Bunched beam electron cooler for low-energy RHIC operation

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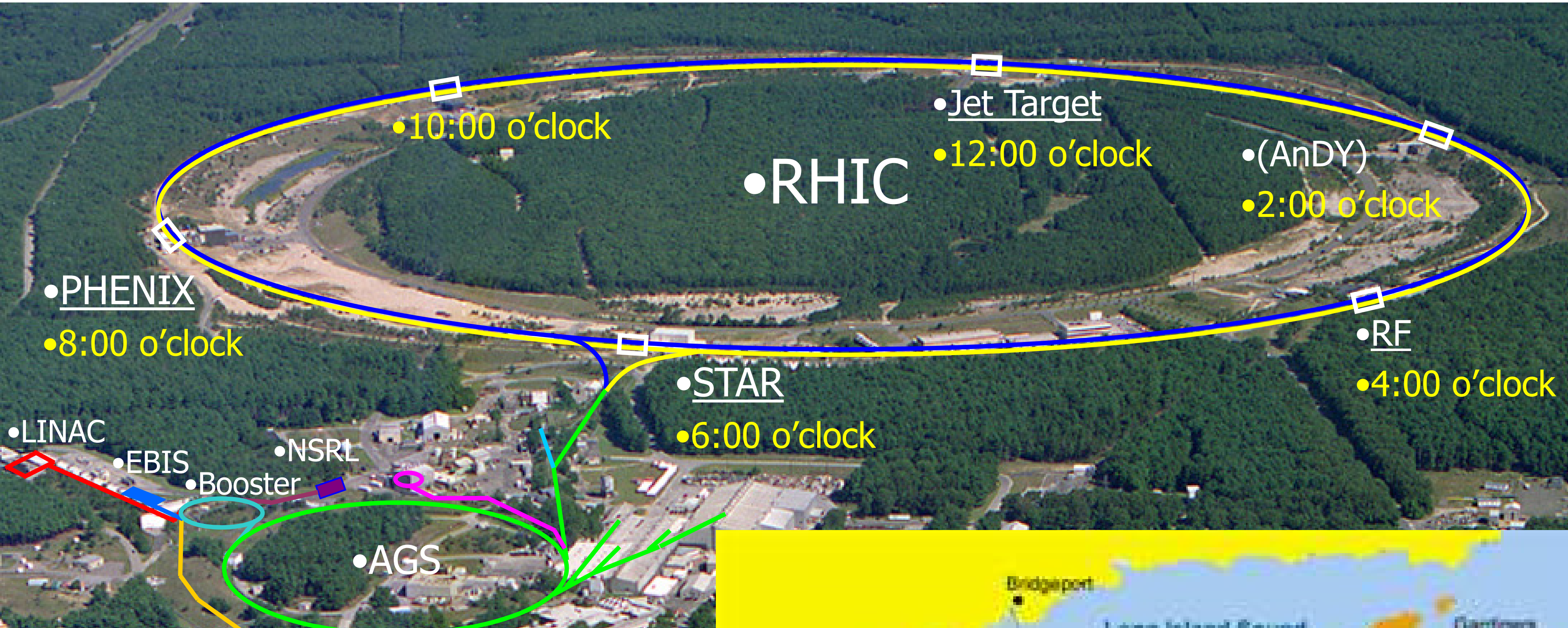
Relativistic Heavy Ion Collider (RHIC) & Collider-Accelerator complex (C-AD) @ BNL



Operated modes (beam energies):

Au–Au **3.8/4.6/5.8/10**/13.5/19.5/31/65/**100** GeV/n

d–Au* 100 GeV/n

Cu–Cu 11/31/100 GeV/n

p↑–p↑ 11/31/**100, 250** GeV

low-energy operation

Planned or possible future modes:

Au – Au 2.5 GeV/n

U – U 100 GeV/n

p↑ – Au* 100 GeV/n

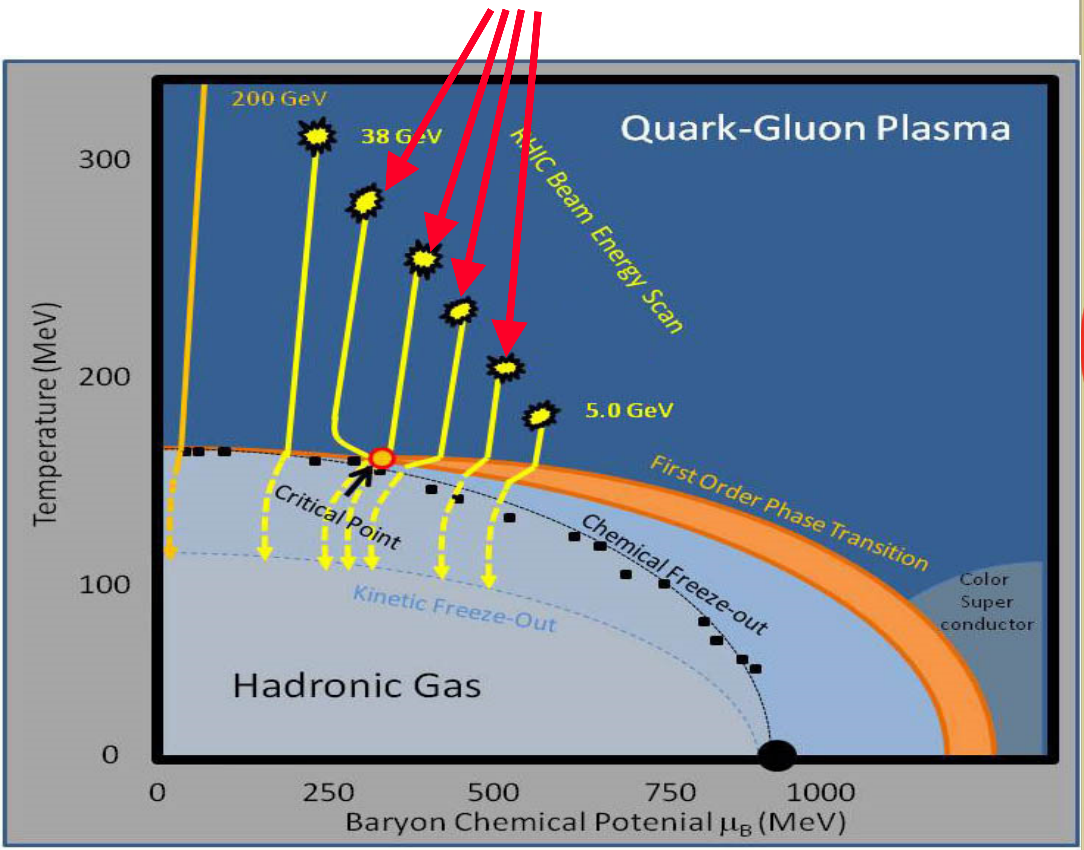
Cu – Au* 100 GeV/n (*asymmetric rigidity)

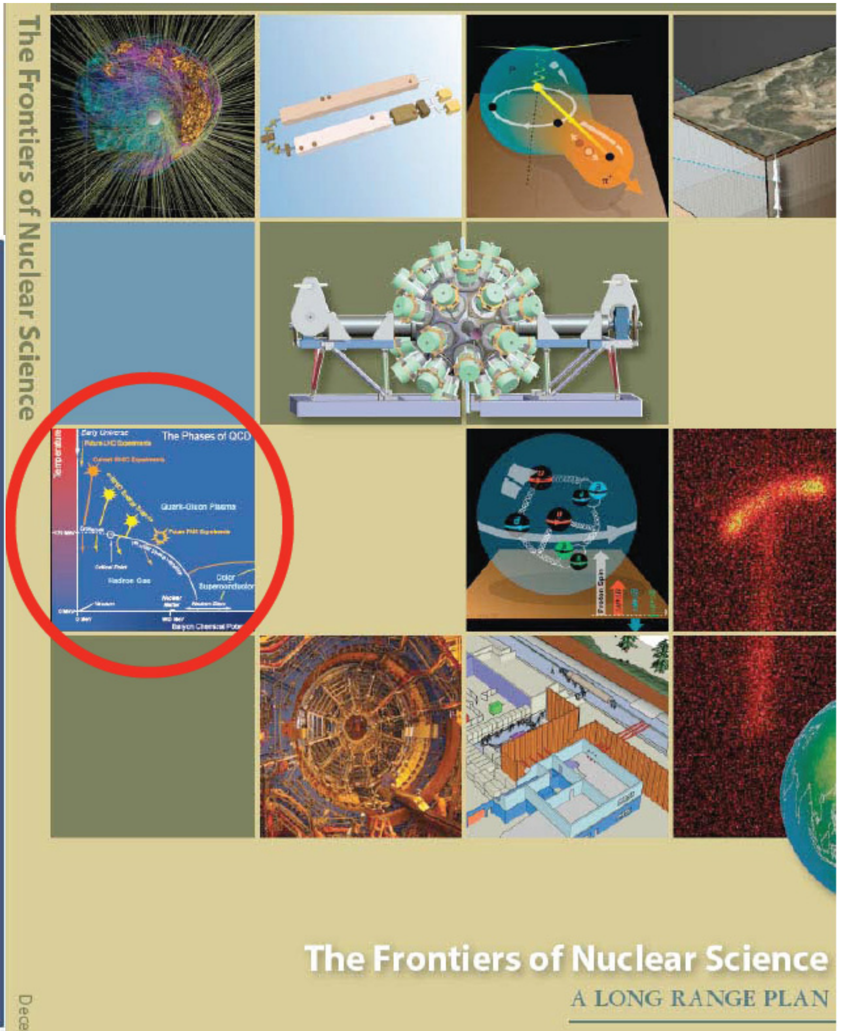
Low-Energy RHIC program:

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)





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.

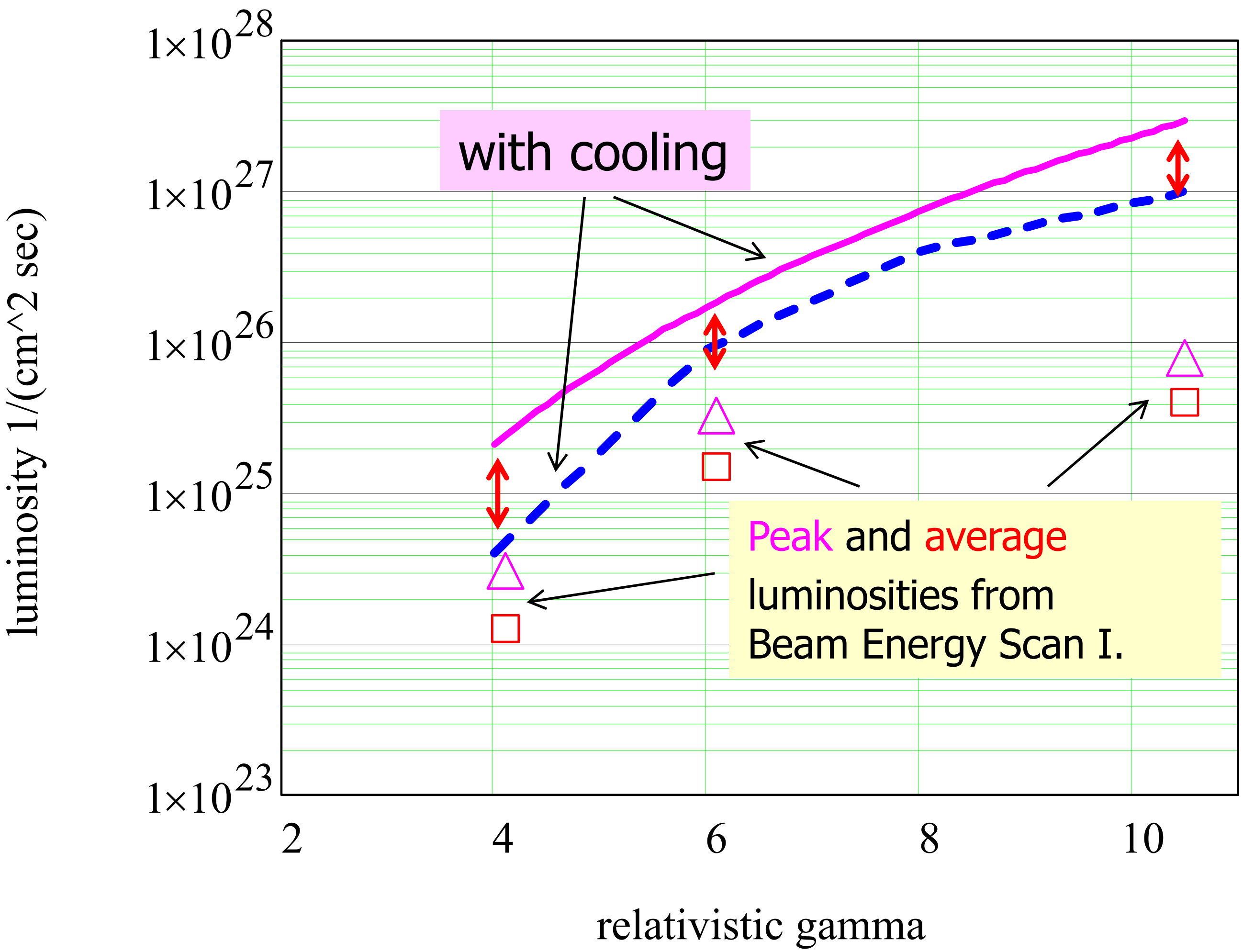
At low energies in RHIC luminosity has a very fast drop with energy (from γ^3 to γ^6). As a result, achievable luminosity becomes extremely low for lowest energy points of interest.

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

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.

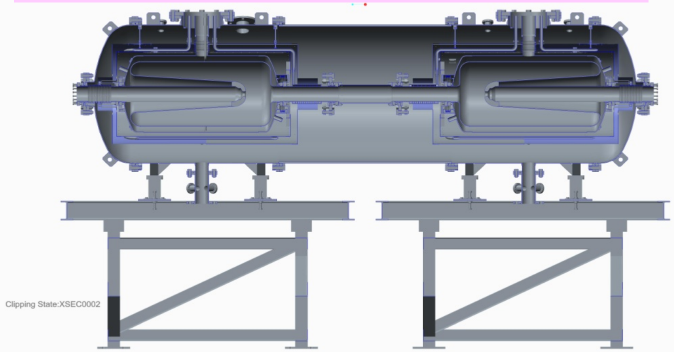
Low-Energy RHIC electron Cooler (LEReC)

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

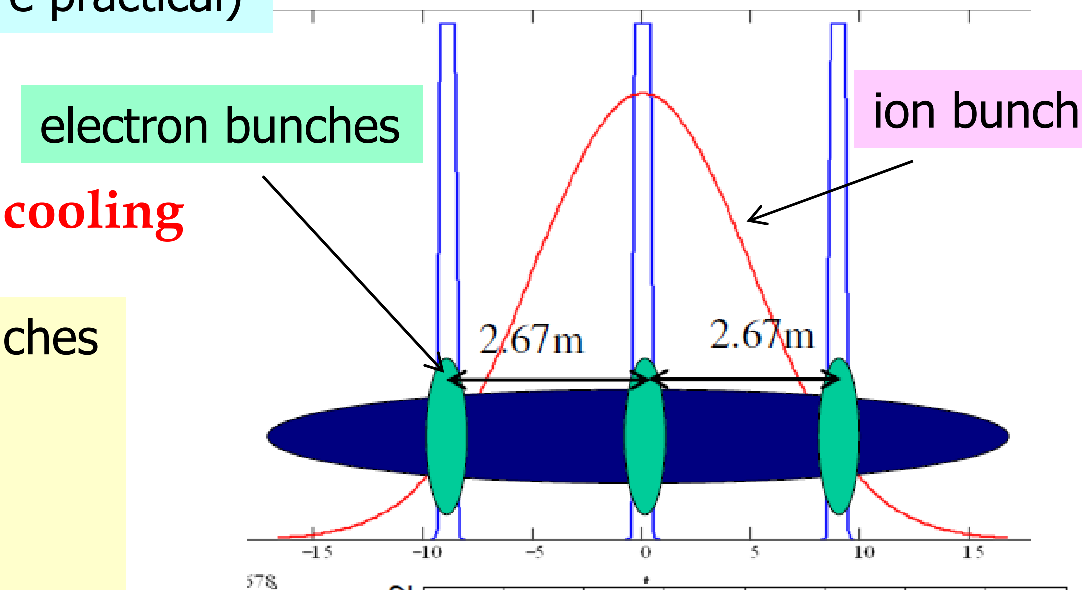
A natural way for high-energy cooling
(when RF acceleration becomes more practical)

LEReC:

- **First bunched beam electron cooling**

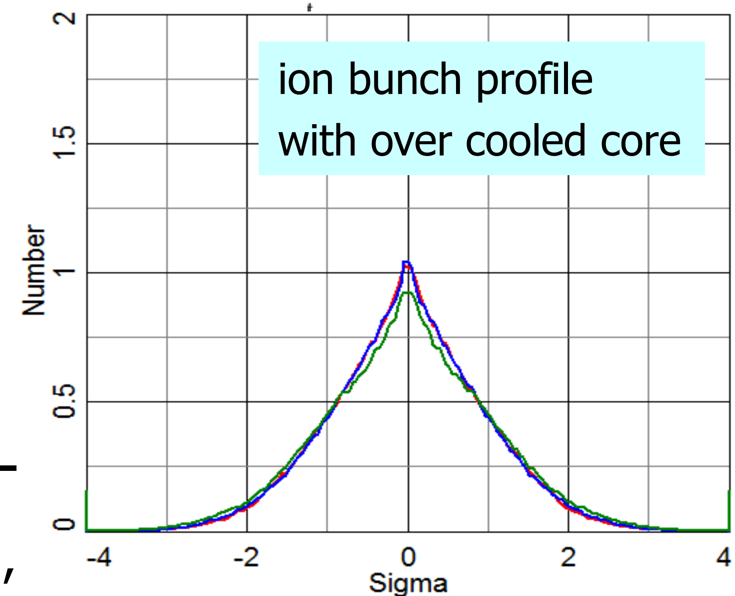
1) Putting a "train" of electron bunches on a single ion bunch.

2) Possibly "painting" through ion bunch length.

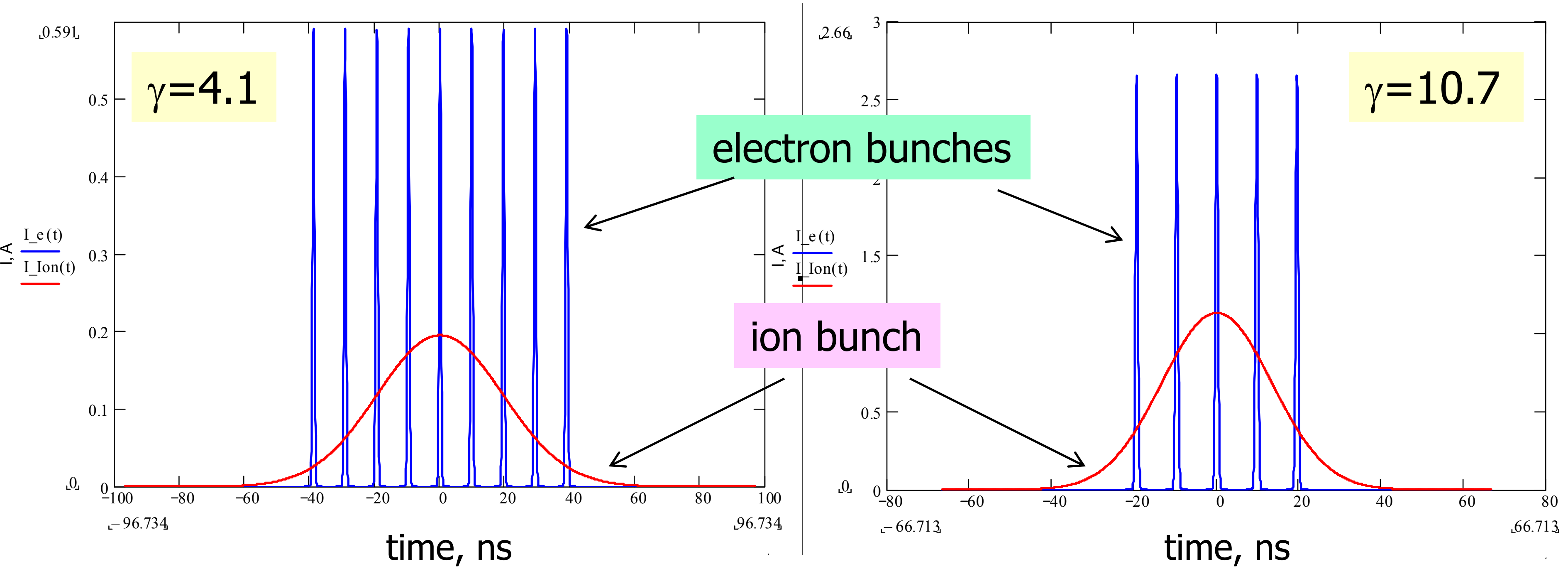


- **First electron cooling in a collider**

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

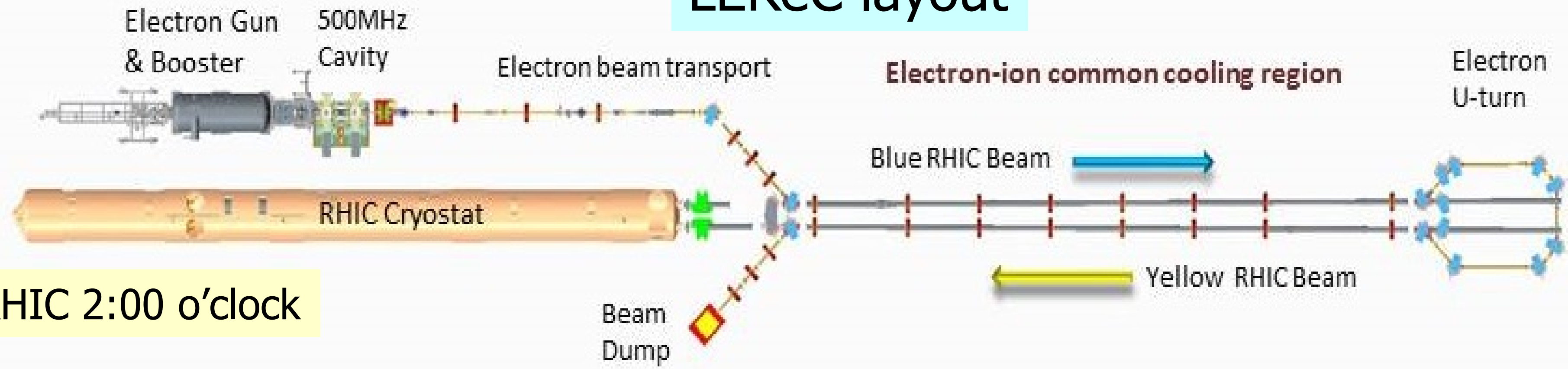


γ=4.1, Q=0.45 nC/bunch , length=0.75 ns, I_peak=0.6A, (bunches 12 ns apart)

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

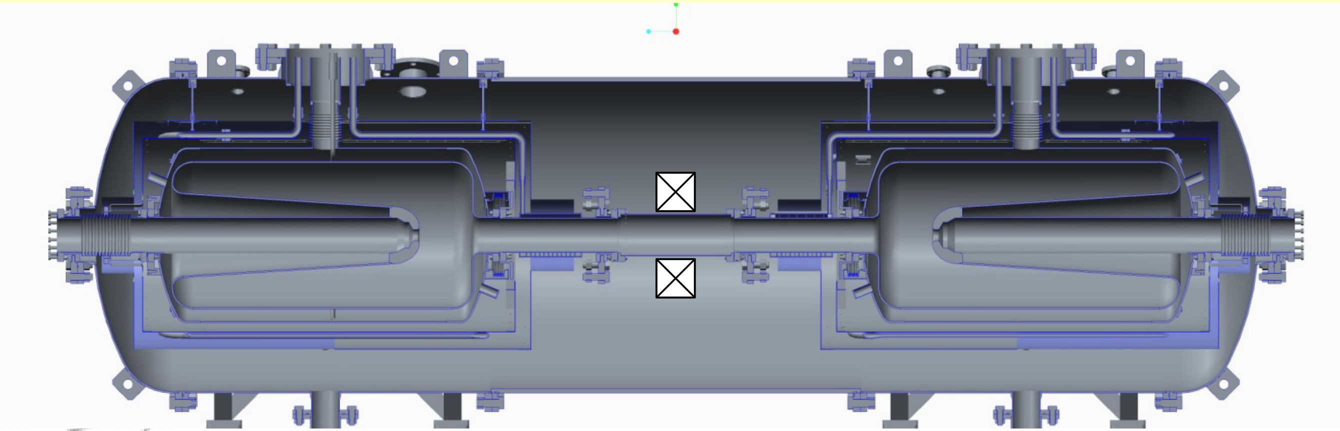


RHIC 2:00 o'clock

- **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 (6th 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

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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 experiment.

LEReC: un-magnetized electron cooling

For LEReC based on RF electron beam continuous magnetic field (in cooling section) is not required. 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.

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

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

- **Requires strict control of transverse angular spread of electrons in the cooling section.**

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

- **LEReC: need to keep total contribution (including from emittance, space charge, remnant magnetic fields) below 150 μrad (for γ=4.1).**

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

LEReC parameters

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 (5x1.4 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.

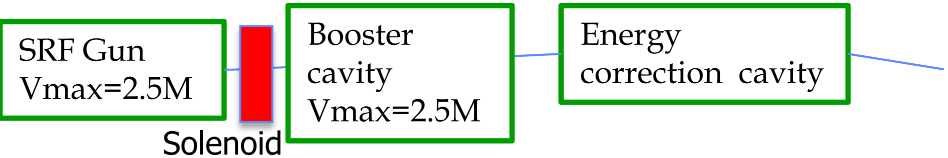
- Keeping low transverse angular spread for the electron beam in the cooling section with a proper engineering design.

- 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.

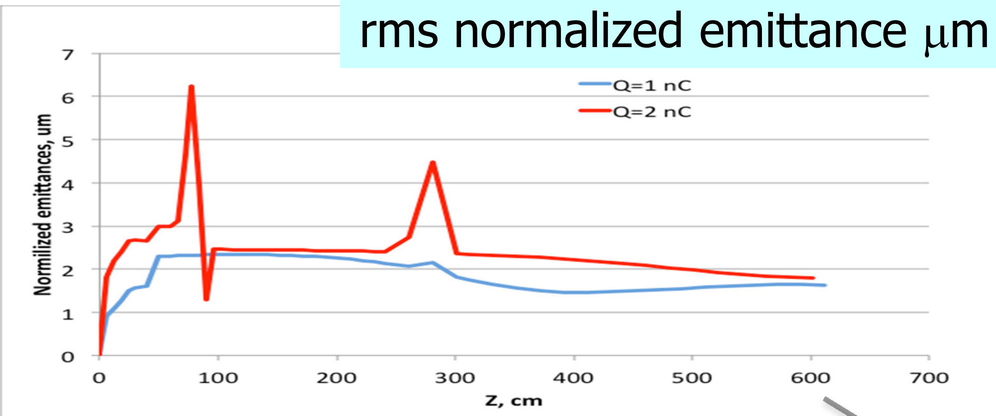
Example of beam dynamics in accelerator *PARMELA* simulation



Electron bunches:
- Q=1 and 2 nC
- T_FWHM=0.75 nsec
- R_cathode=2 mm

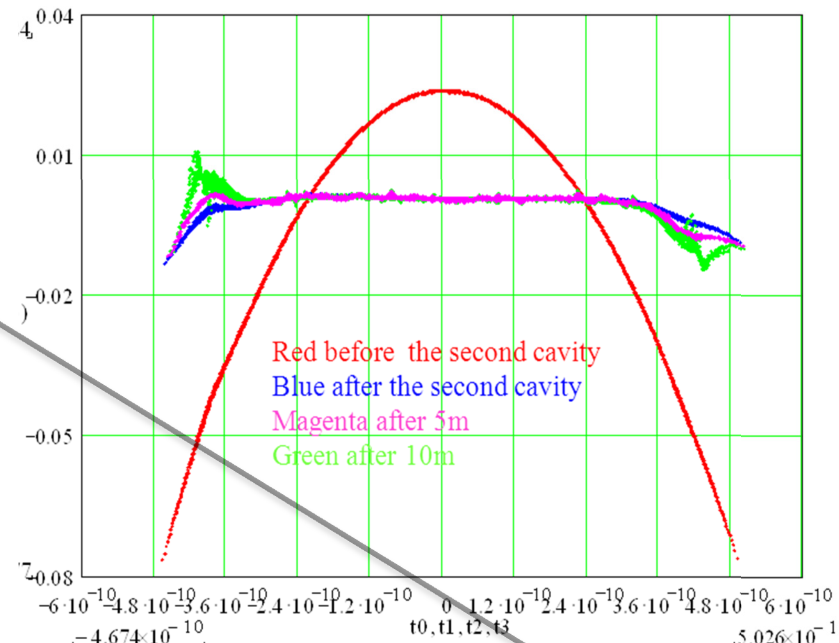
D. Kayran

rms normalized emittance μm

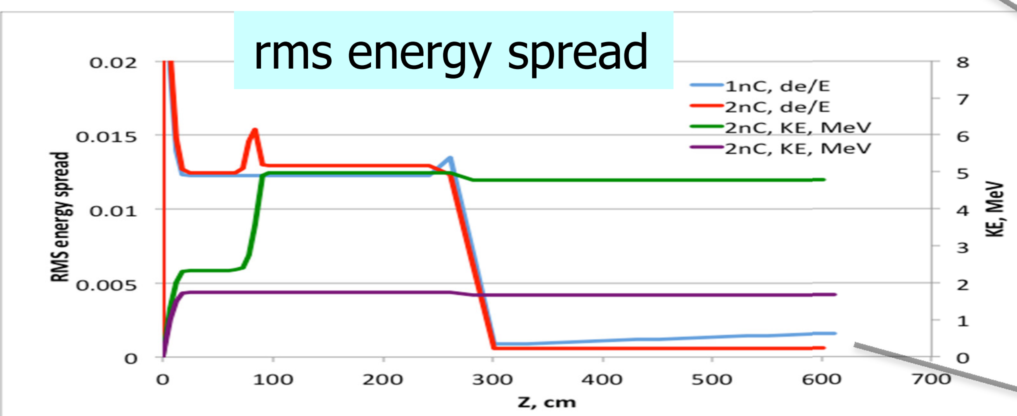


For Q=1nC (γ=4) and Q=2nC (γ=10.7)

Longitudinal phase space (γ=4.1):



rms energy spread



For Q=1nC (γ=4.1) and Q=2nC (γ=10.7)

γ	Q, nC	ε, um	de/E
4.1	1	1.8	7e-4
10.7	2	2.1	5e-4

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Requirement on magnetic field in the cooling section

γ=4.1:

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

Passive (mu-metal shielding) or active control with correction coils to suppress B_residual below required level in free space between the solenoids.

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 2 m of cooling section

Residual magnetic field from solenoids in cooling region:

W. Meng

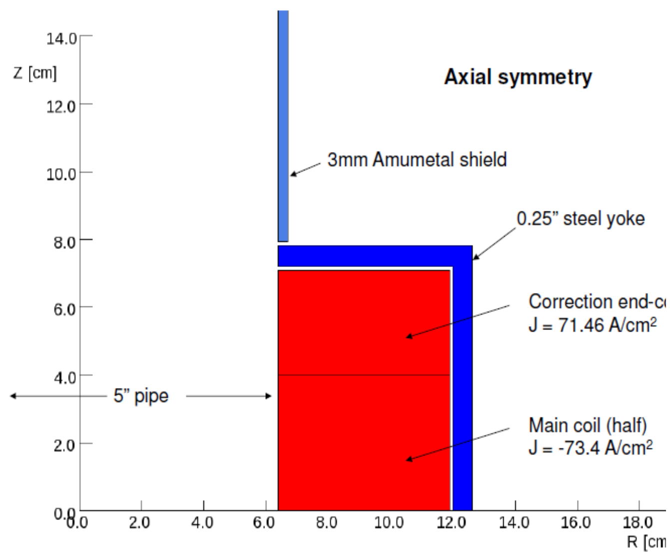
$$B_z < 1G$$

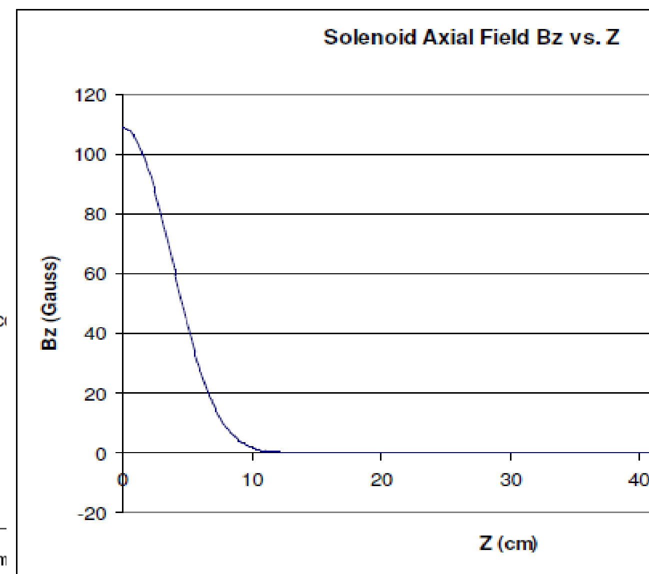
at z=10.7 cm

FNAL

shielding

Solenoid design





Some 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).

Summary

1. Electron cooling can provide significant luminosity improvement for low-energy RHIC operation.
2. Present electron cooler design is based on SRF gun bunched beam cooling. Electron accelerator is similar to Coherent Electron Cooling Proof-of-Principle accelerator, which is being presently installed in RHIC, and will use the same cryo system developed at RHIC 2:00 o'clock region.
3. New low-frequency RF system (4.5 MHz) is being planed for low-energy RHIC operation with electron cooling, to maximize potential luminosity gains and provide good beam lifetime.

- Implementation of electron cooling for RHIC operation at low energies is expected to take about 4 years.

Thank you.