Low Energy RHIC electron Cooling (LEReC)

LEReC overview and status

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for LEReC team

RHIC Meeting
May 11 2015

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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).

- 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 first bunched beam electron cooler.
  - commissioning first electron cooling in a collider.

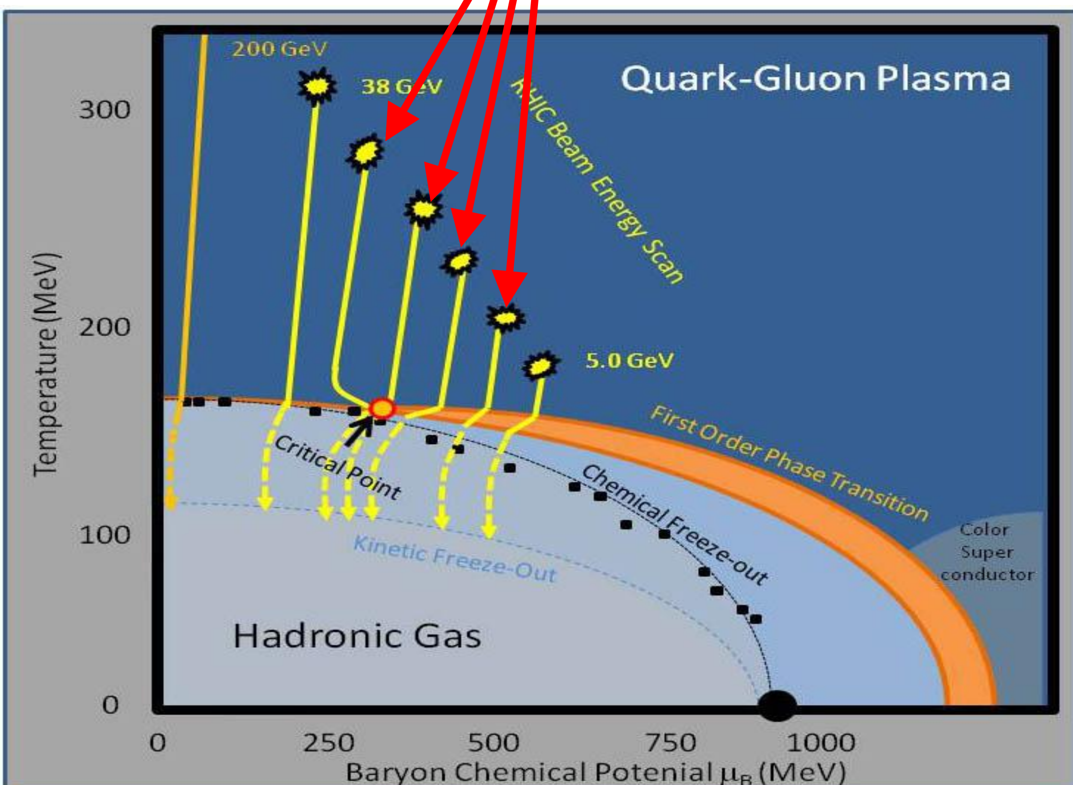
- Many new accelerator systems will need to be built, installed and commissioned, including several RF systems, magnets, beam instrumentation, etc.

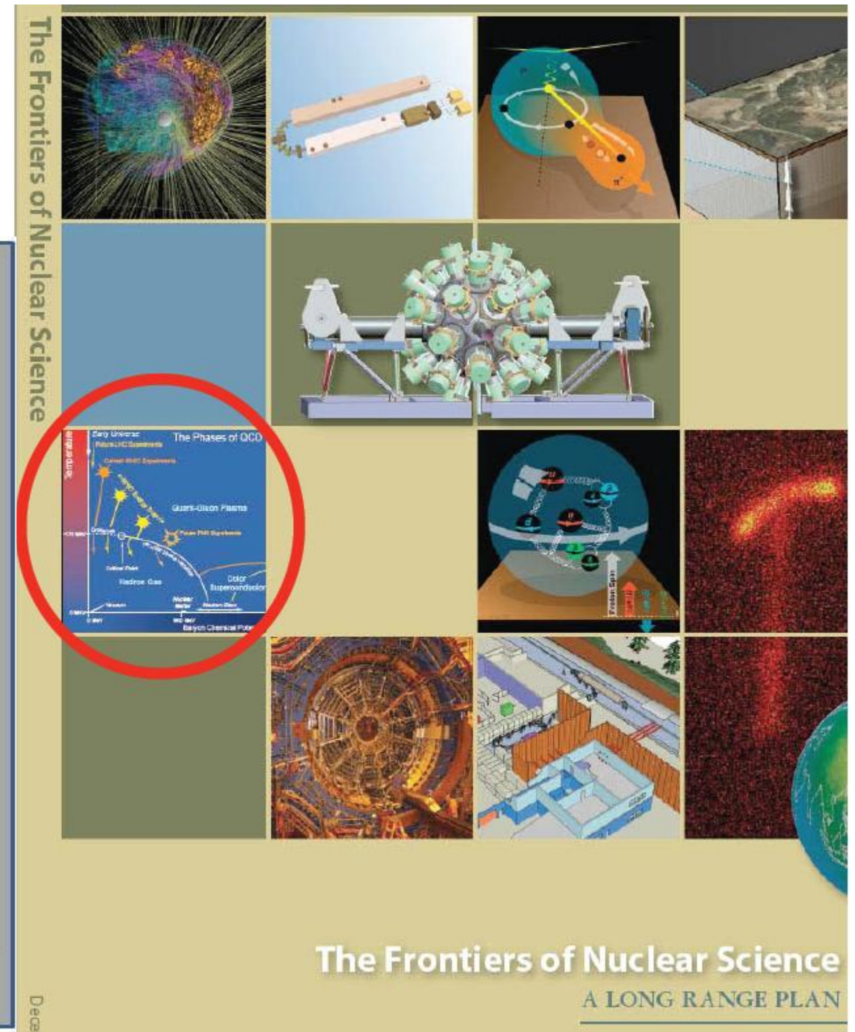
Low Energy RHIC Physics program

Beam Energy Scan I, center of mass energies: $\sqrt{s_{NN}}$ = 5, 6.3, 7.7, 8.8, 11.5, 14.6, 19.6, 27 GeV

(2010 & 2011 & 2014 RHIC runs)

Search for QCD phase transition Critical Point





BES Phase II Proposal

BES Phase II is planned fo[r] ...

	LEReC Phase-I		LEReC-II: energy upgrade		
E_{ke} (MeV)	1.6	2.0	2.6	3.5	4.9
$\sqrt{S_{NN}}$ (GeV)	**7.7**	**9.1**	**11.5**	**14.5**	**19.6**
μ_B (MeV)	420	370	315	250	205
BES I (MEvts)	4.3	---	11.7	24	36
Rate(MEvts/day)	0.25*	0.6%	1.7*	2.4%	4.5*
BES I $\mathcal{L}$ (1×10^{25}/cm^{2}sec)	0.13	0.5%	1.5	2.1%	4.0
BES II (MEvts)	100	160	230	300	400
eCooling (Factor)	4	4	4	8	15(4)
Required Beam (weeks)	**14**	**9.5**	**5.0**	**2.5**	**3.0+**

Luminosity is especially low at lowest energies.

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.

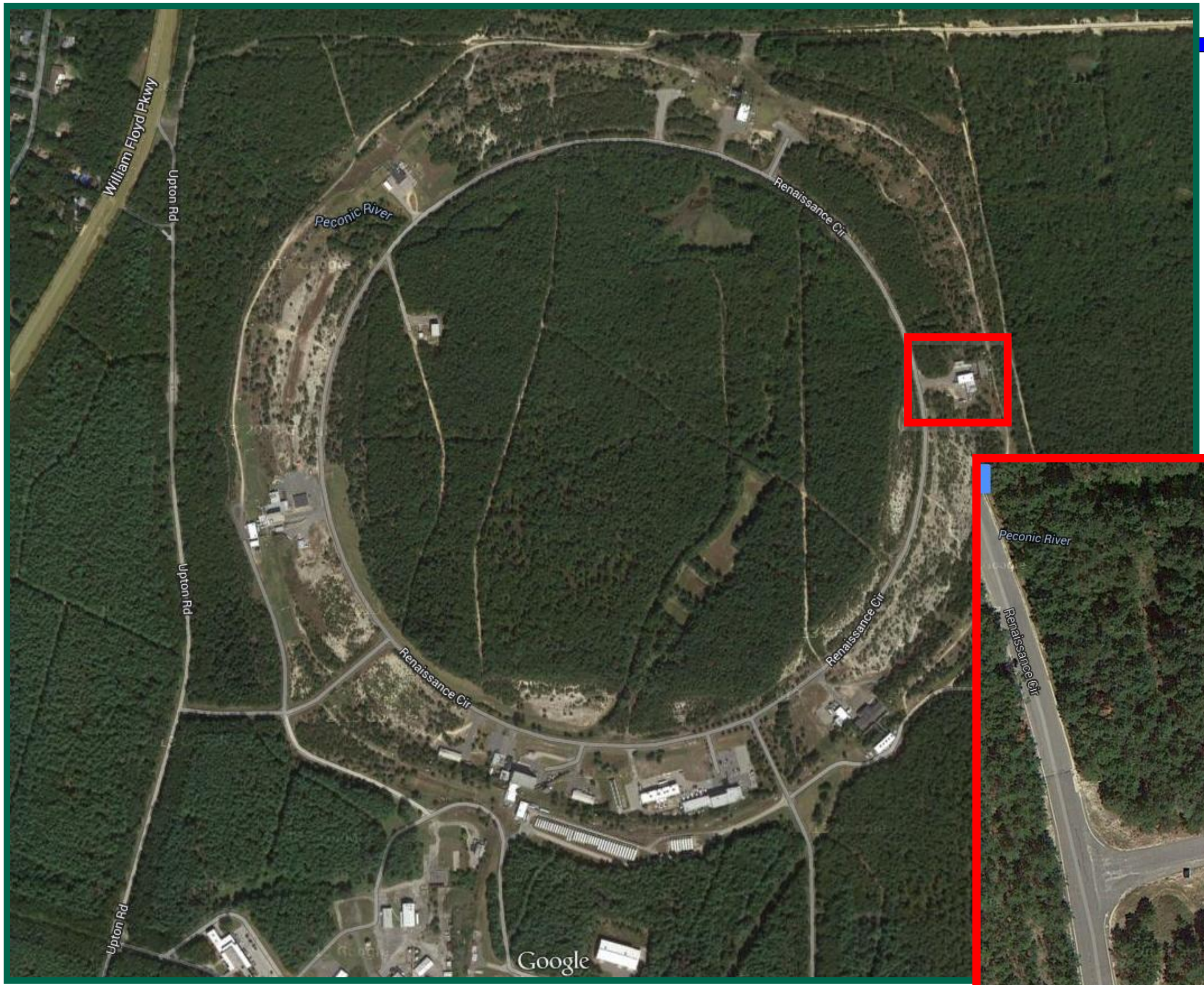
However, significant luminosity improvement can be provided with electron cooling applied directly in RHIC at low energies.

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: 2-5 MeV

Location – RHIC 02:00 Region (IR2)



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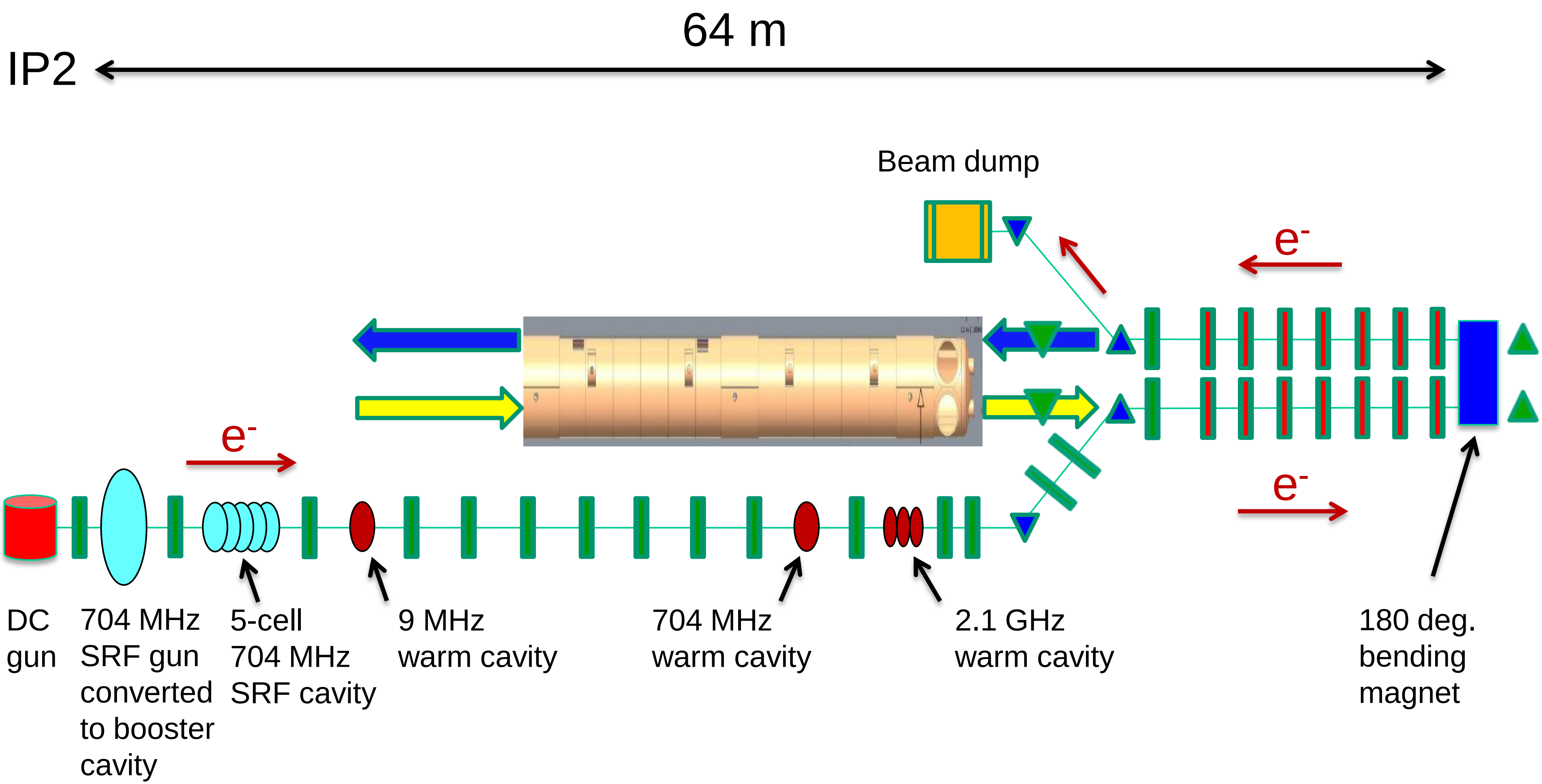
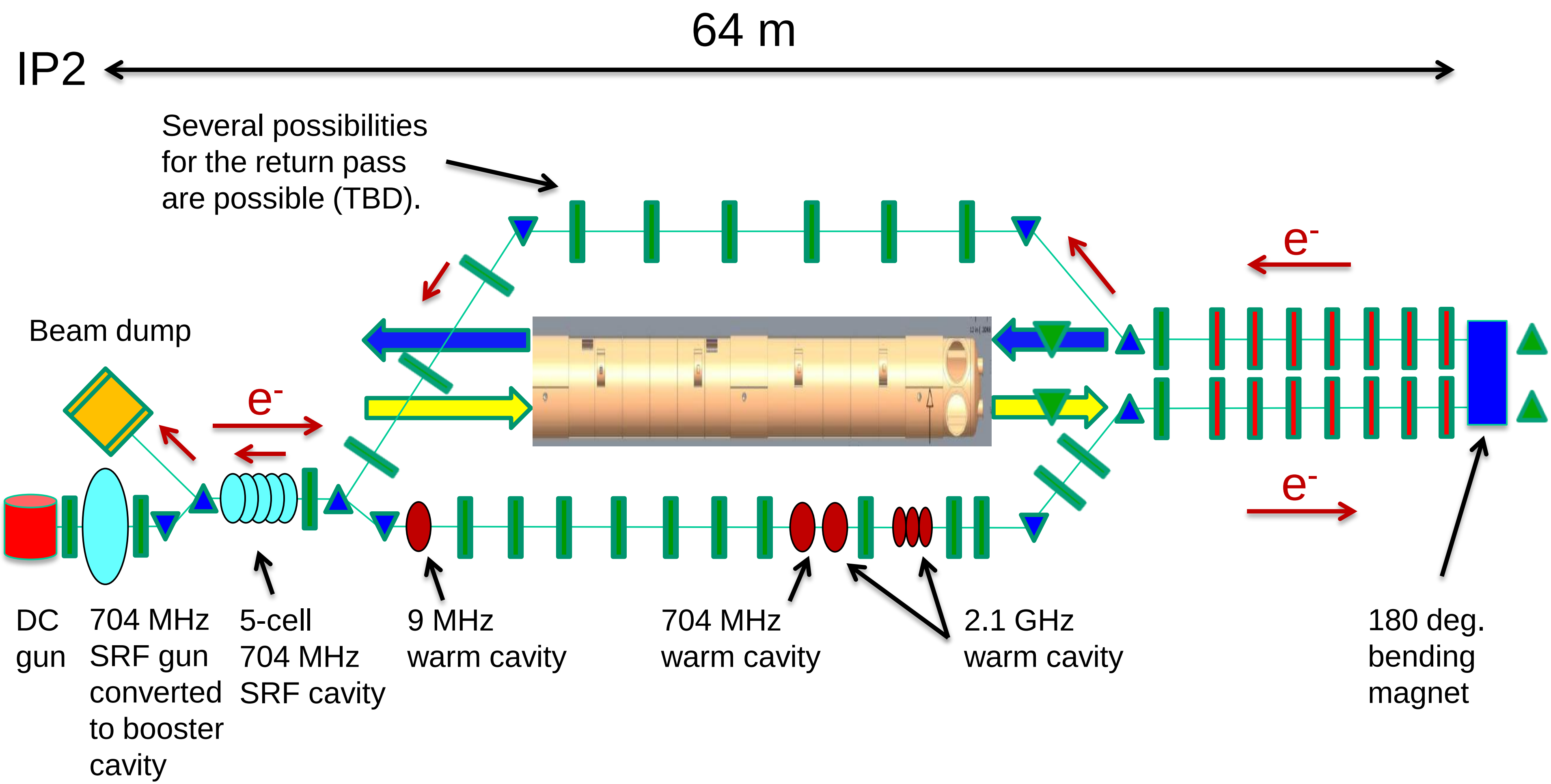
LEReC Phase-I (electron beam energies 1.6-2MeV):

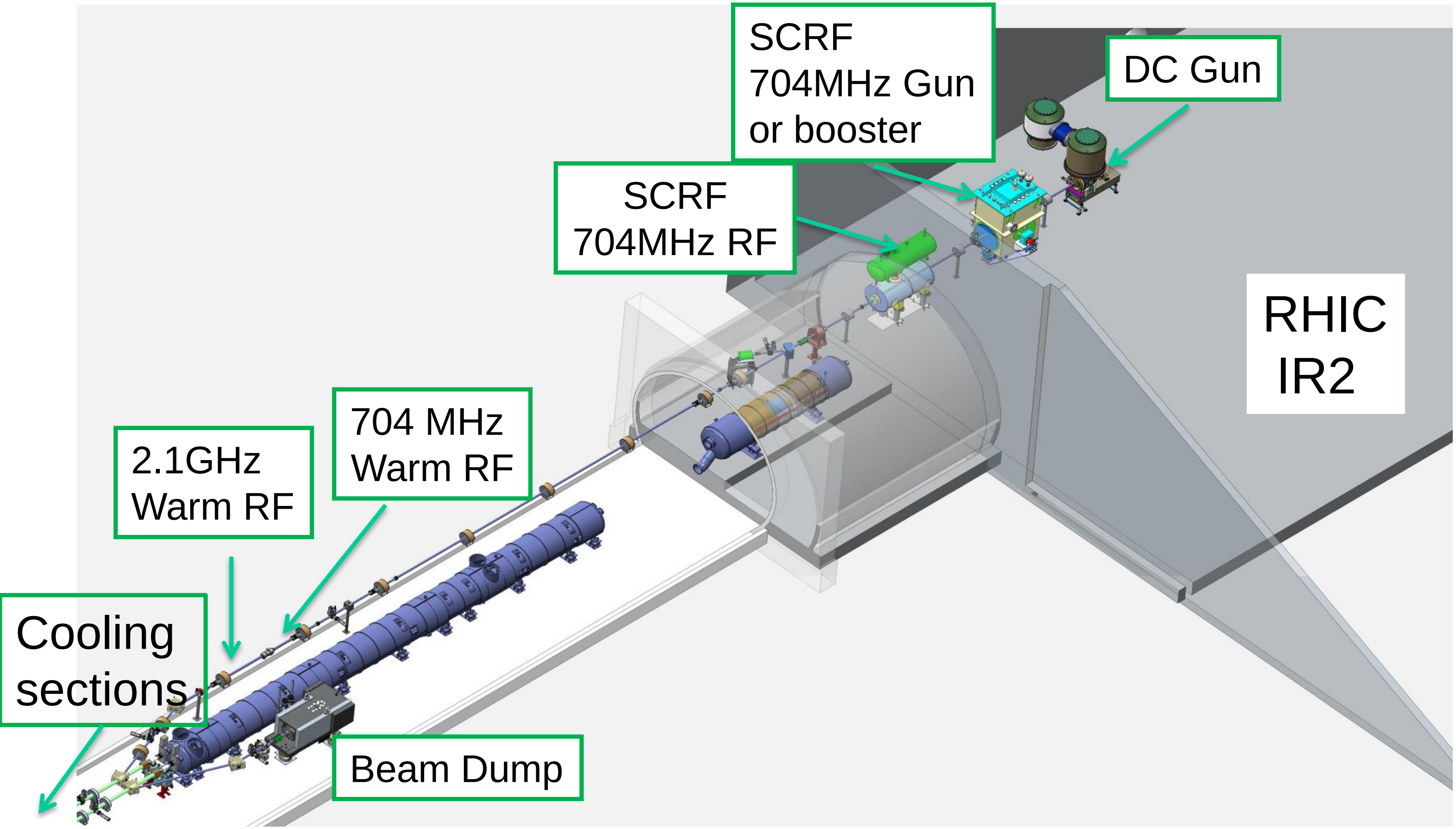
Gun-to-dump mode of operation



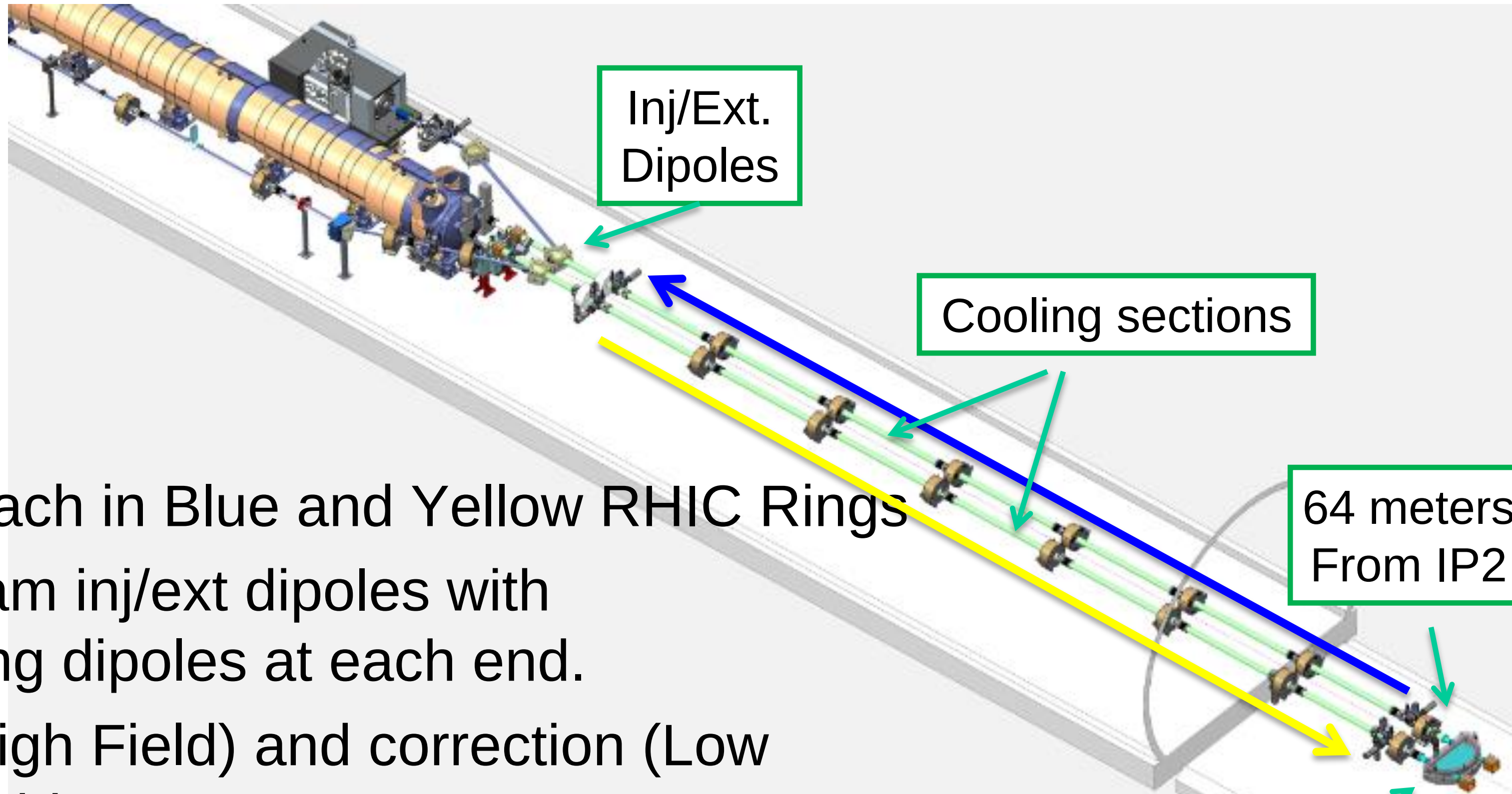
LEReC Phase-II (energy upgrade to 5 MeV):
Energy Recovery Linac (ERL) mode of operation



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



LEReC Phase-I layout: cooling sections in RHIC



- 18 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 to be built by Cornell
- **704 MHz SRF gun with maximum energy of 2 MeV**
  (the SRF gun will be used as a booster cavity for
  the DC gun option).
- **704 MHz SRF 5-cell cavity (acceleration to 5 MeV in ERL mode).**
- 2.1 GHz (3rd harmonic of the SRF frequency) warm cavity for energy spread correction; 704 MHz warm cavity;
  9 MHz warm cavity for beam loading correction.
- Electron beam transport from IP2 region to cooling sections
- Cooling sections in Yellow and Blue RHIC rings – about 20 m long with space-charge correction solenoids.
- U-turn 180 deg. dipole magnet between cooling section in Yellow and Blue RHIC Rings.
- Beam Instrumentation.
- **Electron beam dump.**

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

Full region of energies

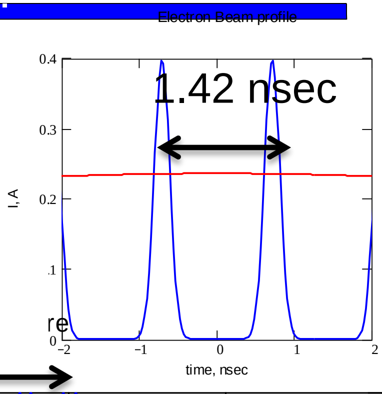
Ion beam parameters		
Gamma	4.1	10.7
RMS bunch length	3.2 m	2 m
N_{au}	0.5e9	2e9
I_peak	0.24 A	1.6 A
Frequency	9.1 MHz	9.34 MHz
Beta function@cooling	30 m	30 m
RMS bunch size	4.3 mm	2.7 mm
RMS angular spread	140 urad	90 urad

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

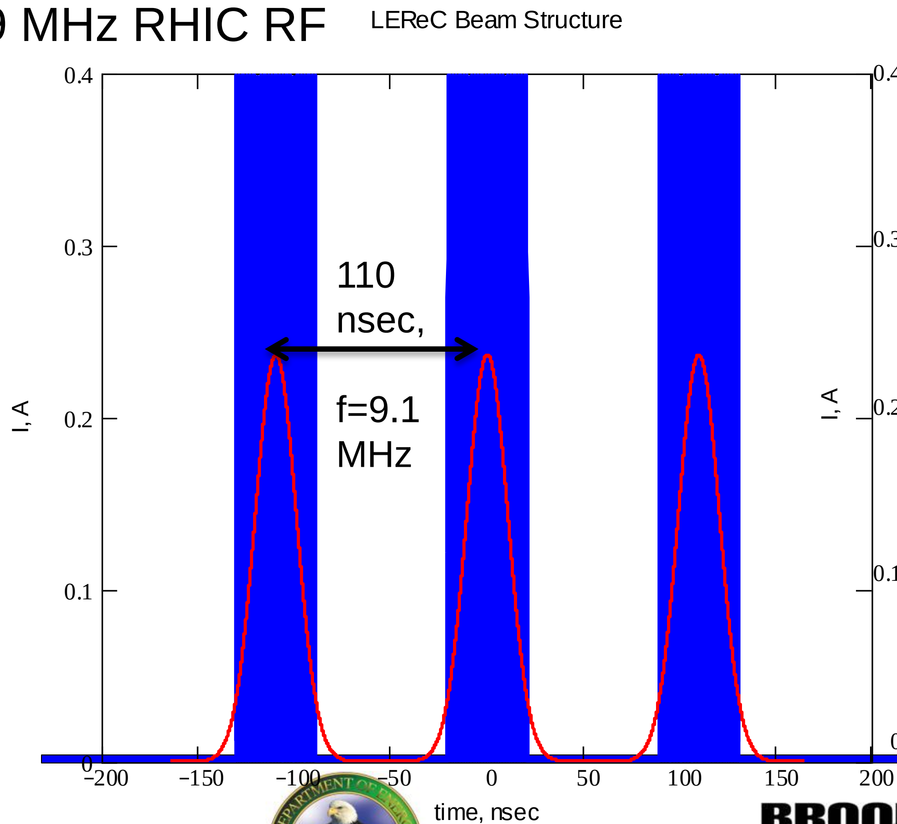
LEReC beam structure in cooling section
Example for γ= 4.1 (E_{ke}=1.6 MeV)

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

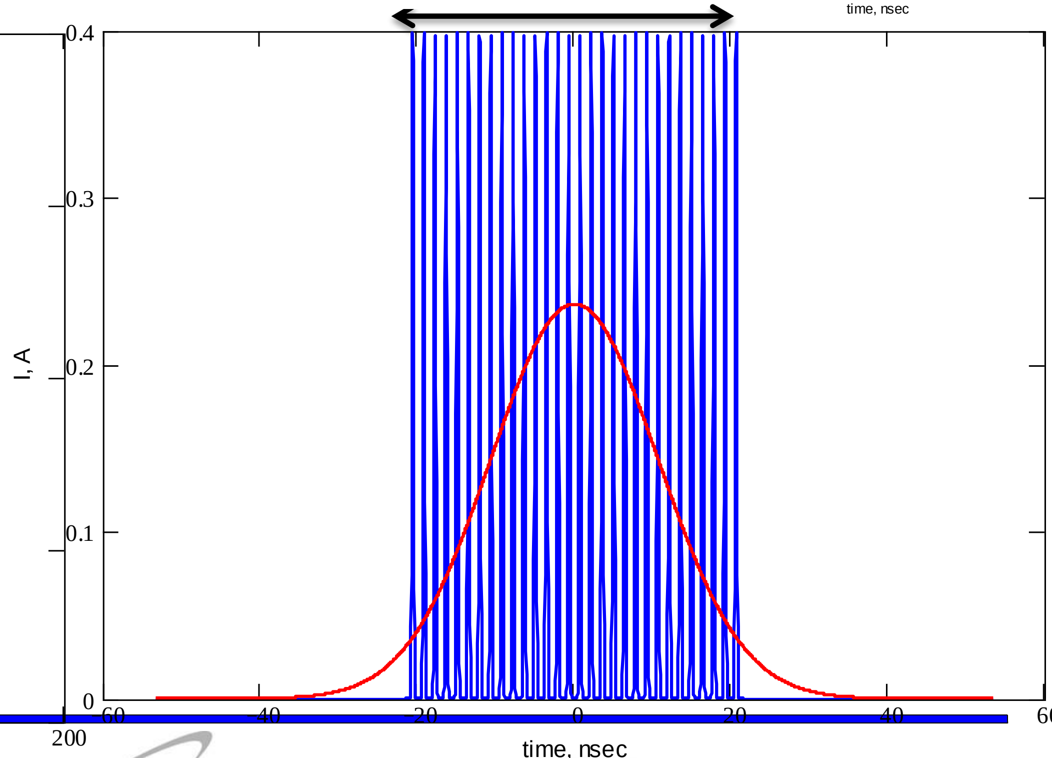
Electrons:
f_SRF=703.518MHz
Rms length=3 cm, I_peak=0.4 A
Q_e=100 pC



9 MHz RHIC RF



30 electron bunches



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LEReC electron source/gun status and plans

The critical element for the overall facility commissioning is the availability of a tested and functional electron source.

- **2015-16:** Continue SRF gun beam tests in Bldg. 912 (ERL) with new cathode stalk, new 704 MHz LEReC laser system towards CW operation with high-current is under development (goal for LEReC is to demonstrate and show stable operation with bunch charges up to 300 pC and average currents up to 50 mA by early 2016).
- **2015-16:** Contract with Cornell on DC gun started. Goal is to have operational DC gun by mid 2016.

704 MHz SRF gun progress

1. Aug. to Oct. 2013: Commissioned SRF gun cavity with copper cathode stalk inserted.

   →Found operational parameters: 1.85 MV, 180 ms, 1 Hz - limited by multipacting in the stalk.

   →Design a new multipacting-free cathode stalk with Ta tip for high QE => high current electron beam.

2. May 28 to Jun. 18, 2014: Commissioning with Cs_3Sb photocathode

   → Commissioned all subsystems and demonstrated system integration;

   → dark current was observed.

3. Nov. 17, 2014 to present: First photoemission beam commissioning

   → Observed photoemission beam: 8pC bunch charge/1 μA average current

4. March 2015:

   → new cathode stalk with Ta tip commissioned;

   → beam studies are coming.

LEReC DC gun requirements

Operating voltage: 400-500 kV, Cornell University (CU)

Charge per bunch (LEReC Phase-1, 2017-18): ***100 pC (CU)***

Average current (LEReC Phase-1, 2017-18): ***30 mA (CU)***

Charge per bunch (LEReC Phase-II, 2018-19): **300 pC (CU)**

Average current (LEReC Phase-II, 2018-19): 50mA with 300pC bunch charges

Needed beam quality:

Rms normalized emittance < 2 μm for charges up to 300pC (from the gun) – demonstrated by CU

RMS energy spread <2e-4 (from gun/ripple contribution)

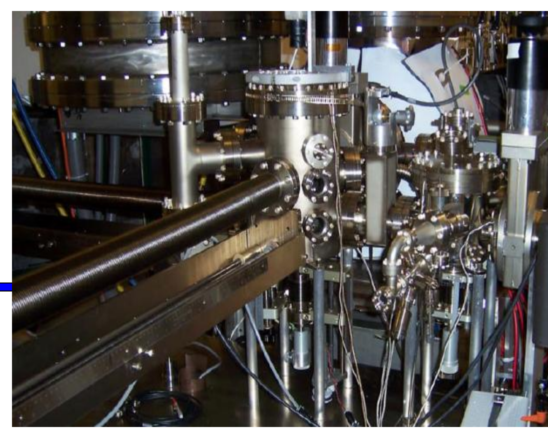
- Stable 24/7 operation

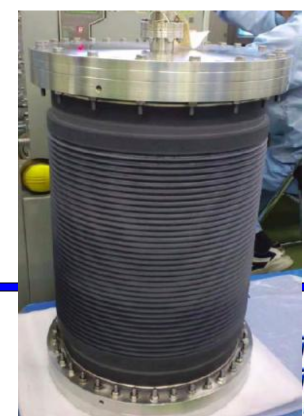
-Cathodes exchanging mechanism for quick cathode replacement without significant delay on operation.

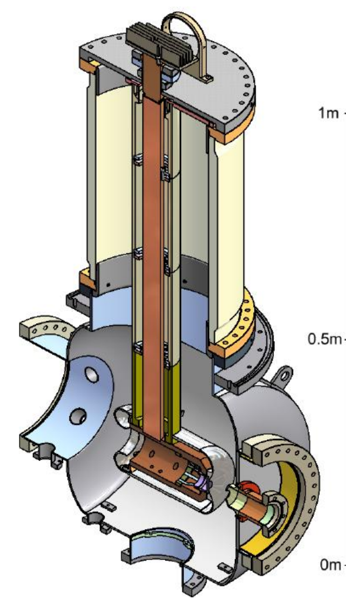
Contract with Cornell to build DC gun for LEReC (identical to existing Cornell's gun)

Includes engineering and design support for gun, power supply, cathode design, cathode changing mechanism, and cathode coating chamber.

- Design and fabrication planning contract in place
- 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
- Installation and commission by BNL w/Cornell support







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).

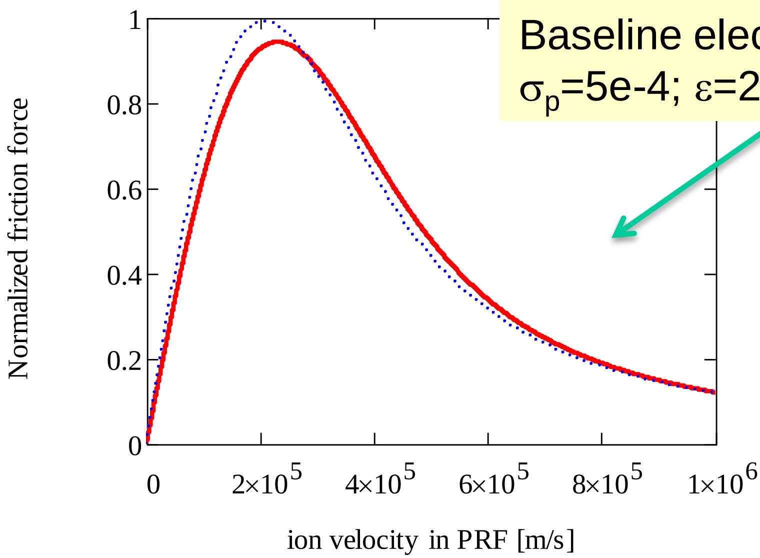
asymptotic for $v_{ion} < \Delta_e$:

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

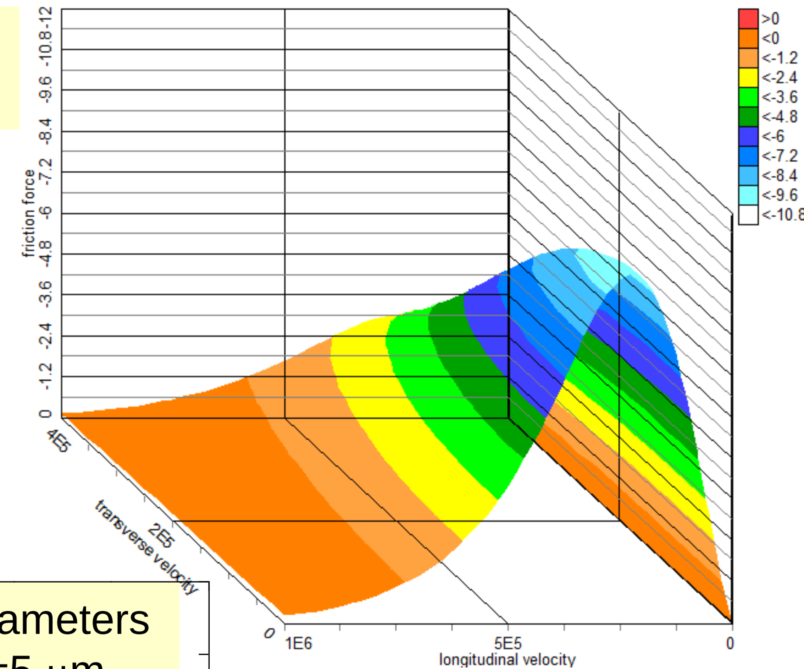
$$\vec{F} = -\frac{4\pi Z^2 e^4 n_e L}{m} \frac{\vec{v}_i}{\beta^3 c^3 \left((\gamma\vartheta)^2 + \sigma_p^2\right)^{3/2}}$$

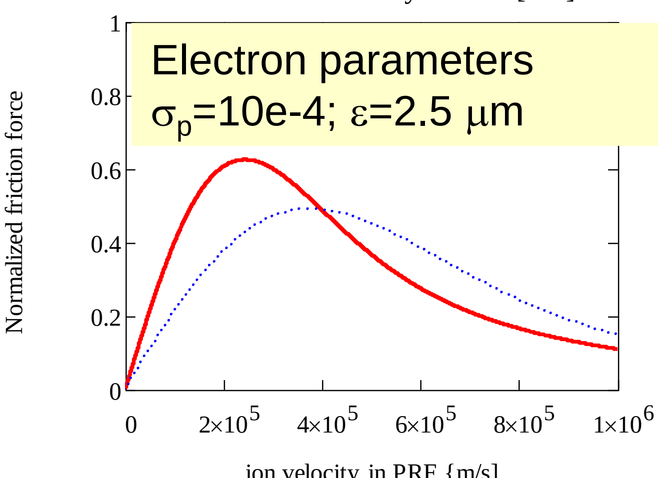
Requirement on electron angles:
For γ=4.1: σ_p=5e-4; θ<150 μrad

LEReC cooling force

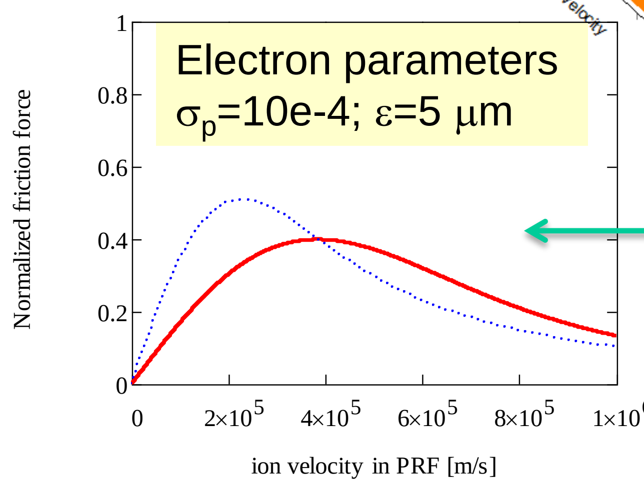


Baseline electron parameters
σ_p=5e-4; ε=2.5 μm





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.

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

- Linac-based bunched beam electron cooling is a natural approach for high energies.

- For low energies, like in LEReC, there are many challenges to use this approach which have to be carefully addressed:

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

Requires stretching electron beam bunches to keep energy spread growth due to the longitudinal space charge to an acceptable level.

- Keeping low transverse angular spread for the electron beam in the cooling section with a proper engineering design:

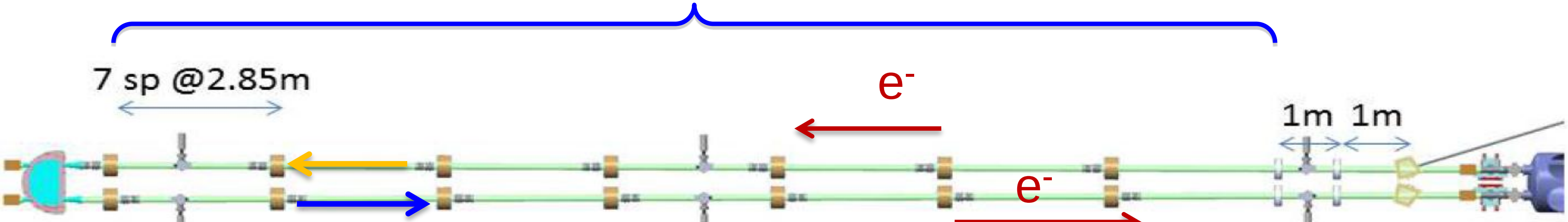
Correction solenoids and mu-metal shielding.

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

- Quality of the beam should be preserved through the entire beam transport and both cooling sections.

Cooling section

- The cooling section is the region where the electron beam overlaps and co-propagates with the ion beam to produce cooling. The electron beam first cools ions in Yellow RHIC ring then it is turned around (U-turn) and cools ions in Blue RHIC ring and then goes to the dump. The electron beam must maintain its good quality all the way through the second cooling section in Blue ring.
- The Blue and Yellow ring cooling sections are about 20 meters each. No recombination suppression is planned. Some space is taken up by matching solenoids, space-charge correction solenoids, steering dipoles and beam position monitors used to keep the electron beam and ion beam in close relative alignment.
- Short (10cm) correction solenoids will be place every 3 m of the cooling section.
- 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, every 3 m of cooling section.



Requirement on magnetic field in the cooling section

γ=4.1:

Passive mu-metal shielding to suppress B_residual to required level of 1mGauss in free space between the solenoids.

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.

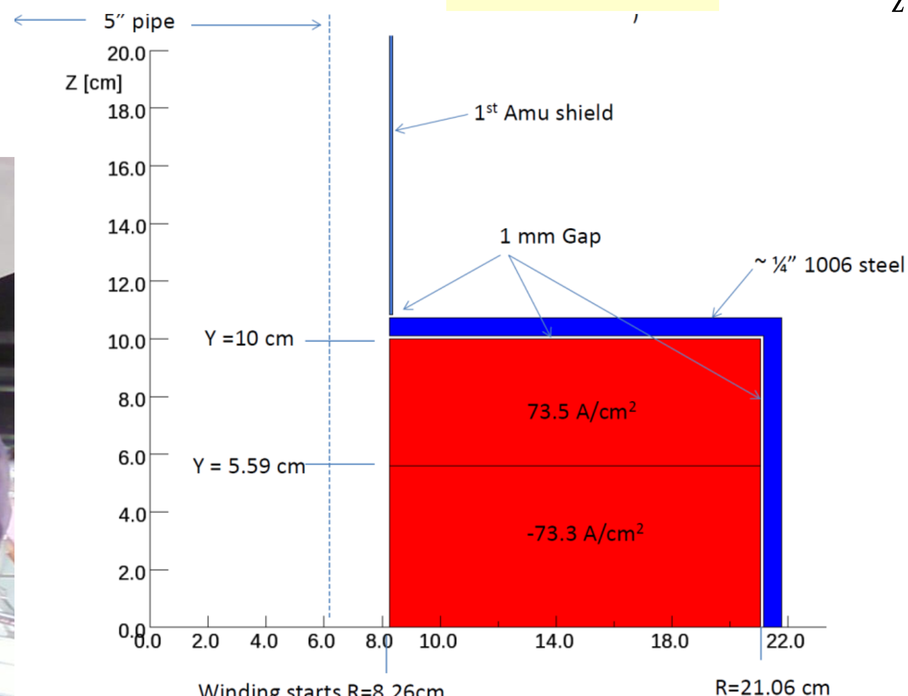
Residual magnetic field from solenoids in cooling region:

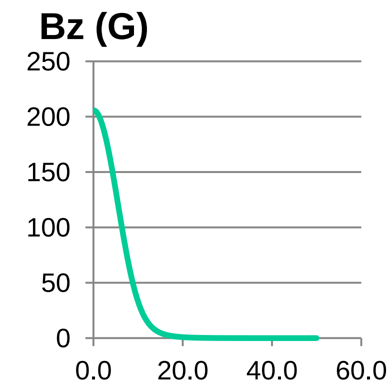
W. Meng

$B_z < 1G$ at z=19 cm

FNAL

shielding





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 of 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.
- 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

Luminosity limits for RHIC operation at low energies

For present 28 MHz RHIC RF at lowest energies we are limited both by space charge and RF bucket acceptance (significant beam losses), which strongly limits luminosity improvement with cooling.

Better gain in luminosity is possible if one can tolerated operation with longer bunches for lowest energies:

$$\Delta Q_{sc} = -\frac{Z^2 r_p}{A} \frac{N_i}{4\pi\beta^2\gamma^3\varepsilon} \frac{C_r}{\sqrt{2\pi}\sigma_s}$$

If bunch length is relaxed, we can now cool transverse emittance which in turn allows to reduce β^*. Losses on transverse acceptance will be minimized as well.

Luminosity gains from electron cooling will be maximized by using **new 9 MHz RHIC RF system** which is being built to improve beam lifetime at low energies.

Recent developments

- Due to extension of RHIC running (additional FY17 RHIC run was added), Beam-Energy Scan II Physics Program is delayed from 2018-19 to 2019-2020.

- LEReC Phase I (up to 2 MeV): need to be fully operational for Run-19.
- LEReC Phase II (ERL mode up to 5 MeV): operational for Run-20.

- High Priority Items approved by DOE November 2014 ($1M) are under procurements with installations of cooling sections to start in Fall of 2015.

- Contract with Cornell University for construction of DC photoemission electron gun is signed April 2015 and is underway.

- Awaiting final approval for the rest of LEReC Phase-I scope from DOE.

LEReC cooling section Design Room activities

Design 180º dipole chamber for impedance review (KH)

LF & HF solenoid and 20º dipole fabrication drawings (KH)

BPM chamber and buttons (VDM)

Beam Line 5” bellows with shields fabrication drawings (GW)

20º dipole vacuum chamber for impedance review (KH)

180º dipole fabrication drawings (KH)

Beam Instrumentation PM and ES drive fabrication drawings (GW and VDM)

180º dipole magnet and vacuum chamber integration + large sliding bellows (KH)

Beam Instrumentation PM and ES Vacuum Chambers & ferrite insert (GW)

Beam Instrumentation PM ferrite insert (GW)

180º and 20º dipole vacuum chamber (KH)

20º and 180º stand drawings (KH)

Beam line solenoid stand LF Solenoid, BPM, and long pipe are to be independently positioned and surveyed on common stand.

Magnetic Shielding drawing and solenoid magnetic measurement test station

Cable tray and penetration drawings

LEReC Design Room activities (continued)

Phase 2: 5 cell cavity positioning (RM)

DC Gun Vacuum Chamber Fabrication Drawings (JH)

DC Gun SF6 Pressure chamber specification control drawings (JH)

Phase 2: 5 cell cavity positioning (RM) – Revised Position

Phase 1 and 2 cryogenic system layout (RM)

DC Gun stands (JH)

DC Gun cathode insertion drive

2.1 GHz warm cavity specification control drawings

704 MHz warm cavity specification control drawings

DC Gun to Booster SRF booster cavity beam line

DC Gun cathode coating system upgrade – coating system vacuum chamber

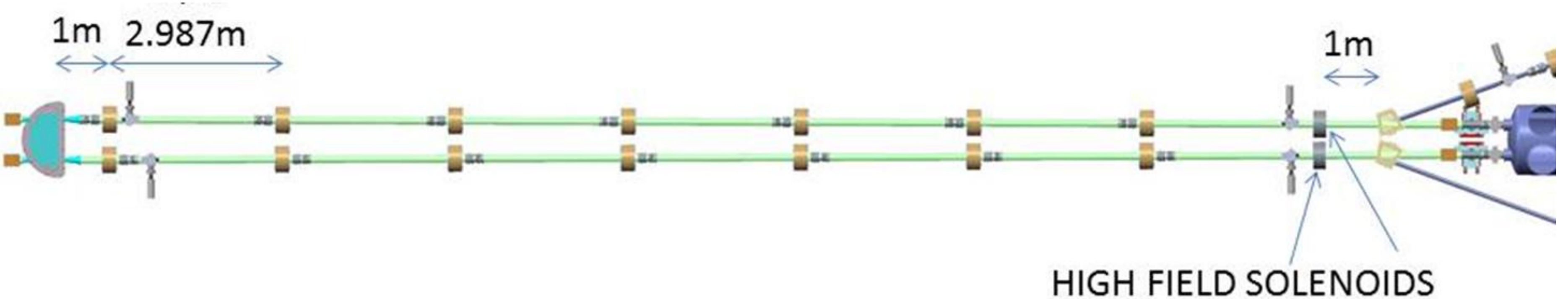
Transport line layout drawing (RM/VDM)

LEReC Timeline (FY 2015)

FY 2015: Detailed system design, procurement specifications, engineering design reviews, facility modifications plans and drawings.

Detailed Design Underway Cooling Section (High Priority Items):

- Compensating Solenoids – contract awarded
- Matching Solenoids – contract awarded
- 20° Dipole – out for bid
- 180° Dipole – design complete
- Beam Instrumentation: BPMs, PM, ES, Vacuum: shielded valves and bellows.



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Compensating and Matching Solenoids

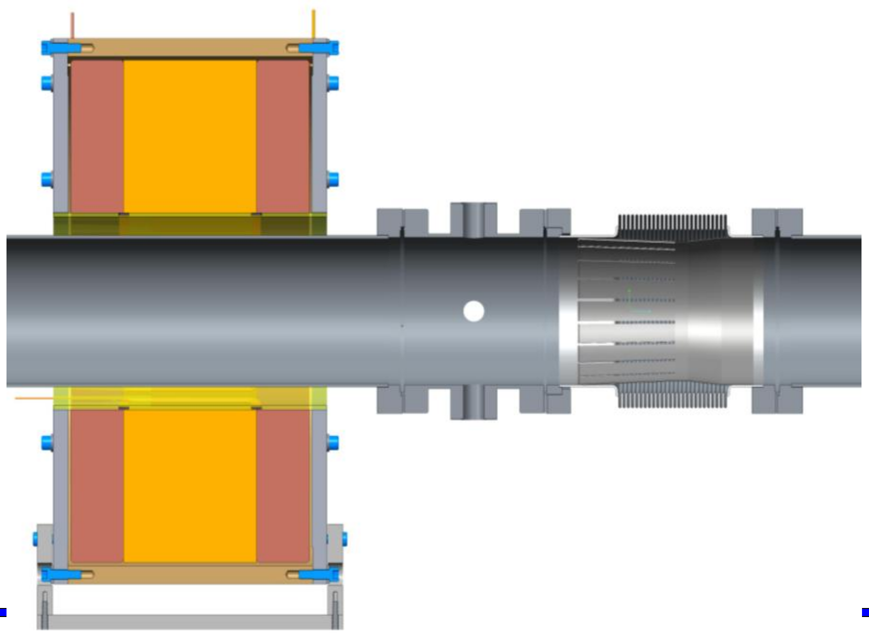
Contract Awarded: 9/15/2015 delivery for both

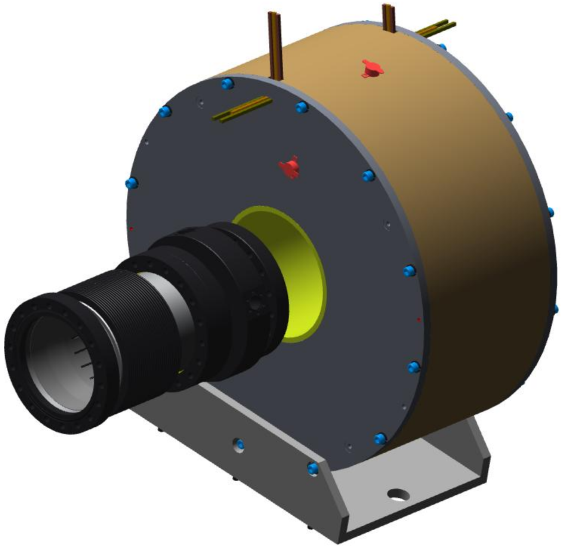
Design support stand assembly – provide space for mu metal shields,
separate beam pipe stand support.

Magnetic shielding analysis (Wuzheng)

Design prototype mu metal shields and supports.

Magnet measurement fixture plan for prototype and design test fixtures.





20º Dipole Magnet

Drawings checked – Spec/SOW approved (4/1/2015).

Requisition approved SOW – 2 magnets by 10/1/2015.

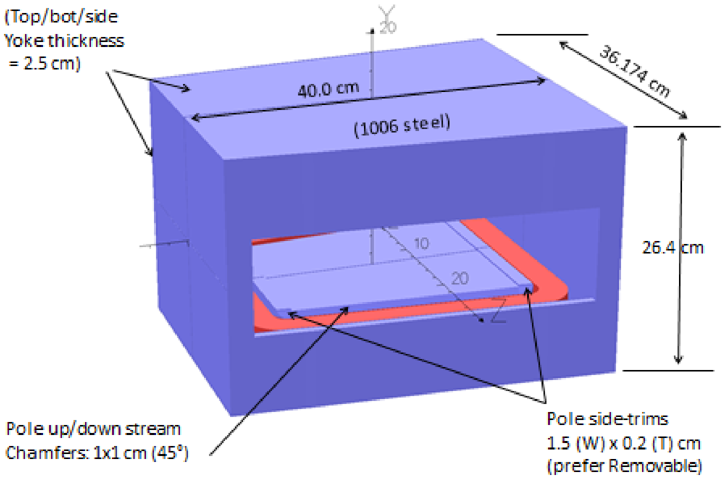
Out for Bid

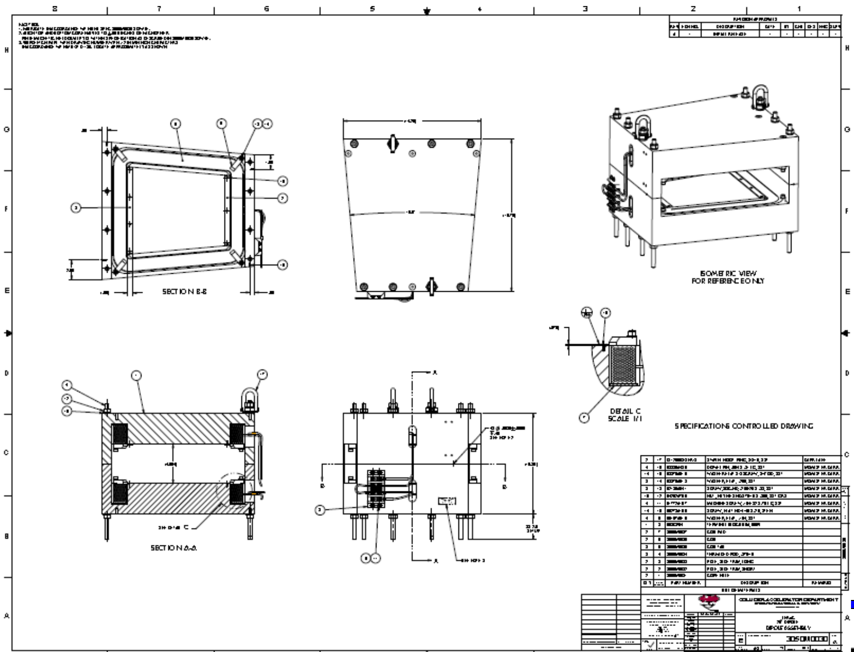
Distance Between Pole Faces = 10.4 cm (4.1 in.)

Magnet Vertical Gap = 10 cm

Vacuum Chamber V Aperture = 9.5 cm (3.74 in.)

LEReC 20-degree Dipole (Gap clearance=10 cm)
(distance between pole faces =10.4 cm)





Electron tracking results and field qualities along trajectory
on R=1 cm curved cylinder:

	Ek = 5 MeV	Ek = 1.6 MeV
Current per coil (Amp-turn)	1053.288	393.192
Overall current density (A/mm²) (overall coil cross-section 3.0x4.8 cm)	0.73145	0.27305
Central Gap Field (Gauss)	251.20	93.73
Half b1-integral (dipole) (G-cm)	3.1982E3	1.1930E3
Half b3-integral (6-pole) (G-cm) [Ratio to dipole integral]	1.803E-2 [5.64E-6]	7.019E-3 [5.88E-6]
Half bending angle from tracking tests (required 10°)	10.013°	10.006°

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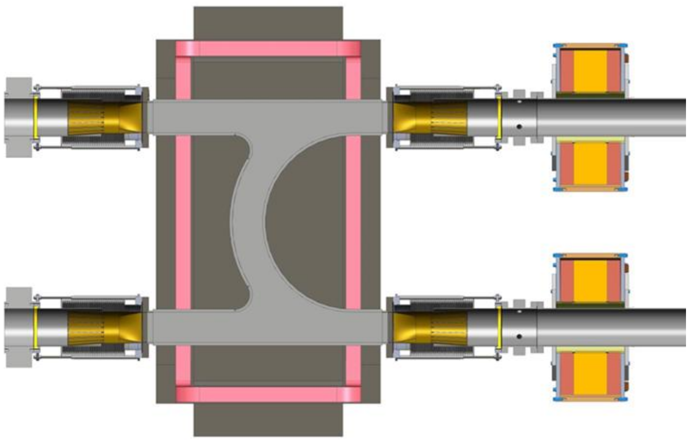
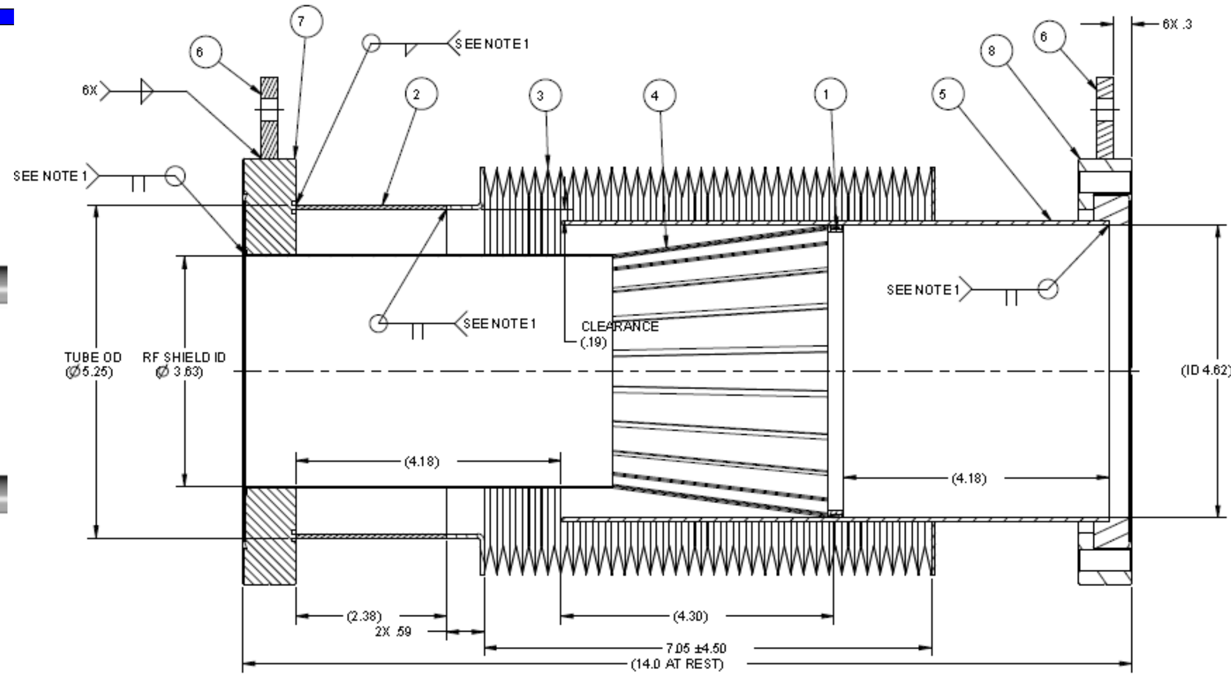
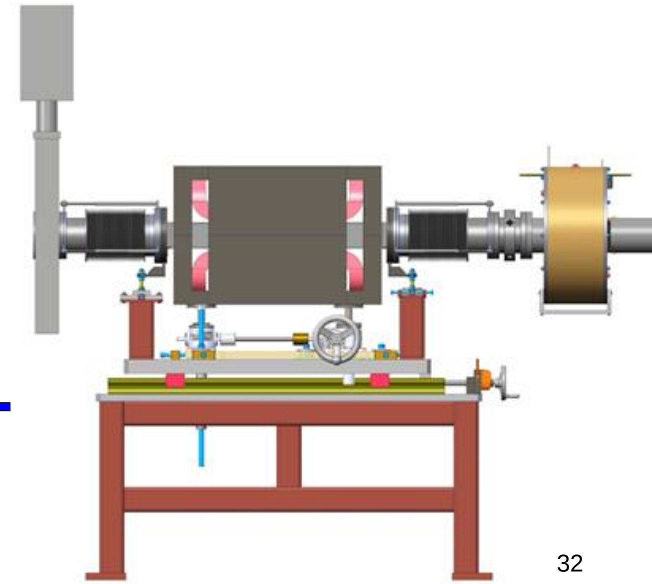
180° Dipole Magnet





Crossing tube aperture (3.94 in. vertical)

Circular tube, vacuum Chamber ID = 9.5 cm (3.75 in.)



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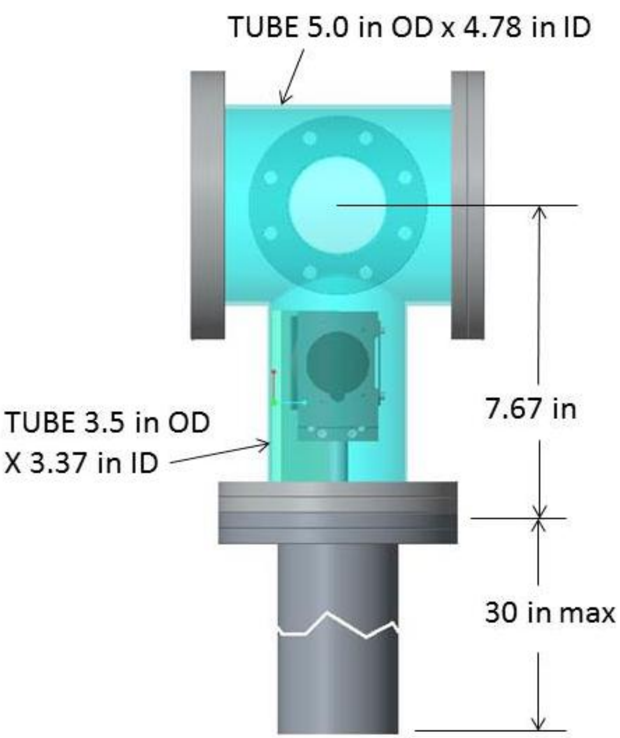
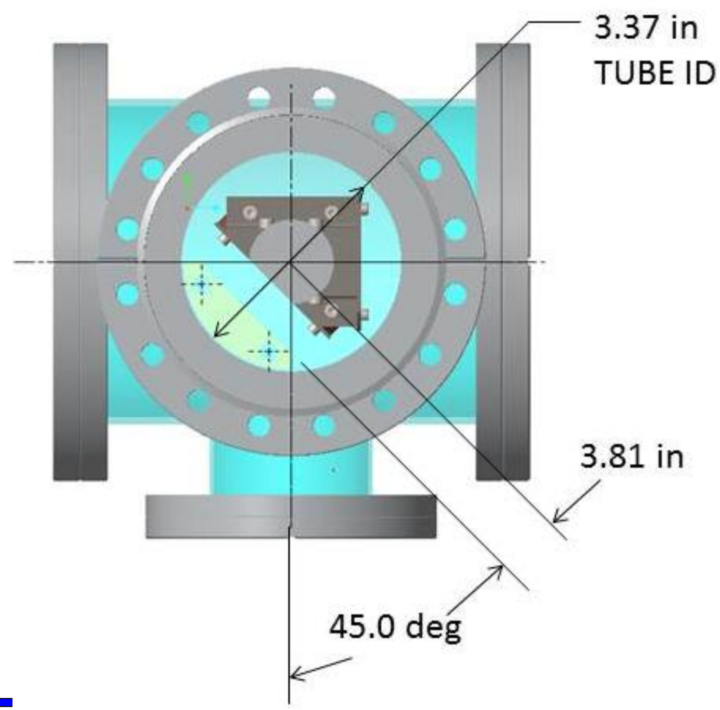
Profile Monitors – New designs for Cooling Section

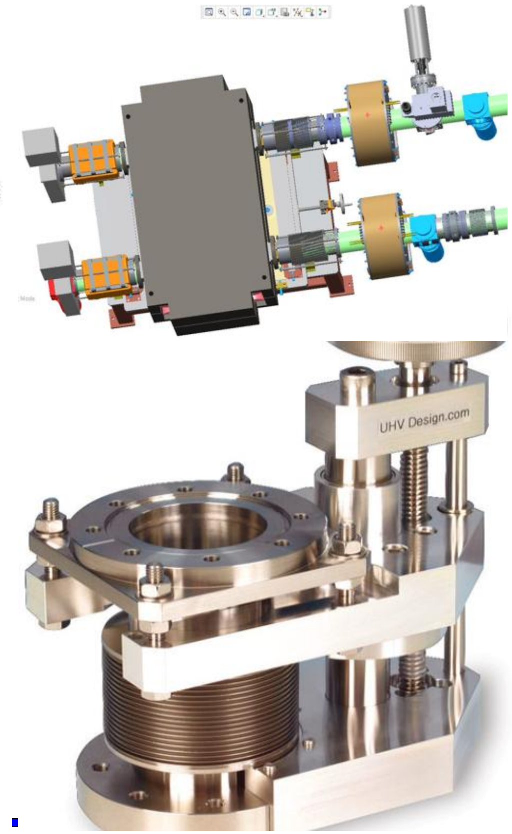
Utilize commercial vacuum linear feedthrough/drive system (D. Weiss)

Need to adapt YAG screen/mirror holder and emittance slits to drive shaft.

Create fabrication drawings for YAG screen/mirror holder and emittance slits

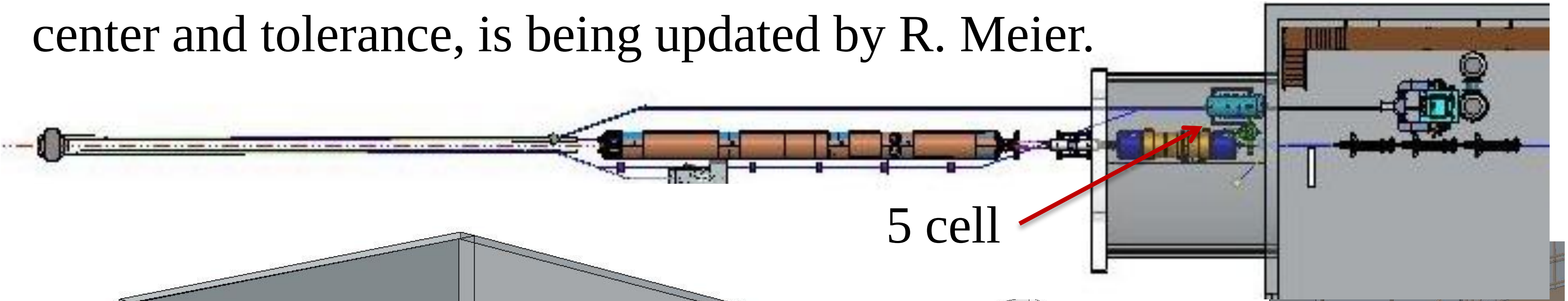


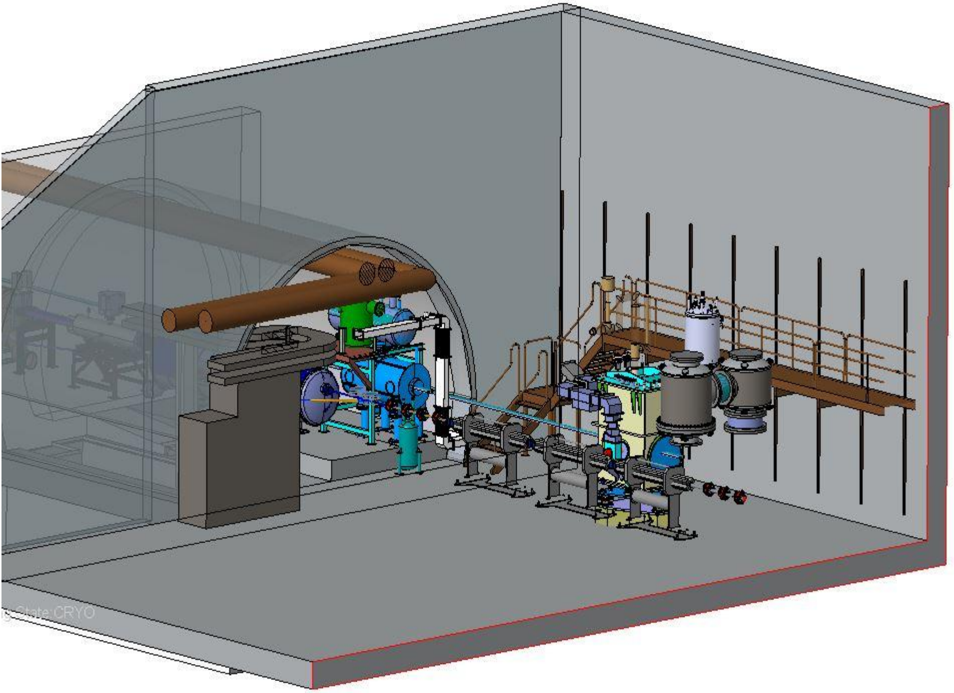


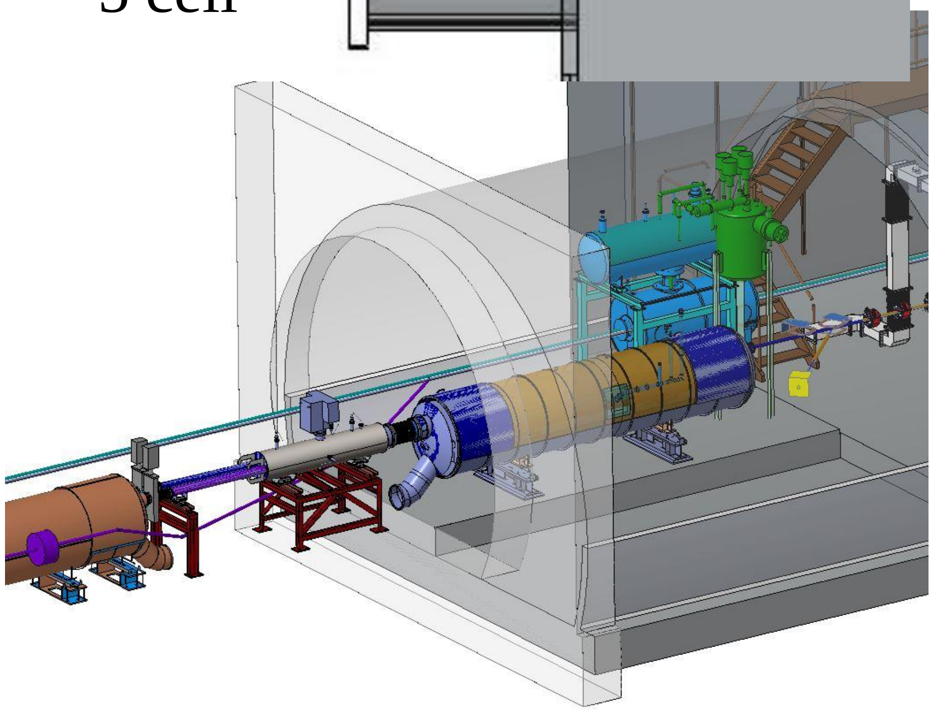


LEReC accelerator and 5-cell SRF cavity location

Location of egun and 5-cell, the beam line length and distance from IR center and tolerance, is being updated by R. Meier.







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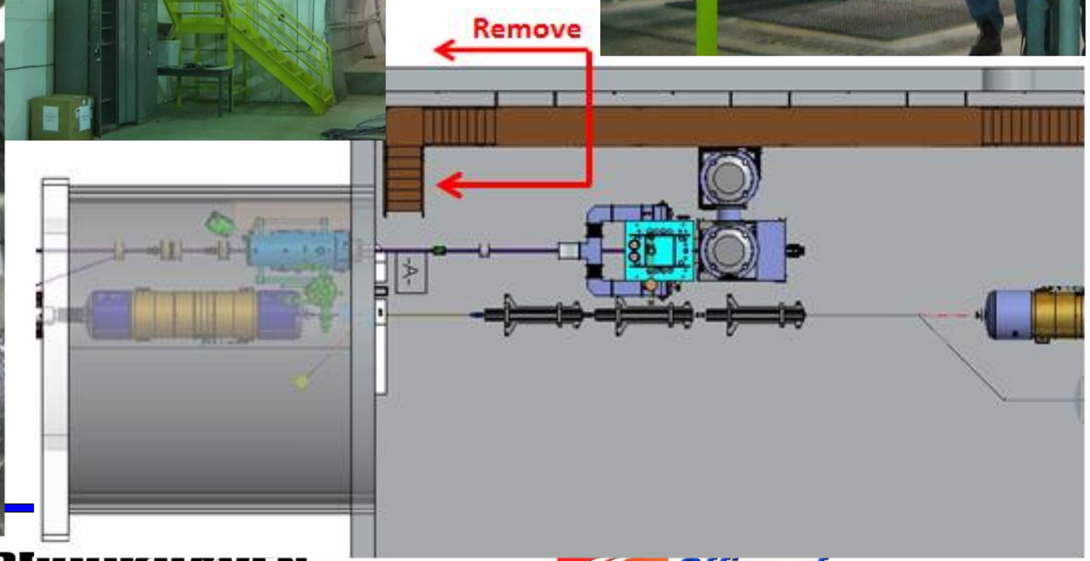
Sector 2 Modifications

Move cable tray
Modify cable tray
Move Access Controls Gate
Remove stairway and part of cross-over platform



LEReC timeline

SRF gun:

May - Dec 2014: **SRF gun commissioning w/beam (in 912 blockhouse).**

2015-2016: **SRF gun commissioning w/beam with new cathode stalk.**
High-current commissioning in CW mode (LEReC tests in 912).

DC gun:

May 2015 – mid 2016: **DC gun construction by Cornell University.**

2016: **DC gun commissioning at Cornell.**

End of 2015: Start of cooling sections installation

2016: Start installation of electron beam transport and warm RF cavities

June 2017 – Feb.2018: Move and install SRF Gun, SRF cavity, beam dump, etc.

End of 2017-March 2018: Systems commissioning (RF, cryogenics, etc.)

April - Sept 2018: LEReC commissioning with e-beam in RHIC tunnel

October 2018: **RHIC Run-19 BES-II physics program (commissioning of cooling with Au ion beams). RHIC Run-20 BES-II program (LEReC Phase-II)**

Summary

- Although electron cooling has been applied in numerous machines, LEReC must demonstrate several innovations. It will be the first application of electron cooling in a collider with additional challenges related to beam lifetime.
- LEReC is also a prototype of future high-energy electron cooler based on RF acceleration of electron beams.
- Most of LEReC cooling section magnets are already under contract. Plan is to start installation at the end of 2015.
- Engineering design of other major components is in progress.