Low Energy RHIC electron Cooling (LEReC) Project

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for the LEReC team

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COOL'15
Workshop on Beam Cooling and Related Topics
Newport News, Virginia USA
JSA Jefferson Lab

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).

This requires:

- ❑ Building and commissioning of new state of the art electron linear accelerator (LEReC will be first linac-based cooler).
- ❑ Produce and transport 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, including several RF systems, magnets, beam instrumentation, etc.

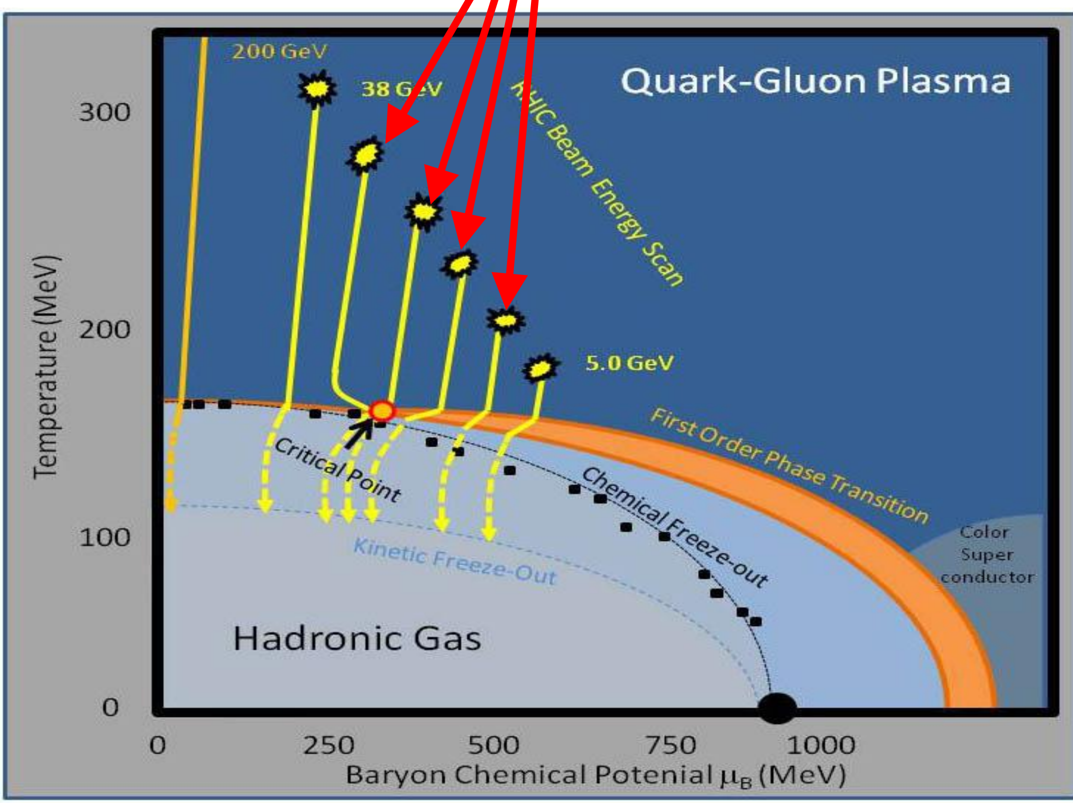
Low Energy RHIC Physics program

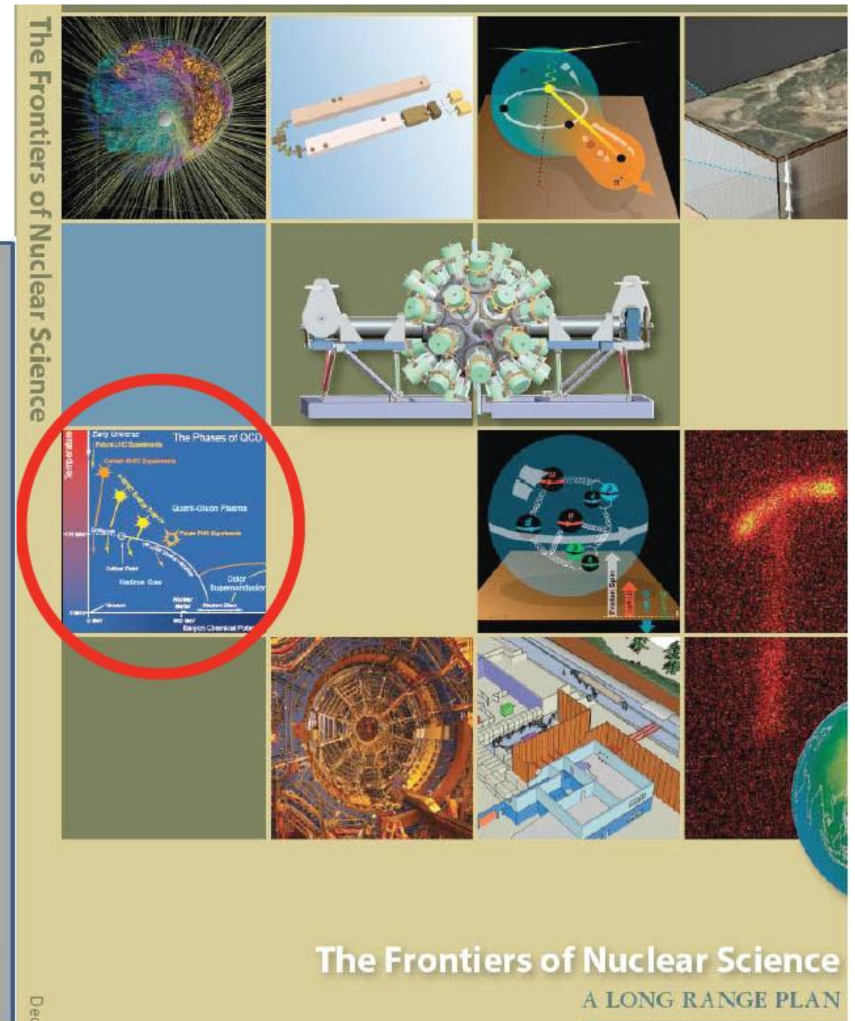
Beam Energy Scan I, center of mass energies:

$\sqrt{s_{NN}}$ = 7.7, 9, 11.5, 14.6, 19.6, 27 GeV

Search for QCD phase transition Critical Point

(2010 & 2011 & 2014 RHIC runs)





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, 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.

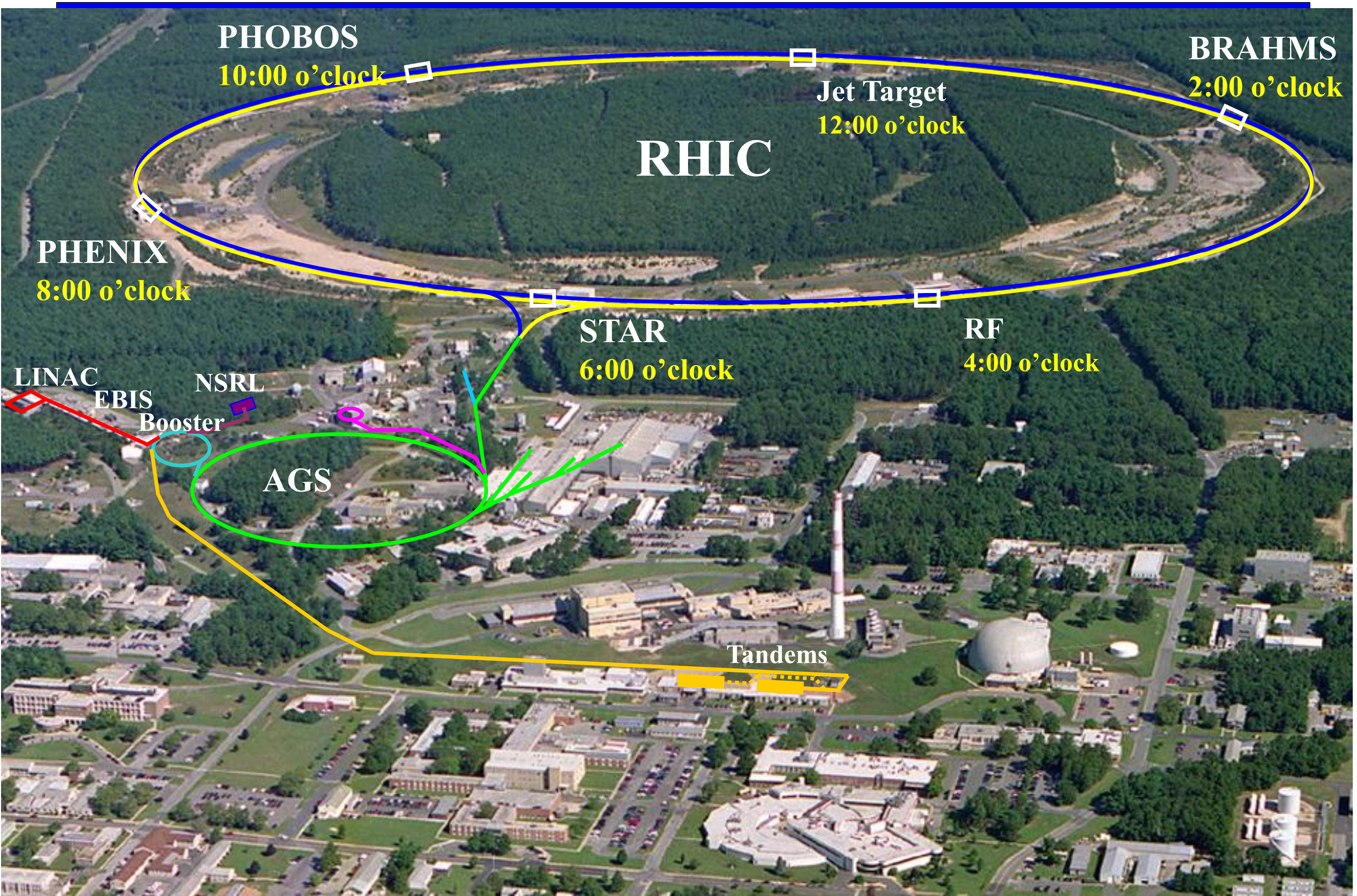
However, significant luminosity improvement can be provided with electron cooling applied directly in RHIC at low energies.

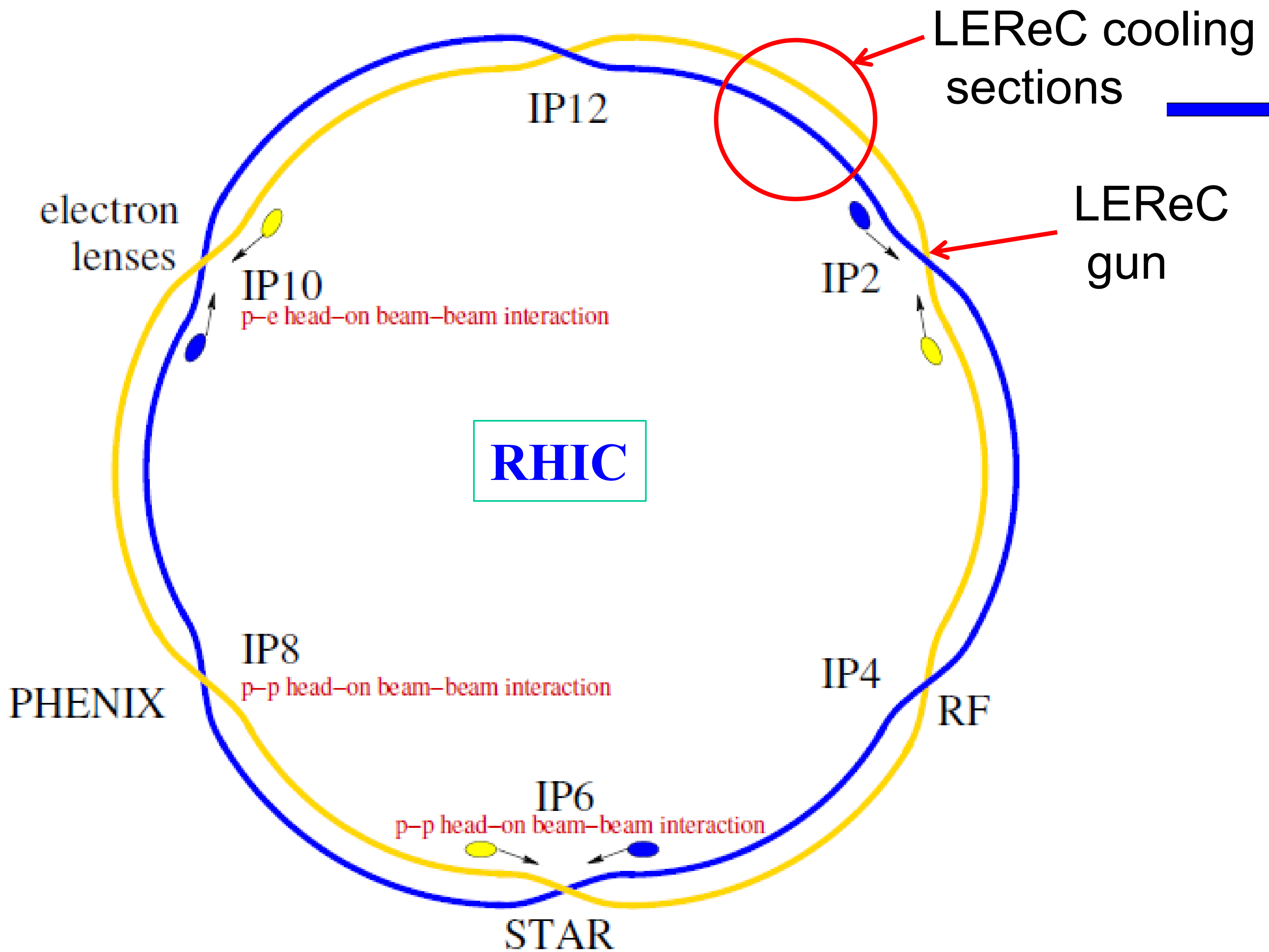
To cover all energies of interest need electron accelerator:
$E_{e,kinetic}$=1.6-5 MeV

LEReC Phase I: 1.6 - 2 MeV

LEReC Phase II
energy upgrade: up to 5 MeV

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

Choice of electron cooler accelerator

- For high energies (from few MeV to hundreds of MeV) RF-based acceleration and bunched electron beam cooling appears to be a natural approach (studied in detail for RHIC-II high-energy electron cooling in 2001-07, for example).

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

For LEReC we considered:

DC electrostatic accelerator (DC beam)

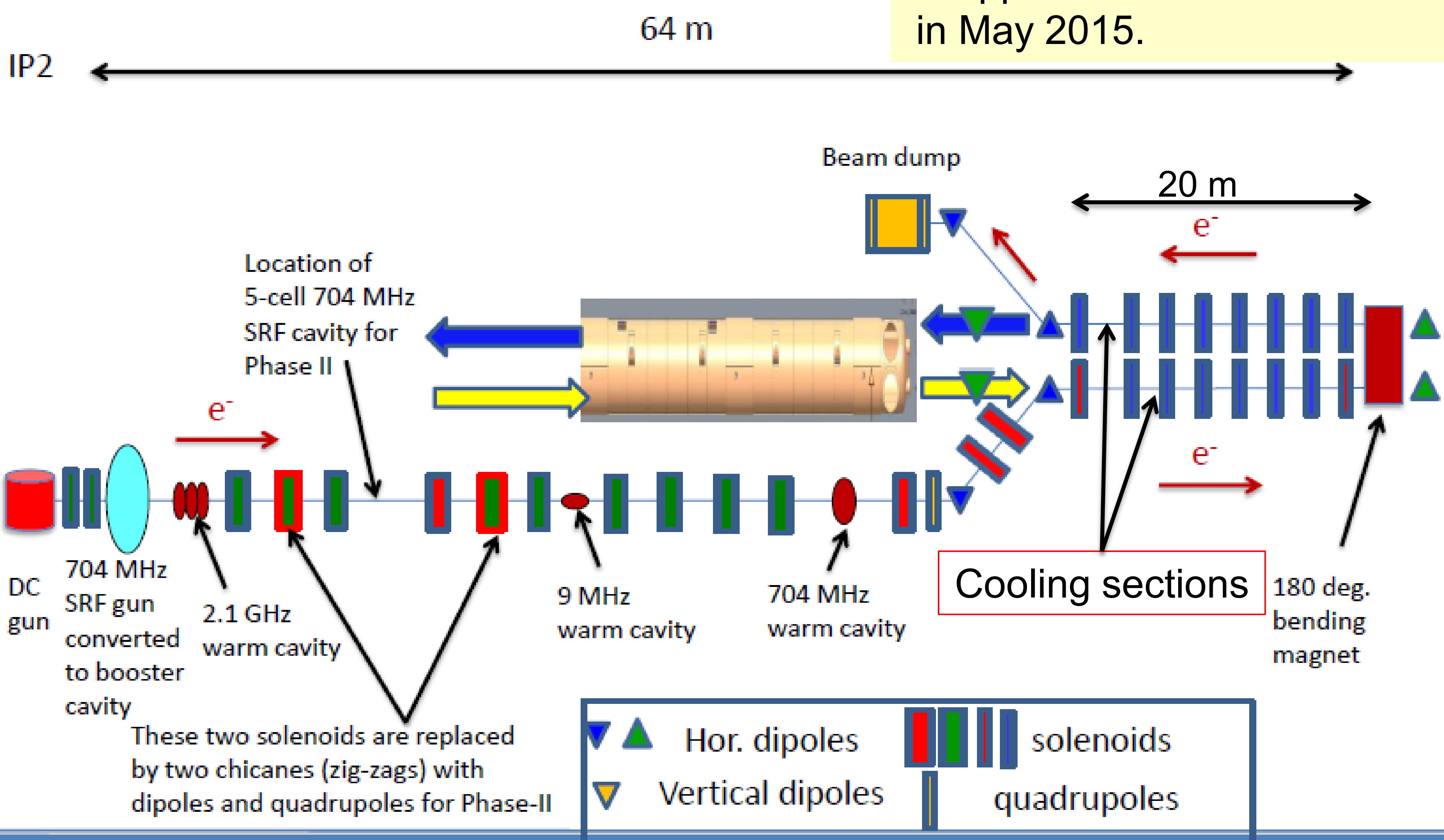
Low-frequency (84 MHz) RF accelerator (bunched beam)

High-frequency (704 MHz) RF accelerator (bunched beam)

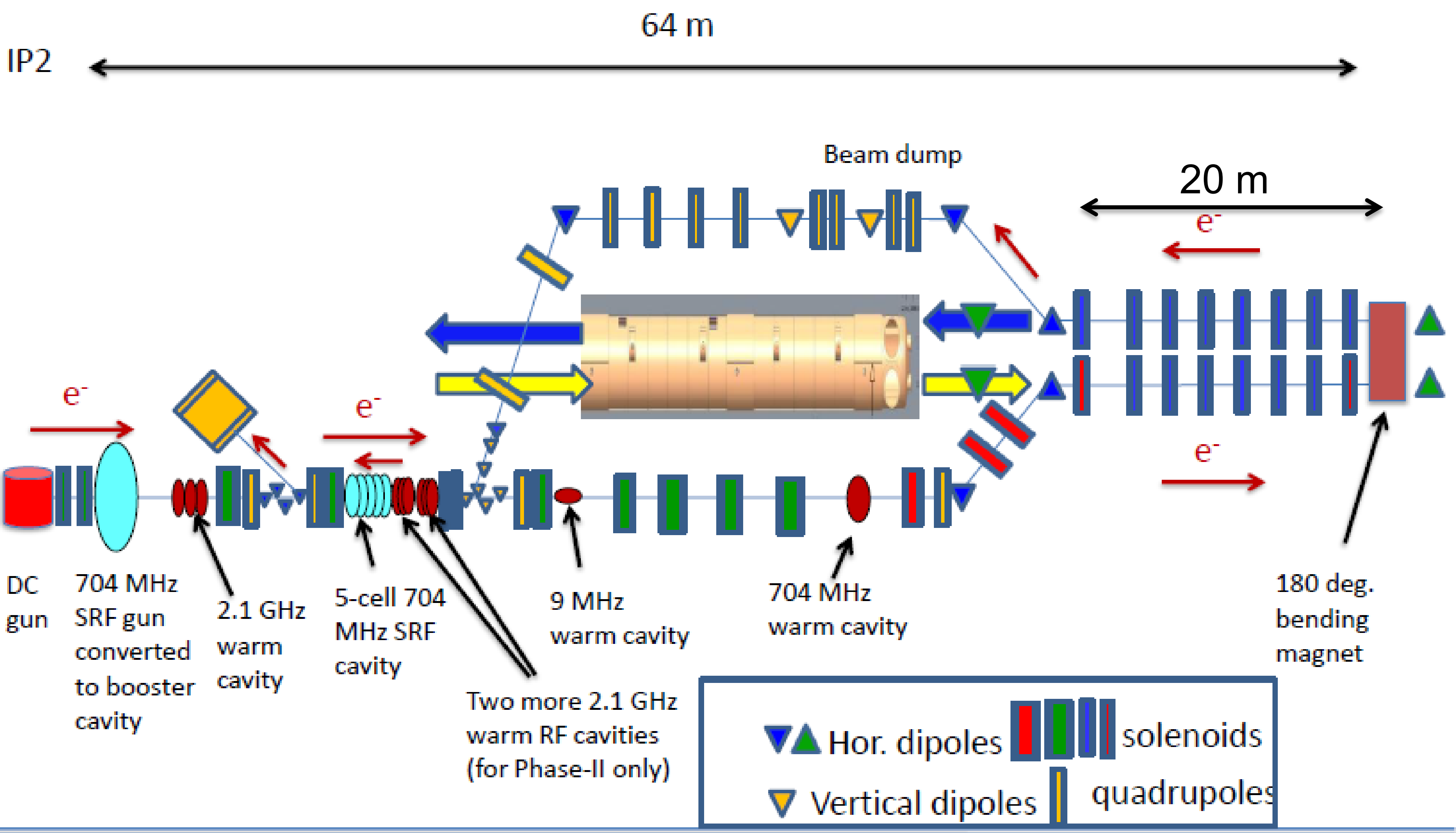
The main problem for bunched electron beam approach is to provide beam transport without significant degradation of beam emittance and energy spread, especially at low energies.

LEReC Phase-I (electron beam energies 1.6-2MeV): Gun-to-dump mode

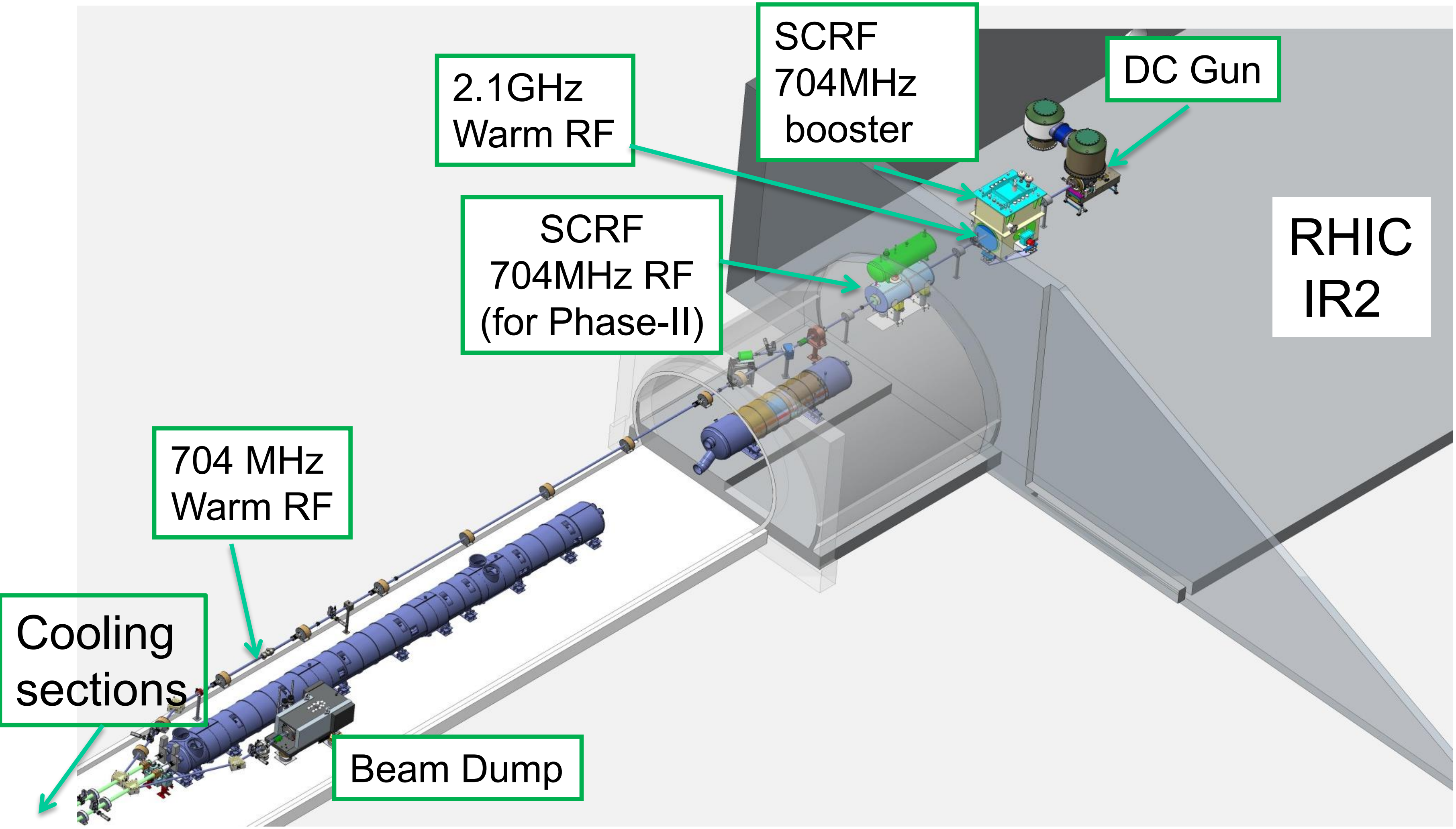
LEReC Phase-I
is approved for construction
in May 2015.



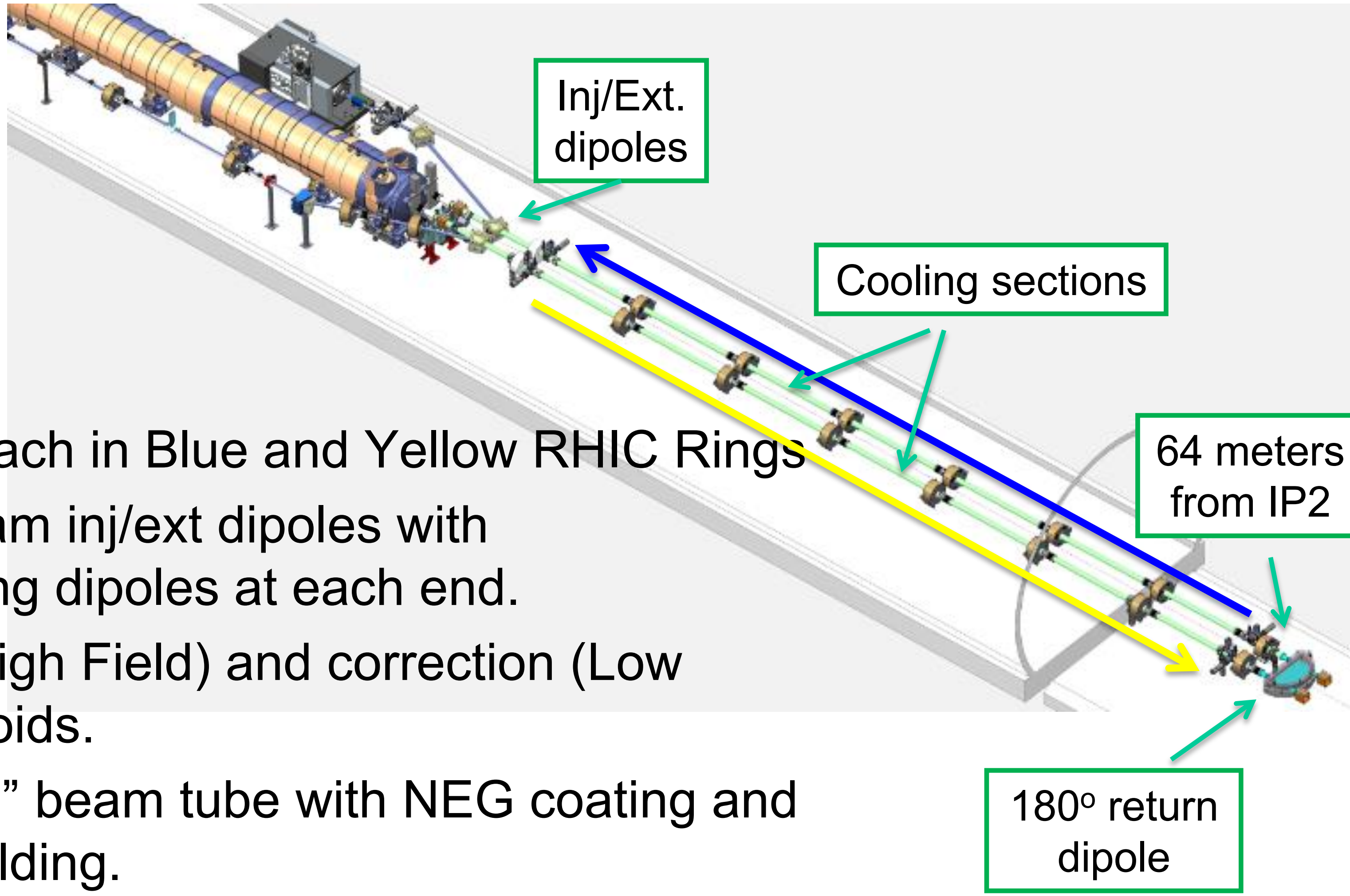
LEReC Phase-II (electron beam energies up to 5MeV): shown as ERL mode; other possibility are being evaluated



LEReC Phase-I layout – electron Gun and transport line system



LEReC layout: cooling sections in RHIC



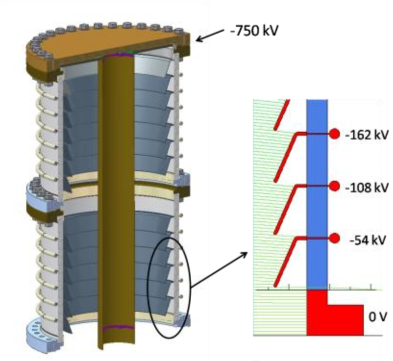
- 20 Meters each in Blue and Yellow RHIC Rings
- Electron beam inj/ext dipoles with compensating dipoles at each end.
- Matching (High Field) and correction (Low Field) solenoids.
- RHIC “warm” beam tube with NEG coating and μ metal shielding.

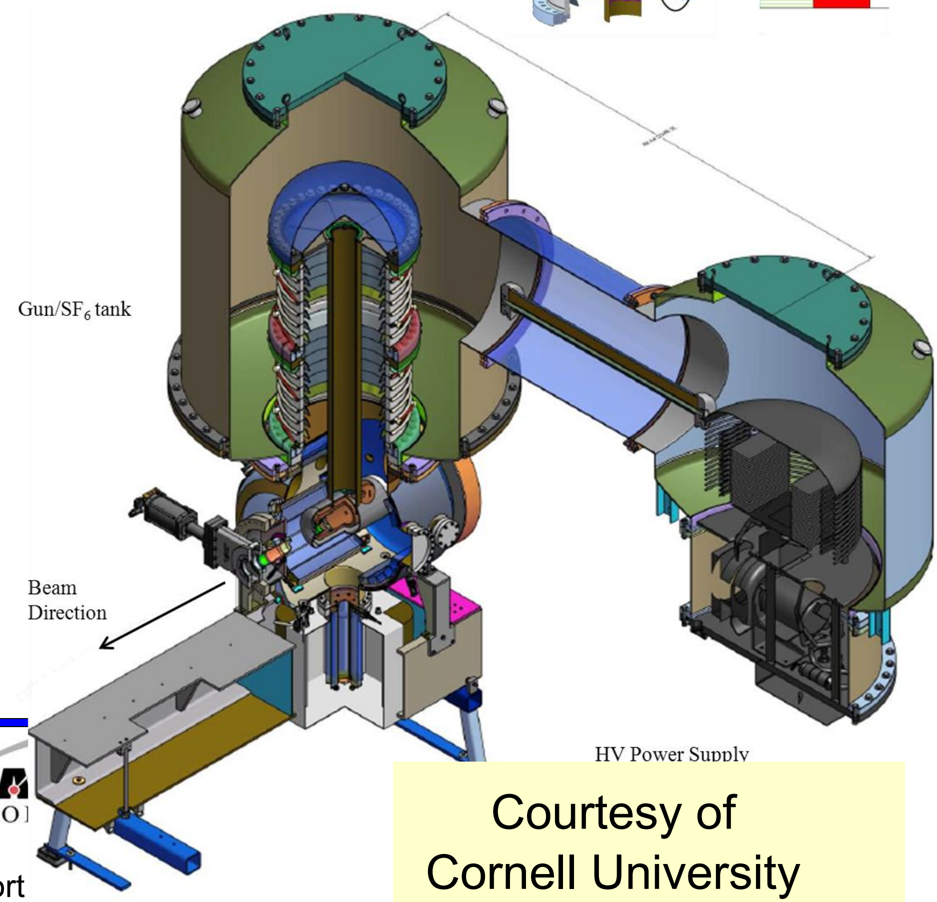
LEReC scope
(**green** – existing equipment under commissioning in Bldg. 912/ERL)

- DC photoemission gun (400kV) **with the 704 MHz SRF gun used as a booster cavity (up to 2 MV).**
- The electron beam is generated by illuminating a K_2CsSb photocathode with green (532 nm) light from a laser.
- **704 MHz SRF 5-cell cavity (acceleration to 5 MeV in ERL mode for Phase-II).**
- 2.1 GHz (3rd harmonic of the SRF frequency) warm cavity for energy spread correction; 704 MHz warm cavity for removing energy chirp; 9 MHz warm cavity for beam loading correction.
- Long electron beam transport from IP2 region to cooling sections.
- Cooling sections in Yellow and Blue RHIC rings – about 20 m long with the space-charge correction solenoids.
- U-turn 180 deg. dipole magnet between cooling section in Yellow and Blue RHIC Rings.
- Beam Instrumentation and **electron beam dump.**

Contract with Cornell to build DC gun for LEReC (identical to existing Cornell's gun #2)

- Construction of DC photoemission gun is in progress
- Available spare power supply and high voltage assembly
- Cornell fabrication of critical components
- BNL fabrication and procurement of other components
- BNL installation interface, safety calculations, and reviews
- Assembly and testing at Cornell in 2016
- Installation and commission by BNL w/Cornell support





Courtesy of Cornell University

LEReC-I (1.6-2MeV) and LEReC-II (up to 5MeV) requirements

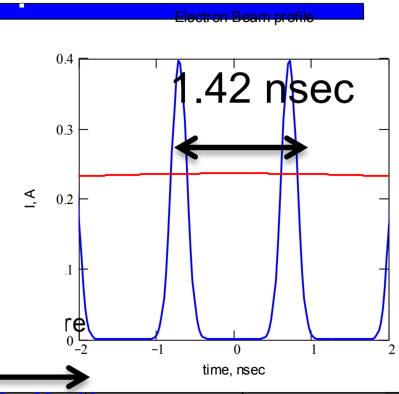
Full region of energies

Ion beam parameters		
Gamma	4.1	10.7
RMS bunch length	3.2 m	2 m
N_{au}	0.5e9	2e9
I_peak	0.24 A	1.6 A
Frequency	9.1 MHz	9.34 MHz
Beta function@cooling	30 m	30 m
RMS bunch size	4.3 mm	2.7 mm
RMS angular spread	140 urad	90 urad
Electron beam cooler requirement		
Cooling sections	2x20 m	2x20 m
Charge per ion bunch	3 nC (30x100pC)	5.4 nC (18x300pC)
RMS norm. emittance	< 2.5 um	<2 um
Average current	30 mA	50 mA
RMS energy spread	<5e-4	< 5e-4
RMS angular spread	<150 urad	<100 urad

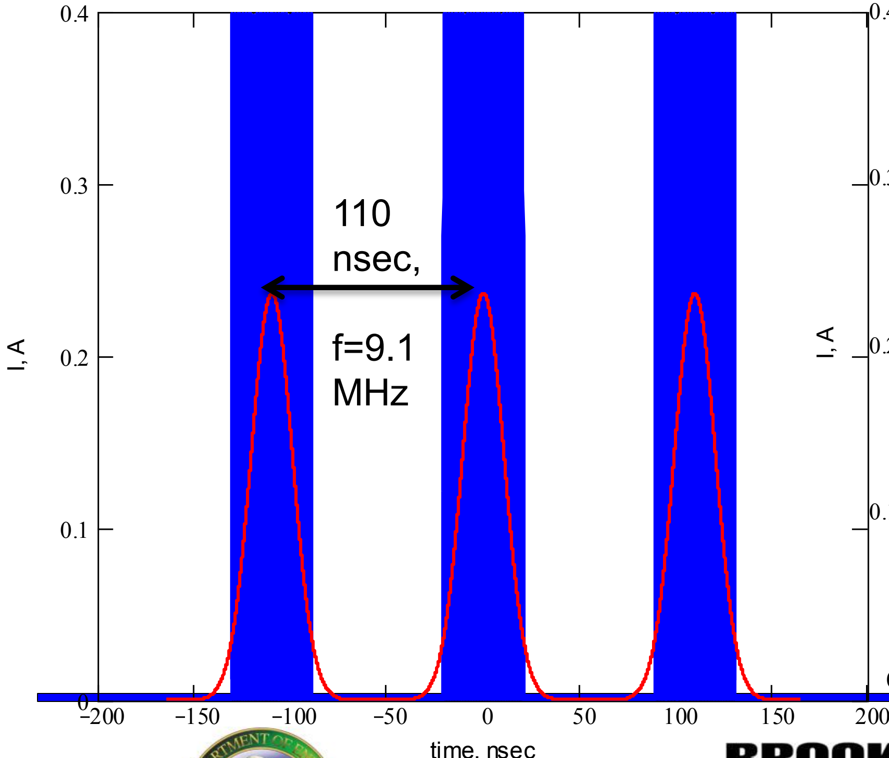
LEReC beam structure in cooling section
Example for γ= 4.1 (E_{ke}=1.6 MeV)

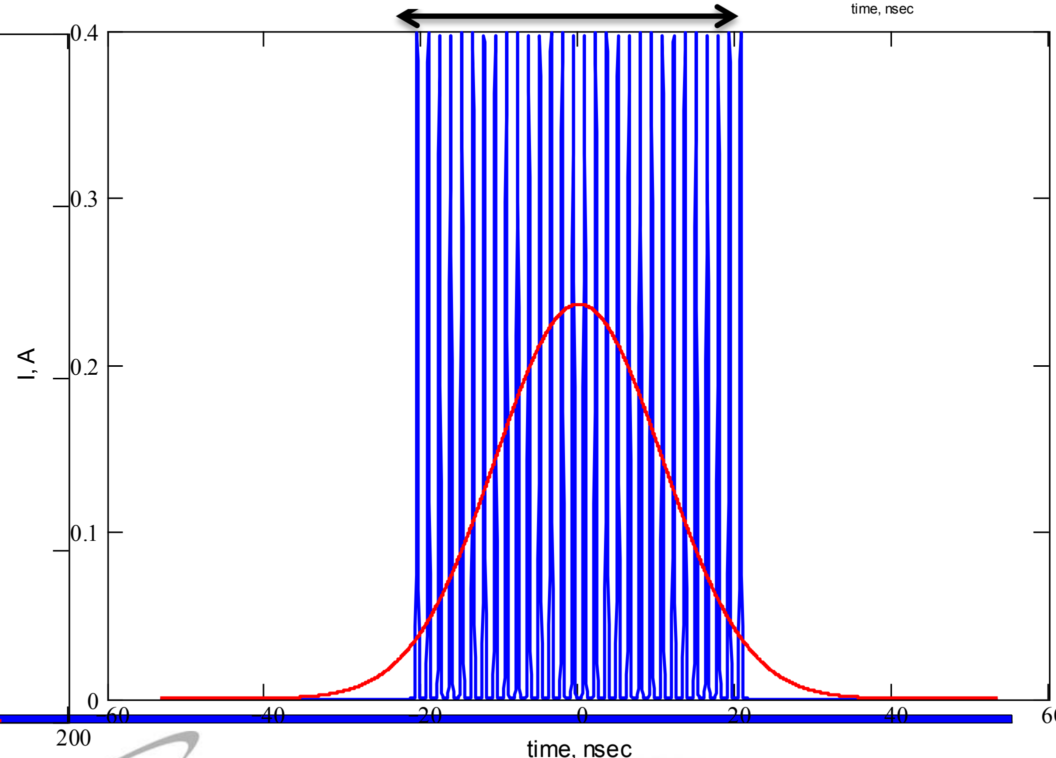
Ions structure:
120 bunches
f_rep=120x75.8347 kHz=9.1 MHz
N_ion=5e8, I_peak=0.24 A
Rms length=3.2 m

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



9 MHz RHIC RF





LEReC: 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 (for γ=4.1).

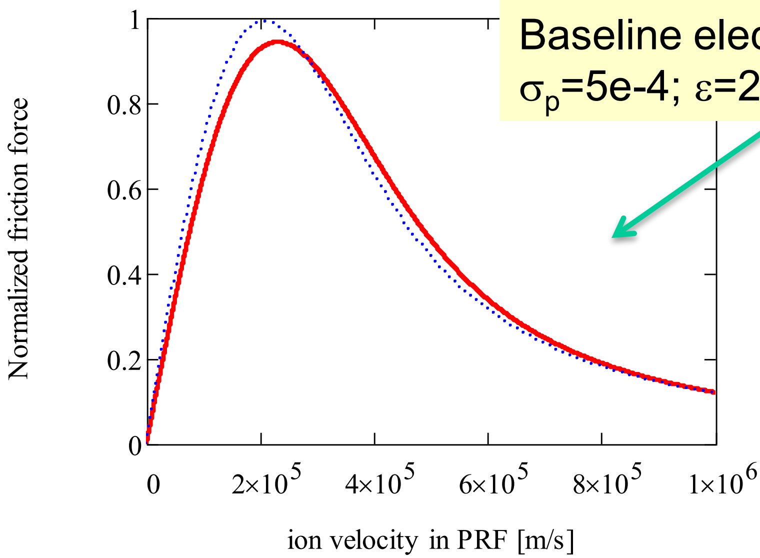
asymptotic for $v_{ion} < \Delta_e$:

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

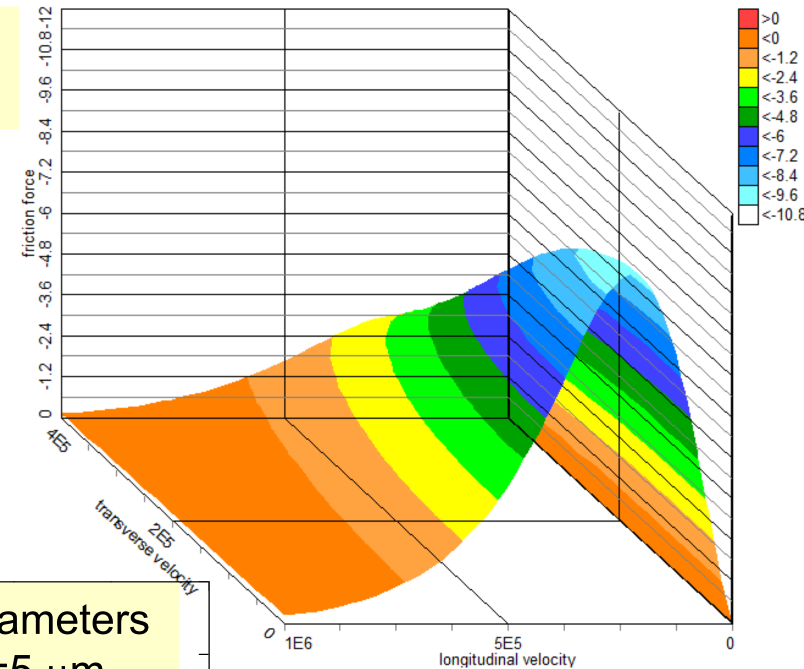
$$\vec{F} = -\frac{4\pi Z^2 e^4 n_e L}{m} \frac{\vec{v}_i}{\beta^3 c^3 \left((\gamma\vartheta)^2 + \sigma_p^2\right)^{3/2}}$$

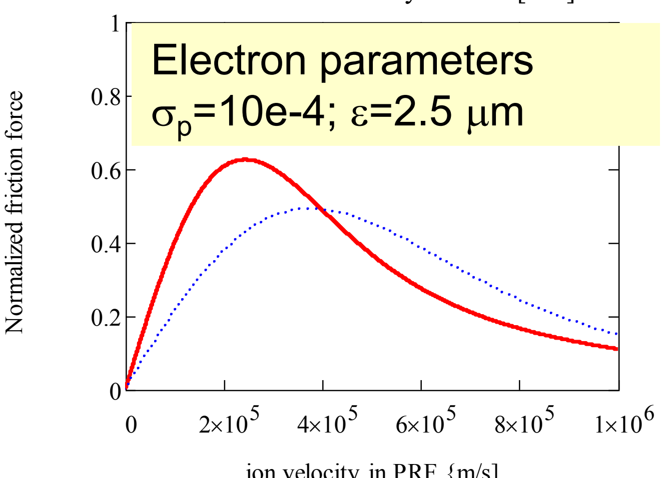
Requirement on electron angles:
For γ=4.1: σ_p=5e-4; θ<150 μrad

Cooling force for LEReC parameters

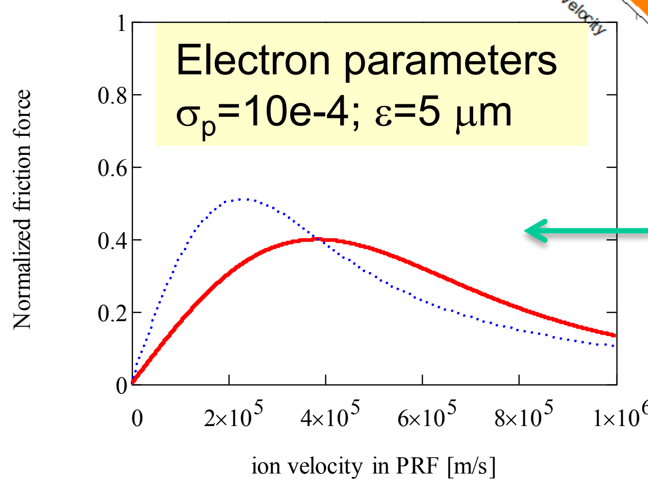


Baseline electron parameters
σ_p=5e-4; ε=2.5 μm





Electron parameters
σ_p=10e-4; ε=2.5 μm



Electron parameters
σ_p=10e-4; ε=5 μm

Cooling reduction with both emittance and energy spread twice worse than requirement.

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LEReC challenges

- 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.
- Repeatability of electron beam transport at low energies.
- 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

For low energies (<5 MeV), like in LEReC, there are many challenges to use RF-based approach which have to be carefully addressed:

Beam transport of electron bunches without significant degradation of beam emittance and energy spread at low energies:

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.

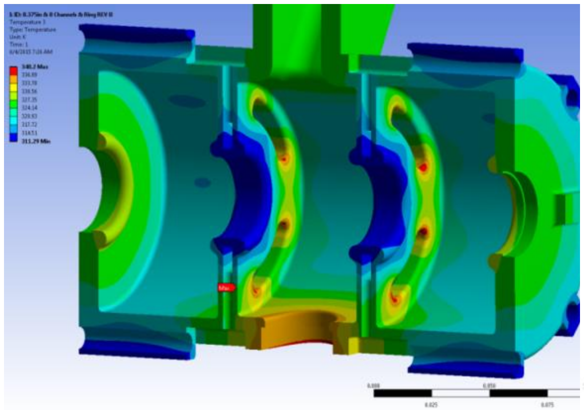
Suppression of residual magnetic field:

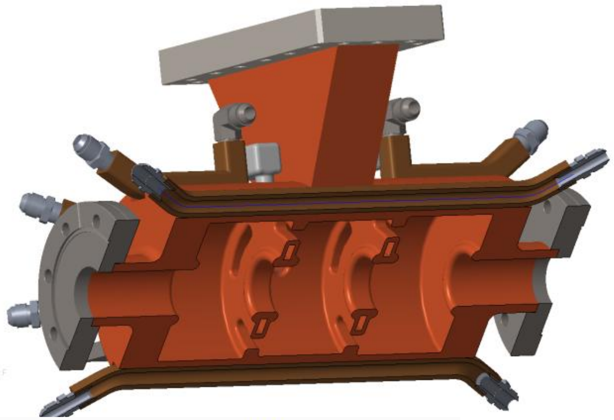
Cooling sections are covered by several layers of Mu-metal shielding.

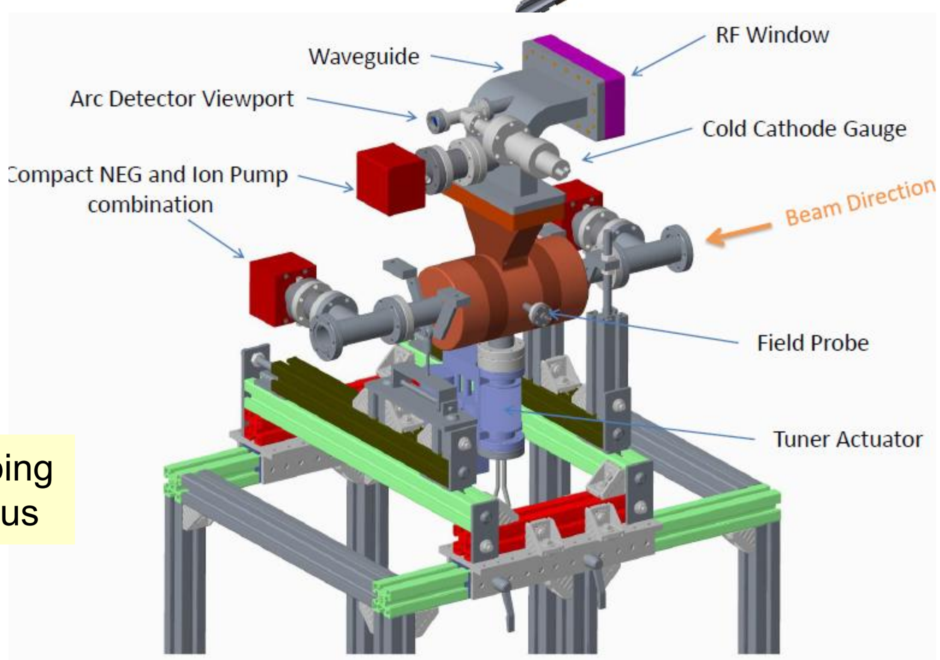
Electron beam with small emittance and energy spread should be provided for several energies of interest.

Warm RF Cavities: 2.1 GHz and 704 MHz

2.1 GHz NCRF cavity

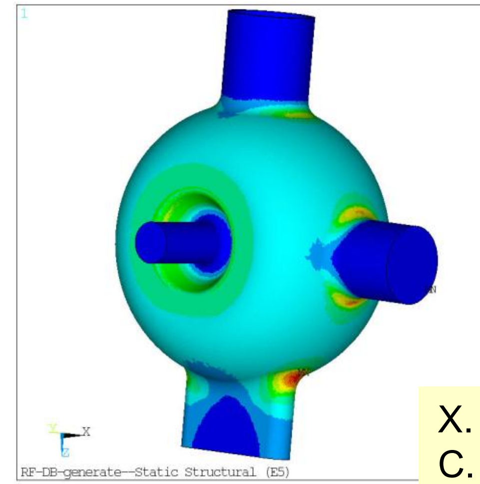




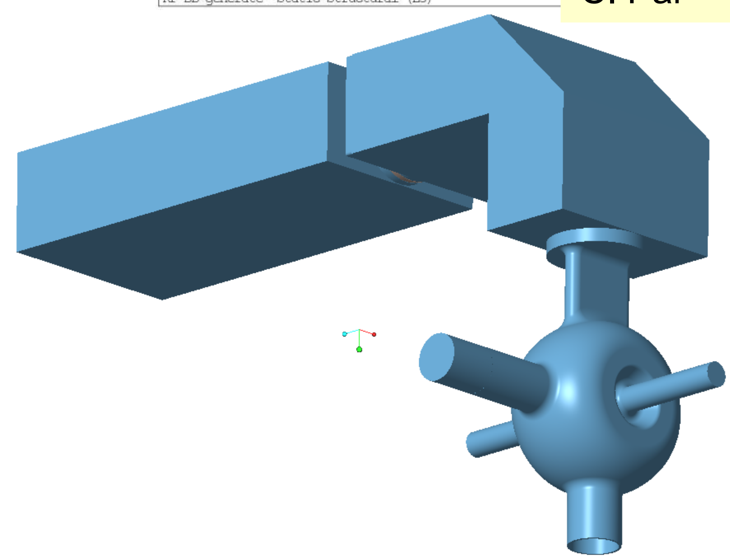


X. Binping
C. Brutus

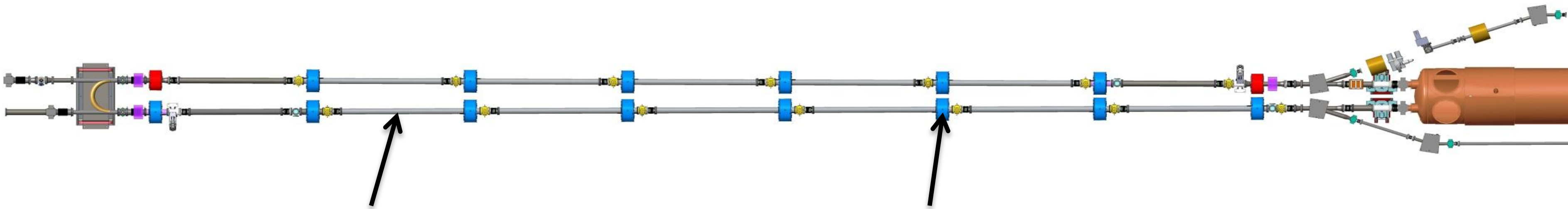
704 MHz NCRF cavity



X. Binping
C. Pai



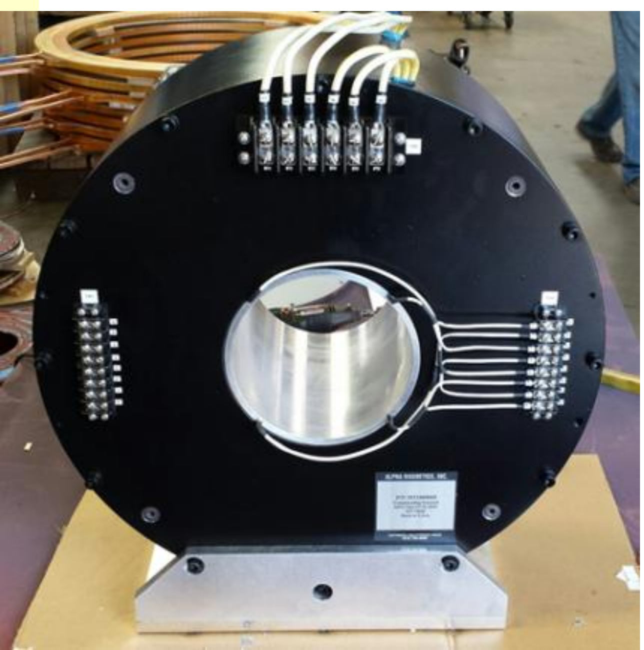
Requirement on magnetic field in the cooling section

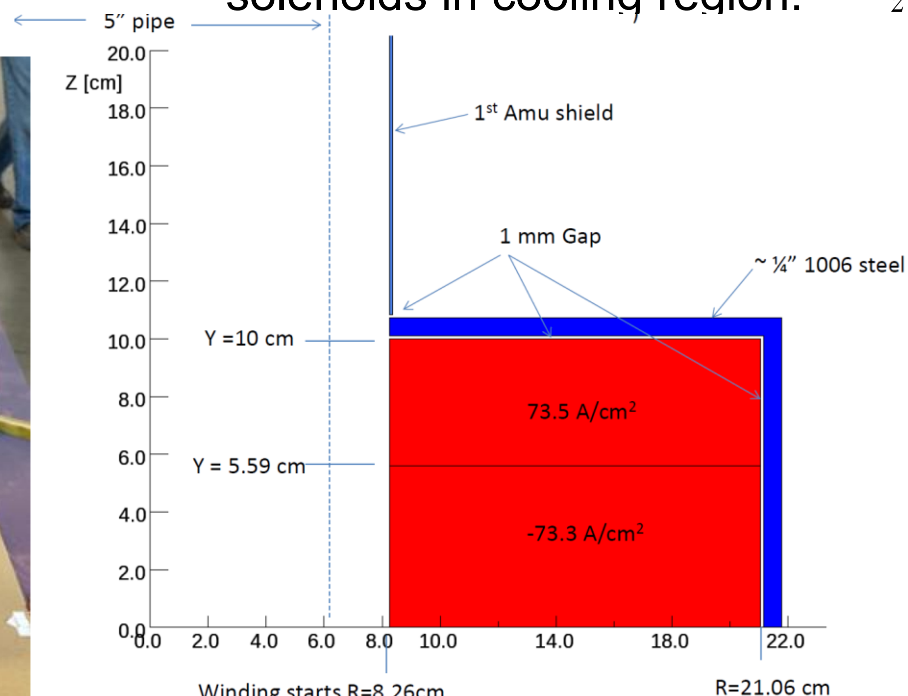


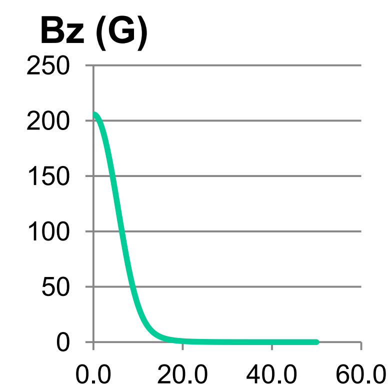
Passive (mu-metal shielding) to suppress B_residual to required level (<2.5 mG) in free space between the solenoids (cooling region).

Distance covered by magnetic field from solenoids (200 G) will be lost from cooling. Expect about 40 cm to be lost from cooling from each solenoid.

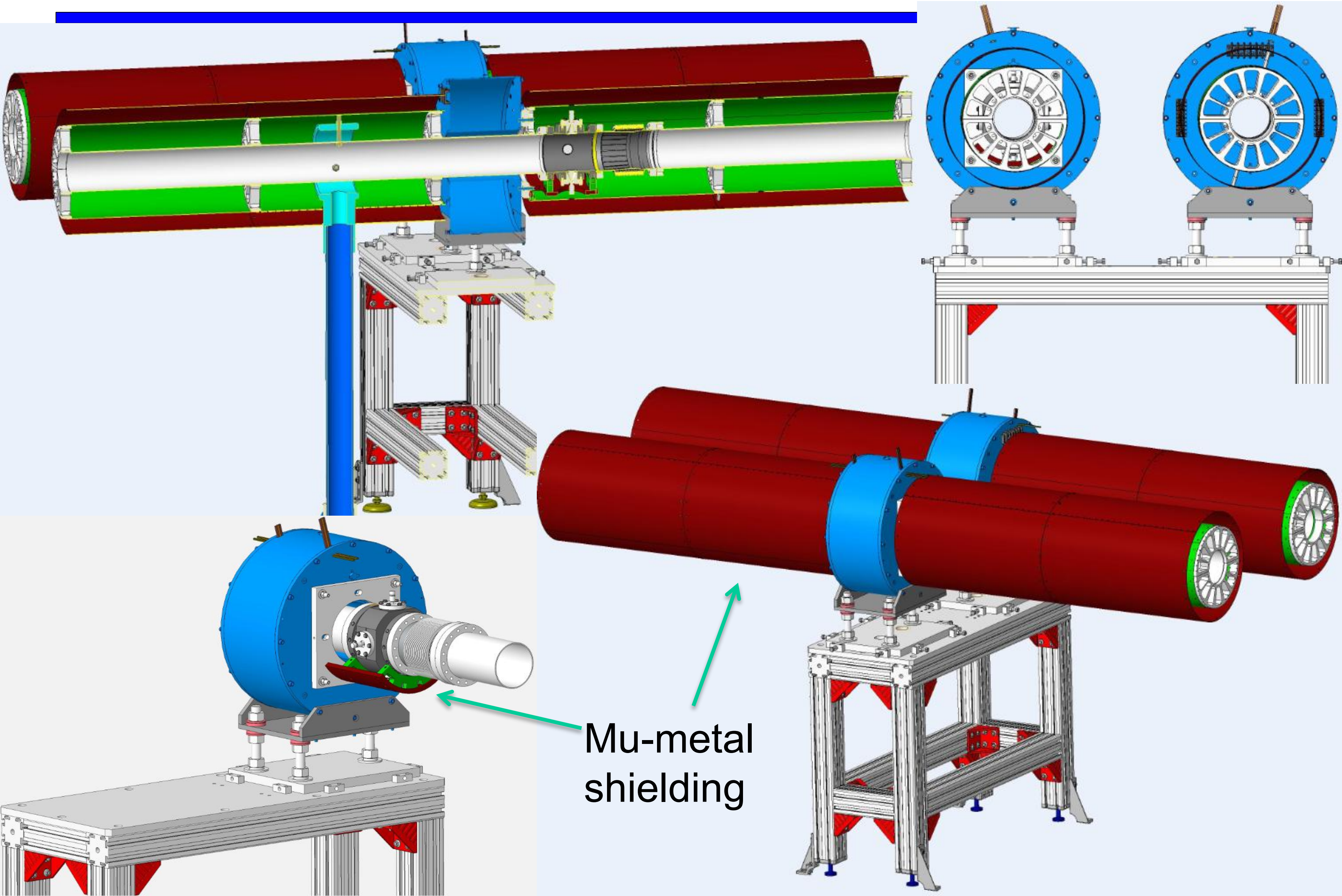
Residual magnetic field from solenoids in cooling region: $B_z < 1G$ at z=19 cm







One sector of 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.
- 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 talk
by M. Blaskiewicz

- 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 Phase-I timeline

LEReC Phase-I (2 MeV RF electron cooler):

May 2015	**Approved by DOE for construction**
2015-2017:	Commissioning of equipment in R&D ERL (Bldg. 912)
May 2015 – 2016:	DC photoemission gun construction by Cornell University. DC gun commissioning at Cornell.
End of 2015:	Start installation of cooling sections in RHIC
2016:	Start installation of electron beam transport and warm RF cavities
June 2017 – Feb.2018:	Move and install SRF components, beam dump, etc.
2017-March 2018:	Systems commissioning (RF, cryogenics, etc.)
April - Sept 2018:	**LEReC commissioning with e-beam in RHIC tunnel**
End of 2018:	**RHIC Run-19 Beam Energy Scan-II physics program (commissioning of cooling with Au ion beams)**

Summary

- LEReC will be first electron cooler based on the RF acceleration of electron beam. It is also a prototype of future high-energy electron coolers.
- It will be the first application of electron cooling in a collider with additional challenges related to beam lifetime.
- Phase-I of the LEReC project is approved for construction.
- Most of LEReC cooling section magnets are already under contract. First magnets arrived and are under measurements. Other major elements are in their final stages of the design.
- LEReC commissioning with beam will start in 2018.

Acknowledgments

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

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  B. Dunham, C. Gulliford, K. Smolenski, V. Veshchervich and others

Thank you

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