Accelerator Physics Design Requirements and Challenges of RF Based Electron Cooler LEReC

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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.

Low-energy RHIC operation

Electron cooling (a well known method of increasing phase-space density of hadron beams):

- "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

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

Energy scan of interest:

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

At low energies in RHIC luminosity has a very fast drop with energy (from γ^3 to γ^6). As a result, achievable luminosity becomes extremely low for lowest energy points of interest.

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 charge, pC	130	170	200
Effective charge used for cooling	100	130	150
Bunches per macrobunch	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 without macrobunches is also being considered.

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 $v_{ion} < \Delta_e$:

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

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

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

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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.

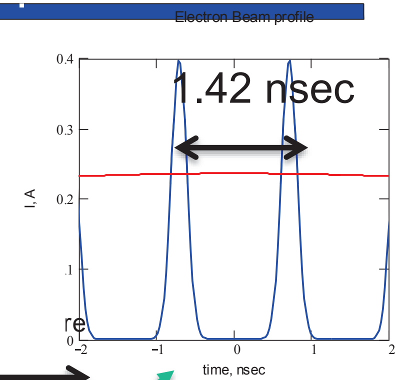
1) Putting a “macrobunch” of electron bunches on a single ion bunch.
2) Can possibly use “slow painting” - move electron bunches through the ion bunch slowly to effectively cool all amplitudes.

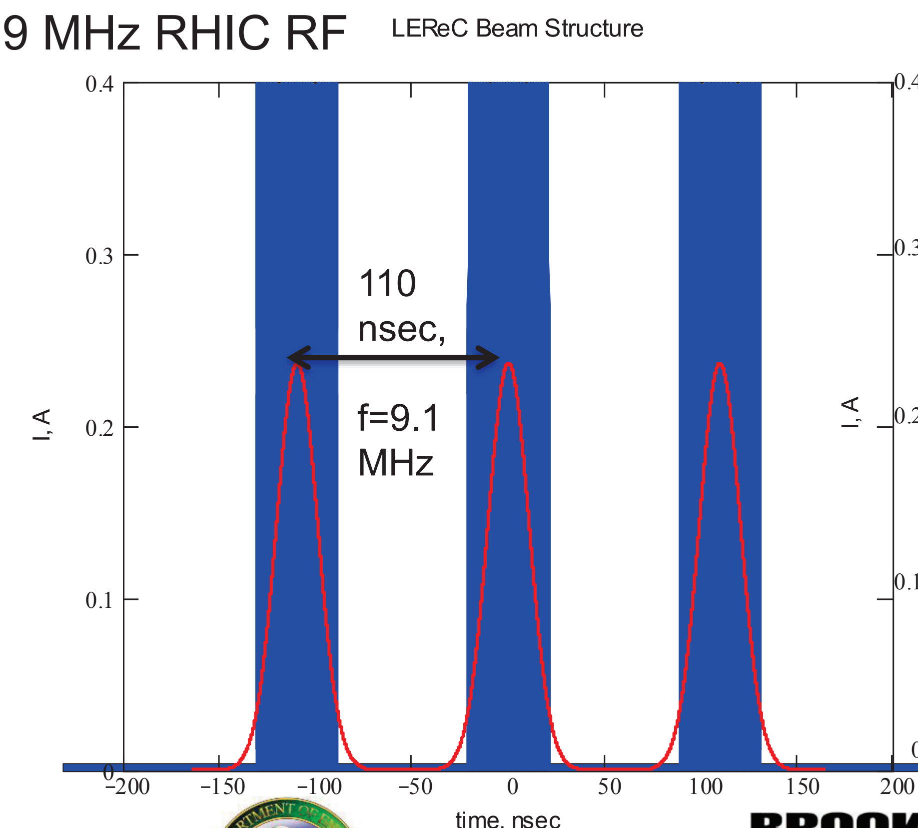
We use analytic formalism and numerical models developed as part of RHIC-II bunched beam electron cooling studies.

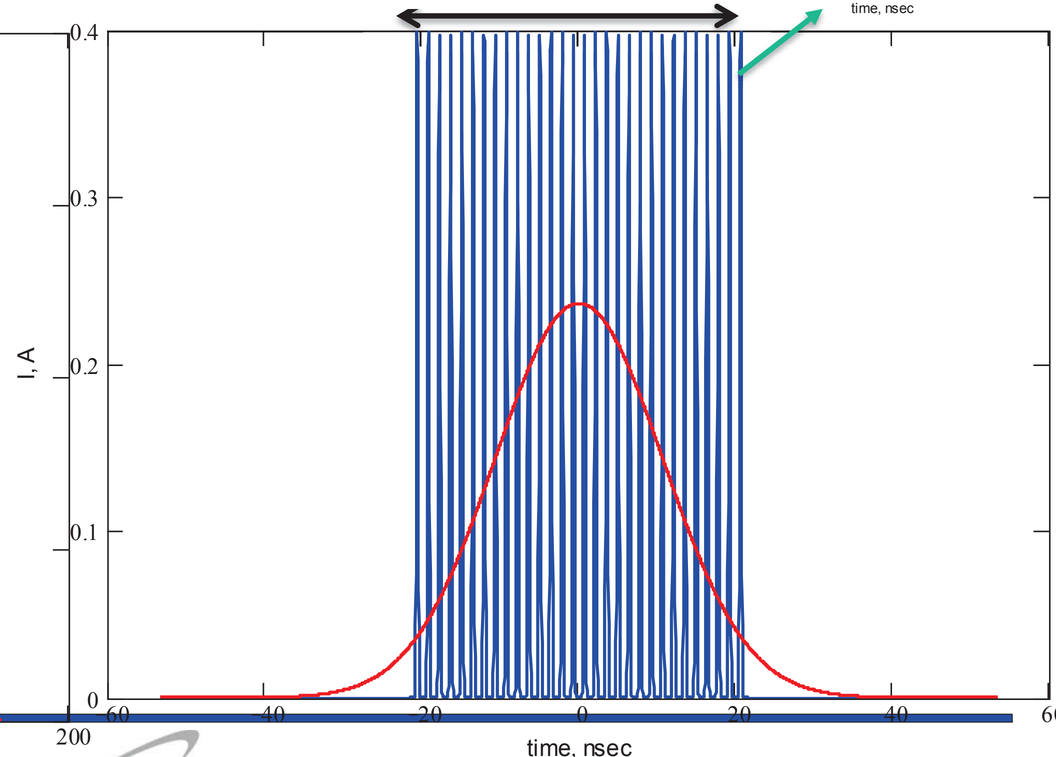
LEReC beam structure in cooling section
Example for γ= 4.1 (E_{ke}=1.6 MeV)

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







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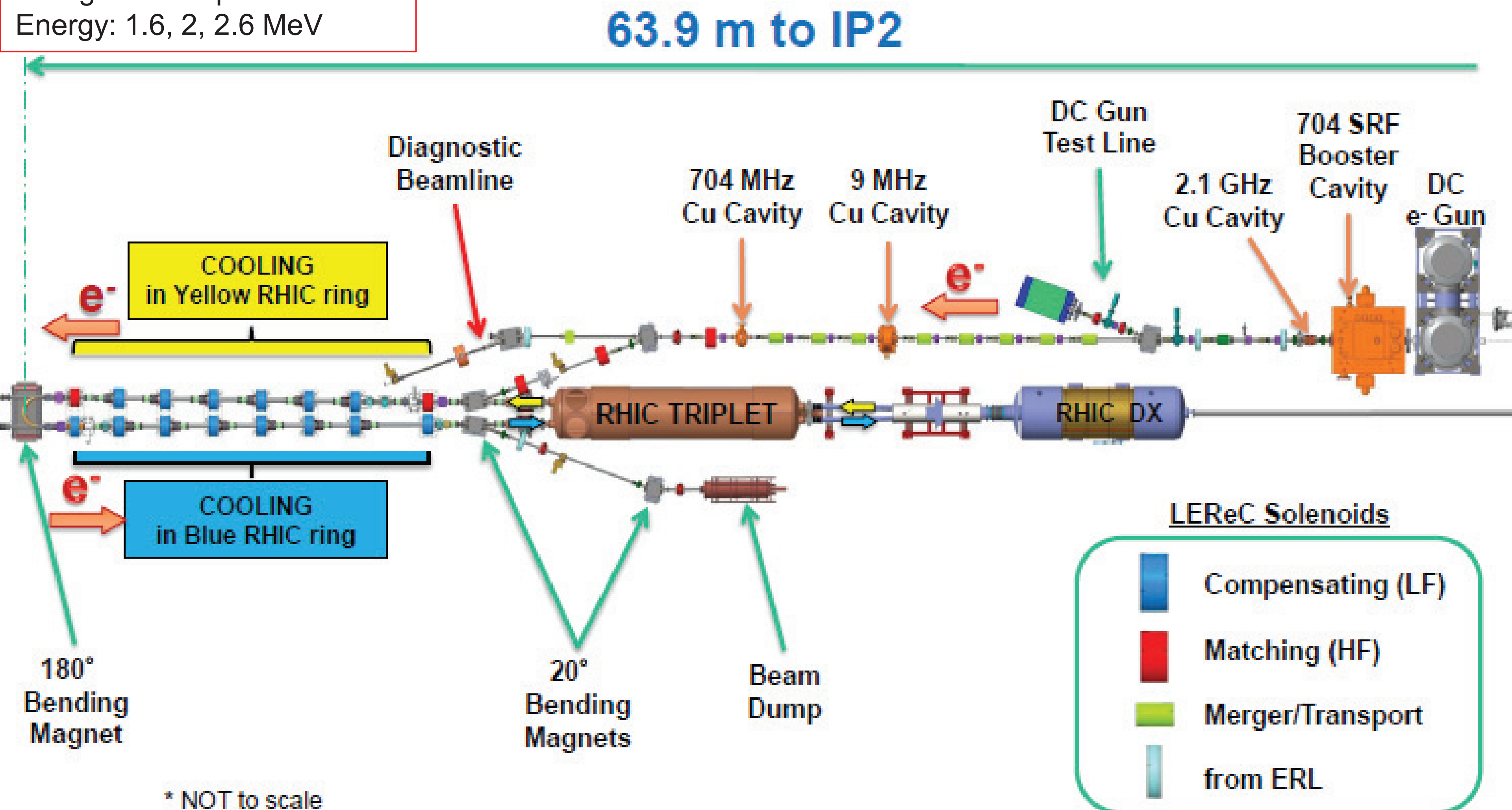
LEReC Accelerator

<u>Electron beam requirements at cooling sections:</u>
Energy spread: < 5e-4
Angular spread : <150 urad
Charge: 3-4nC per Ion bunch
Energy: 1.6, 2, 2.6 MeV



* NOT to scale

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LEReC challenges

- Produce 3-D high-brightness electron beam (technology developed for FELs).
- Transport of such electron beams.
- 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).

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.

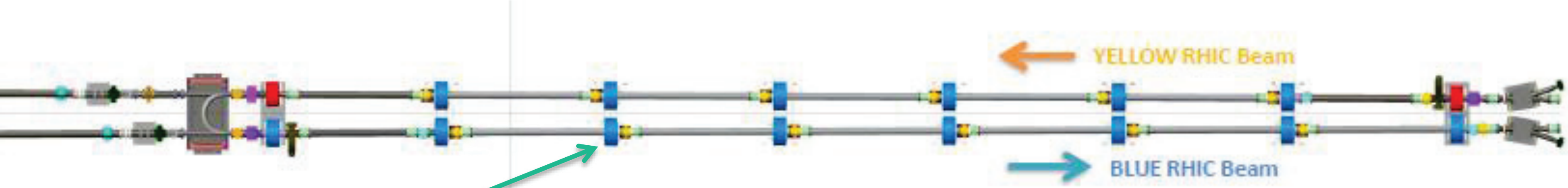
We found that these effects are most difficult to control < 2 MeV.

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.

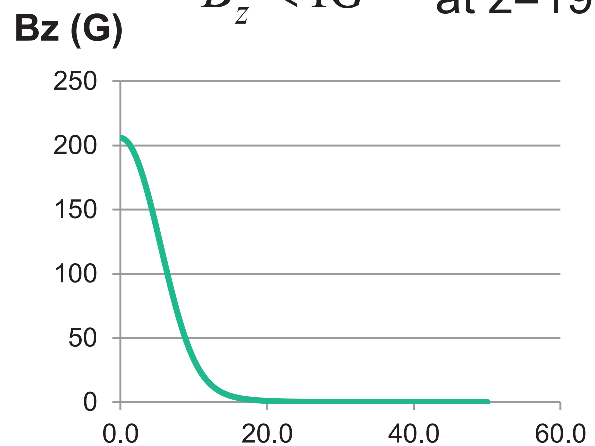
See J. Kewisch et al., WEPOB56.

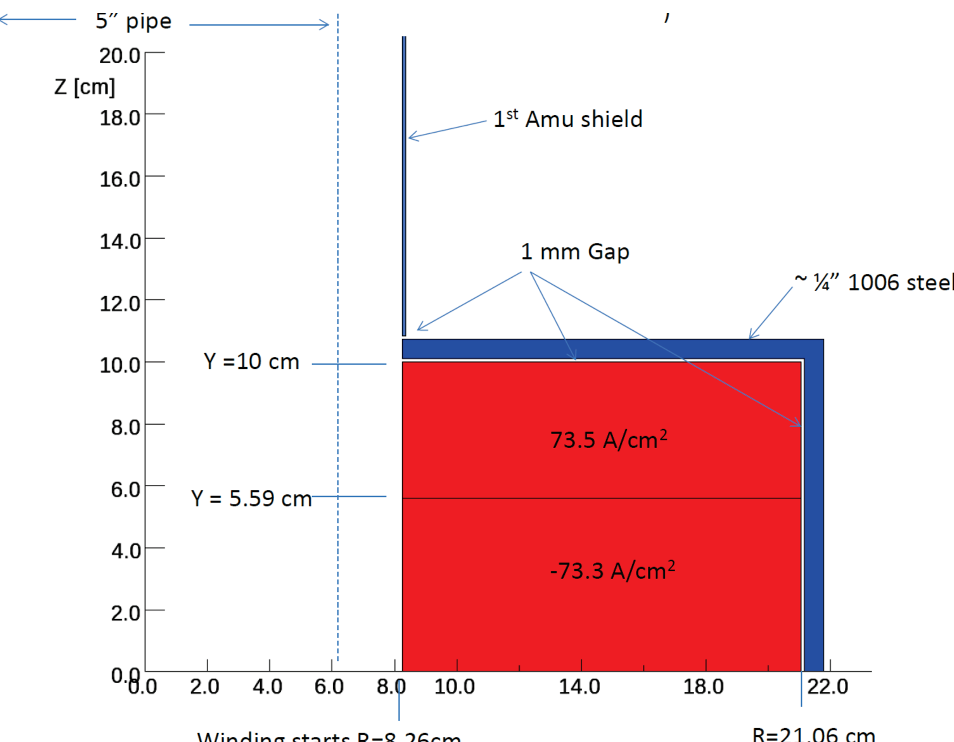
Requirement on magnetic field in the cooling section

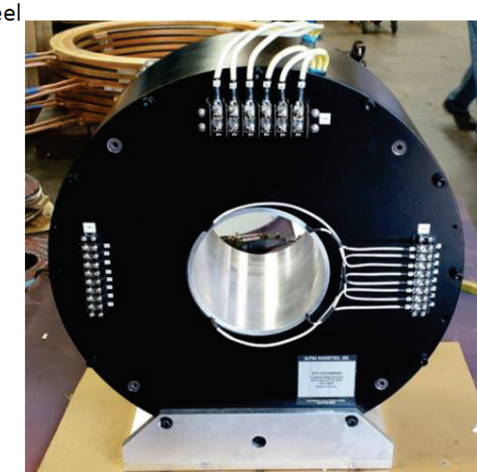


Distance covered by magnetic field from solenoids will be lost from cooling. Expect about 40 cm to be lost from cooling from each solenoid.

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







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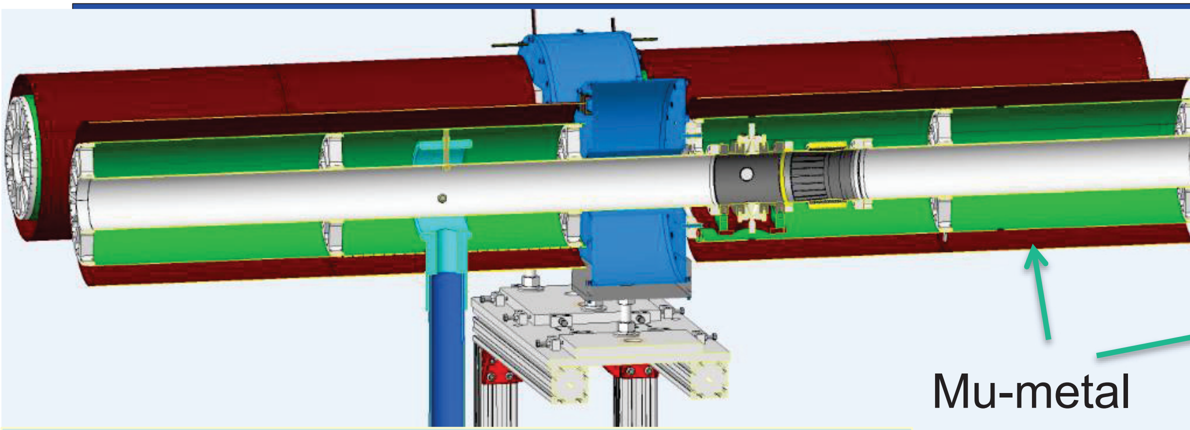
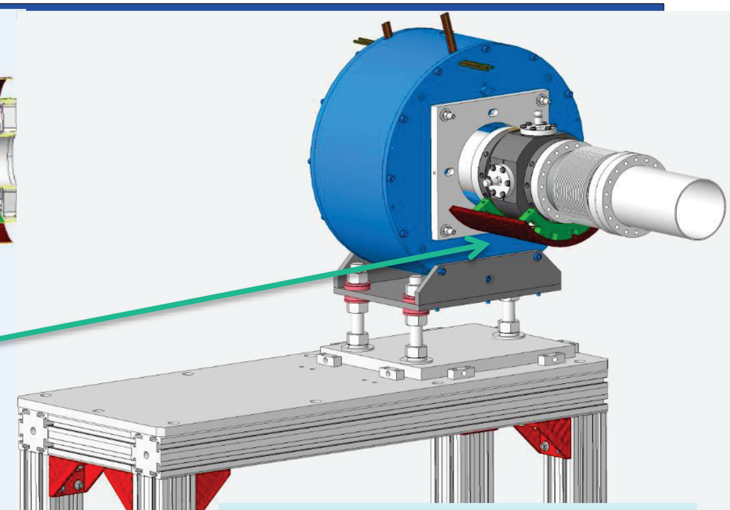
Mu-metal shielding design for cooling sections



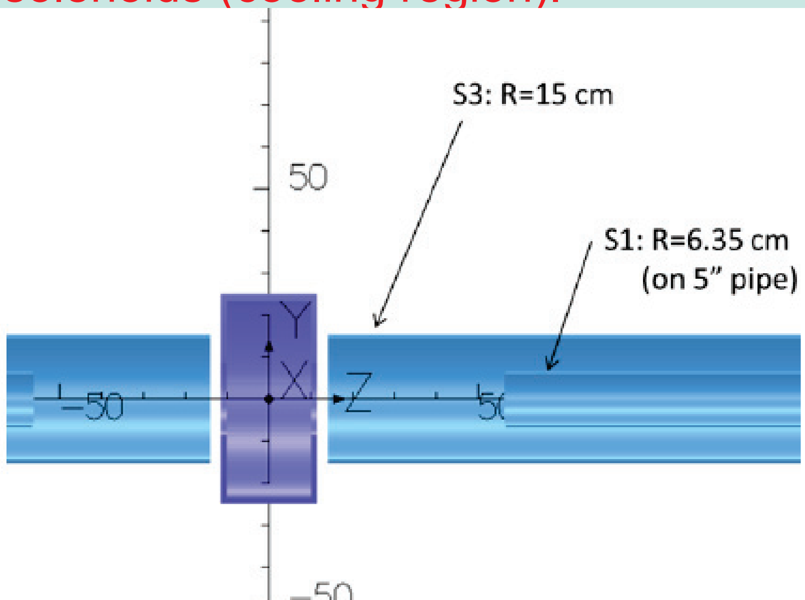


Mu-metal shielding

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 (2016).



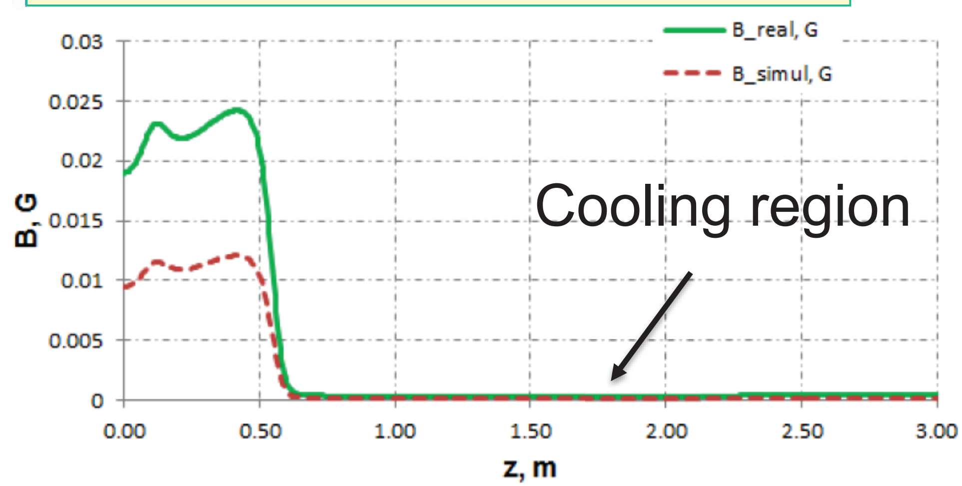


Figure 5: Simulated and "real" (multiplied by 2) residual magnetic field in the cooling section.

Effects on hadron beams

- Effects of electron bunches on ion beam dynamics (tune modulation due to electron beam space-charge) led to requirement to "lock" electron beam on fixed location within ion bunch to avoid betatron resonances. Remaining "random noise effect" sets requirements on jitter on electron bunch timing and bunch current.

G. Wang , BNL Tech Note, C-A/AP/536 (2015).

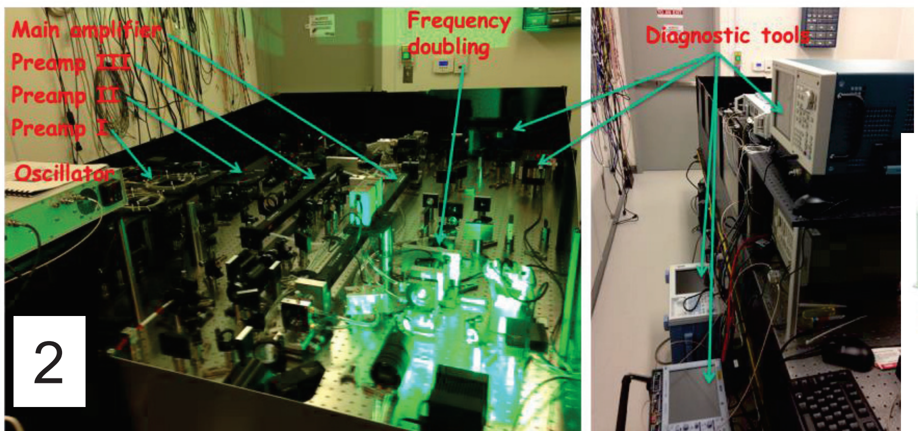
- Due to synchrotron motion of ions tune modulation may cause additional emittance growth due to the synchro-betatron resonances and diffusion due to the intra-beam scattering. For LEReC, such additional transverse heating has to be counteracted by electron cooling.

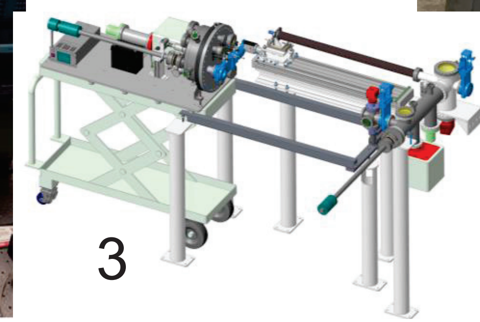
See M. Blaskiewicz , WEA3IO01.

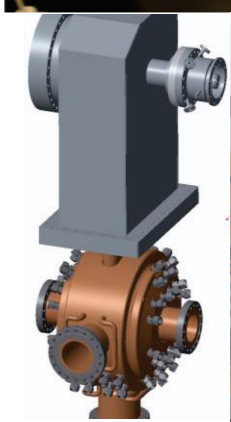
- Hadron beam lifetime in the presence of cooling:
  - need to avoid creation of dense core
  - lifetime limitations due to the space charge
  - interplay of space charge and beam-beam effects

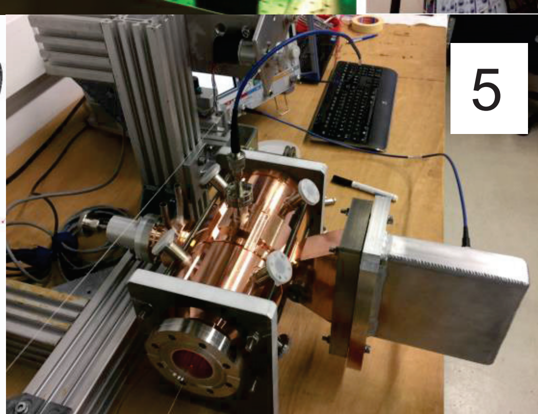
LEReC Critical Technical Systems

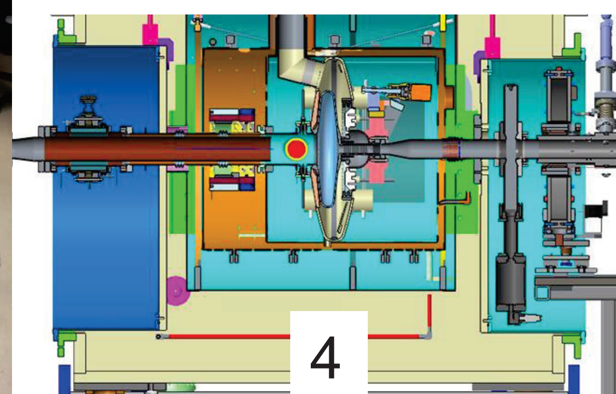
1. DC photocathode electron gun
2. High-power fiber laser system
3. Cathode production deposition and delivery systems
4. SRF Booster cavity
5. 2.1 GHz and 704 MHz warm RF cavities



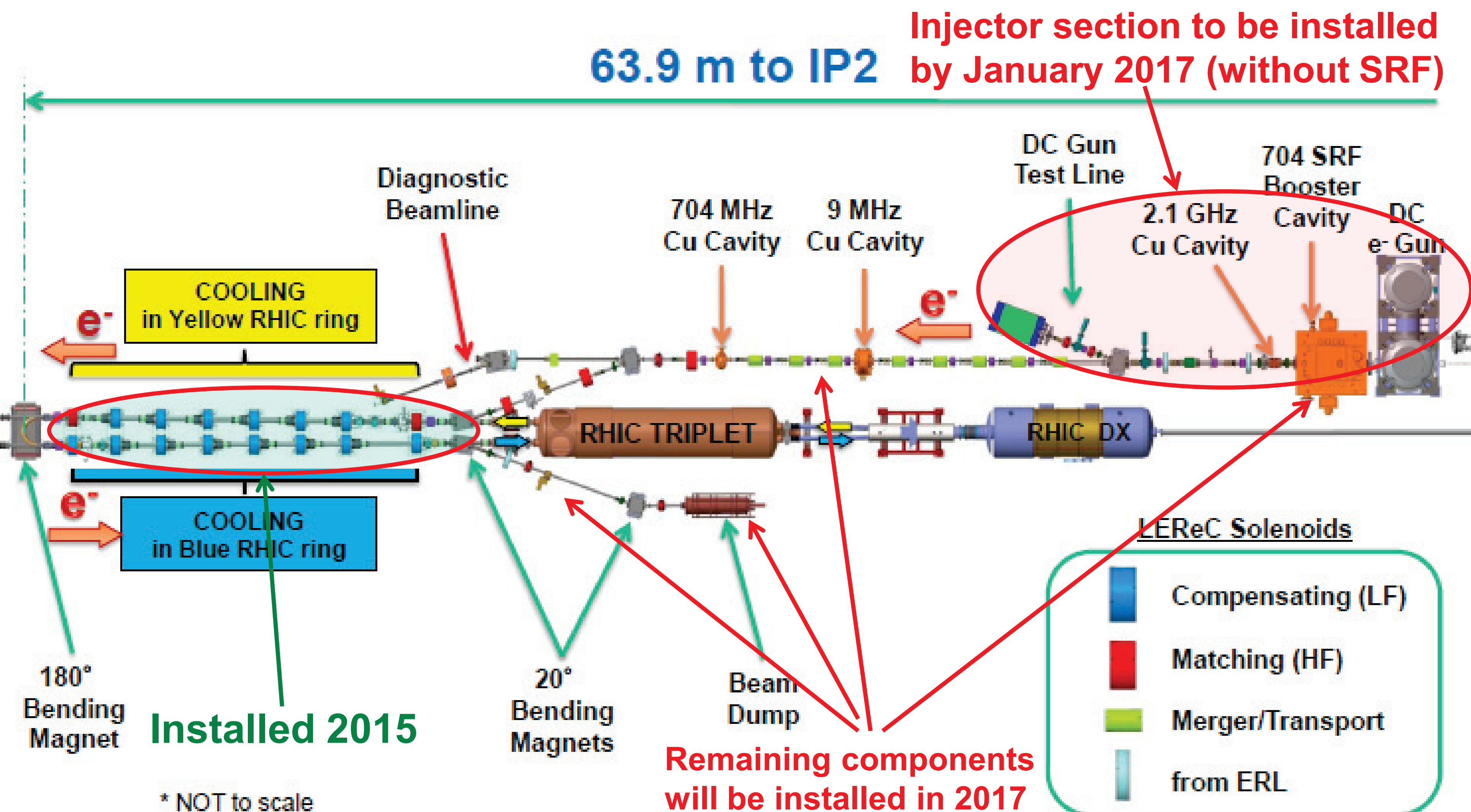








LEReC accelerator (100 meters of beamlines with the DC Gun, 5 RF systems, many magnets and instrumentation devices)



LEReC timeline

May 2015:	**Project approved by DOE for construction**
January 2016:	**Cooling section magnets installed**
April 2016:	**Laser assembled, commissioning started**
August 2016:	**DC gun assembled at Cornell**
Sep.-Oct. 2016:	DC gun conditioning at Cornell University
Oct.-Nov. 2016:	DC gun assembly and tests at BNL
Nov.-Dec. 2016:	Install DC gun test beamline and laser transport in RHIC
January 2017:	Start DC gun tests with beam; start commissioning of warm RF cavities
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:	Start 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).

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 engineering and construction phase.
- Cooling section solenoids already installed.
- Laser is under commissioning.
- Injection section (without SRF booster) and laser transport to be installed in Fall of 2016.
- DC gun tests with beam are planned to start January 2017.
- Commissioning with electron beam of full LEReC accelerator will start in 2018.

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