Beam dynamics limits for Low-Energy RHIC ("critRHIC" project)

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Low-energy RHIC operation

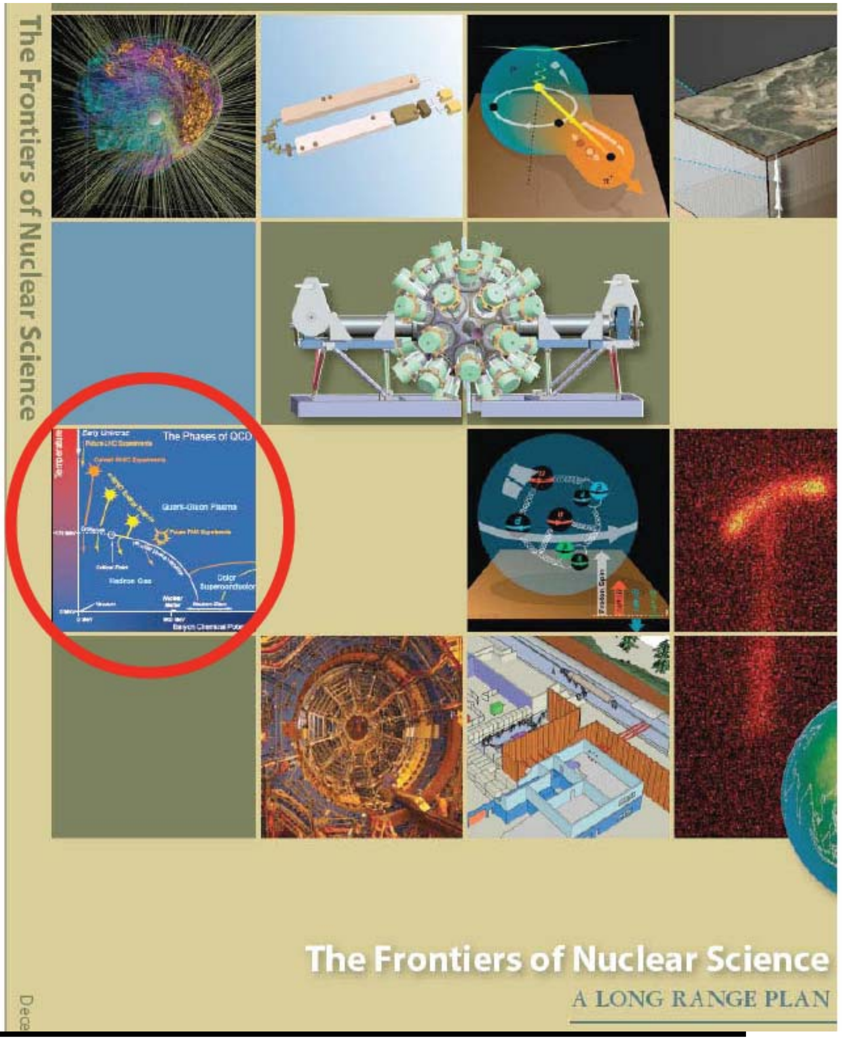
There is substantial and growing interest in RHIC heavy ion collisions with c. m. energy in the range $\sqrt{s_{NN}}$= 5-50 GeV/n

RIKEN workshop (BNL, March 2006):

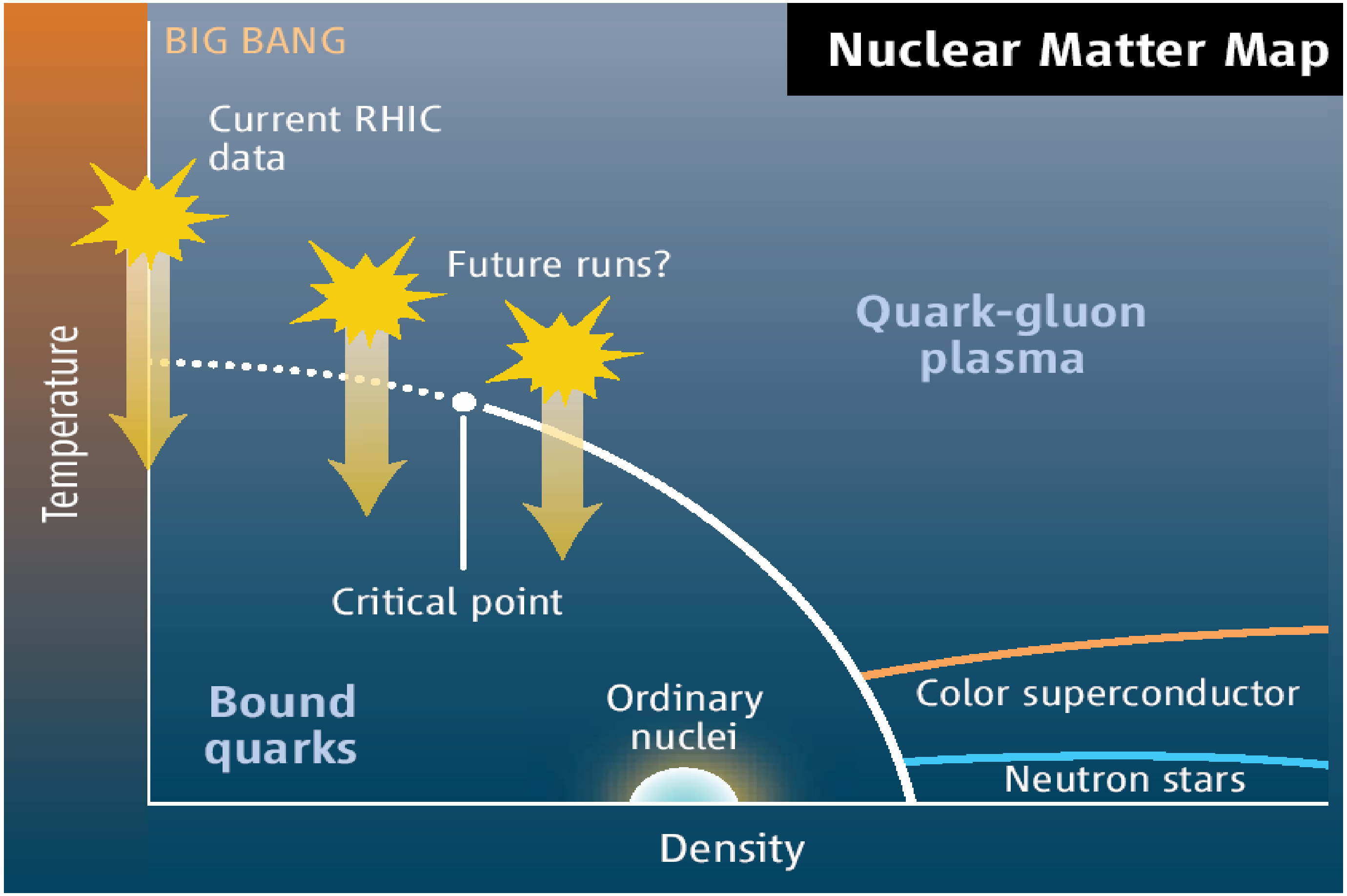
"Can we discover the QCD critical point at RHIC?"

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

Three test runs were done in 2006, 2007, 2008 at low-energies in RHIC (Todd Satogata et al., PAC07; RHIC 2008 retreat).



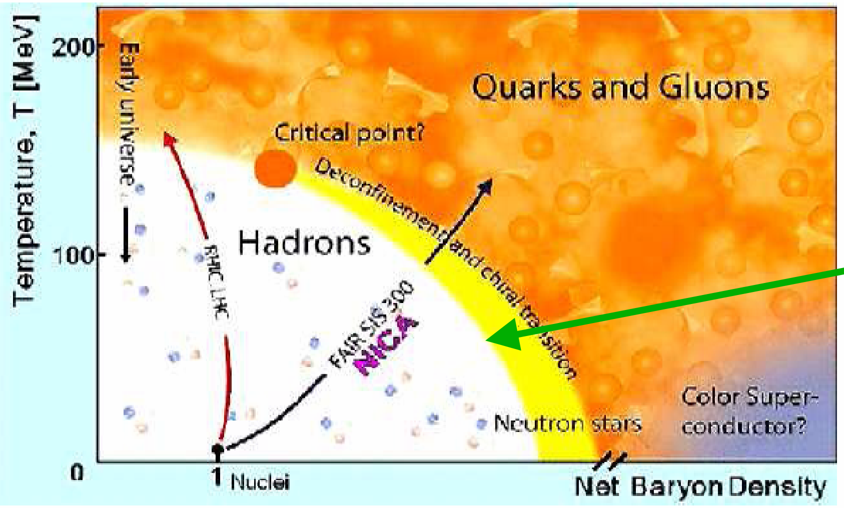
Low-energy RHIC operation: 2.5-25 GeV/n



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 physics (FAIR, NICA projects) – RHIC beyond 2010 ?



High statistics/ luminosity is needed.

deconfinement and/or chiral symmetry restoration phase transitions

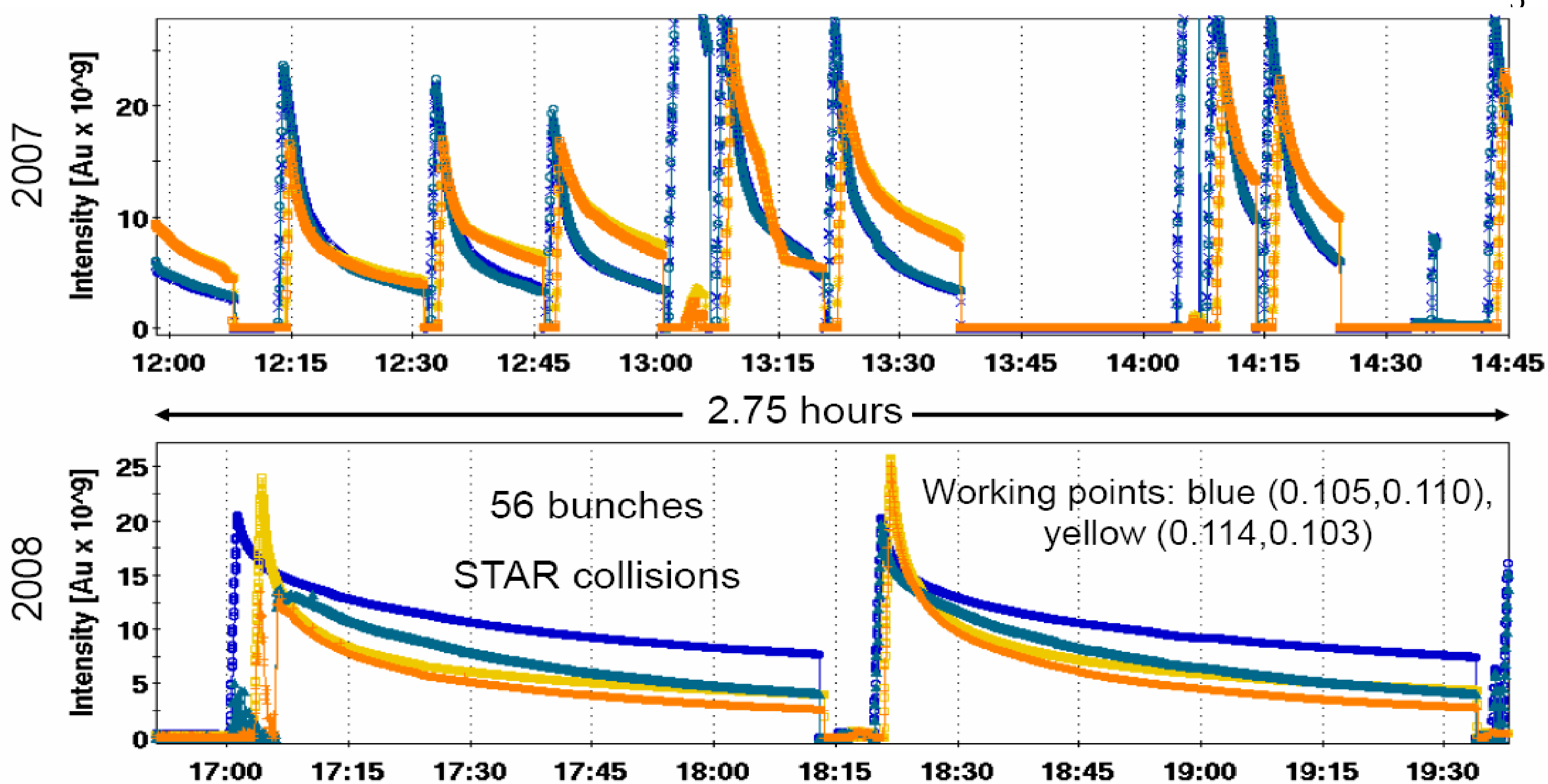
the first stage

- 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)**

T. Satogata (RHIC retreat, March 31, 2008) @ γ=4.9



- 2008 blue beam lifetime: 3.5 minutes (fast), 50 minutes (slow)
- Sextupole reversal and elimination of octupoles clearly helped beam lifetime
- Injection efficiency and yellow beam lifetime can clearly benefit from further tuning

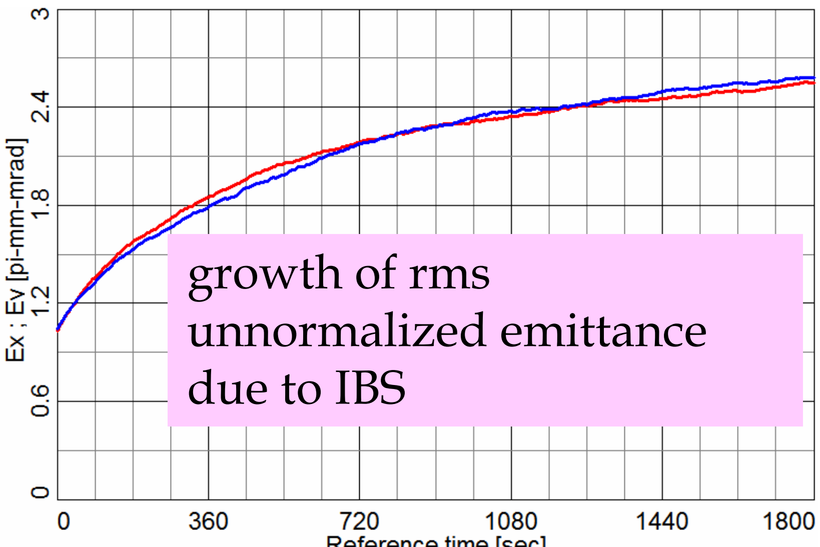
Summary of 2008 low-energy test run

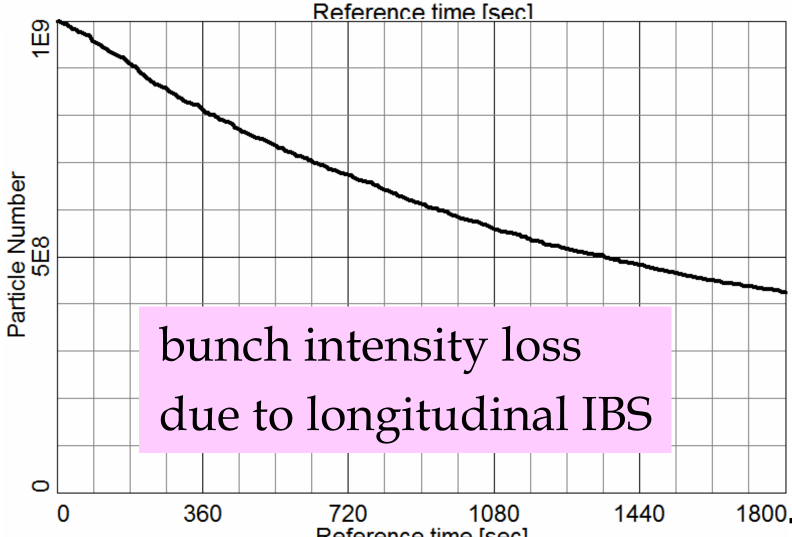
T. Satogata (RHIC retreat, March 31 2008)

- $\sqrt{s_{NN}}$ = 9 GeV
  - All setup worked very well with h=366; commendations to setup team!
  - Defocusing sextupole reversal, octupole removal improved blue lifetime by x4!
  - ~50-60% injection efficiency
  - STAR collisions about 13h after first beam; PHENIX about 24h after first beam
  - Clean vernier scans, unambiguous collisions achieved in both experiments
  - Experiment useful event rates: 0.7-1Hz with 56 bunches, 0.4-0.5e9/bunch
    - Luminosity max 3.5×10^{23} cm^{-2} s^{-1}, average 1.2×10^{23} cm^{-2} s^{-1}
  - Problems: cogging, AGS-RHIC synchro, kicker timing, PHENIX collision signal, intensity dynamic range for IBS measurements

- $\sqrt{s_{NN}}$ = 5 GeV
  - Timing setup worked very well with h=387; more commendations!
  - 10% injection efficiency, very nonlinear lattice (main dipole b_2 large)
  - Problems: b4-dh0 ps failure, limited bunched beam, nonworking orb correction due to linear model

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

Beam dynamics luminosity limits

IBS:

- Strong IBS growth - can be easily counteracted by Electron Cooling system.

Beam-beam:

- Becomes significant limitation for RHIC parameters only at $\gamma > 10$.

Space-charge::

- At lowest energies, strongest limitation on achievable ion beam peak current is expected to be given by space-charge effects. This prohibits application of strong electron cooling.

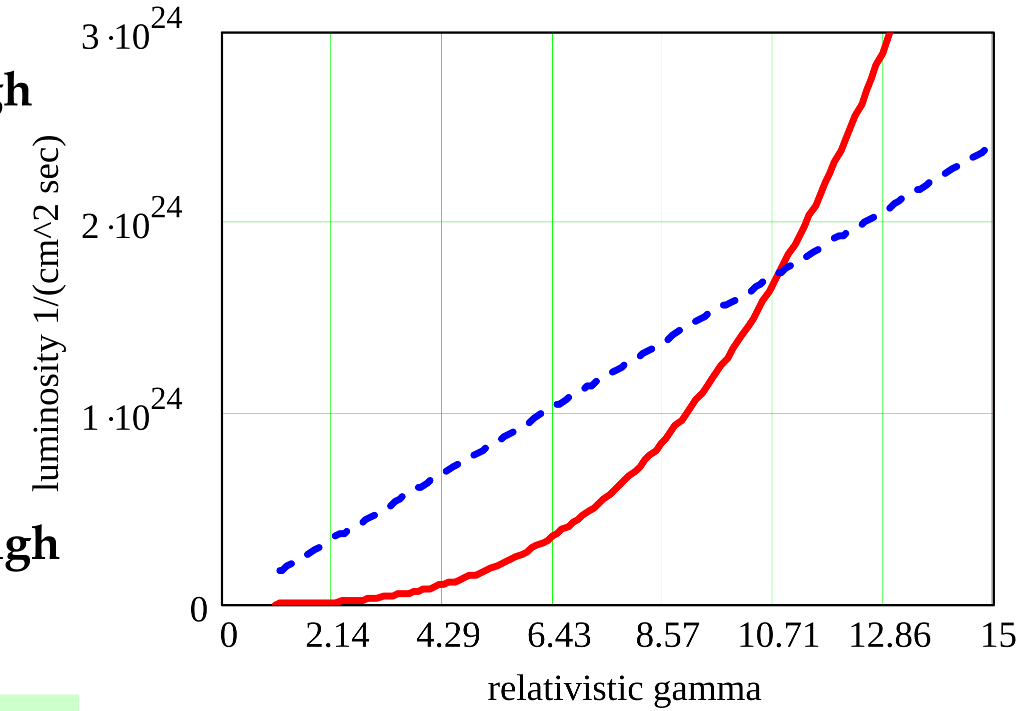
Luminosity limitation by space-charge and beam-beam

Luminosity expressed through beam-beam parameter ξ:

$$L = \frac{A}{Z^2 r_p} \frac{N_i c}{\beta^* C} \frac{2\gamma\beta^2}{1+\beta^2} f\left(\frac{\sigma_s}{\beta^*}\right)\xi$$

Luminosity expressed through space-charge tune shift ΔQ:

$$L = \frac{A}{Z^2 r_p} \frac{N_i c}{\beta^*} \frac{\sqrt{2\pi}\sigma_s}{C^2} \gamma^3 \beta^2 f\left(\frac{\sigma_s}{\beta^*}\right)\Delta Q$$



Blue dash line: beam-beam limitation with beam-beam parameter 0.005 per IP.

Red: space-charge limitation with ΔQ=0.05

What is acceptable space-charge tune shift for long life time in RHIC with collisions?

This question could be explored by measurement during the test runs at low-energy.

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

In June 2007 test run with ΔQ=0.03 the life time was bad although it seems to be related to other effects.

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

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

- Presently, we assume that ΔQ=0.05-0.07 as a limit for RHIC (since we would like to have long life time in RHIC – minutes). Perhaps, cooling can help to operate at slightly larger space-charge tune shift.

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

γ	h (rf harmonic number)	$\varepsilon_{95\%,n}$ µm	N, ×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)

   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)

2007 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.

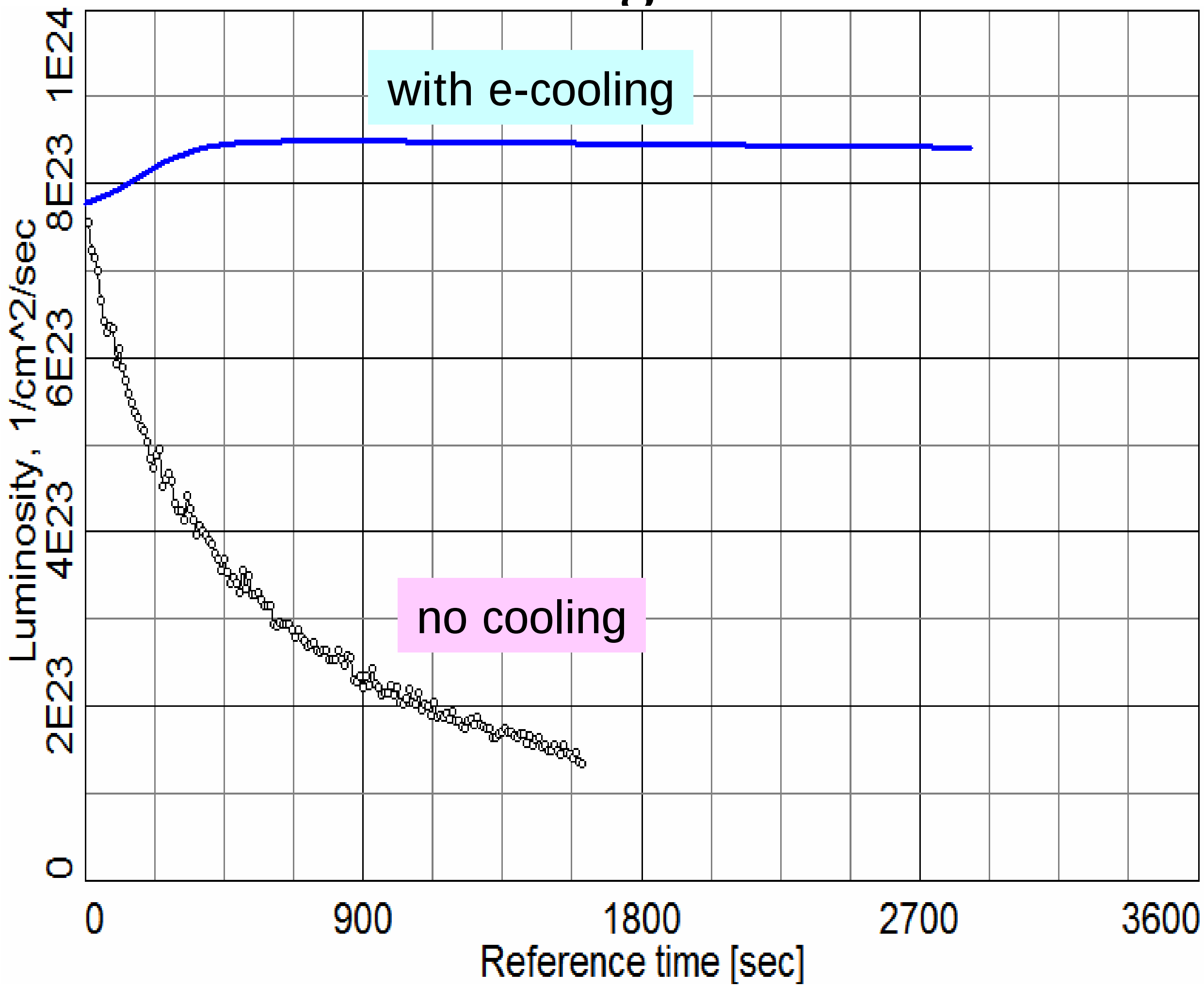
   1.2 Building new 3MeV DC electron cooler.

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.).

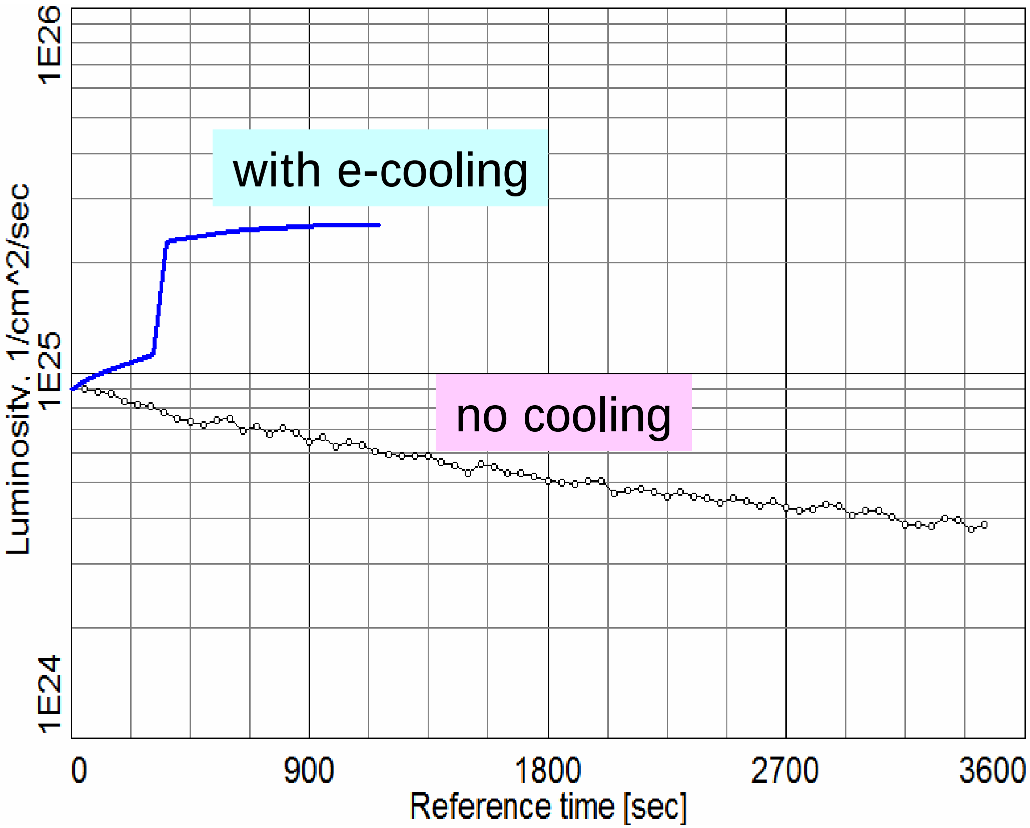
   2.2 Using 56 MHz cavity to produce long electron bunch with required parameters for cooling (studies by X. Chang et al.).

γ=2.7 – lowest energy point. Luminosity with and without electron cooling.



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

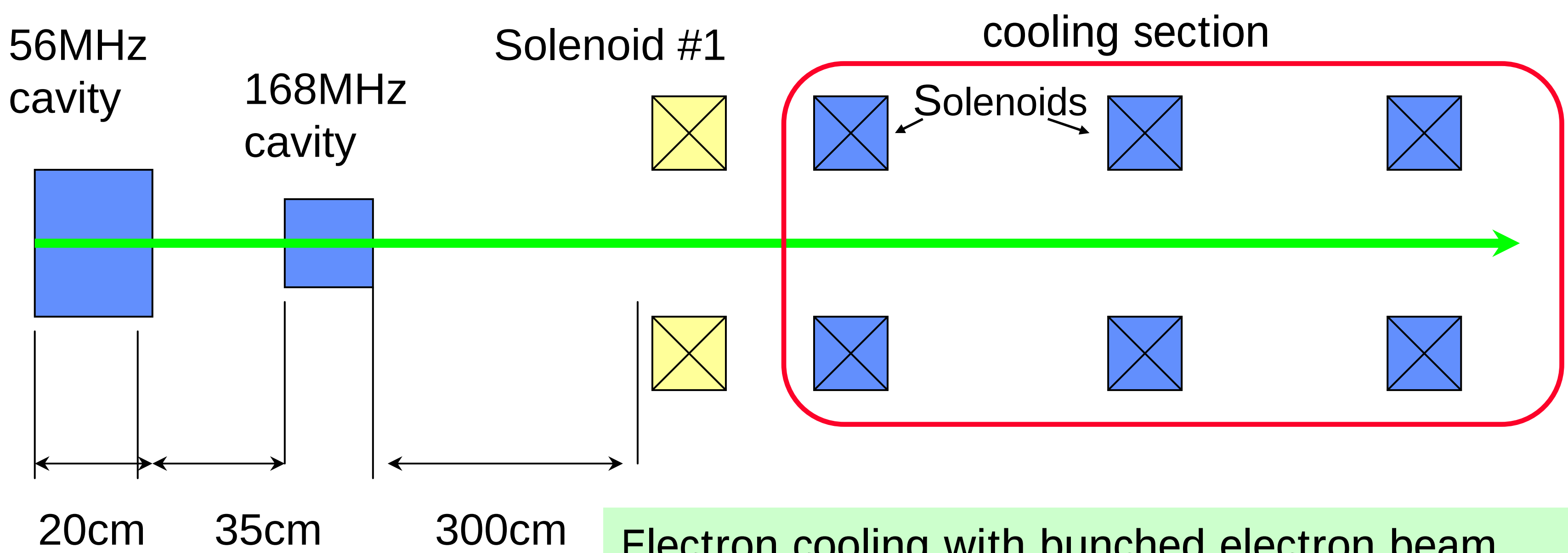
Luminosity with and without electron cooling.



At higher energies, by providing sufficient cooling we can cool emittance of ion beam until space-charge limit, which in turn allows to decrease β*.

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

RF gun cooler based on 56MHz gun (X. Chang et al.)

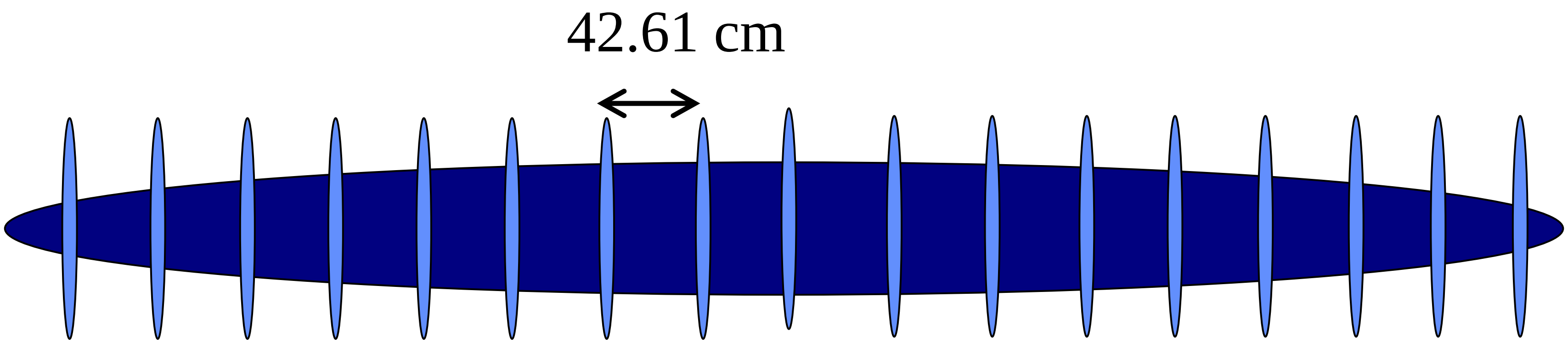


Electron cooling with bunched electron beam produced by 56MHz cavity – long bunch is needed to minimize space-charge effect in beam transport at low-energies.

Result of electron beam simulations using 56 MHz gun

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

RF gun approach using 703MHz gun of ERL under construction at BNL (D. Kayran et al.)

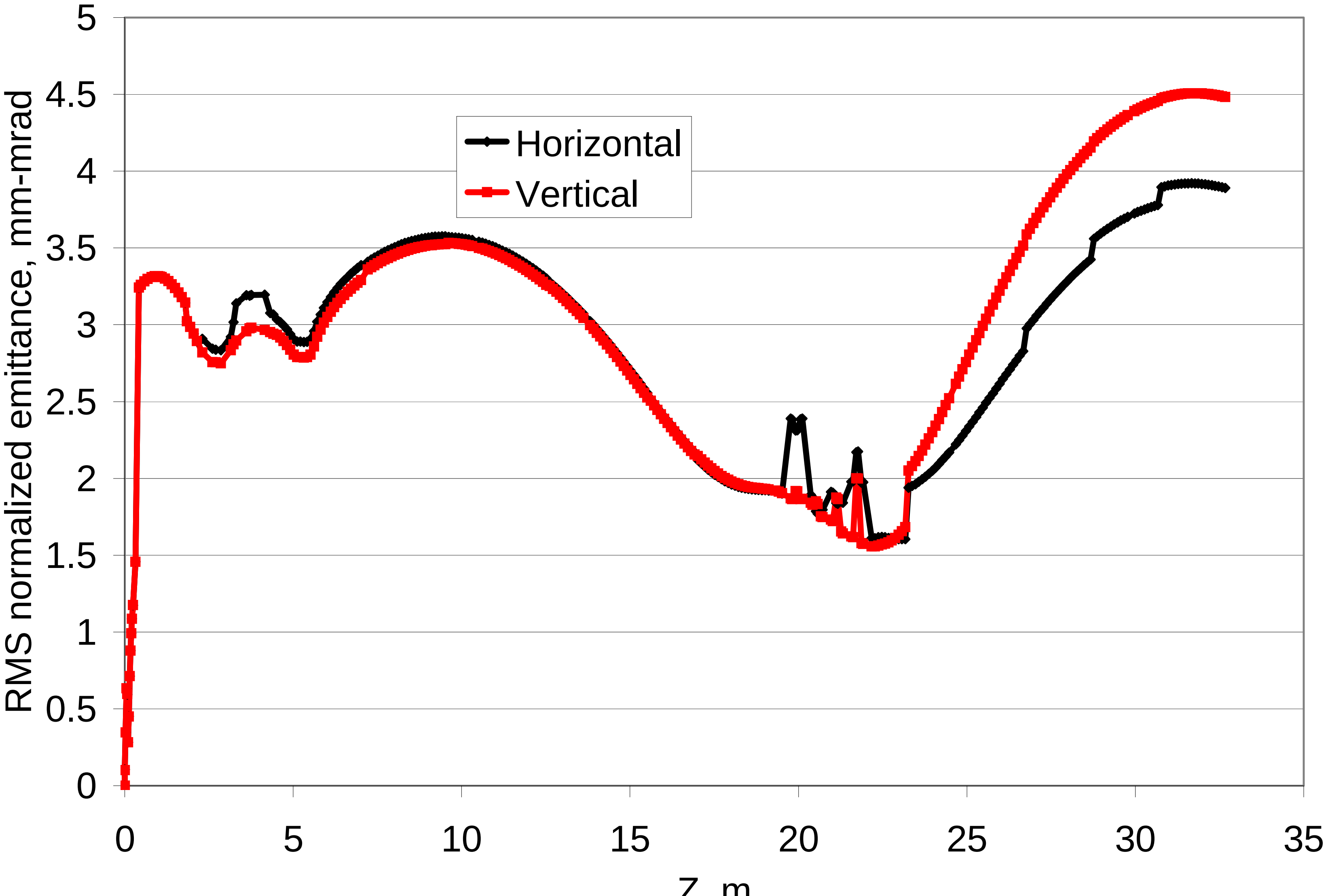


20 electron bunches:

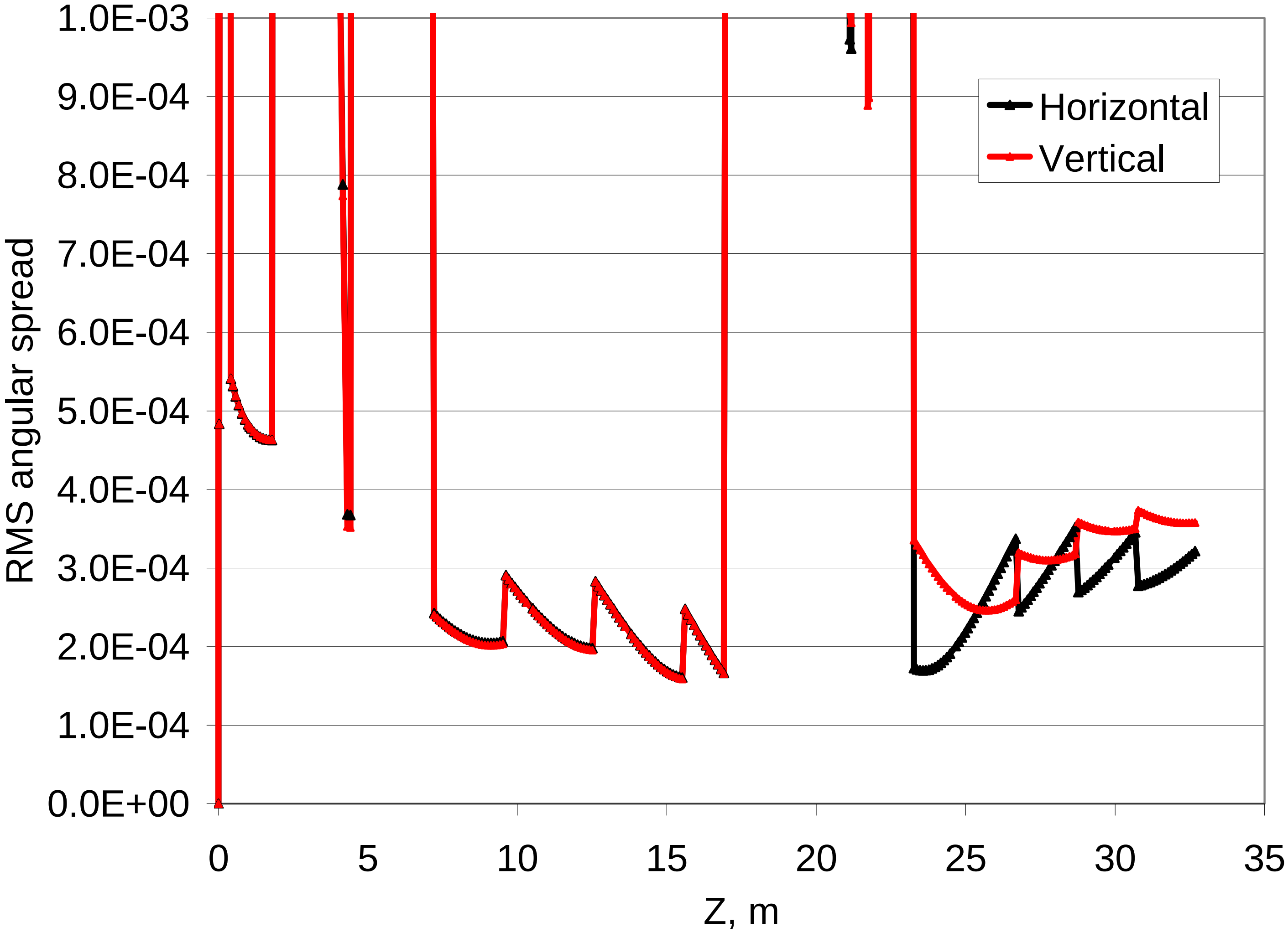
charge per bunch 50 pC , electron bunches are 42.61 cm apart

Ion bunch full bucket: length ~ 10 m

Normalized emittances evolution (for 703 MHz gun approach)



RMS angular spread evolution (for 703 MHz gun approach)



Possible luminosity improvements at low-energies

1. **E-cooler:**

- Expect factor of 3-6 improvement in L if space-charge limit is reached. Larger factor if not space-charge limited (see Ref. [6] for details)

2. **Top-off mode:**

- Expect factor of 2-3 improvement in L
- Replace 1-4 RHIC bunches every AGS cycle, beam stays in RHIC only 3-7 minutes.
- Needs modification of RHIC injection and extraction system

3. **IBS below transition and use of 56 MHz cavity:**

- Expect about factor of 2 in L
- 56 SRF cavity will be commissioned in FY11.

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We are grateful to Al Pendzick for providing cost estimate of possible cooling scenarios {see Ref. [6]}.

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[6] A. Fedotov et al., "Feasibility of electron cooling for low-energy RHIC operation", Collider-Accelerator Tech Note C-A/AP/ (April 2008).