Low Energy RHIC electron Cooling (LEReC)

LEReC overview: project goal and cooling approach

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

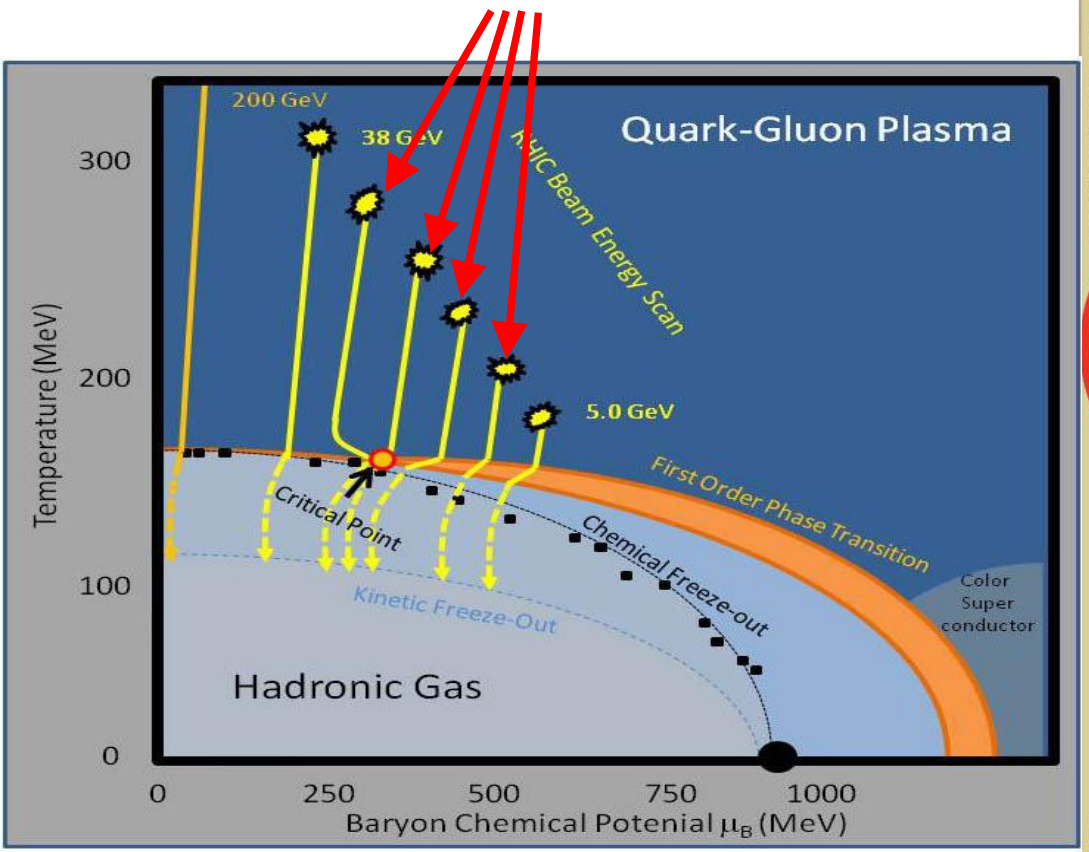
- Many new accelerator systems will need to be built, installed and commissioned, including several RF systems, magnets, beam instrumentation, etc.

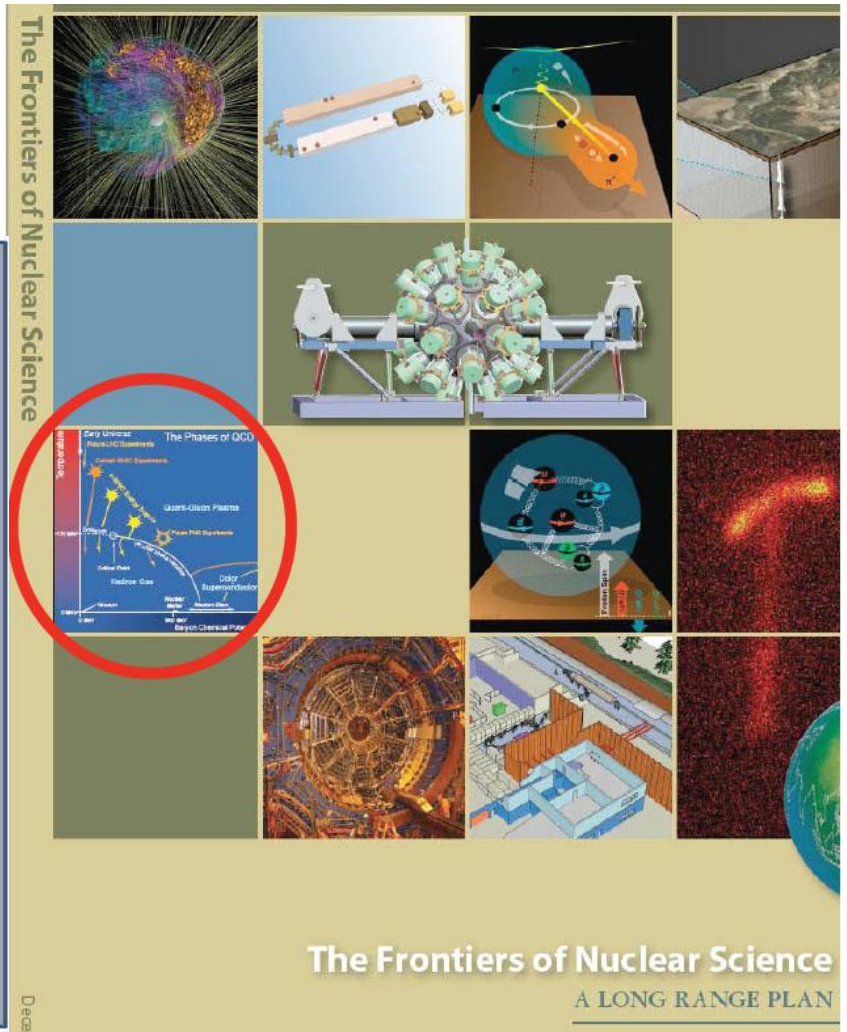
Low Energy RHIC Physics program

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 for two 22 cryo-week runs in 2018 and 2019

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.

LEReC-I:

LEReC-II: energy upgrade

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.

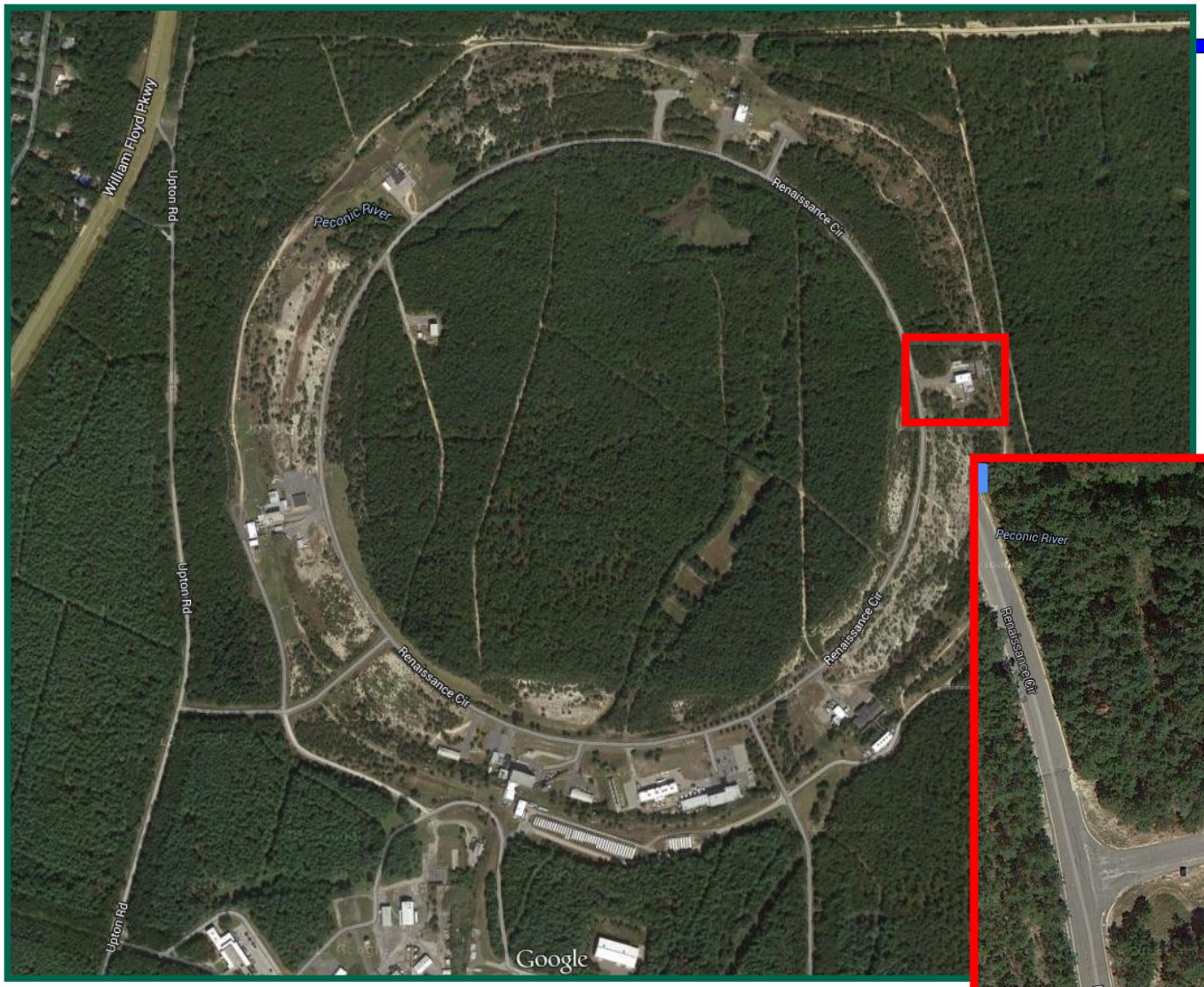
However, significant luminosity improvement can be provided with electron cooling applied directly in RHIC at low energies.

To cover all energies of interest need electron accelerator:
$E_{e,kinetic}$=1.6-4.9 MeV

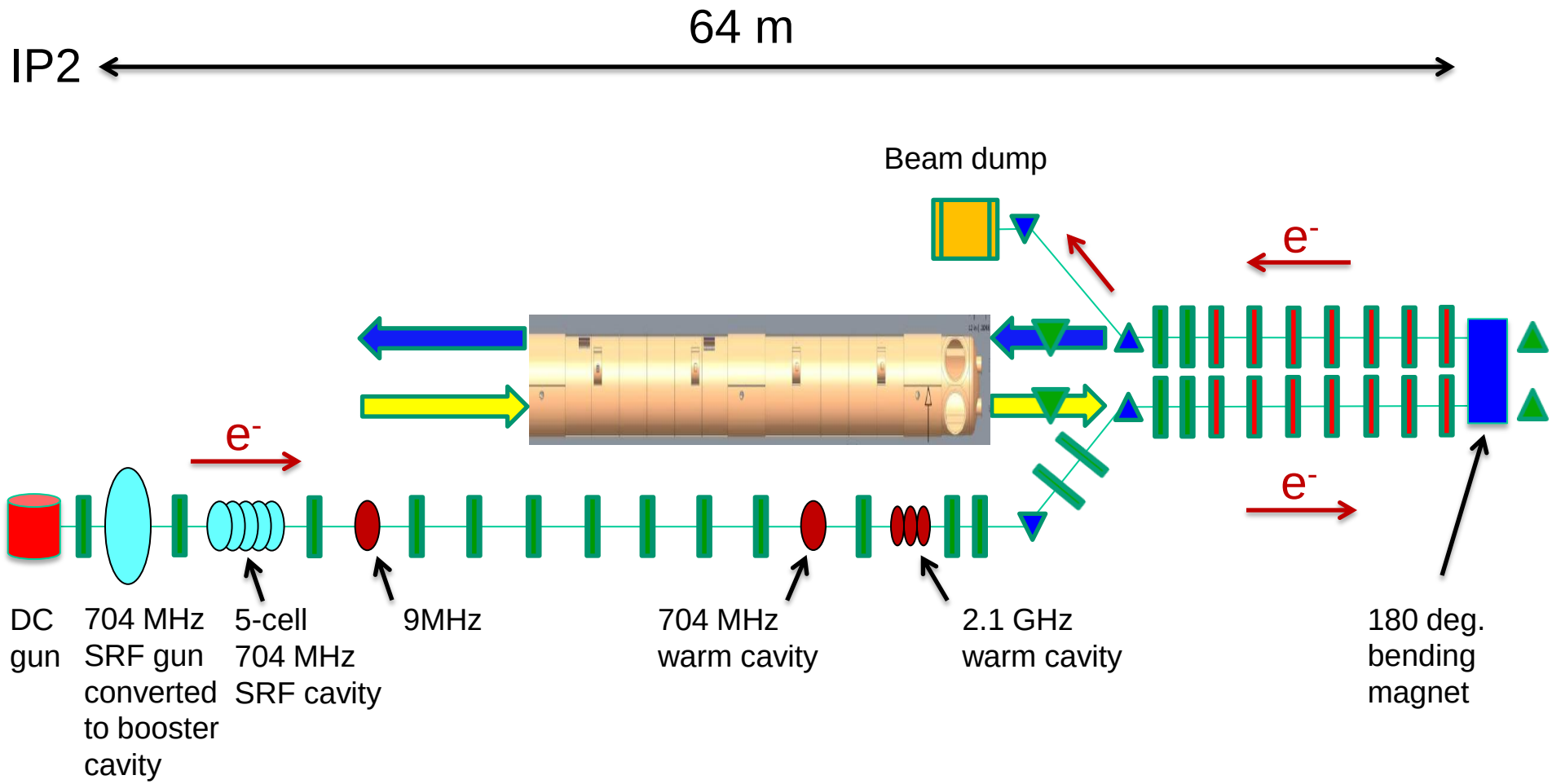
LEReC (2018): 1.6-2 MeV

LEReC energy upgrade (2019): 2-5 MeV

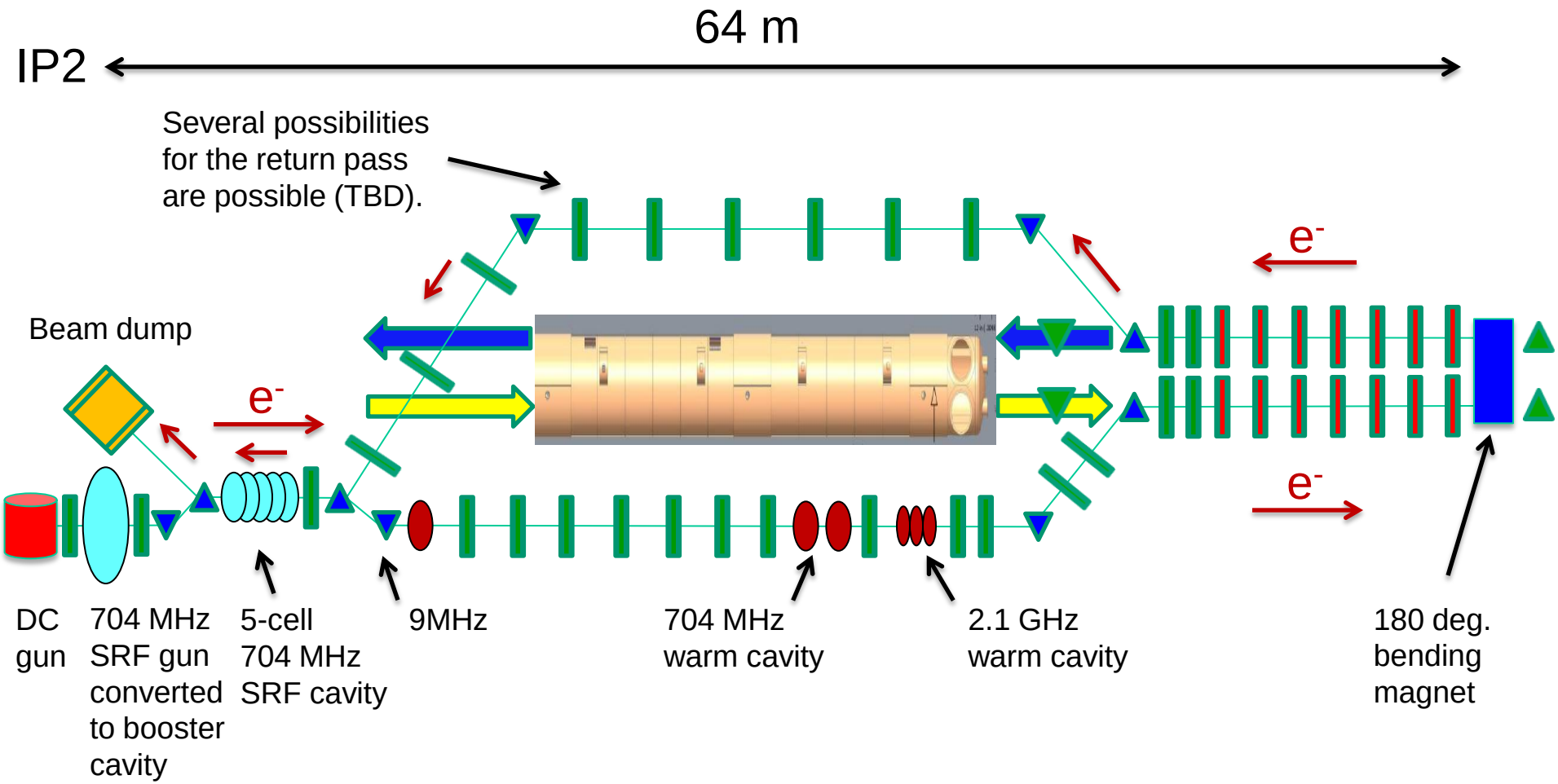
Location – RHIC 02:00 Region (IR2)



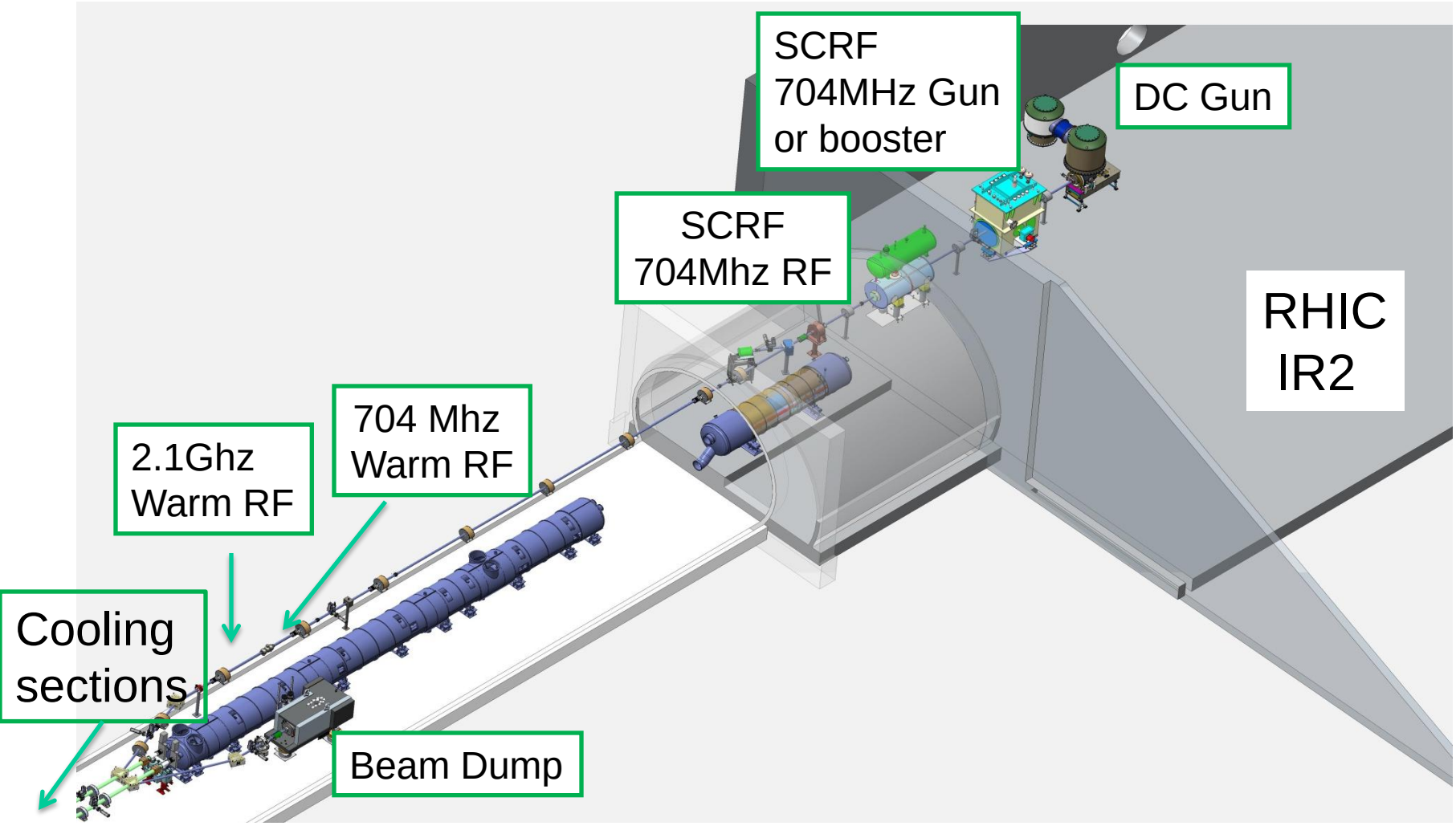
LEReC-I (1.6-2MeV): Gun-to-dump mode



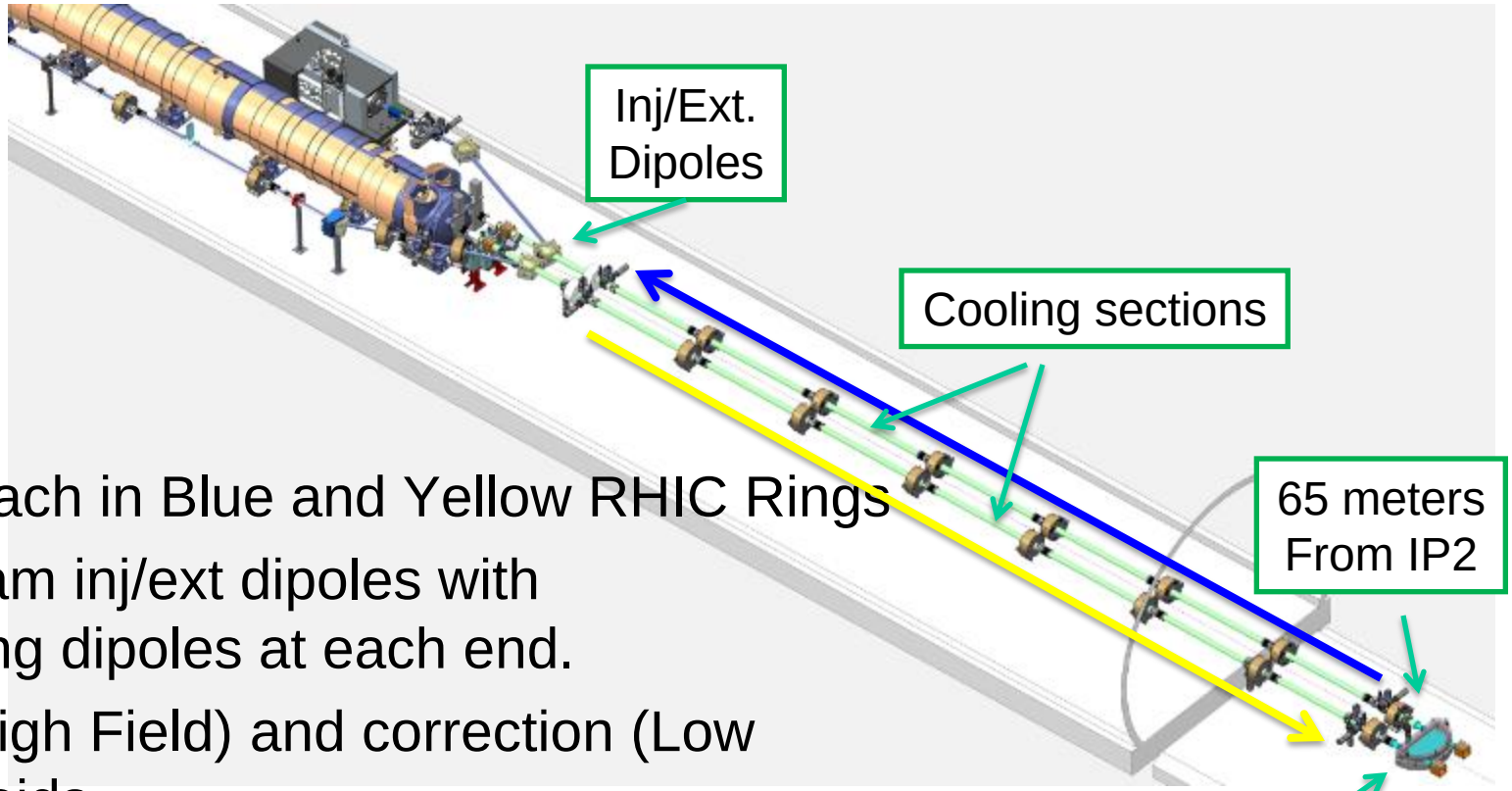
LEReC-II (energy upgrade to 5 MeV): ERL mode of operation



LEReC layout – electron Gun and transport line system



LEReC 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)

- **704 MHz SRF gun with maximum energy of 2 MeV or** DC gun **with the SRF gun used as a booster cavity.**
- **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 section
- Cooling sections in Yellow and Blue RHIC rings – about 20 m long with space-charge compensating solenoids.
- U-turn 180 deg. dipole magnet between cooling section in Yellow and Blue RHIC Rings.
- **Electron beam dump.**

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

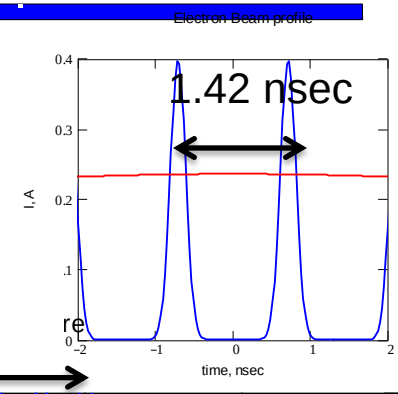
Full region of energies

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

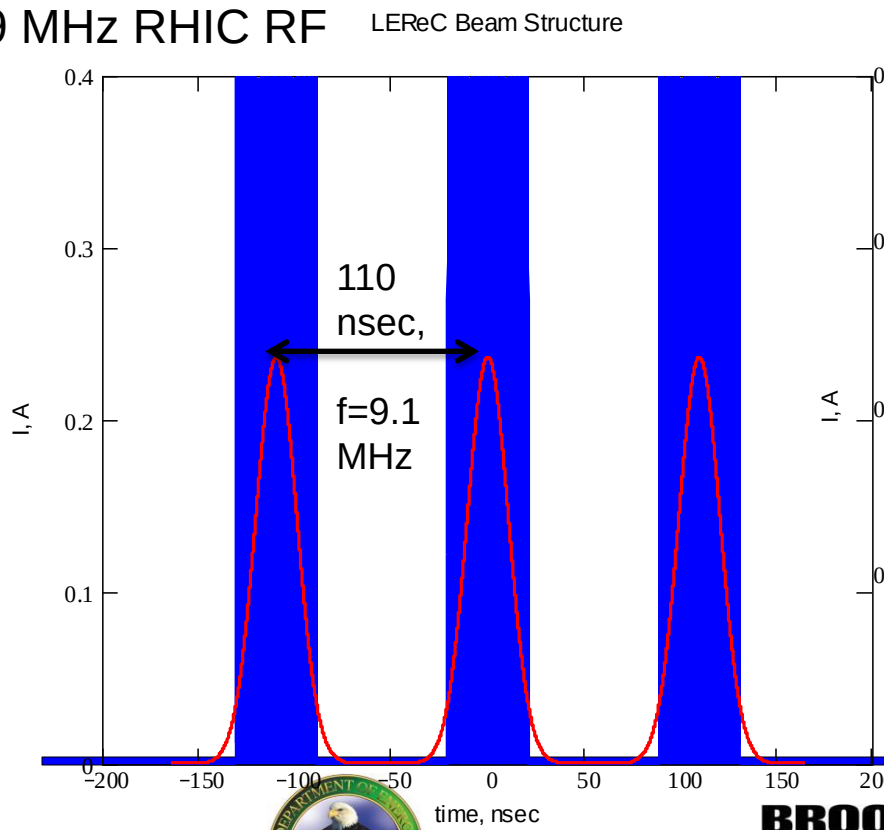
LEReC beam structure in cooling section
Example for γ= 4.1 (E_{ke}=1.6 MeV)

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

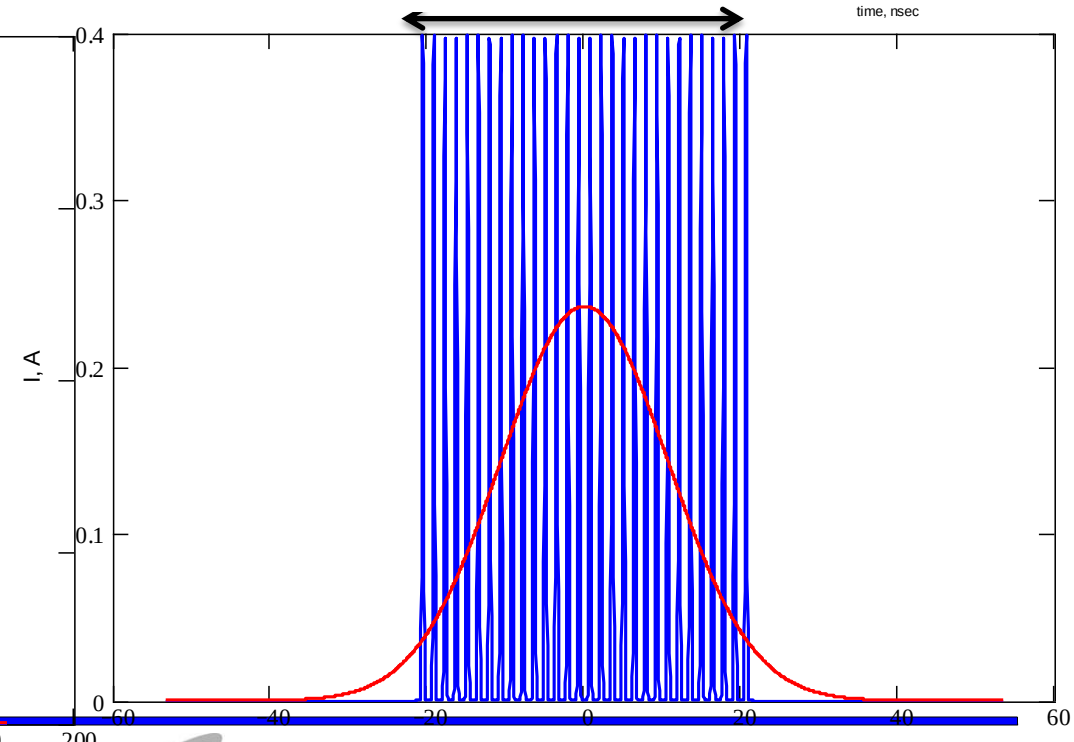
Electrons:
f_SRF=703.518MHz
Rms length=3 cm, I_peak=0.4 A
Q_e=100 pC



9 MHz RHIC RF



30 electron bunches



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March 2015

Some summary points from MAC review (December 8-10, 2014) report on LEReC

- Although electron cooling has been applied in numerous machines, this is by far the most ambitious application to date and must demonstrate several innovations.

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

LEReC electron source status and plans

- **2015:** Continue SRF gun beam tests in Bldg. 912 with new cathode stalk, new 704 MHz LEReC laser system towards CW operation with high-current is under development (goal is to demonstrate 300 pC bunch charges and average currents up to 50 mA needed for LEReC by early 2016).

- **November 2014:** Collaboration and work on 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

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)

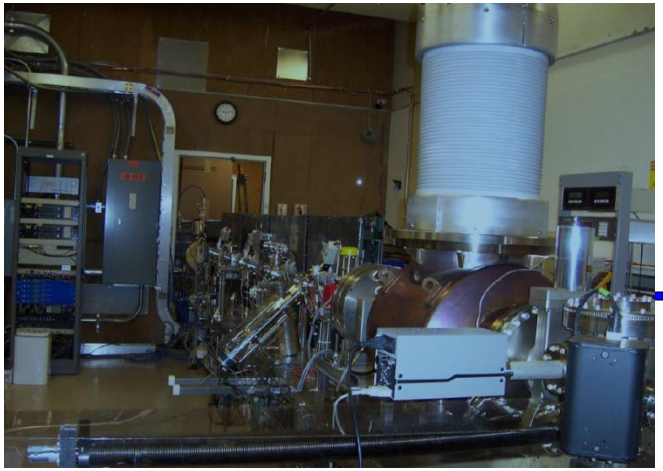
- Stable 24/7 operation

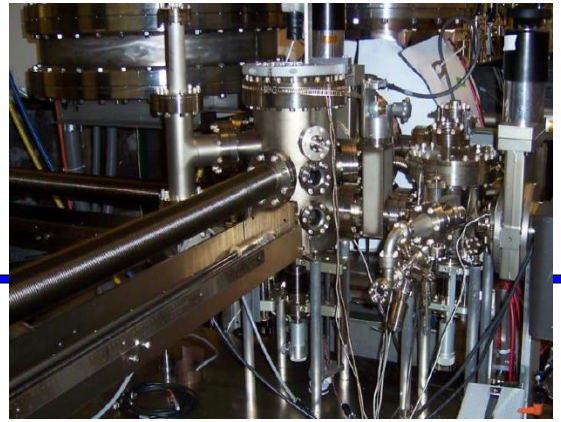
-Cathodes exchanging mechanism for quick cathode replacement without significant delay on operation.

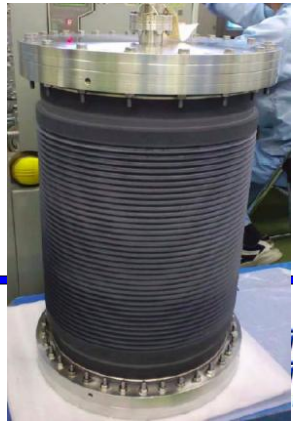
Contract with Cornell to build DC gun for LEReC (identical to existing Cornell's gun)

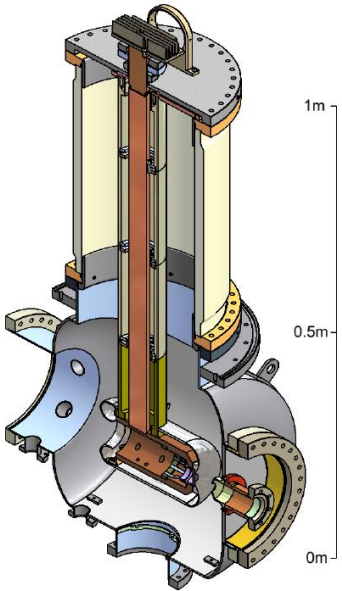
Includes engineering and design support for gun, power supply, cathode design, cathode changing mechanism, and cathode coating chamber.

- 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).

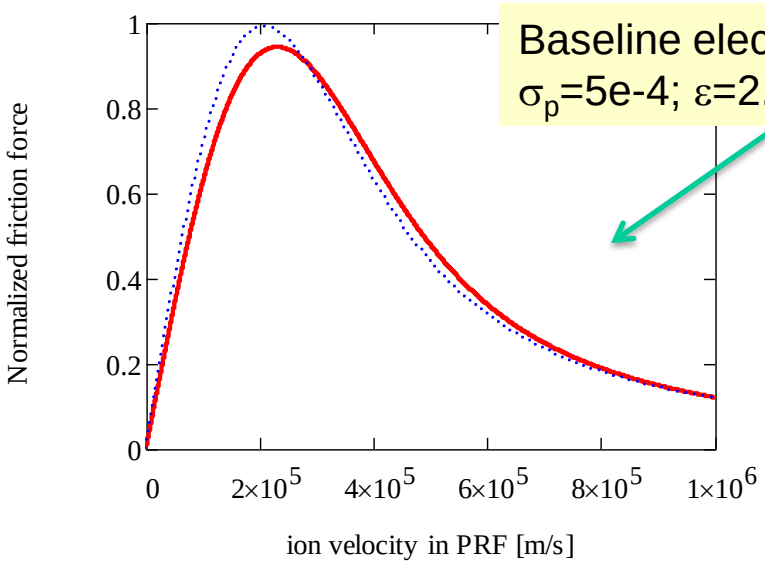
asymptotic for $v_{ion} < \Delta_e$:

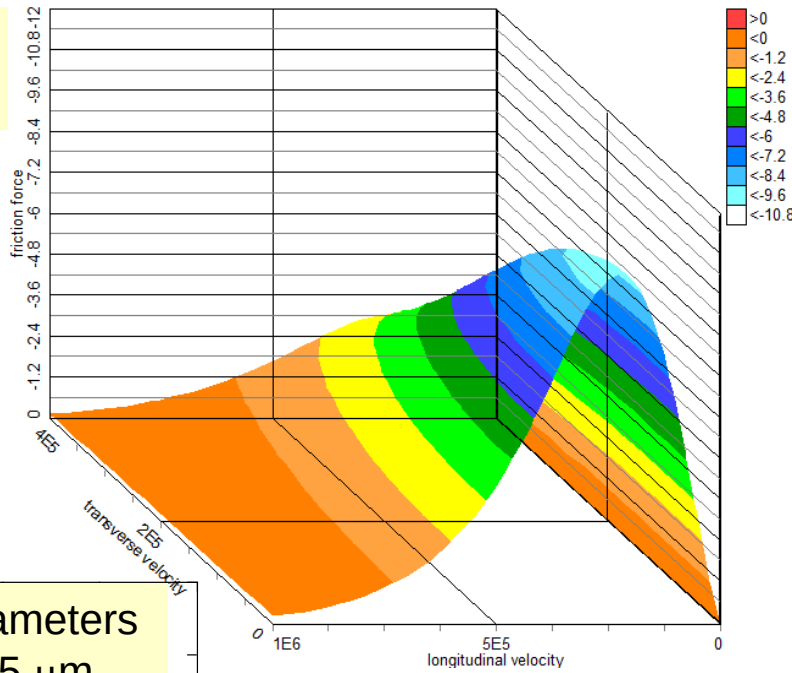
$$\vec{F} = -\frac{4\pi Z^2 e^4 n_e L}{m} \frac{\vec{v}_i}{\Delta_e^3}$$

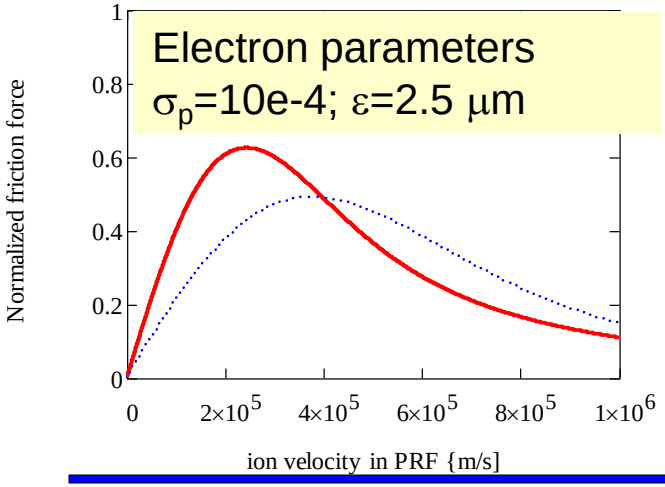
$$\vec{F} = -\frac{4\pi Z^2 e^4 n_e L}{m} \frac{\vec{v}_i}{\beta^3 c^3 ((\gamma\vartheta)^2 + \sigma_p^2)^{3/2}}$$

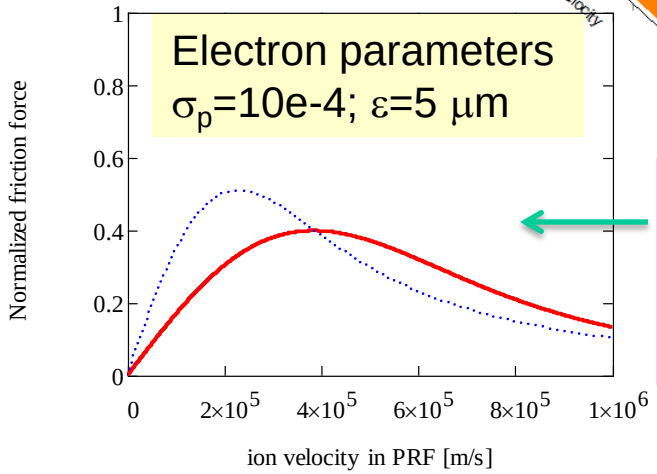
Requirement on electron angles:
For γ=4.1: σ_p=5e-4; θ<150 μrad

LEReC cooling force









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:

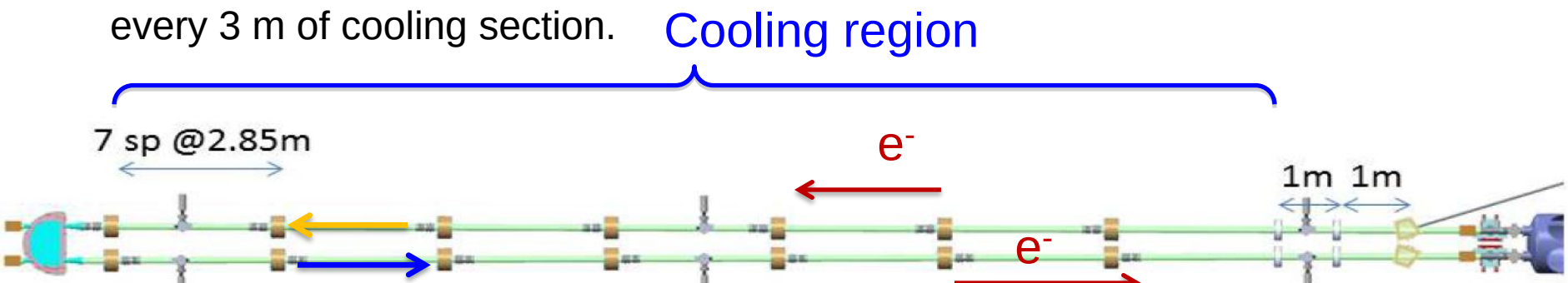
  Correction solenoids and mu-metal shielding.

- 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:

B_residual=2.5mG ->angles: 35 μrad after L=3m.

Passive (mu-metal shielding) to suppress B_residual to required level (<2.5 mG) 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.

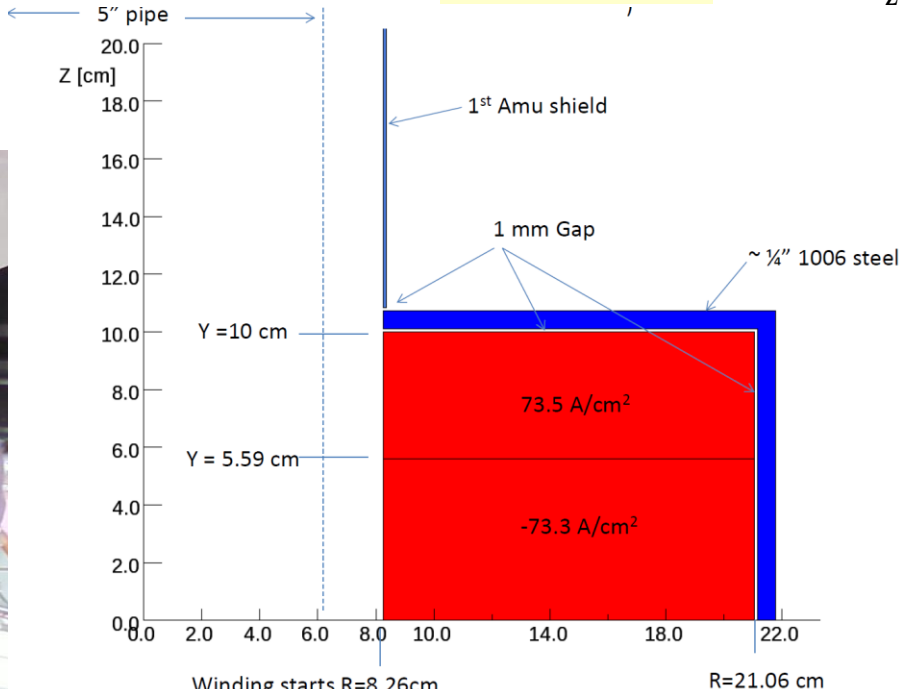
Residual magnetic field from solenoids in cooling region:

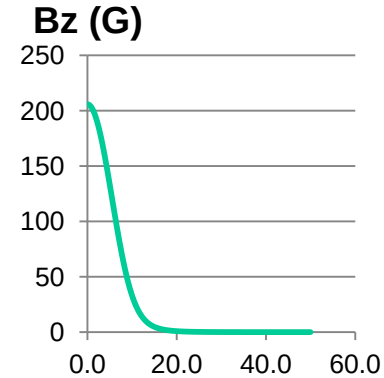
W. Meng

$B_z < 1G$ 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 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.
- 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

Measured beam lifetime (without collisions)

Table 1. Overview of several experiments (without collisions).

ΔQ_{sc} (x,y)	τ [s]	γ	Comments
0.03	2000	10	$5\sigma_x$ acceptance, Q_s=0.002, no attempt for other w.p.
0.05, 0.04	1600	6.1	$>3\sigma_x$ acceptance, Q_s=0.006
0.085, 0.065	700	6.1	$>3\sigma_x$ acceptance, Q_s=0.006
0.1	70	4.1	$2.2\sigma_x$acceptance, Q_s=0.013

During 2009-12 several dedicated APEX experiments were done to study beam lifetime with large space charge spread and different beam-beam parameters.

Proc. of HB10: THO1C03;
Proc. of PAC11: THP081;
Proc. of IPAC12:WEPPR086

Table 2. Best observed beam lifetimes for significant space charge (without collisions).

ΔQ_{sc}	τ	γ	Comments
0.02	> 6 h	10	Both rings
0.027-0.029	5/3h	10	Yellow/Blue
0.035	~2h	10	Yellow only, w.p. near integer

Lifetime was improved by moving to a working point near integer.

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.

LEReC timeline (based on January 2015 baseline)

SRF gun:

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

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

DC gun:

April 2015 - March 2016: **DC gun construction by Cornell University.**

March-July 2016: **DC gun commissioning at Cornell.**

End of 2015: Installation of cooling sections

July 2016 – March 2017: Move and install Gun, RF cavity, beam dump, cryo, PS, instrumentation and magnets in RHIC

January-May 2017: Systems commissioning (RF, cryogenics, etc.)

June - Sept 2017: LEReC commissioning with e-beam in RHIC tunnel

October 2017: **RHIC Run-18 BES-II physics program (commissioning of cooling with Au ion beams). May be shifted by a year if BES-II is delayed to Run-19**

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.