Status of Bunched Beam Low Energy RHIC electron Cooling (LEReC) Project

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for the LEReC team

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COOL17, Bonn, Germany

LEReC Project Mission/Purpose

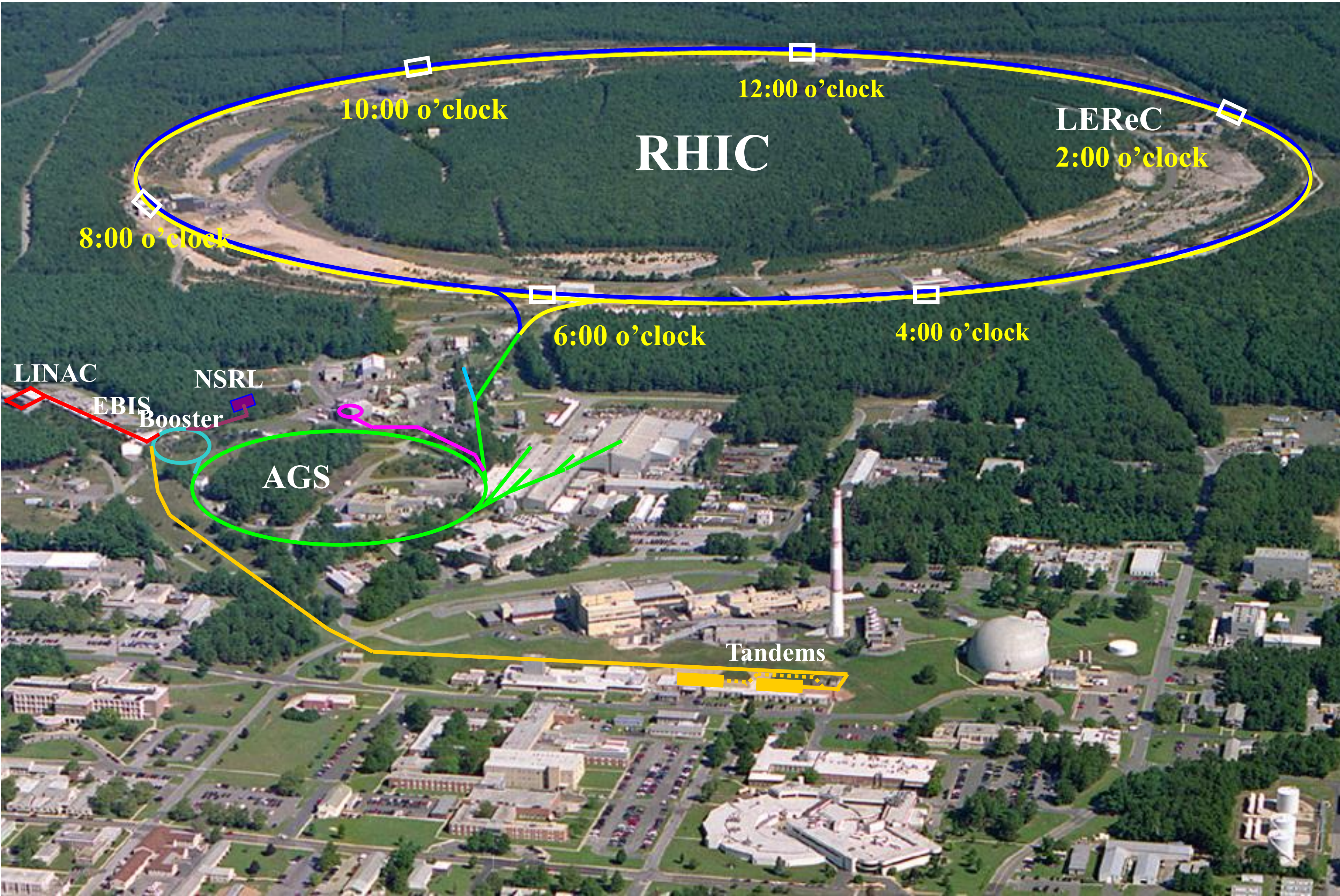
The purpose of the LEReC is to provide luminosity improvement for RHIC operation at low energies to search for the QCD critical point (Beam Energy Scan Phase-II physics program).

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

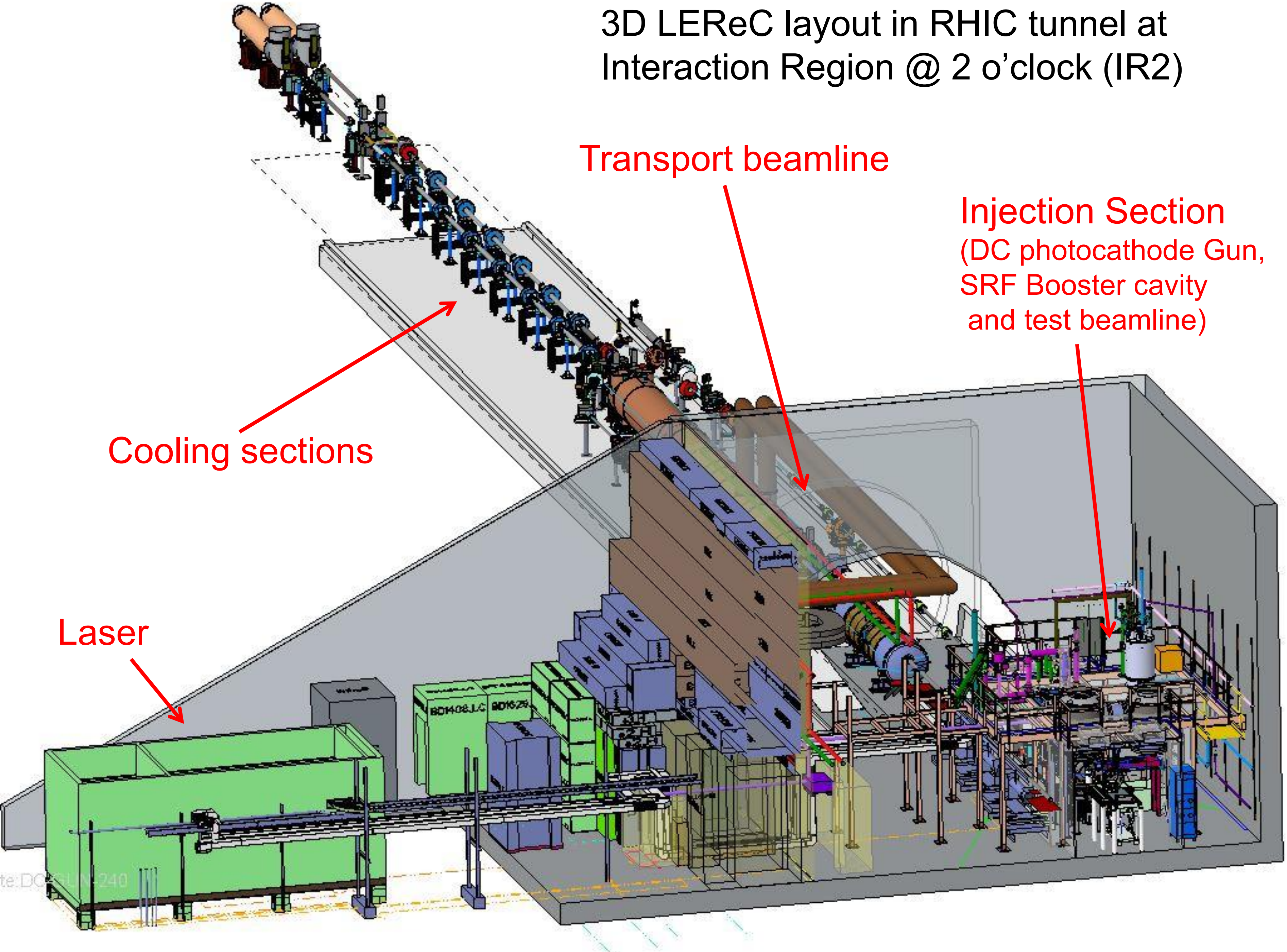
To provide luminosity improvement with such approach requires:

- 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
- Commissioning of bunched beam electron cooling
- Commissioning of electron cooling in a collider

RHIC @ BNL, Long Island, New York



3D LEReC layout in RHIC tunnel at Interaction Region @ 2 o'clock (IR2)



Choice of electron cooler accelerator

- For high energies (from a few to several tens of MeV) RF-based acceleration and bunched electron beam cooling appears to be an attractive approach (studied in detail for RHIC-II 55 MeV high-energy electron cooler proposal in 2001-2007, for example).

- For medium energies 2-5 MeV, different approaches are possible:

For LEReC we considered:

DC electrostatic accelerator (DC beam)

RF accelerator (bunched beam) - final choice

The main challenge for bunched electron beam approach is to provide beam transport without significant degradation of beam emittance and energy spread, especially at low energies.

LEReC design energies

RHIC Beam Energy Scan II Physics Program 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 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: un-magnetized electron cooling

This will be the first cooling without any magnetization.

Un-magnetized friction force:

$$\vec{F} = -\frac{4\pi n_e e^4 Z^2}{m} \int \ln\left(\frac{\rho_{\max}}{\rho_{\min}}\right) \frac{\vec{V} - \vec{v}_e}{\left|\vec{V} - \vec{v}_e\right|^3} f(v_e) d^3 v_e$$

- Un-magnetized cooling:

  very strong dependence on relative angles between electrons and ions.
- Requires strict control of both transverse angular spread and energy spread of electrons in the cooling section.
- LEReC: need to keep total contribution (including from emittance, space charge, remnant magnetic fields) below 150 μrad.

asymptotic for $v_{ion} < \Delta_e$:

$$\vec{F} = -\frac{4\pi Z^2 e^4 n_e L}{m} \frac{\vec{v}_i}{\Delta_e^3}$$

$$\vec{F} = -\frac{4\pi Z^2 e^4 n_e L}{m} \frac{\vec{v}_i}{\beta^3 c^3 ((\gamma \vartheta)^2 + \sigma_p^2)^{3/2}}$$

Requirement on electron angles:
For γ=4.1: σ_p=5e-4; θ<150 μrad

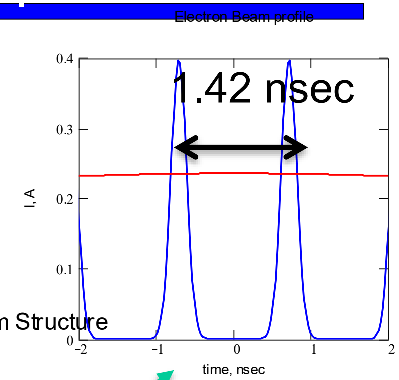
Bunched beam electron cooling for LEReC

- 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 bunch trains with individual electron bunches of about 80 ps full length.
- Accelerate such bunches with RF and maintain beam quality.
- Deliver and maintain beam quality in 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
Example for γ= 4.1 (E_{ke}=1.6 MeV)

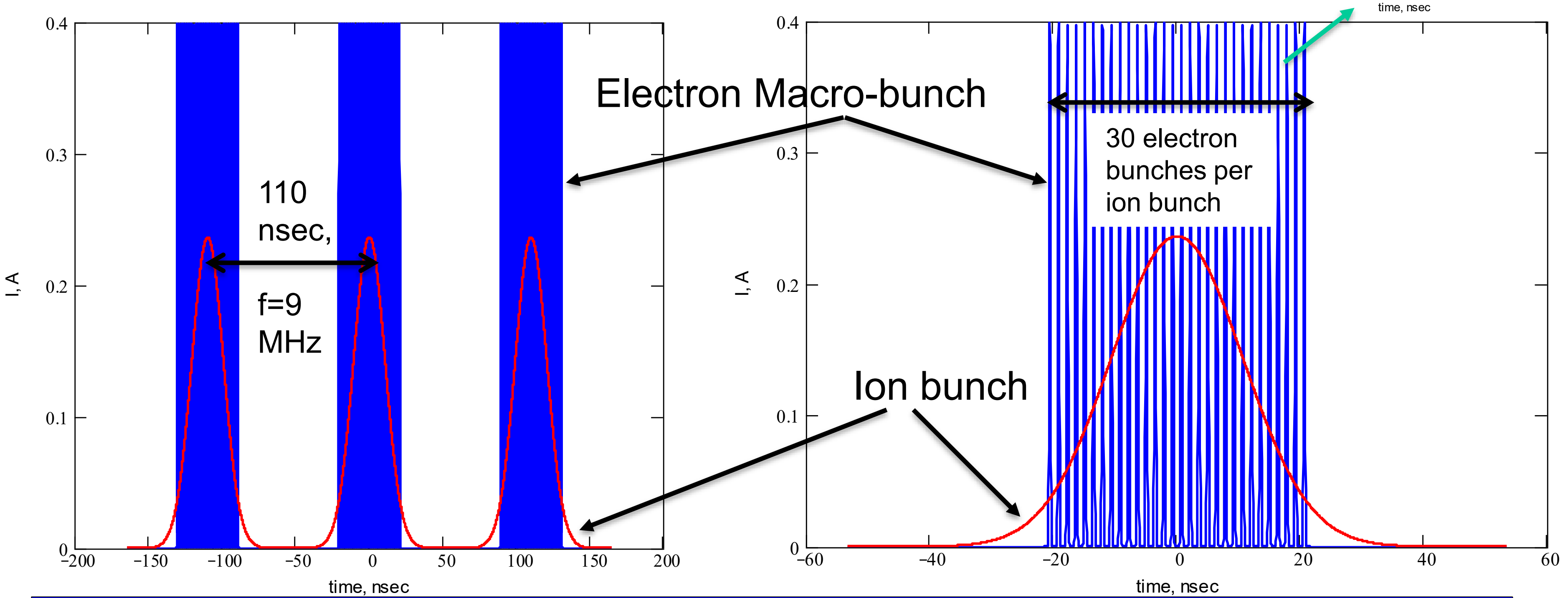
Ions structure:
120 bunches
f_rep=120x75.8347 kHz=9.1 MHz
N_ion=5e8, I_peak=0.24 A
Rms length=3.2 m

Electrons:
f_SRF=703.5 MHz
Q_e=100 pC, I_peak=0.4 A
Rms length=3 cm



LEReC Beam Structure

9 MHz bunch structure

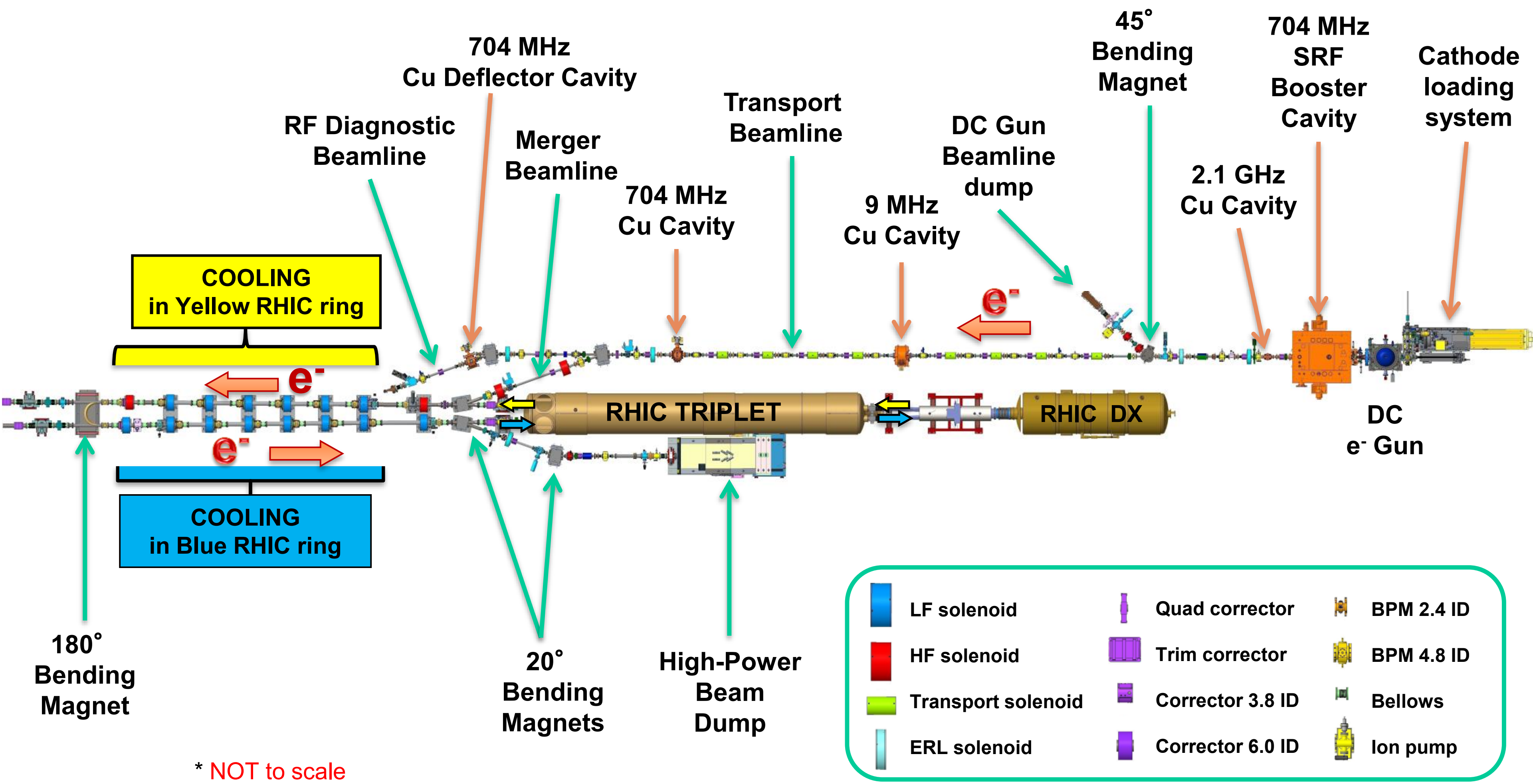


A. Fedotov, COOL'17, Bonn, Germany, September 18-22, 2017

RF gymnastics

- The 704 MHz SRF booster cavity will not only accelerate the electrons but also introduce an energy chirp which causes ballistic stretching of the bunch as it drifts through the transport beam line.
- Additional 704 MHz warm cavity removes the energy chirp before electron and ion beams are merged in the cooling section.
- Warm cavity operating at 2.1 GHz (3^{rd} harmonic of 704 MHz, located next to the SRF booster) removes the curvature of the bunch shape in longitudinal phase space.
- 9 MHz warm RF cavity is being employed to remove bunch-by-bunch energy variation within the 30 bunch train (macro-bunch) caused by beam loading in the RF cavities.

LEReC Accelerator Layout



Electron beam transport

The use of RF-based approach requires careful considerations:
Beam transport of electron bunches without significant degradation of beam 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:

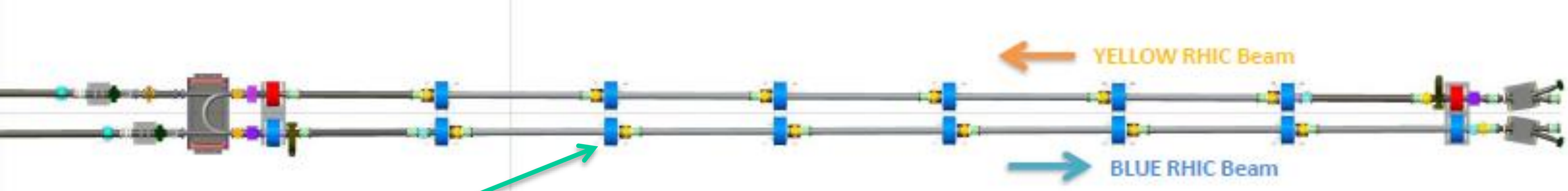
Correction solenoids in the cooling section are used to keep transverse angular spread to a required level.

Strict control of electron angles in cooling sections:

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

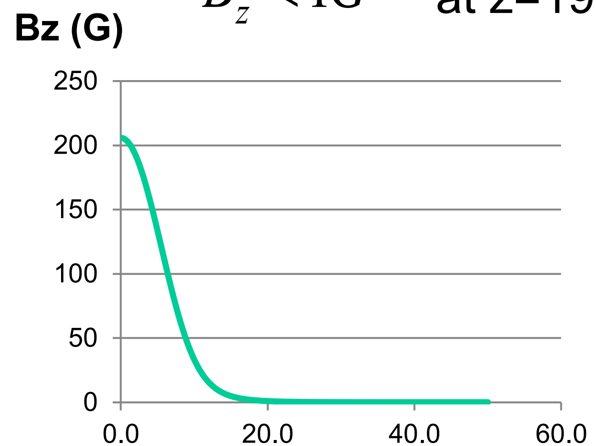
We found that these effects are most difficult to control < 2 MeV.

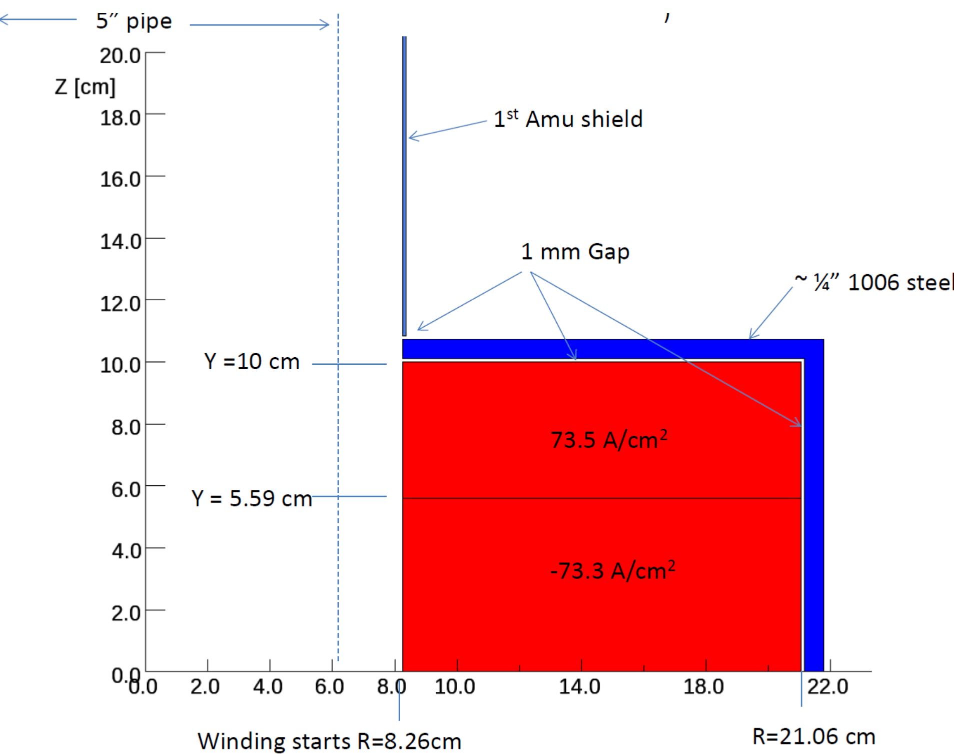
Requirement on magnetic field in the cooling section

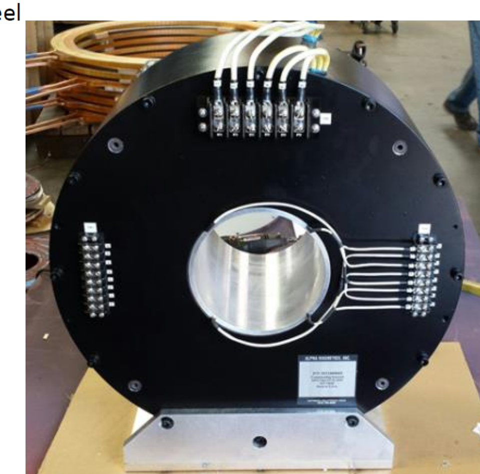


Distance covered by magnetic field from solenoids will be lost from cooling. Expect about 40 cm to be lost from cooling from each solenoid.

Residual longitudinal magnetic field from solenoids in cooling region: $B_z < 1G$ at z=19 cm







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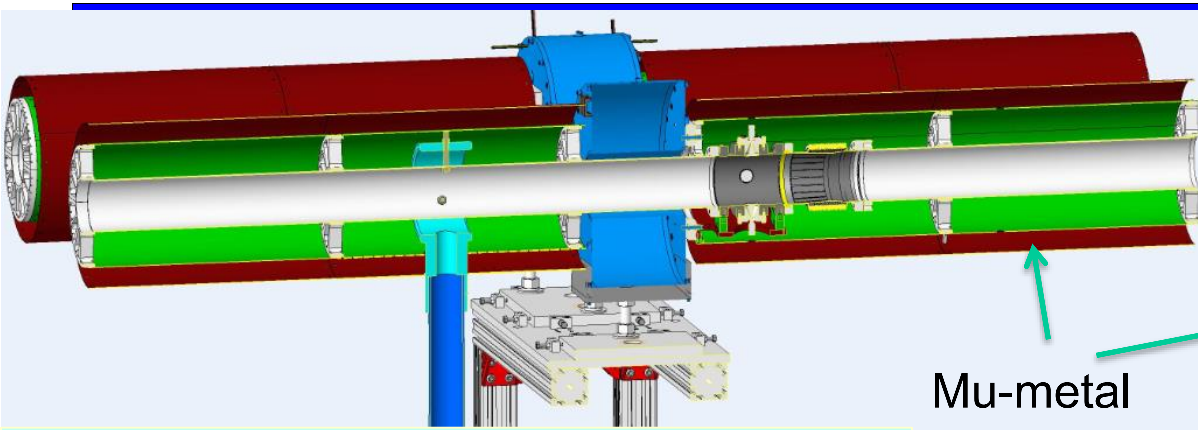
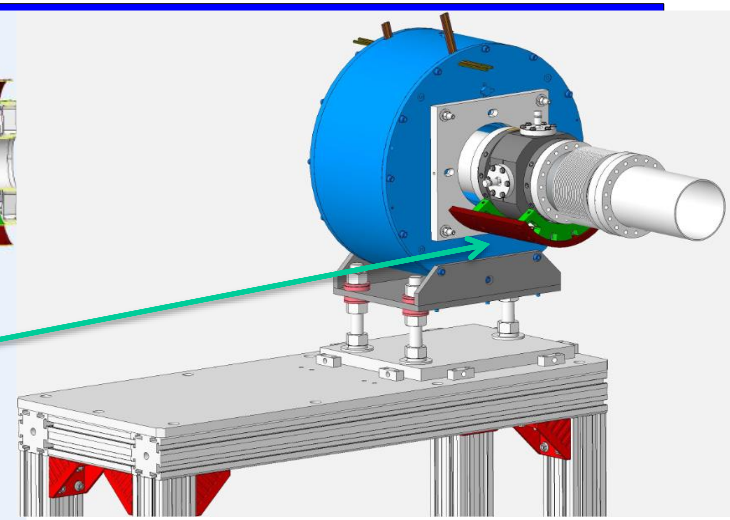
Mu-metal shielding design for cooling sections

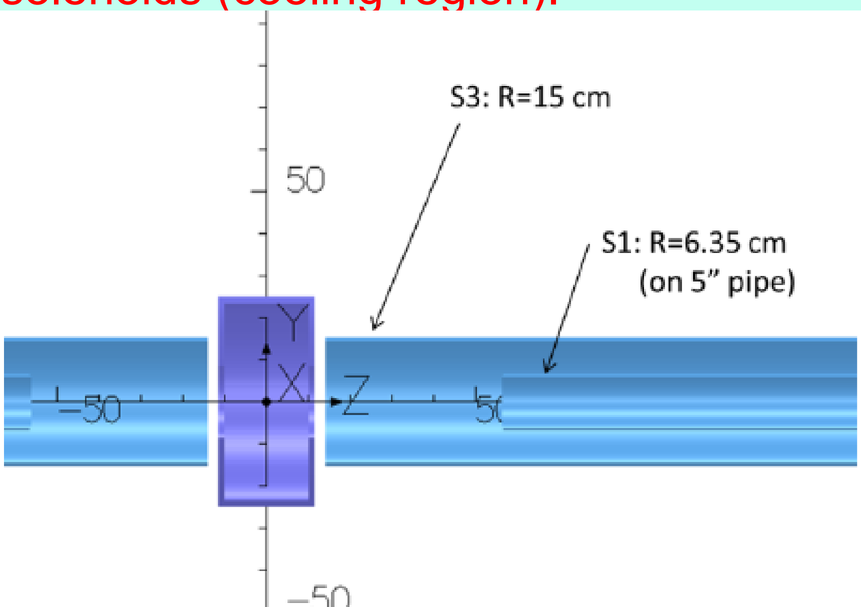




Mu-metal shielding

Mu-metal shielding to suppress transverse magnetic fields to required level in free space between the solenoids (cooling region).

Requirement: $\int B_{\perp}(z)dz \leq 0.6\, G \cdot cm$



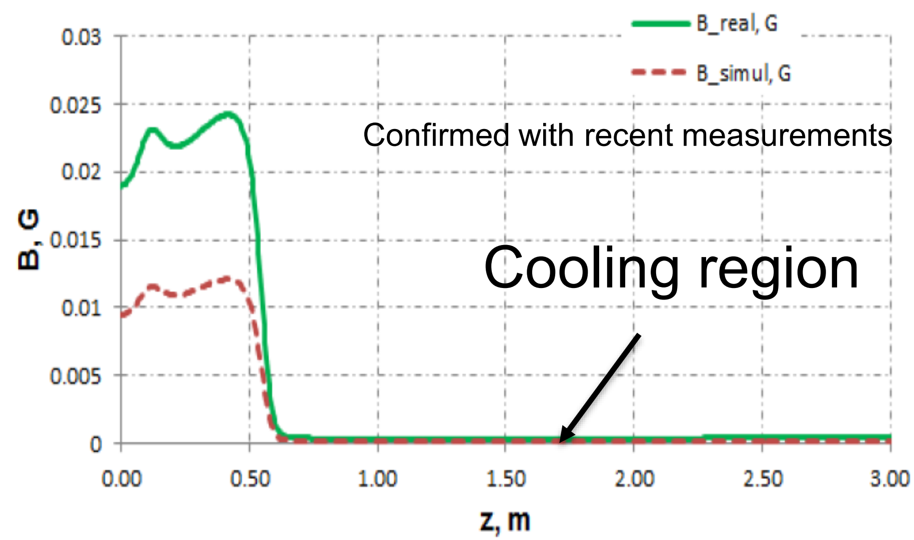


Figure 5: Simulated and "real" (multiplied by 2) residual magnetic field in the cooling section.

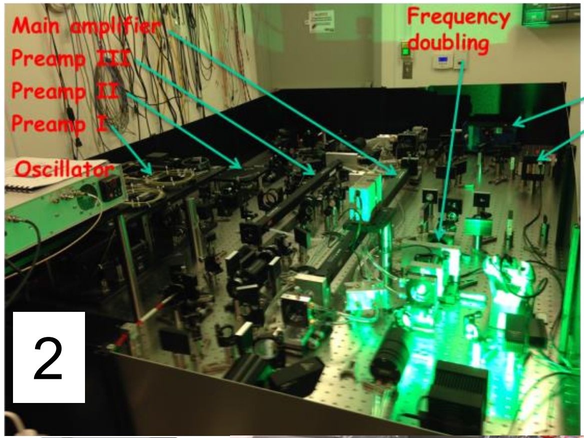
Production of bunched electron beam suitable for cooling

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

- Photocathodes
- High power fiber laser
- Laser beam shaping
- Operation of HV DC gun (400-500kV) with high charge and high average current
- RF gymnastics and stability control

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



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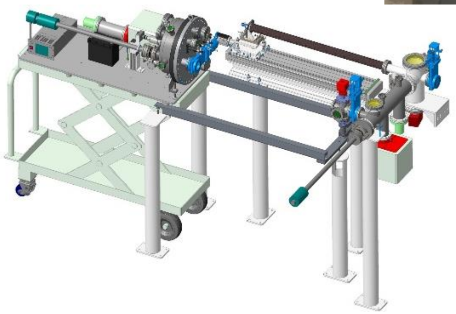
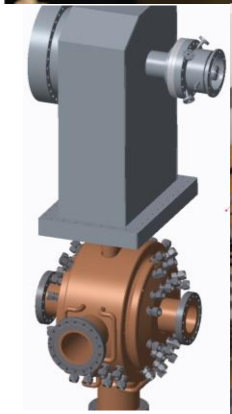
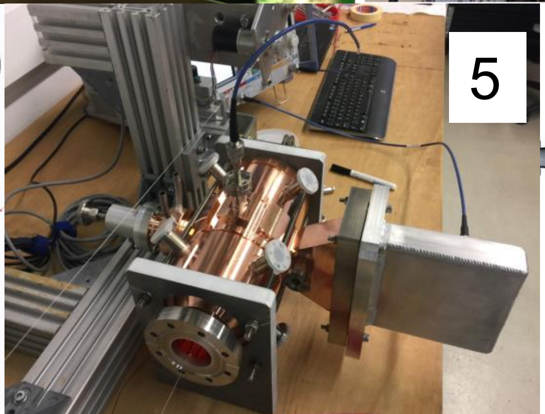
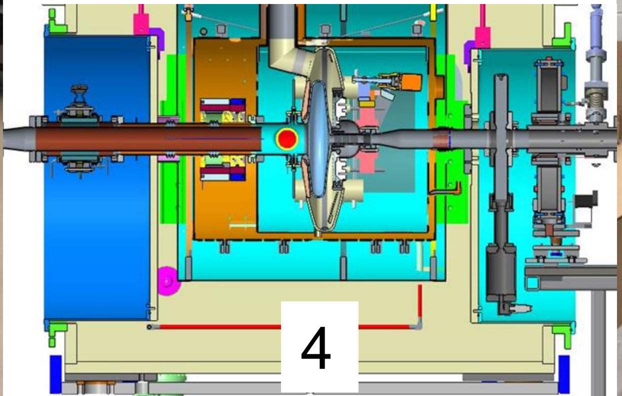
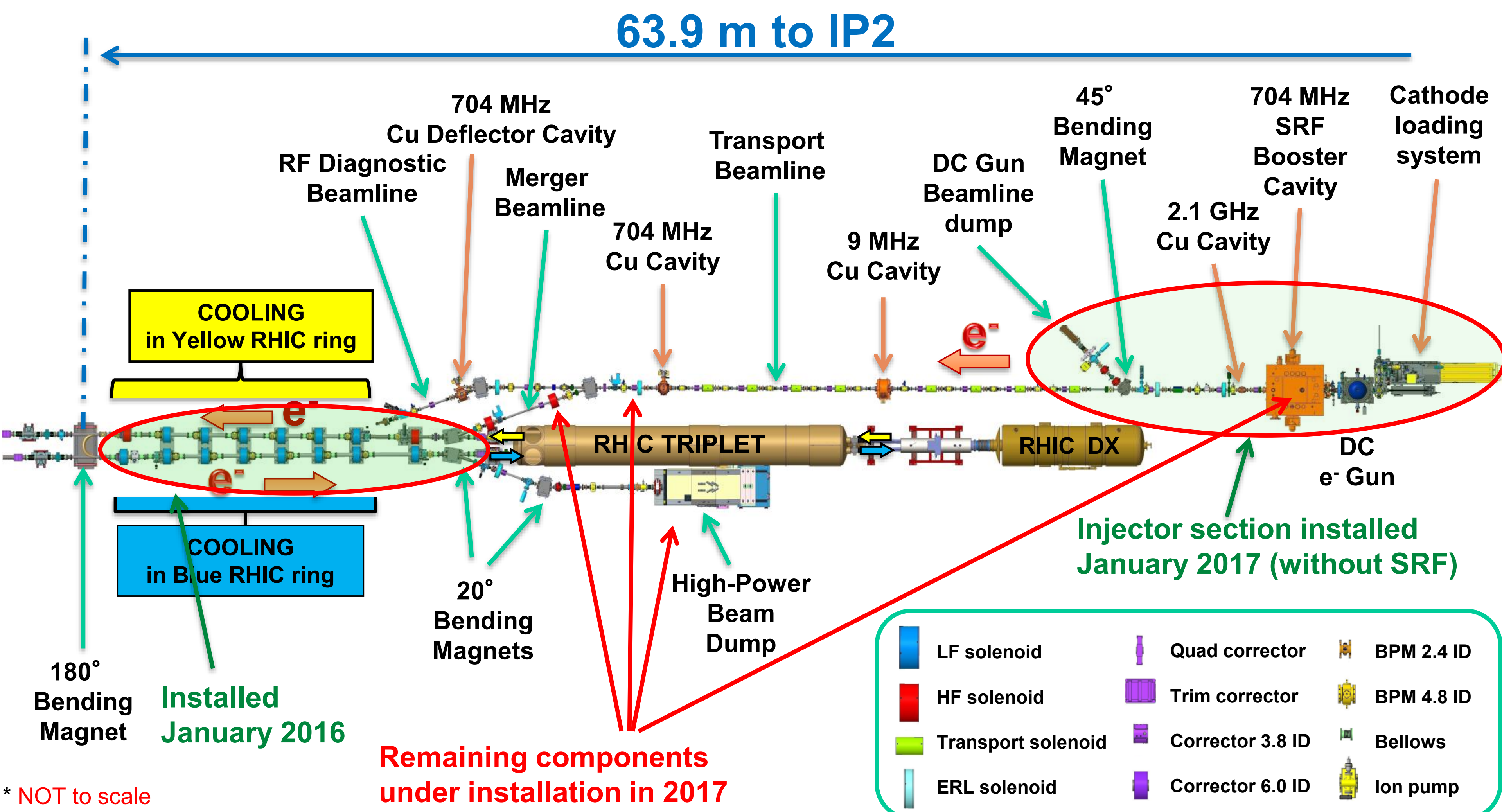




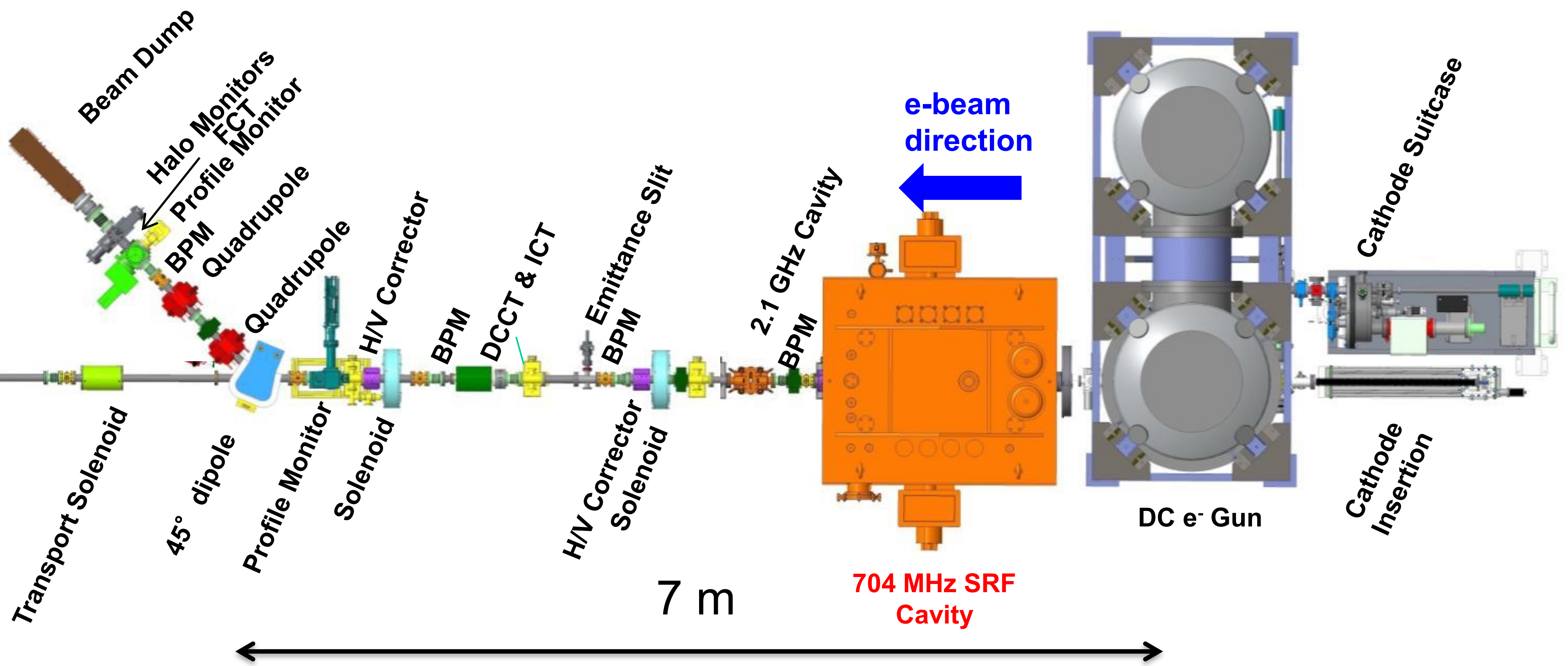




LEReC accelerator (100 meters of beamlines with the DC Gun, 5 RF systems, many magnets and instrumentation devices)

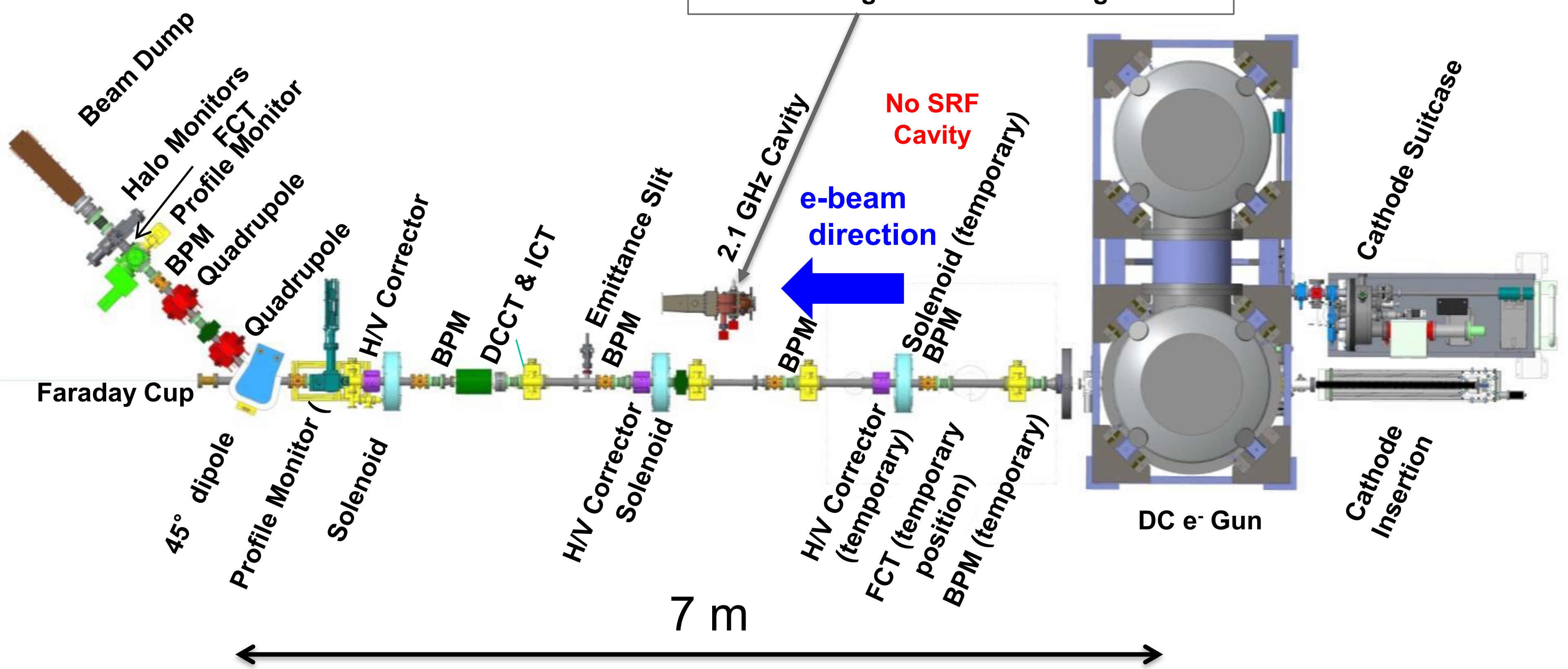


LEReC Injection section (zoom in), 2018



Gun Test setup 2017
(no RF components in beam line)

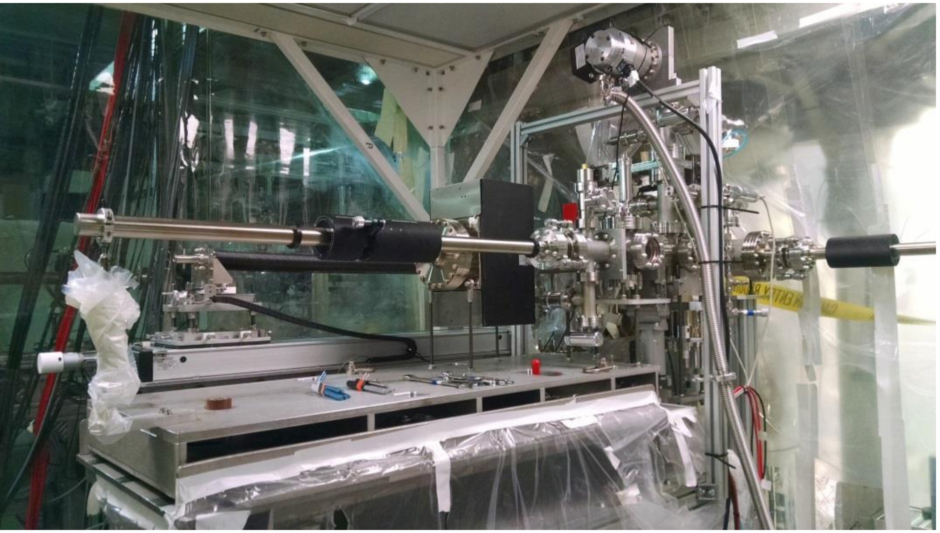
2.1 GHz warm cavity:
The cavity was installed outside of beamline to decouple its commissioning from the DC gun commissioning.



LEReC Gun Test beamline under construction (November 2016)

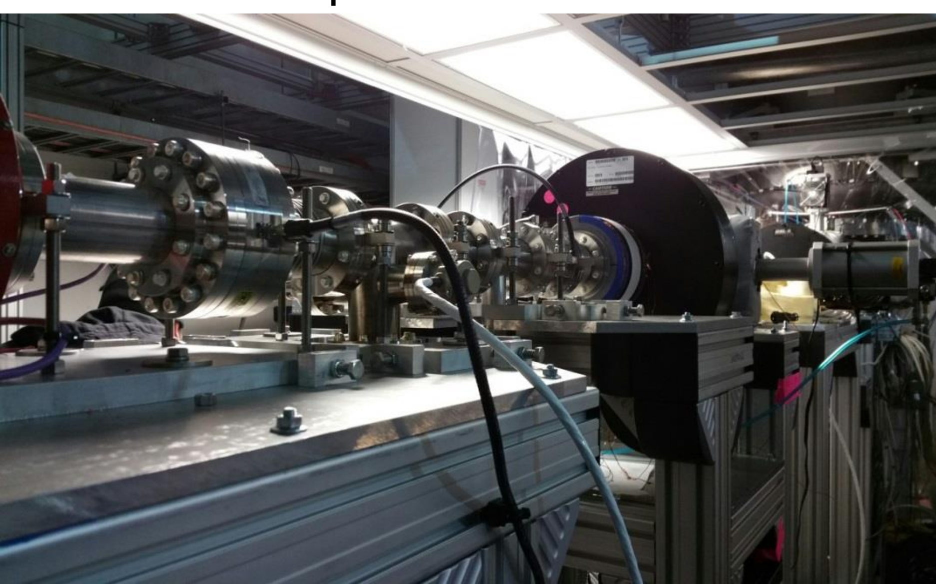
LEReC DC Gun test beamline (installation complete in RHIC IR2, February 2017)

Cathode insertion system

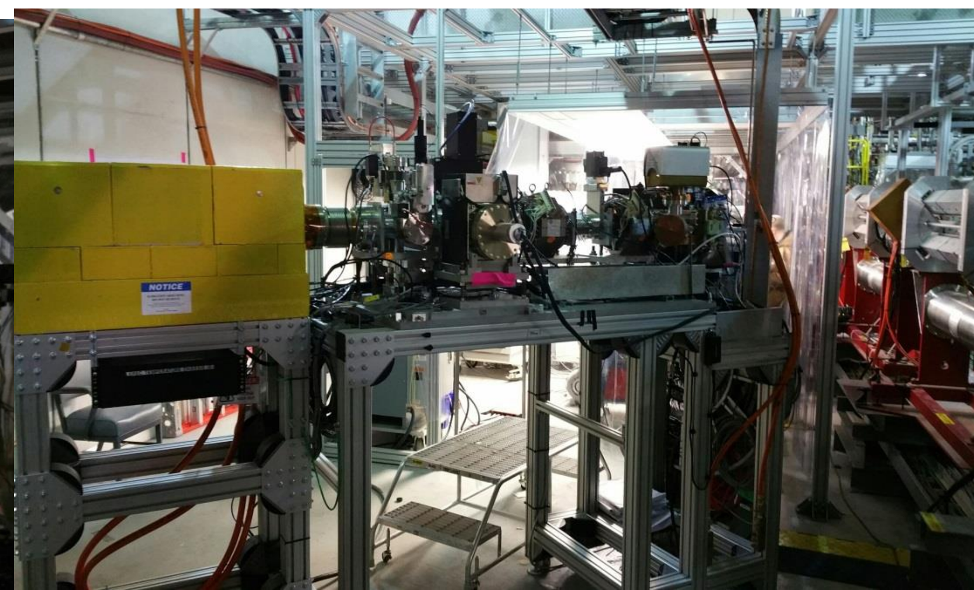


Gun transport section

Transport beamline



Extraction line and beam dump



First photocurrent (DC) observed (April 18, 2017)

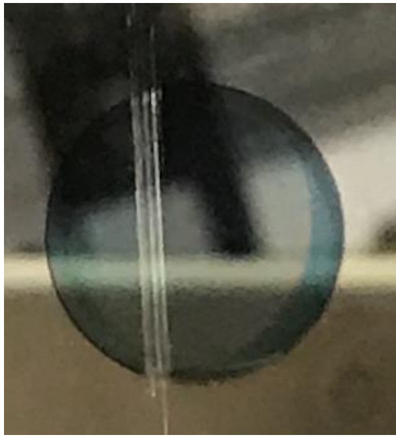
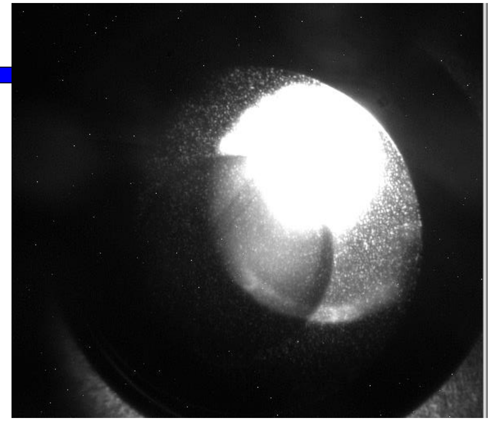
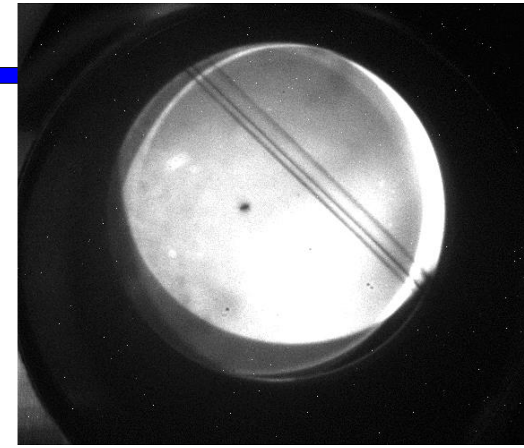


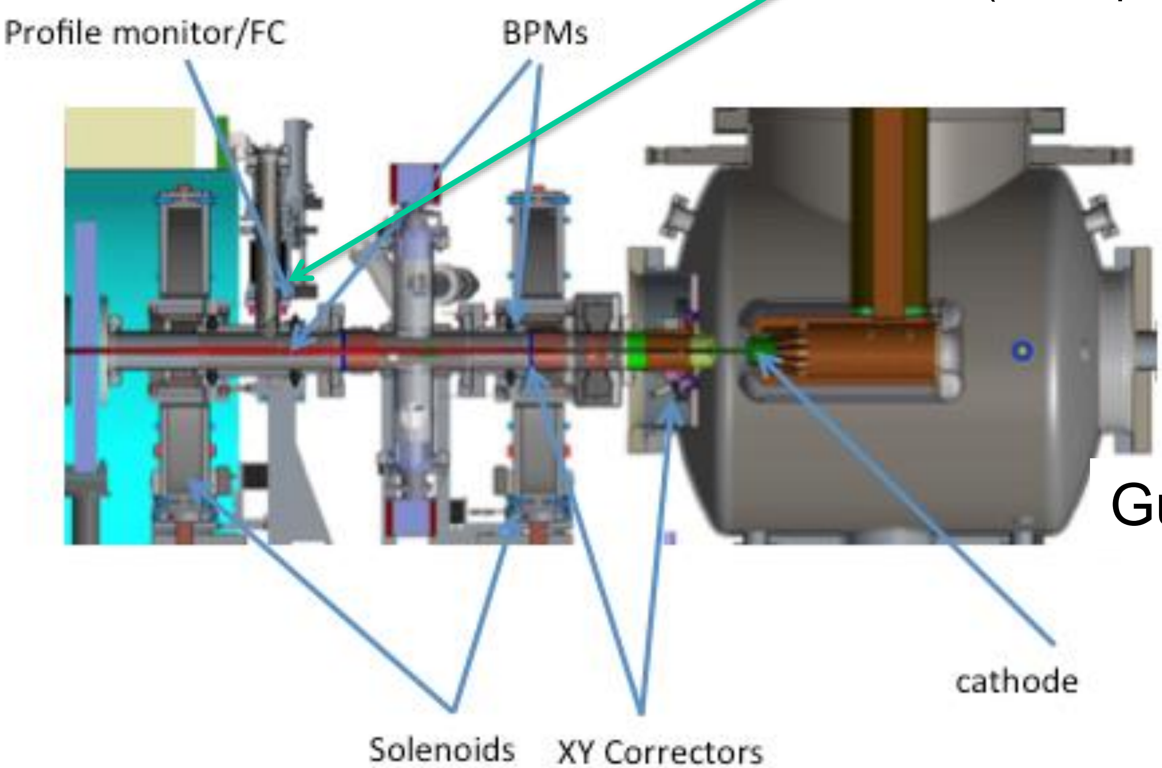
Photo cathode visible light image before installation



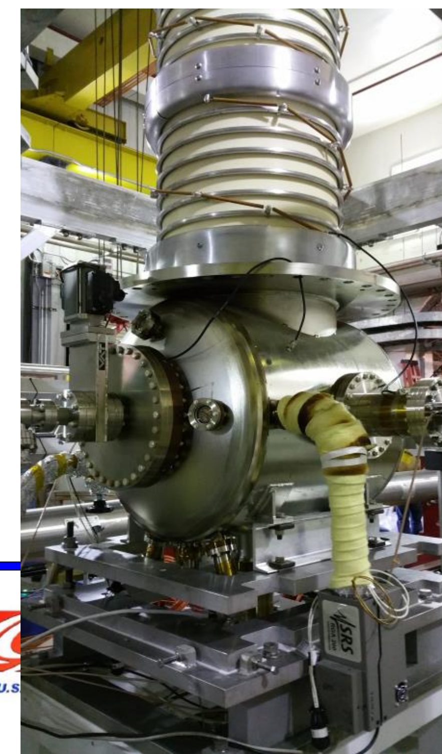
Cathode camera image with LED lamp on



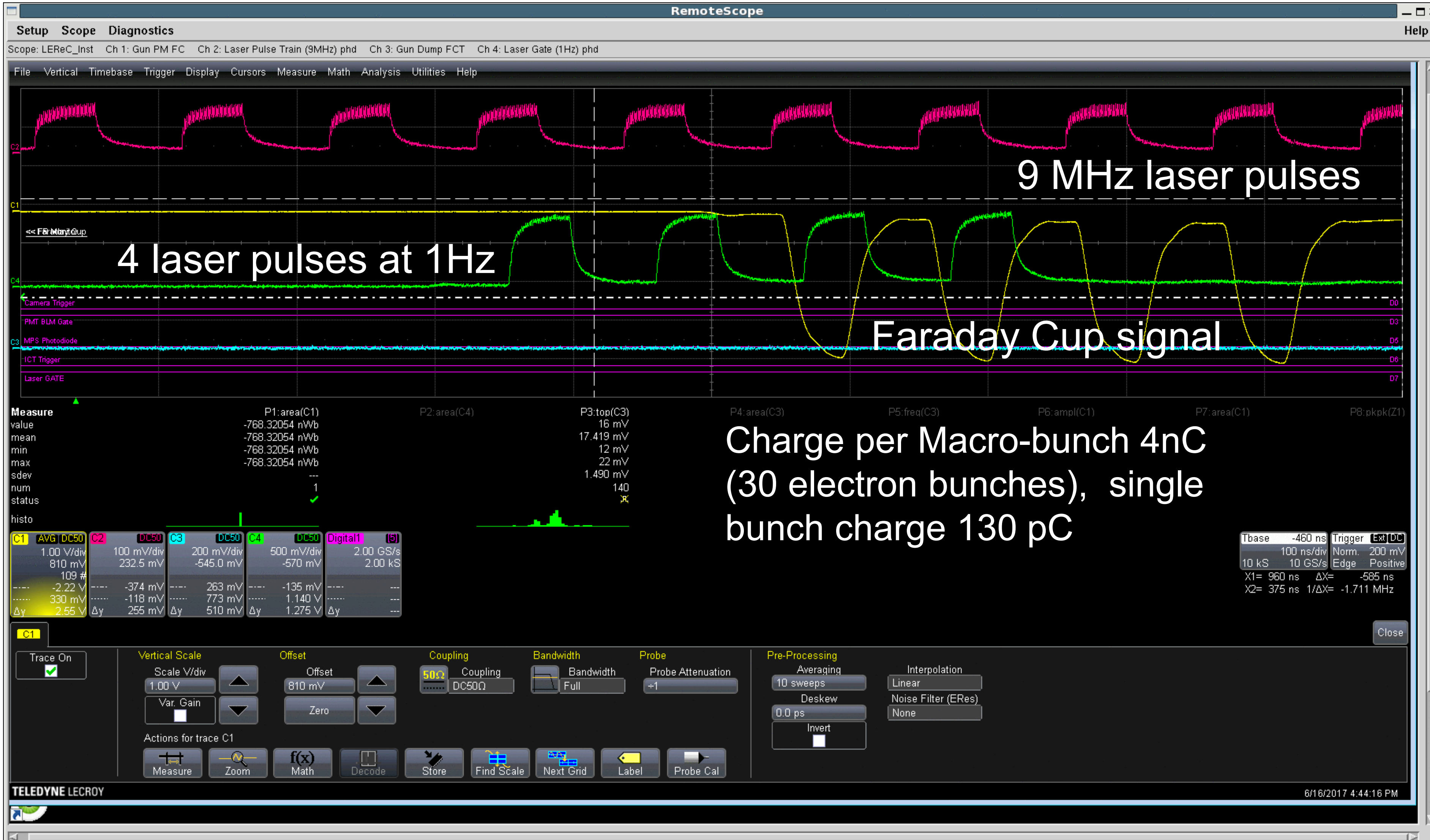
Photocurrent image result of LED (beam profile monitor)



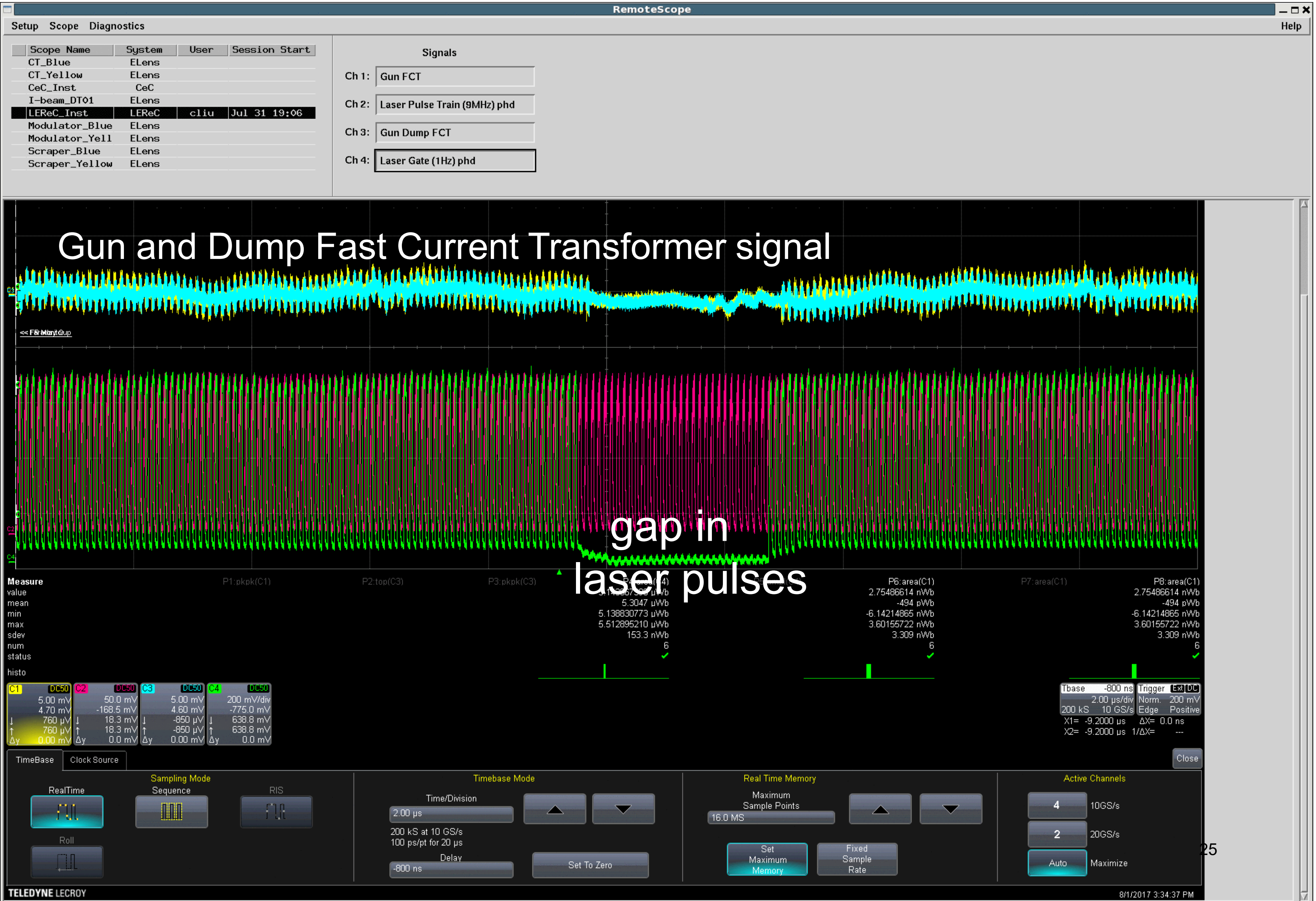
Gun



Pulsed beam operation (June 16, 2017)



First CW operation (August 1, 2017)

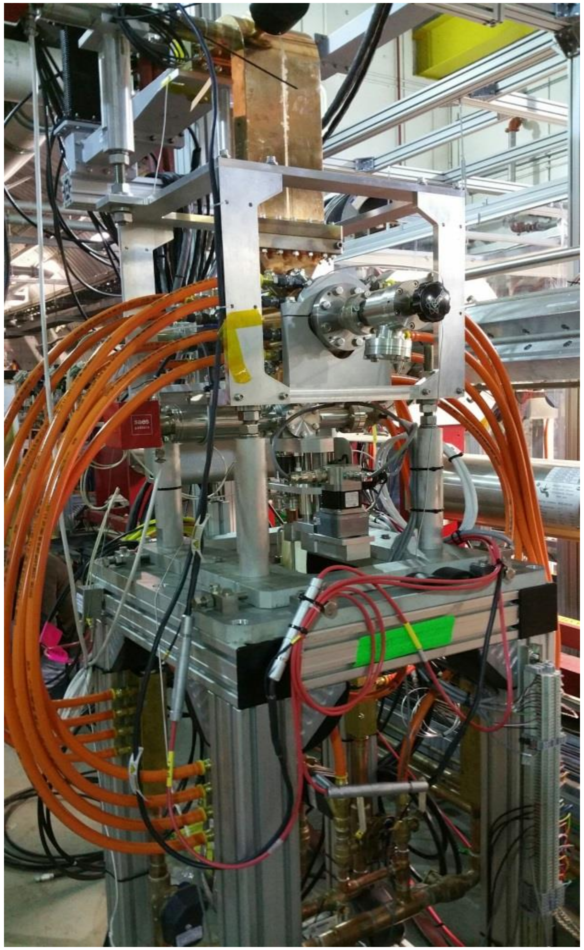


LEReC DC Gun Tests Highlights

- **December 2016:** DC Gun was conditioned to 455kV with stable operation at 400kV, which is design goal.
- **April 18, 2017:** first electron beam (DC)
- **May 5:** First pulsed electron beam using high-power green laser; beam propagated all the way to the beam dump
- **June 16:** Delivered cathode with design QE value (>1%) inside the gun
- **June 16: Demonstrated LEReC design electron bunch charge (130pC/laser pulse; 4nC per macro-bunch)**
- **August 1:** First CW operation (at 9MHz)
- **August 1:** Achieved 1mA CW current
- **August 11: Achieved 10mA CW current**

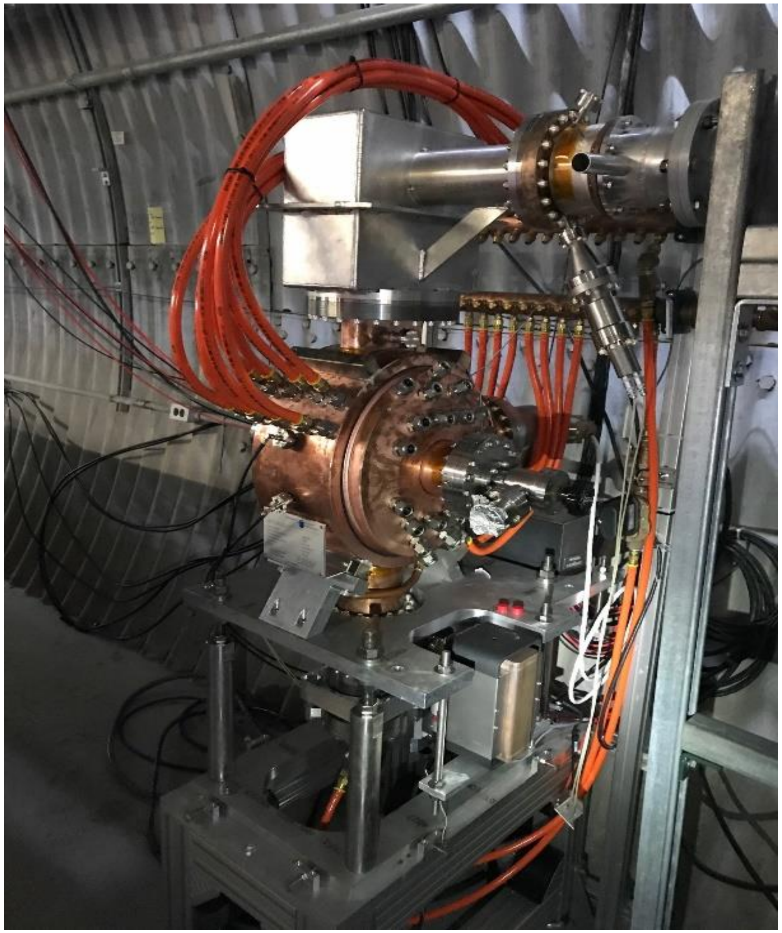
2.1 GHz warm RF cavity
(installed and tested at high power)

RF tested to 220 kV in CW mode (design value 250kV)



704 MHz warm RF cavity (installed and tested at high power)

RF tested to 250kV (design value 400kV, will need 250kV for operation)

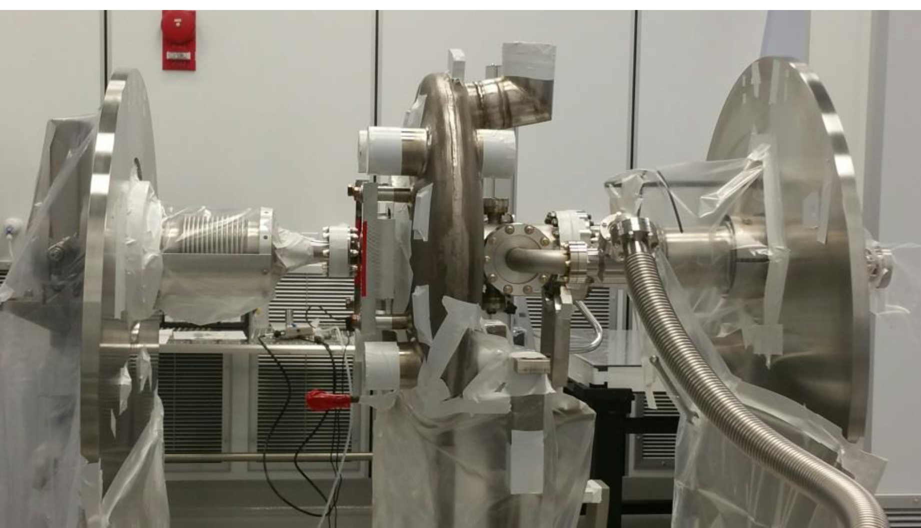


LEReC SRF booster cavity

SRF Booster cavity assembled and RF tests started in June, 2017:

- The general behavior of the cavity has been excellent.
- Based on the FPC Qext calibration and forward power achieved CW voltage is 2.2MV (maximum required for LEReC). Note that voltage calibration is at best accurate to +/-10% at this point.
- The downstream HOM damper insert installed (September), additional cavity tests will be performed to verify no degradation of RF performance.

Cavity string assembly in clean room



Cavity inside cryostat

LEReC project timeline

May 2015:	**Project approved by DOE for construction**
January 2016:	**Cooling section magnets installed**
April 2016:	**Laser assembled**
September 2016:	**DC gun assembled at Cornell**
October 2016:	**DC gun delivered to BNL**
November 2016:	**Approval from DOE for DC Gun Tests received**
December 2016:	**DC gun successfully conditioned in RHIC IR2**
February 2017:	**DC Gun Test beamline and laser transport installed in RHIC**
April 2017:	**DC gun tests/commissioning with beam started**
July-Dec. 2017:	Installation of remaining components
Dec.'17-Feb. 2018:	Systems commissioning (RF, SRF, cryogenics, etc.)
February 2018:	Start commissioning of full LEReC accelerator with e-beam
September 2018:	Demonstrate electron beam parameters needed to start commissioning of cooling process
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. As such, it is also a prototype of future high-energy electron coolers.
- It will be the first application of electron cooling in a collider.
- Project is in full construction and commissioning phase.
- Injection section (without SRF booster) and laser transport successfully commissioned in 2017.
- Final installation is underway.
- Commissioning with electron beam of full LEReC accelerator will start in 2018.

Acknowledgement

LEReC project greatly benefits from help and expertise of many people:

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with numerous help from many others from various groups of the Collider-Accelerator and other Departments of the BNL. As well as FNAL, ANL, JLAB and Cornell University.

Details can be found in recent LEReC publications:

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

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.