Low Energy RHIC electron Cooling (LEReC):
Challenges and Commissioning Progress

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on behalf of the LEReC team

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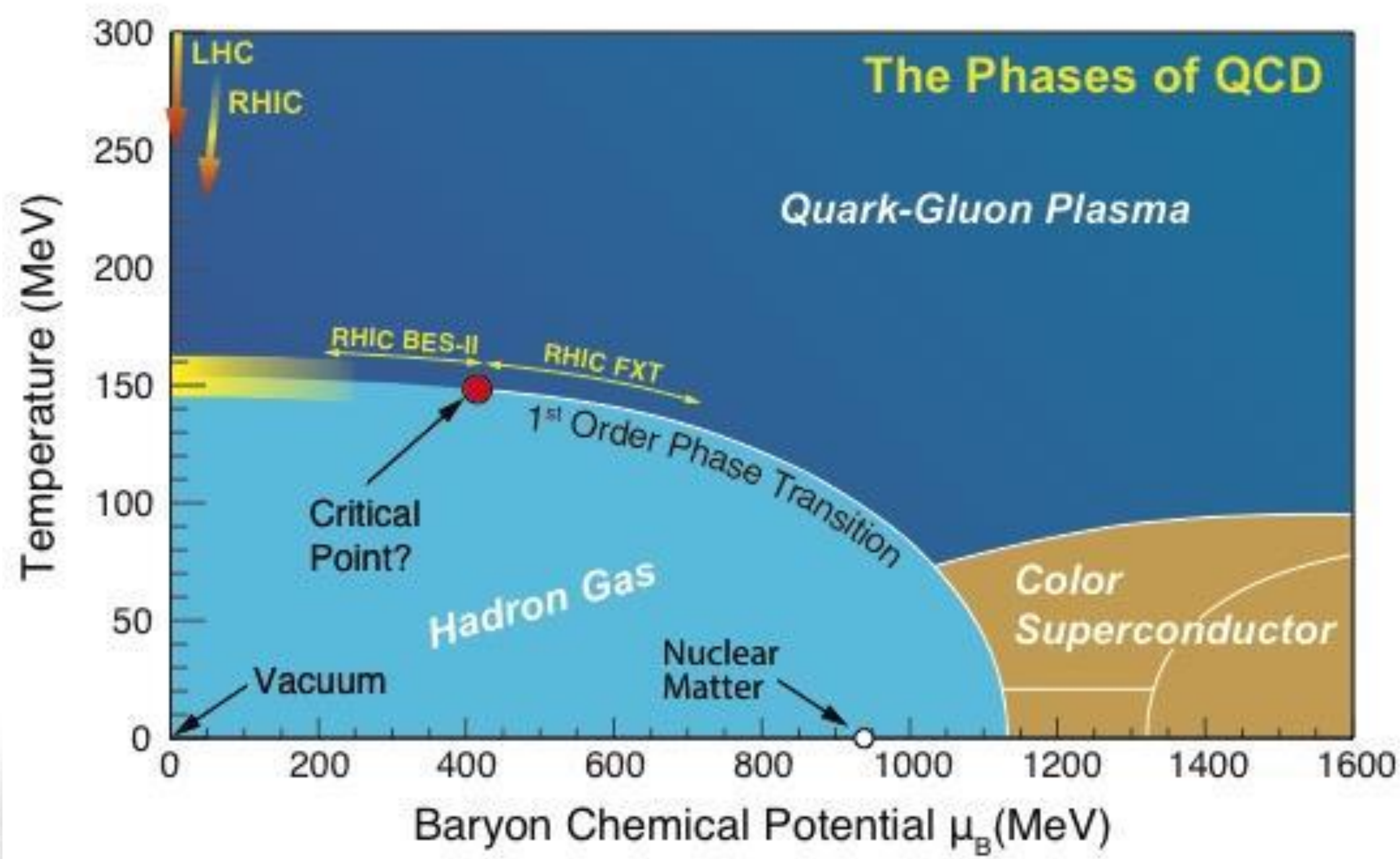
BROOKHAVEN NATIONAL LABORATORY
U.S. DEPARTMENT OF ENERGY

Outline

- Low-Energy RHIC and beam dynamics challenges
- Low-Energy RHIC electron cooler (LEReC)
- Stages of LEReC commissioning
- Commissioning challenges
- Commissioning progress

Low-Energy RHIC physics program:

Search for a Critical Point on the QCD phase diagram.
Beam Energy Scan I (2010-14) and BES-II (2019-21)



Beam dynamics limits for low-energy RHIC operation

The beam lifetime observed during operation at low energies ($\gamma < 10$), was limited by machine nonlinearities and other (high intensity) limitations such as:

Intra-beam Scattering (IBS):

- IBS growth can be counteracted by electron cooling

Beam-beam:

- For beam-beam parameter much smaller than space-charge tune shift, can be mitigated by a proper choice of working point

Space-charge:

- Requirement of long lifetime sets smaller limit on allowable space-charge tune shift values. We are minimizing space-charge limitation by a proper choice of working point and by implementing low-frequency RF system to provide collisions with longer bunches.

See, for example:
A. Fedotov et al., "Beam lifetime and limitations during low-energy RHIC operation", THP081, PAC11
C. Montag et al., "RHIC performance during the 7.5GeV low energy Run", TUPRO031, IPAC14
and references therein.

Low-energy RHIC operation

Electron cooling technique:

- "cold" electron beam is merged with ion beam which is cooled through Coulomb interactions
- electron beam is renewed and velocity spread of ion beam is reduced in all three planes

At low energies in RHIC electron cooling can help to improve luminosity lifetime by counteracting Intra-Beam Scattering (IBS).

requires co-propagating electron beam with the same average velocity as velocity of hadron beam.

BES-II energies of interest:

$\sqrt{s_{NN}}$ = **7.7, 9.1, 11.5, 14.6, 19.6 GeV**

LEReC : 1.6 – 2.6 MeV (electrons kinetic energies)

Luminosity improvement without electron cooling (needed RHIC performance demonstrated in 2016)

LEReC Project Goals

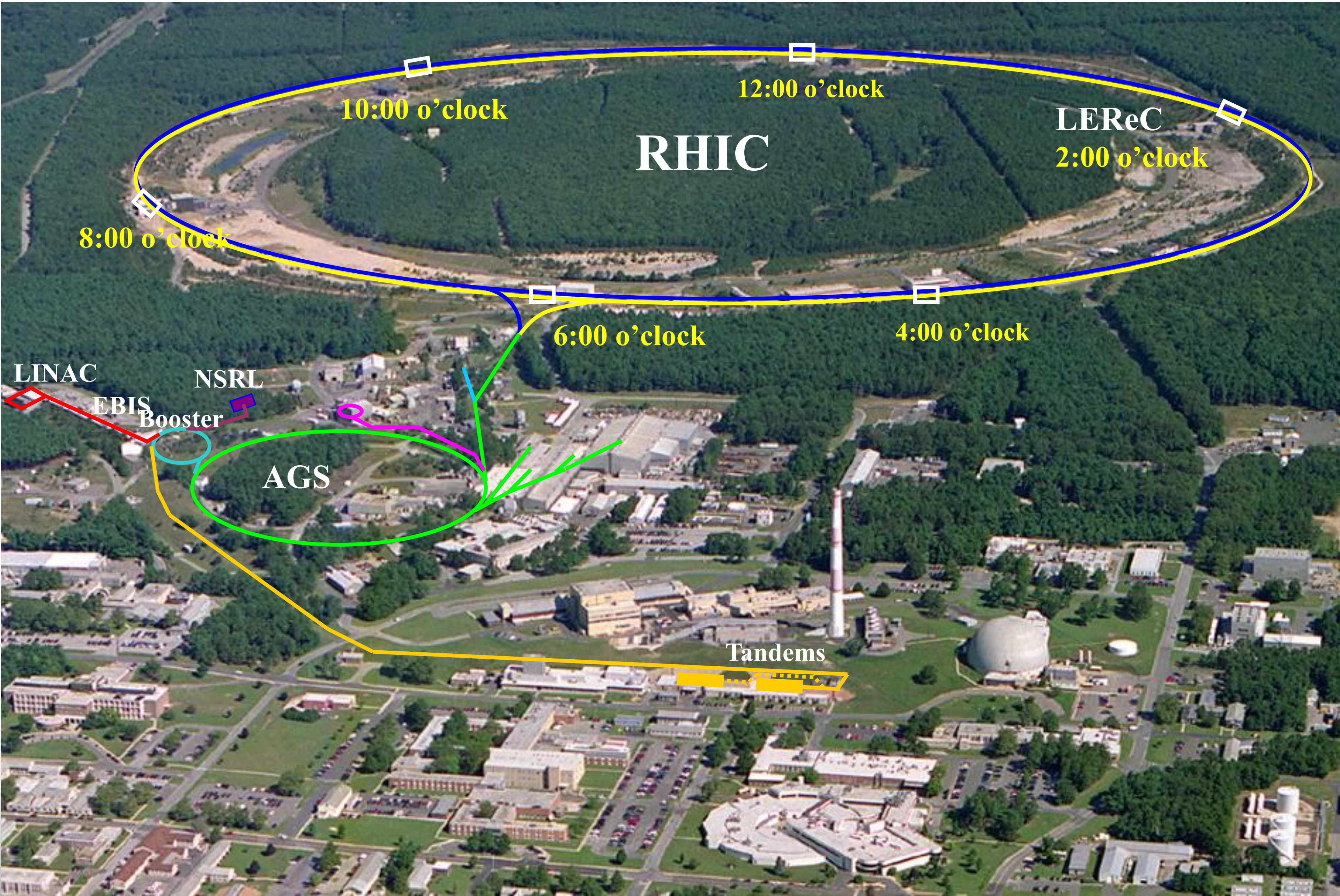
The goal of the LEReC project is to provide luminosity improvement for RHIC operation at low energies to search for the QCD critical point (Beam Energy Scan Phase-II physics program).

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

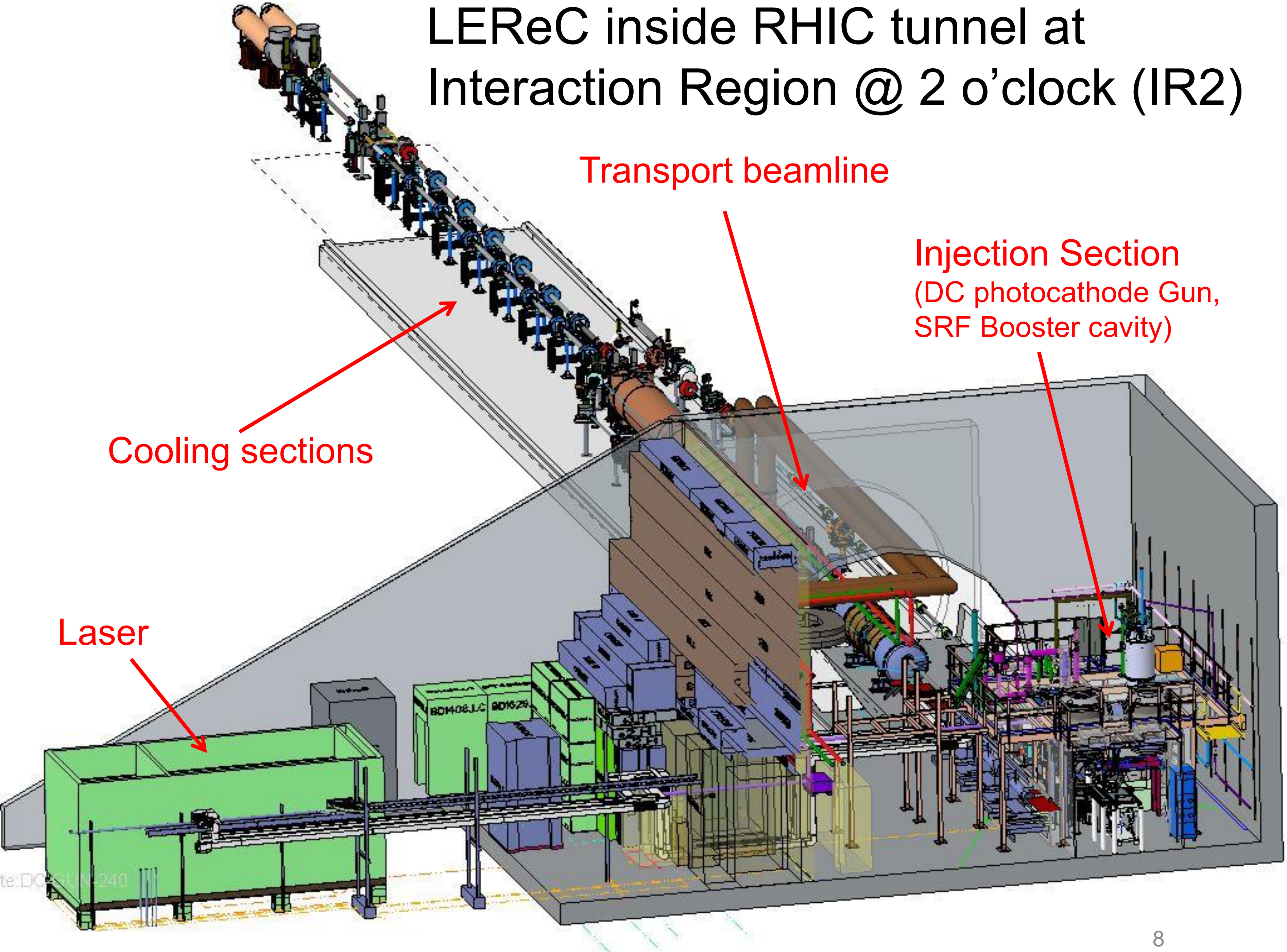
To provide luminosity improvement with such approach requires:

- **Building and commissioning of new state of the art electron accelerator**
- Produce electron beam with beam quality suitable for cooling
- Transport with RF acceleration maintaining required beam quality
- Achieve required beam position and energy stability in cooling sections
- Commissioning of bunched beam electron cooling
- Commissioning of electron cooling in a collider

RHIC @ BNL, Long Island, New York

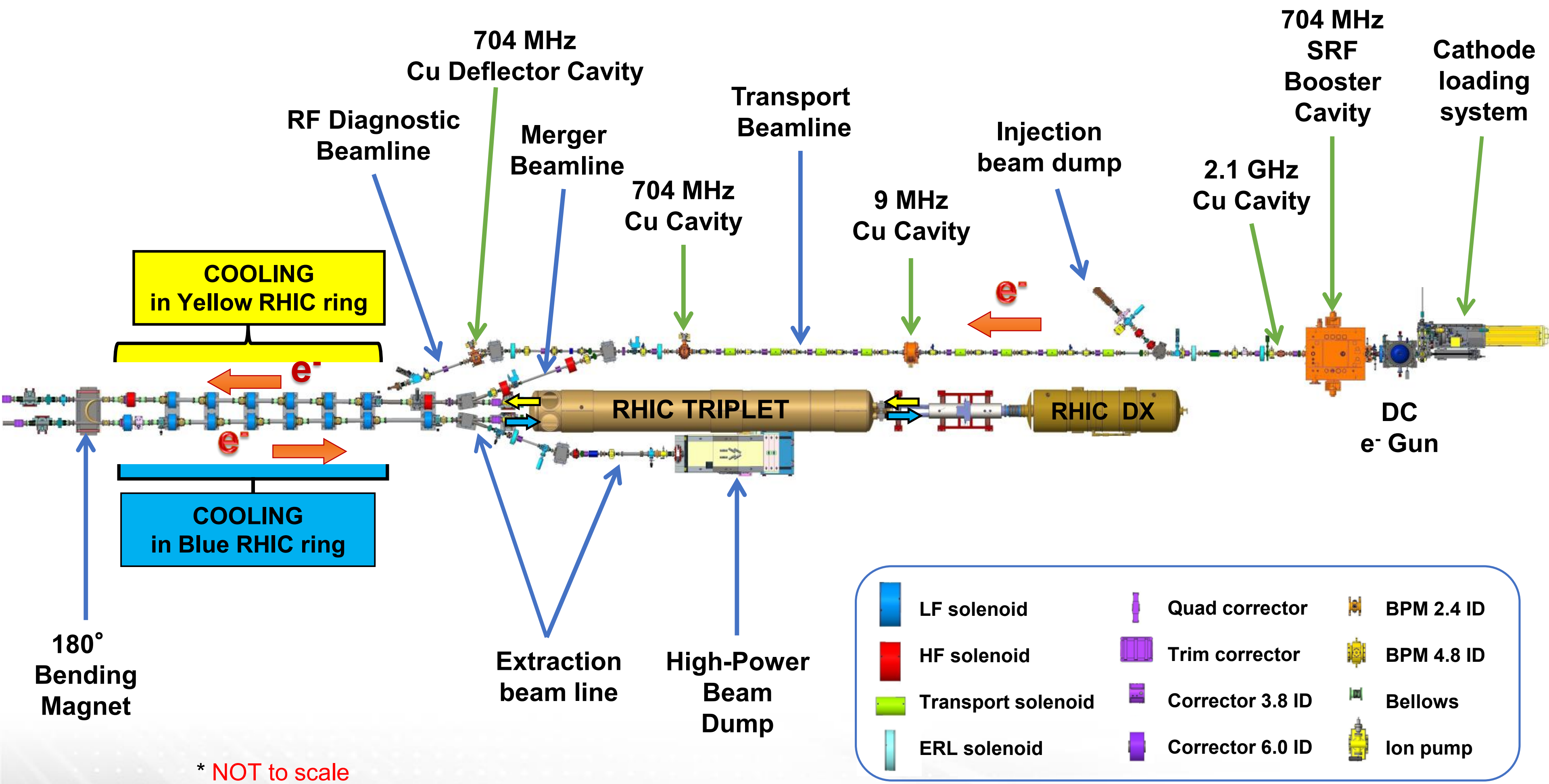


LEReC inside RHIC tunnel at Interaction Region @ 2 o'clock (IR2)



LEReC Accelerator

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



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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.

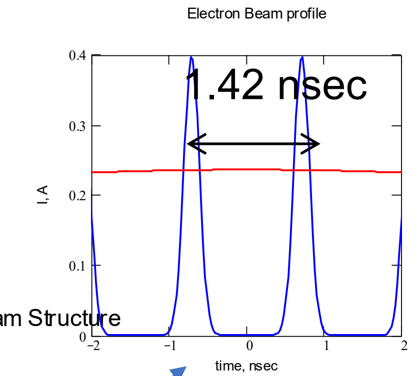
- Accelerate such bunches with RF and use RF gymnastics (several RF cavities) to achieve energy spread required for cooling. Deliver and maintain beam quality in both cooling sections.

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

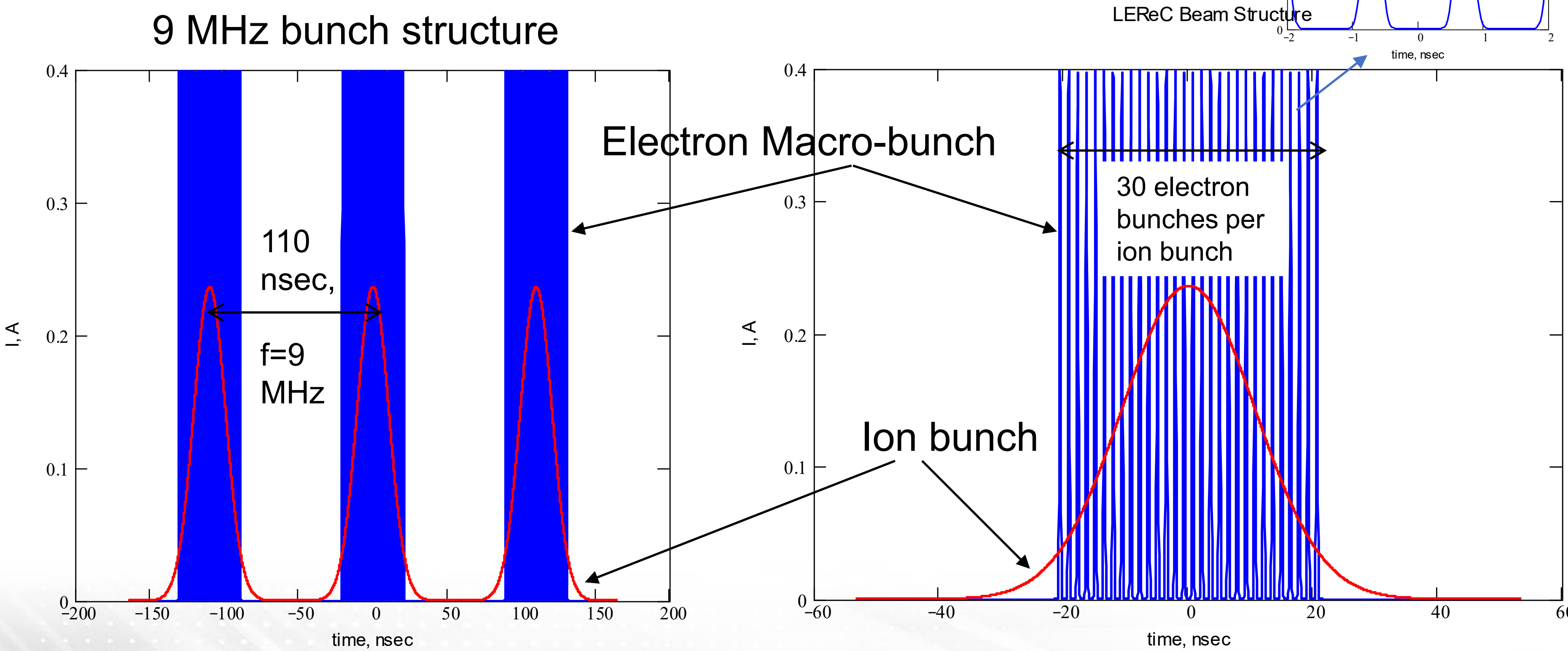
LEReC beam structure in cooling section

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



9 MHz bunch structure



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:

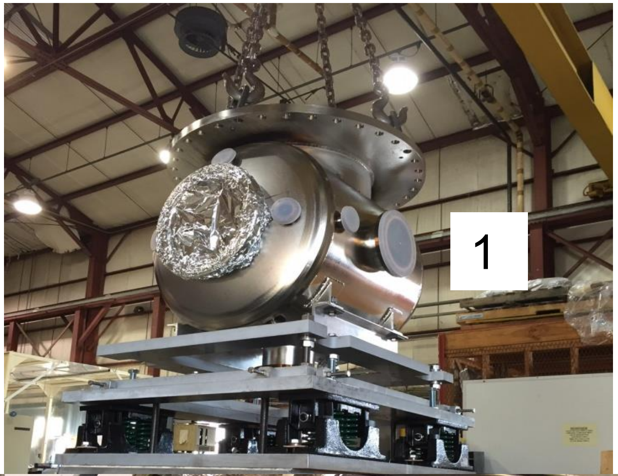
Correction solenoids in the cooling section are used to keep transverse angular spread to a required level.

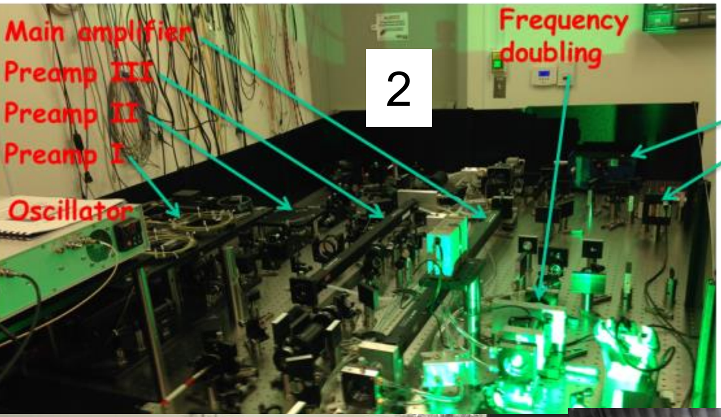
Strict control of electron angles in cooling sections:

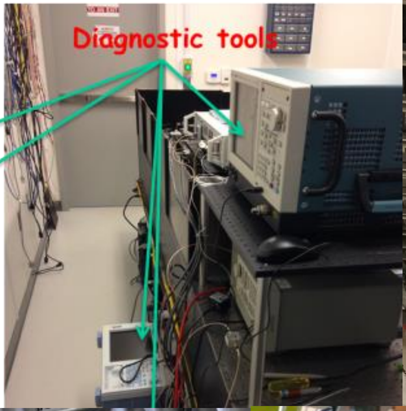
Cooling sections are covered by several layers of Mu-metal shielding.

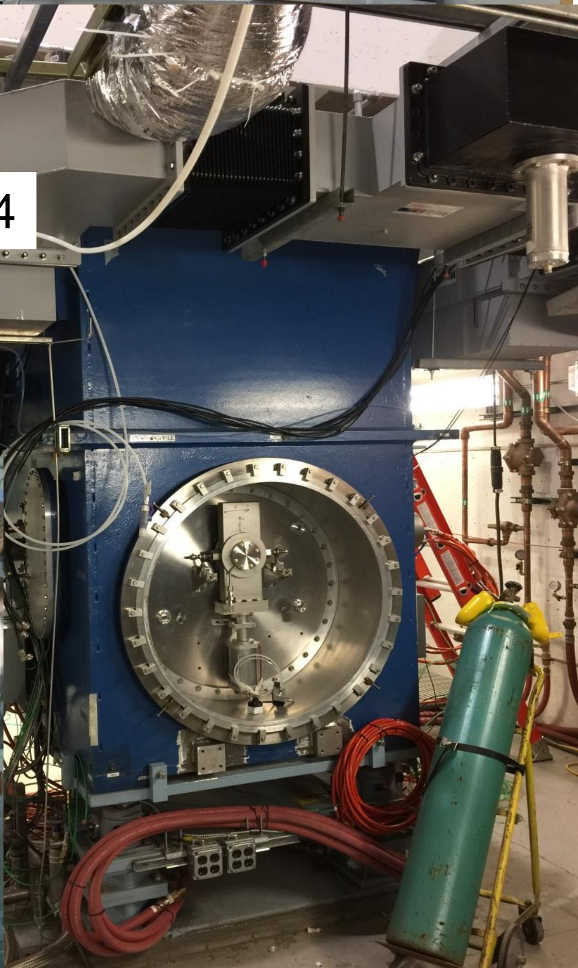
LEReC Critical Technical Systems

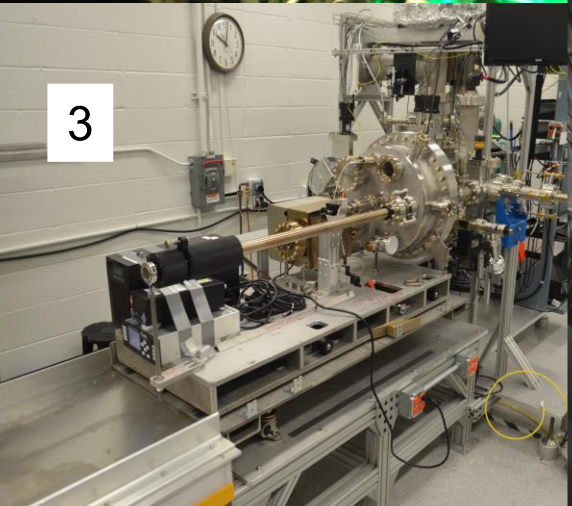
1. DC photocathode electron gun and HV PS
2. High-power fiber laser system and transport
3. Cathode production deposition and delivery systems
4. SRF Booster cavity
5. 2.1 GHz and 704 MHz warm RF cavities

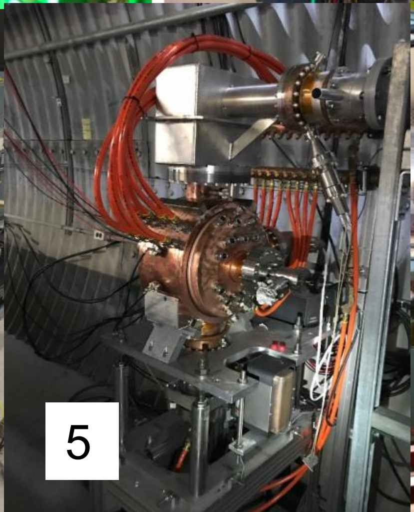


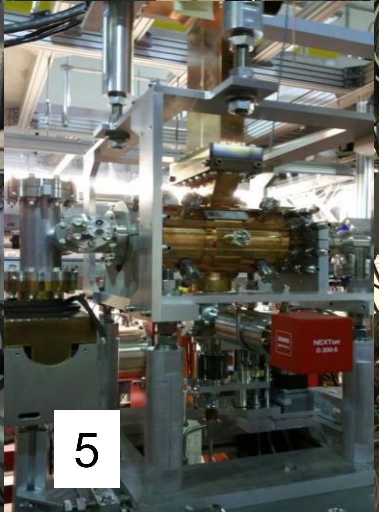




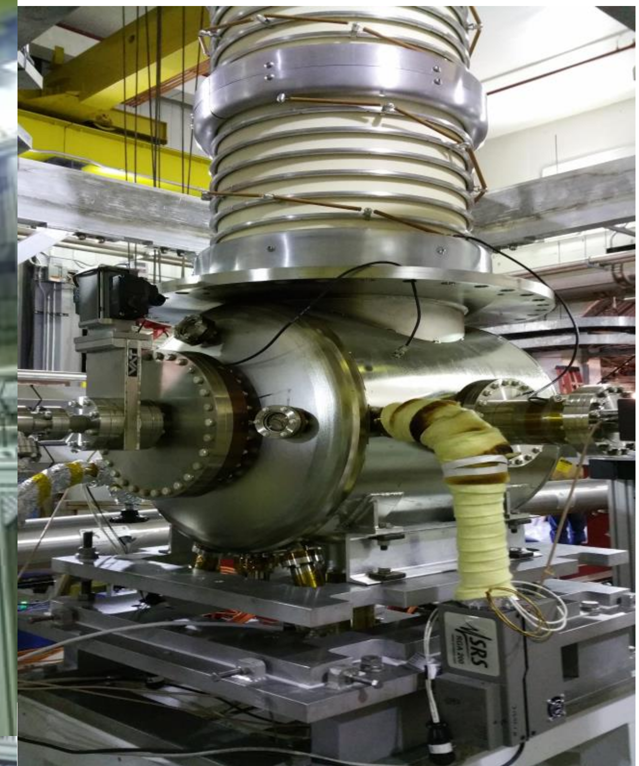


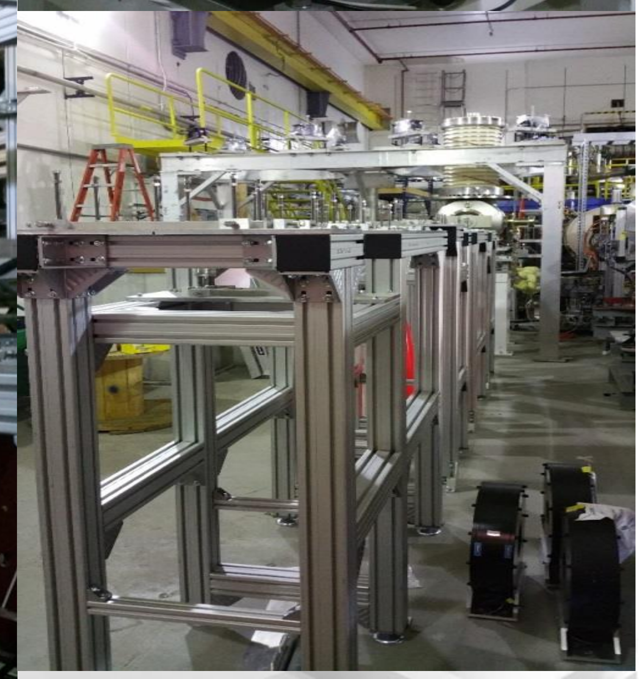




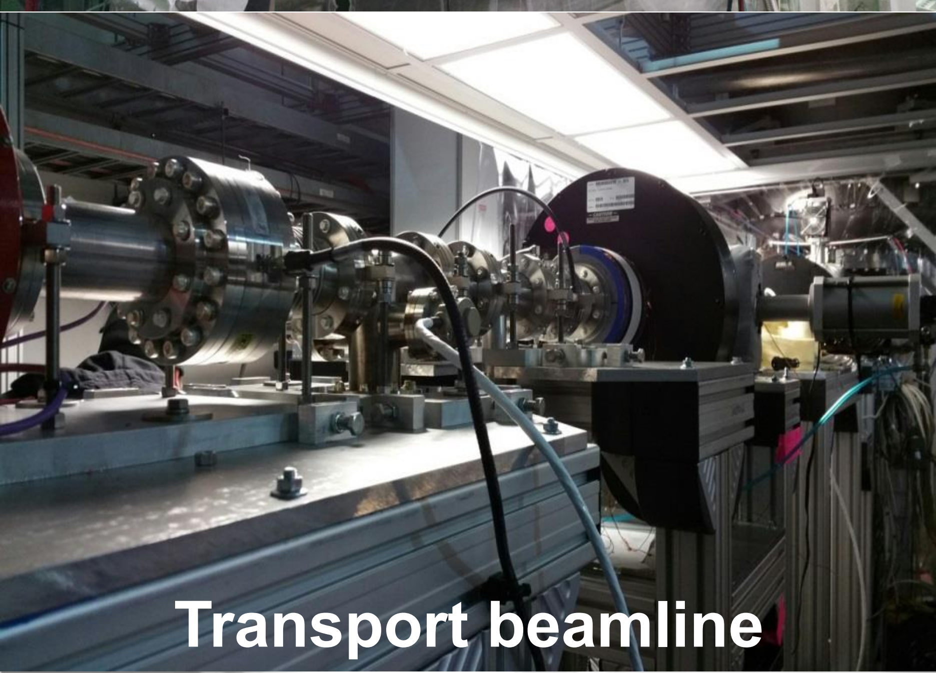


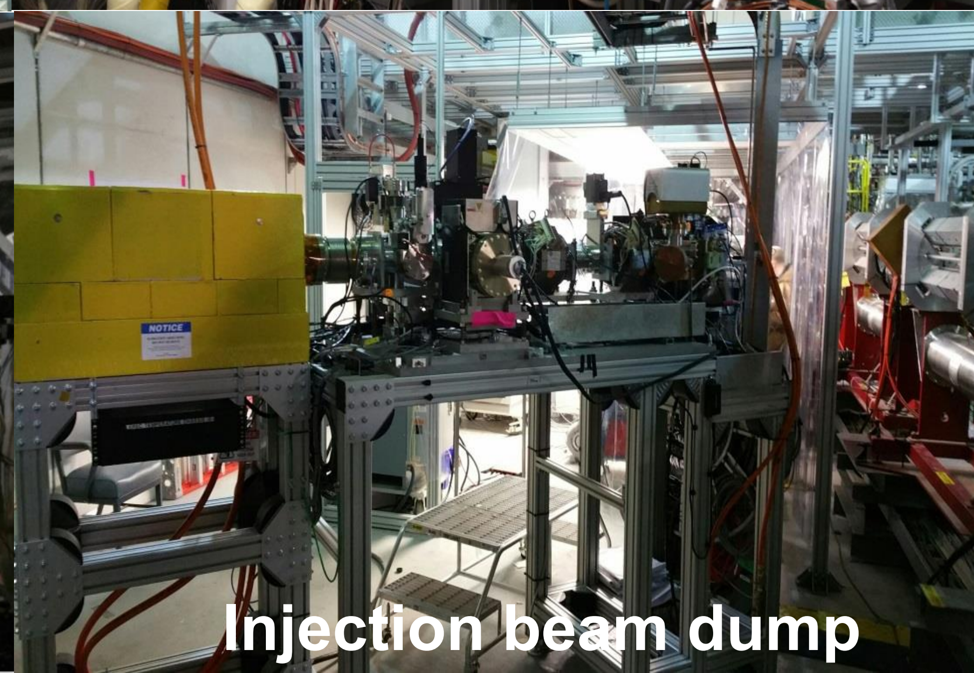
LEReC construction 2016





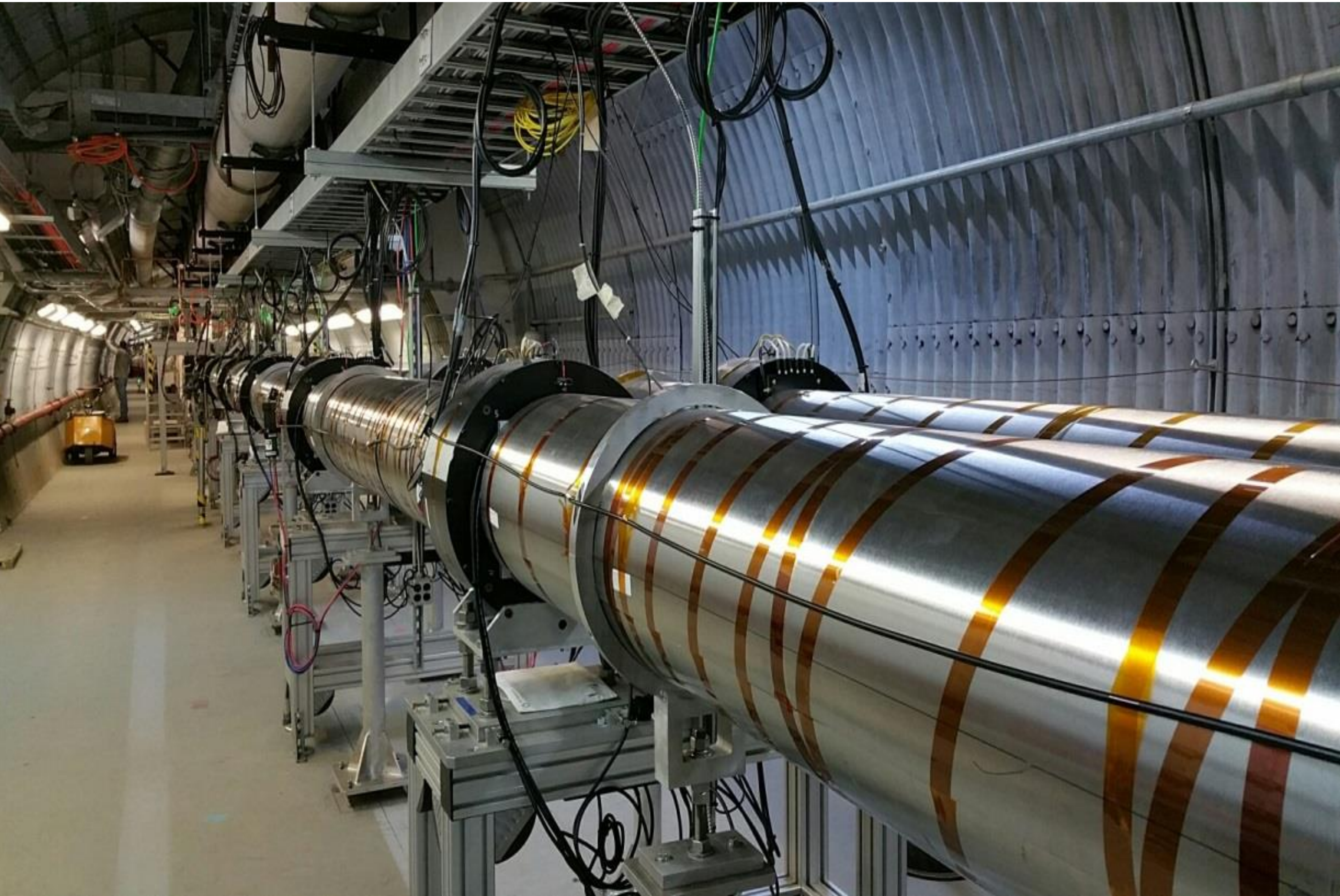
LEReC DC Gun test beamline (2017)





Full LEReC Installation (October 2017)

LEReC cooling sections fully installed (2018)



Commissioning with e-beam

- **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

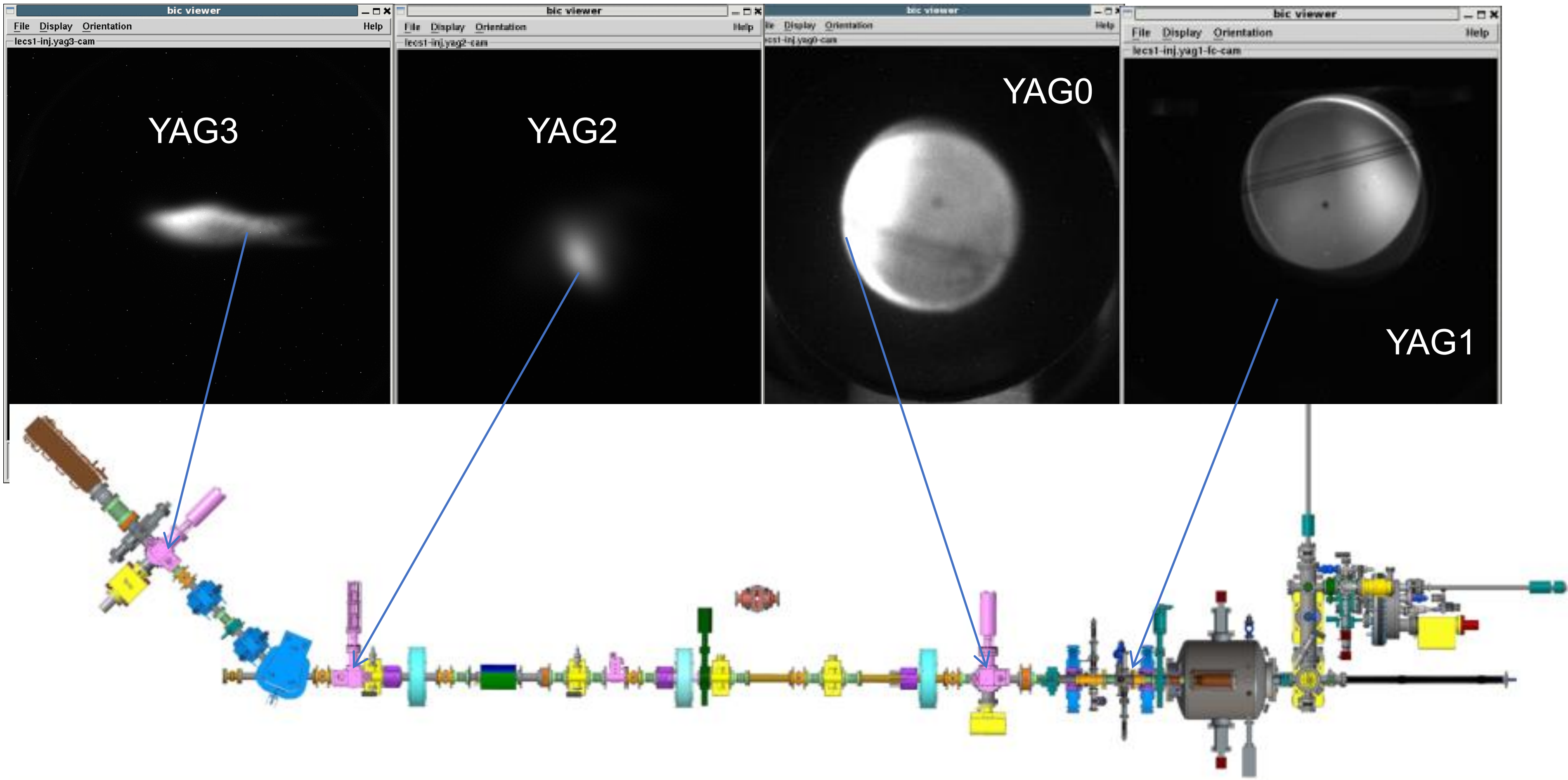
Goals: Achieve stable high-current operation of accelerator with electron beam parameters suitable for cooling.

- **Phase 3** (2018-2019): Transition to operations

Goals: Commissioning LEReC for operation at higher energies. Achieve needed stability (energy, orbit) of electron beam. Develop necessary stability feedbacks.

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

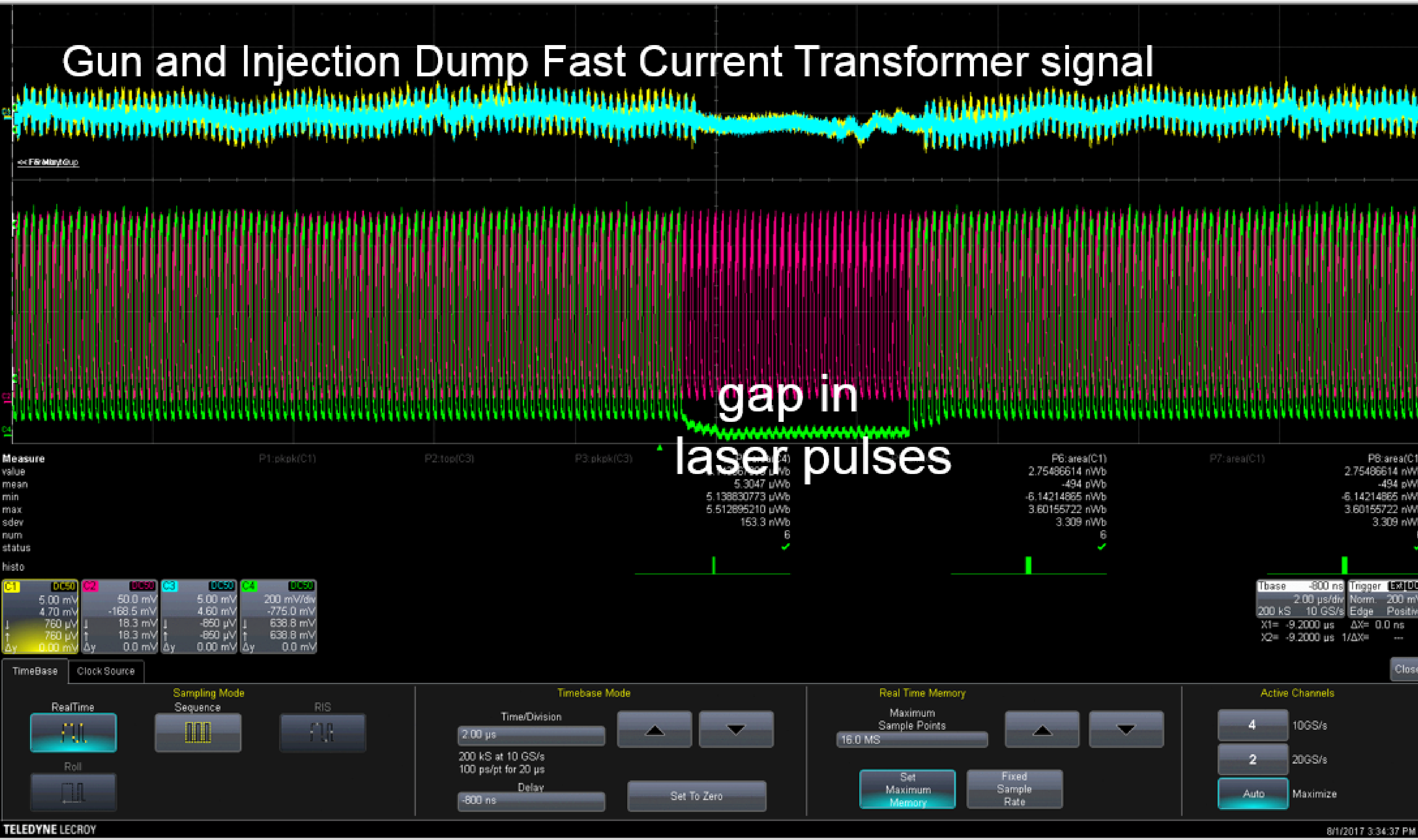
Start of commissioning with beam (April 2017)



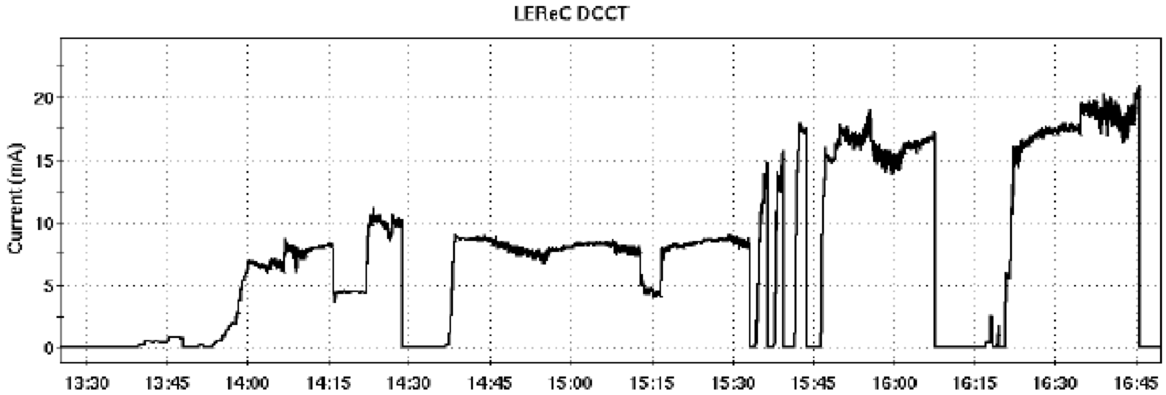
Initial commissioning started with LED lamp illuminating photo cathode.

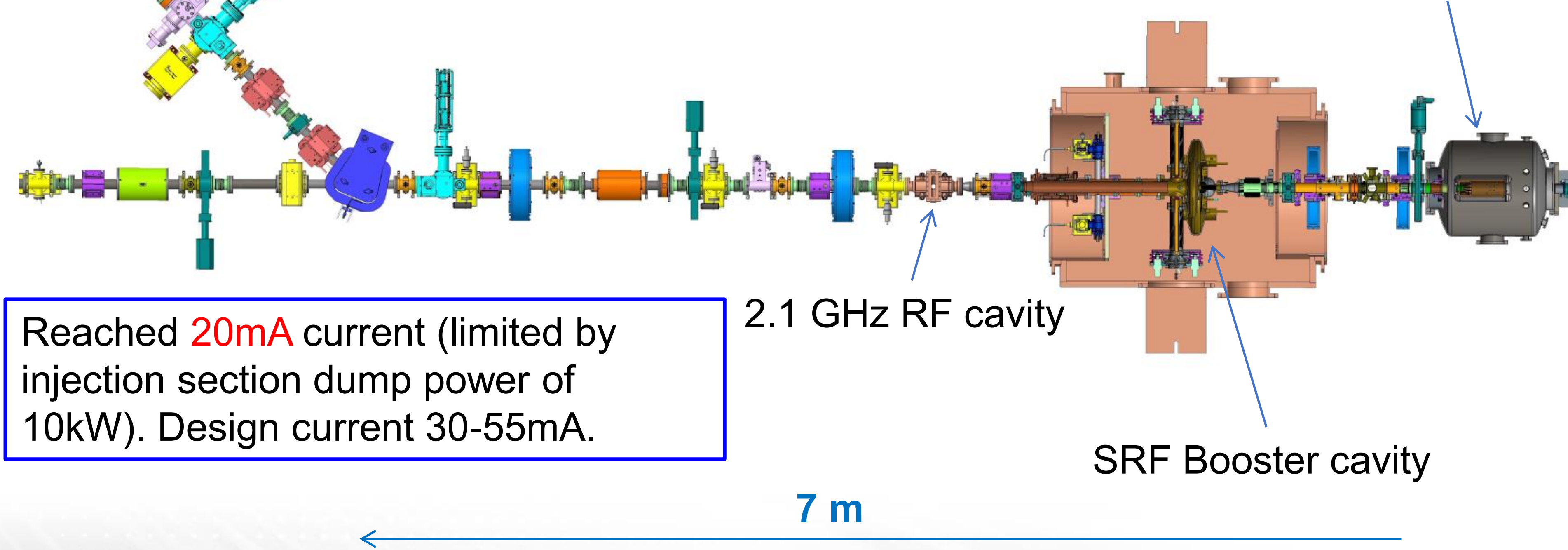
It allowed us to start commissioning Faraday cups, Profile monitors and magnets.

First CW operation in Gun Tests (August 1, 2017)



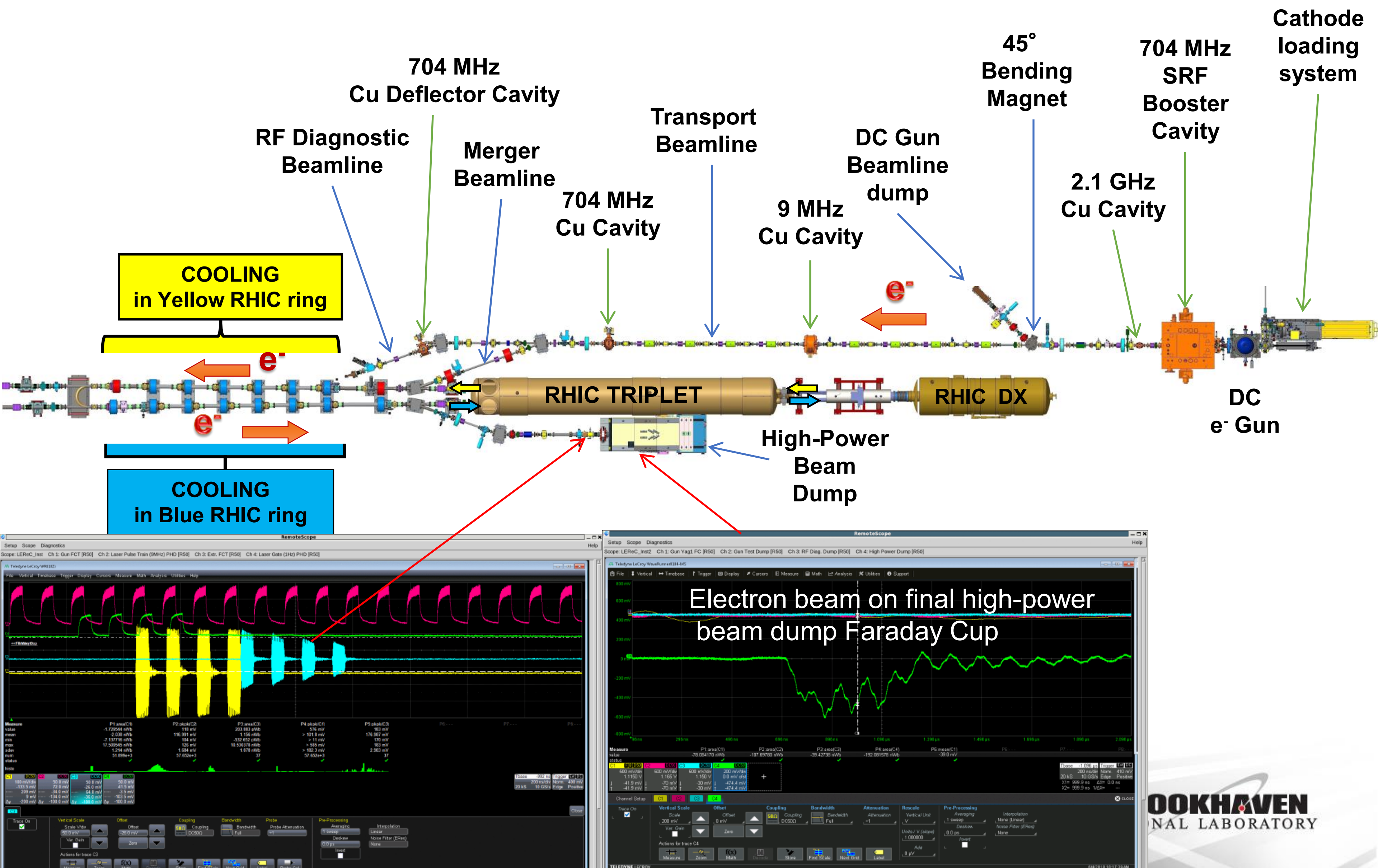
LEReC Injection section (June 6, 2018)





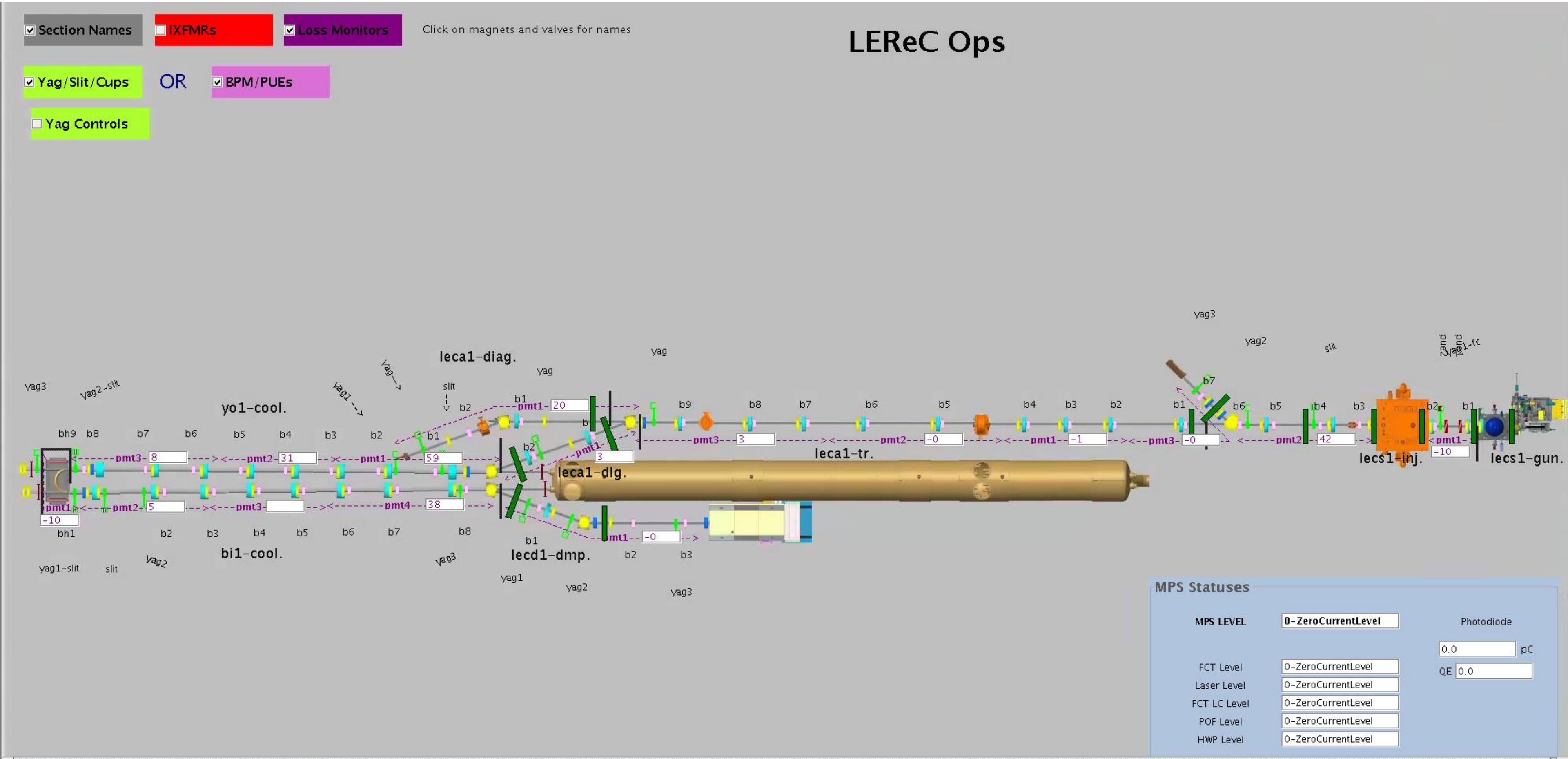
Reached 20mA current (limited by injection section dump power of 10kW). Design current 30-55mA.

LEReC: beam propagated all the way to final beam dump

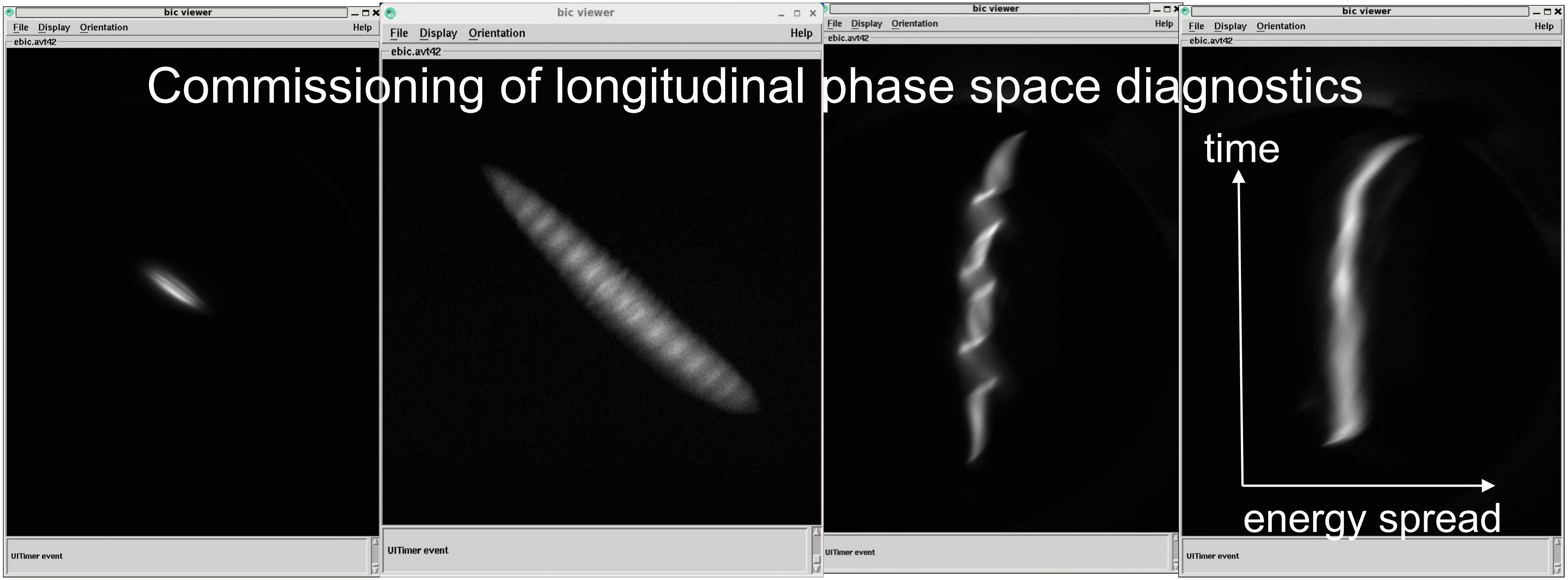


Instrumentation commissioning

LEReC commissioning heavily relies on beam instrumentation:
BPMs, Profile Monitors (YAGs), Charge and Current (FCT, ICT, DCCT, Faraday Cups), Emittance (multi-slits, slit scanners), energy (spectrometer), longitudinal phase space monitor, loss monitors, energy matching (recombination, Schottky)



RF cavities working together
(704MHz SRF Booster, 3rd harmonic 2.1GHz , 704MHz energy correction and 704MHz deflecting cavities)



/RHIC/Systems/LEReC/RF/Operations/LEReC_RF_Summary

Page PPM Device Data Tools Buffer Help

	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

LEReC Commissioning progress

- Commissioning of electron accelerator is progressing well.
- Propagated electron beam through all beamlines, including both cooling sections and to all beam dumps (injection, RF diagnostics and high-power beam dumps).
- Achieved design bunch charge (4nC/macro-bunch) including transverse laser shaping (3mm iris).
- RF cavities are synchronized and are being used for RF gymnastics and longitudinal phase space optimization.
- Started high-current CW commissioning in injection section. Reached 20mA current (limited by injection section dump power of 10kW). Design operational current 30-55mA.

Commissioning challenges

As with any new machine, we have problems with new hardware which are being addressed as we move forward:

- Stability of DC Gun HVPS
- Laser stability
- RF stability
- Effect of RF noise on instrumentation electronics (BPMs, FCTs)
- Electronics survival in radiation environment inside RHIC tunnel
- Other hardware issues

Cooling commissioning challenges

To start commissioning of cooling during Run-19, we need:

- Fully commissioned electron accelerator with all hardware problems resolved
- Achieve electron beam parameters required for cooling
- Achieve required stability of electron beam in cooling sections
- Achieve required stability of ion beam in cooling sections

Once we have Au ions in RHIC in 2019 commissioning of cooling will start and will include:

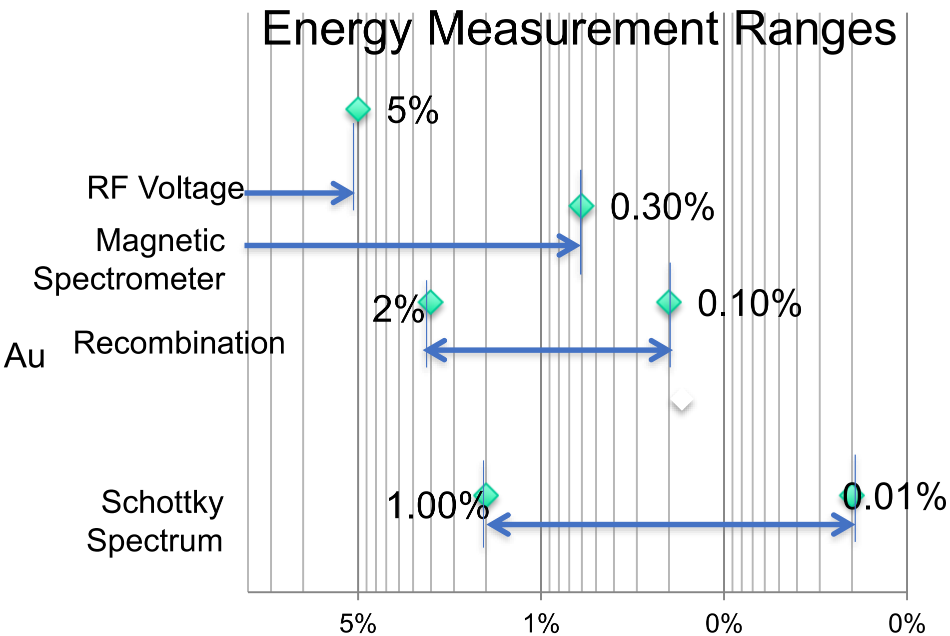
- Interaction of electron and ion beams: with e-beam parameters established (current, energy, energy spread, emittance, required stability) establish overlap between Au and electron beams in (x, y, p)
- Demonstration of bunched beam cooling
- Effects on hadron beam (cooling vs. heating)
- Effects on electron beam
- Control of ion distribution under cooling
- Cooling and beam lifetime (as a result of many effects)
- Preserve cooling performance from one cooling section to another
- Work on optimization between cooling process and luminosity improvement

Cooling commissioning strategy

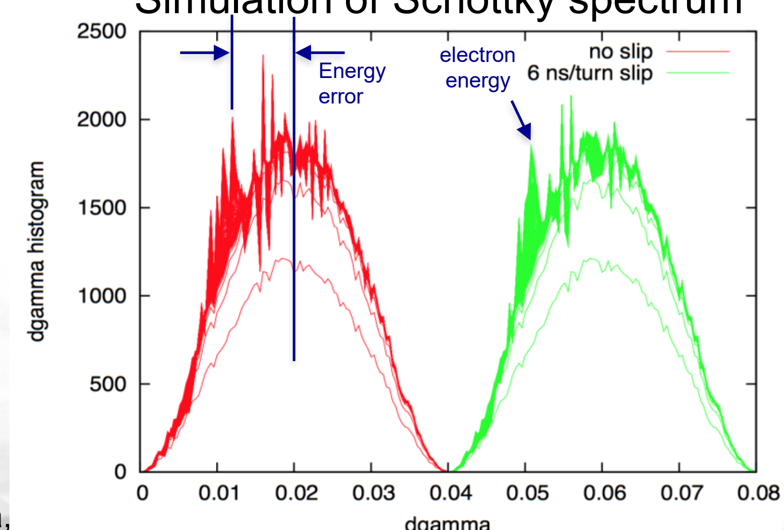
With e-beam parameters established (current, energy, energy spread, emittance) need to maximize overlap between Au and electron beams.

General strategy:

- Bring Au and e-beams in close proximity
  - In (*x*,*y*) using BPMs ($\Delta x,y \sim 50\ \mu m$)
  - In momentum through absolute measurement of Au and e-beams ($\Delta p/p \sim 10^{-3}$)
  - In momentum through observation of Schottky spectra with unbunched Au beam ($\Delta p/p$ acceptance of Au beams ~ 10^{-2})
- Maximize overlap of Au and e-beams in (x,y,p)
  - Observation of Au^{78+} produced in recombination (recombination monitors)
  - Observation of cooling effect with WCM Schottky
- IPM and WCM will show evolution of transverse and longitudinal profiles under cooling



Simulation of Schottky spectrum



LEReC project timeline

May 2015:	Project approved by DOE for construction
April 2016:	High-power laser assembled
October 2016:	DC gun delivered to BNL
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
January-Feb. 2018:	Systems commissioning (RF, SRF, Cryogenics, Instrumentation, Controls, etc.)
March-Sept. 2018:	Commissioning of full LEReC accelerator with e-beam
2019:	Commissioning of cooling with Au ion beams during RHIC Run-19.

Summary

- LEReC will be first electron cooler based on the RF acceleration of electron beam.
- It will be the first application of electron cooling in a collider.
- Installation of electron accelerator is complete.
- Commissioning with electron beam of full LEReC accelerator started in March 2018 and is progressing well.
- Commissioning of cooling process will start in Run-19.

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.