

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

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# Low-energy RHIC operation

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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?”

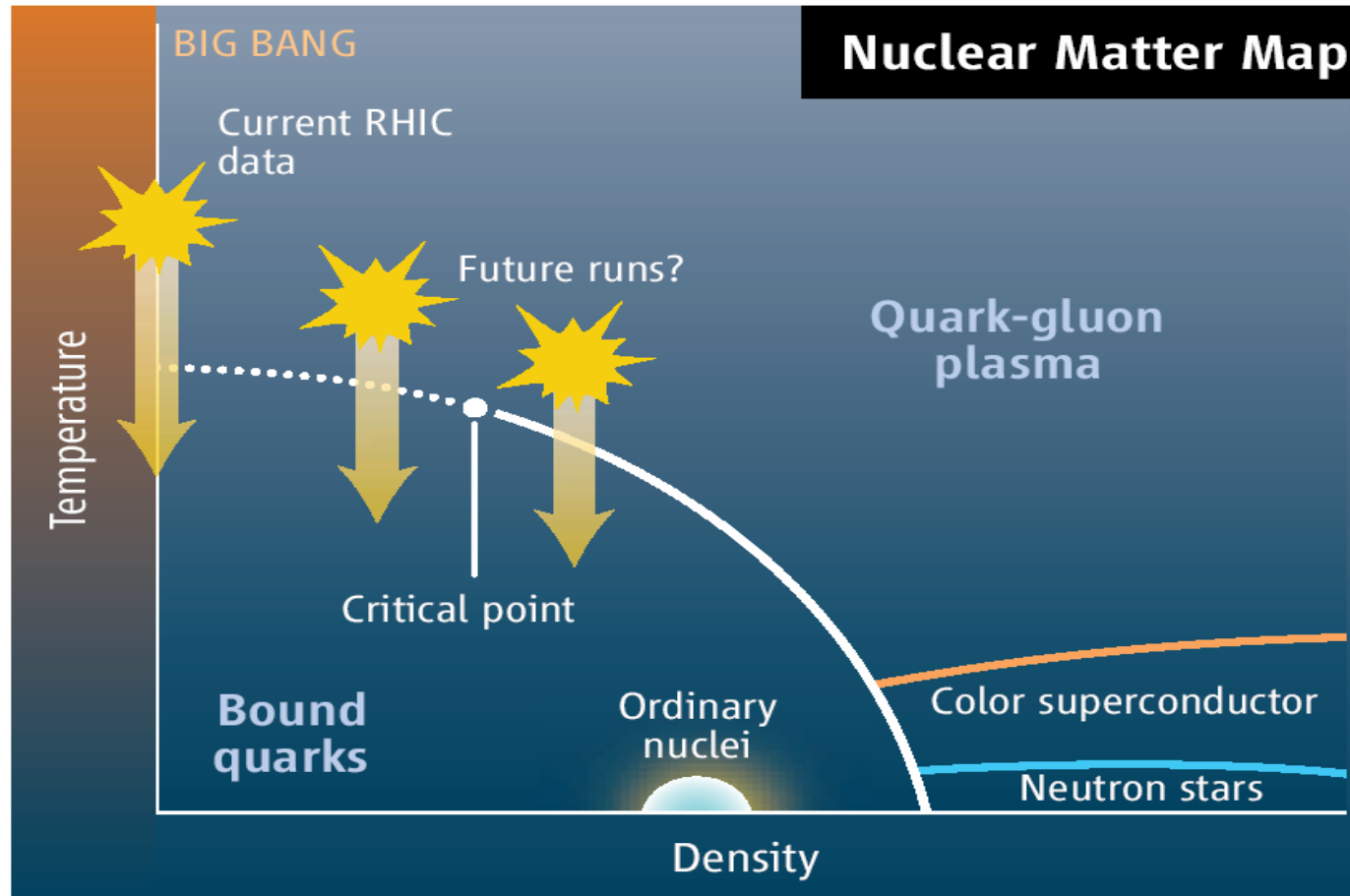
Suggested energy scan:  $\sqrt{s_{NN}} = 5, 6.3, 7.6, 8.8, 12.3, 18, 28$  GeV/n

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

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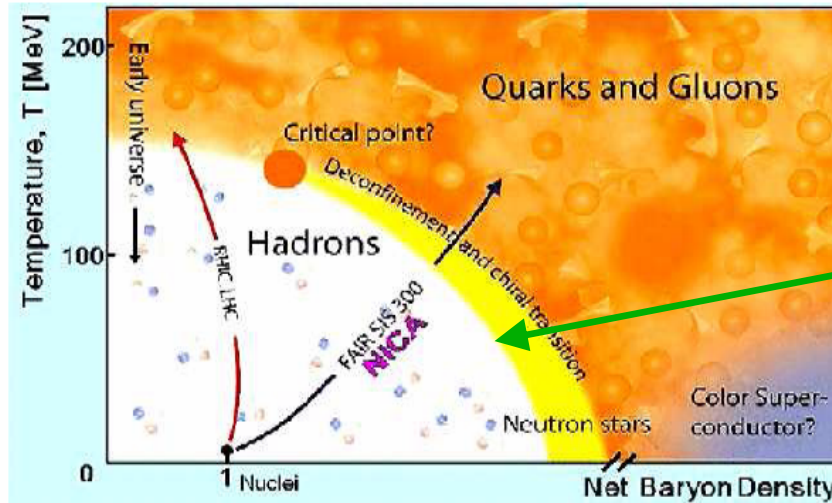


A. Cho, Science, 312 (14 Apr 2006)

**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).

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

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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

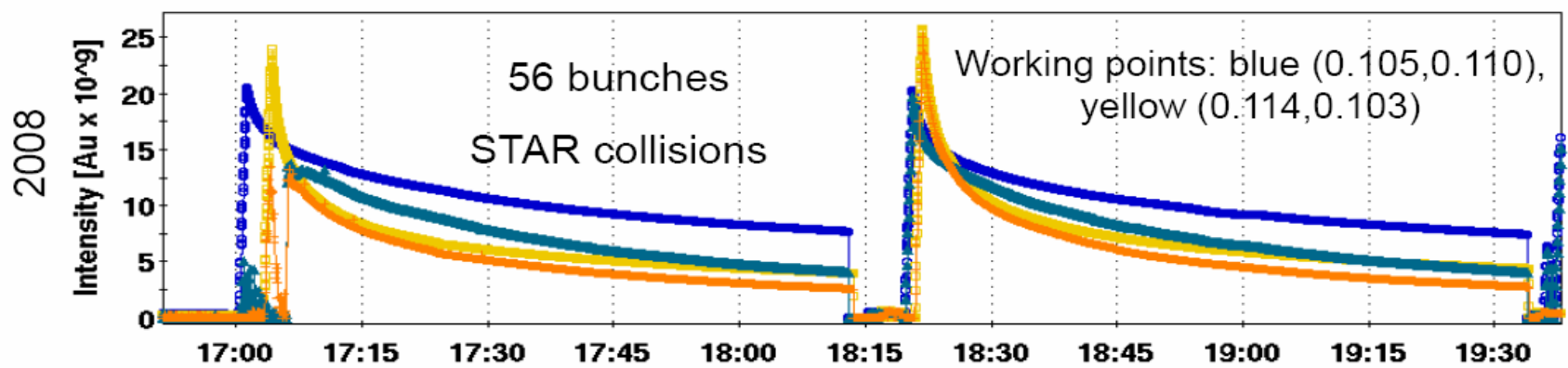
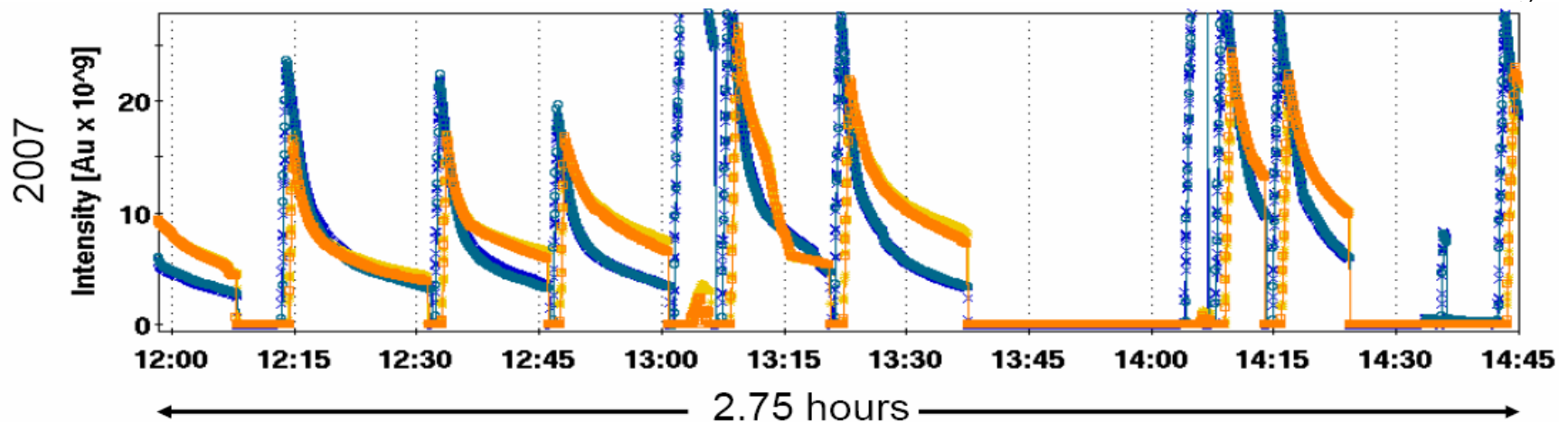
## the second stage

- ♣ Electromagnetic probes (photons and dileptons)

T. Satogata (RHIC retreat, March 31, 2008)

@  $\gamma=4.9$

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- 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

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## ■ $\sqrt{s_{NN}} = 9 \text{ GeV}$

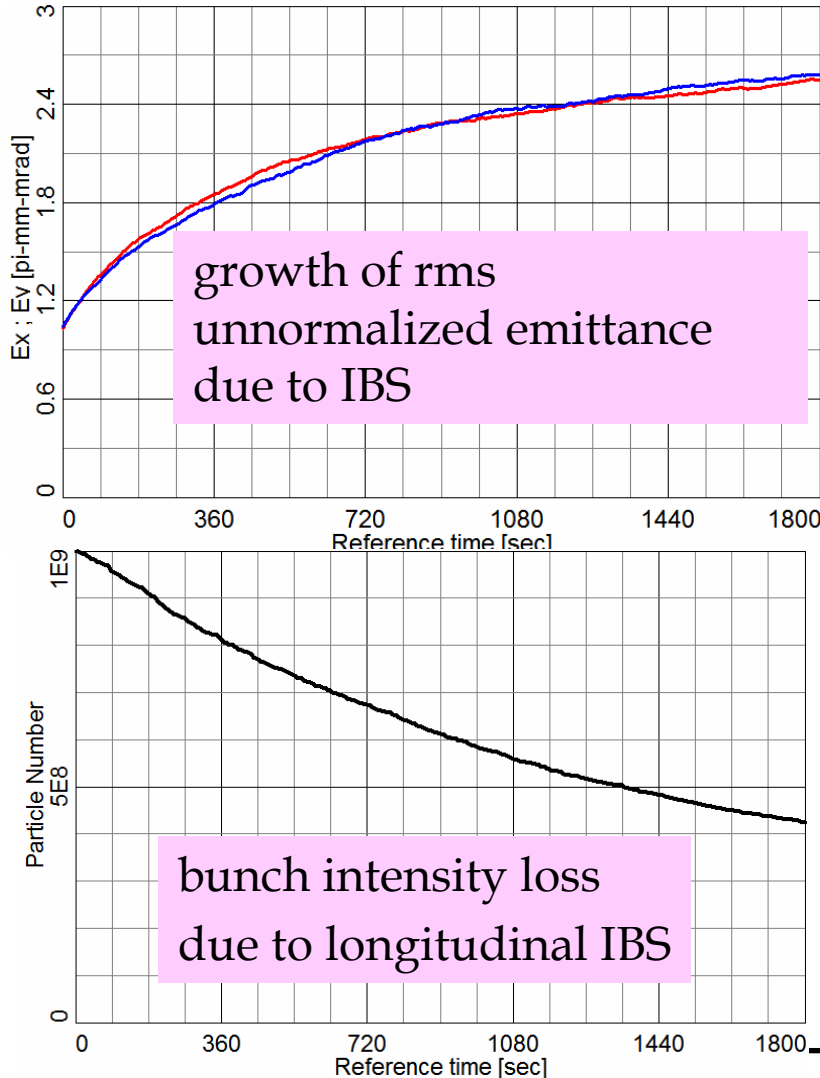
T. Satogata (RHIC retreat, March 31 2008)

- 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  $3.5 \times 10^{23} \text{ cm}^{-2} \text{ s}^{-1}$ , average  $1.2 \times 10^{23} \text{ cm}^{-2} \text{ s}^{-1}$
- Problems: cogging, AGS-RHIC synchro, kicker timing, PHENIX collision signal, intensity dynamic range for IBS measurements

## ■ $\sqrt{s_{NN}} = 5 \text{ GeV}$

- Timing setup worked very well with  $h=387$ ; more commendations!
- 10% injection efficiency, very nonlinear lattice (main dipole  $b_2$  large)
- Problems:  $b_4$ -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 $\gamma$	2.68
Bunch intensity, $10^9$	1.0
Rms momentum spread	$4 \times 10^{-4}$
Rms bunch length, cm	155
Rms emittance (unnormalized), $\mu\text{m}$	1.04
RF harmonic	387
RF voltage, kV	300

# Beam dynamics luminosity limits

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## 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.



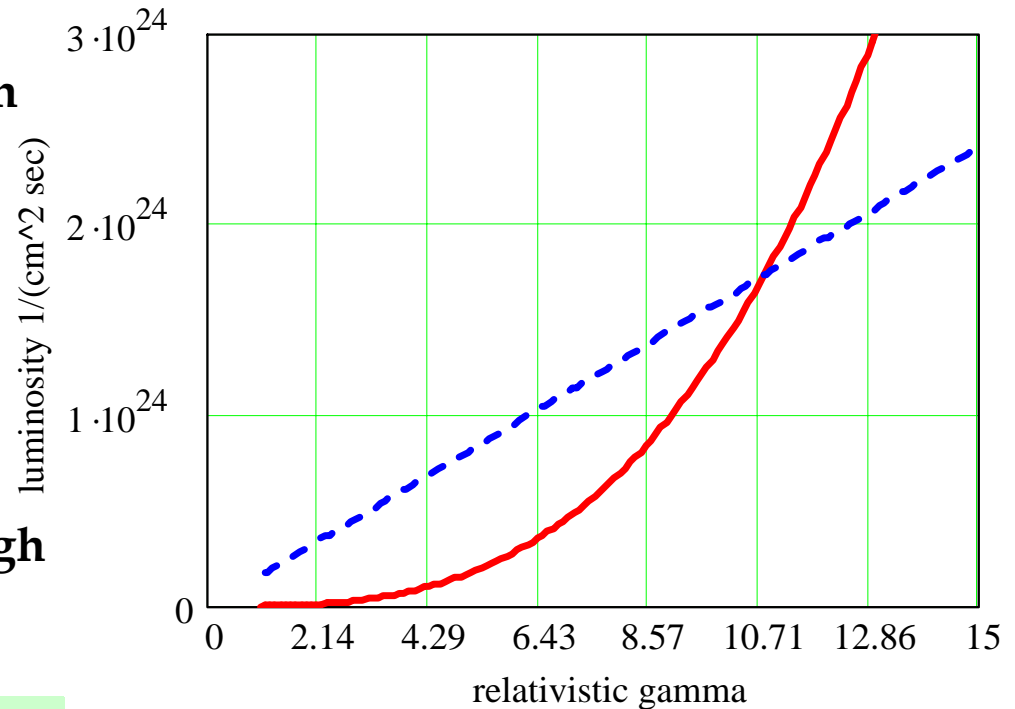
# Luminosity limitation by space-charge and beam-beam 9

Luminosity expressed through  
beam-beam parameter  $\xi$ :

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

Luminosity expressed through  
space-charge tune shift  $\Delta Q$ :

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



Blue dash line: beam-beam limitation  
with beam-beam parameter 0.01 per IP.

Red: space-charge limitation with  $\Delta Q=0.05$

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

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

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

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

- for example, in SPS, life time of few minutes with  $\Delta Q=0.1$  was reported
- in LEAR, electron cooling allowed to increase  $\Delta Q$  to 0.1 in operation
- Presently, we assume that  $\Delta Q=0.05-0.07$  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

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$\gamma$	h (rf harmonic number)	$\epsilon_{95\%,n}$ $\mu\text{m}$	$N, \times 10^9$ (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<sub>2</sub>

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

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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:

2007 estimates by T. Satogata

$$E_{ke}=0.86-2.8 \text{ MeV}$$

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

$\sqrt{s_{NN}}$ [GeV]	$\mu_B$ [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

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## 1. DC cooler:

- 1.1 Using Recycler (FNAL) e-cooler when it becomes available.
- 1.2 Building new 3MeV DC electron cooler.

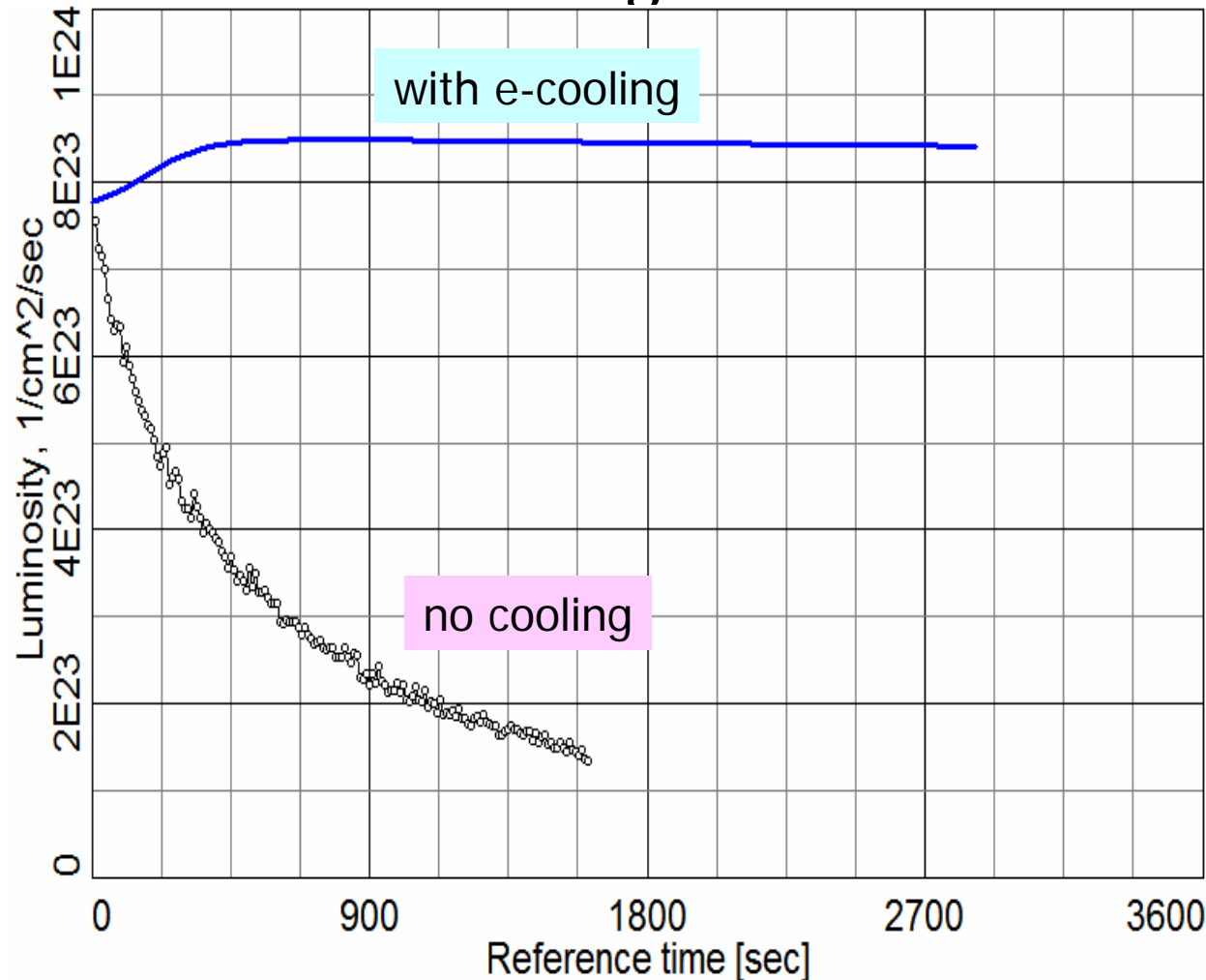
## 2. RF gun cooler:

- 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. ).



$\gamma=2.7$  - lowest energy point. Luminosity with and without electron cooling.

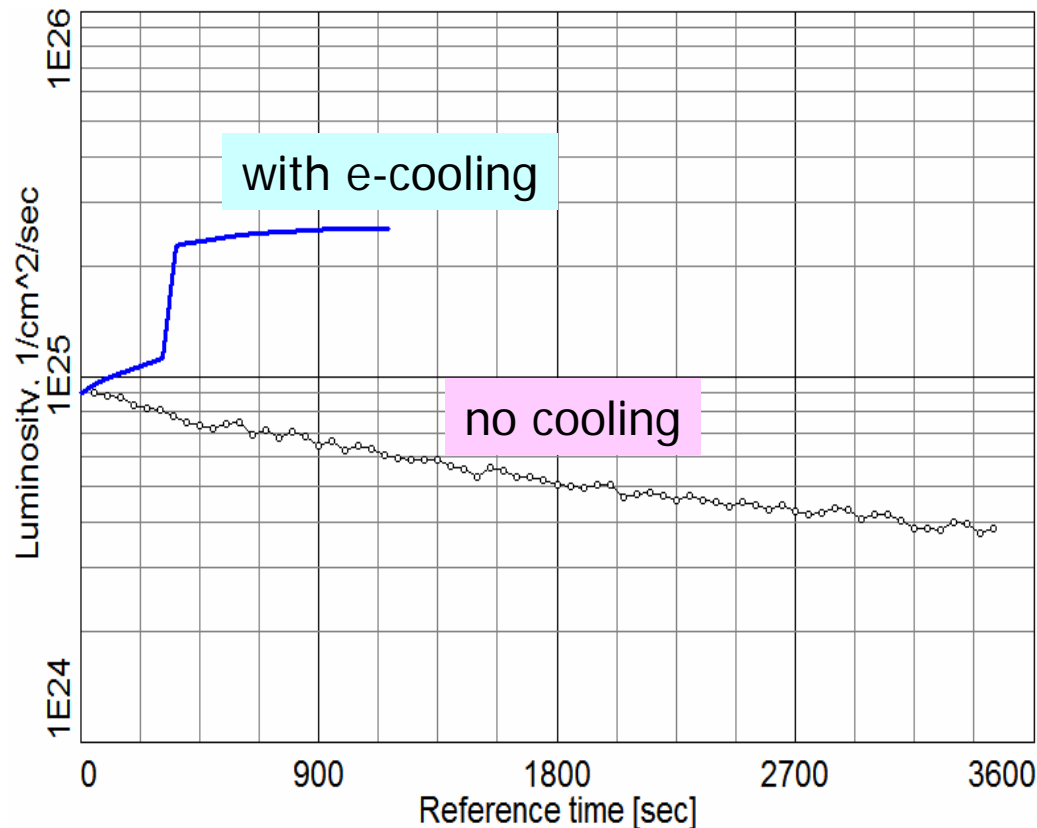
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$\gamma=6.6$  – highest energy point of the cooler planned.

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## Luminosity with and without electron cooling.

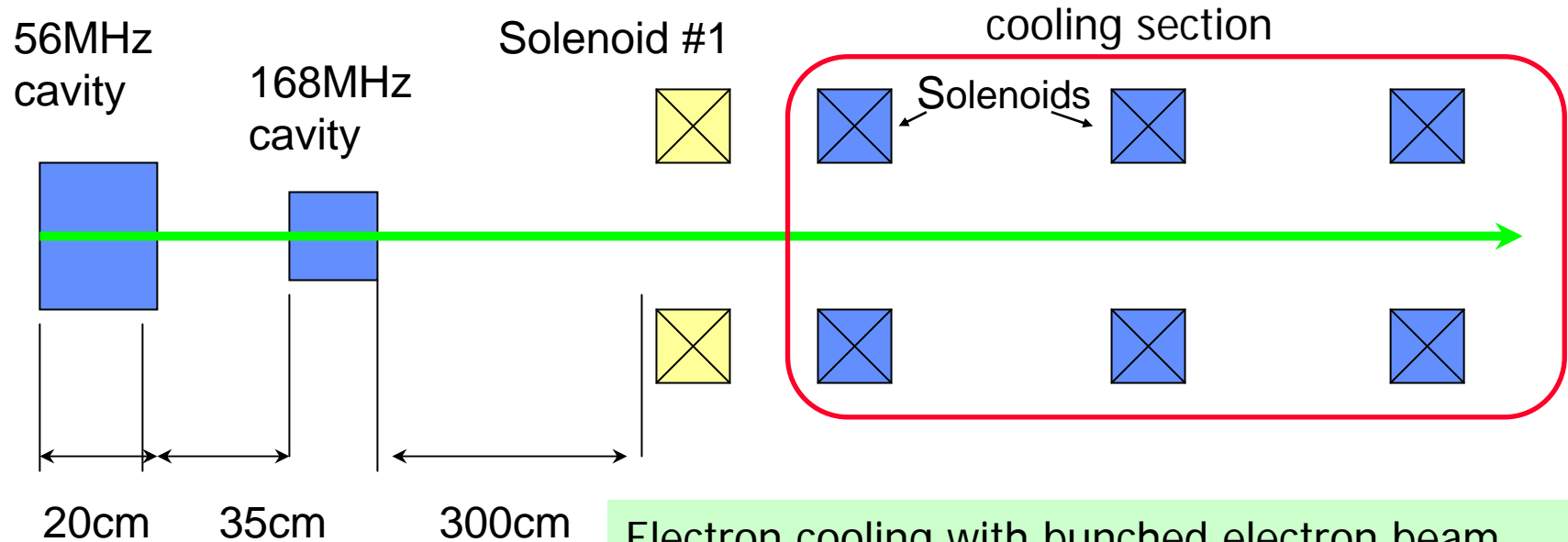


At higher energies, by providing sufficient cooling we can cool emittance of ion beam until space-charge limit, which in turn allows to decrease  $\beta^*$ .

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.)

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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.

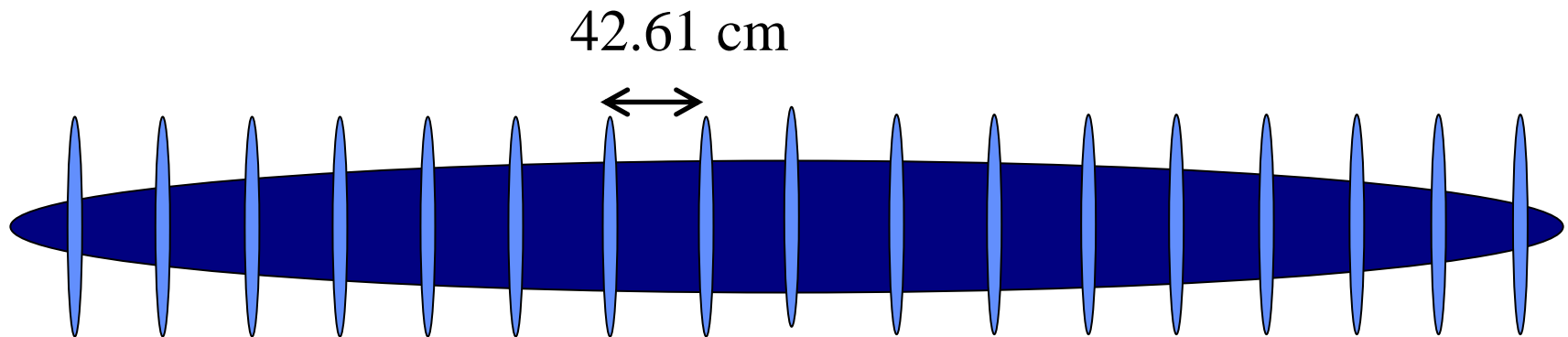
# Result of electron beam simulations using 56 MHz gun

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

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

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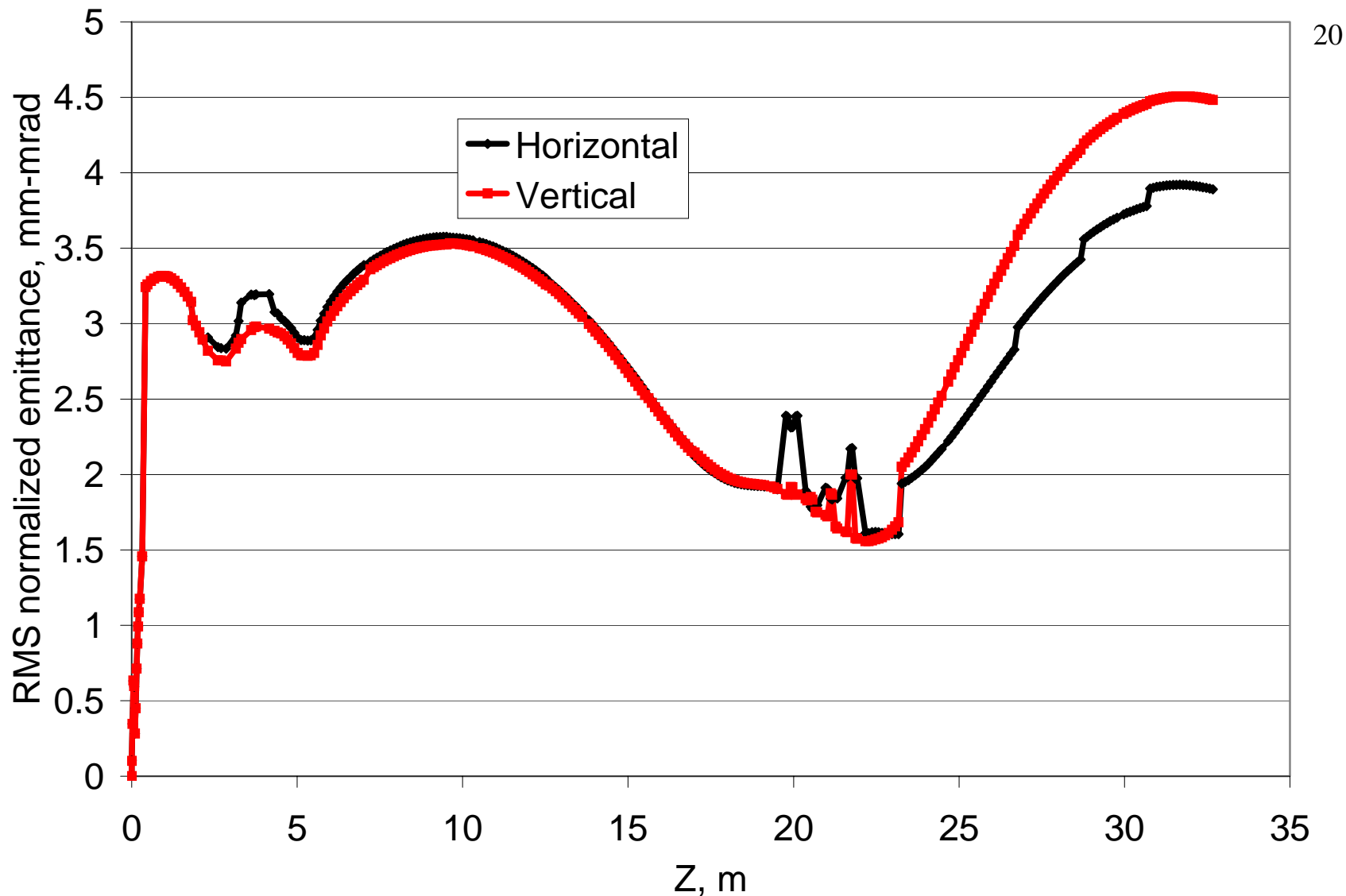


20 electron bunches:

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

Ion bunch full bucket: length  $\sim 10$  m

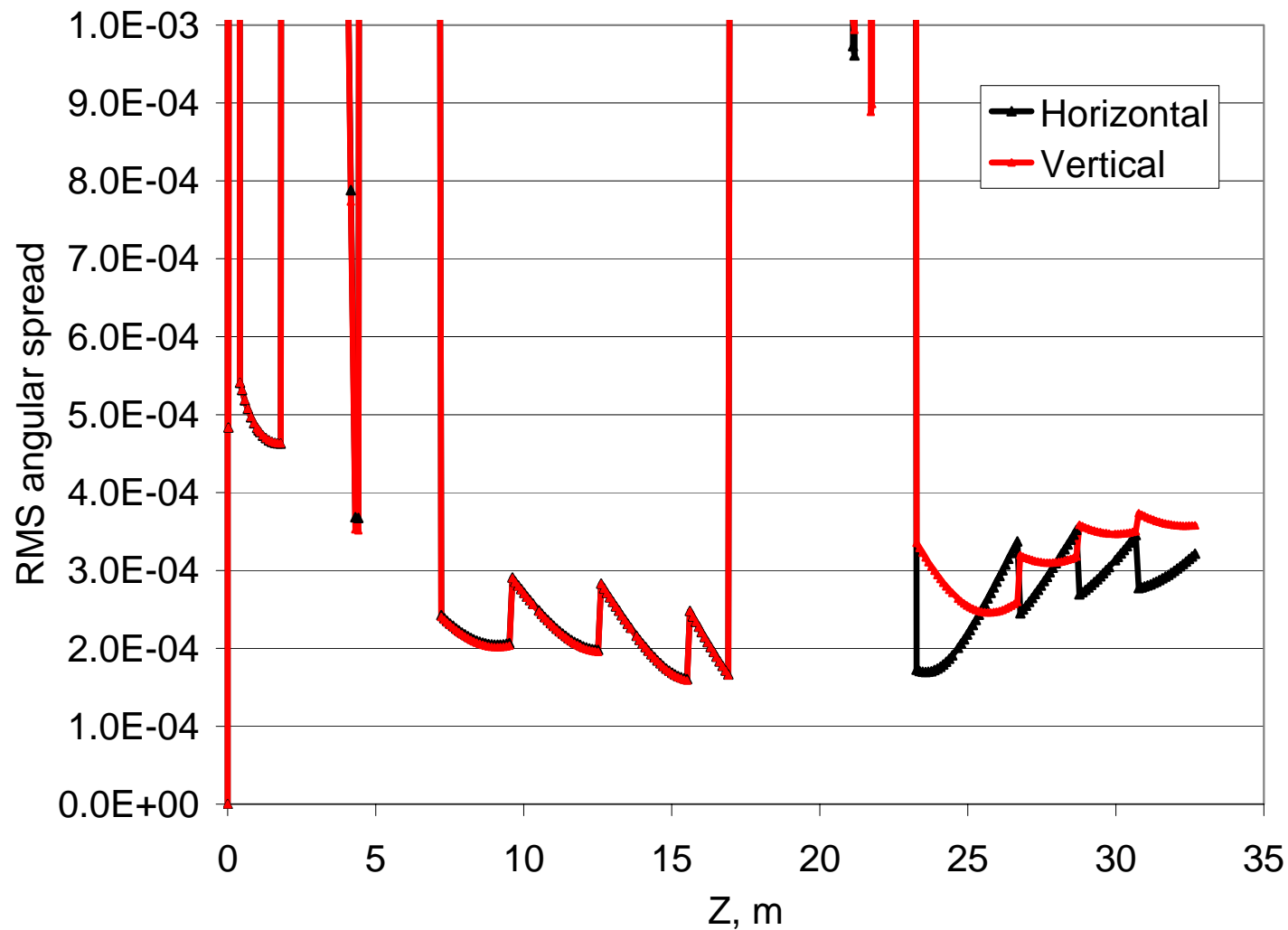
## Normalized emittances evolution (for 703 MHz gun approach)





## RMS angular spread evolution (for 703 MHz gun approach)

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# Possible luminosity improvements at low-energies

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## 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.

# ACKNOWLEDGMENTS

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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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