Electron Cooling for Low-Energy RHIC Operation

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Low-energy RHIC operation

There is substantial and growing interest in RHIC heavy ion collisions with c. m. energy in the range $\sqrt{s_{NN}}$= 5-50 GeV/nucleon

- Corresponds to Au beams in RHIC with γ=2.7 to 26.8
- Present injection of Au ions in RHIC is at γ=10.5

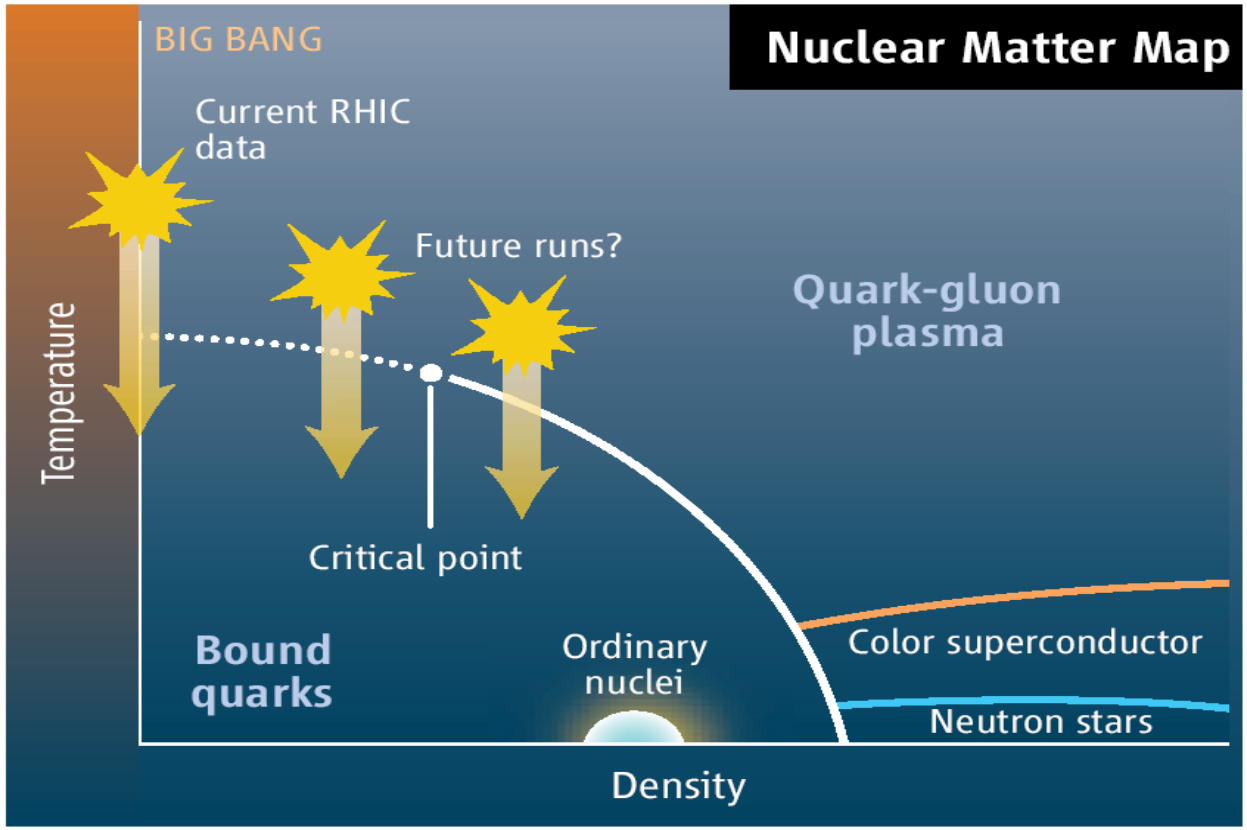
RIKEN workshop (BNL, March 9-10, 2006):

"Can we discover the QCD critical point at RHIC?"

Suggested energy scan: $\sqrt{s_{NN}}$ = 5, 6.3, 7.6, 8.8, 12.3, 18, 28 GeV/n

Two 1-day test runs were done in 2006 and 2007 at low-energies to access the challenges and to make projections for low-energy operation (Todd Satogata et al., PAC07).

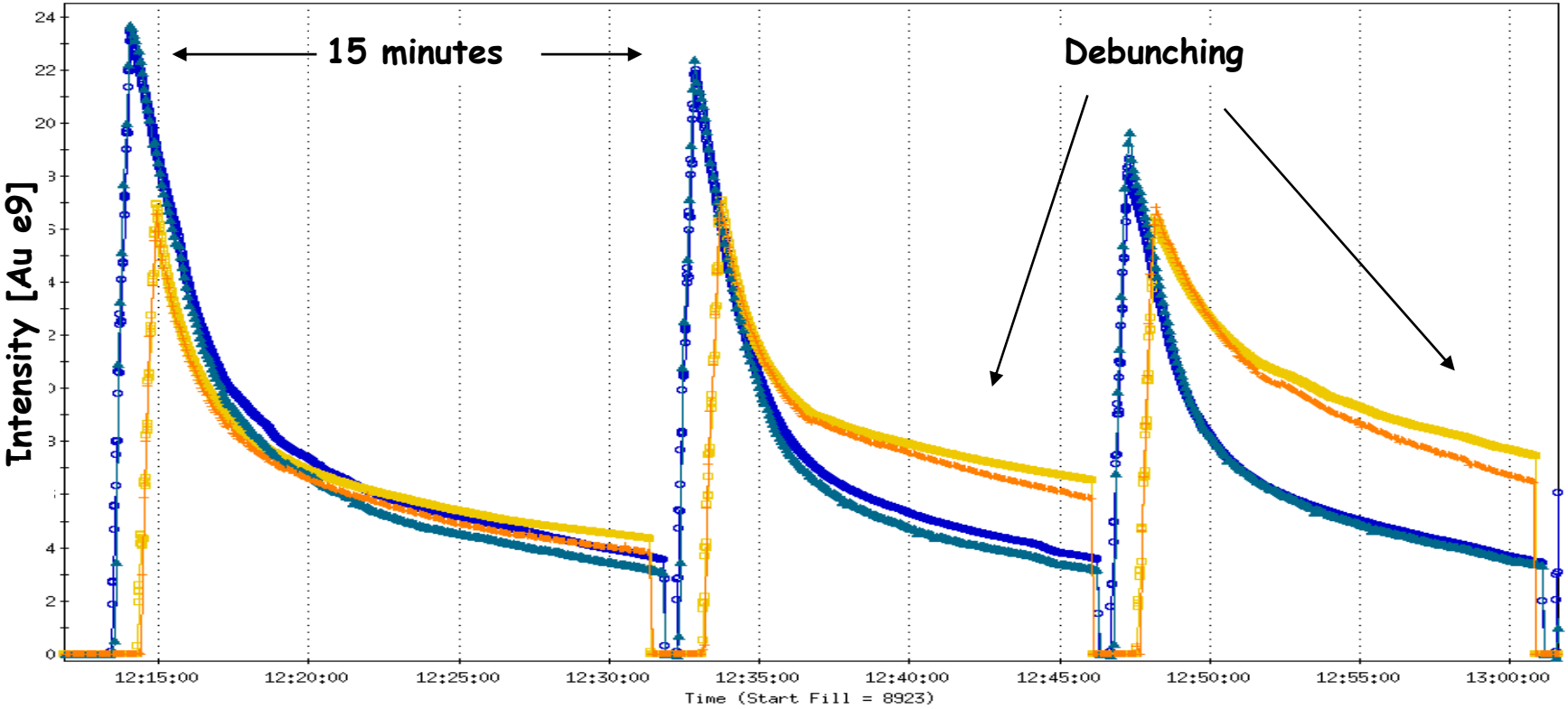
Low-energy RHIC operation: 2.5-25 GeV/n



Landmark study. Physicists have seen a smooth transition from bound quarks to quark-gluon plasma (dotted line). They now hope to find the point beyond which the transition becomes violent (white line).

A. Cho, Science, 312 (14 Apr 2006)

Low–energy RHIC operation: June 11, 2007 test Run at $\sqrt{s}$ = 9.2 GeV/n (γ=4.93)



T. Satogata et al. PAC07

RHIC Low Energy Program Plans

- **RHIC low-energy operation is challenging**

  - RF acceptance, IBS, vertex, etc.

- **Tests of low-energy operation were successful**

  - At $\sqrt{s_{NN}}$=9.2 GeV/n produce 100-700 Hz BBC rates in STAR

  - Peak luminosity was about 1.5×10^{24} $cm^{-2}s^{-1}$ (for γ=4.93)

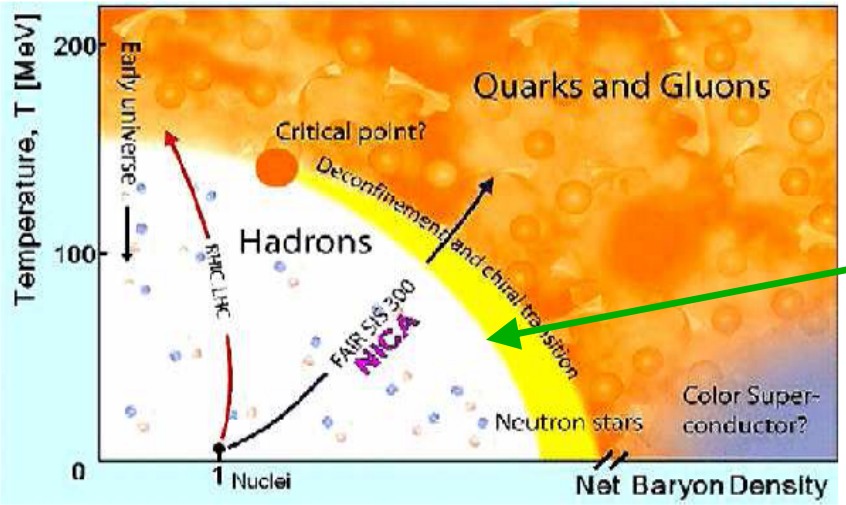
- **RHIC Program Advisory Committee recommended 14 week operation in 2009-2010 (Run-10).**

  - Obtaining minimum requested 5M events per energy point seems feasible (this low luminosity run is proposed for Run-10).

  - No RHIC upgrades with e-cooler in RHIC is presently planned on this time scale.

  - Obtaining higher statistic 50-500M (already requested by some of the experiments) in the future may be possible with electron cooling in RHIC at these energies.

Low-energy physics (FAIR, NICA) – RHIC beyond 2010 ?



High statistics/ luminosity is needed.

deconfinement and/or chiral symmetry restoration phase transitions

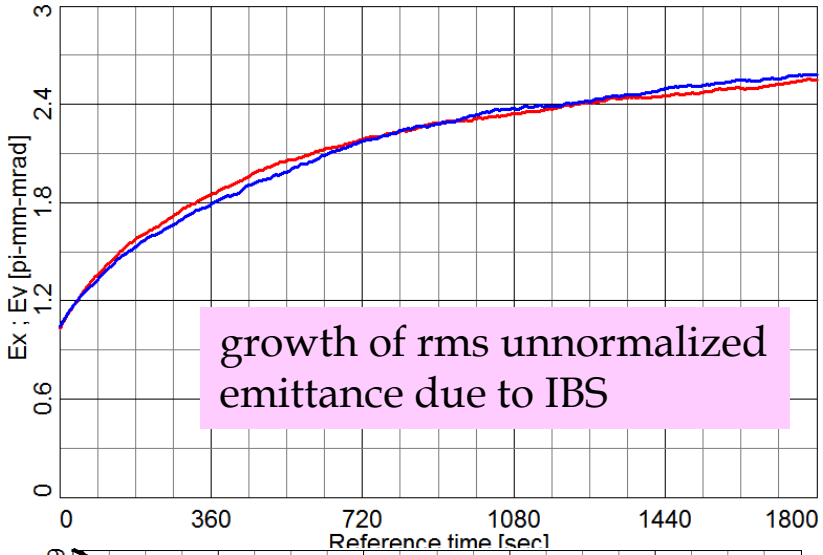
the first stage

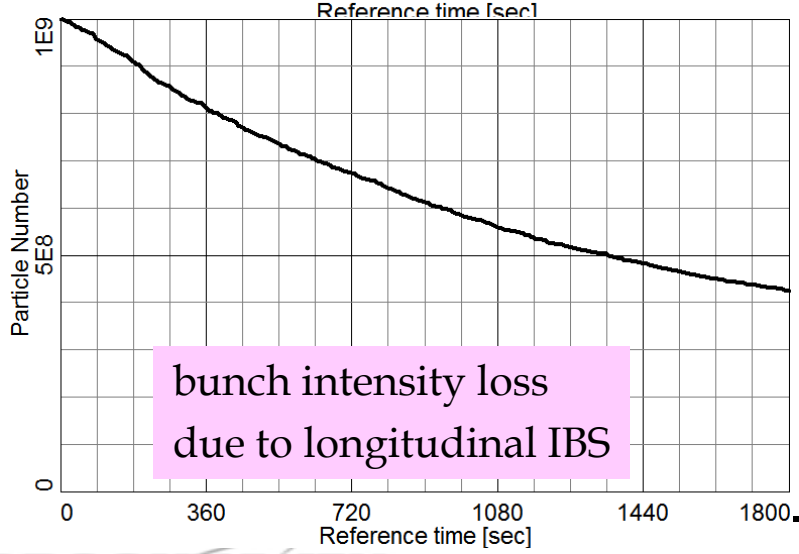
- Multiplicity and global characteristics of identified hadrons including multi-strange particles
- Fluctuations in multiplicity and transverse momenta
- Directed and elliptic flows for various hadrons
- HBT and particle correlations

the second stage

- **Electromagnetic probes (photons and dileptons)**

IBS for Au ions in RHIC for lowest energy point





Simulation parameters

Parameters	Value
Kinetic energy of Au ions, GeV/nucleon	1.57
Relativistic γ	2.68
Bunch intensity, 10^9	1.0
Rms momentum spread	4×10^{-4}
Rms bunch length, cm	155
Rms emittance (unnormalized), μm	1.04
RF harmonic	387
RF voltage, kV	300

Limitations

- At low energies IBS growth can be easily counteracted by Electron Cooling system.
- In fact, if IBS would be the only limitation, electron cooling would allow cooling until beam equilibrium between cooling and IBS is reached, which would result in a dramatic luminosity increase.
- However, the strongest limitation on achievable ion beam peak current at these lowest energies is expected to be given by space-charge effects. This prohibits application of strong electron cooling.

What is acceptable tune-shift for good life time in RHIC with collisions?

We do not know – it is machine specific and depends on many things.

This question could be explored by measurement during the test run for low-energy (planned for March 10-11, 2008).

At injection energy, with space-charge tune shift of dQ=0.01, life time in RHIC is good.

In June 2007 test run with dQ=0.03 the life time was bad although it could be related to other effects as well.

- for example, in SPS, life time of few minutes with dQ=0.1 was reported

- in LEAR, electron cooling allowed to increase dQ to 0.1 in operation

- Presently, we assume that dQ=0.05-0.07 as a limit for RHIC (since we would like to have long life time in RHIC). Perhaps, cooling can help to operate at slightly larger space-charge tune shift, if cooling times are significantly less than characteristic growth times.

Incoherent space-charge tune shift for lowest energy points in RHIC

γ	h (rf harmonic number)	$\varepsilon_{95\%,n}$ μm	N, $\times 10^9$ (ion bunch intensity)	$\Delta Q_{sc,G}$ (Gaussian distribution)	$\Delta Q_{sc,fb}$ (full bucket, parabolic distribution)
2.67	387	15	0.5	0.12	0.07
3.37	375	15	1	0.15	0.08
4.41	369	15	1	0.1	0.05
4.7	366	15	1	0.07	0.04
6.6	360	15	1	0.04	0.02

Possible scenarios under constraint of space-charge limit

1. Colliding coasting beam would reduce space-charge tune shift and, with electron cooling, would allow significant luminosity increase. However, present detector system is not set for such approach. Discussion with physicists is in progress.
2. (working scenario, shown in next slides)

   Operating with bunched beam at space-charge limit with 110 bunches in the machine - favored by the experiments, since they require 100 nsec bunch spacing for now.

RHIC low-energy electron cooler energies of interest

The lowest energy points from proposed energy scan ion kinetic energies: E_{ki}=1.57, 2.2, 2.9, 3.45, 5.2 GeV/nucleon can benefit the most from electron cooling.

These corresponds to electron beam kinetic energies:

E_{ke}=0.86-2.8 MeV

Cooling at such energies was demonstrated (Recycler cooler at FNAL)

estimates by T. Satogata

$\sqrt{s_{NN}}$ [GeV]	μ_B [MeV]	<BBC Rate> [Hz]	Days/ Mevent	# events	# beam days
4.6	570	3 (~5)	9 (3)	5M	45 (15+1)
6.3	470	7 (~50)	4 (0.3)	5M	20 (3+1)
7.6	410	13 (~150)	2 (0.1)	5M	10 (1+1)
8.8	380	20 (300)	1.5 (<1)	5M	7.5 (1+1)
12	300	54 (~1000)	0.5 (<1)	5M (>5M)	2.5 (1+1)
18	220	>100 (>1000)	0.25 (<1)	5M (>5M)	1.5 (1+1)
28	150	>100 (>1000)	0.25 (<1)	5M (>5M)	1.5 (1+2)

Options for the cooler

1. DC cooler

   1.1 Using Recycler (FNAL) e-cooler when it becomes available – operates at 4.3 MeV. Can go up to 5 MeV. However, requires a lot of space (height) - new building to host Pelletron, modifications for operation at low energies is needed, etc.

   1.2 Building new 3MeV DC electron cooler.

2. RF gun cooler:

   2.1 Using 703 MHz gun and cooling with a pulse of electron bunches (20 low-charge 50pC bunches per pulse) to reduce space-charge effects is a single bunch (studies by D. Kayran et al.).

   2.2 Using 56 MHz cavity to produce long electron bunch with required parameters for cooling (studies by X. Chang et al.).

at the end most cost effective option will be selected

Two approaches of RHIC Low-Energy Cooler were considered to counteract beam loss on recombination.

1. **Magnetized:**

   Requires large electron emittance to control recombination. As a result, requires strong solenoid to control such large emittance.

   field about B=0.5T; solenoid length 10-20 meters

2. **Non-magnetized:**

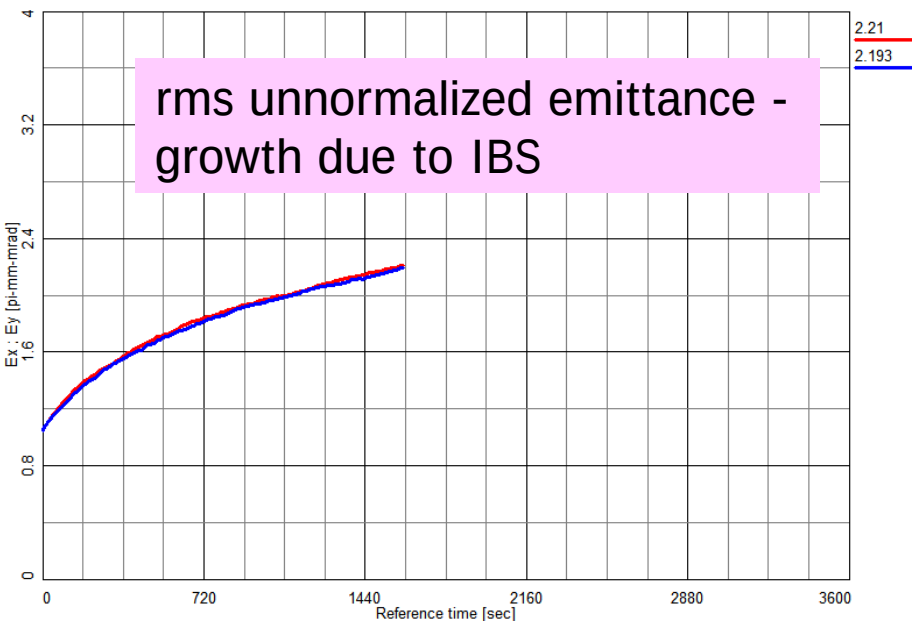
   Uses weak undulator, as in RHIC-II cooler design, to control recombination.

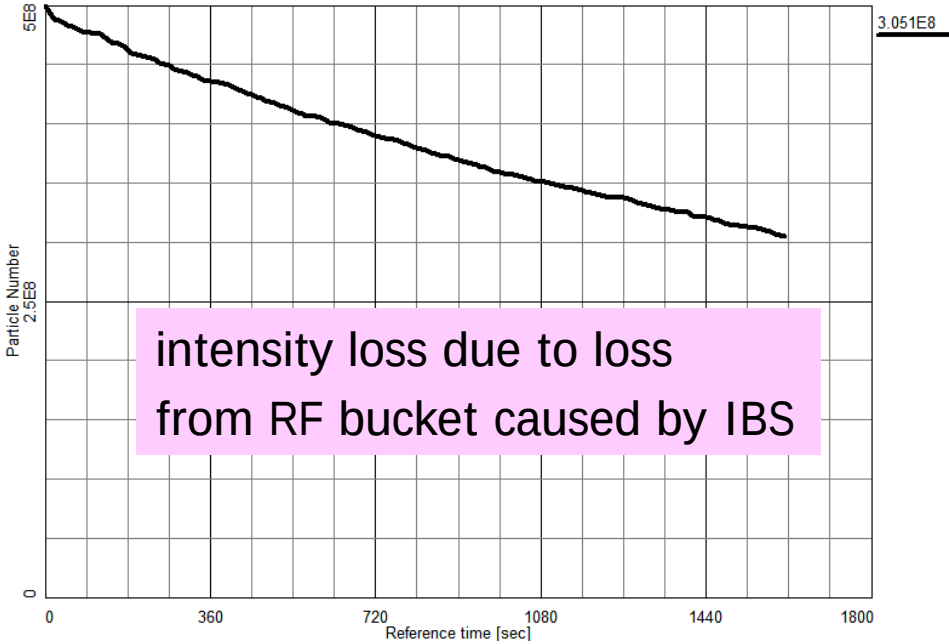
   undulator field about B=3G, period λ=8cm

At this point, non-magnetized approach with weak undulator appears to be a more robust approach. However, accurate consideration of beam transport and various collective effects, as was done for RHIC-II, should be performed before the final decision is made.

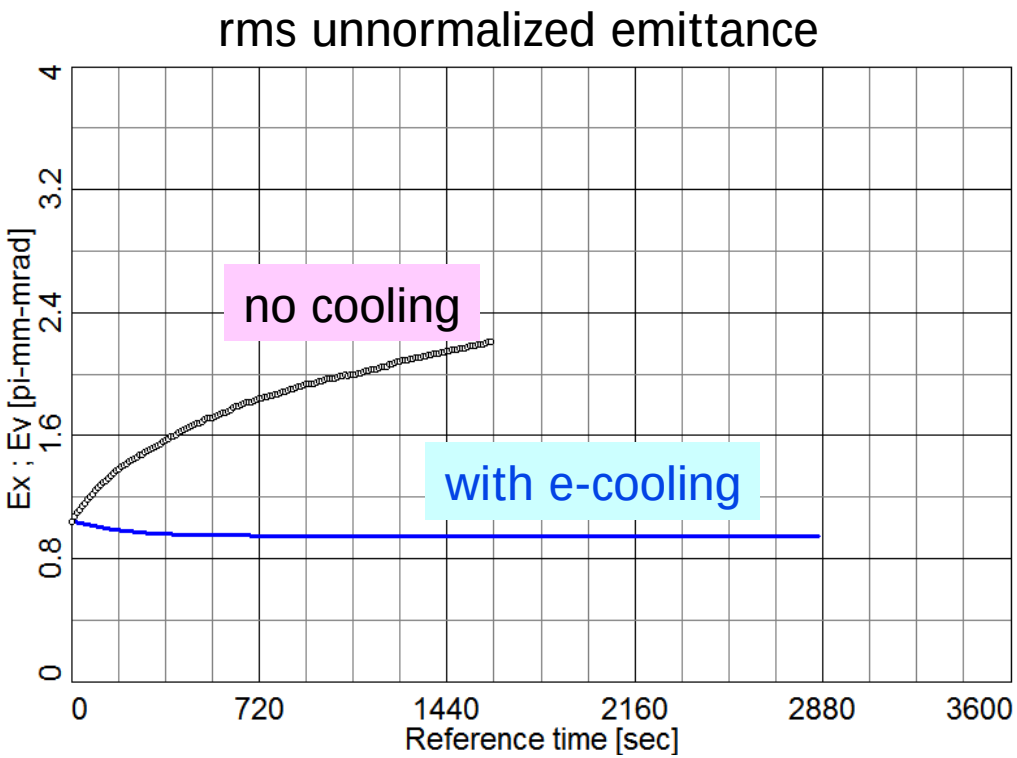
IBS simulations for lowest energy point: γ=2.67 (kinetic energy of electrons 0.87 MeV)

Initial ion beam parameters: N=0.5e9, ε=15μm (95%,n), full-bucket (tune shift dQsc=0.07).





γ=2.67. Simulations of emittance evolution without and with electron cooling which just compensates IBS.



γ=2.67 (N_ion=0.5e9)

E-cooler parameters needed to just counteract IBS:

L=10 m – length of cooling section

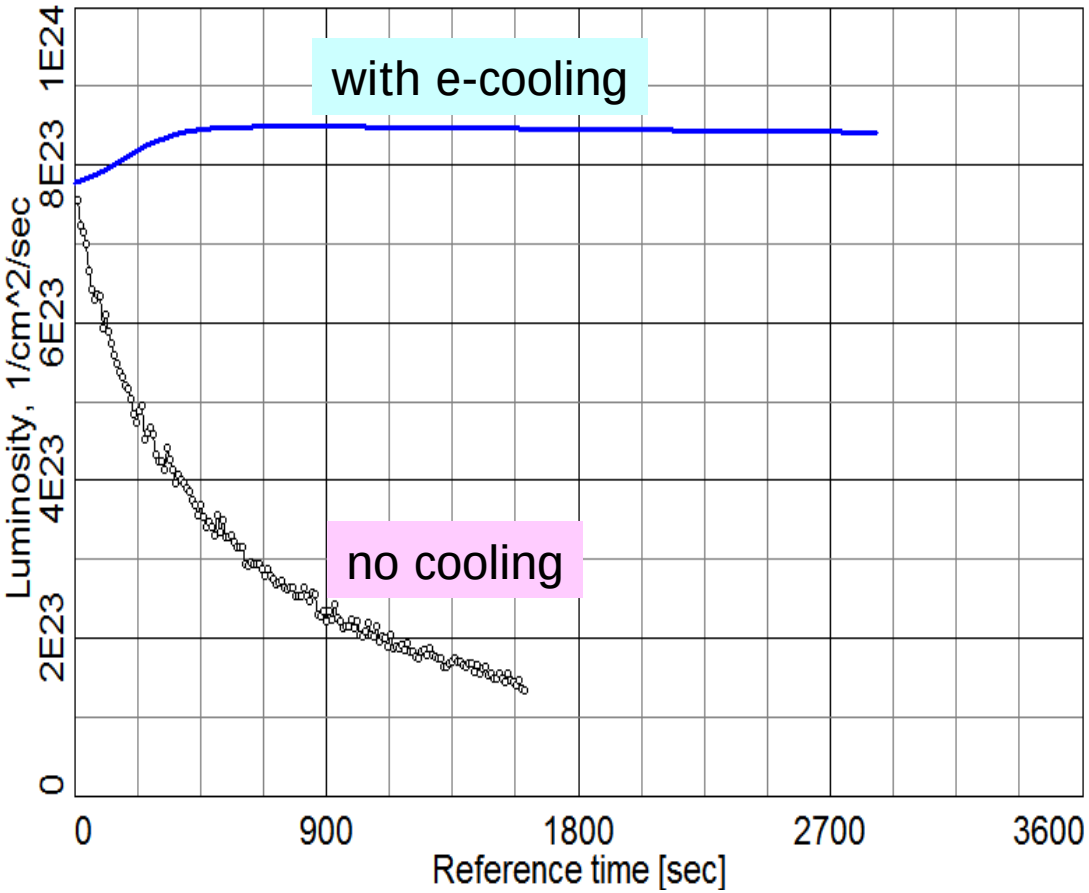
Q=2nC; $\varepsilon_{rms,n}$=6 μm; rms dp/p=5e-4

or

Q=1nC, $\varepsilon_{rms,n}$=3 μm, rms dp/p=5e-4

γ=2.7 – lowest energy point.

Luminosity with and without electron cooling.



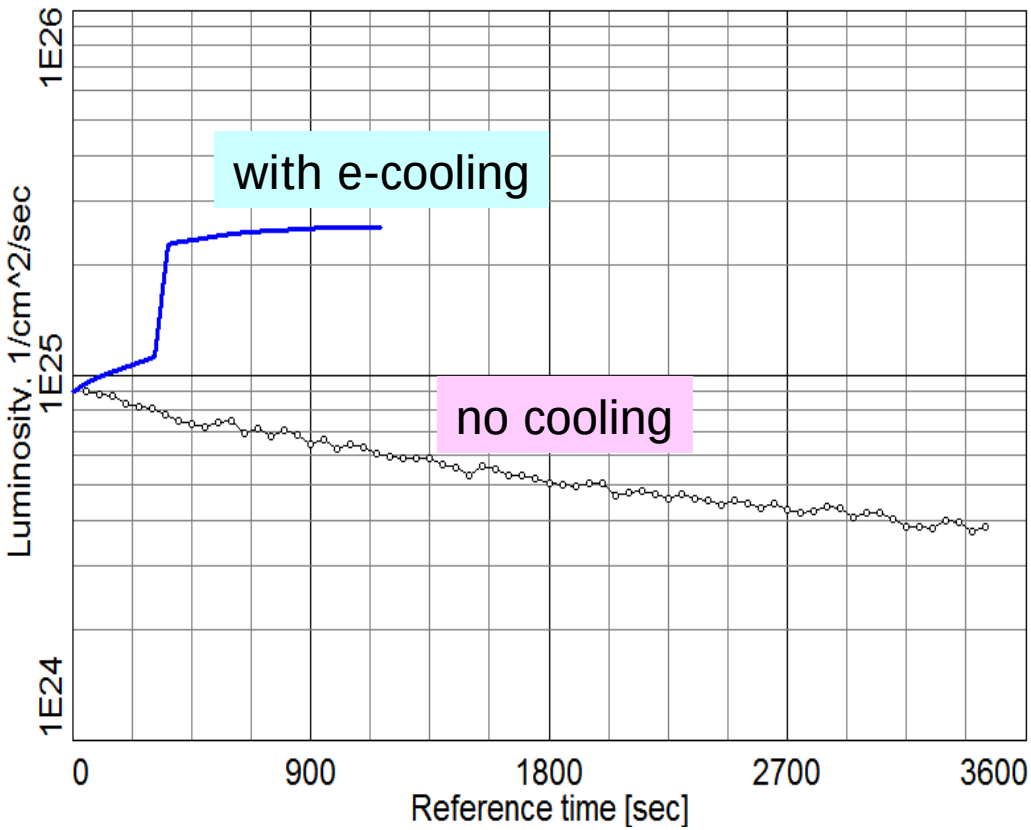
Assuming 15 minutes stores without cooling.

Electron cooling gives factor of 3 in integrated luminosity.

If, with cooling, one can operate with larger space-charge tune shift, additional factor in luminosity improvement may be possible.

γ=6.6 – highest energy point of the cooler planned.

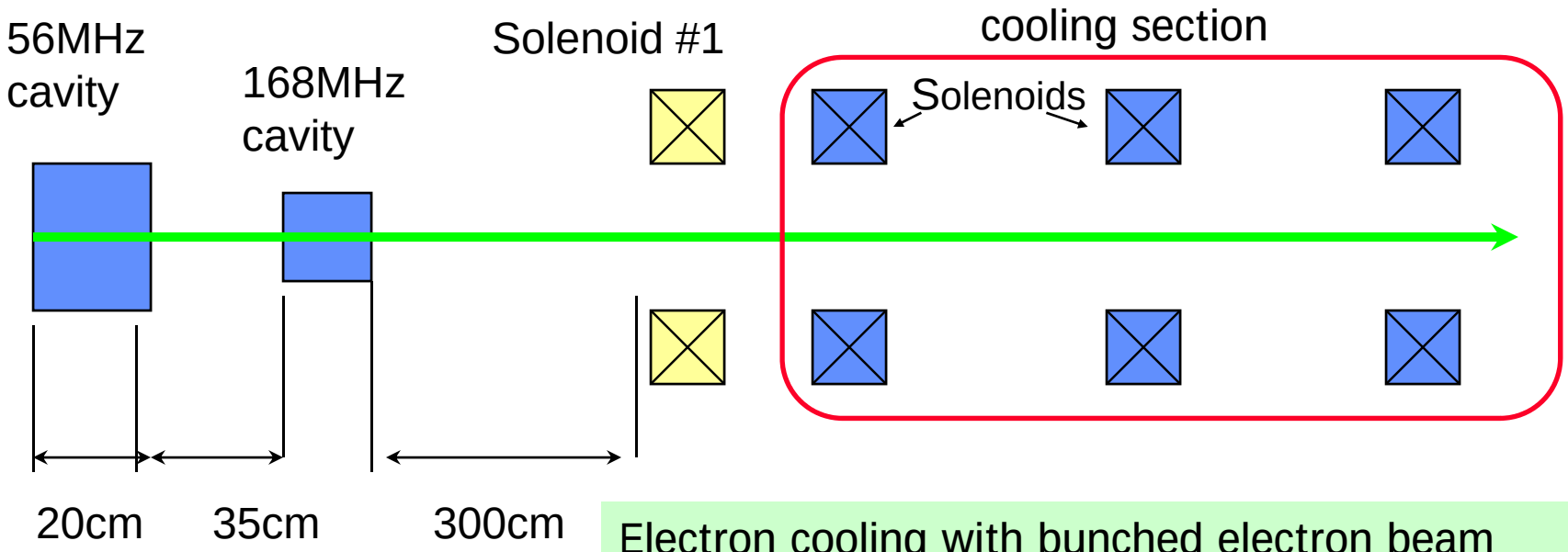
Luminosity with and without electron cooling.



At higher energies, by providing sufficient cooling (2nC with 3 μm electron beam emittance was used in simulation), we can cool emittance of ion beam until space-charge limit, which in turn allows to decrease beta*.

In example shown, electron cooling provides a factor of 6 improvement in integrated luminosity.

Possible configuration of electron cooler (X. Chang)

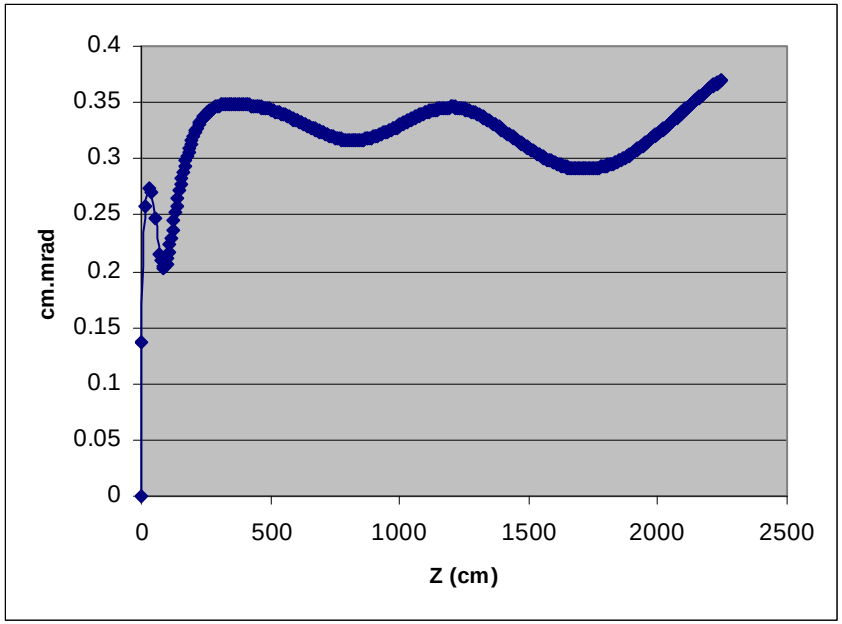


Electron cooling with bunched electron beam produced by 56MHz cavity – long bunch is needed to minimize space-charge effect in beam transport at low-energies.

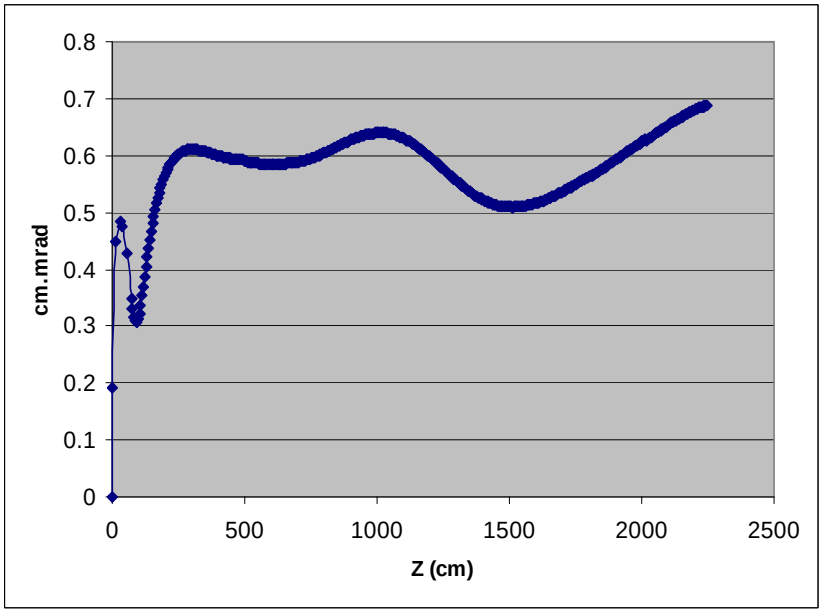
γ=2.65 – lowest energy point of interest

Results of simulations using beer-can distribution (full bunch length=45cm)
Figures show normalized rms emittance of electron beam.

Electron beam charge 1 nC



Electron beam charge 2nC

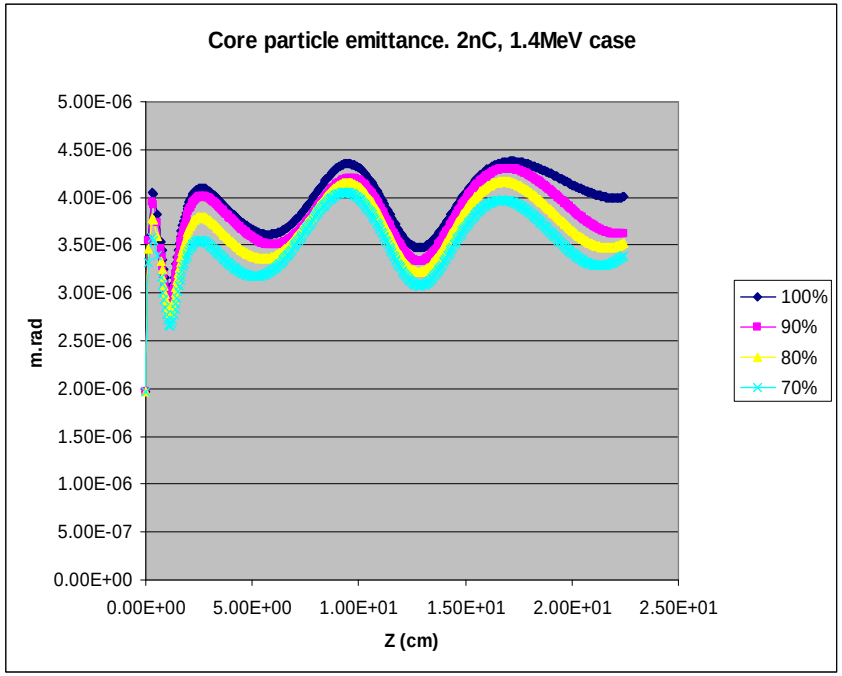


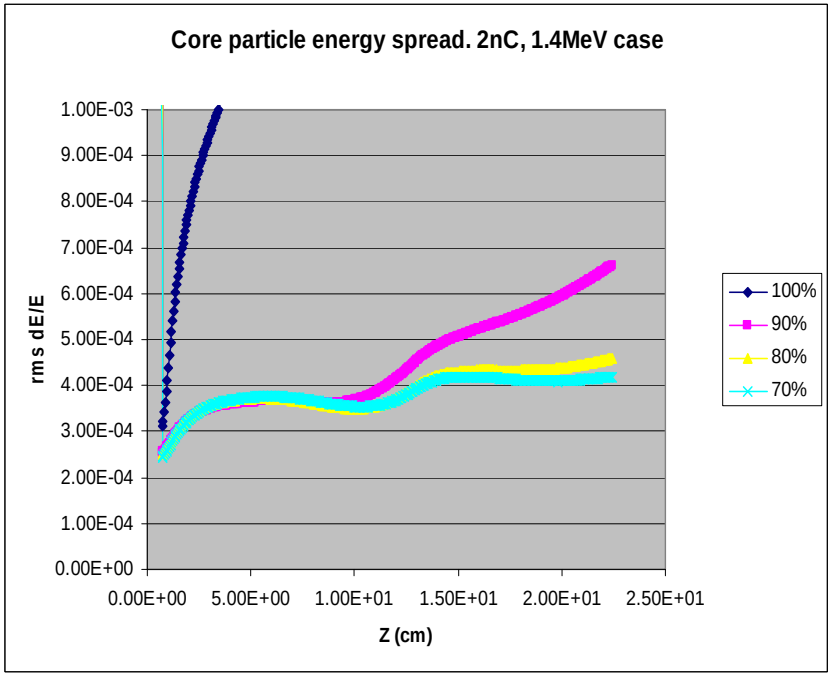
Electron beam performance at higher energies

It gets easier to maintain good emittance at higher energies.

For the highest energy of the cooler with kinetic energy of 2.8 MeV, we would like to have rms emittance of electrons to be around 3 μm for 2 nC.

no screening from walls included





Result of electron beam simulations using 56 MHz gun

Kinetic Energy (MeV)	Charge (nC)	Rms parameters	Requirement	Simulation
0.85	1	$\Delta E/E$	5×10^{-4}	~5×10^{-4}@80% core (0.8nC)
		emittance (mm.mrad)	~ 3	~3.2
	2	$\Delta E/E$	5×10^{-4}	<5×10^{-4}@60% core (1.2nC)
		emittance (mm.mrad)	5-6	~6
1.4	1	$\Delta E/E$	5×10^{-4}	<3.5×10^{-4}@90% core (0.9nC)
		emittance (mm.mrad)	~ 3	~2.3
	2	$\Delta E/E$	5×10^{-4}	4×10^{-4}@80% core (1.6nC)
		emittance (mm.mrad)	~5-6	~4

Luminosities with and without cooling

Scaling to lowest energy point at γ=2.7 gives very rough conservative predictions of peak luminosity of about:

$L_{peak} \sim 1\times10^{23}$ cm^{-2}s^{-1}

However, due to rapid debunching and strong transverse emittance growth, the store length will be just a few minutes with an average luminosity of about:

$\langle L \rangle \sim 3\times10^{22}$ cm^{-2}s^{-1}

Test run at γ=2.7 (planned for March 11, 2008) is needed to have more accurate estimate.

Electron cooling directly in RHIC at energies γ=2.7 - 6.6 can provide:

1) At lowest energy points – about factor of 3 in integrated luminosity
2) At higher energy points – about factor of 6 in integrated luminosity
3) Additional factors in luminosity may be possible if operation at larger space-charge tune shifts under cooling become possible.
4) Longer store times which is useful for the detectors.

Summary

1. **Electron cooling can provide significant luminosity improvement for low-energy RHIC operation.**
2. **Luminosity increase with electron cooling is limited by space-charge tune shift, not by cooling power.**
3. **Various options for the cooler are being considered**

   - DC cooler: electron beam parameters were demonstrated (Recycler, FNAL).

   - RF cooler: electron beam parameters look feasible in simulations.
4. **If significant luminosity increase for low-energy RHIC operation is requested in the future (for example, in Run-12 or Run-13), detailed design of electron cooler should start ASAP.**