Low-energy RHIC electron Cooler (LEReC) Overview

A. Fedotov for LEReC team

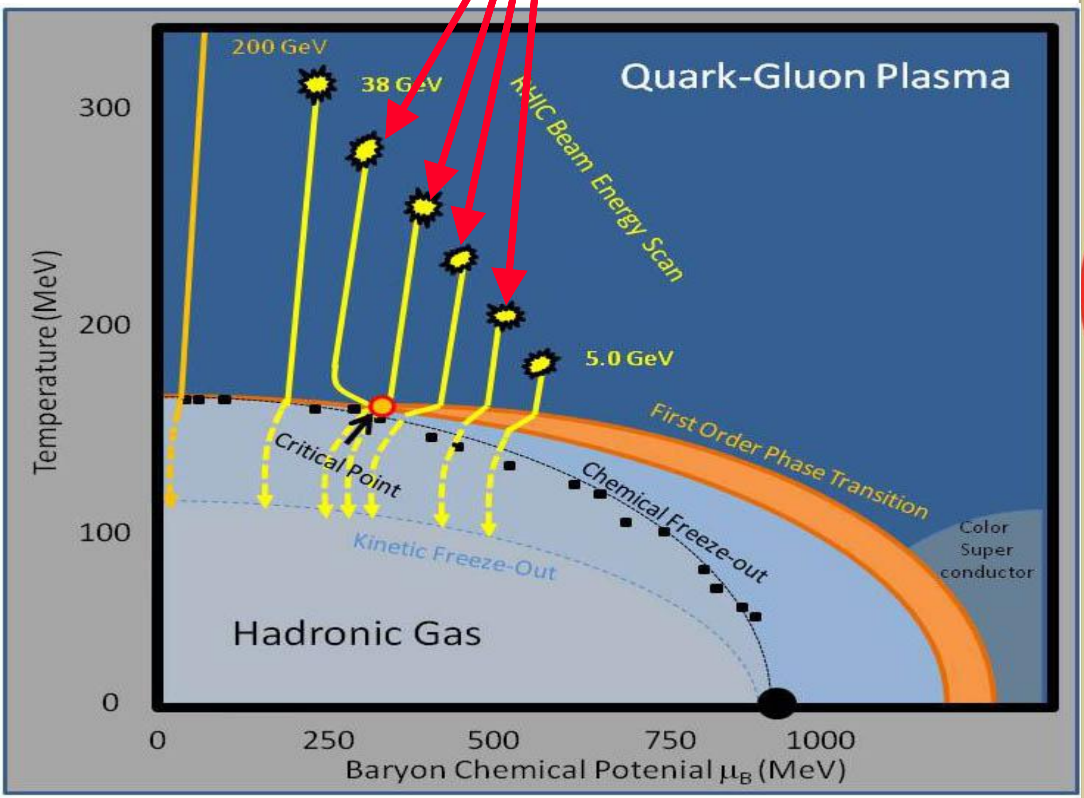
RHIC meeting October 28, 2013

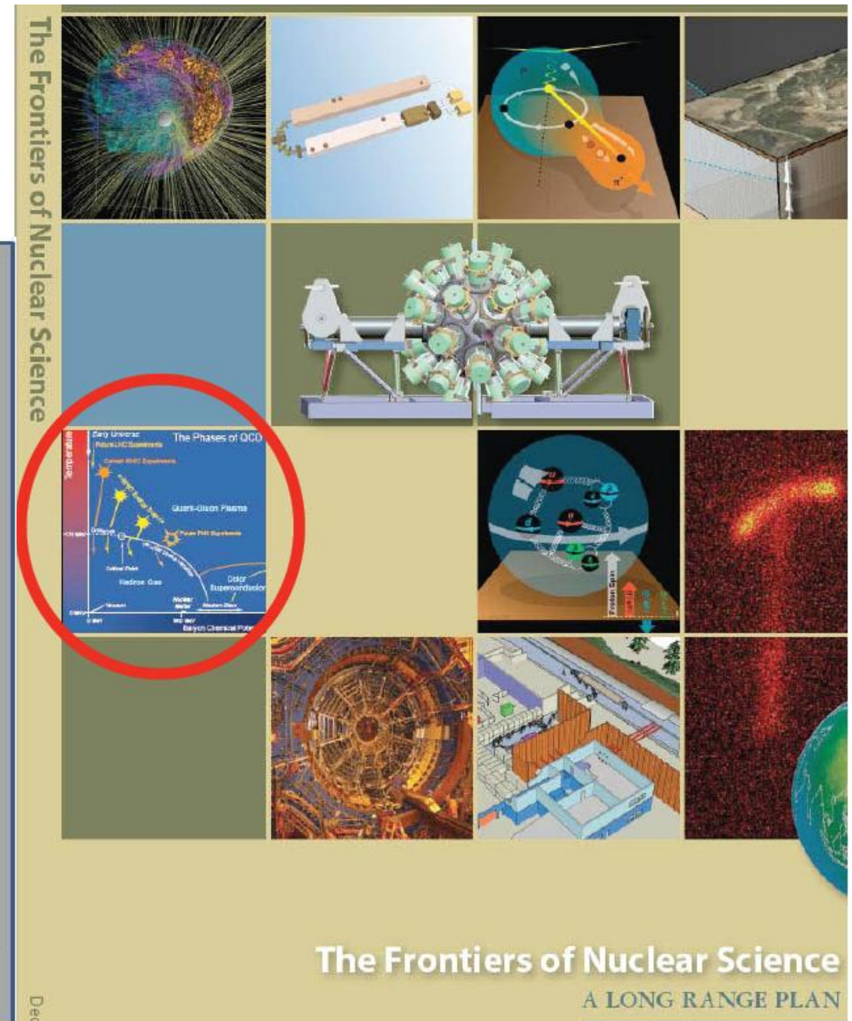
Low-Energy RHIC program:

Operation with heavy ions to search for
QCD phase transition Critical Point

Beam Energy Scan I, center of mass energies:
$\sqrt{s_{NN}}$ = 5, 6.3, 7.7, 8.8, 11.5, 18, 27 GeV

(2010 & 2011 RHIC runs)

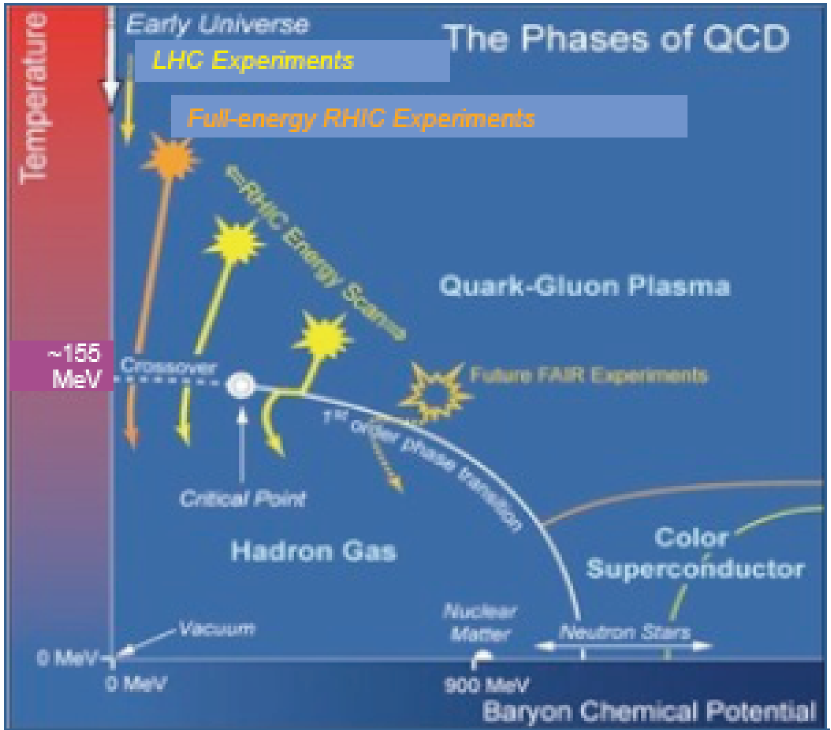




RHIC: Science Goals for the Next Decade

•B. Mueller (2013)

Quantify properties of the QGP by measuring **heavy quarks** and features of the QCD phase diagram as functions of temperature and net quark density.



Search for a QCD Critical endpoint via low-energy scan in RHIC-II era

Exploit new discovery potential in searches for a **QCD critical point** and for the nature and influence of quantum fluctuations in initial densities and gluon vacuum excitations.

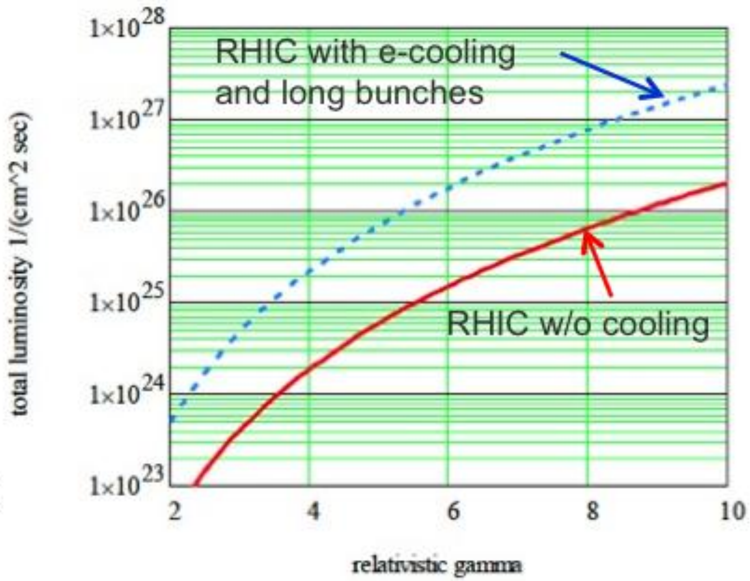
Continue explorations of the role of **soft gluons in cold nuclear matter** (gluon saturation, gluon and sea quark contributions to proton spin). Precursor to eRHIC program.

Caveat: Budget constraints make a deliberate execution of a decadal program of scientific inquiry challenging

Future Upgrades

•B. Mueller (2013)

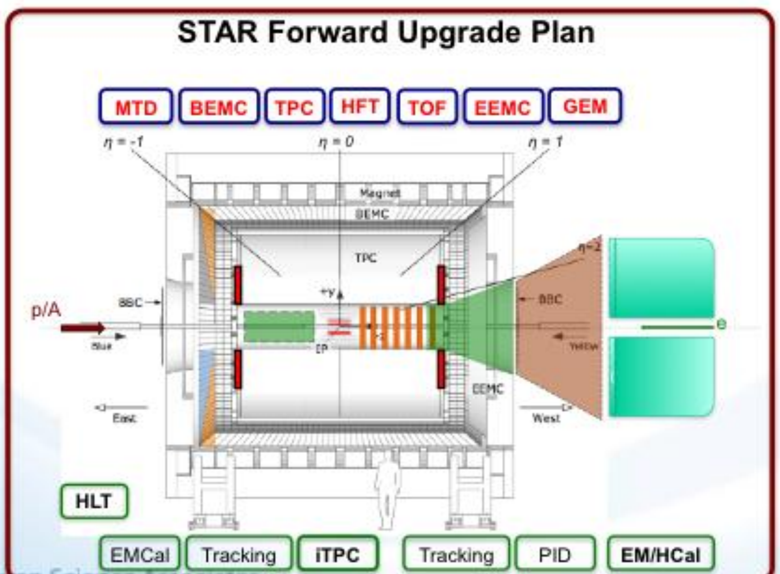
Bunched beam electron cooling; ~10x luminosity; ready after 2017

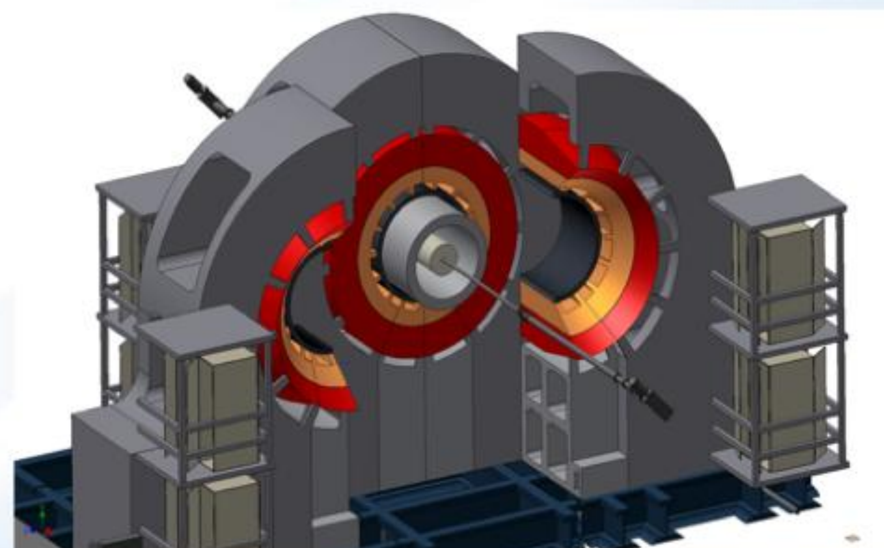


Other machine options: polarized ^{3}He; coherent e-cooling for p+p

Detector upgrades:

- sPHENIX solenoid, EMCAL + HCAL for jet physics @ RHIC
- STAR forward upgrade for p+A and transverse spin physics
- PHENIX MPC-EX,
- STAR TPC pad rows





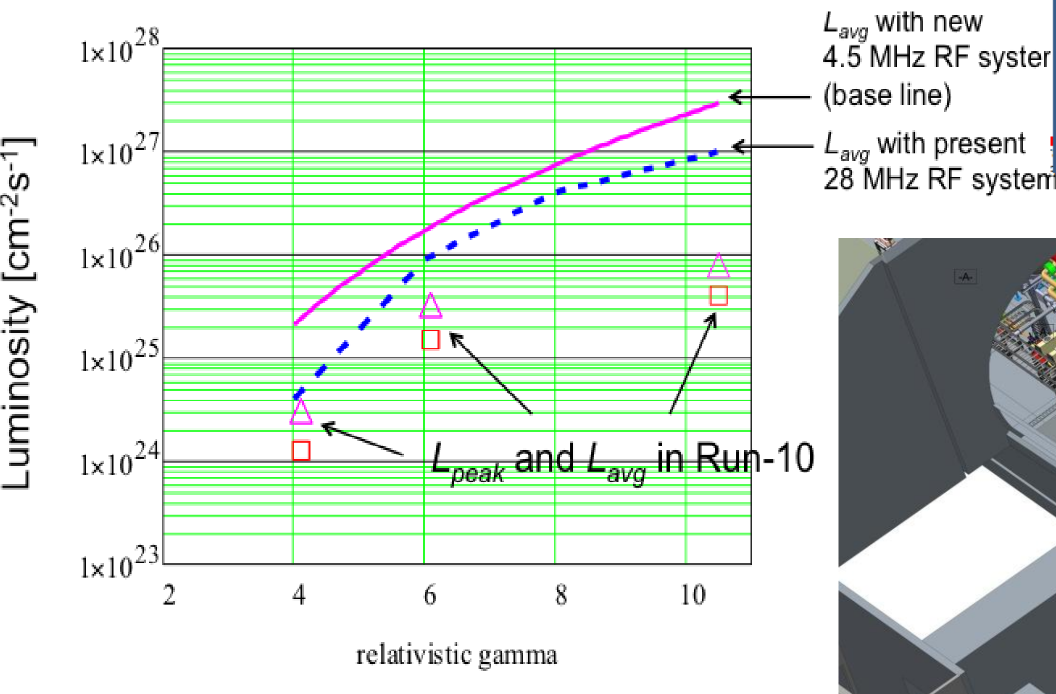
Run Schedule for RHIC

•B. Mueller (2013)

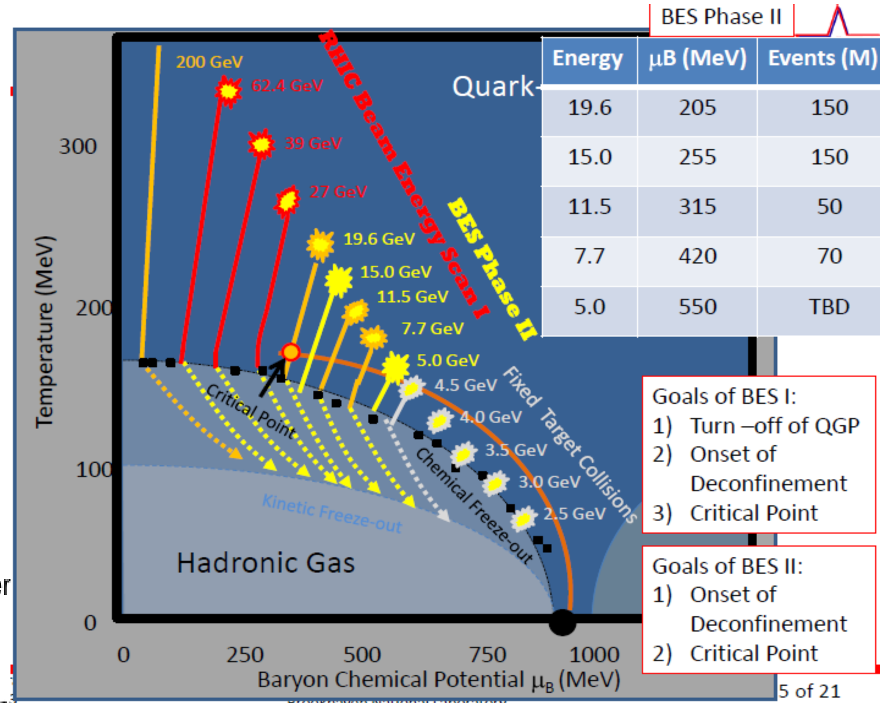
Years	Beam Species and Energies	Science Goals	New Systems Commissioned
2013	• 500 GeV pol p+p	• Sea quark and gluon polarization	• upgraded pol'd source • STAR HFT test
2014	• 200 GeV Au+Au • 15 GeV Au+Au • Fixed Au target test	• Heavy flavor flow, energy loss, thermalization, etc. • Quarkonium studies • QCD critical point search	• Electron lenses • 56 MHz SRF • full STAR HFT • STAR MTD
2015-2016	• p+p at 200 GeV • p+Au, d+Au, ^{3}He+Au at 200 GeV • High statistics Au+Au	• Extract η/s(T) + constrain initial quantum fluctuations • More heavy flavor studies • Sphaleron tests	• PHENIX MPC-EX • Coherent electron cooling test
2017	• No Run		• Electron cooling upgrade
2018-2019	• 5-20 GeV Au+Au (BES-2)	• Search for QCD critical point and deconfinement onset	• STAR ITPC upgrade
2020	• No Run		
2021-2022	• Long 200 GeV Au+Au w/ upgraded detectors • p+p/d+Au at 200 GeV	• Jet, di-jet, γ-jet probes of parton transport and energy loss mechanism • Color screening for different QQ states	• sPHENIX
2023-24	• No Runs		• Transition to eRHIC

Low-Energy RHIC electron Cooler (LEReC) for Au-Au $\sqrt{s_{NN}}$ = 7 − 20 GeV

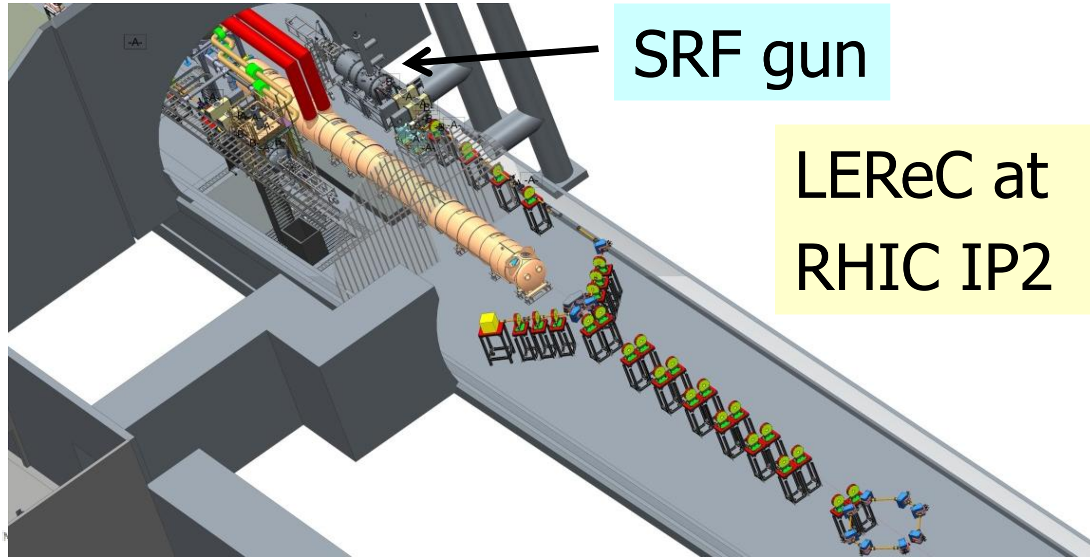
- **Major design choices made**
- **Accelerator Physics Design review: 13-14 August 2013 - approved**
- **DOE review: 27-30 January 2014**
- **Finish installation in 2017**
- **Operation for physics starting 2018**



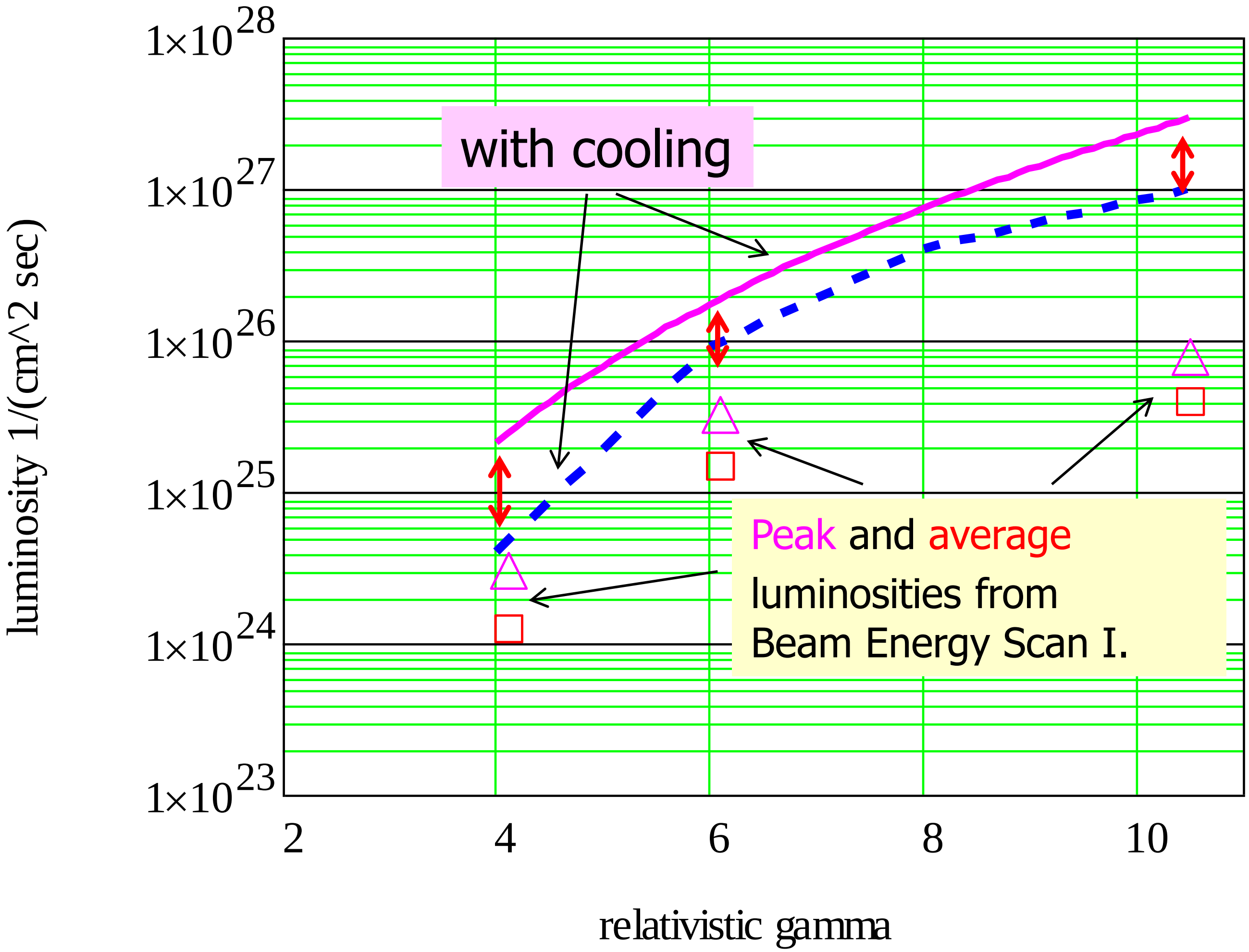
LEReC luminosity gain: 10x with new RF system



Energy	μB (MeV)	Events (M)
19.6	205	150
15.0	255	150
11.5	315	50
7.7	420	70
5.0	550	TBD



Luminosity projection with cooling upgrade (for present 28 MHz and proposed 4.5 MHz RHIC RF systems)



Expected improvement with electron cooling:

Blue-dash line: possible improvement in average luminosity with present 28 MHz RF.

Magenta: maximum potential improvement in average luminosity (with new RF system).

*achievable luminosity ↕ should be somewhat smaller than indicated by the magenta line because of the uncertainty about beam lifetime due to a combination of various processes.

Potential for luminosity improvement with longer bunches

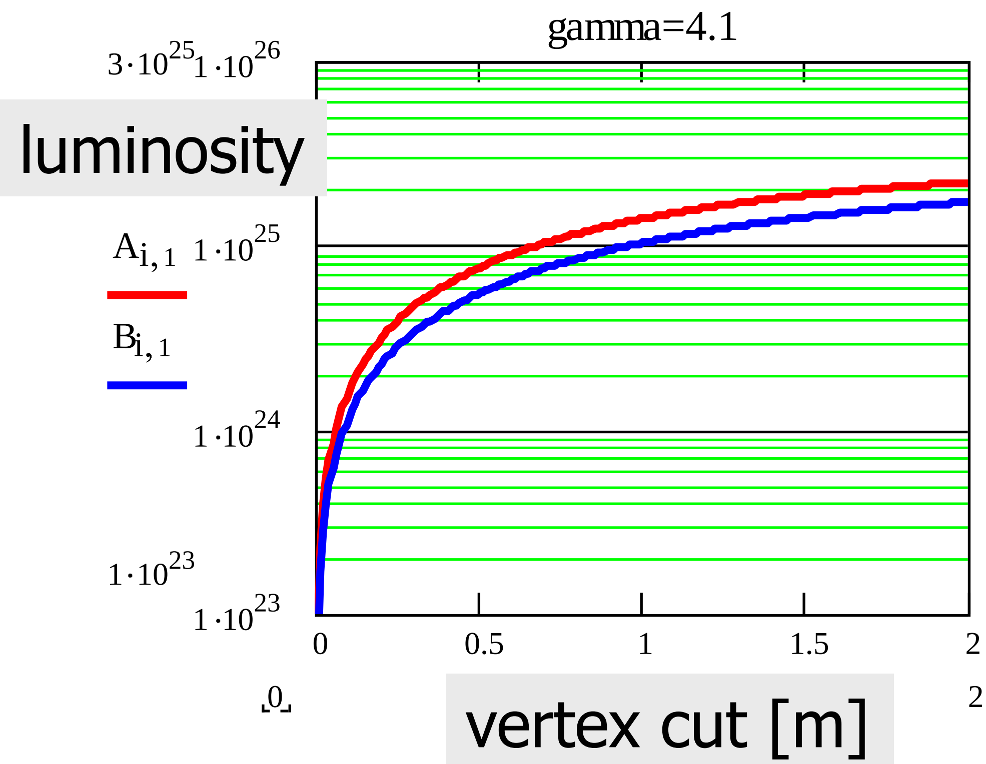
For present 28 MHz RF at lowest energies we are limited both by space charge and RF bucket acceptance (significant beam losses), which strongly limits luminosity improvement with cooling.

Additional 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.

Proposed new RHIC RF system



Luminosity of cooled beams:

Red – 9 MHz (55ns full length)

Blue – 4.5 MHz (100ns full length)

Presently, 4.5 MHz RF is considered, to simplify design due to smaller voltage required.

For details:
C-A/AP/476
C-A/AP/477

By going from 120 bunches (9 MHz) to 60 bunches (4.5 MHz) we loss factor of two in luminosity. This is recovered by increasing bunch intensity.

Bunch length of **6 m rms (4.5 MHz) vs 3 m (9 MHz)** may appear to reduce useful luminosity within detector +/-1m significantly. However, keeping the same space-charge tune shift, longer bunches allow us to cool emittance stronger and reduce beta* accordingly. Resulting luminosities with both RF systems are thus comparable (apart for hour-glass factor).

New RHIC 4.5MHz (or 9MHz) RF

- A concept and feasibility study has been started for the 4.5MHz cavity design for the low energy gold program.

- Two design typologies are being considered for this effort.

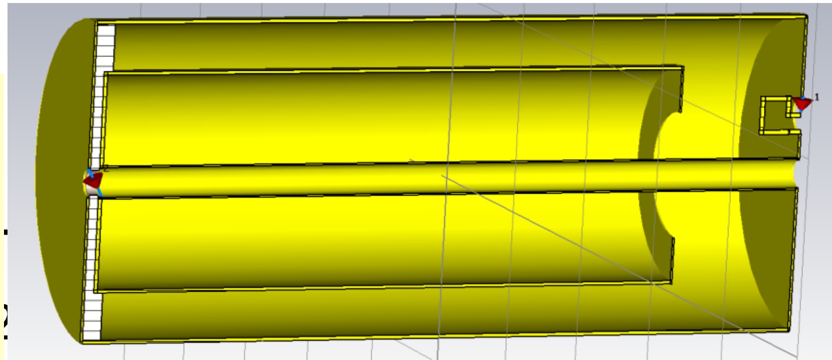
  » **Ferrite Loaded Cavity**

  A ferrite loaded cavity design has been fabricated and initial performance testing has been performed.

Alumina Disk Reentrant Cavity

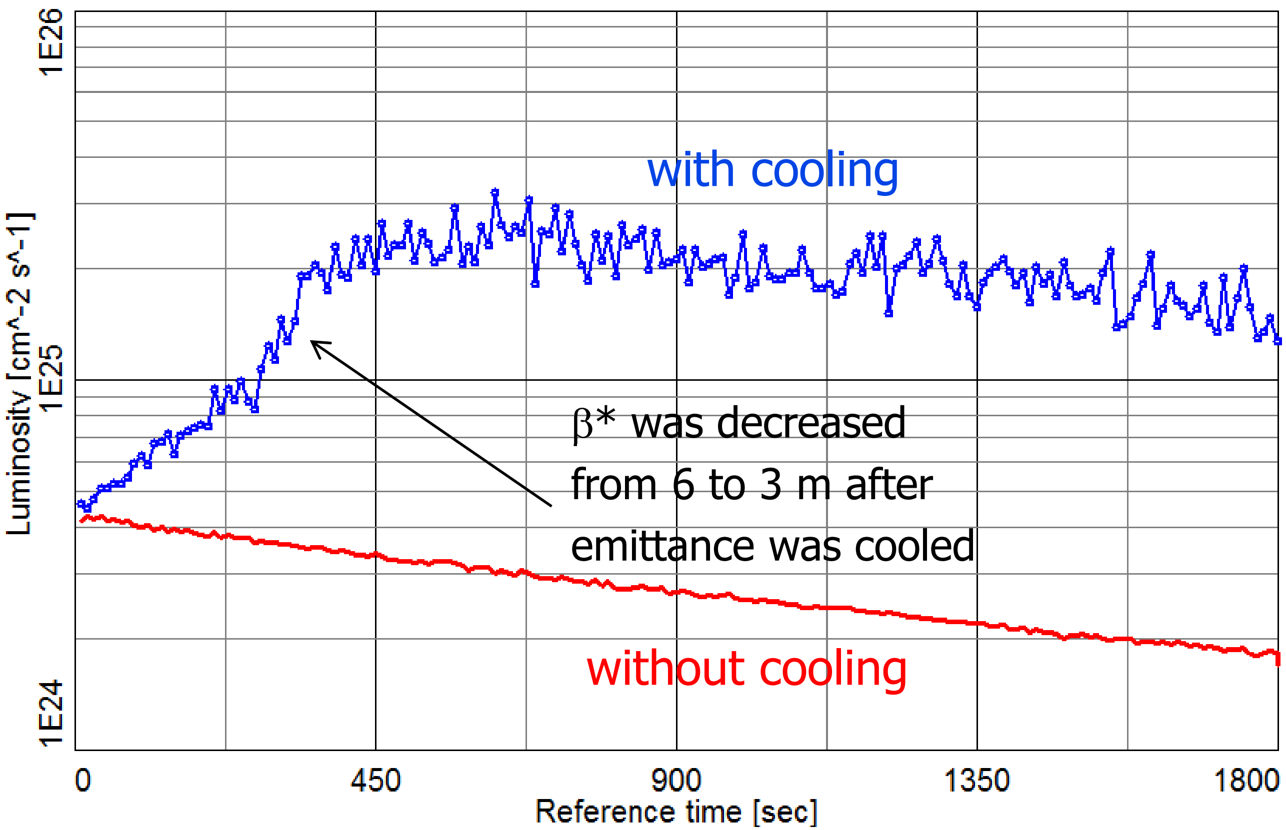
Preliminary simulations of an alumina disk reentrant cavity design have been completed and building a scaled down version is currently underway.

- Center Frequency = 4.55MHz
- Estimated Q = 4000
- Estimated Drive Power = 5KW
- Max Voltage = 40KV



γ@4.1 (sqrt[s]=7.7 GeV), Simulations assuming new 4.5 MHz RHIC RF system

- **Luminosity (simulations) with longer bunches (4.5 MHz)**



Initial bunch parameters:
N=0.75e9,
σ_s=5.8 m (rms length)
ΔQ_{sc}=0.019 (space-charge spread)

Allows to cool transversely and decrease β*.

Even larger luminosity than shown since we should be able to start with smaller β* from the beginning.

γ@10.7 (sqrt[s]=20 GeV)
(can use both new 4.5 and present 28 MHz RHIC RF)

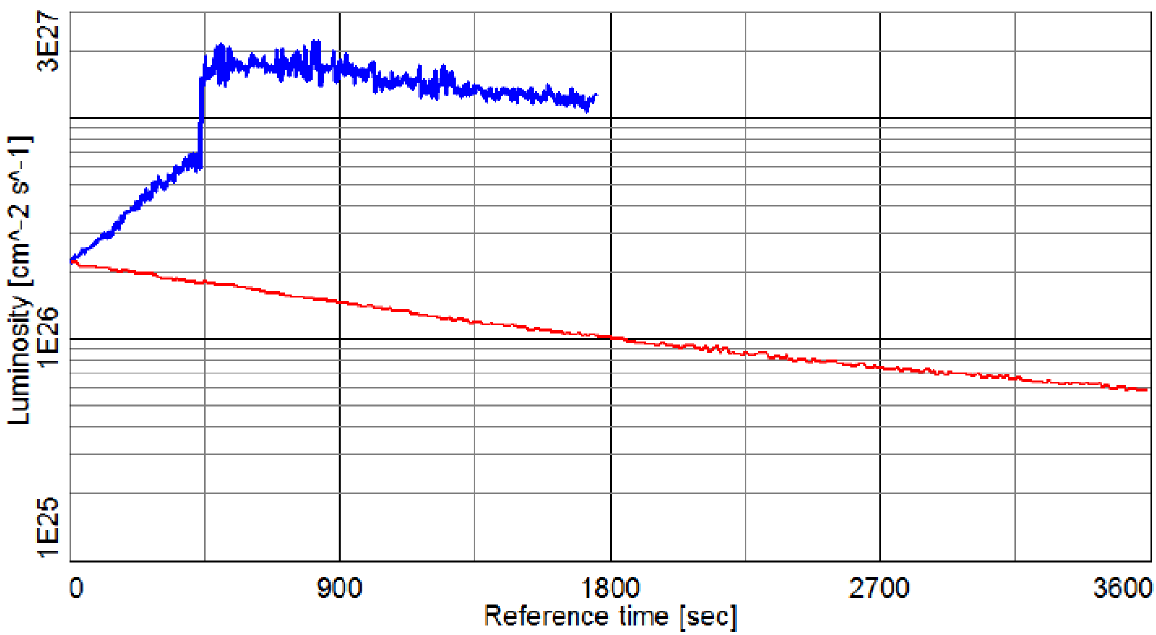


Figure 2. Luminosity at γ=10.7 and 28 MHz RF (450 kV) for initial β*=3m, 111 bunches with $1.5\cdot 10^9$ bunch intensity and transverse 95% normalized emittance of 15 mm mrad. Red curve: IBS and losses from RF bucket only; blue curve: IBS, losses from RF bucket and electron cooling.

Better luminosity improvement is expected for higher energy points of proposed BES-II, since we do not have strong limitation from space charge or physical/dynamic aperture.

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.

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.

Energy scan of interest:
(center of mass energies)
$\sqrt{s_{NN}}$ = 5, 6.3, 7.6, 8.6, 12, 16, 20 GeV

Electron accelerator:
$E_{e,kinetic}$=0.9-4.9 MeV

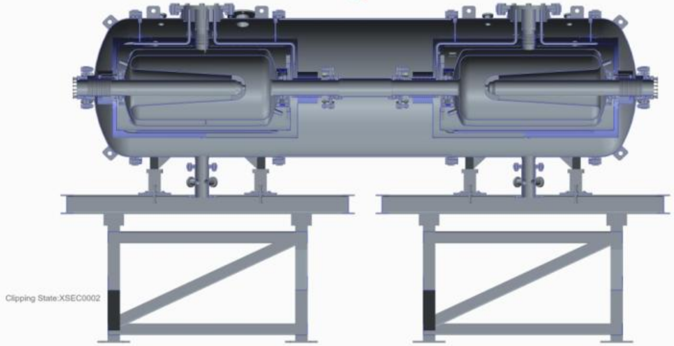
Low-Energy RHIC electron Cooler (LEReC)

Different approaches are possible:

1. DC accelerator (Pelletron from FNAL, the only e-cooler which operated at such high electron energy as 4.3 MeV)
   suitable for cooling: < $\sqrt{s_{NN}}$ =20 GeV

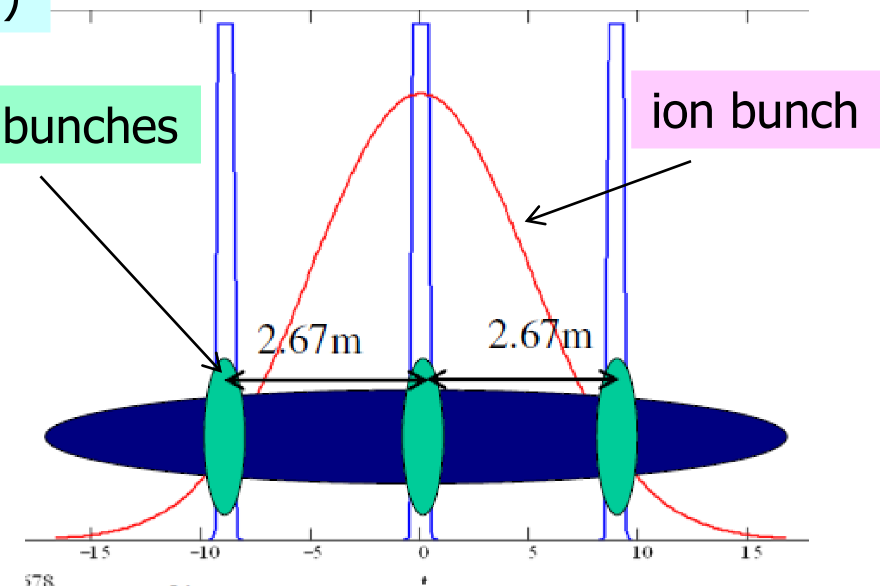
2. RF-gun bunched beam electron cooler - (SRF gun and booster cavity) designed to reach $\sqrt{s_{NN}}$ =20 GeV
   present baseline approach for LEReC

compact approach (5 MeV):



Bunched beam electron cooling

A natural way for high-energy cooling
(when RF acceleration becomes more practical)

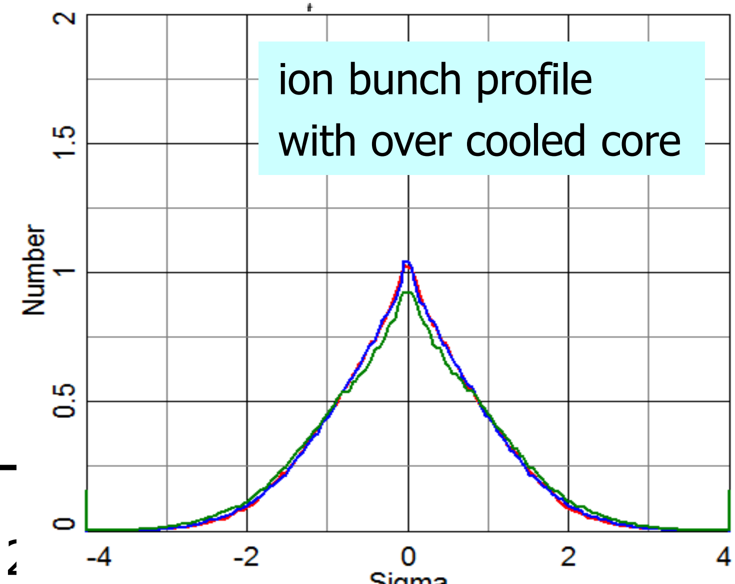


LEReC:

- **First bunched beam electron cooling**

1) Putting a "train" of electron bunches on a single ion bunch.

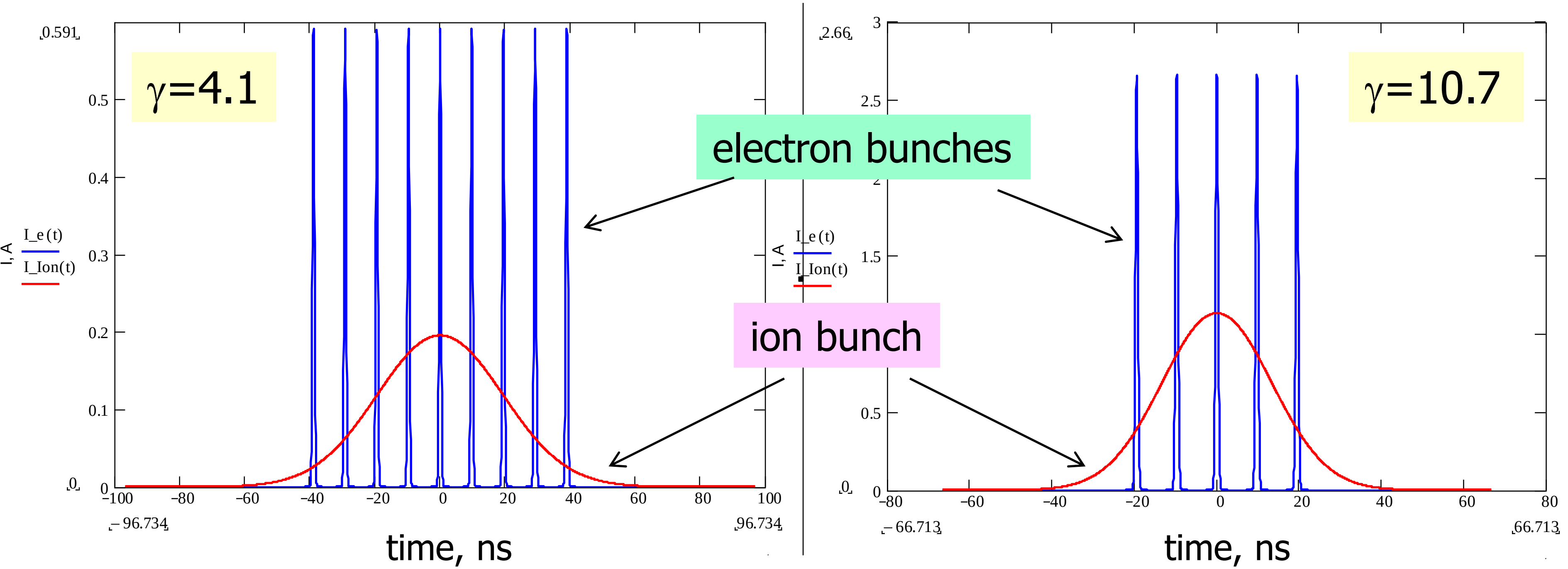
2) Possibly "painting" through ion bunch length.



- **First electron cooling in a collider**

Requires careful control of ion beam distribution under cooling to avoid over cooling (shown in the plot) of beam core.

Using "trains" of electron bunches for cooling

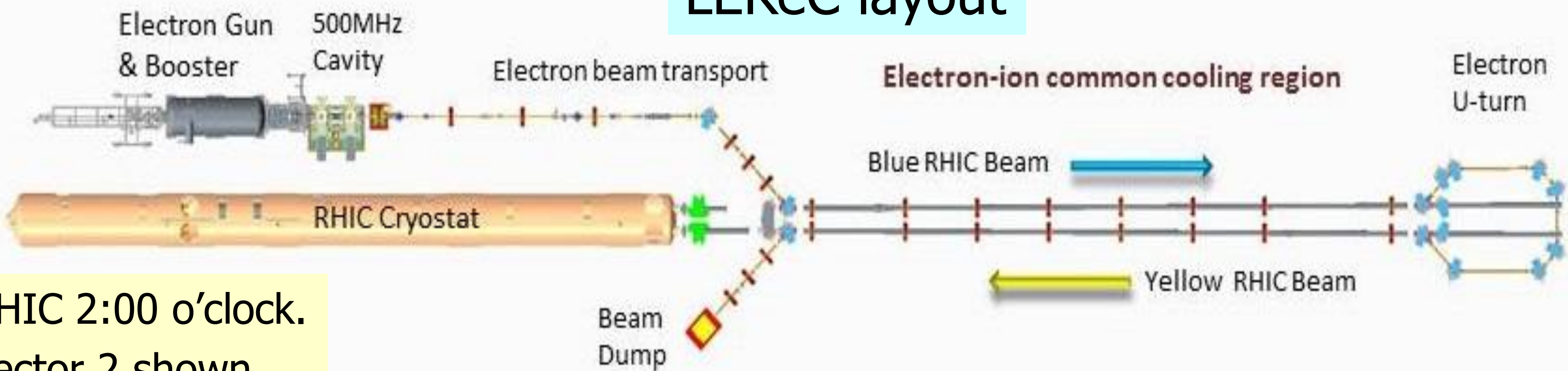


γ=4.1, Q=0.45 nC/bunch , length=0.75 ns, I_peak=0.6A, (bunches 12 ns apart)

γ=10.7, Q=2nC/bunch , length=0.75 ns, I_peak=2.5A, (bunches 12 ns apart)

- **Electron cooling will be provided with a train of electron bunches placed on a single ion bunch.**
- **For very long ion bunches (proposed 4.5 MHz RF) at lowest energies in RHIC we can place up to 9 electrons bunches on a single ion bunch.**
- **For higher energies we can place 5 electron bunches on a single ion bunch.**

LEReC layout

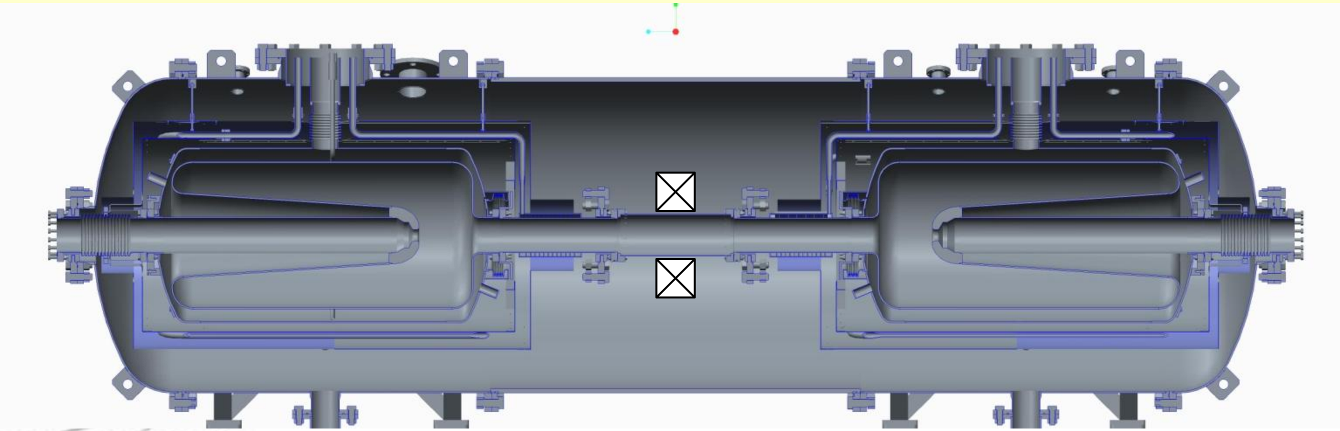


RHIC 2:00 o'clock.
Sector 2 shown.

- **84.5 MHz SRF gun with maximum energy of 2.5 MV.**
- **2.5 MV booster 84.5 MHz SRF cavity in the same cryostat.**
- **507 MHz energy correction warm cavity (6^{th} harmonic).**
- **Electron beam transport.**
- **Cooling section in Blue RHIC ring – 14 m long. Short (10cm) correction solenoids (200G) located every 2m. U-turn between cooling section in Blue and Yellow RHIC rings.**
- **Cooling section in Yellow Ring.**
- **Dump for the electron beam.**

LEReC SRF accelerator

- The electron accelerator (a short linac) will consist of a two-cavity superconducting RF (SRF) cryomodule producing beam with energy up to 5 MeV and normal conducting cavity for energy spread correction.
- The cryomodule will house:
  - A photoemission SRF gun of a quarter wave resonator (QWR) type, operating at 84.5 MHz;
  - A 84.5 MHz QWR SRF booster cavity;
  - There will be a superconducting solenoid (with magnetic field up to 1 kG) between two SRF cavities.
- 507 MHz normal conducting cavity will correct energy spread due to RF curvature of the SRF cavities.



designed
in collaboration
with ANL

SRF gun design considerations

- The SRF gun design will be similar to the 112 MHz SRF gun built by Niowave for the Coherent Electron Cooling (CeC) experiment at BNL (under construction) with the following major differences:
  1) The gun cavity shape will be optimized to improve surface fields and reduce wall losses;
  2) The gun will be equipped with two high-power fundamental RF power couplers;
  3) There will be a frequency tuner of an improved design.

112 MHz SRF gun (Niowave Inc.) being installed in RHIC tunnel for the CEC PoP experiment.

SRF accelerator parameters

Beam			
Lorentz factor	4.1	10.7	10.7
RHIC RF frequency	4.55 MHz	4.67 MHz	28.03 MHz
Electron beam kinetic energy	1.58 MeV	4.96 MeV	4.96 MeV

SRF gun and booster			
SRF frequency	84.48 MHz	84.47 MHz	84.47 MHz
Gun voltage	1.65 MV	2.58 MV	2.58 MV
E_{pk}	25.7 MV/m	40.3 MV/m	40.3 MV/m
B_{pk}	52.5 mT	82.2 mT	82.2 mT
R/Q	122.7 Ohm	122.7 Ohm	122.7 Ohm
Geometry factor	34.7 Ohm	34.7 Ohm	34.7 Ohm
Cavity *Q* factor at 4.5 K	2.7e9	2.7e9	2.7e9
Gun RF power	30.7 kW	84.9 kW	92.5 kW
Frequency tuning range	78 kHz	78 kHz	78 kHz
Booster voltage	0	2.58 MV	2.58 MV
Booster RF power	0	84.9 kW	92.5 kW

Cooler requirements

Ion beam parameters		
Gamma	4.1	10.7
RMS bunch length	5.8 m	4.2 m
N_{au}	0.75e9	3e9
I_peak	0.2 A	1 A
Frequency	4.55 MHz	4.67 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	2x12 m	2x12 m
Charge per ion bunch	4 nC (9x0.44nC)	7 nC (5x**1.4 nC**)
RMS norm. emittance	< 2.5 um	**<2 um**
Average current	18.2 mA	**32.7 mA**
RMS energy spread	<5e-4	**< 4e-4**
RMS angular spread	<150 urad	**<90 urad**

Electron beam transport at low energies

- **Bunched beam cooling is a natural approach for high energies.**
- **For intermediate energies, like LEReC 1-5 MeV, there are some challenges which has to be carefully addressed:**

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

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

- The attainment of required low energy spread in the electron bunch relies on shielding of the longitudinal space-charge force with the vacuum chamber and use of long electron bunches.

- 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 since the same beam will be used for cooling in both RHIC rings.

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 Blue RHIC ring then it is turned around (U-turn) and cools ions in Yellow 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 Yellow ring.
- The Blue and Yellow ring cooling sections are about 12 meters each (exact length to be fixed). No recombination suppression is planned. Some space is taken up by 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 2 m of the cooling section.
- Distance covered by magnetic field from solenoids (100-200 G) will be lost from cooling. Expect about 20-25 cm to be lost from cooling from each solenoid, every 2m of cooling section (design by W. Meng).

Requirement of magnetic field suppression in cooling section:

γ=4.1: B_residual=2.5mG ->angles: 70 μrad after L=2m.

Requirement on total rms angular spread : < 150 μrad (γ=4.1)

Passive (mu-metal shielding) or active (Helmoltz coils) should guarantee that B_residual is below required level in free space between compensating solenoids.

Emittance of 2 μm gives 130 μrad for 30m β-function.

Present approach: shielding <0.2mG (angles <35 μrad after 12 m).

transverse momentum imparted to the electron beam by these magnetic fields is acceptably low if the fields can be limited to approximately 2 mGauss.

In order to accomplish this, the Electron Cooling section will be shielded by three concentric cylindrical layers of high initial permeability alloy. A geometry that achieves this goal and that fits within the radial limitations imposed by the solenoid design is parameterized in Table 2.

Table 2: Magnetic Shielding Parameters

Mu (initial)	11000
Layer thickness	1 mm
Inside radius of layer 1	109.5 mm
Inside radius of layer 2	120.6 mm
Inside radius of layer 3	133.3 mm
Total magnetic attenuation for DC fields	3000

FNAL

Using an 80% Nickel-Iron-Molybdenum alloy satisfies

Residual magnetic field from solenoids in cooling region

W. Meng

$$B_z < 1G$$

$$\int B_r dz < 0.5G \cdot cm$$

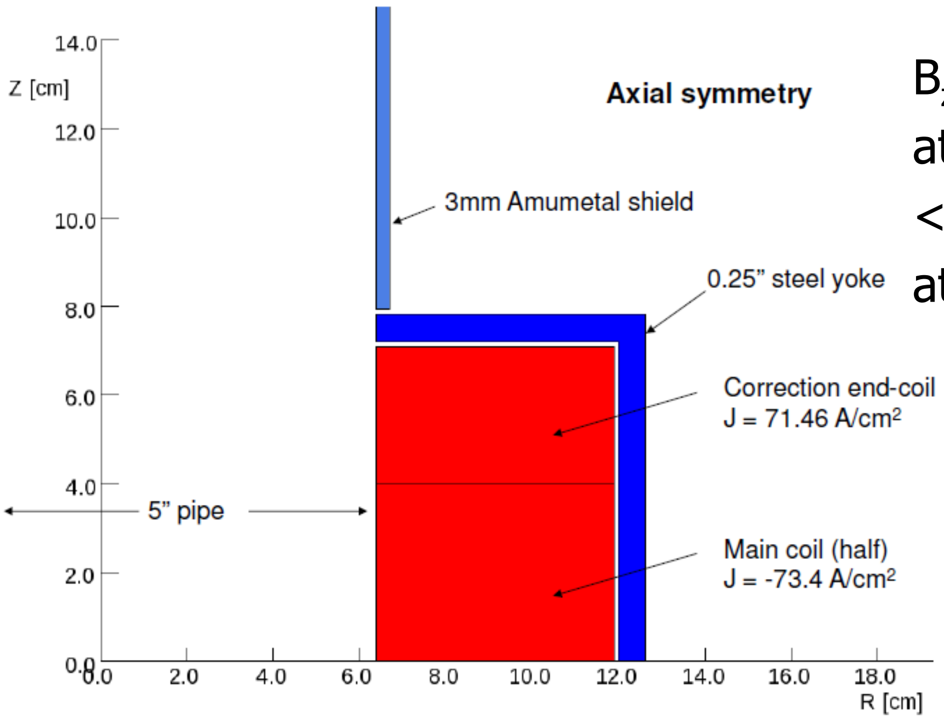
at z=10.7 cm

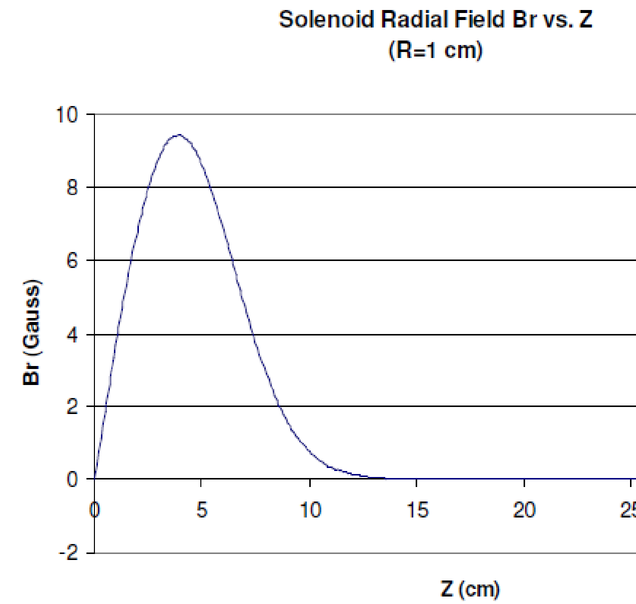
B_z=0.5 G

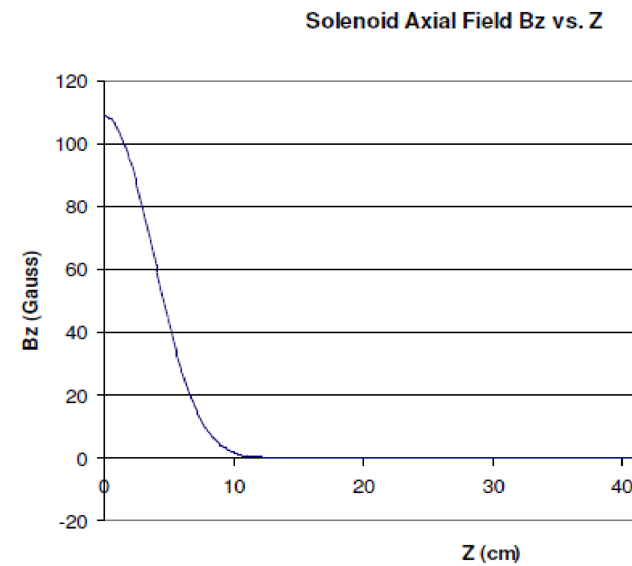
at z=11.3cm

<0.01 G

at Z=13cm







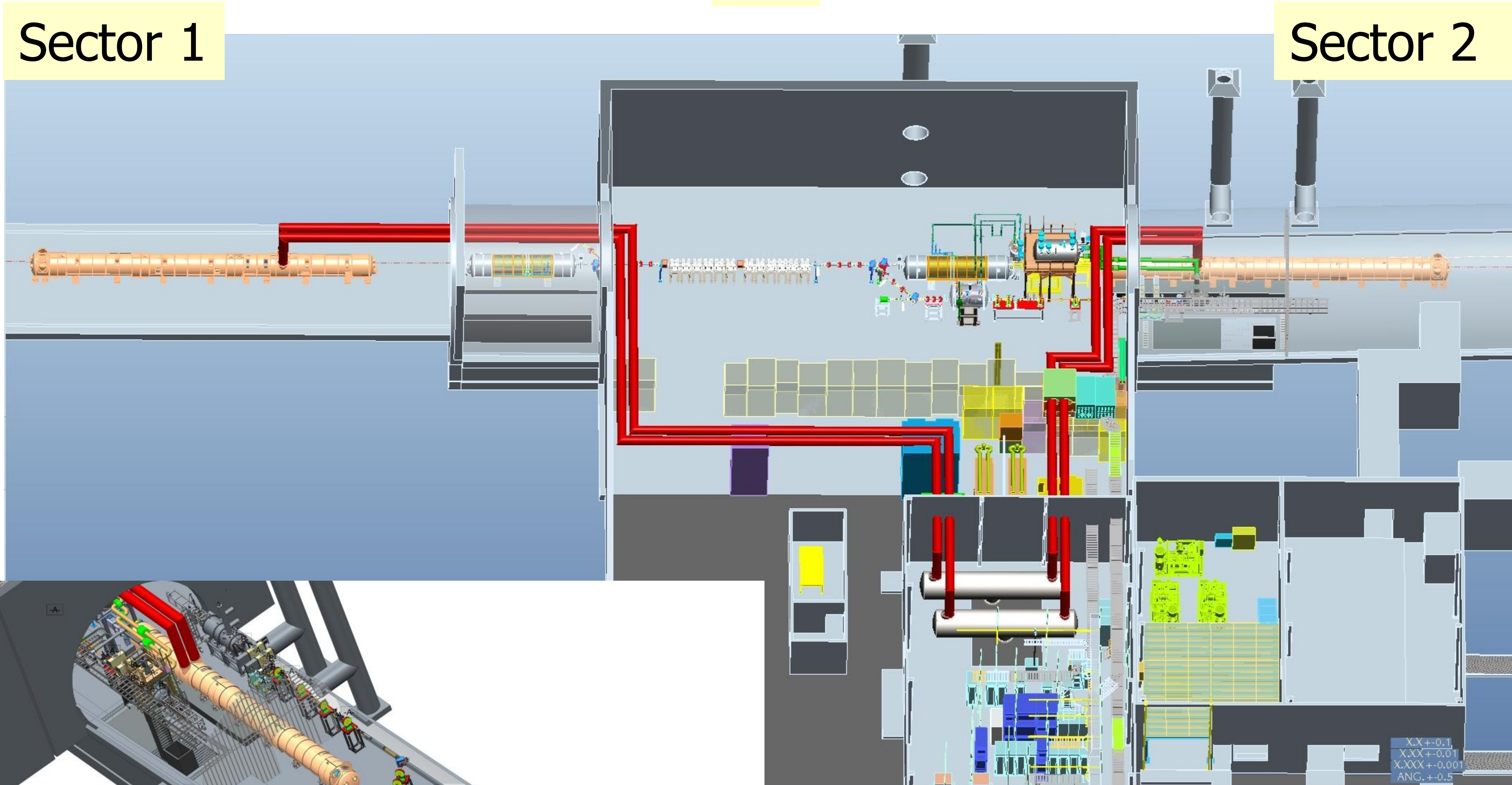
Challenges

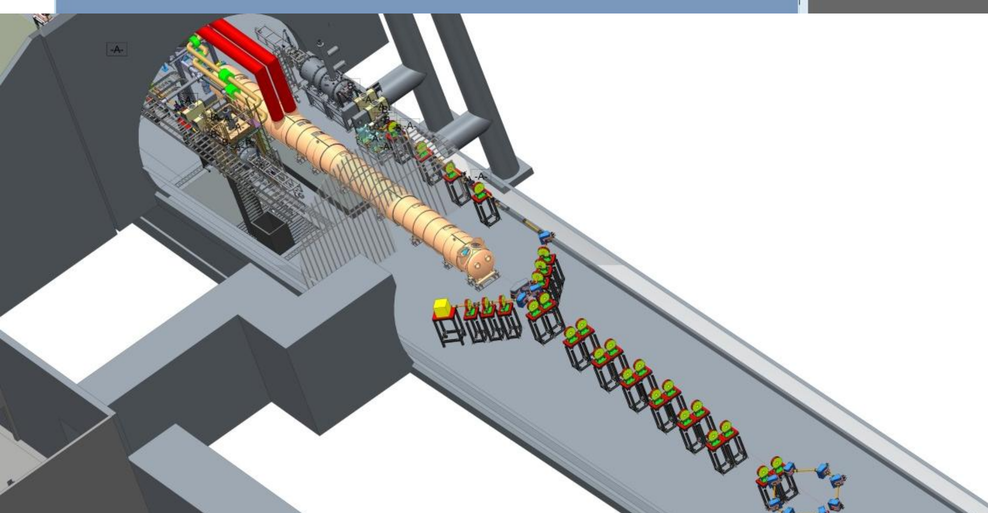
- Operation in a wide range of energies; control of electron angles in the cooling section to a very low level for all energies.
- Repeatability of electron beam transport at low energies.
- Use the same electron beam to cool ions in two collider rings: preserving beam quality from one cooling section to another.
- Stable CW operation of the SRF gun with required charge per bunch and beam currents.

Cooling in a collider:

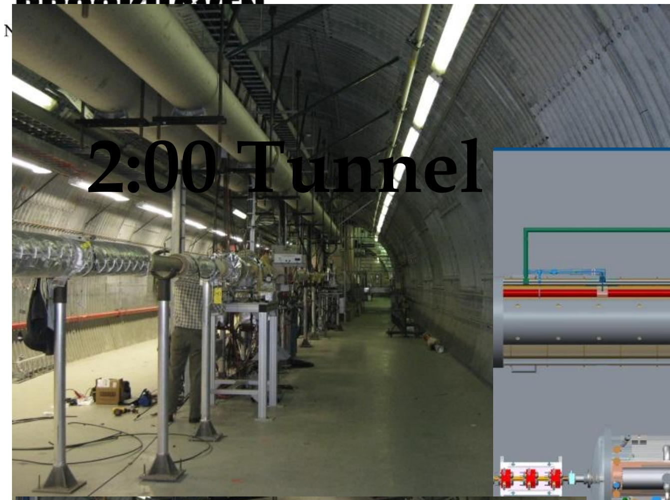
- Control of ion beam distribution. Do not overcool beam core.
- Effects on hadron beam.
- Interplay of space-charge and beam-beam in hadrons.
- Cooling and beam lifetime (as a result of many effects).

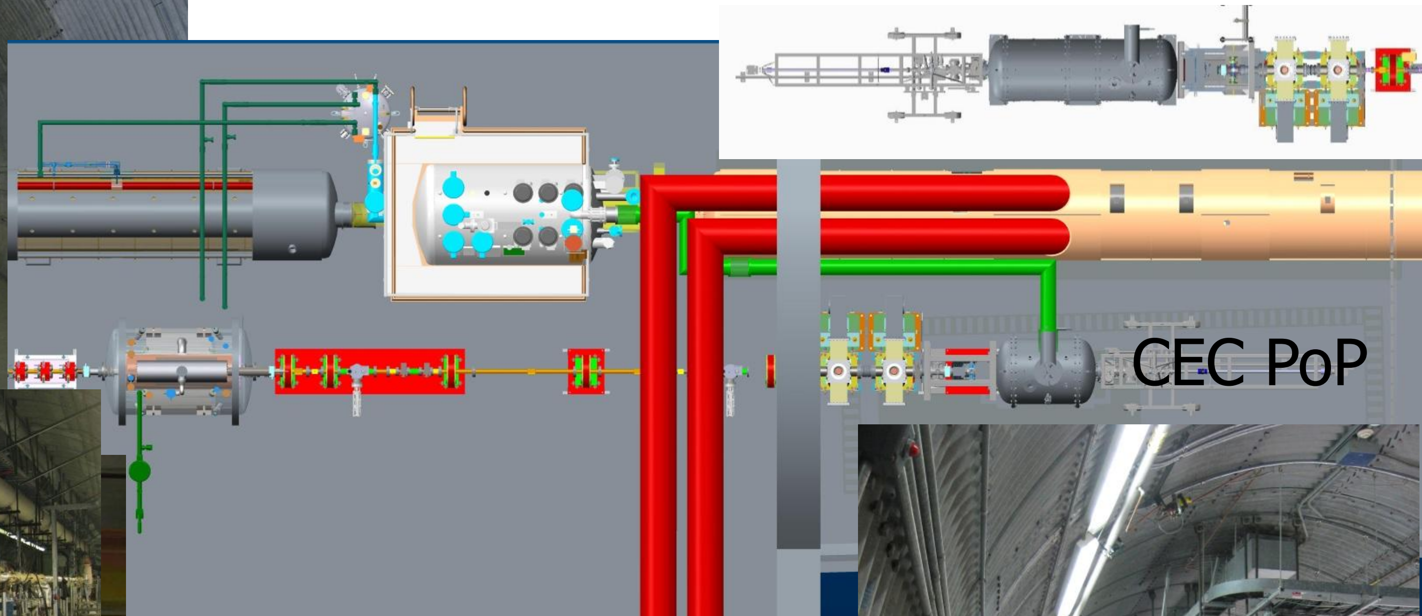
IP2



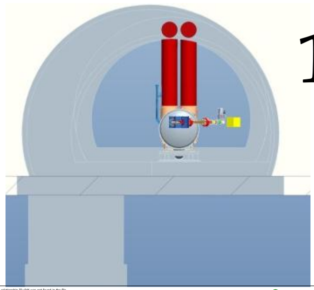


Sector 2



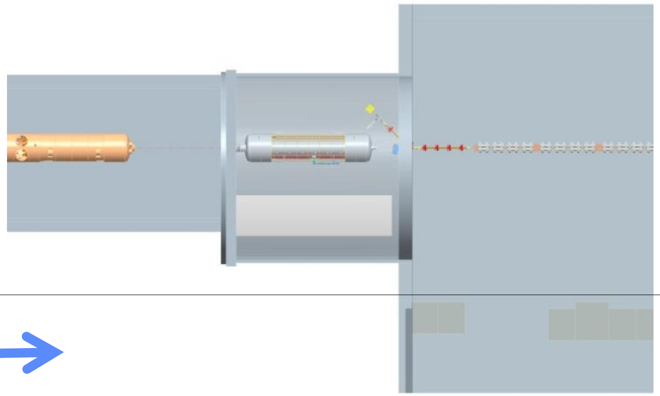


1:00 Tunnel



•24m to larger tunnel

•+ 32m to QHS



Offers more space
for longer cooling section
(gives some safety margin
for cooling)

Recent proposed changes

- **LEReC location: changed to Sector 1**
- **Electron beam injected at 40m from IP**
- **Cooling section: 42-61m from IP**
- **Matching to U-turn: 61-63.4m**
- **63.4m – compact U-turn**
- **Some diagnostics has to be moved to accommodate new cooling section in Sector 1:**

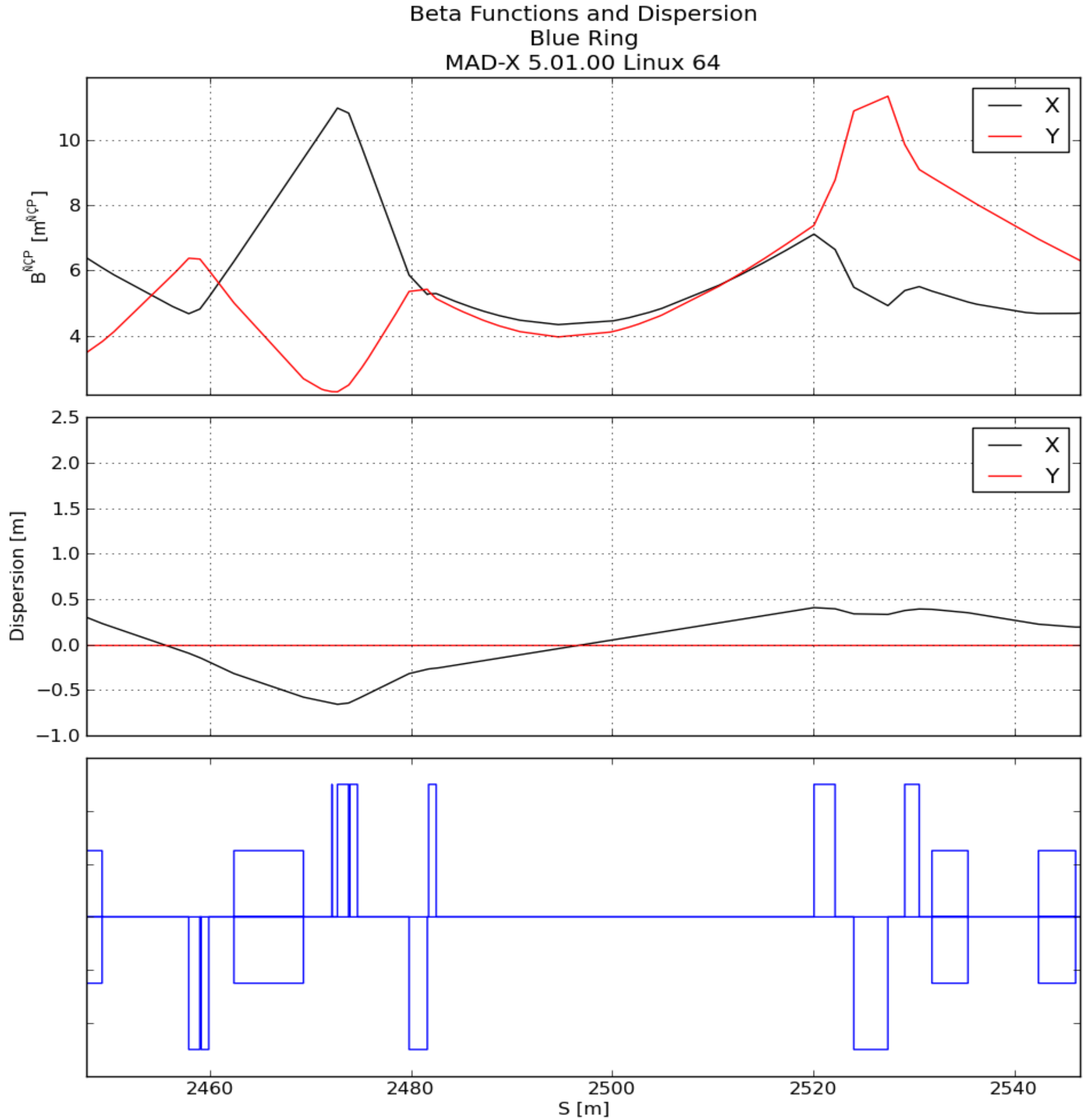
For example, IPM's and ARTUS kicker

Sector 1

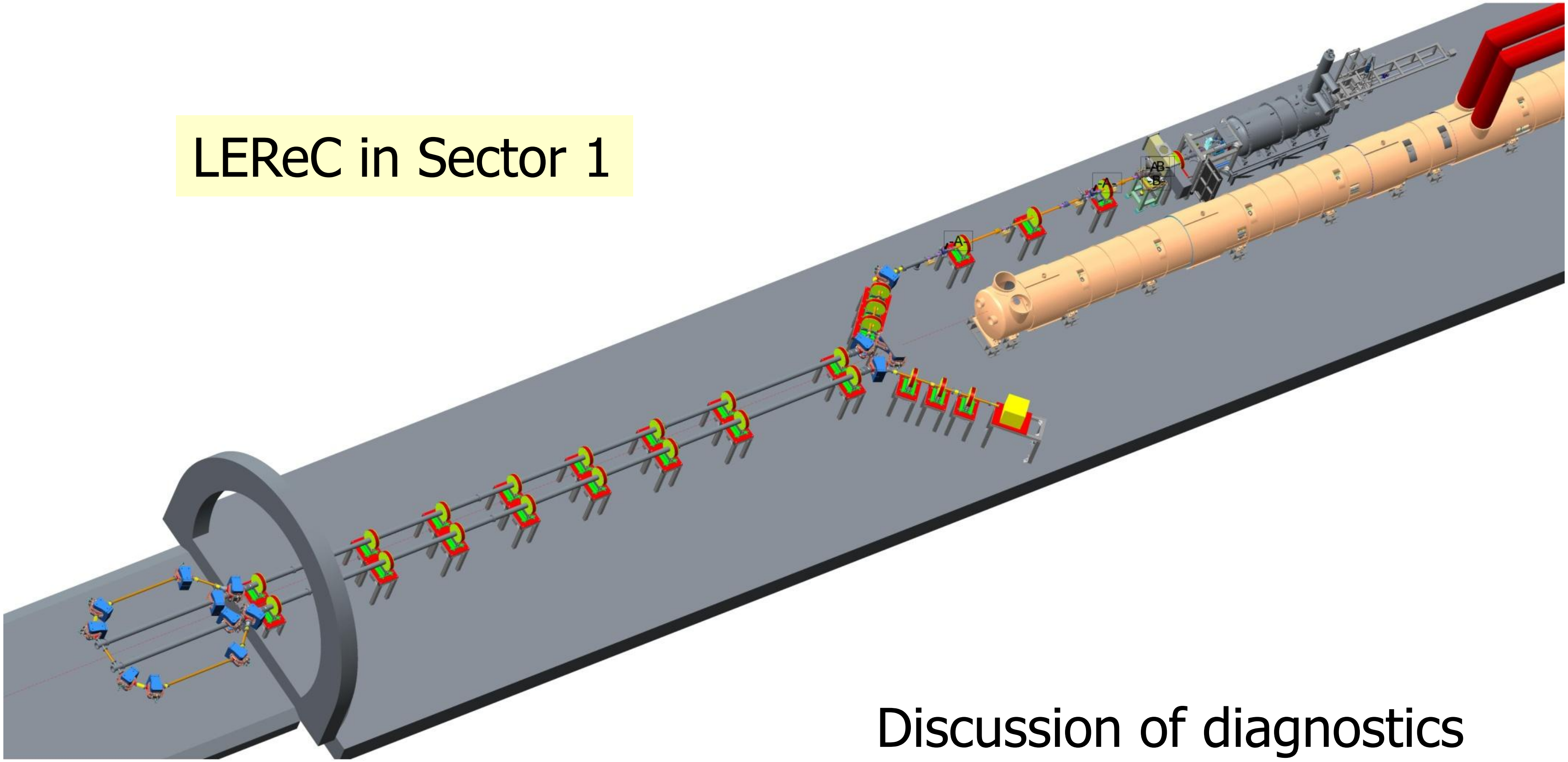
Present diagnostics

Meters from IP1	Yellow Outer Label	Name	Blue Inner Label	Name
38.4		Start of warm sector		Start of warm sector
38.7		10 Hz GOF Magnet		10 Hz GOF Magnet
40m			MBPM1	Moveable BPM (LF Schottky)
41.8	KKR-1	Quad pick-up		
41.8-43.5	KKR-2	PLL BBQ PU (Moveable)		
42.7	KKR-1		IPM H	B-Ionization PM Horiz
				Beam Loss Monitor
43.7			KKR-1	Hybrid Kicker
			Electron detector V	MCP & RHIC ED Vertical
45.7			EDH-ANL	Electron Detector Horizontal
46.1	TMKH	ARTUS Kicker Horizontal (start)		
48.1	TMKH	ARTUS Kicker Horizontal (end)		
	EDV	Electron detector V		
		Pin diodes (4)		
53.1	LM	Lumi-mon (only a cross)	GCK+TMKV	ARTUS Kicker V(or Bunch-by-Bunch longit damper?)
		Beam Loss Monitor	GCK+TMKV	ARTUS Kicker V(or Bunch-by-Bunch longit damper?)
55	IPM-V	Y-Ionization PM Vert		
63m				
65m		**New IPM-V ???**		**New IPM-H ???**

RHIC optics in cooling section will be different



LEReC in Sector 1



Discussion of diagnostics relocation is underway

LEReC timeline

FY2013 Physics approach/accelerator design approved – August 13-14, 2013 review.

FY2013 Design Safety Questionnaire (NEPA) and Davis-Bacon reviews - completed.

FY2013 Preliminary LEReC layout and lattice -completed.

FY2013 SCRF Cavities physics design and performance specifications - completed.

FY2014 Engineering "kick-off" meeting/assignments – October 4, 2013.

FY2014 DOE review (cost, schedule, risks) and approval: January 27-30 2014

FY2014 Engineering systems PDR, systems specifications, building requirements/system loads.

FY2014 Order SCRF Cavities/cryostat, SC solenoid, RF amplifiers, energy correction system.

FY2015 Detailed design – long lead procurements.

FY2015 Support building modification design/contracts (2015 shutdown modifications)

FY2015 Move RHIC beamline components (2015 shutdown modifications)

FY2016 Receive and test LEReC beamline and cryogenic components

FY2016 Shutdown installation LEReC beamline and cryogenic components

FY2017 Engineering commissioning for LEReC beamline and cryogenic components

FY2017 Final installation and commissioning of SRF accelerator with beam.

FY2018 Cooling commissioning and operations (Run-18)

Summary

- **Electron cooling promises to provide significant luminosity increase for Beam Energy Scan II.**
- **With present 28 MHz RHIC RF, desired 10-fold improvement from cooling could be expected only at highest energies. At lowest energies expected luminosity improvement could be about a factor of 3 only, due to significant transverse acceptance limitation and uncertainty whether beam lifetime will improve if only very weak transverse cooling is allowed due to the space-charge limitation.**
- **Operation with longer bunches allows us to apply significant transverse cooling which should improve beam lifetime at lowest energies and relax space-charge limitations. Thus it offers better path forward towards maximum luminosity gains with cooling.**
- **With long bunches (new low-frequency RF) and cooling one can expect to get closer to a 10-fold increase in luminosity even for lower energy points (exact improvement factor will depend on beam lifetime due to various effects and optimization of 3-D electron cooling in a collider).**