Electron Cooling in RHIC:

Low Energy RHIC electron Cooling (LEReC) Project

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for the LEReC team

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BROOKHAVEN NATIONAL LABORATORY

a passion for discovery

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LEReC Project Mission/Purpose

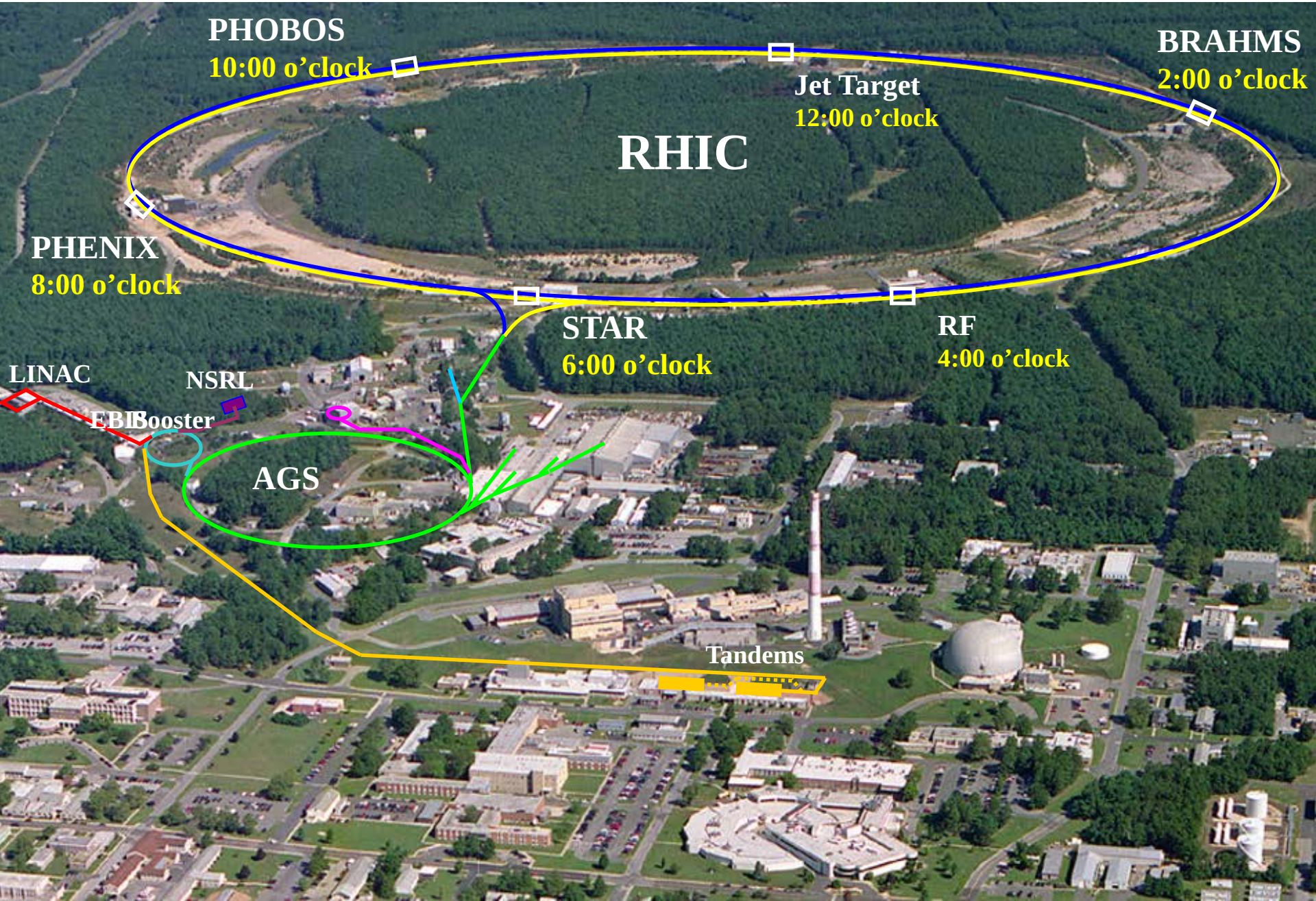
The purpose of the LEReC is to provide significant luminosity improvement for RHIC operation at low energies to search for the QCD critical point (Beam Energy Scan Phase-II physics program).

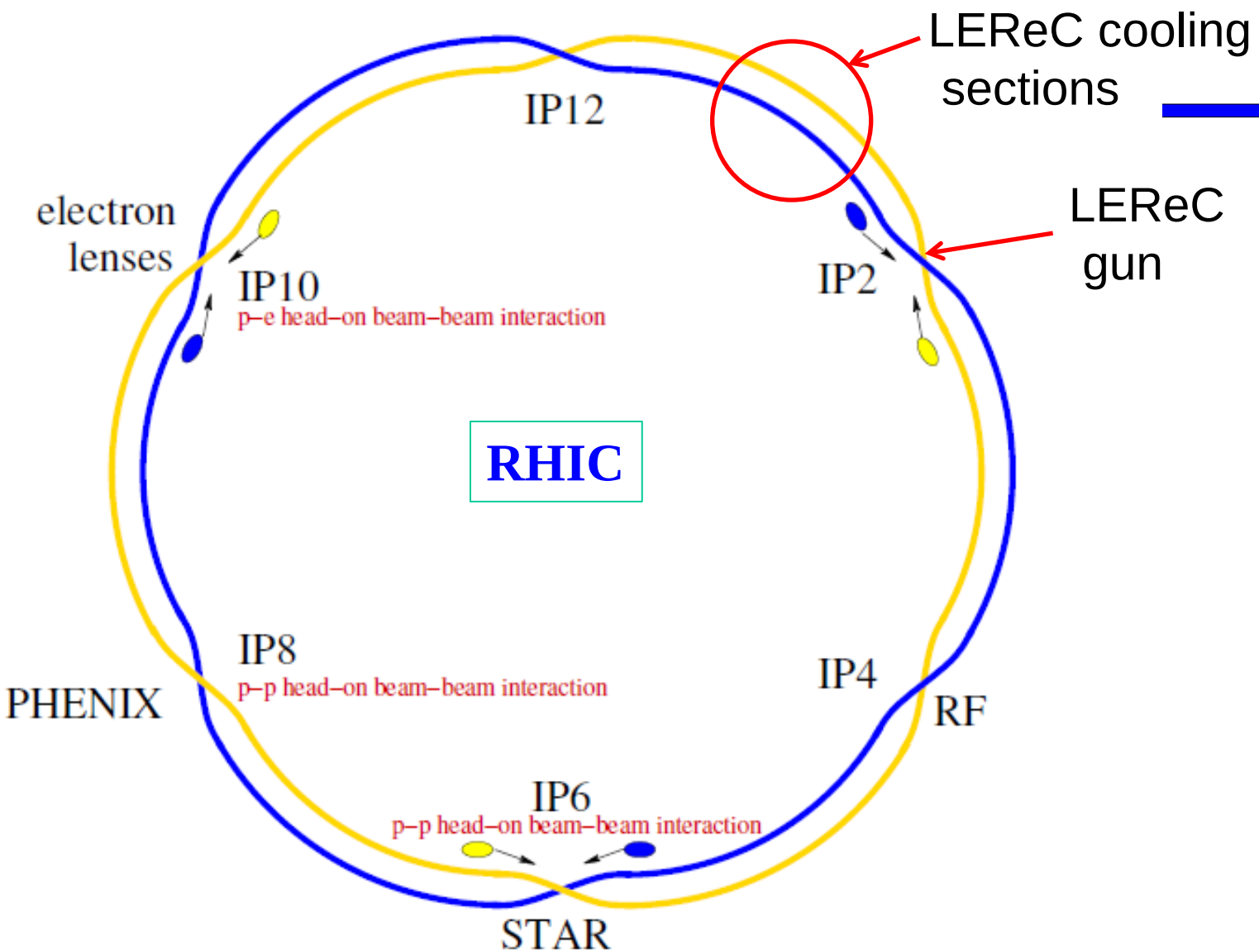
LEReC will be first linac-based electron cooler (bunched beam cooling).
To provide luminosity improvement with such approach requires:

- Building and commissioning of new state of the art electron linear accelerator.
- Produce and transport with RF acceleration high-brightness electron beam with electron beam quality suitable for cooling.
- Commissioning of bunched beam electron cooling.
- Commissioning of electron cooling in a collider.

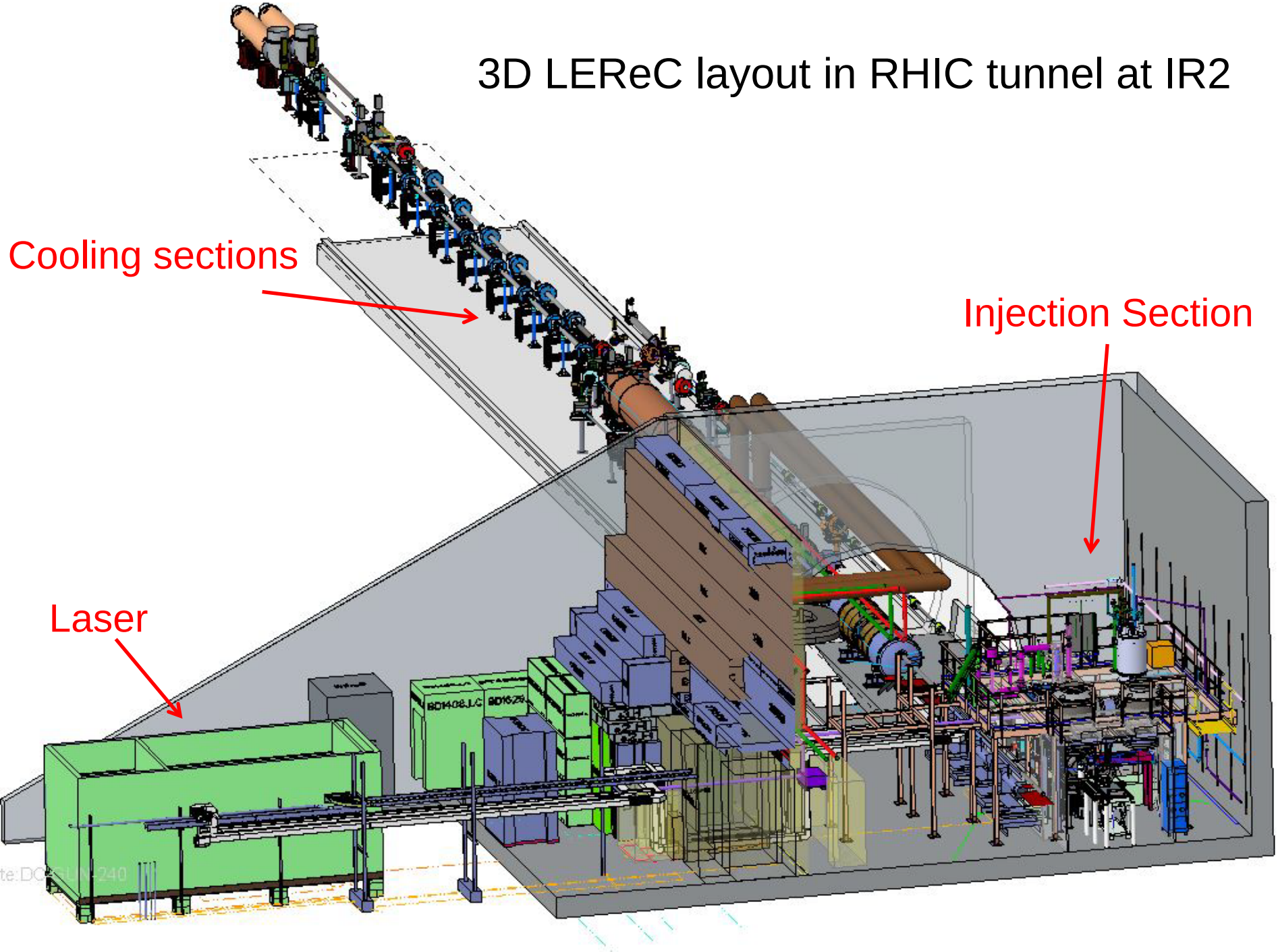
Many new accelerator systems will need to be built, installed and commissioned.

RHIC @ BNL, Long Island, New York

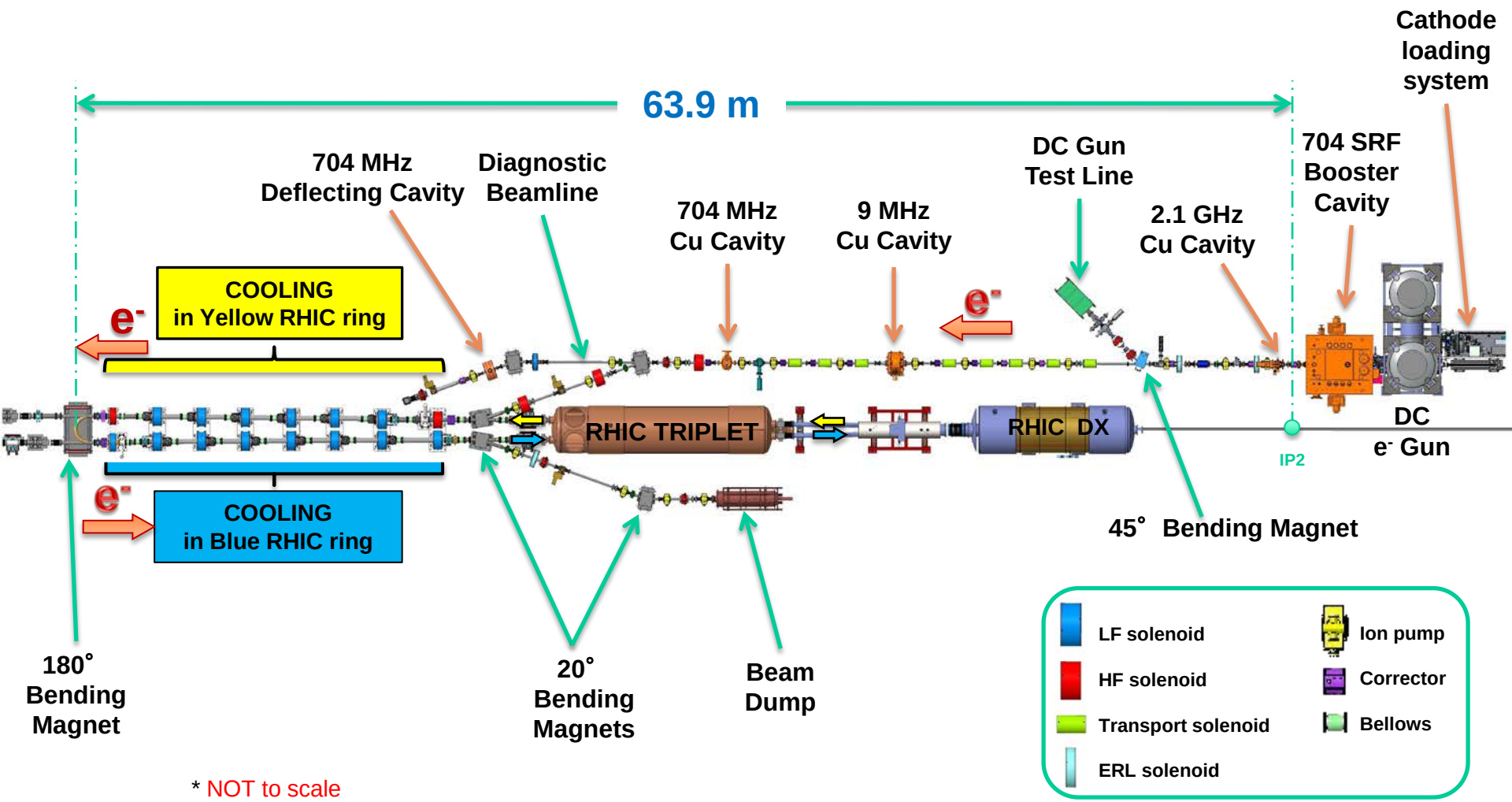



LEReC cooling sections
LEReC gun
IP12
electron lenses
IP10
p–e head–on beam–beam interaction
IP2
RHIC
IP8
p–p head–on beam–beam interaction
PHENIX
IP4
RF
IP6
p–p head–on beam–beam interaction
STAR

3D LEReC layout in RHIC tunnel at IR2



LEReC layout*



* NOT to scale

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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)

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

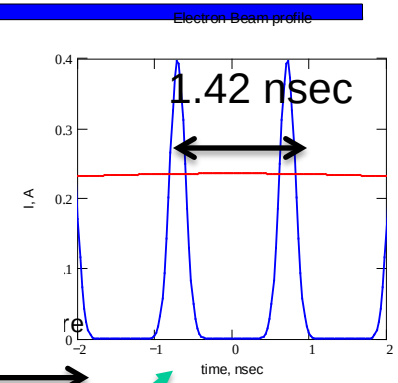
Bunched beam electron cooling for LEReC

- Produce electron bunches suitable for cooling (high-brightness in 3D: both emittance and energy spread)
- Accelerate such bunches with RF and maintain beam quality
- Deliver and maintain beam quality in cooling section
- 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)

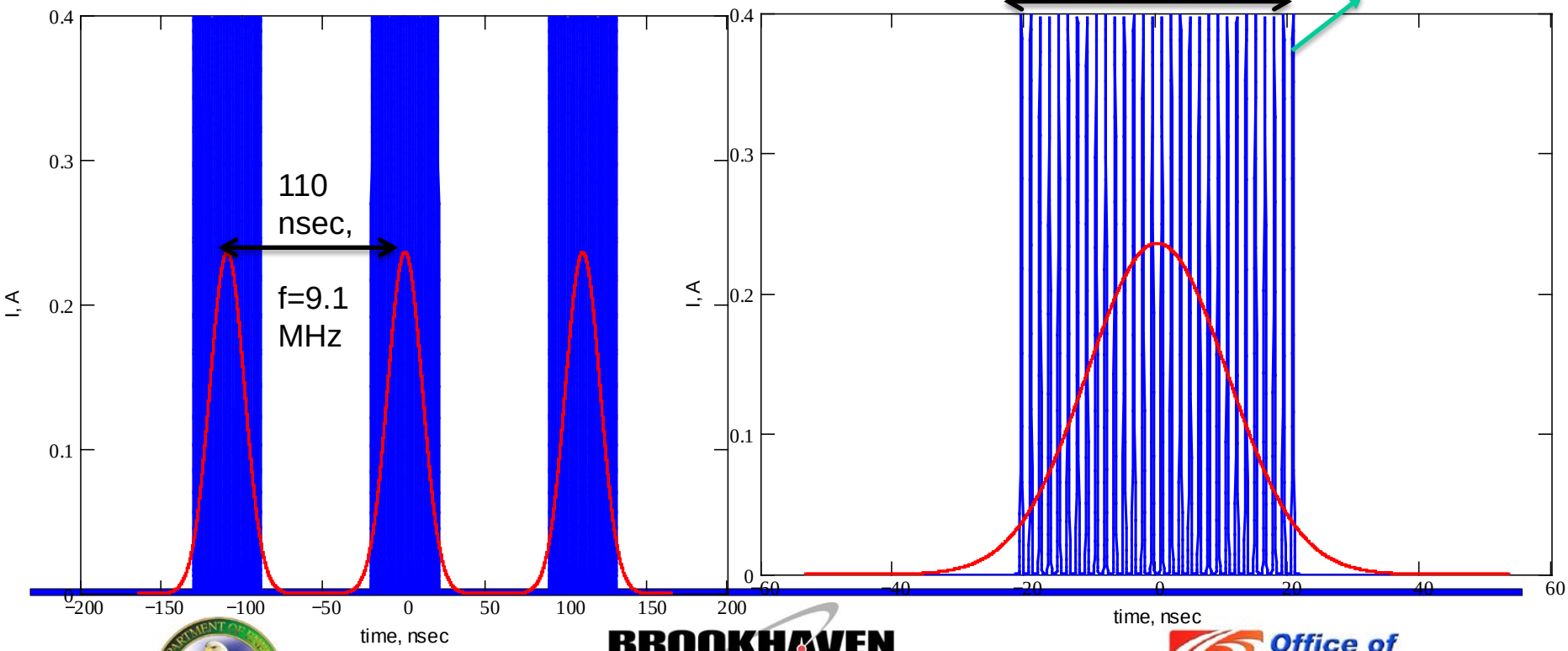
Ions structure:
120 bunches
f_rep=120x75.8347 kHz=9.1 MHz
N_ion=5e8, I_peak=0.24 A
Rms length=3.2 m

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



9 MHz RHIC RF

LEReC Beam Structure



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LEReC challenges

- Produce 3-D high-brightness electron beam (technology developed for FELs).
- Transport of such electron bunches maintaining “cold” beam
- Operation in a wide range of energies; control of electron angles in the cooling section to a very low level for all energies.
- Electron cooling without any help from magnetization: requires very strict control of both longitudinal and transverse electron velocity spread.
- Use the same electron beam to cool ions in two collider rings: preserving beam quality from one cooling section to another.
- Bunched beam electron cooling.

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).

Production of bunched electron beam suitable for cooling

- LEReC is based on the state of the art physics and technology:

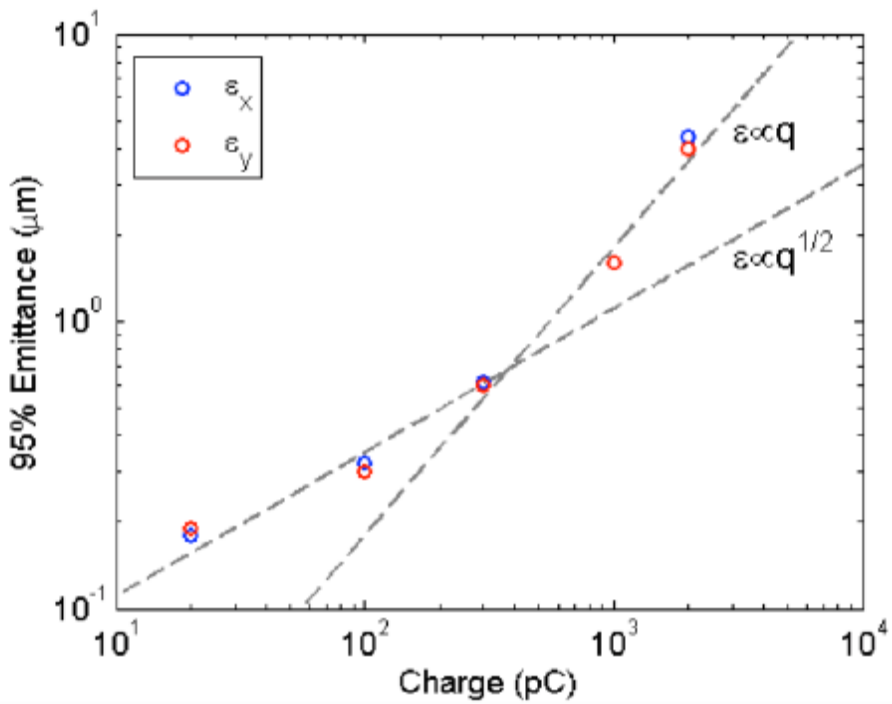
- Photocathodes
- High power laser
- Laser beam shaping
- Operation of HV DC gun (400-500kV) with high charge and high average current
- RF gymnastics and stability control

DC photocathode guns

- In recent years DC photocathode guns successfully demonstrated high-brightness electron beams. Also, good progress with high-average current.

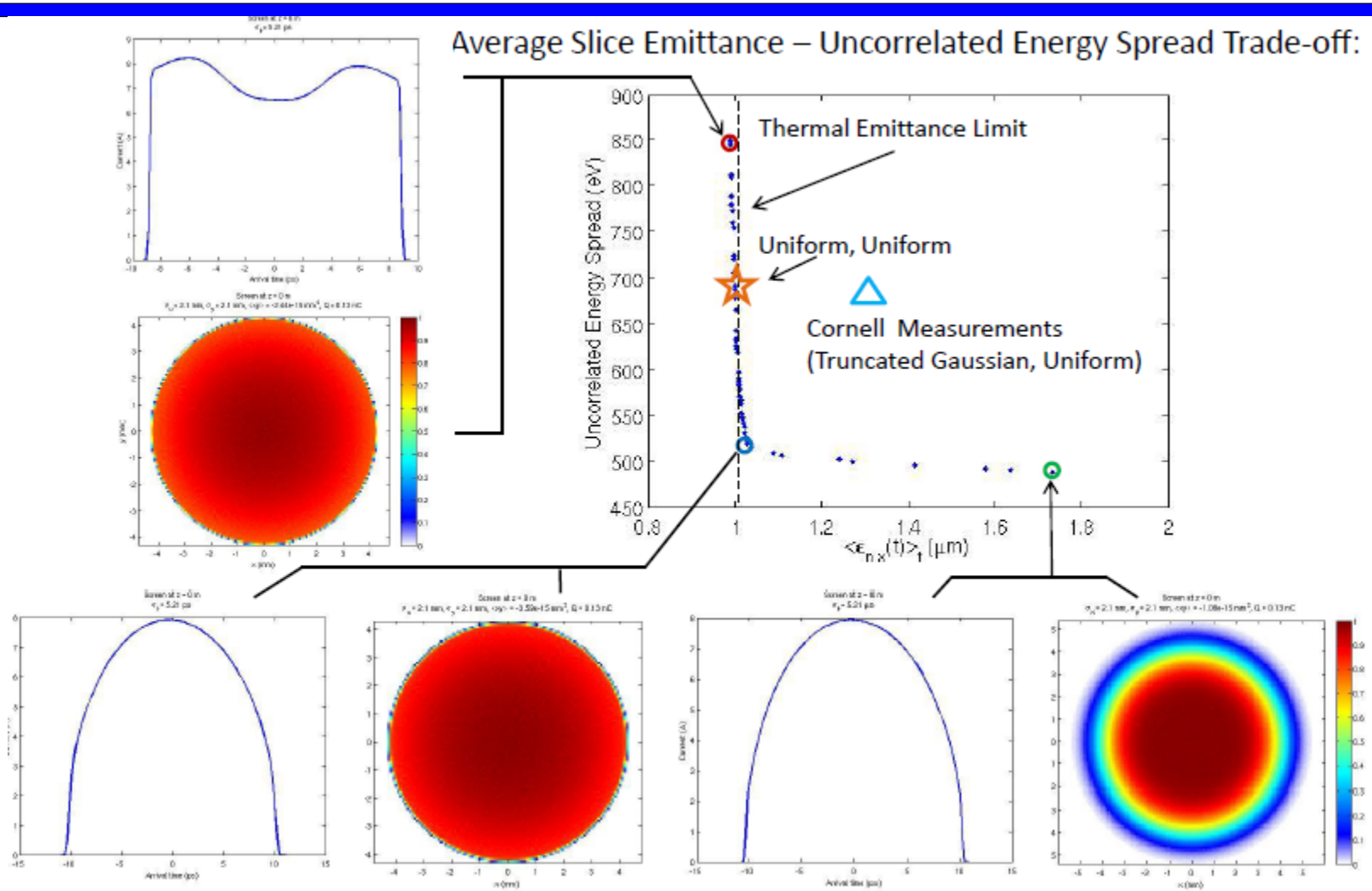
Cornell Laboratory for Accelerator-based Sciences and Education (CLASSE)

Q (pC)	Peak current (A)	Emittance (95%, µm)
20	5	H: 0.18 V: 0.19
100	11.5	H: 0.32 V: 0.30
300	32	H: 0.62 V: 0.60
1000	50	H: 1.6 V: 1.6
2000	56	H: 4.4 V: 4.0

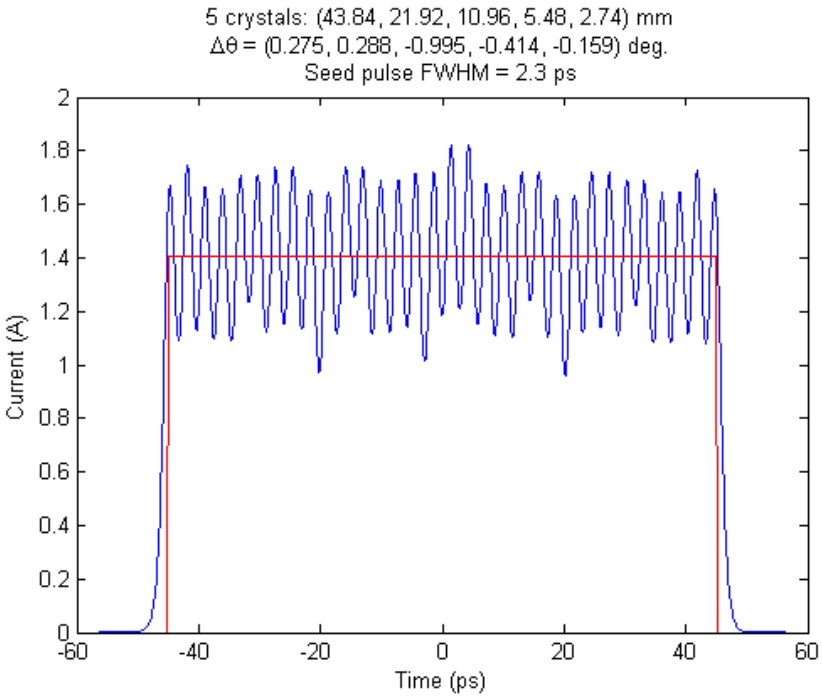


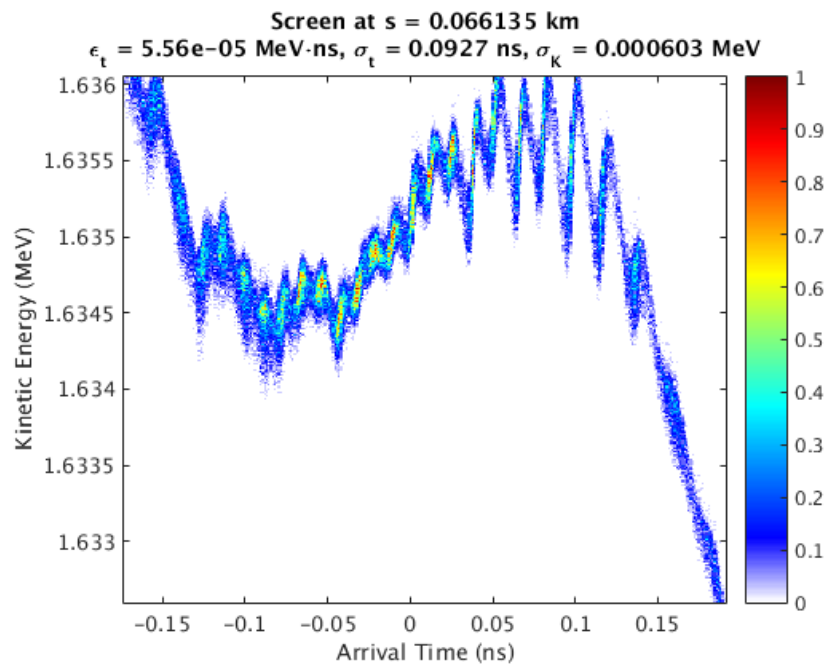
*Courtesy of Cornell University

Example of laser pulse shape optimization with the GPT code (Colwyn Gulliford, Cornell University)



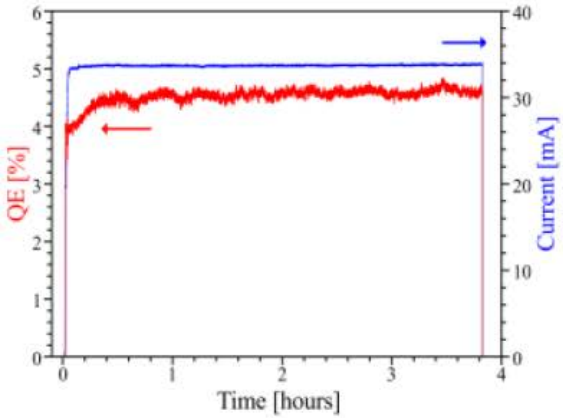
Distribution produced with laser pulse stacking

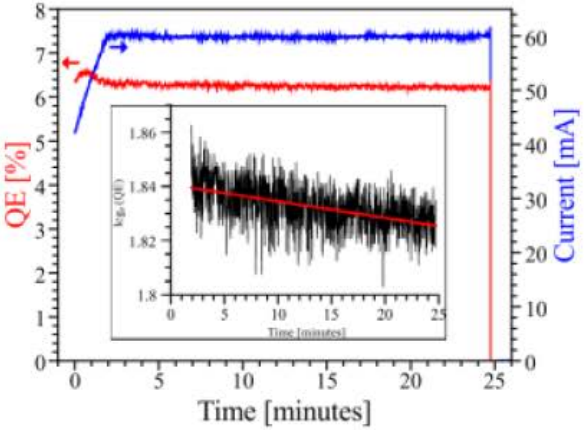


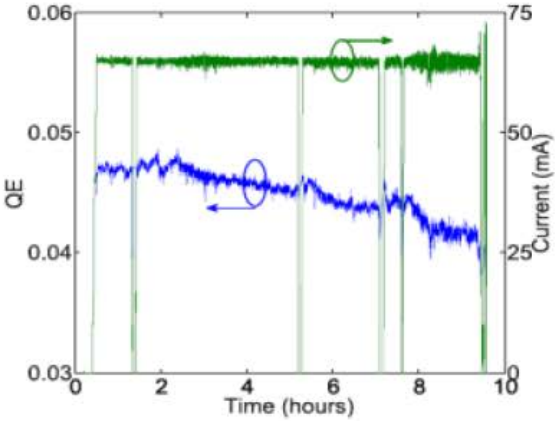


LEReC design requirement on pulse stacking: < 40% peak-to-peak modulation

The Cornell photoinjector







Cs_3Sb
QE @ 520 nm 4%
Max AVG current **33 mA**
Lifetime >> 500 C
NO QE DECAY

Cs_2KSb
QE @ 520 nm 6.5%
Max AVG current **60 mA**
Lifetime >> 2000 C
1/e QE 30 hr

Na_2KSb
QE @ 520 nm 4.5%
Max AVG current **65 mA**
Lifetime >> 2000 C
1/e QE 66 hr

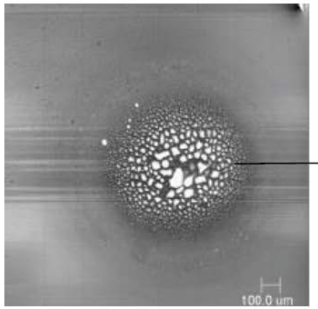
75mA for a short period of time.

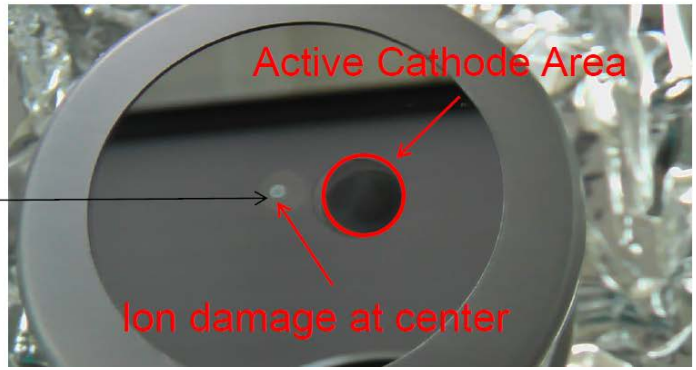
Alklai antimonide based photocathode have been extensively tested in DC gun of the ERL injector prototype at Cornell

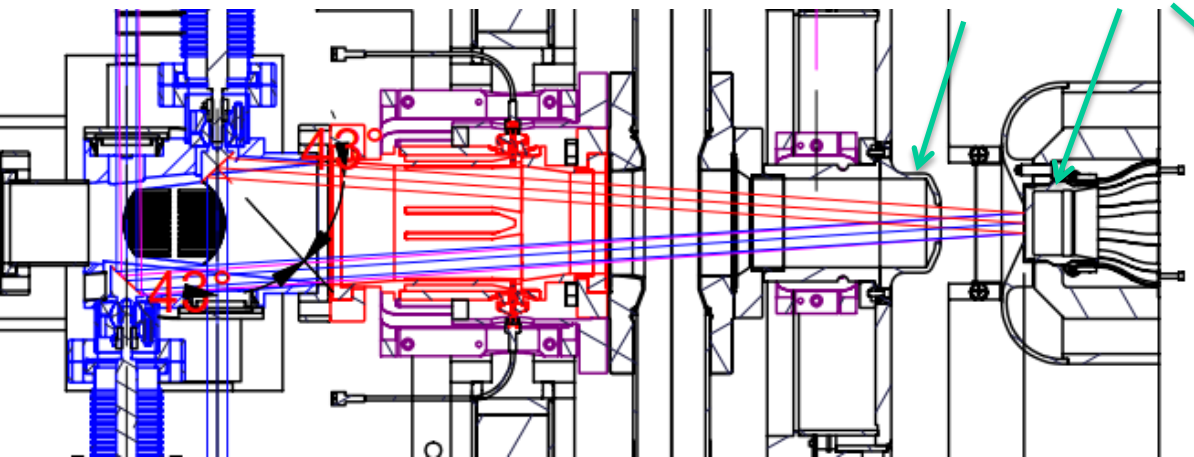
*Courtesy of Cornell University

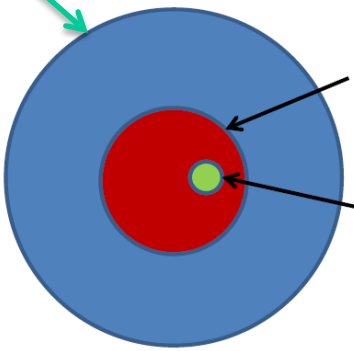
Cornell experience

- High charge -> Large laser spot
- High-current -> off cathode center; 3mm center spot is damaged due to ion back bombardment. Only small area on the cathode is activated to avoid halo generation.
- Anode clips laser light at 9 mm from cathode center









Maximum area that can be used by geometry = 9 mm radius

For 100-200 pC, 3-4 mm diameter spot, 4-6 mm from center.

LEReC DC Gun requirements and performance demonstrated at Cornell (with similar Gun)

- **LEReC DC gun requirements:**
  1. Stable operation at 400kV
  2. High-charge (100-200pC), small emittance (< 2 um, rms)
  3. High average current (about 50mA with macro-bunches and up to 85mA in full CW)
  4. Long cathode lifetime (> 1 day per cathode, preferably closer to a week).
     Laser is designed with enough power to compensate for QE drop.

- **Cornell Gun demonstrated performance:**
  1. Stable operation at 400kV
  2. High-charge (300pC) with small emittance (<0.6 um, 95%)
  3. High average current of 65mA (although, not at the same time as item #2); requires operation with laser spot off cathode center
  4. Long cathode lifetime for current operation (1/e QE 66 hours)

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. Some 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.

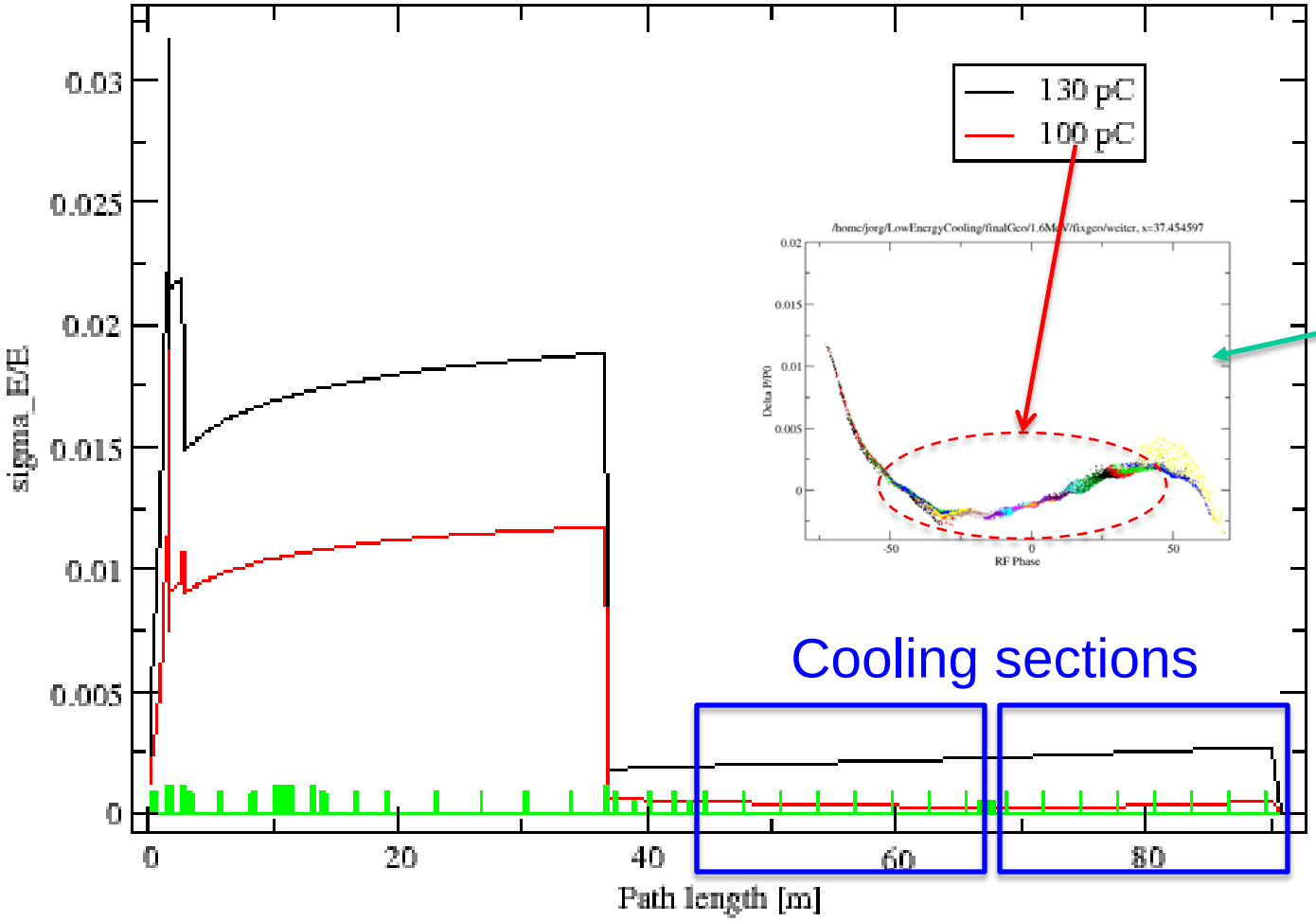
We found that these effects are most difficult to control < 2 MeV.

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 (3rd 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.

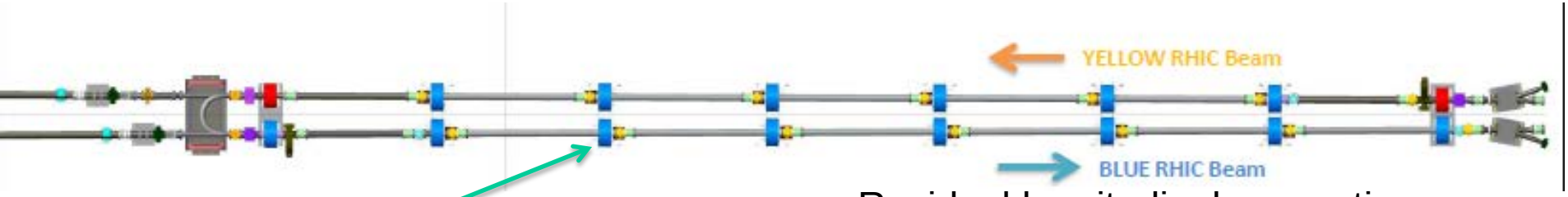
Evolution of beam energy spread in LEReC transport

J. Kewisch et al., Proceedings of ERL15 (Stony Brook, NY, 2015), WEICLH1058.
J. Kewisch et al., Proceedings of NAPAC16 (Chicago, IL, 2016), WEPOB56.



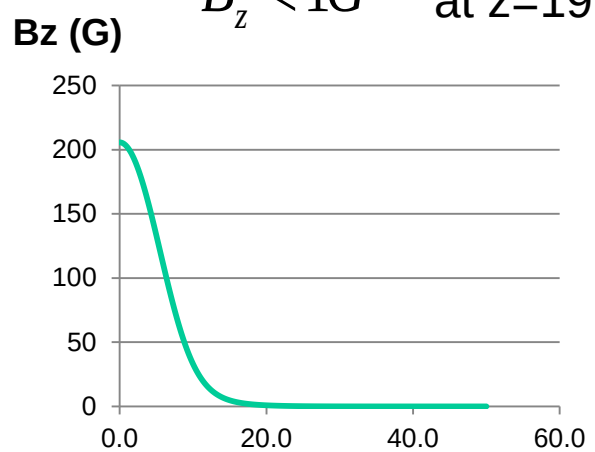
Longitudinal phase space in cooling section

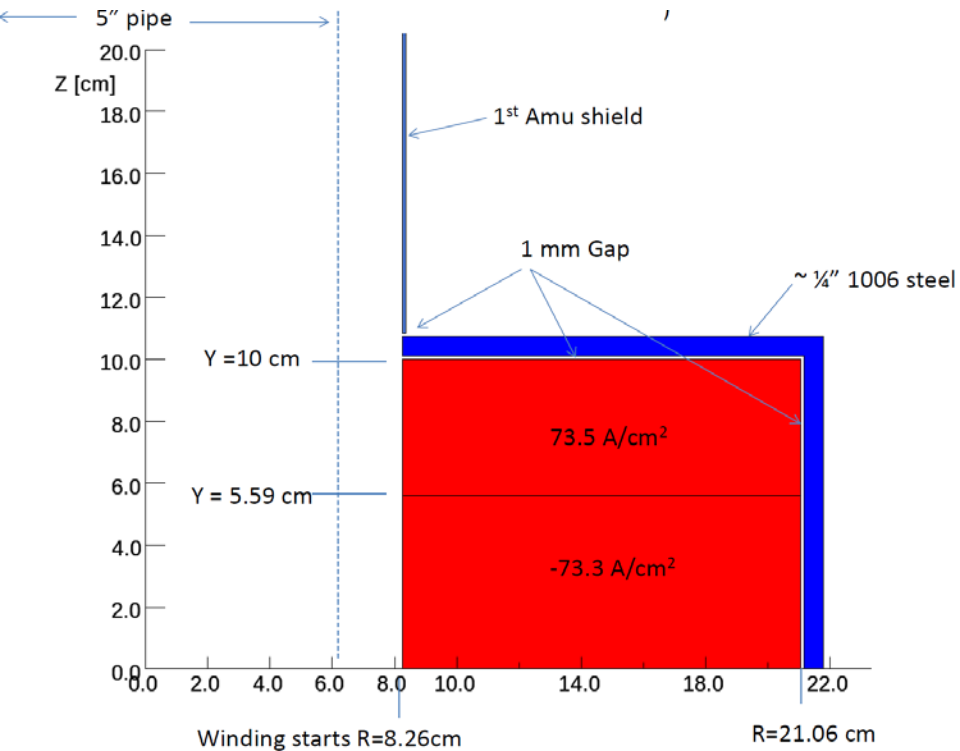
Requirement on magnetic field in the cooling section

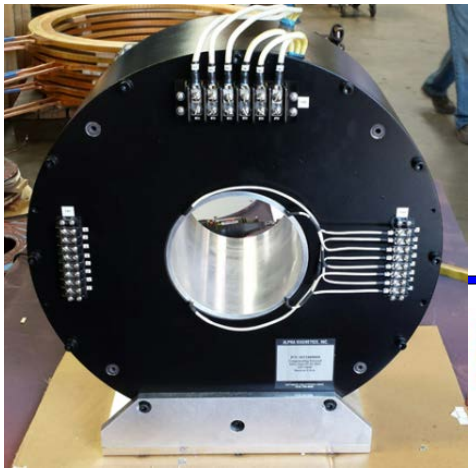


Distance covered by magnetic field from solenoids will be lost from cooling. Expect about 40 cm to be lost from cooling from each solenoid.

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







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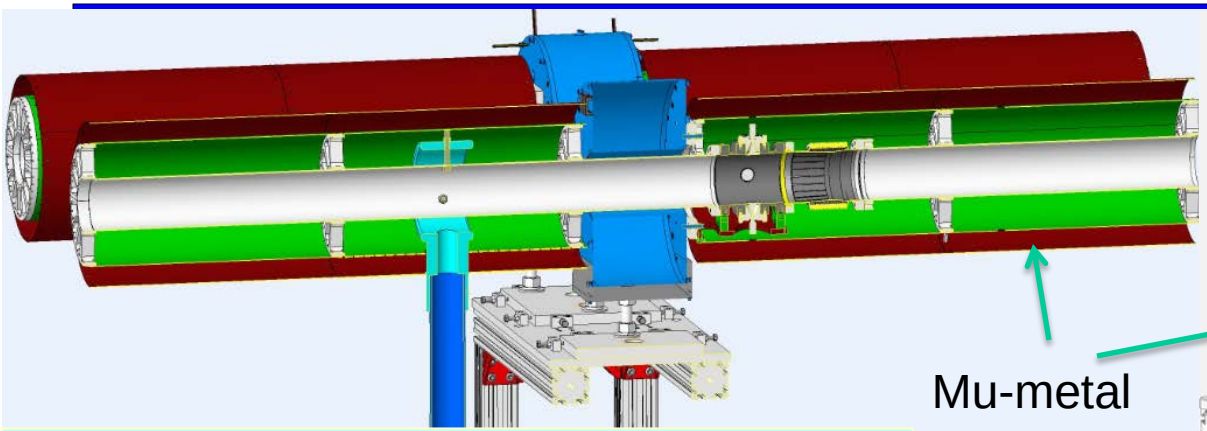
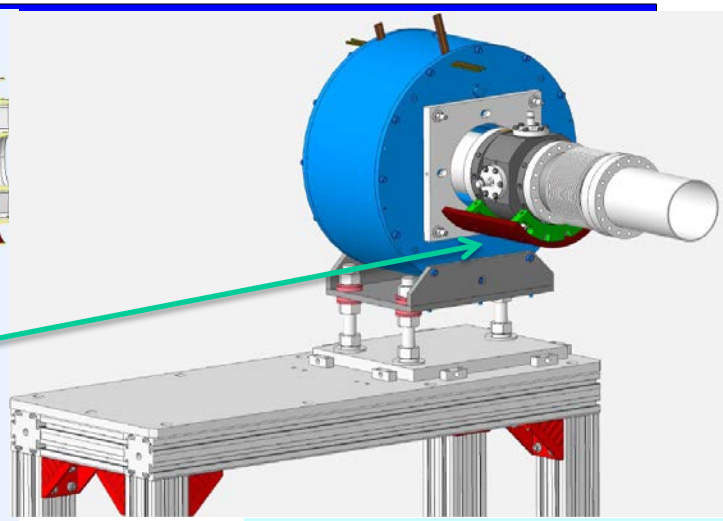
Mu-metal shielding design for cooling sections



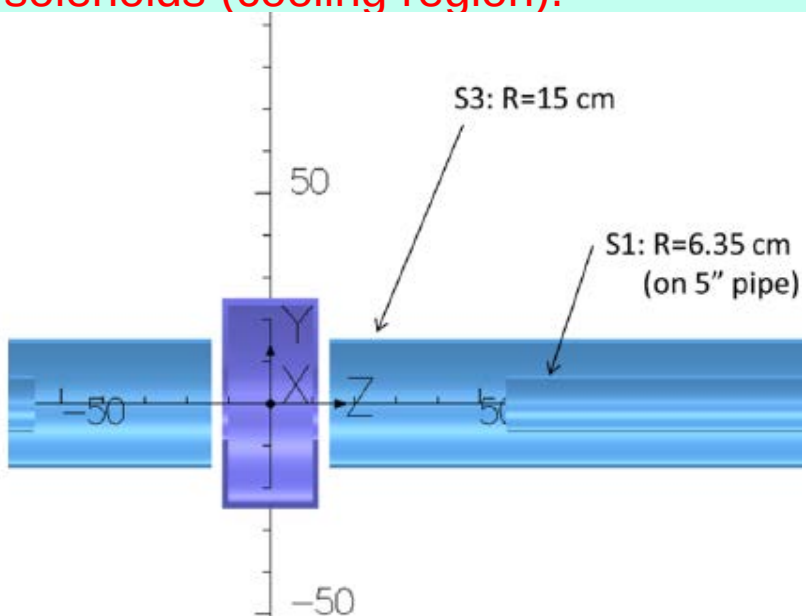
Mu-metal shielding



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

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

S. Seletskiy et al., BNL Tech Note C-A/AP/561, April 2016.



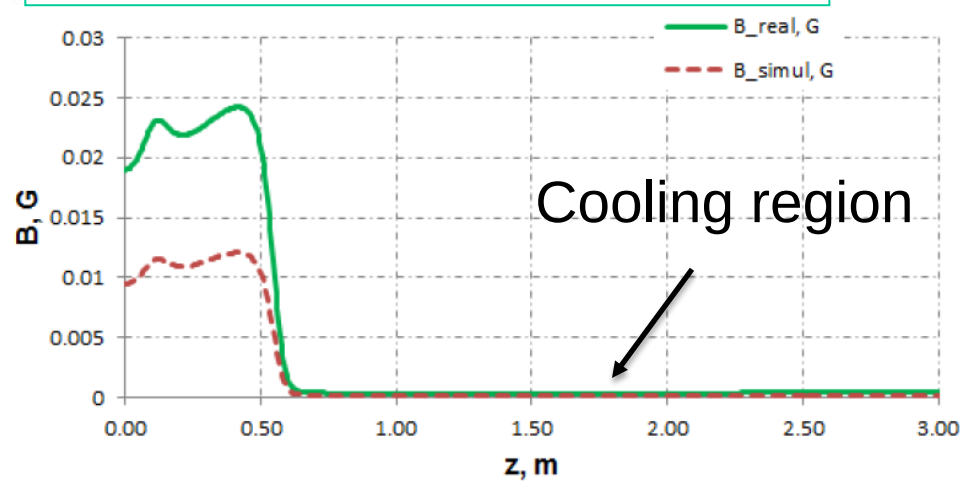
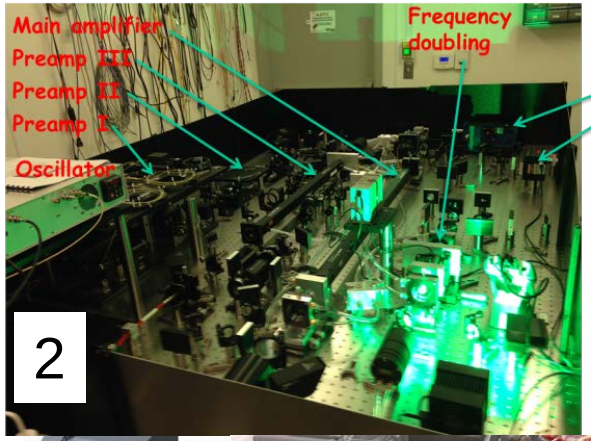
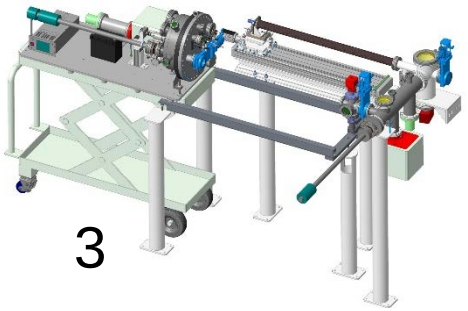


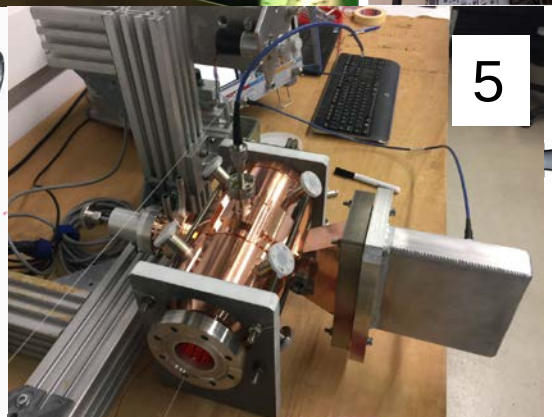
Figure 5: Simulated and "real" (multiplied by 2) residual magnetic field in the cooling section.

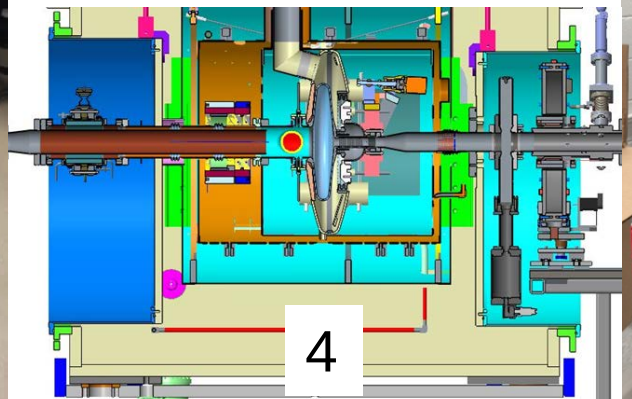
LEReC Critical Technical Systems

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

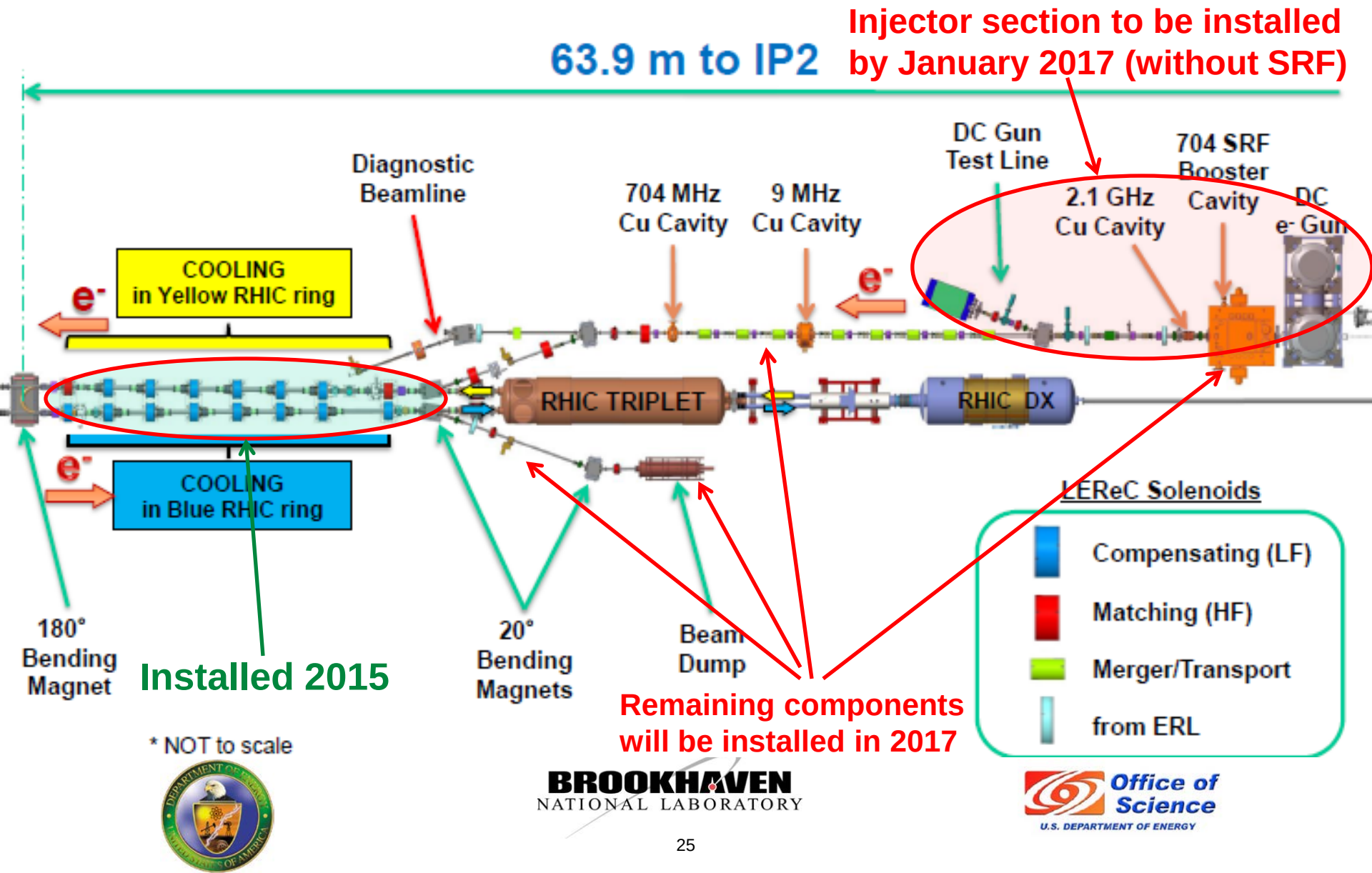








LEReC accelerator (100 meters of beamlines with the DC Gun, 5 RF systems, many magnets and instrumentation devices)



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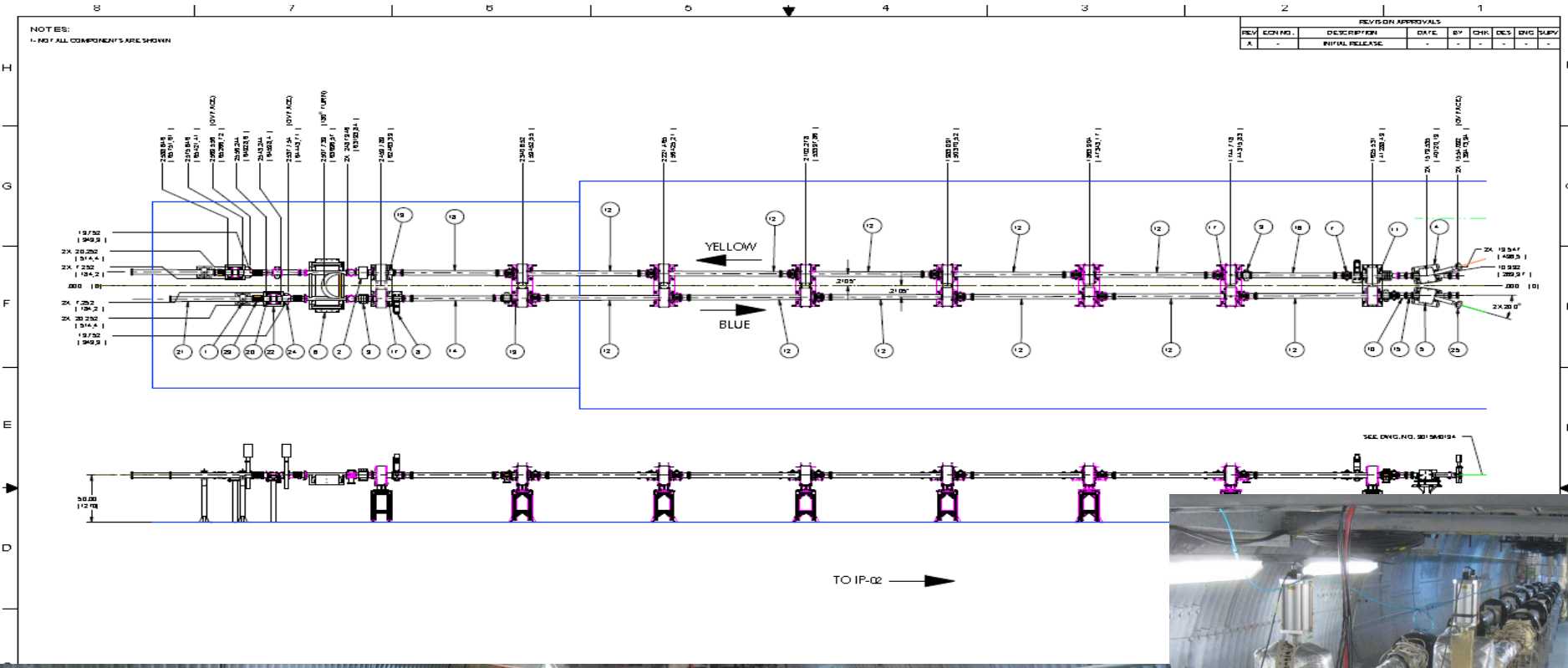
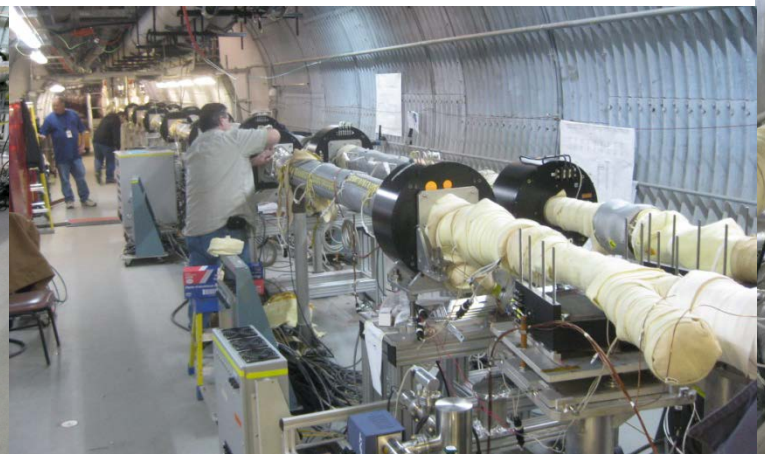
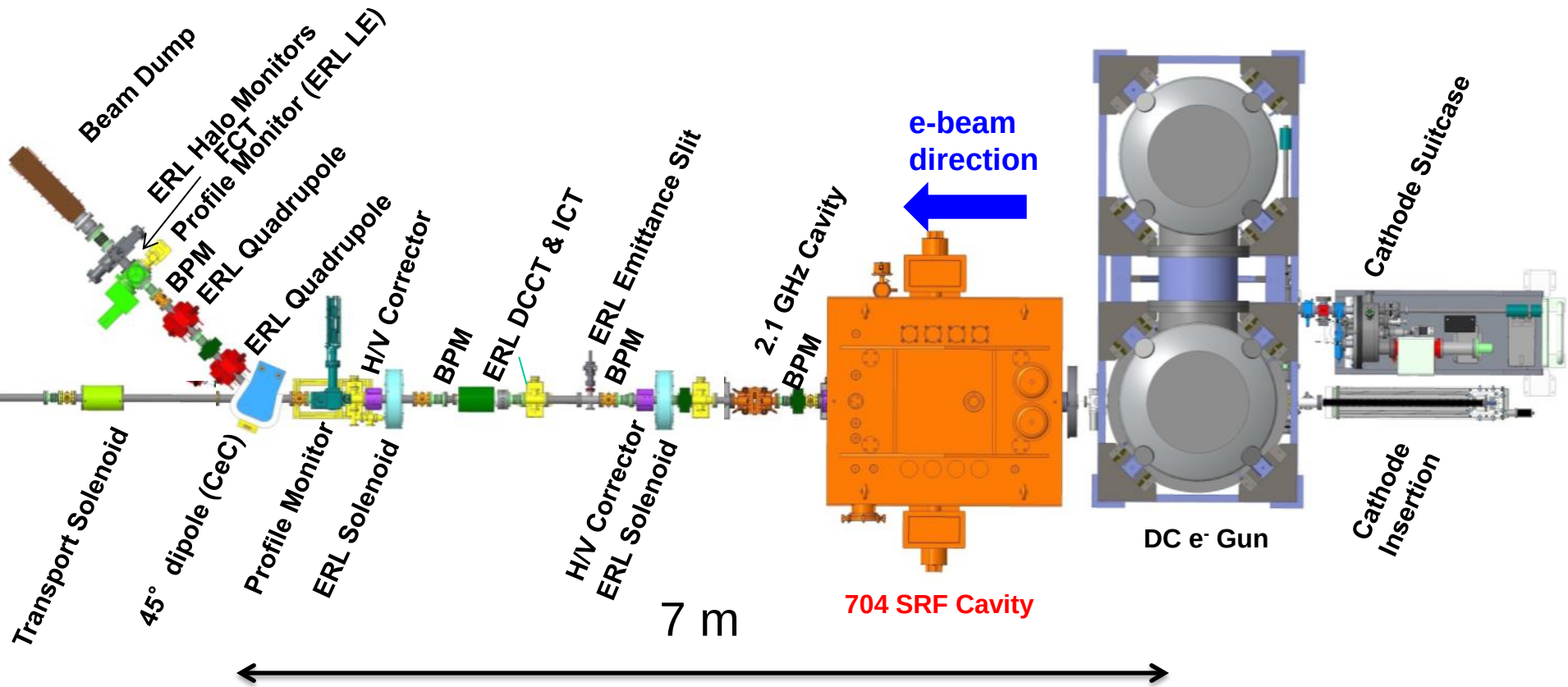
Solenoid magnets for cooling sections installed - January 2016 (mu-metal shielding will be installed Summer 2017)



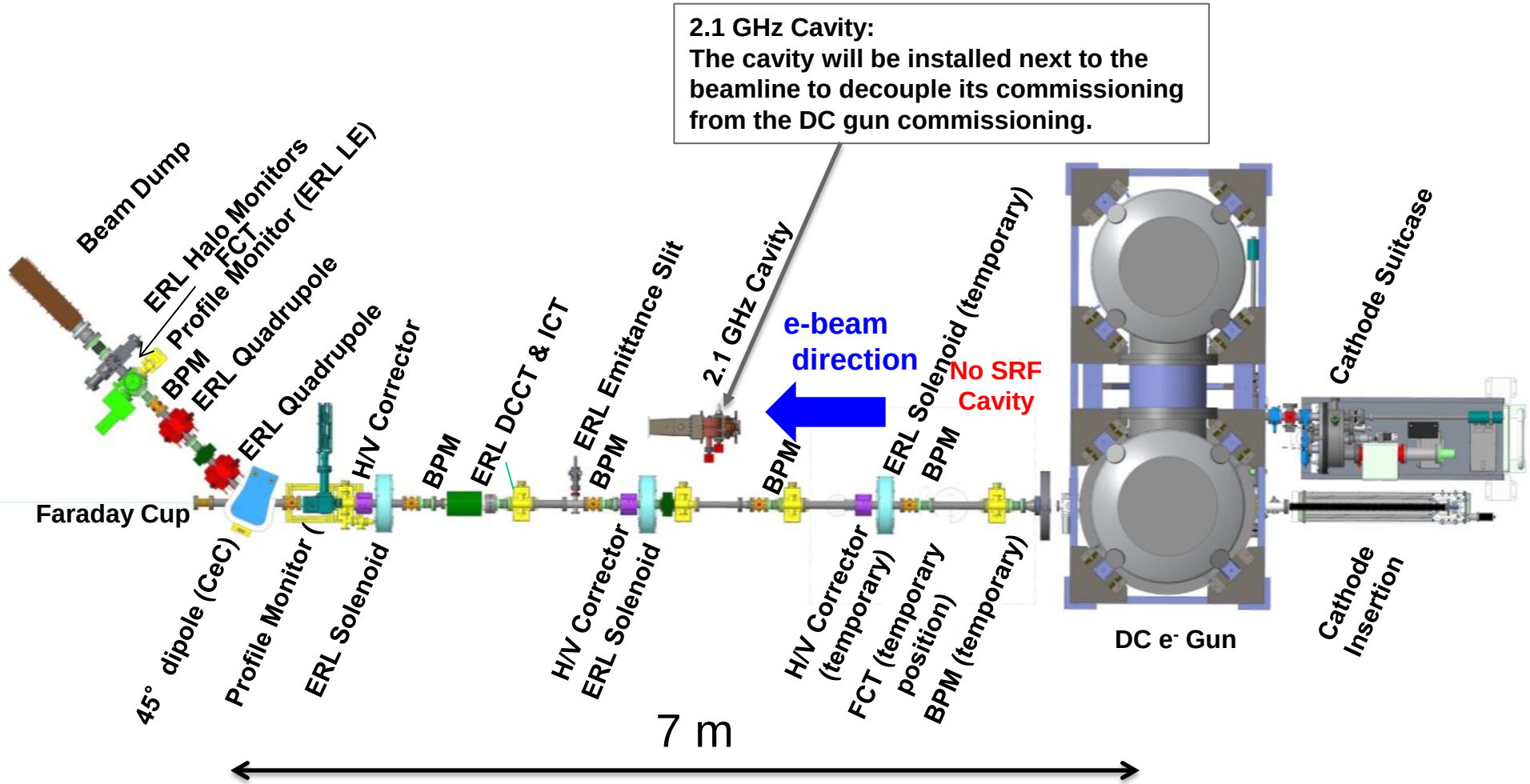


LEReC Injection section (zoom in)



DC gun test setup 2016-2017

(no RF components in beam line)



LEReC Gun test is the first stage of LEReC configuration (2017)

The goal : test critical LEReC equipment in close to operation condition.

Components to be tested:

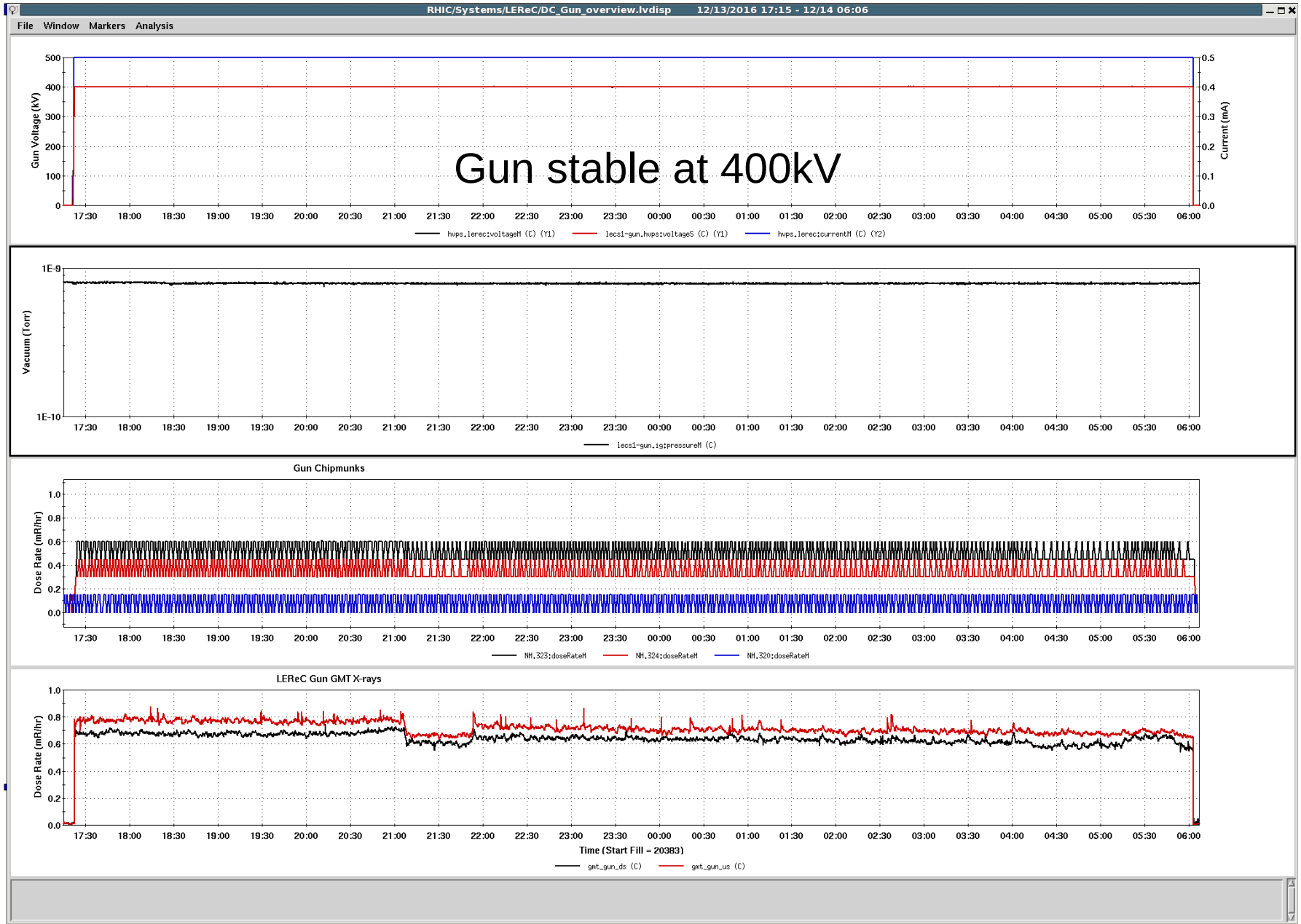
- Laser beam delivery system (laser, laser shaping, laser transport, laser pulse stability, etc)
- Vacuum components with controls
- Cathode manipulation system
- DC gun characterization (stability, ripple, maximum operation voltage, electron beam quality)
- Magnets, power supply.
- Beam instrumentation: charge and current measurements, beam position (response matrix) measurements, beam loss monitor detectors, beam profile and halo measurements
- Control system (timing system, machine protection system, control of laser, gun power supply, magnets power supplies, beam instrumentation)
- High average power beam extraction and beam dump system.
- Start exploring high current operation issues

LEReC DC photocathode Gun

- Gun was built by Cornell University
- High Voltage pre-conditioning at Cornell – October 3-11, 2016
- Delivered to BNL – October 18, 2016.
- Installation in RHIC tunnel in IR2 - Nov. 2016
- Conditioned at IR2: Nov.-Dec. 2016

BNL clean room (10/21/16)

LEReC Gun conditioning at RHIC IR2 (November 30-December 14, 2016)



Installation of LEReC DC Gun test beamline

LEReC timeline

May 2015:	**Project approved by DOE for construction**
January 2016:	**Cooling section magnets installed**
April 2016:	**Laser assembled, commissioning started**
September 2016:	**DC gun assembled at Cornell**
October 2016:	**DC gun pre-conditioned at Cornell and delivered to BNL**
Nov. 4, 2016:	**Approval from DOE for DC Gun Tests received**
November 2016:	**DC gun assembly installed in RHIC IR2**
December 2016:	**DC gun succesfully conditioned in RHIC IR2**
Nov.'16-Jan.'17:	**Install DC Gun Test beamline and laser transport in RHIC**
Feb.-June 2017:	DC gun tests with beam
July-Dec. 2017:	Move and install SRF and cryogenics components; high-power beam dump, diagnostics beam line and all remaining LEReC components
2017-February 2018:	Systems commissioning (RF, cryogenics, etc.)
March 2018:	Commissioning of full LEReC accelerator with e-beam
September 2018:	Early project finish date (electron beam parameters needed to start commissioning of cooling process demonstrated). Commissioning of cooling with Au ion beams during RHIC Run-19 (2019).

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