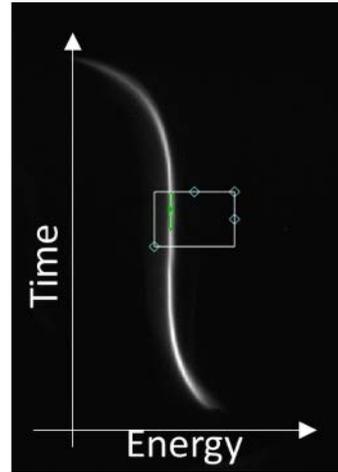


Longitudinal phase space measurement in RF diagnostic line

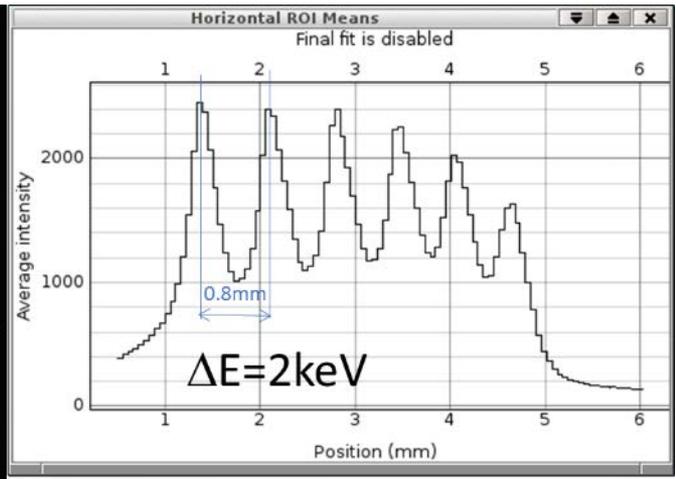
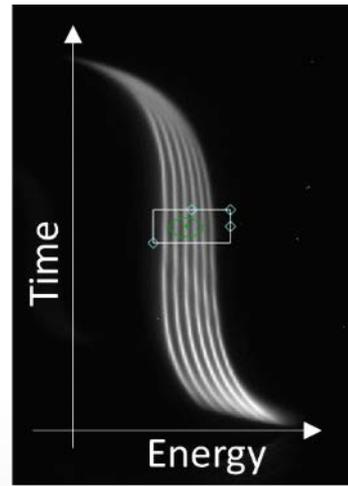


- First dogleg merger dipole is off
- Beam goes to RF diagnostic line
- 20 degree dipole produced dispersion
- Deflecting cavity produces time dependent vertical kick

1 macrobunch, 3 nC



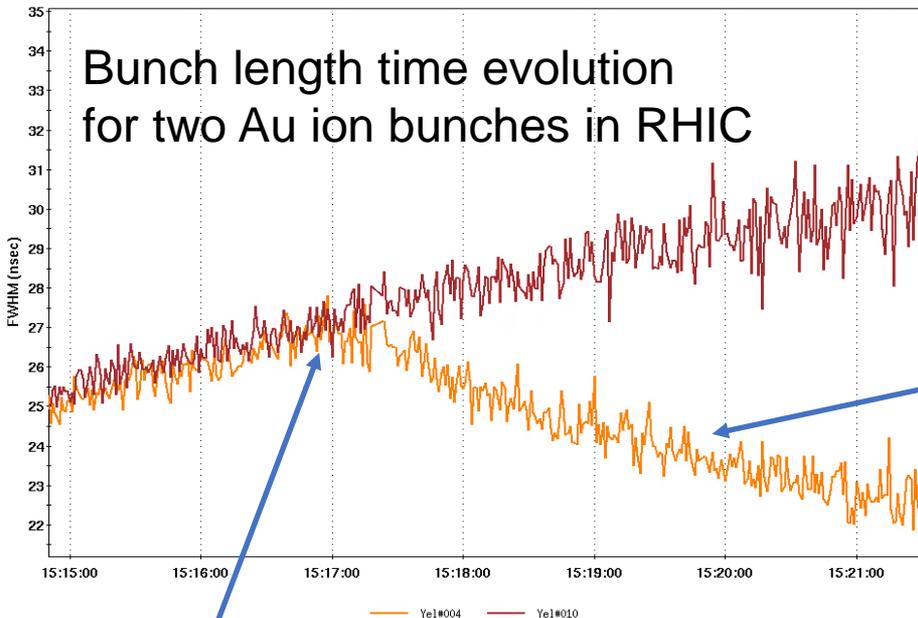
6 macrobunches, 3 nC each



In pulsed mode due to beam loading effect followed bunches have lower energy

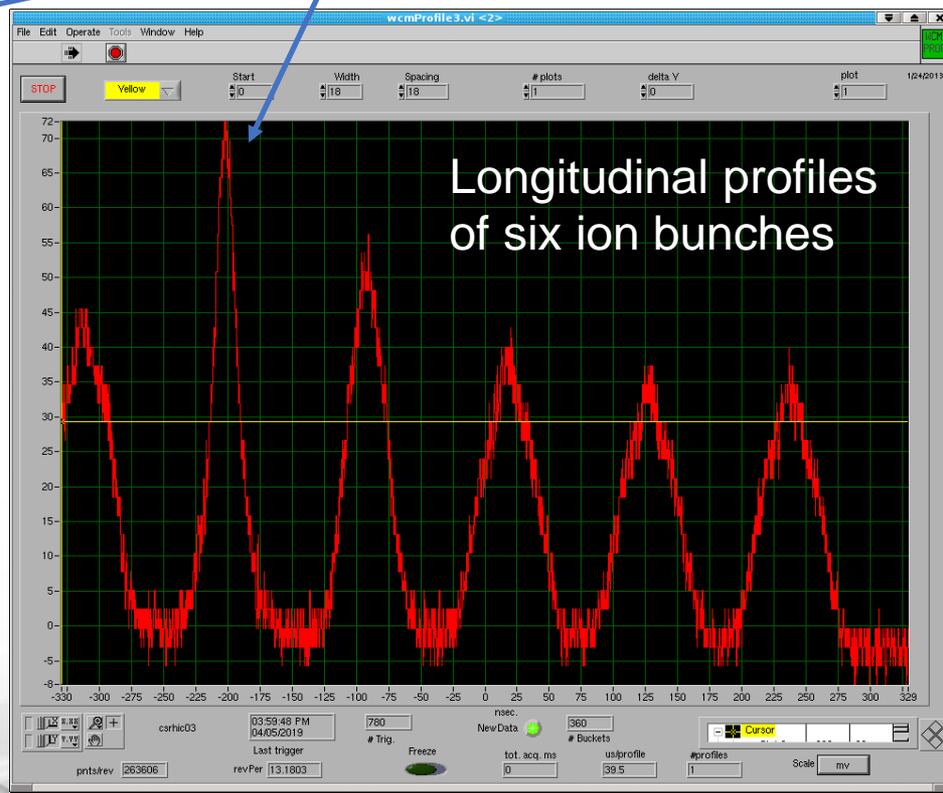
LEReC: First observation of electron cooling using bunched electron beam (April 5, 2019)

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



Longitudinal profiles of six ion bunches

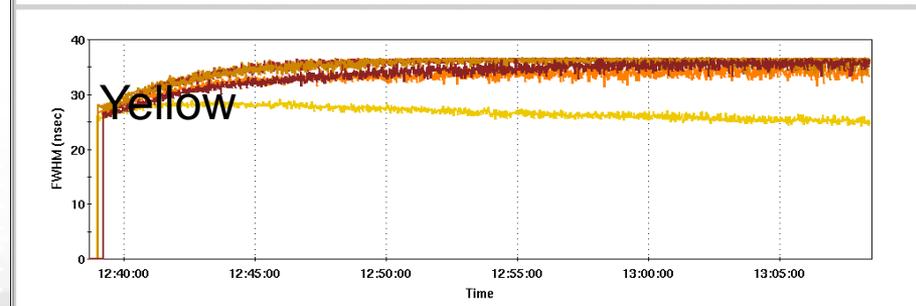
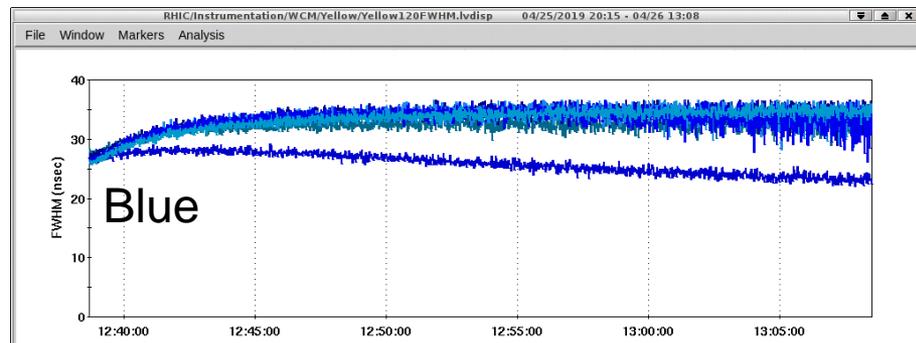
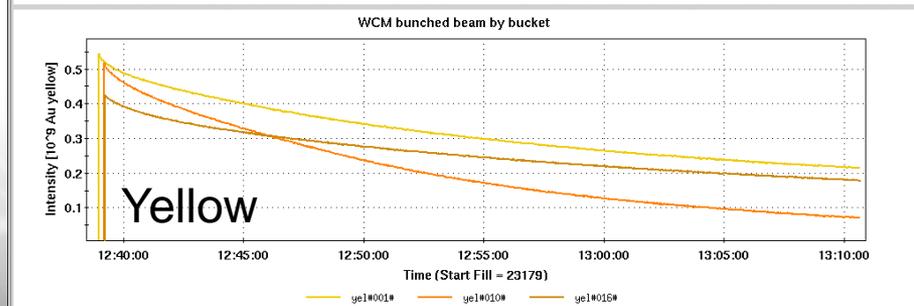
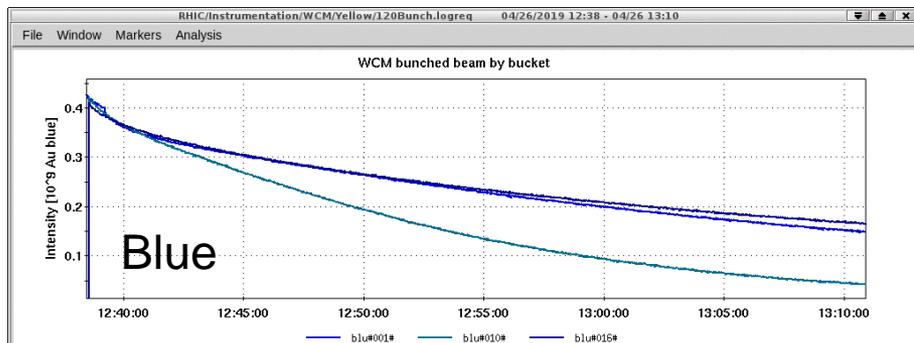
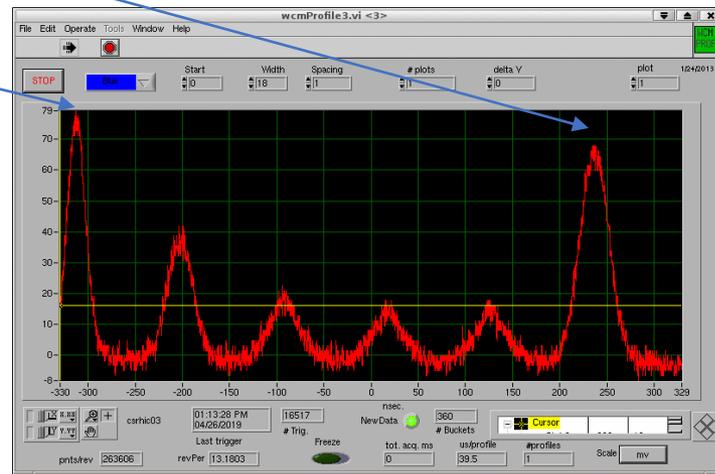
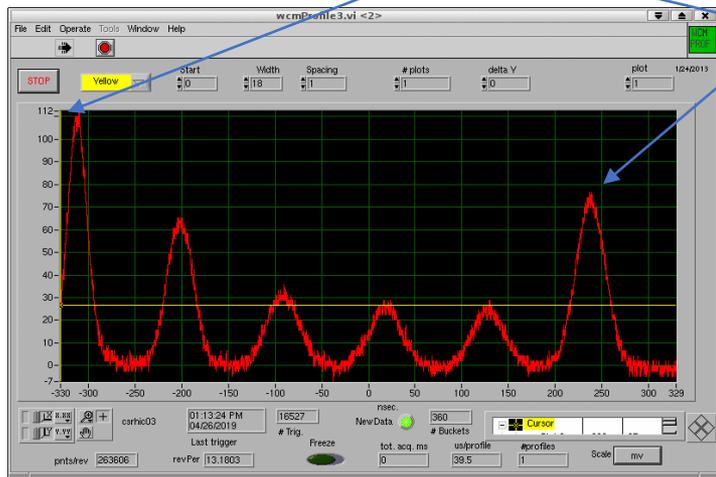
Energy of electrons and ions matched

Simultaneous cooling in both RHIC rings (Apr 26)

Yellow

Cooled, heated and non-interacting bunches

Blue

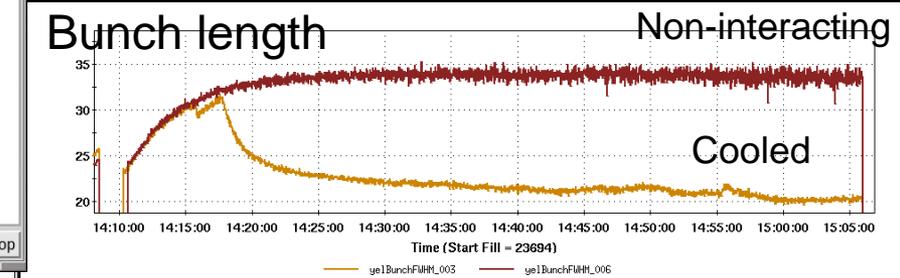
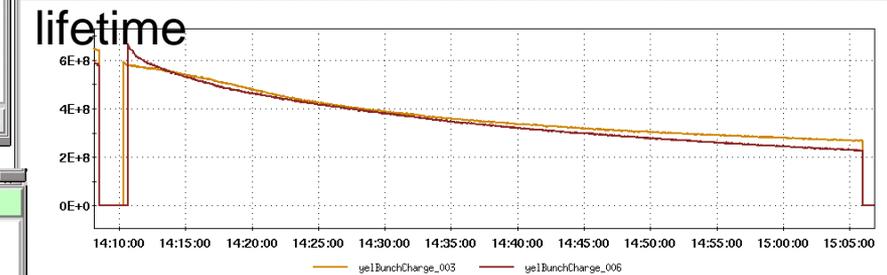
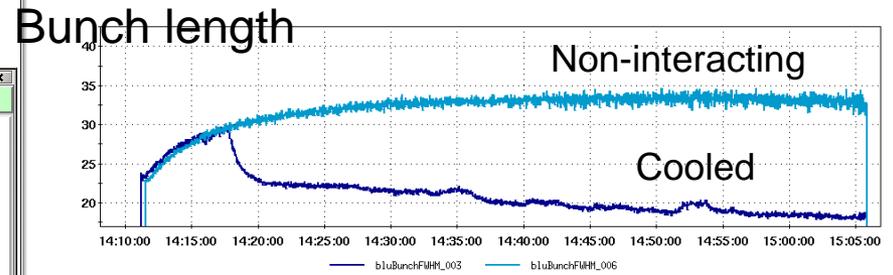
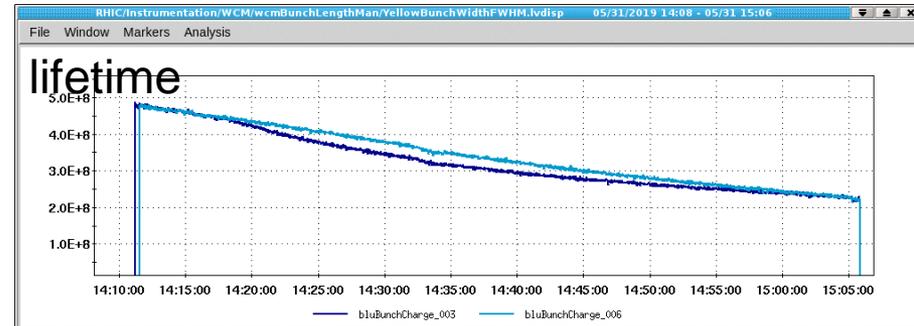
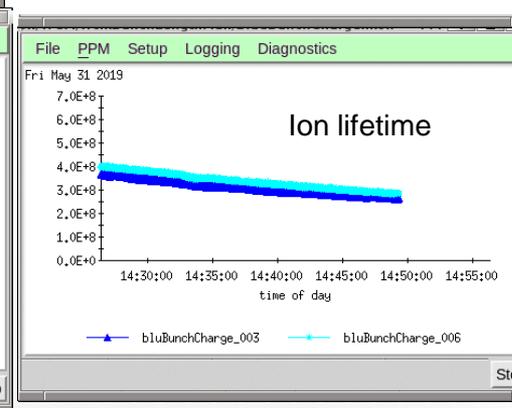
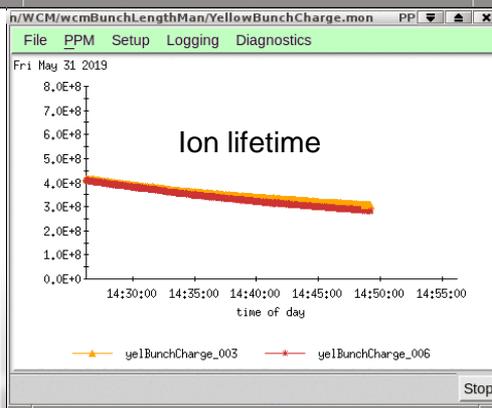
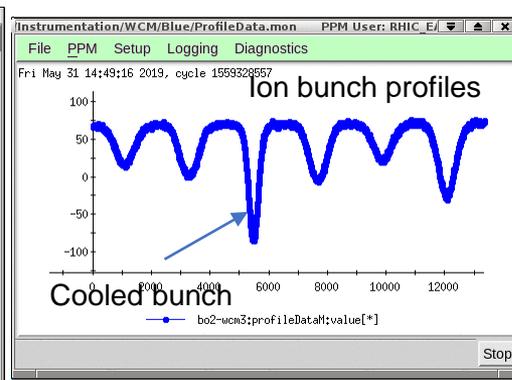
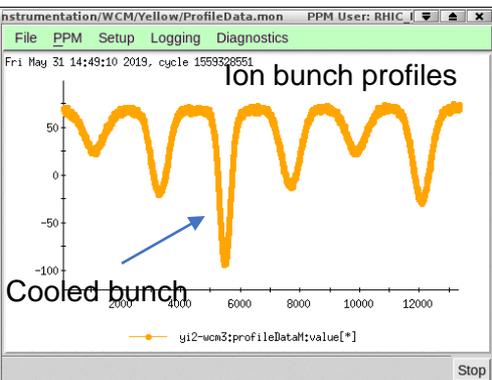


2484 new point(s) successfully added to dataset
Done updating plot 2.

Most recent result of cooling in Yellow and Blue (May 31)

In both rings:

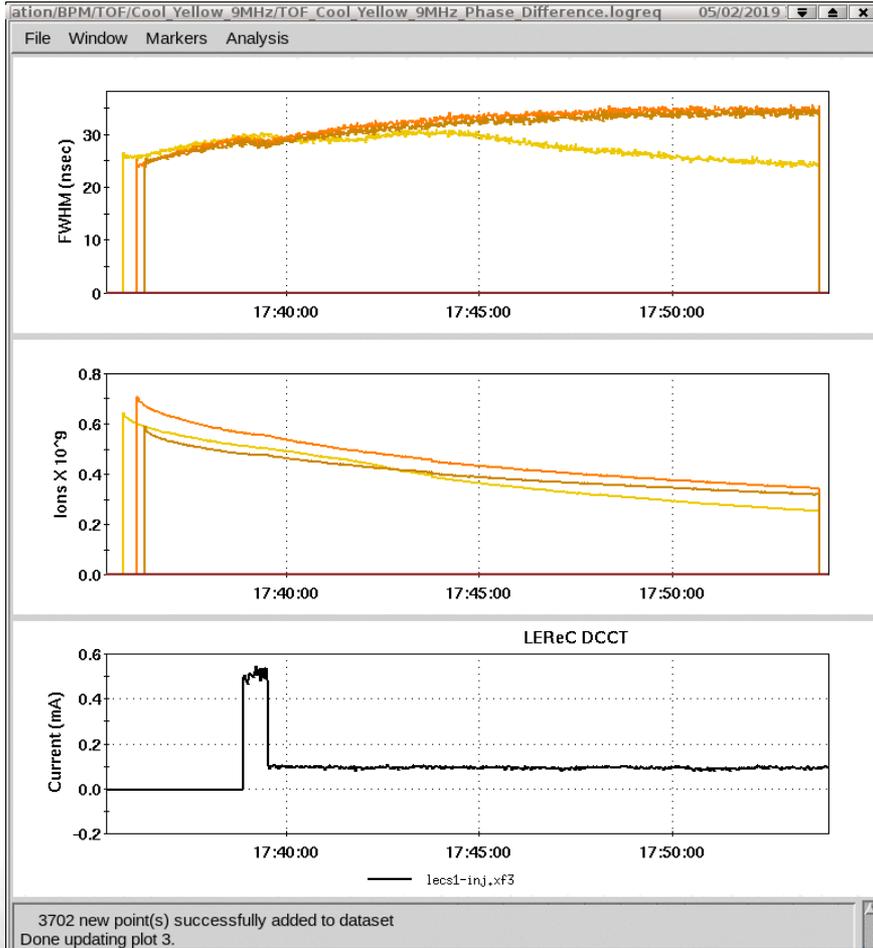
- Cooled and non-interacting has the same life time
- Cooled bunch is kept shorter
- Peak current significantly higher for cooled bunch



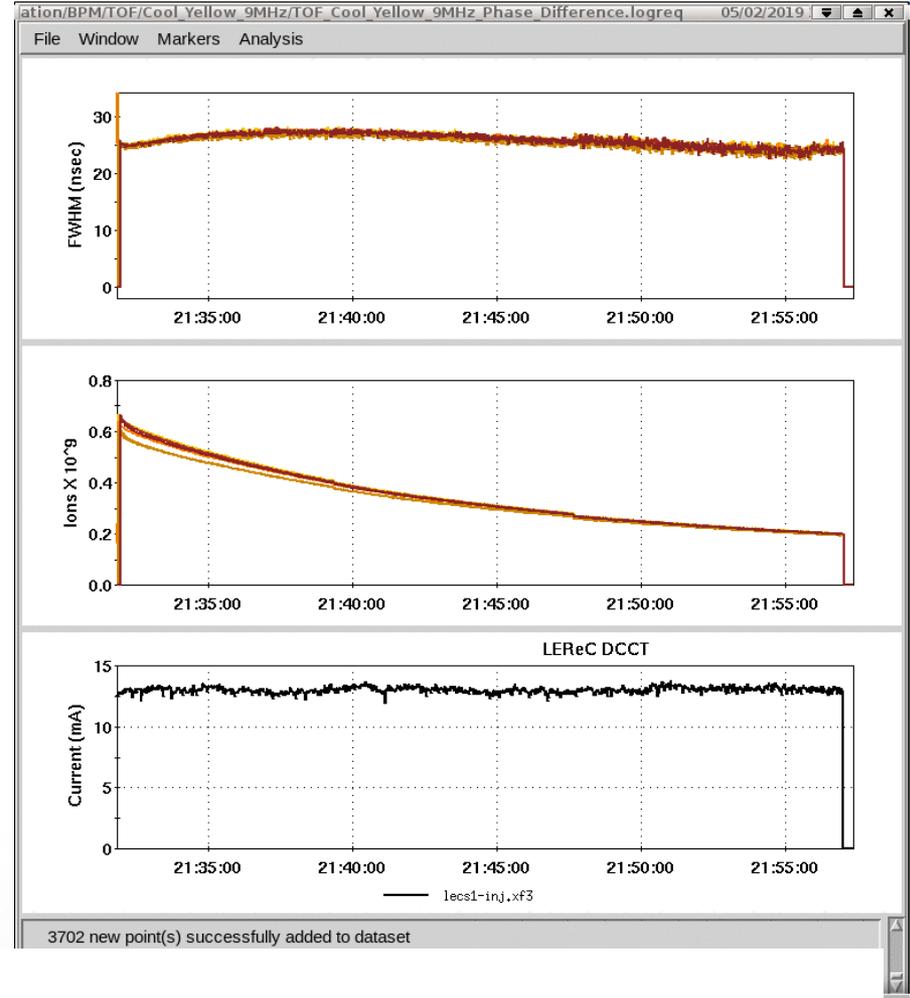
Could not extract dataset information for set 7. Continuing ...
Done updating plot 4.

First cooling (in Yellow) using high-current CW electron beam

76 kHz mode for e-beam.
Only single RHIC bunch is cooled.



9MHz CW (50pC/bunch, 13mA)
All 6 RHIC bunches are cooled.

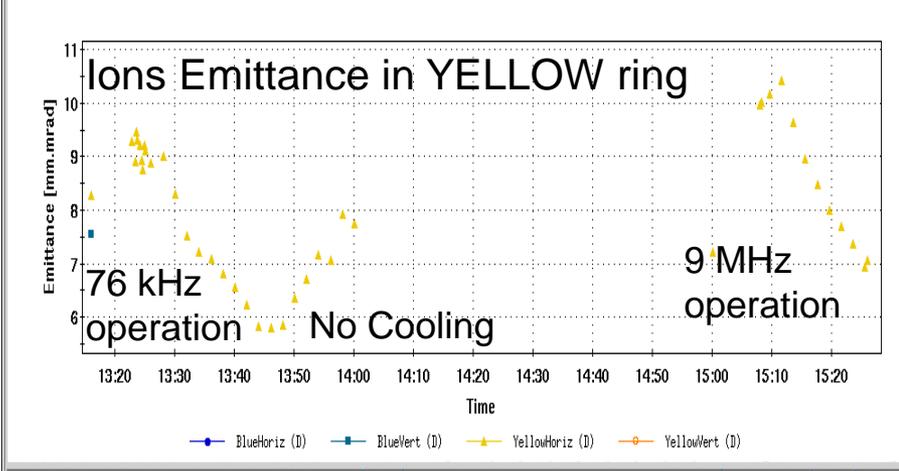
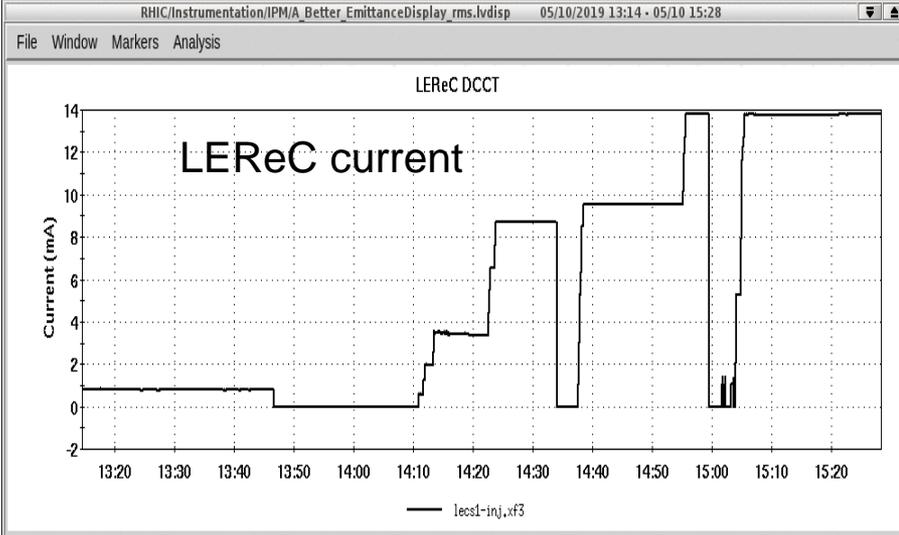
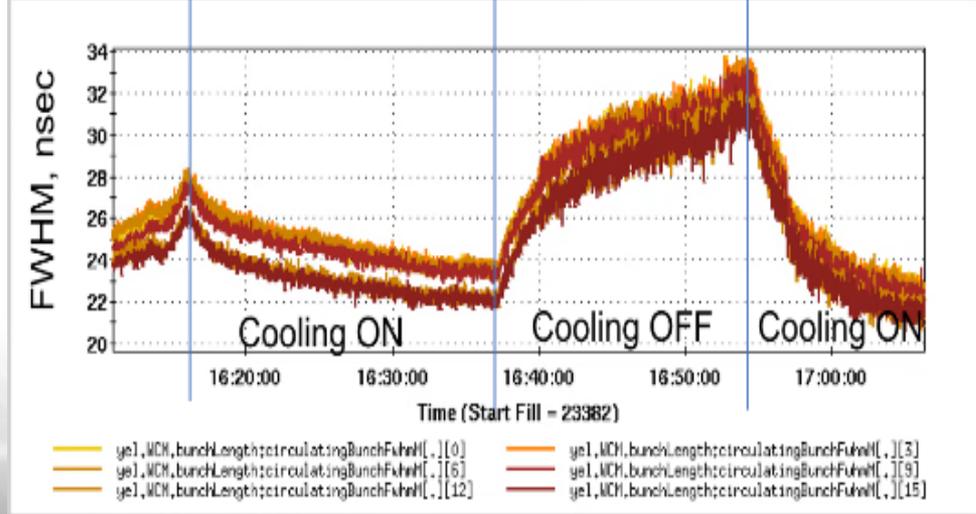
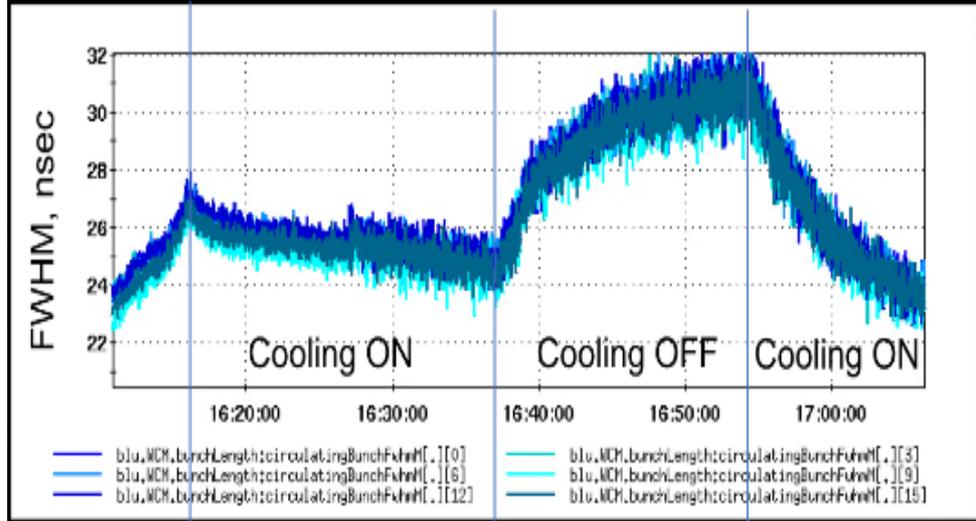


76KHz (left) - single ion bunch being cooled

9MHz CW (right) operation - **all 6 RHIC bunches are cooled**

CW operation at 14 mA and simultaneous cooling in Yellow and Blue RHIC rings, 6 bunches in each

Ion bunch length changes with and without cooling in both RHIC rings



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

LEReC timeline

- May 2015:** LEReC project approved by DOE for construction
- December 2016:** DC gun successfully conditioned in RHIC IR2
- February 2017:** Gun Test beamline installed in RHIC
- April-Aug., 2017:** First 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
- Sept 2018 :** All project Key Performance Parameters achieved
- Oct.-Dec., 2018:** Scheduled upgrades and modifications (NO beam testing)
- December, 2018:** Gun Conditioning and HVPS tests without e-beam
- Jan.-Feb., 2019:** Restart operation with electron beam. Achieved e-beam quality suitable for cooling
- March 2019:** Start commissioning with Au ion beams.
Matched RHIC/LEReC beams energies and trajectories in cooling sections
- Apr 2019:** First cooling in one ring then in both RHIC rings using 76 kHz bunch
- May 2019:** Cooling of 6 bunches in both RHIC rings using 9MHz CW LEReC
- June 2019:** Cooling optimization, studies effect to RHIC collision rate,
Commissioning LEReC at higher energies

Summary

- LEReC is the first electron cooler based on the RF acceleration of electron beam.
- We designed, built and commissioned state of the art electron accelerator which provides beam quality suitable for electron cooling using bunched electron beams.
- First electron cooling using bunched electron beams based on the RF acceleration was demonstrated.
- Ion bunches in both RHIC rings have been cooled simultaneously using the same LEReC beam.
- 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.
- With a bunched beam electron cooling technique now experimentally demonstrated, its application to high-energy cooling can open new possibilities by producing high-quality hadron beams.

Acknowledgement

LEReC success would not be possible without team effort 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!



LEReC team