Low Energy RHIC electron Cooling (LEReC):

Status and Commissioning Results

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on behalf of the LEReC team

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BROOKHAVEN NATIONAL LABORATORY

U.S. DEPARTMENT OF ENERGY

LEReC Project Goals

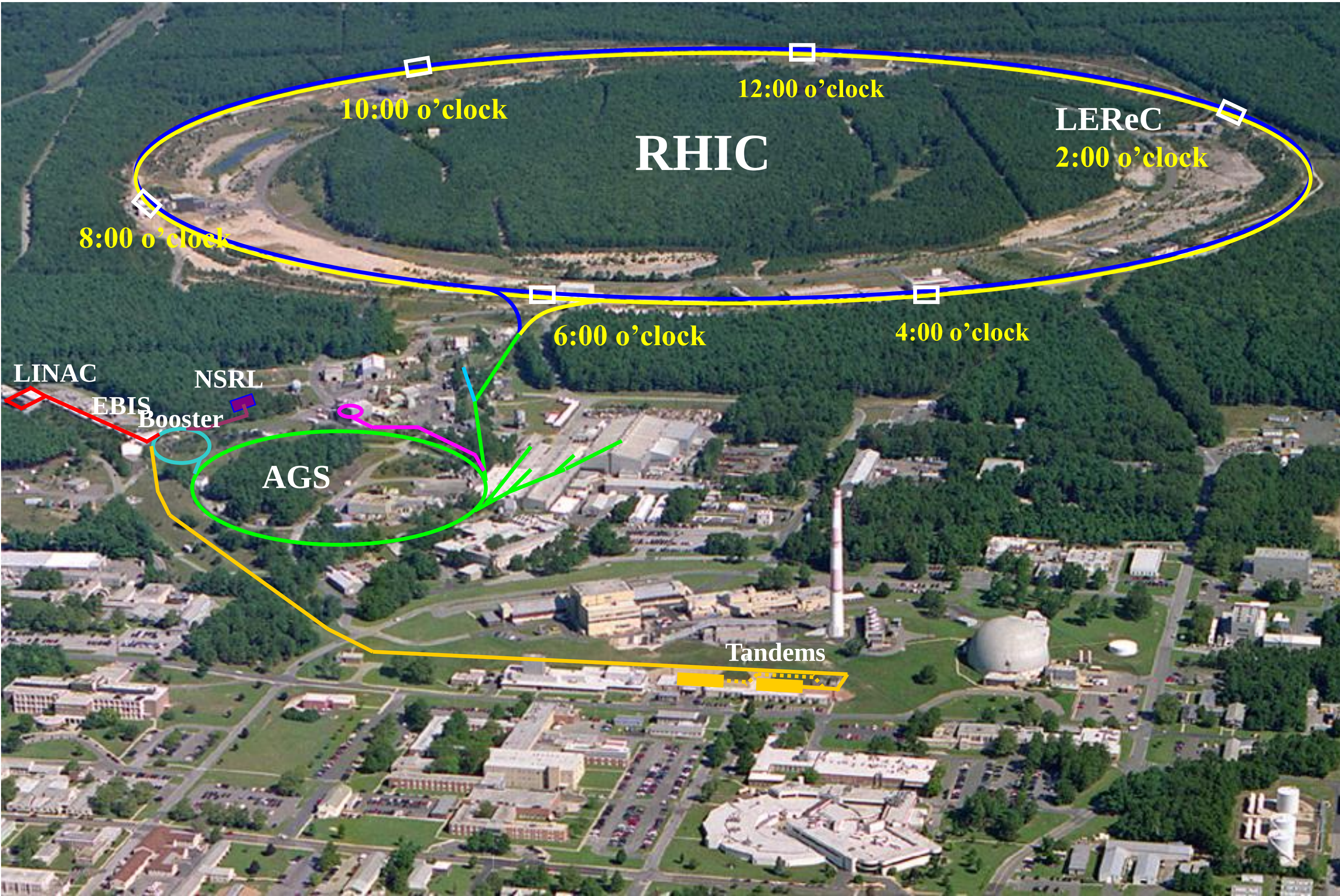
The goal of the LEReC project is to provide luminosity improvement for RHIC operation at low energies to search for the QCD critical point (Beam Energy Scan Phase-II physics program).

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

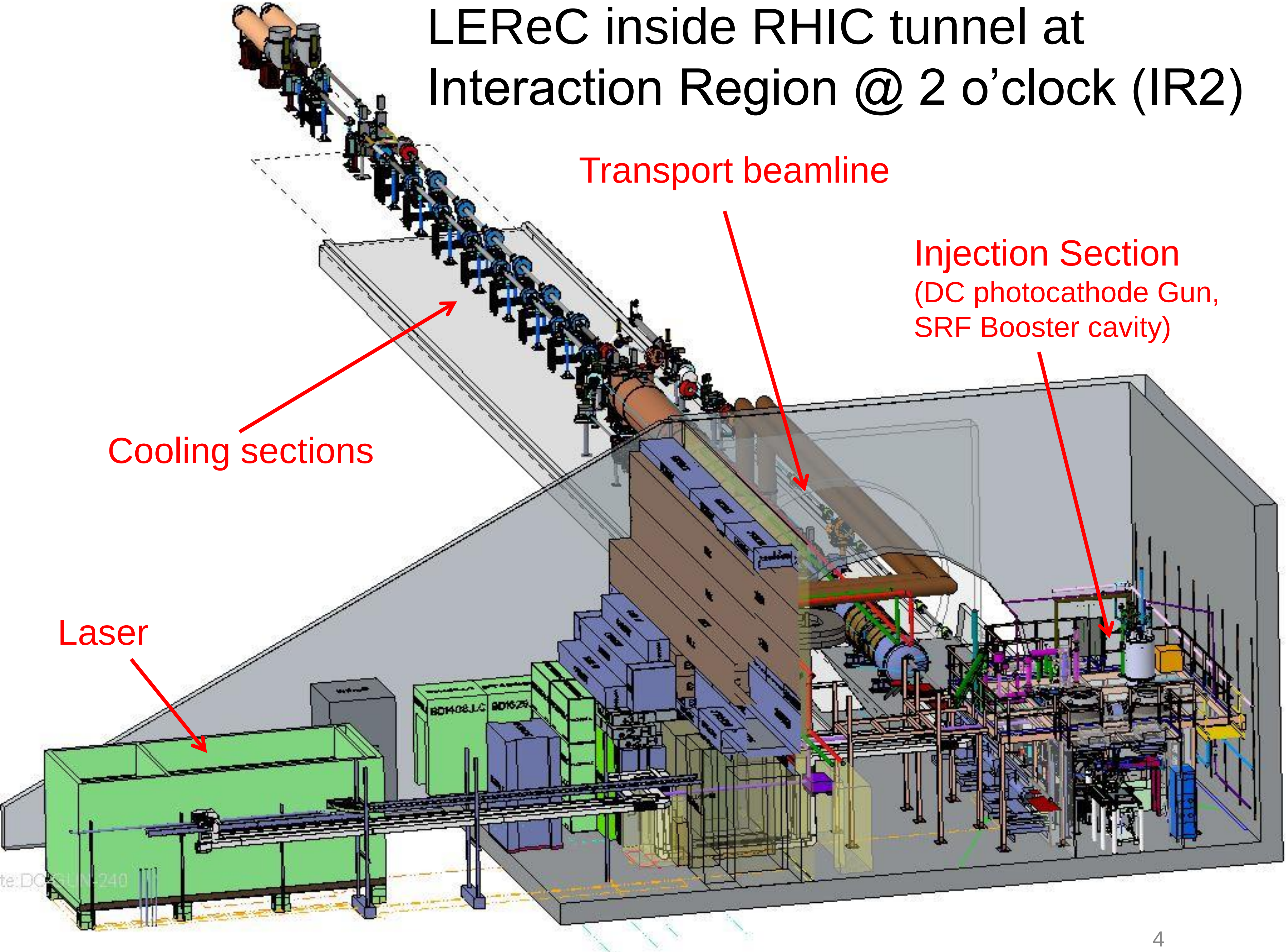
To provide luminosity improvement with such approach requires:

- **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

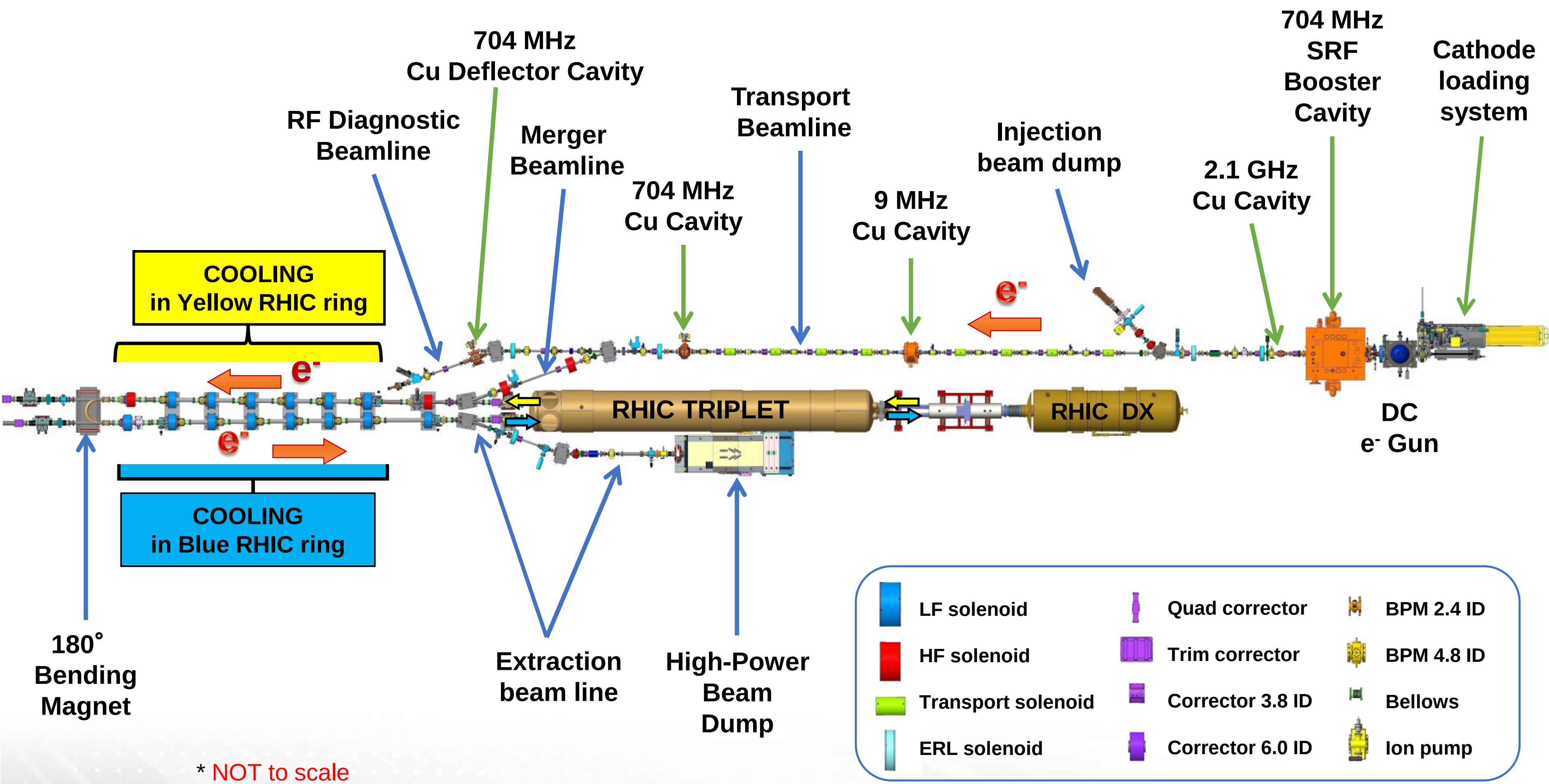


LEReC inside RHIC tunnel at Interaction Region @ 2 o'clock (IR2)



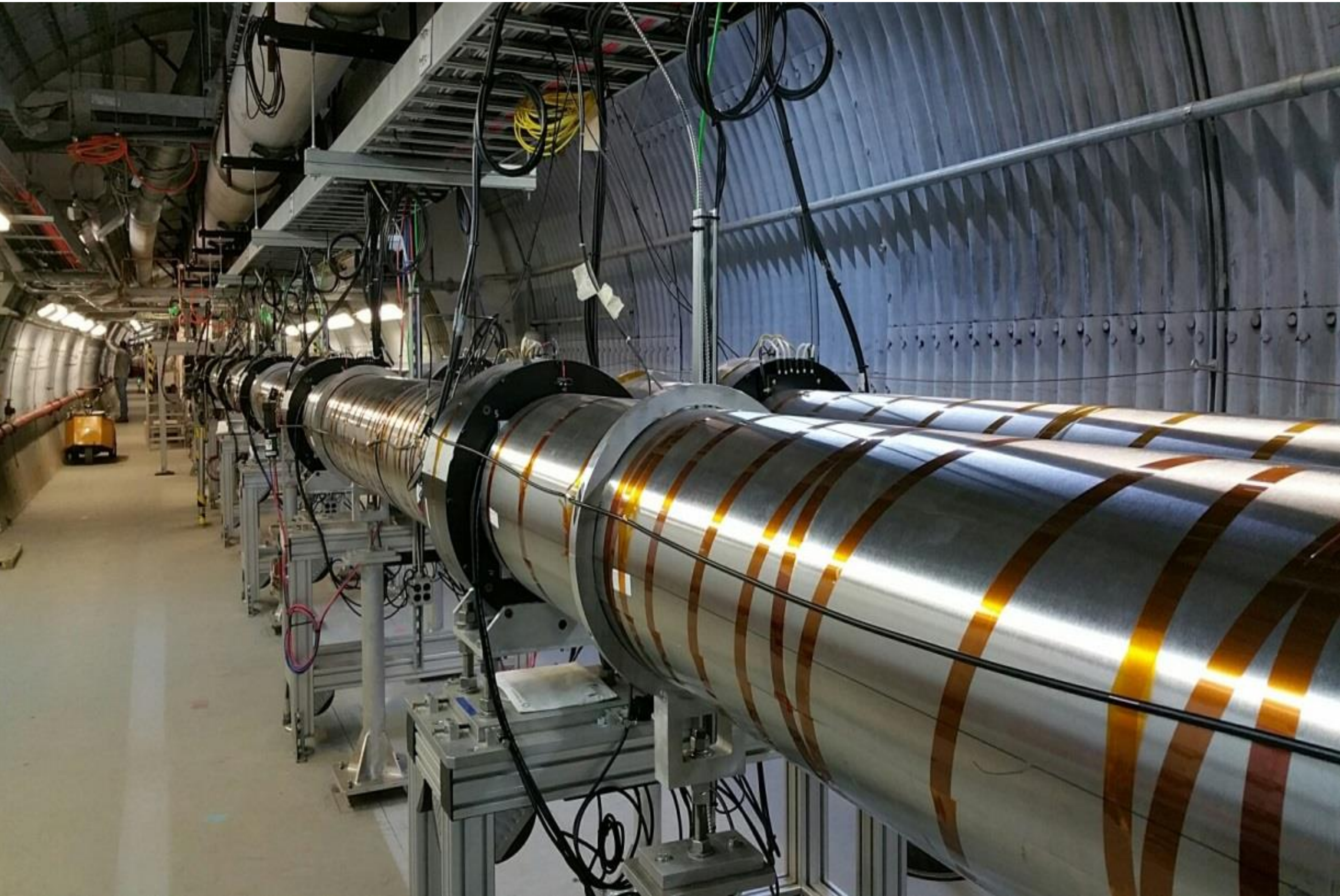
LEReC Accelerator

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



* NOT to scale

LEReC cooling sections fully installed (2018)



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

*CW mode at 704 MHz without macrobunches is also being considered (with even higher average current up to 85 mA)

Bunched beam electron cooling for LEReC

- Produce electron bunches suitable for cooling by illuminating a multi-alkali (CsK_2Sb or NaK_2Sb) 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 will produce required modulations to overlap ion bunches at 9MHz frequency with laser pulse temporal profile shaping using crystal stacking.

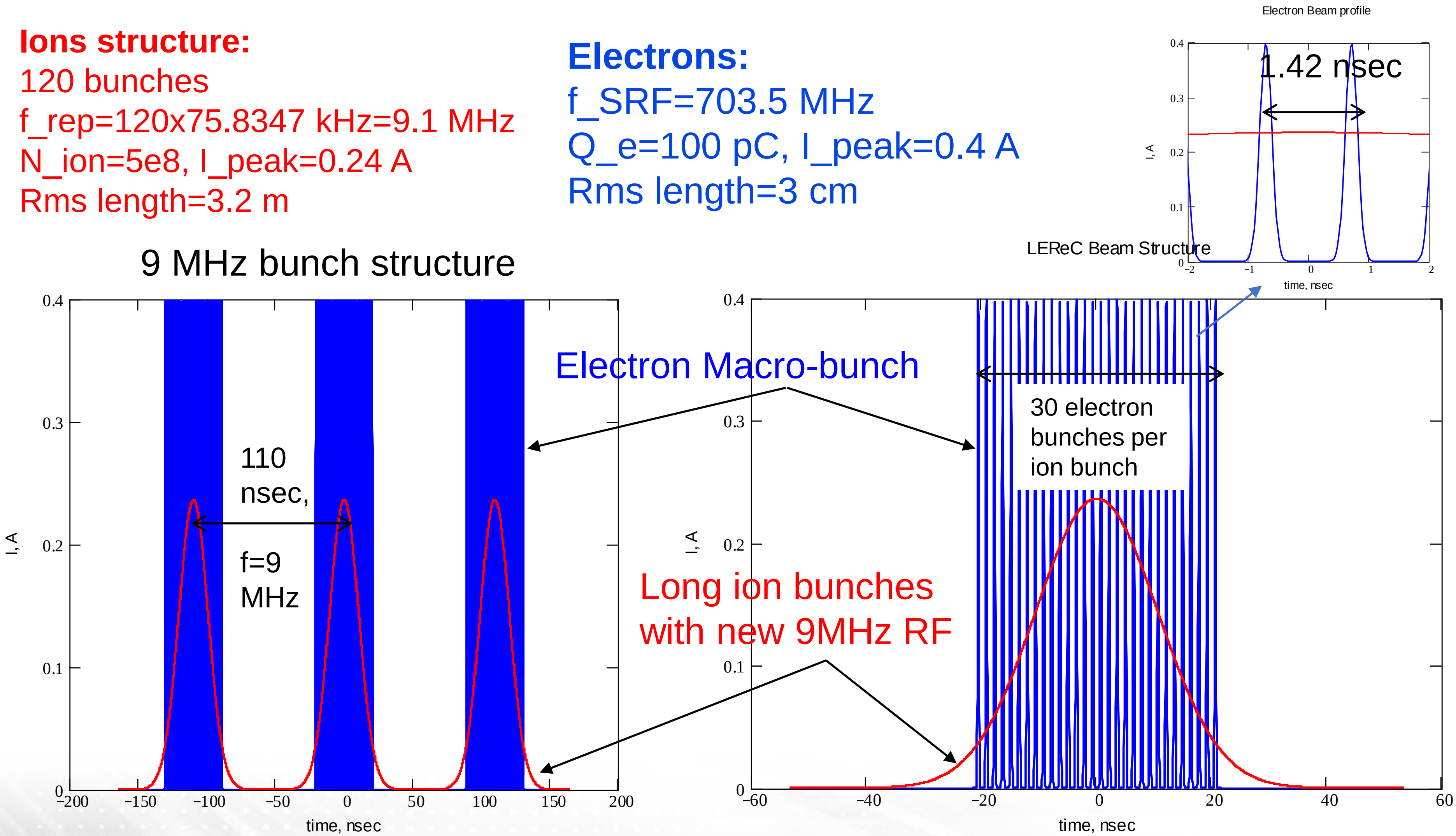
- Accelerate such bunches with RF and use RF gymnastics (several RF cavities) to achieve energy spread required for cooling. Deliver and maintain beam quality in both cooling sections.

- Electron bunch overlaps only small portion of ion bunch. All amplitudes are being cooled as a result of synchrotron oscillations.

LEReC beam structure 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.

Production of electron beam suitable for cooling

- LEReC is based on the State of the Art physics and technology:

- Photocathodes: production and delivery system to support 24/7 operation at high current
- High power fiber laser and transport
- Laser beam shaping
- Operation of DC gun at high voltages (around 400kV) with high charge and high average current
- RF gymnastics and stability control
- Energy stability and control
- Instrumentation and controls

Commissioning with e-beam

- **Phase 1**: DC Gun tests (no RF acceleration)

  (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 Key Performance Parameters. 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.

- **Phase 4** (2019-2020): Commissioning of cooling – requires Au ions at the same energy.

Commissioning challenges

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

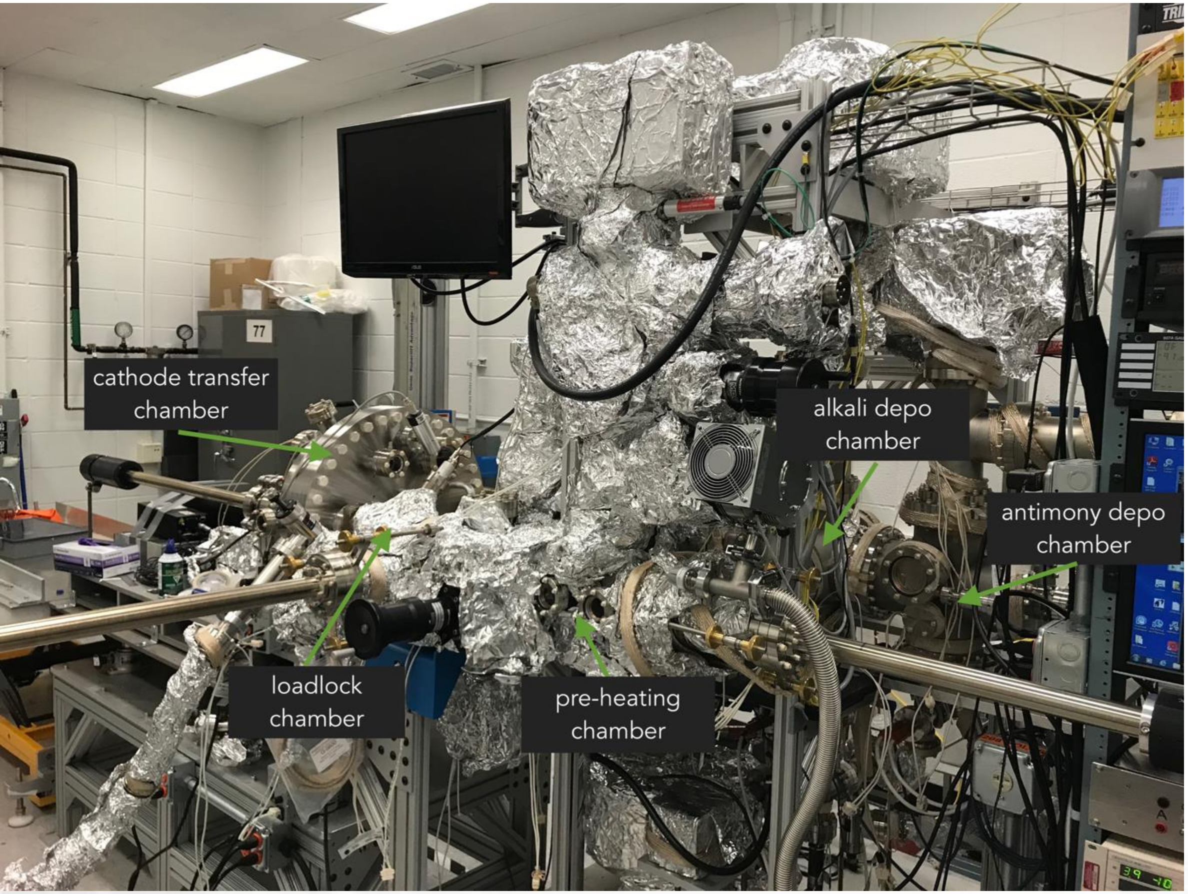
- Stability of DC Gun HVPS
- Gun trips at high current
- Gun performance after the trips which required re-conditioning
- Laser power and stability
- RF reliability
- Effect of RF noise on instrumentation electronics (BPMs, FCTs)
- Electronics survival in radiation environment inside RHIC tunnel
- HP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

As a result of commissioning, many items were identified which require fixes, upgrades and improvements. Presently, they are being addressed during ongoing shutdown period.

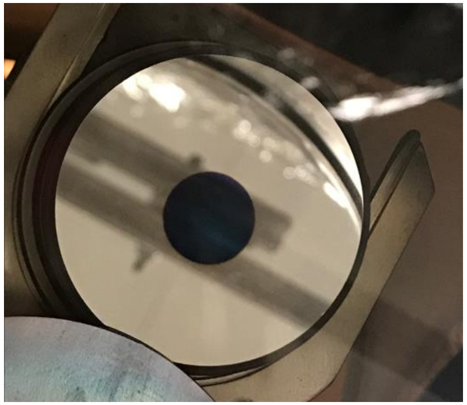
Commissioning highlights

- All major commissioning goals were achieved.
- Various LEReC accelerator systems were fully commissioned including RF, instrumentation, controls, etc.
- All project Key Performance Parameters were successfully achieved.
- Cathode with initial QE around 5% were routinely delivered inside the Gun.
- Established operation both with large active cathode area on centre and small active area off centre.
- Performed many runs at high-currents of 20-30mA in injection section for cathode QE lifetime measurements and Gun stability studies. Measured QE lifetime was quite long. At 25 mA measured QE lifetime was 142 hours, for example.
- Established stable high-current operation of 20mA CW at 1.6MeV all the way to final high power beam dump.
- Measured energy spread in RF diagnostics beam line and in cooling sections are within specs for cooling commissioning.
- Measured emittance values for various bunch charges in cooling sections are within specs for cooling commissioning.
- Commissioned laser intensity feedback. Achieved ~ 0.6% rms laser intensity stability (measured with fast photodiode) and ~ 1% rms electron beam current stability (measured with fast current transformer) with both laser and beam intensity feedback loops.

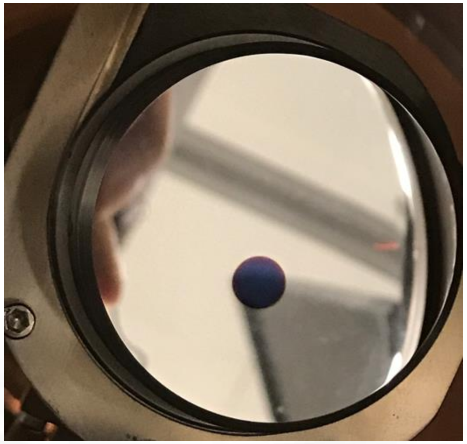
Photocathode production



On center 12mm active area

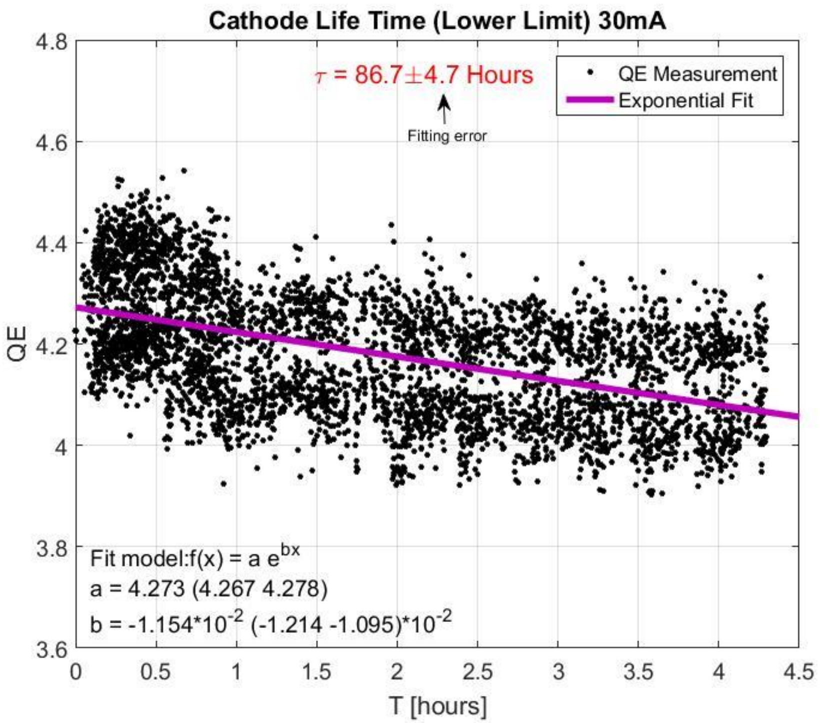


Off center 6mm active area

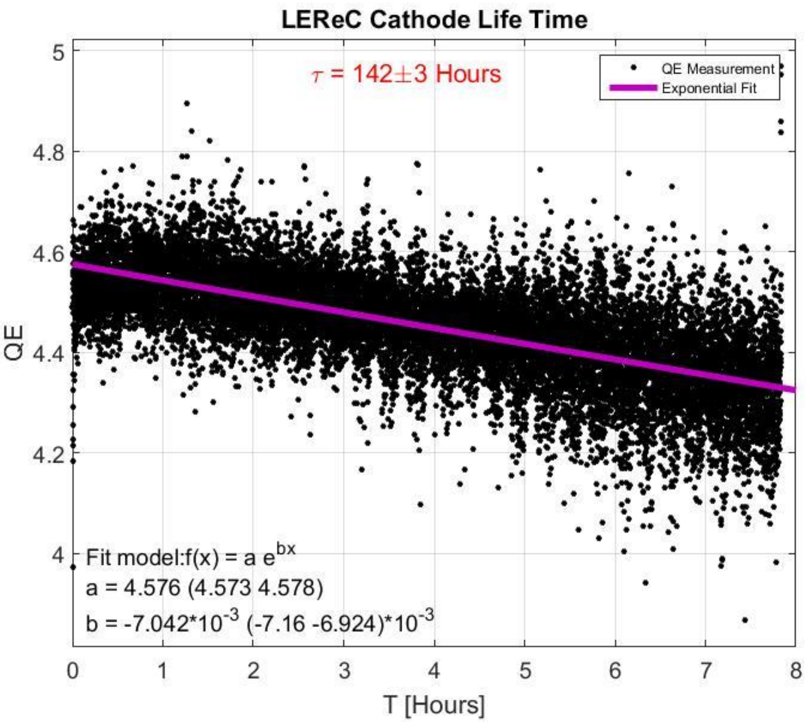


Cathode QE lifetime during high current operation

30 mA beam current, τ = 87 h, QE > 4%

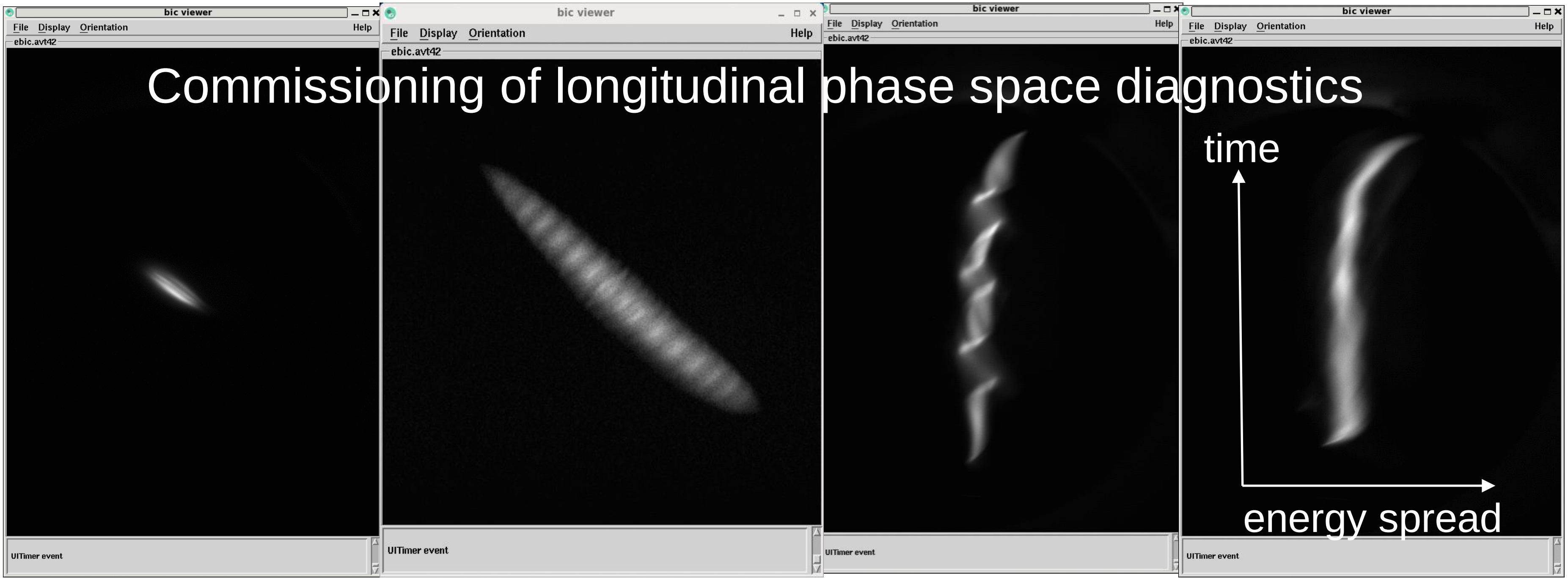


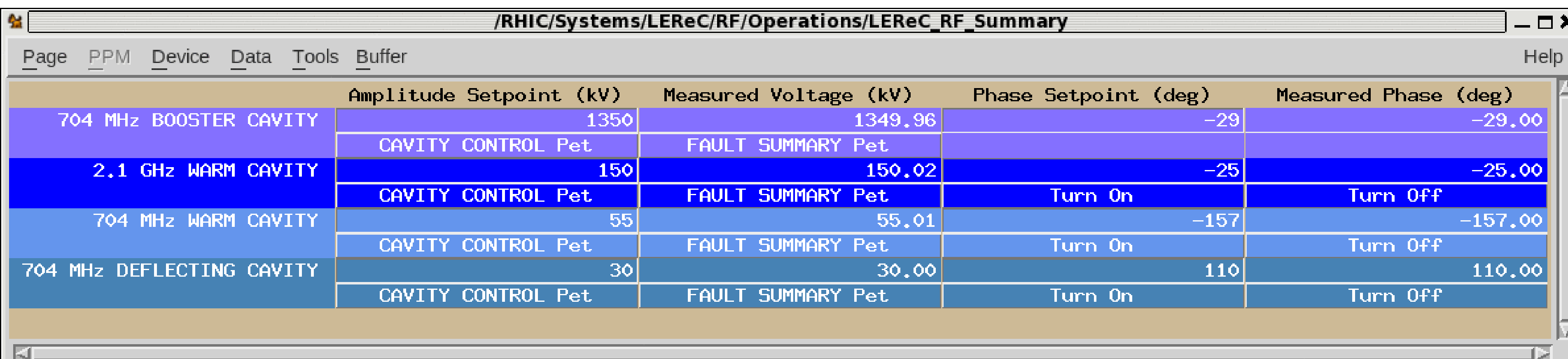
25 mA beam current, τ = 142 h, QE > 4%



Longitudinal phase space RF gymnastics

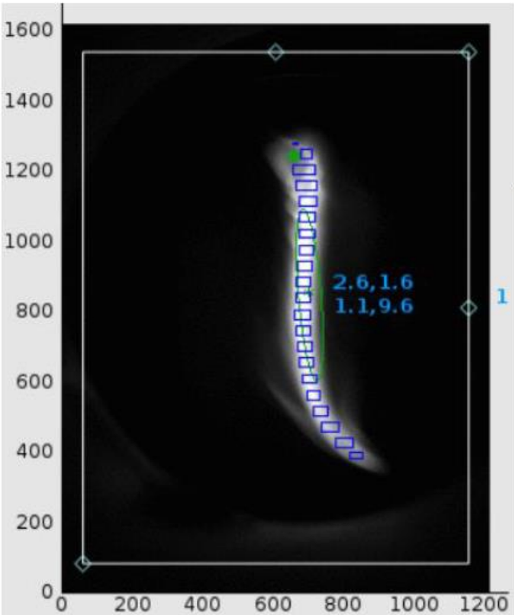
(704MHz SRF Booster, 3rd harmonic 2.1GHz , 704MHz energy correction cavity and
704MHz deflecting cavity)



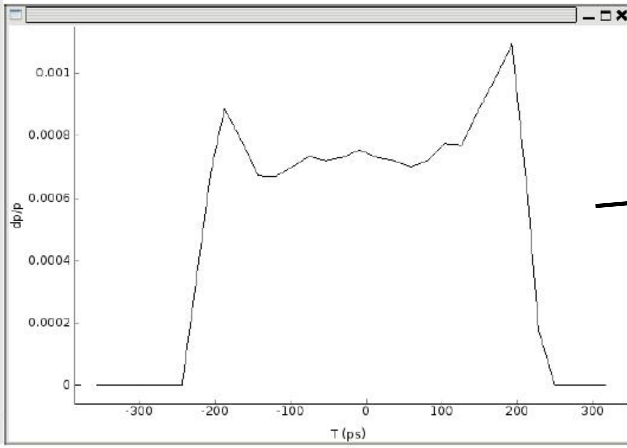


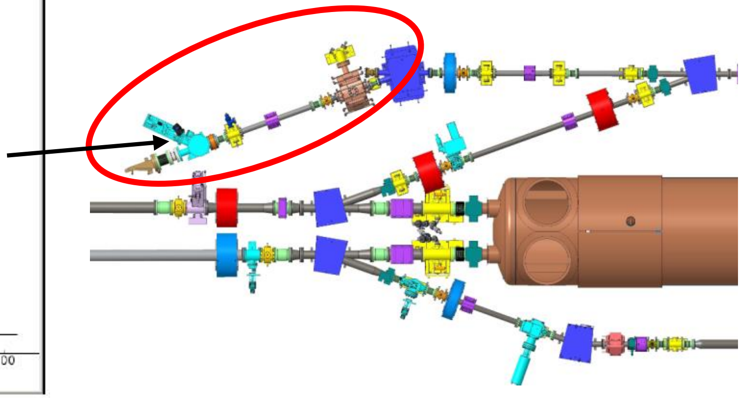
	Amplitude Setpoint (kV)	Measured Voltage (kV)	Phase Setpoint (deg)	Measured Phase (deg)
704 MHz BOOSTER CAVITY	1350	1349.96	-29	-29.00
	CAVITY CONTROL Pet	FAULT SUMMARY Pet		
2.1 GHz WARM CAVITY	150	150.02	-25	-25.00
	CAVITY CONTROL Pet	FAULT SUMMARY Pet	Turn On	Turn Off
704 MHz WARM CAVITY	55	55.01	-157	-157.00
	CAVITY CONTROL Pet	FAULT SUMMARY Pet	Turn On	Turn Off
704 MHz DEFLECTING CAVITY	30	30.00	110	110.00
	CAVITY CONTROL Pet	FAULT SUMMARY Pet	Turn On	Turn Off

Energy spread measurements

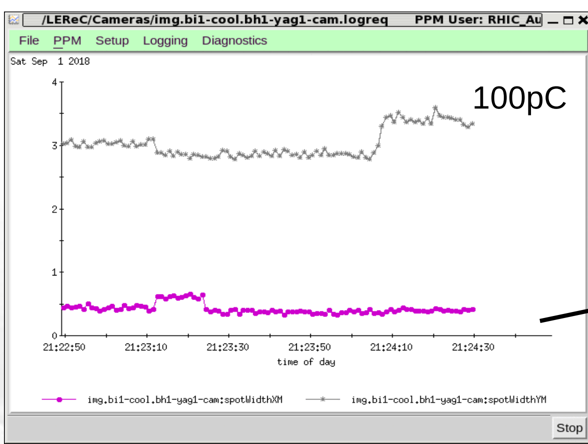


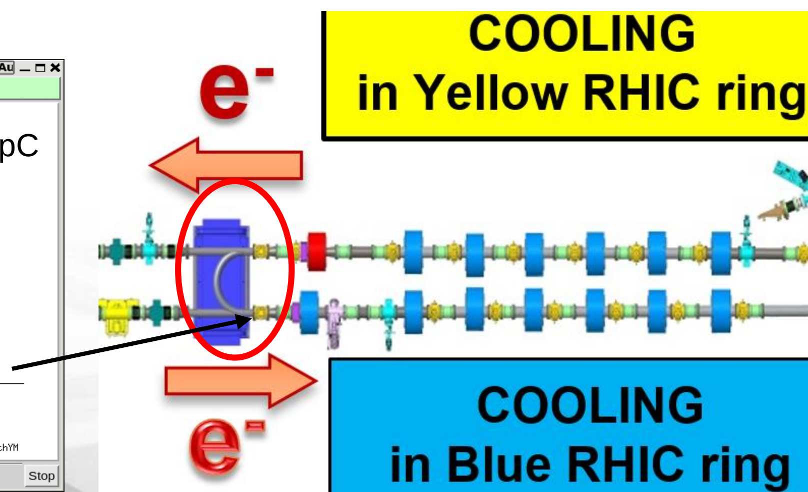
RMS momentum spread in RF diagnostics beam line: rms dp/p < 1×10^{-3}
Image on profile monitor (left), sliced energy spread along the bunch (right).





RMS momentum spread measurement in cooling section: rms dp/p < 1×10^{-3}
RMS horizontal and vertical beam sizes (in mm) on profile monitor after 180 deg. dipole magnet with vertical slit before 180 deg (dispersion 0.7 m).





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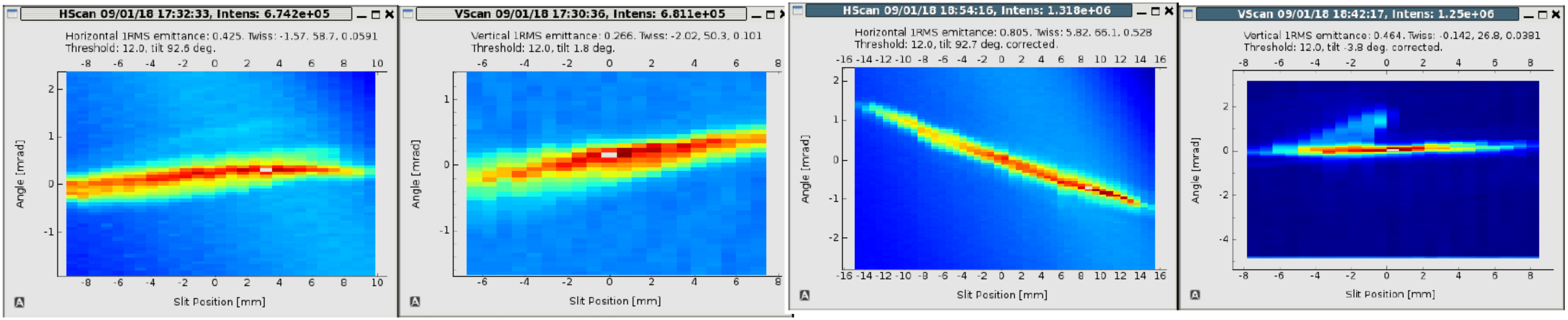
Transverse beam quality measurements in cooling sections

On cathode center operation, Q=100 pC

RMS normalized emittance in Yellow cooling section
Hor = 1.7 μm; Ver = 1.1 μm

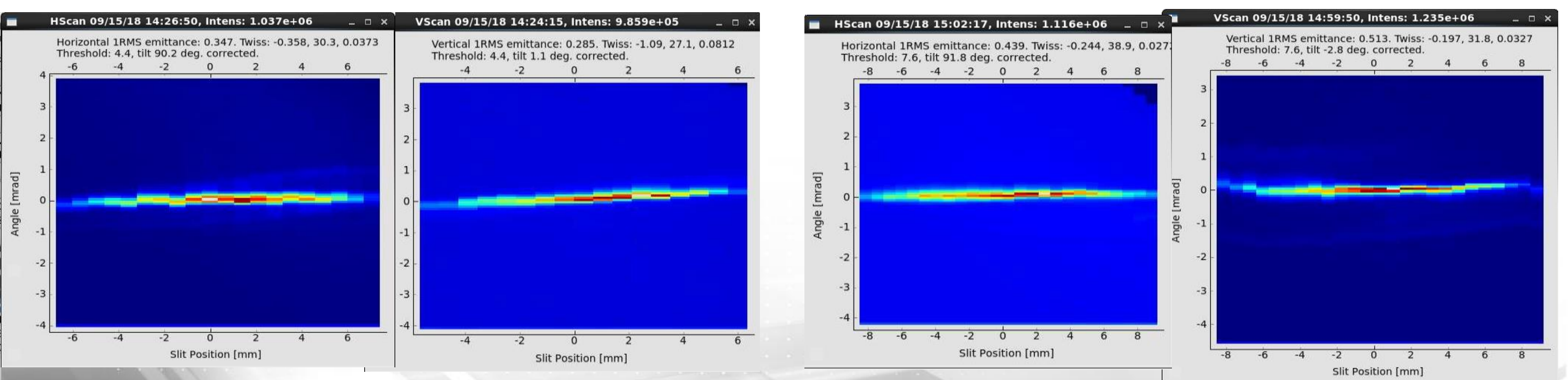
RMS normalized emittance in Blue cooling section:
Hor = 3.2 μm; Ver = 1.9 μm



Off cathode center operation, Q=50pC (after good optics matching)

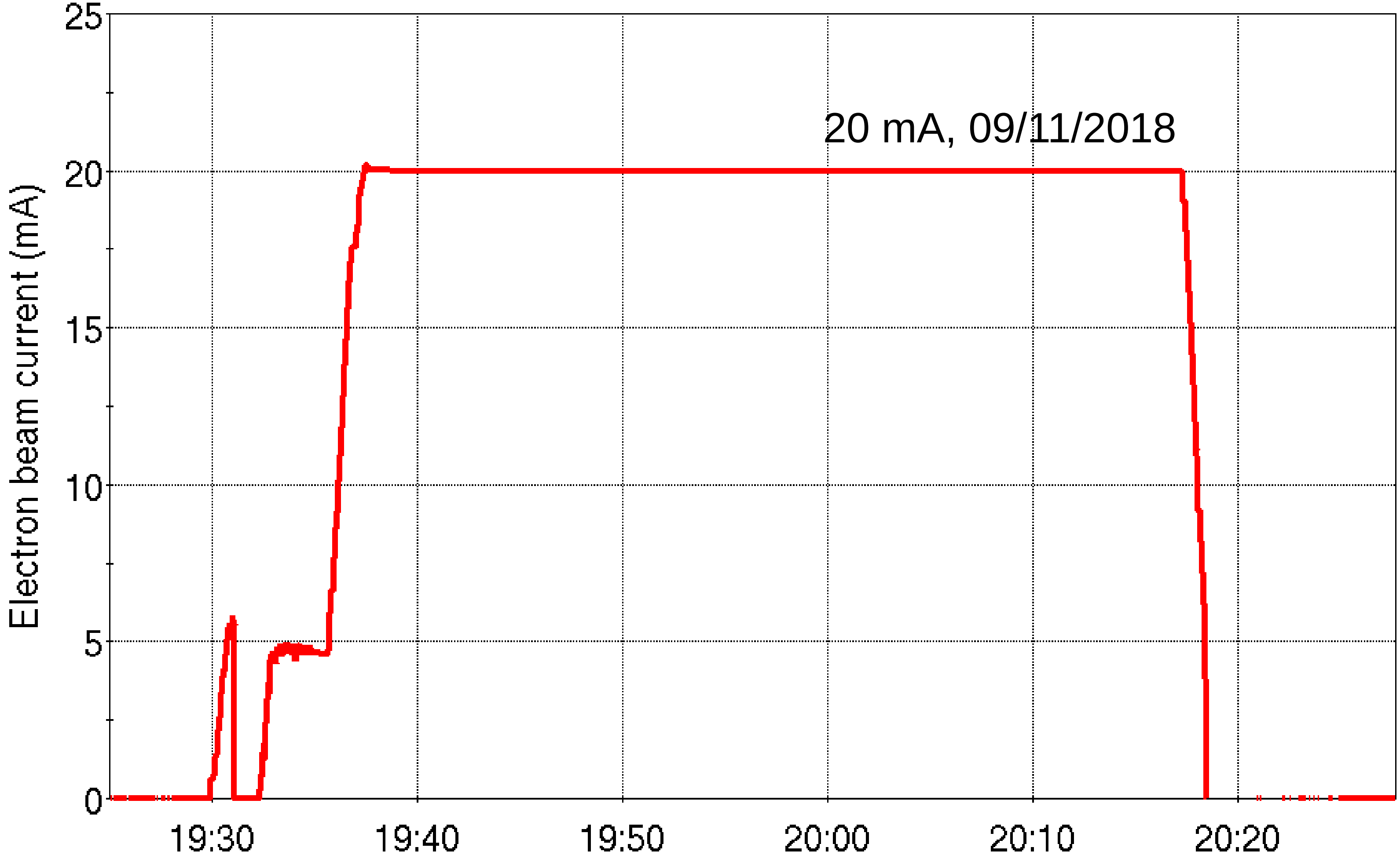
RMS normalized emittance in Yellow cooling section
Hor = 1.4 μm; Ver = 1.2 μm

RMS normalized emittance in Blue cooling section:
Hor = 1.8 μm; Ver = 2.0 μm



High current operation to high-power dump

- 20 mA CW to final high power beam dump at 1.6MeV
- With fast (~500 Hz) and slow (~10 Hz) intensity feedback, ΔI/I < 1% rms



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.

Electron 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).

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

LEReC upcoming plans

Sep. 17, 2018:	Commissioning of LEReC accelerator finished
Sep.17 - Dec.10:	Required upgrades and modifications
Dec.11-30, 2018:	Gun conditioning
January 2, 2019:	SRF booster is at 2K, ready for beam
Jan.-Feb., 2019:	Restart tests with electron beam. Achieve required electron beam and energy stability in cooling sections. Establish all required feedbacks. High currents runs and studies.
March, 2019:	Start commissioning of cooling with ion beam

Summary

- LEReC will be first electron cooler based on the RF acceleration of electron beam. As such, it is also a prototype of future high-energy coolers.
- It will be the first application of electron cooling in a collider.
- Installation of electron accelerator is complete.
- Electron accelerator was successfully commissioned.
- Commissioning of cooling process will start in March of 2019.

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!

Details can be found in recent LEReC publications:

D. Kayran et al., “LEReC Photocathode DC Gun Beam Test Results”, IPAC18, Vancouver, Canada, 2018

D. Kayran et al., “First Results of Commissioning of DC Gun for LEReC”, ERL17, CERN, Switzerland, 2017

S. Seletskiy et al., “Status of the BNL LEReC Machine Protection System”, IBIC17, Grand Rapids, USA, 2017

T. Miller at al., “Low Field NMR Probe Commissioning for LEReC Spectrometer”, IBIC17, Grand Rapids, USA, 2017

J. Kewisch et al., “Tracking of Electrons Created at Wrong RF Phases in LEReC”, IPAC17, Copenhagen, Denmark, 2017

S. Seletskiy et al., “Dependence of LEReC energy spread on laser modulation”, IPAC17, Copenhagen, Denmark, 2017

S. Seletskiy et al., “Alignment of Electron and Ion Beam trajectories in LEReC”, IPAC17, Copenhagen, Denmark, 2017

Z. Zhao et al., “Generation of 180 W average green power from fiber laser”, Optics Express 8138, Vol. 25, No. 7, 2017

A. Fedotov et al., “Accelerator Physics Design Requirements and Challenges of LEReC”, NAPAC16, Chicago, USA, 2016

J. Kewisch et al., “Beam Optics for LEReC”, NAPAC16, Chicago, USA, 2016

D. Kayran et al., “DC Photogun Test for LEReC”, NAPAC16, Chicago, USA, 2016

S. Seletskiy et al., “Magnetic Sheilding of LEReC Cooling Section”, NAPAC16, Chicago, USA, 2016

S. Seletskiy et al., “Absolute Energy Measurement of LEReC Electron Beam”, NAPAC16, Chicago, USA, 2016

M. Blaskiewicz, “Emittance Growth from Modulated Focusing in Bunched Beam Cooling”, NAPAC16, Chicago, USA, 2016

T. Miller et al., “”LEReC Instrumentation Design and Construction”, IBIC16, Barcelona, Spain, 2016

Z. Sorrell et al., “Beam Position Monitors for LEReC”, IBIC16, Barcelona, Spain, 2016

S. Seletskiy et al., “Conceptual Design of LEReC Fast MPS”, IBIC16, Barcelona, Spain, 2016

S. Seletskiy et al., “Study of YAG Exposure Time for LEReC RF Diagnostic Beamline”, IBIC16, Barcelona, Spain, 2016

J.C. Brutus et al., “Mechanical Design of Normal Conducting RF cavities of LEReC”, IPAC16, Busan, Korea, 2016

F. Carlier et al., “Radiation Recombination Detection for LEReC”, IPAC16, Busan, Korea, 2016

Binping Xiao et al., “RF design of Normal Conducting cavities for LEReC”, IPAC16, Busan, Korea, 2016

Binping Xiao et al., “HOM Consideration of 704MHz and 2.1GHz cavities for LEReC”, IPAC16, Busan, Korea, 2016

and references therein to previous publications.