Low Energy RHIC electron Cooling (LEReC):

Commissioning Progress and Plans

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BROOKHAVEN NATIONAL LABORATORY

U.S. DEPARTMENT OF ENERGY

Beam dynamics limits for low-energy RHIC operation

The beam lifetime observed during operation at low energies ($\gamma < 10$) had significant limitations due to the machine nonlinearities. These limitations were worked on during most recent physics runs.

In addition, the high-intensity limitations were:

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.

Intra-beam Scattering (IBS):

- IBS growth can be counteracted by electron cooling

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:

LEReC : 1.6 – 2.6 MeV (electrons kinetic energies)

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

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

LEReC Project Goals

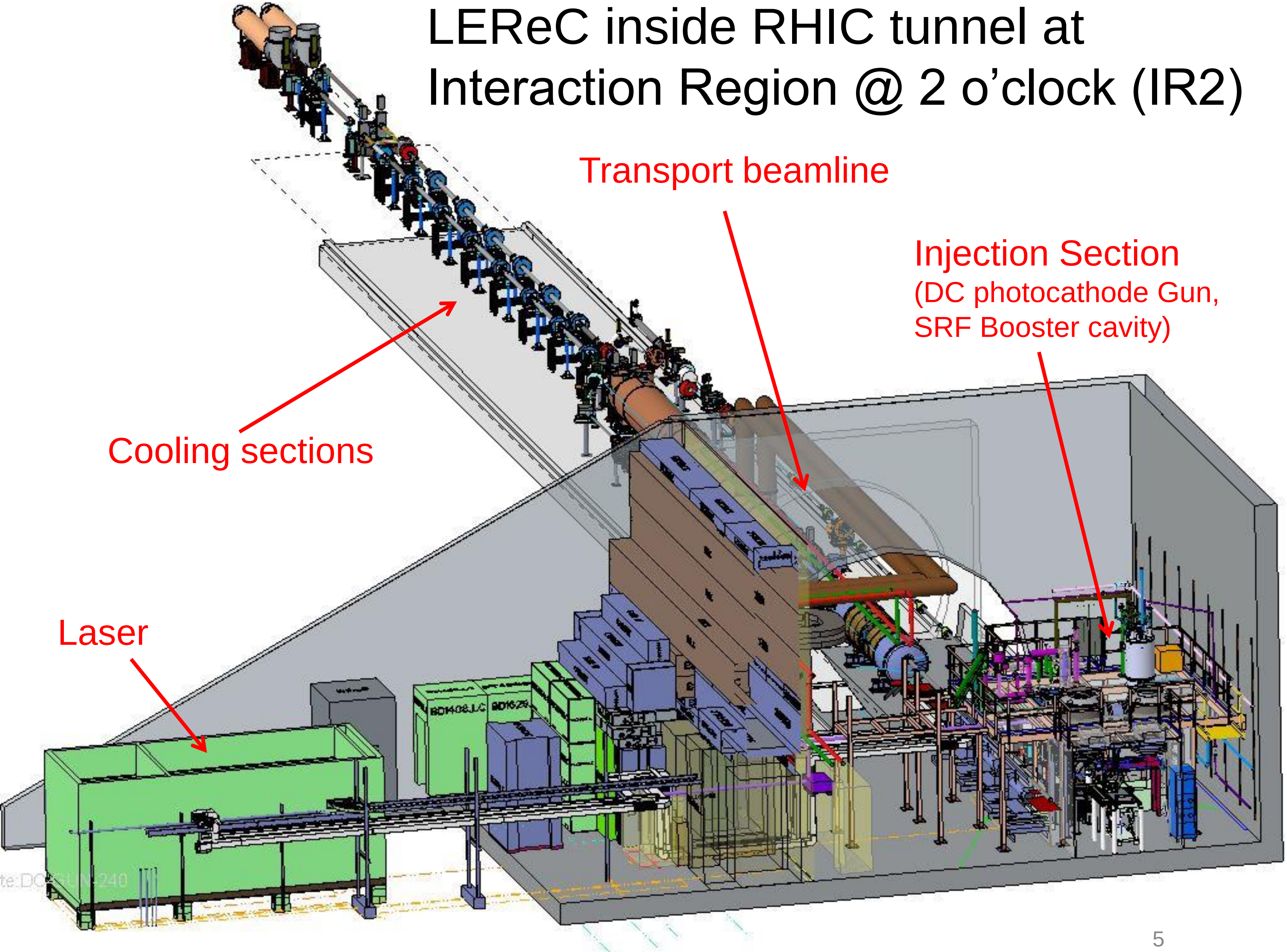
The goal of the LEReC project is to provide luminosity improvement for RHIC operation at low energies to search for the QCD critical point (Beam Energy Scan Phase-II physics program).

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

To provide luminosity improvement with such approach requires:

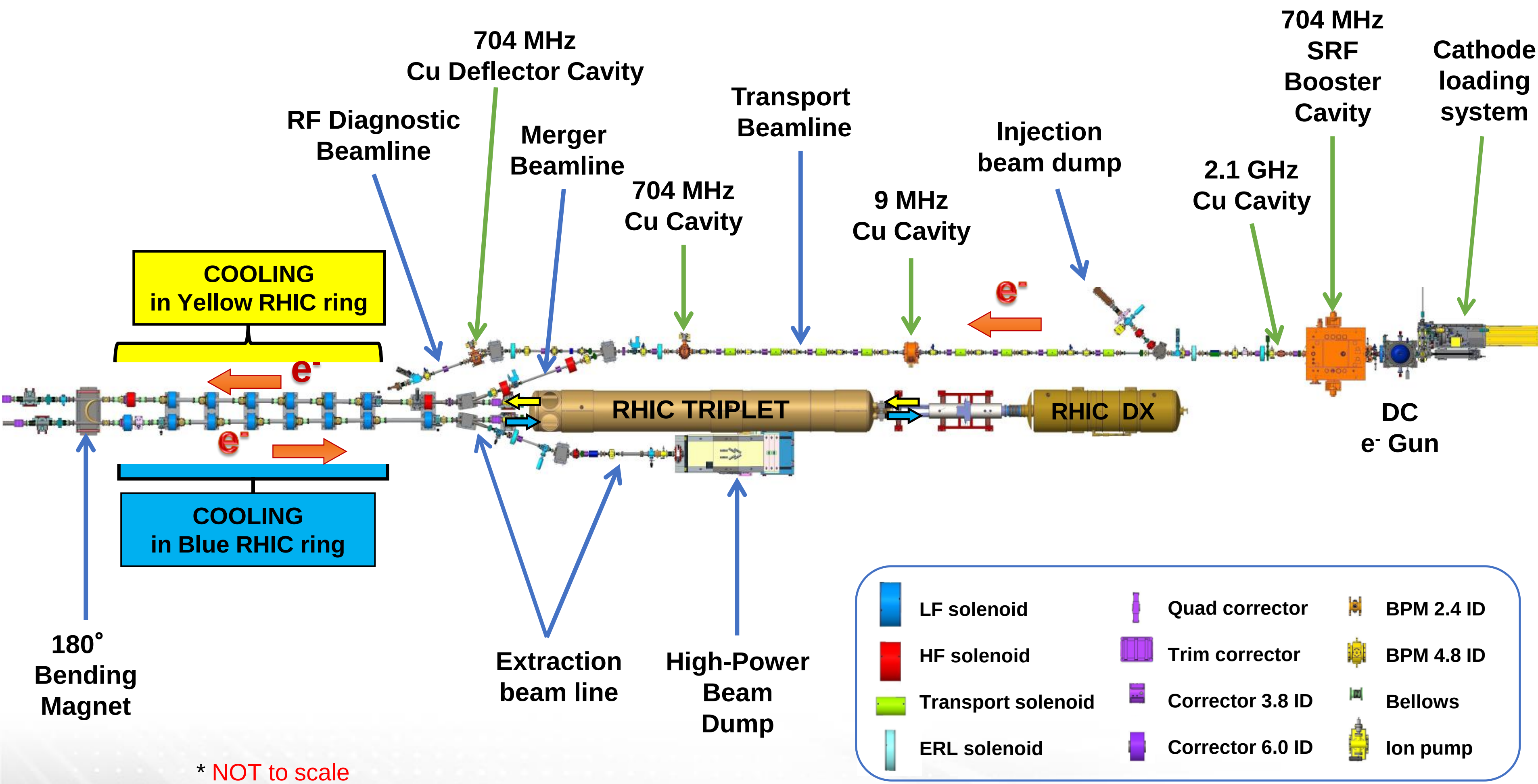
- **Building and commissioning of new state of the art electron accelerator**
- **Produce electron beam with beam quality suitable for cooling**
- **Transport with RF acceleration maintaining required beam quality**
- Achieve required beam position and energy stability in cooling sections
- Commissioning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

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



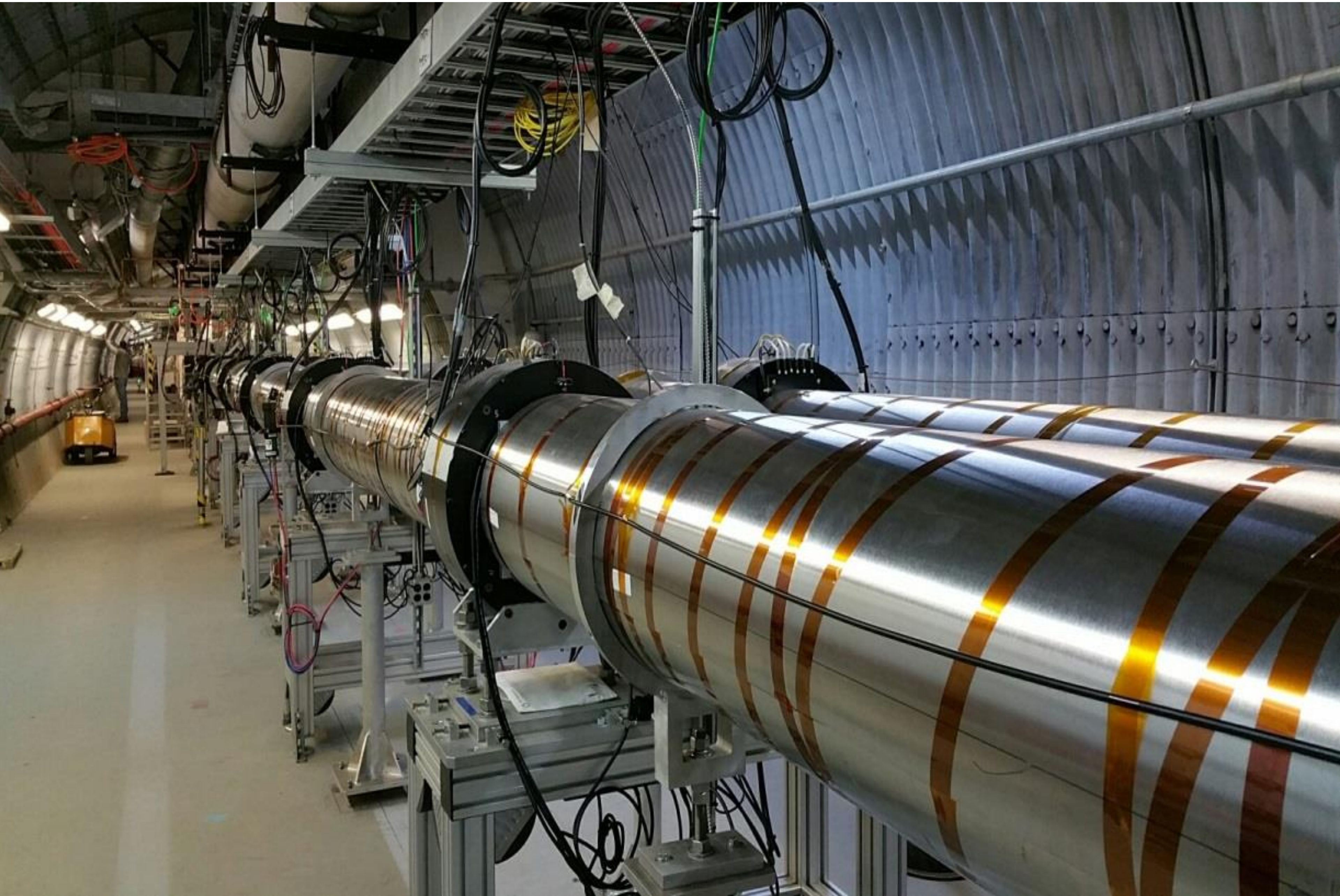
LEReC Accelerator

(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

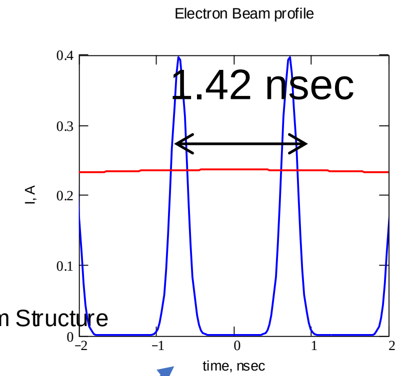
Electron beam requirement for cooling			
Kinetic energy, MeV	1.6*	2	2.6
Cooling section length, m	20	20	20
Electron bunch (704MHz) charge, pC	130	170	200
Effective charge used for cooling	100	130	150
Bunches per macrobunch (9 MHz)	30	30	24-30
Charge in macrobunch, nC	4	5	5-6
RMS normalized emittance, 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)

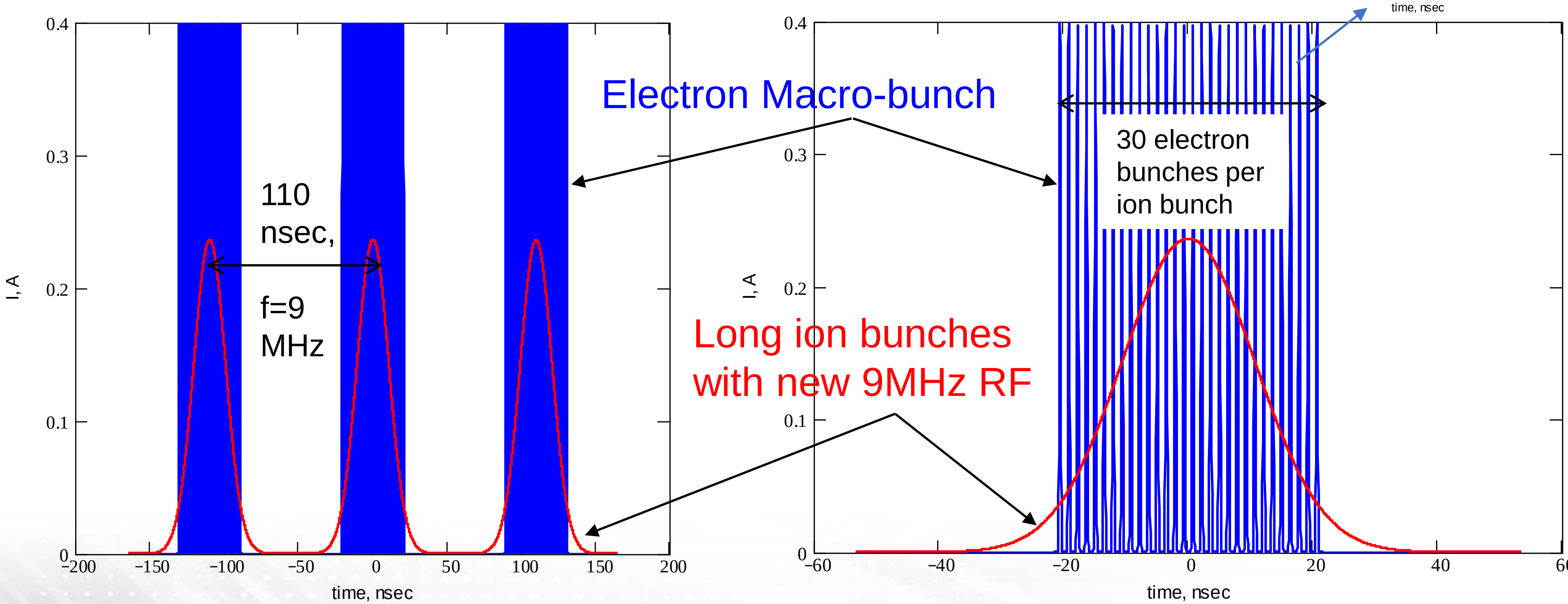
LEReC beam structure in cooling section

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

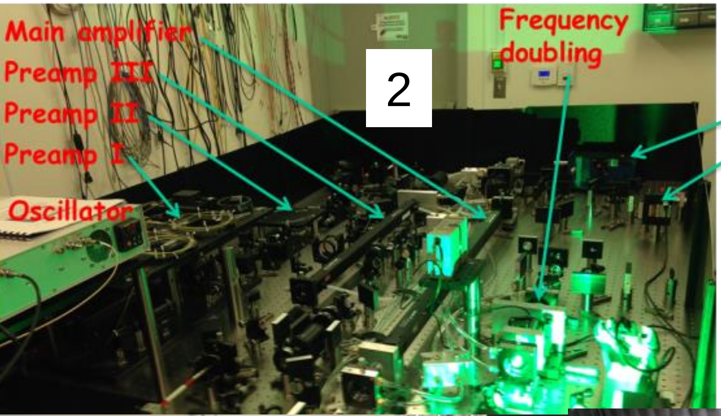


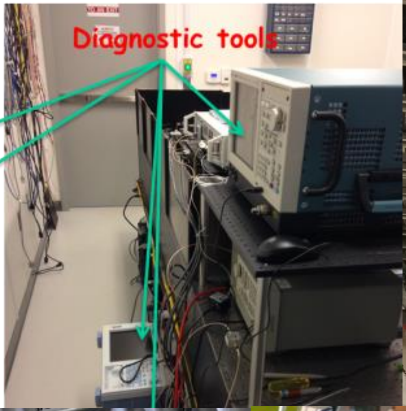
9 MHz bunch structure

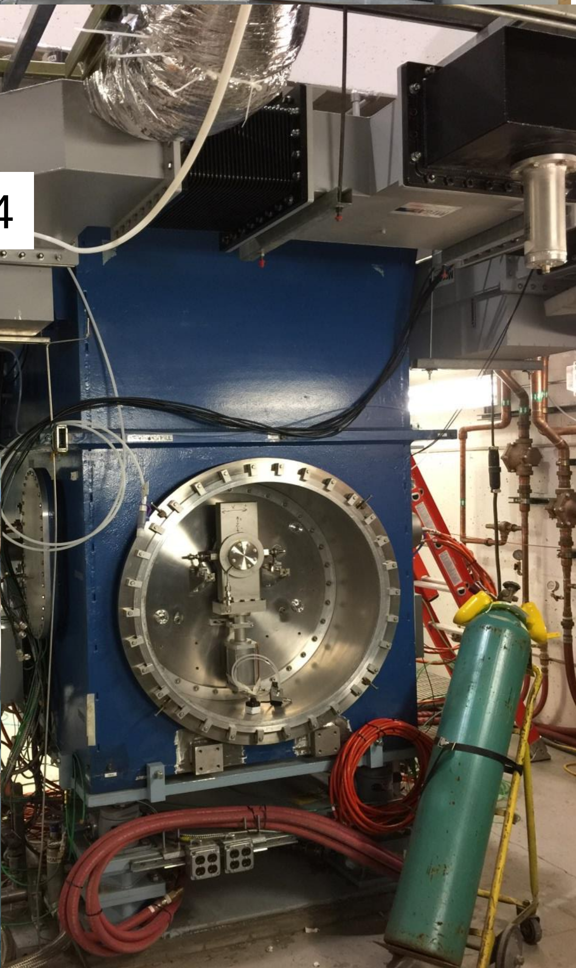


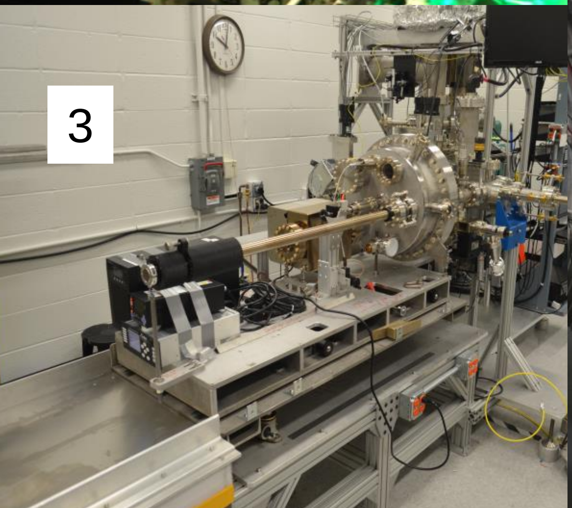
LEReC Critical Technical Systems

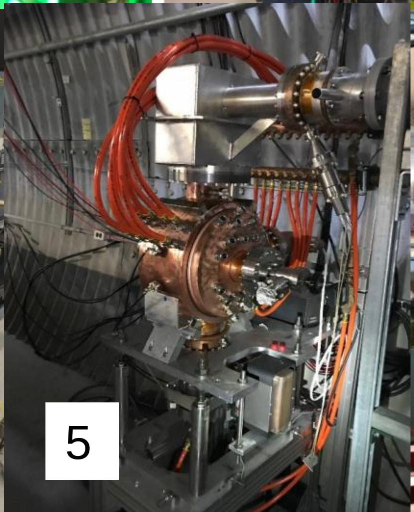
1. DC photocathode electron gun and HV PS
2. High-power fiber laser system and transport
3. Cathode production deposition and delivery systems
4. SRF Booster cavity
5. 2.1 GHz and 704 MHz warm RF cavities

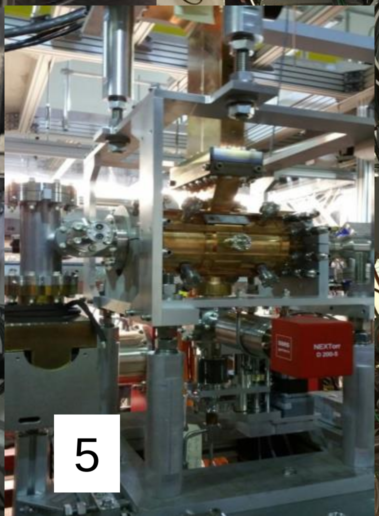












Commissioning with e-beam

- **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

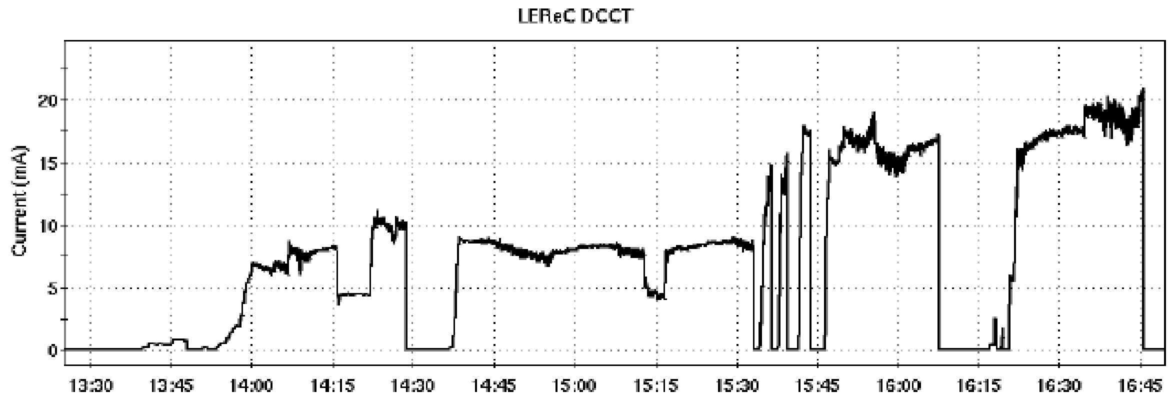
Goals: Achieve stable high-current operation of accelerator with electron beam parameters suitable for cooling.

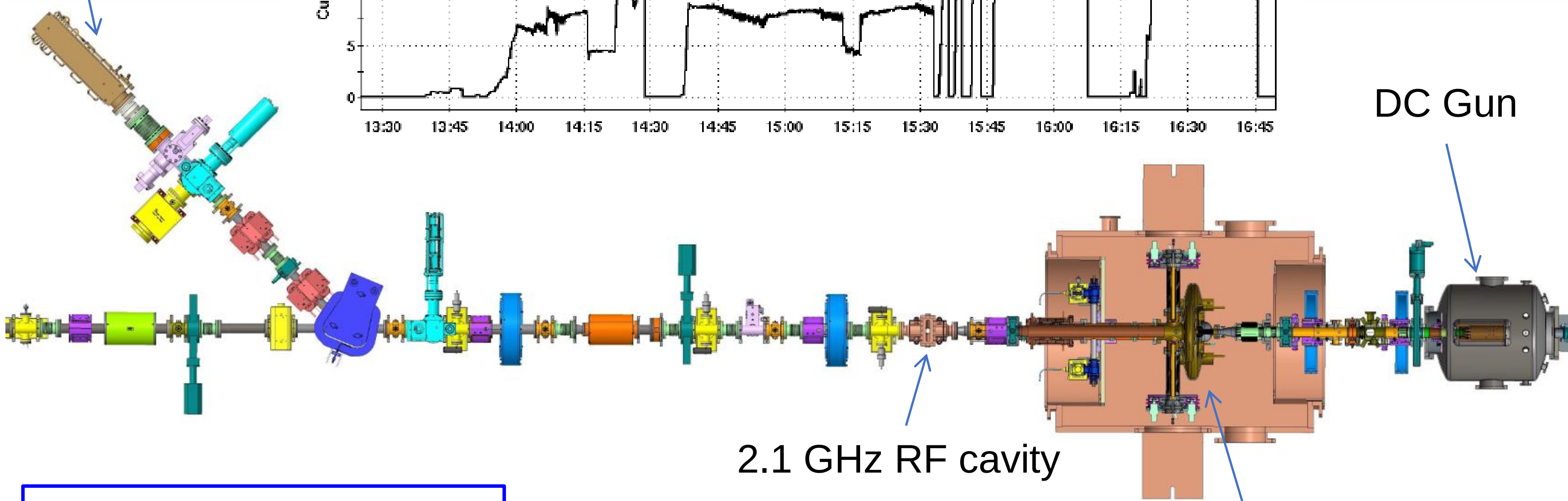
- **Phase 3** (2018-2019): Transition to operations

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.

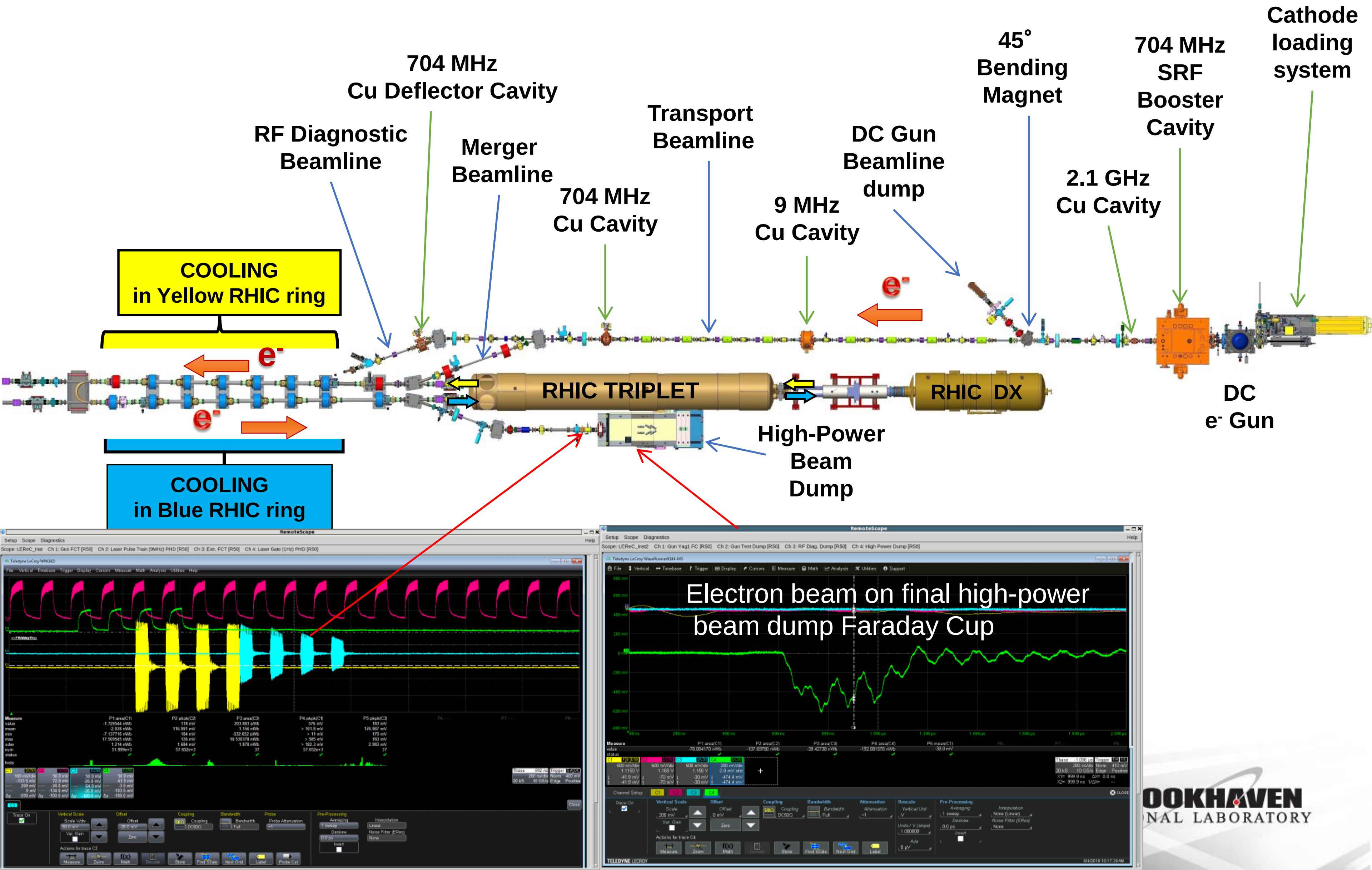
LEReC Injection section (June 6, 2018)





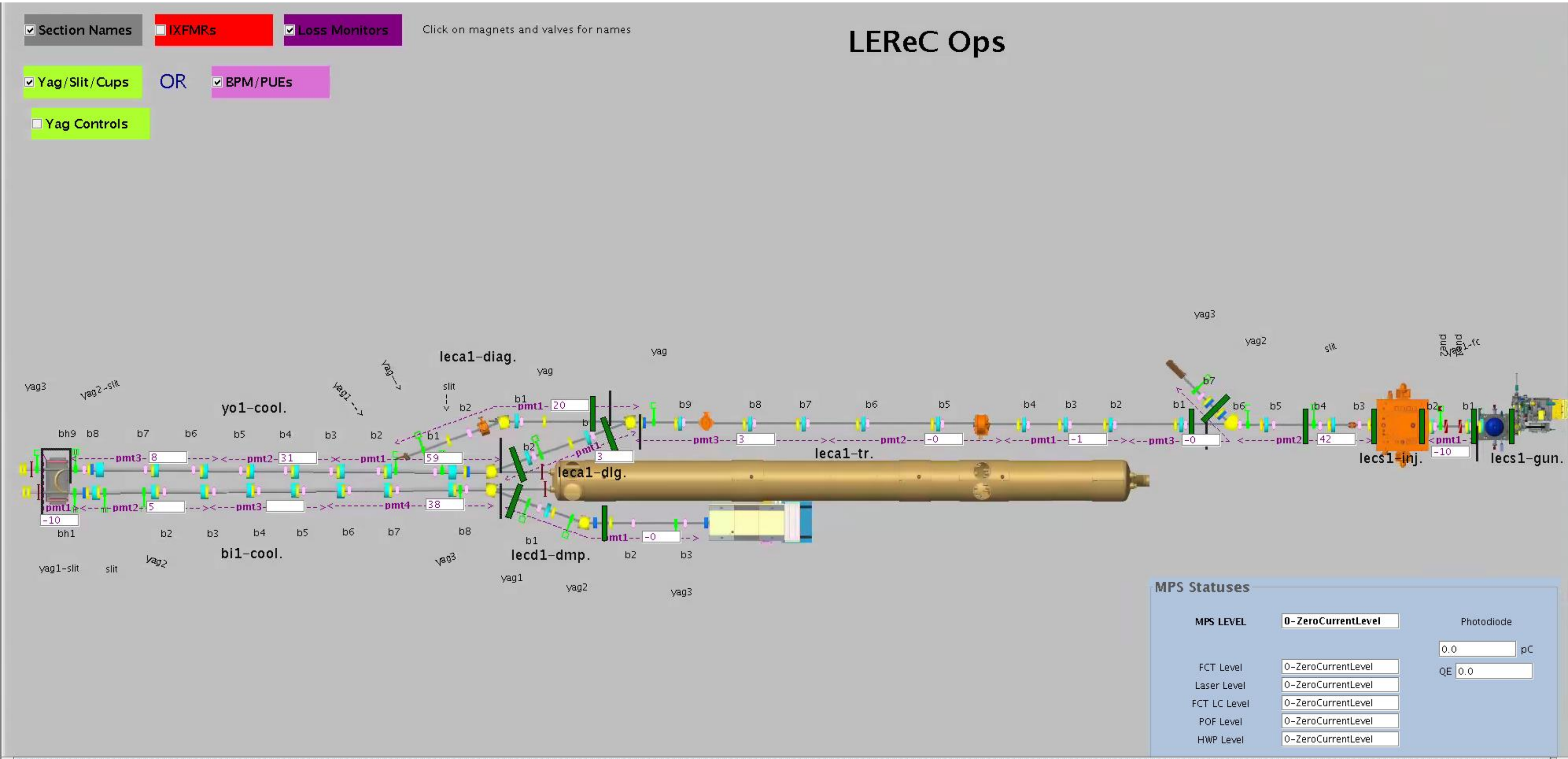
Reached 20mA current.
Design current 30-55mA.

Beam propagated all the way to final beam dump (June, 2018)



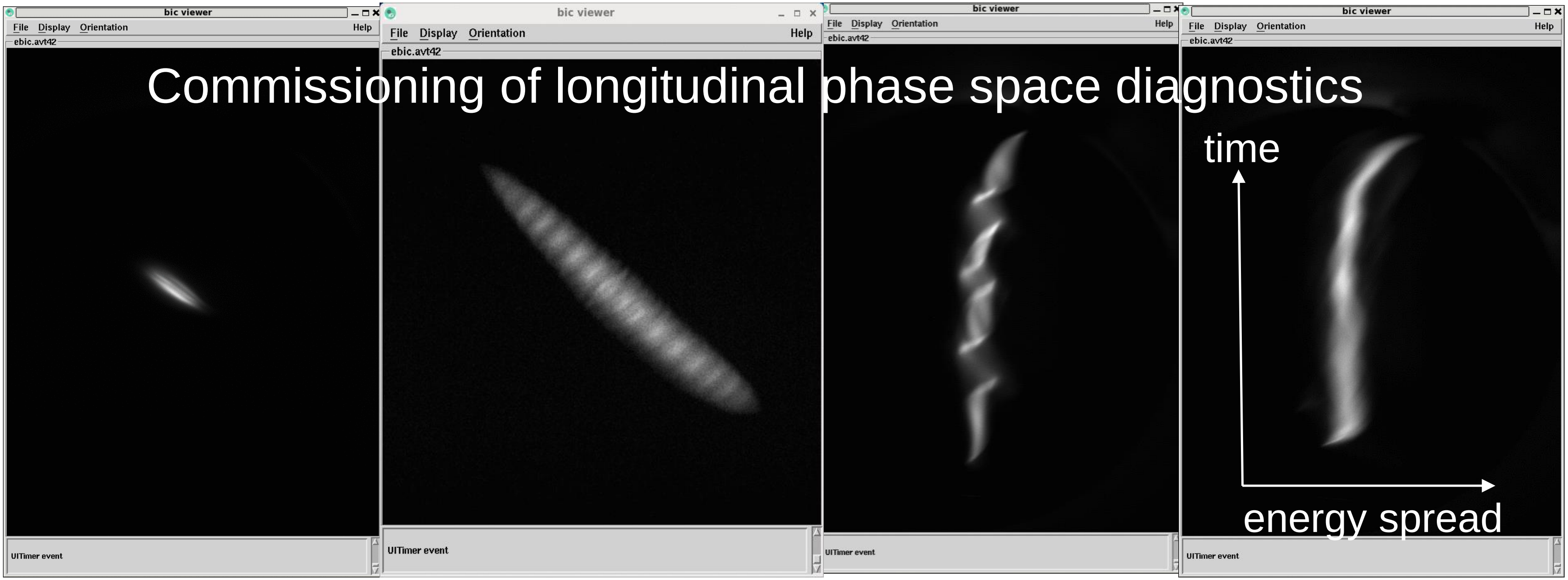
Instrumentation commissioning

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).
- Established reliable production and delivery of cathodes with high QE.
- 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.
- Measured emittance and energy spread in injection and RF diagnostics lines, respectively, are close to design values.
- High-current CW commissioning in injection section. Reached 20mA. Design operational current 30-55mA.

Remaining major commissioning tasks

1. Finish Gun PS tests with Cornell's chassis.
2. Implement changes to BNL chassis and confirm that PS in stable.
3. Pulsed mode: finish commissioning of remaining instrumentation, including energy spectrometer and energy calibration.
4. Achieve required electron beam parameters in both cooling sections.
5. Establish CW transport to high-power beam dump.
6. Establish high-current CW transport to high-power beam dump.
7. Establish required RF stability both in amplitude and phase.
8. Achieve required laser stability and profile uniformity.
9. Establish beam-based alignment.
10. Establish orbit and energy stability control.

Remaining minimum goals (towards Project Key Performance Parameters, KPPs):

1. Establish required electron beam parameters (emittance and energy spread) in both cooling sections.
2. Transport 1mA CW current to high-power beam dump.
3. Study cathode QE lifetime with 30mA current (at reduced energy to injection dump or at full energy to high power beam dump). Need several long term (>1 hour) runs at 30mA.

Remaining maximum goals (beyond KPPs)

1. Establish stable high-current 30mA at 1.6 MeV in high-power beam dump (going through all hold points, faults studies, beam halo/losses studies, etc.)
2. Commission full accelerator at 2.0 MeV
3. Commission full accelerator at 2.6 MeV (requires SRF booster conditioning to 2.2 MV)

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

Few example of items to be addressed by Subsystems

DC Gun HVPS:

- Making power supply stable (tests with Cornell's control chassis underway)
- Voltage ripple measurements and improvement

Laser:

- Stable MPS EOM/PC ratio for CW operation
- Short-term and long term stability; intensity feedback in CW
- Profile uniformity

RF:

- Stable 2.1GHz operation with voltage up to 250kV.
- RF amplitude and phase stability
- Beam-loading and feedforward

Instrumentation:

- Reliable FCT signals; effects of RF noise
- Use of loss monitors in RHIC environment

Gun vacuum:

- Achieve better Gun vacuum for good cathode QE lifetime

For detailed list of items by subsystems one can check slides on:

https://indico.bnl.gov/event/4769/timetable/#20180702

Shutdown work before next year Run

1. Cryogenics: He sub-cooler fix
2. Gun anode assembly modifications (design and fabrication; installed to be decide based on the schedule).
3. Inspection of cathode surface area. Taking Gun apart is a possibility (would result in significant downtime and risk).
4. Adding more pumps to improve Gun vacuum.
5. Gun resistor chain repairs.
6. Adding capacitors for voltage ripple reduction.
7. Implementation of resistor switch (to be decided).
8. Gun-to-booster corrector modifications.
9. Other work. The list of needed work will increase by the end of commissioning.

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:

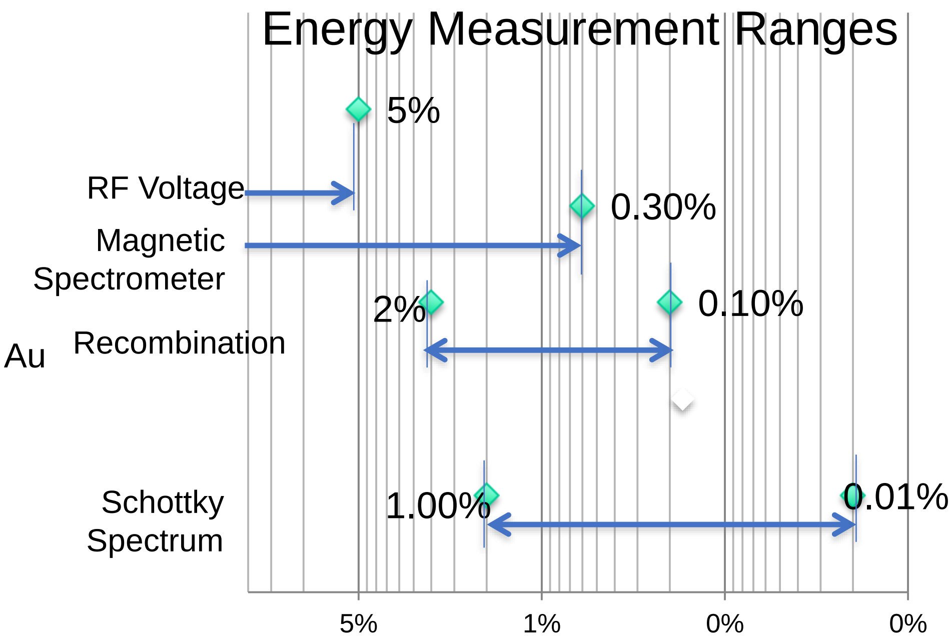
- ➢ Interaction of electron and ion beams: with e-beam parameters established (current, energy, energy spread, emittance, required stability) establish overlap between Au and electron beams in (x, y, p)
- ➢ Demonstration of bunched beam cooling
- ➢ Effects on hadron beam (cooling vs. heating)
- ➢ Effects 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

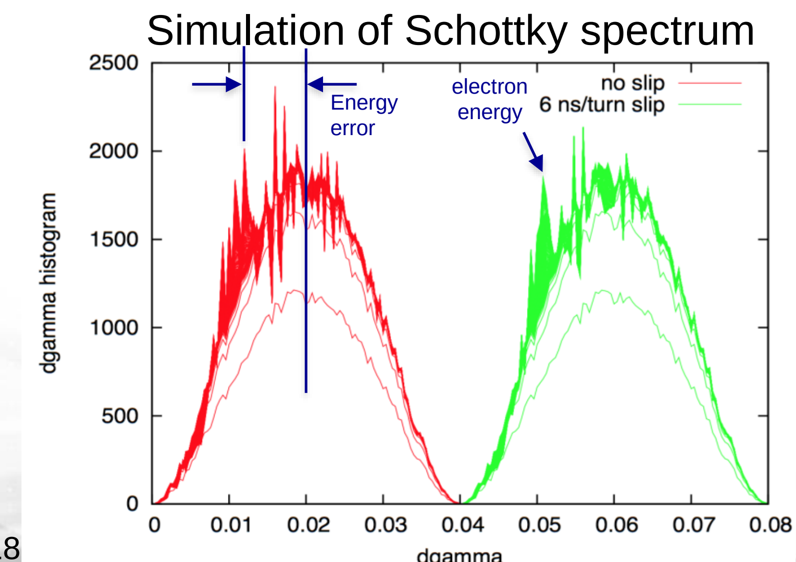
Cooling commissioning strategy

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





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.

LEReC plans after end of commissioning

ALL dates are tentative, schedule for required work during LEReC shutdown is yet to be developed.

September 15, 2018:	LEReC commissioning finished; shutdown work starts
Sep.15 - Dec.15, 2018:	Required repairs/upgrades: very short time for upgrades and modifications
Dec. 15-30, 2018:	Gun conditioning
January 2, 2018:	SRF booster is cold
January 2, 2018:	Restart tests with electron beam. Achieve required electron beam stability in cooling sections.
March 1, 2018:	Start cooling commissioning with ion beam

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Acknowledgement

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As well as FNAL, ANL, JLAB and Cornell University.

Special thanks to LEReC Commissioning Team

led my Dmitry Kayran

Thank you!