Low-energy RHIC electron Cooling (LEReC) related studies

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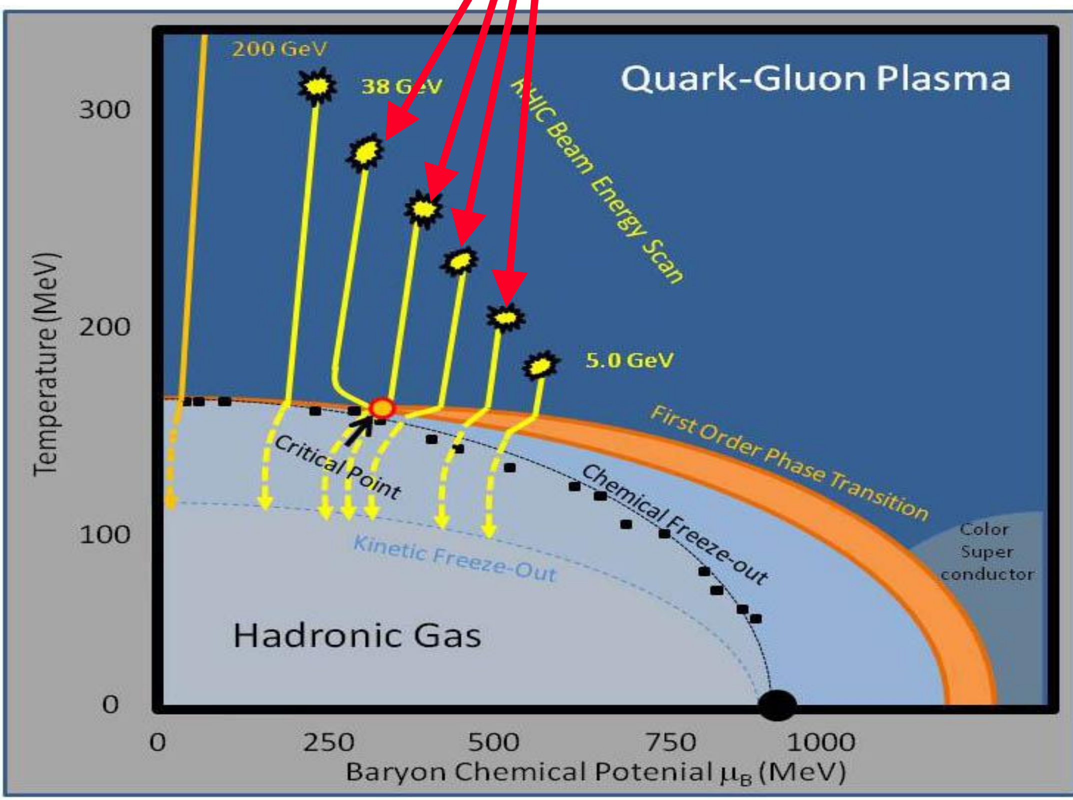
APEX workshop, December 19-20, 2013

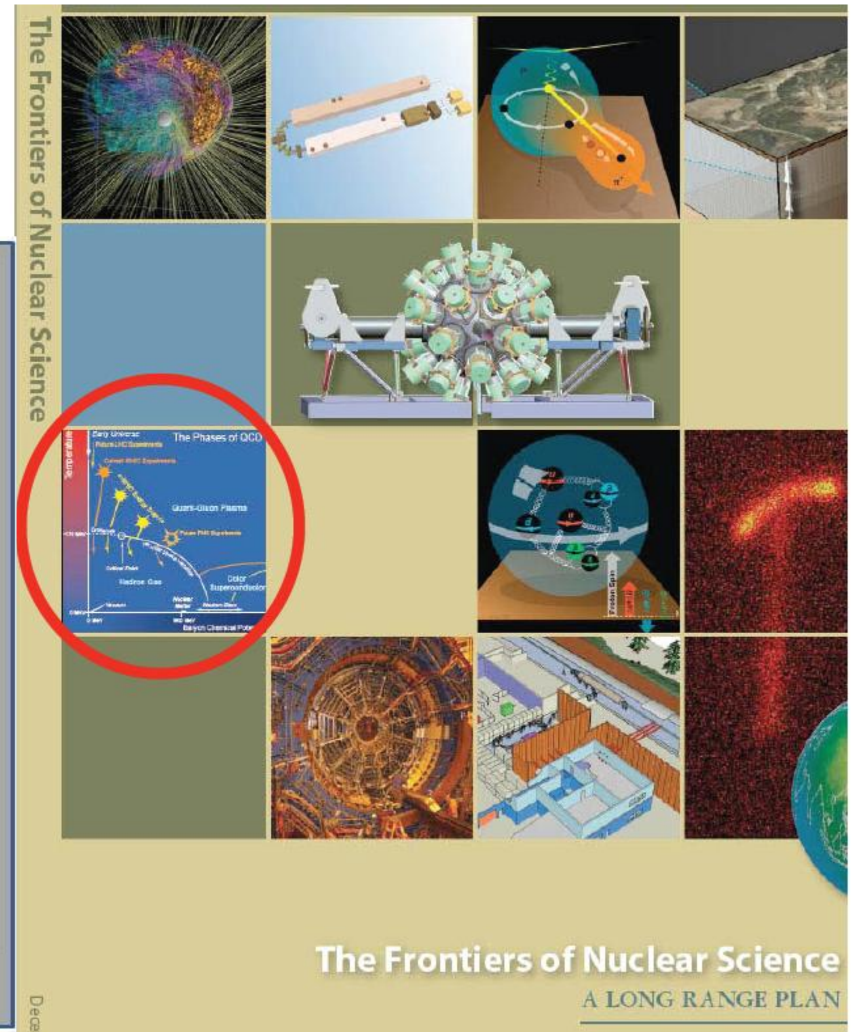
Low-Energy RHIC program:

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)





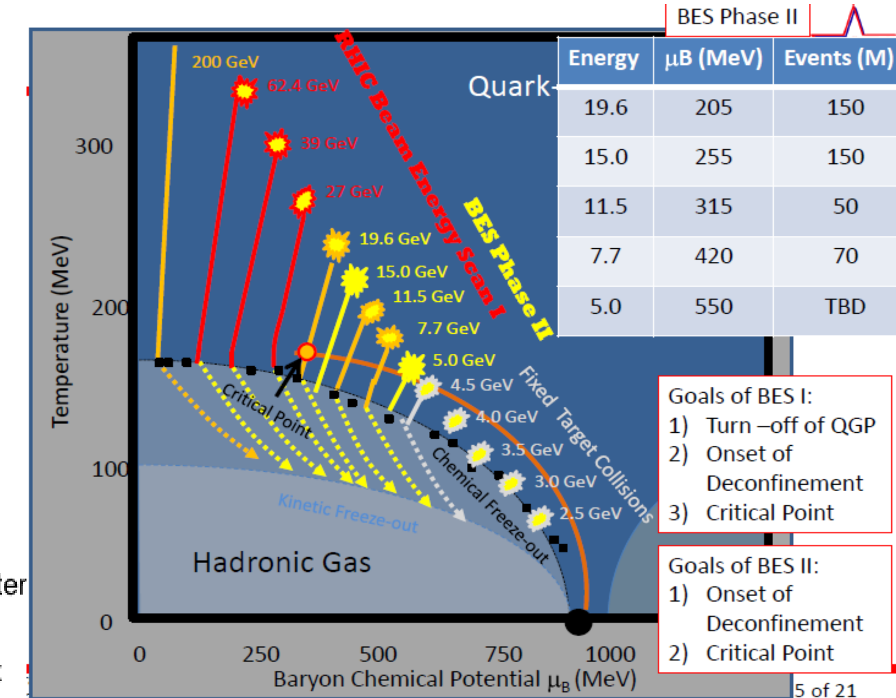
Run Schedule for RHIC

•B. Mueller (2013)

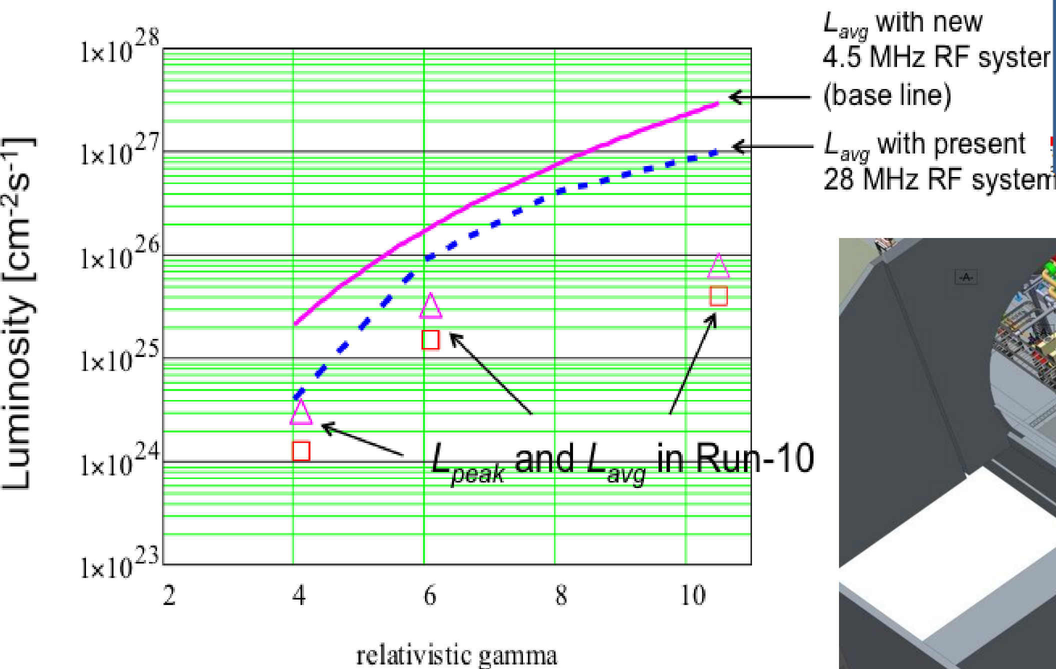
Years	Beam Species and Energies	Science Goals	New Systems Commissioned
2013	• 500 GeV pol p+p	• Sea quark and gluon polarization	• upgraded pol'd source • STAR HFT test
2014	• 200 GeV Au+Au • 15 GeV Au+Au • Fixed Au target test	• Heavy flavor flow, energy loss, thermalization, etc. • Quarkonium studies • 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

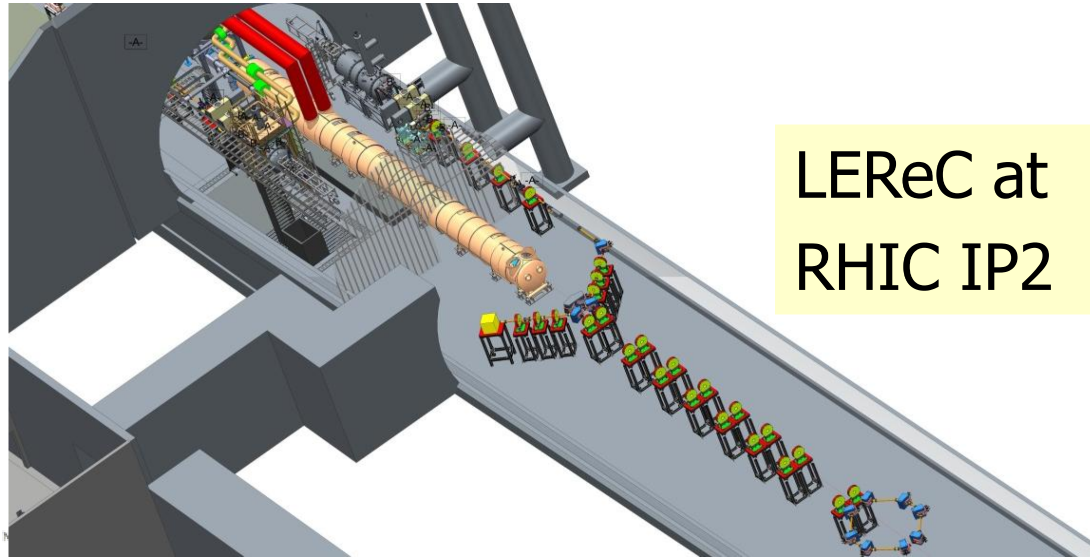
- **Finish installation in 2017**
- **Operation for physics starting 2018**



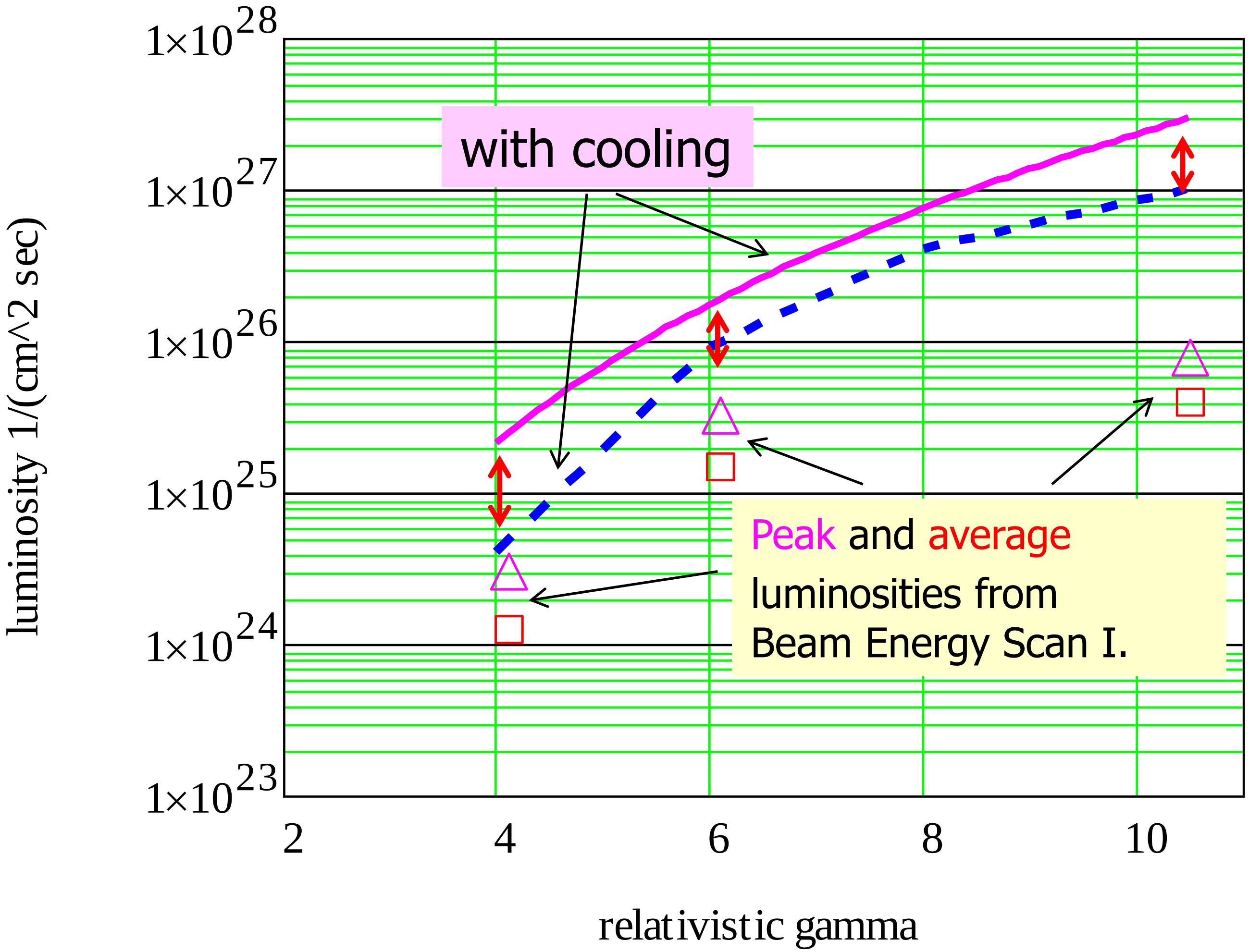
Energy	μB (MeV)	Events (M)
19.6	205	150
15.0	255	150
11.5	315	50
7.7	420	70
5.0	550	TBD



LEReC luminosity gain: 10x with new RF system



Luminosity projection with cooling upgrade (for present 28 MHz and proposed new 4.5 MHz (or 9 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 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

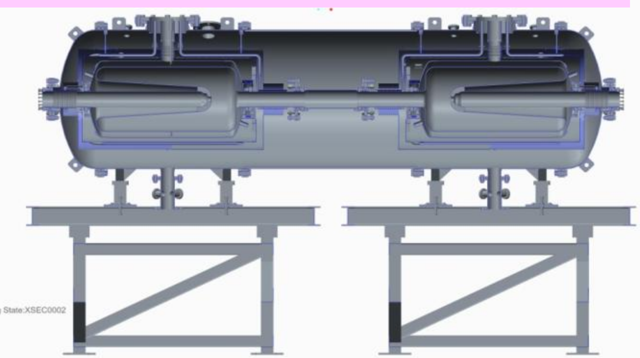
Low-Energy RHIC electron Cooler (LEReC)

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
   baseline: 2009-2012

2. RF-gun bunched beam electron cooler - (SRF gun and booster cavity) designed to reach $\sqrt{s_{NN}} = 20$ GeV →
   baseline: 2012-2013

compact approach (5 MeV):



Beam dynamics luminosity limits for RHIC operation at low energies

On top of dynamic aperture limitation

at lowest energies in RHIC

some fundamental limitations come from:

Intra-beam Scattering (IBS):

- **Strong IBS growth at lowest energies- can be counteracted by Electron cooling**

Beam-beam:

- **Becomes dominant limitation for RHIC parameters at $\gamma > 20$.**

Space-charge:

- **At lowest energies, ultimate limitation on achievable ion beam peak current is expected to be given by space-charge effects (note: not the same as typical space-charge limit in low-energy machines or space-charge dominated beams)**

Luminosity limitation by space-charge and beam-beam

Luminosity expressed through

beam-beam parameter ξ:

$$L = \frac{A}{Z^2 r_p} \frac{N_i c}{\beta^* C} \frac{2\gamma\beta^3}{1+\beta^2} f\left(\frac{\sigma_s}{\beta^*}\right)\xi$$

$$\xi = \Delta Q_{bb} = -\frac{Z^2 r_p}{A} \frac{N_i}{4\pi\beta^2\gamma\varepsilon} \frac{1+\beta^2}{2}$$

Luminosity expressed through

space-charge tune shift ΔQ_{sc}:

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

$$\Delta Q_{sc} = -\frac{Z^2 r_p}{A} \frac{N_i}{4\pi\beta^2\gamma^3\varepsilon} \frac{1}{B_f}$$

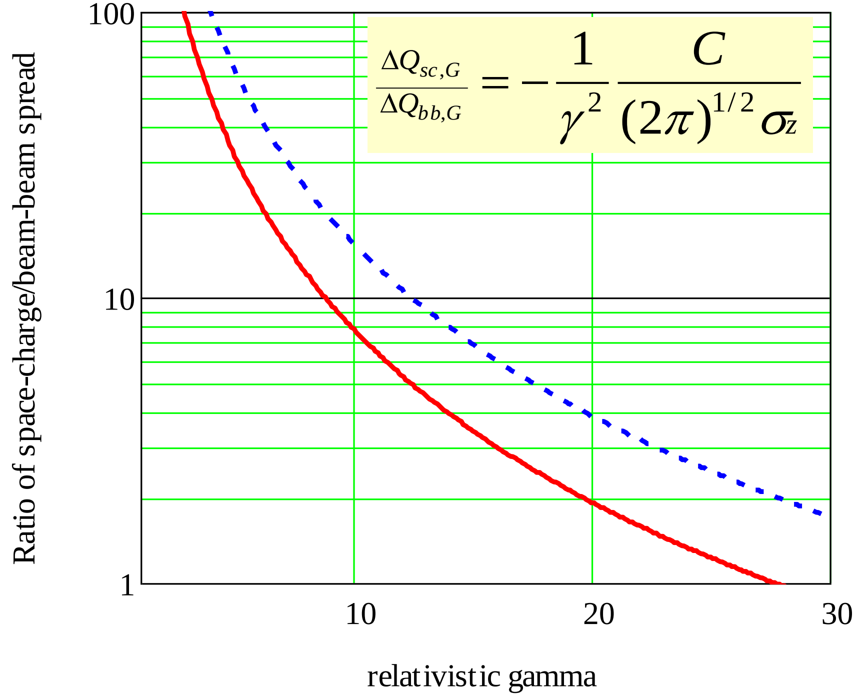


Figure 1: Ratio of space-charge tune spread to beam-beam spread (for heavy ions) at low energies in RHIC for rms bunch length 2 m (red) and 1 m (blue, upper dash line).

Interplay of space-charge and beam-beam effects

APEX studies for low-energy RHIC (with Au ions)

$\Delta Q_{sc} >> \xi$

- **APEX March 2010:**

Au+Au ions: γ=10 (modest space-charge, small beam-beam)

- **Several APEX and Low-Energy RHIC run May - June 2010:**

Au+Au ions: γ=6.1 and γ=4.1 (large space-charge, small beam-beam)

- **June 2011:**

Au+Au ions: γ=10, w.p. near integer (modest space-charge, small beam-beam)

Results published in:
Proc. of HB10: THO1C03
Proc. of PAC11: THP081
Proc. of IPAC12: WEPPR016

APEX studies for eRHIC parameters & luminosity (with protons)

large beam-beam parameter ξ

1. May 2009:

Protons at γ=25 (large beam-beam)

2. June 2009:

Protons at γ=25 and different w.p. (large beam-beam)

3. April 2012:

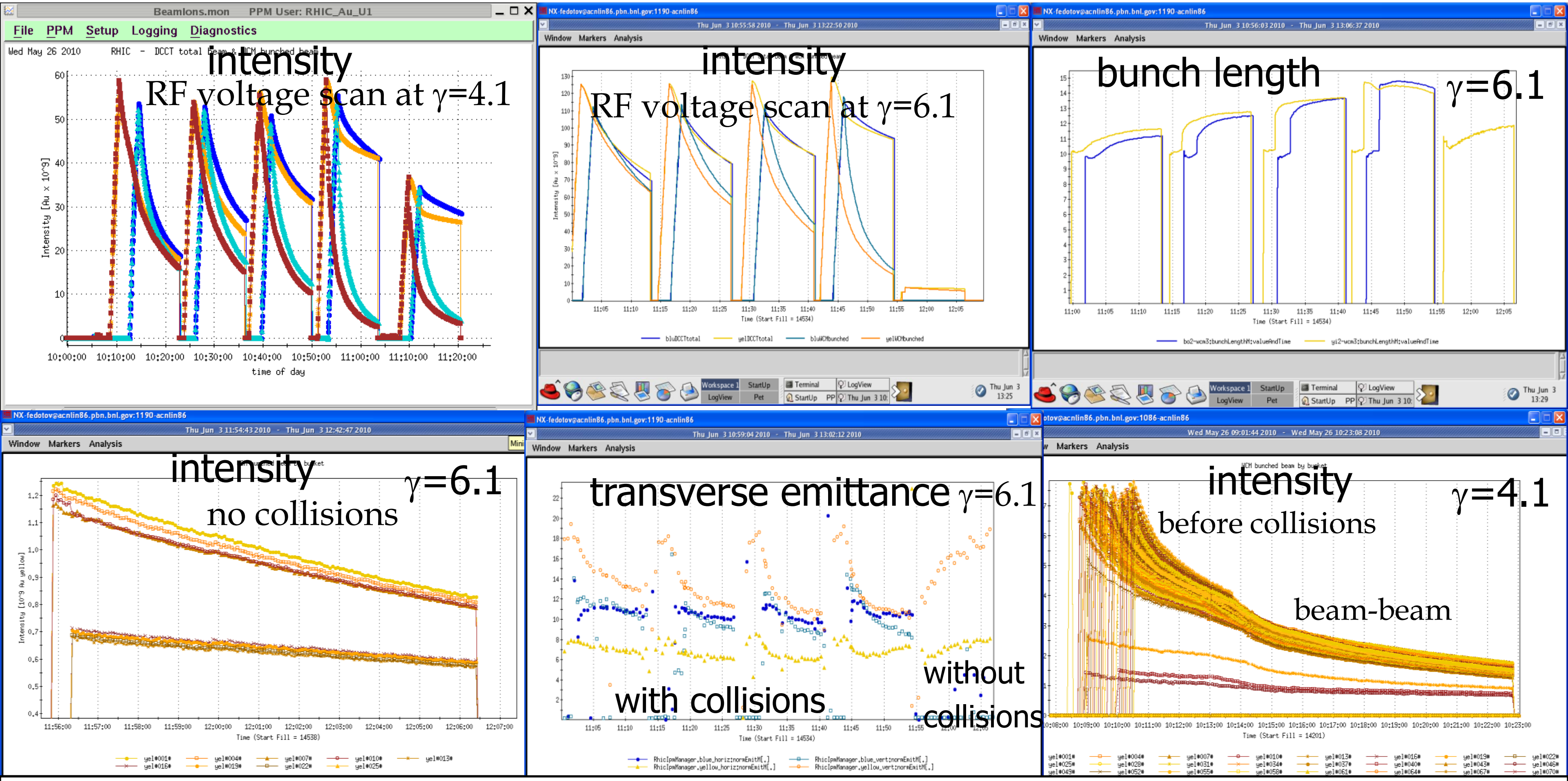
Protons at γ=25 and near integer w.p. (large beam-beam)

Previous APEX studies for low-energy RHIC

- intensity limitations (IBS, space charge)
- space-charge driven long-term beam lifetime (tune spread, high-order resonances, transverse acceptance)
- space-charge limit in a collider (interplay of space-charge and beam-beam effects)
- working point scans
- measurements without sextupoles
- with/without octupoles, tune-amplitude dependence
- RF voltage scan, lifetime dependence on off momentum DA

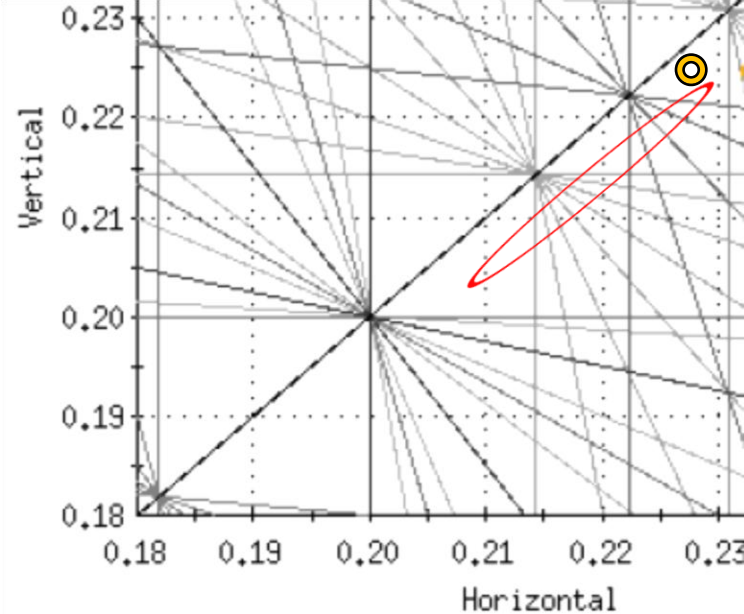
2010 Low-Energy RHIC studies: sqrt[s]=7.7 (γ=4.1) & 11.5 (γ=6.1) GeV

Series of APEX studies were done to understand beam lifetime at low energies.



Effect of working point and beam-beam:

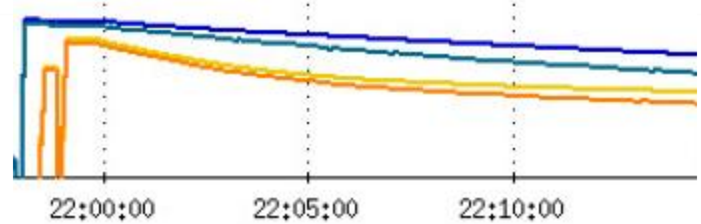
for modest dQsc one should be able to minimize effect of beam-beam.

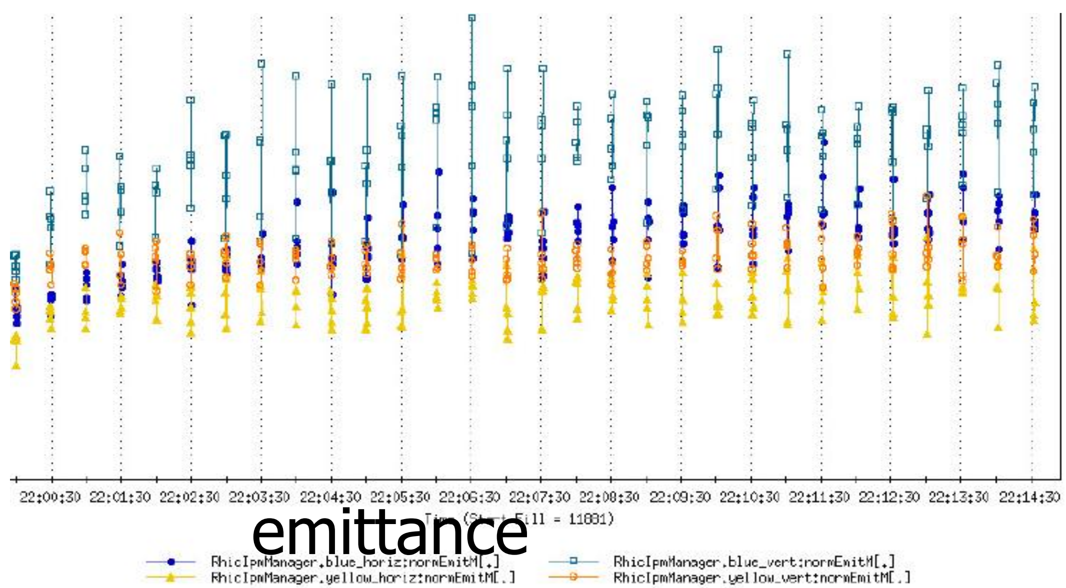


APEX, March 9, 2010:

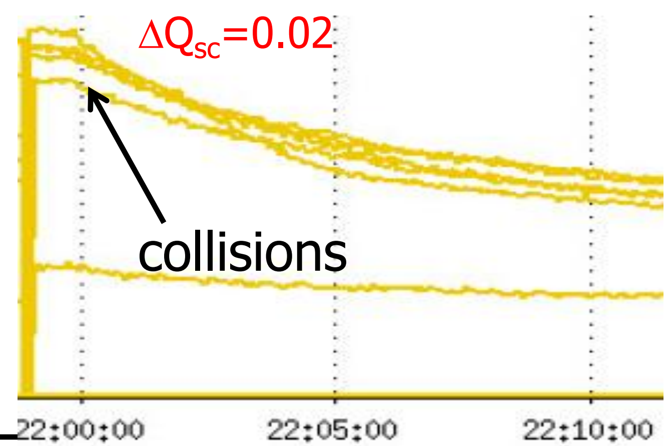
APEX Au ions at γ=10.5
w.p.=(0.0228, 0.0226)
maximum ΔQ_{sc}=0.03, ξ=0.002

$\Delta Q_{sc} >> \xi$



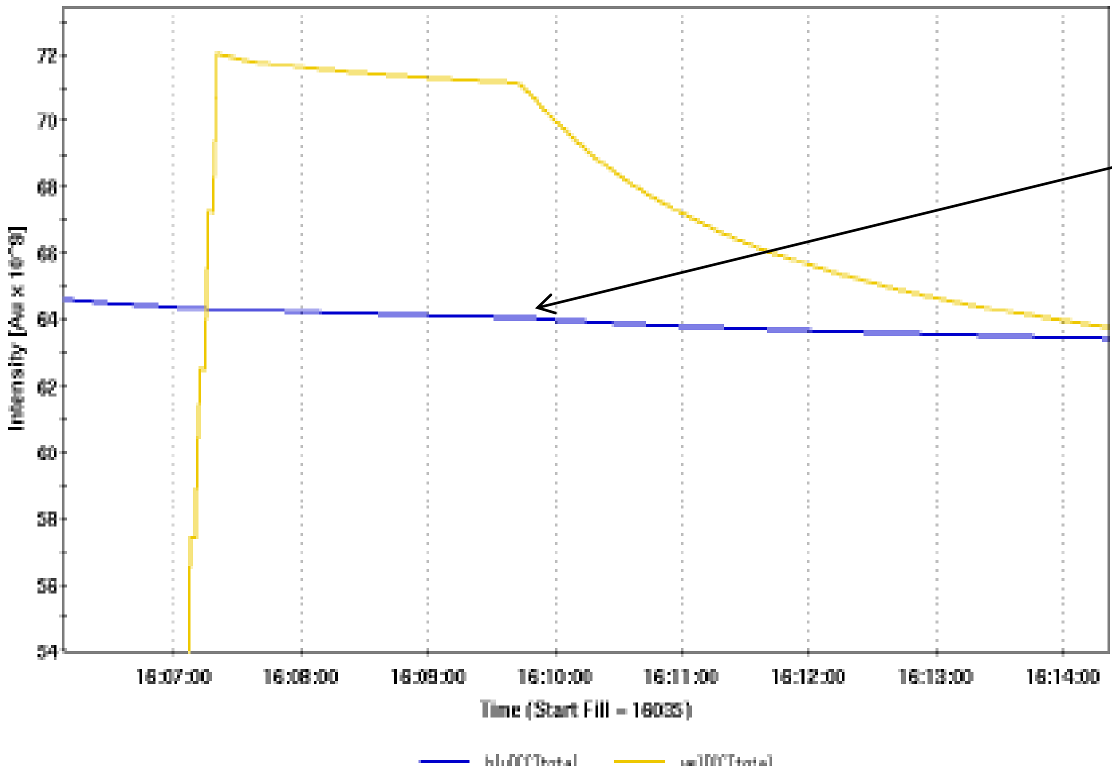


emittance



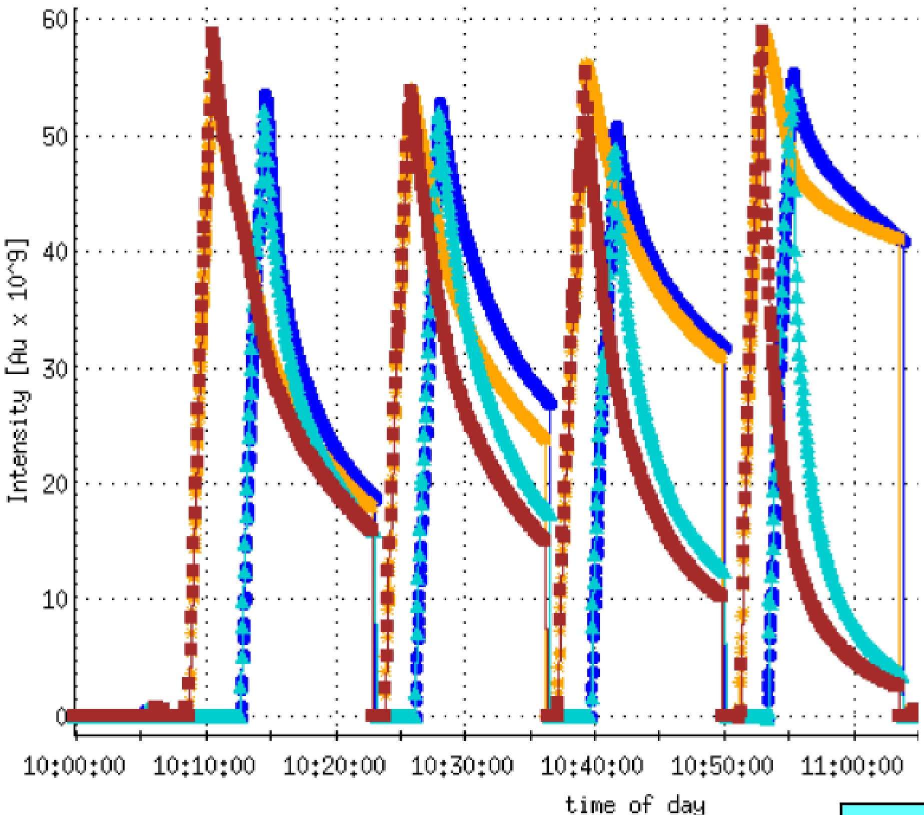
APEX, June 9, 2011

APEX Au ions at γ=10.5
Blue: w.p.=(0.08, 0.07), as planned
Yellow: w.p.=(0.08, 0.09)
maximum ΔQ_{sc}=0.03, ξ=0.002



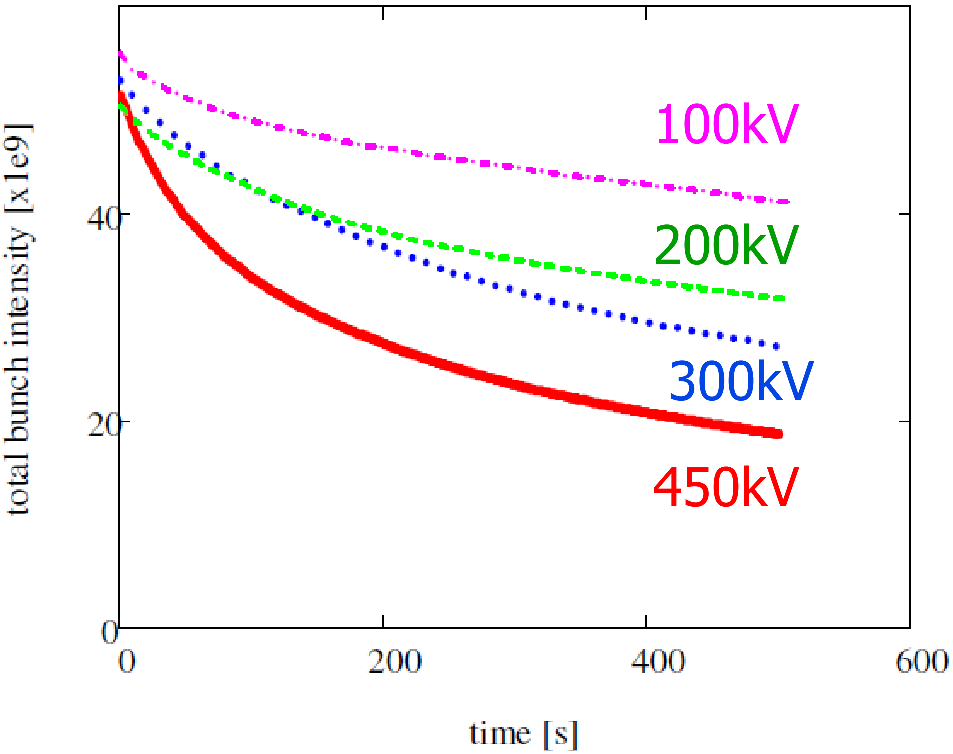
Almost no effect on beam lifetime in Blue after collisions.

RF voltage scan at γ=4.1



Four stores with 450, 300, 200 and 100kV RF voltage per ring.

Lifetime of de-bunched beam



τ [s]	V_{rf} [kV]	A_s [eV-s/n]	$\Delta p/p_{max}$ (bucket height)
80	450	0.2	0.0019
200	300	0.165	0.0015
300	200	0.135	0.0013
500	100	0.095	0.0009

Measured beam lifetime (without collisions)

Table 1. Overview of several experiments (without collisions).

ΔQ_{sc} (x,y)	τ [s]	γ	Comments
0.03	2000	10	$5\sigma_x$ acceptance, Q_s=0.002, no attempt for other w.p.
0.05, 0.04	1600	6.1	>$3\sigma_x$ acceptance, Q_s=0.006
0.085, 0.065	700	6.1	>$3\sigma_x$ acceptance, Q_s=0.006
0.1	70	4.1	$2.2\sigma_x$acceptance, Q_s=0.013

During 2009-12 several dedicated APEX experiments were done to study beam lifetime with large space charge spread and different beam-beam parameters.

For details see

Proc. of HB10: THO1C03;

Proc. of PAC11: THP081

Table 2. Best observed beam lifetimes for significant space charge (without collisions).

ΔQ_{sc}	τ	γ	Comments
0.02	> 6 h	10	Both rings
0.027-0.029	5/3h	10	Yellow/Blue
0.035	~2h	10	Yellow only, w.p. near integer

Lifetime was

improved by moving to a working point near integer.

Intensity dependent effects without collisions: at γ=6.1 vs. γ=4.1

For the same space-charge tune spreads (used here as intensity parameter):

1. dQ close to 0.1: 100 s (γ=4.1), 750 s (γ=6. 1)
2. dQ around 0.05: 300 s (γ=4.1), 1600 s (γ=6.1)

What was different:

Transverse acceptance (collimators: 2 (γ=4.1) vs. 3 sigma (γ=6. 1)) and

synchrotron modulation (Q_s=0.013 (γ=4.1) vs. 0.0064 (γ=6. 1)).

Perhaps, with e-cooling running at dQ=0.05 and retracted collimators reasonably good beam lifetime can be achieved. Even better beam lifetime might be possible if some improvements are achieved, as discussed in previous slides.

Note: Without aperture limitation (higher energy) and working point close to an integer, lifetime of 2 h was measured for dQsc=0.03.

Potential for luminosity improvement with longer bunches

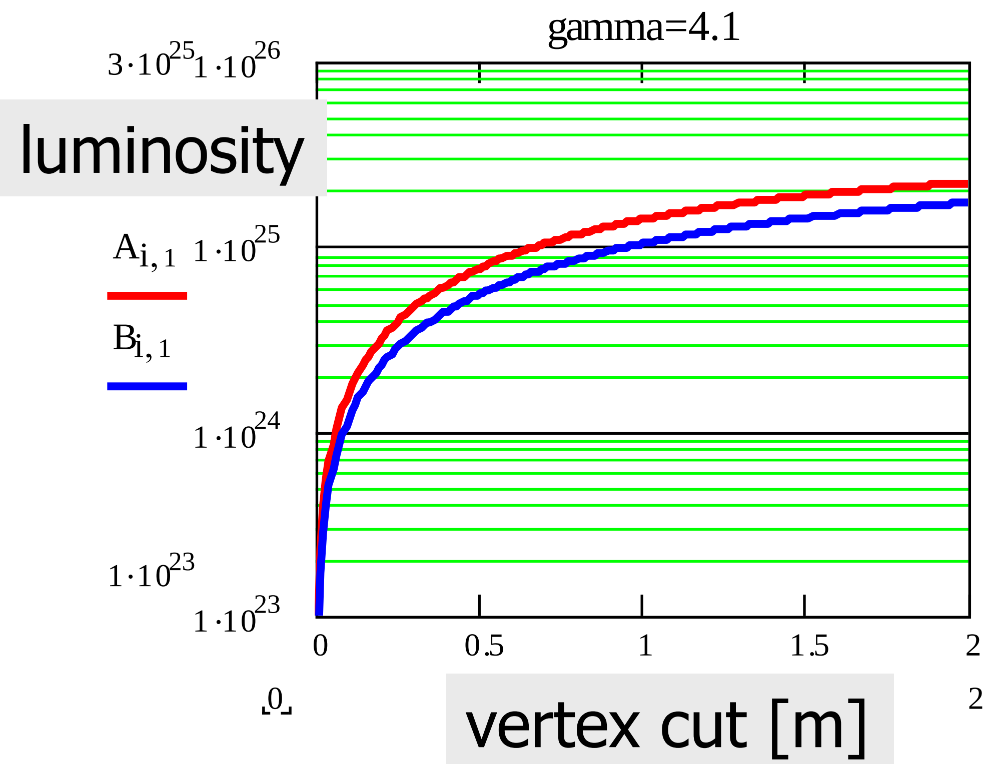
For present 28 MHz RF at lowest energies we are limited both by space charge and RF bucket acceptance (significant beam losses), which strongly limits luminosity improvement with cooling.

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.

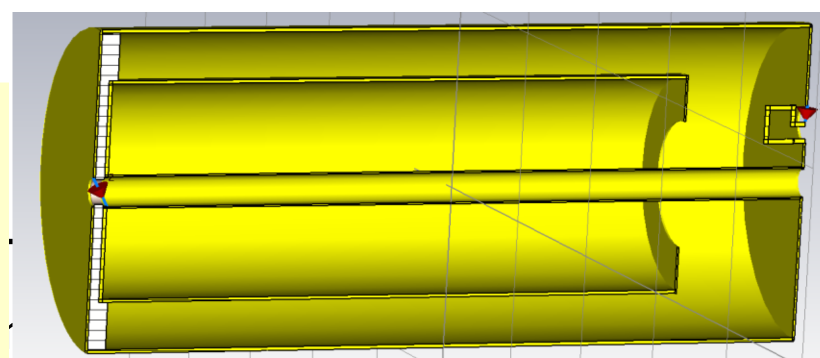
  » **Ferrite Loaded Cavity**

  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



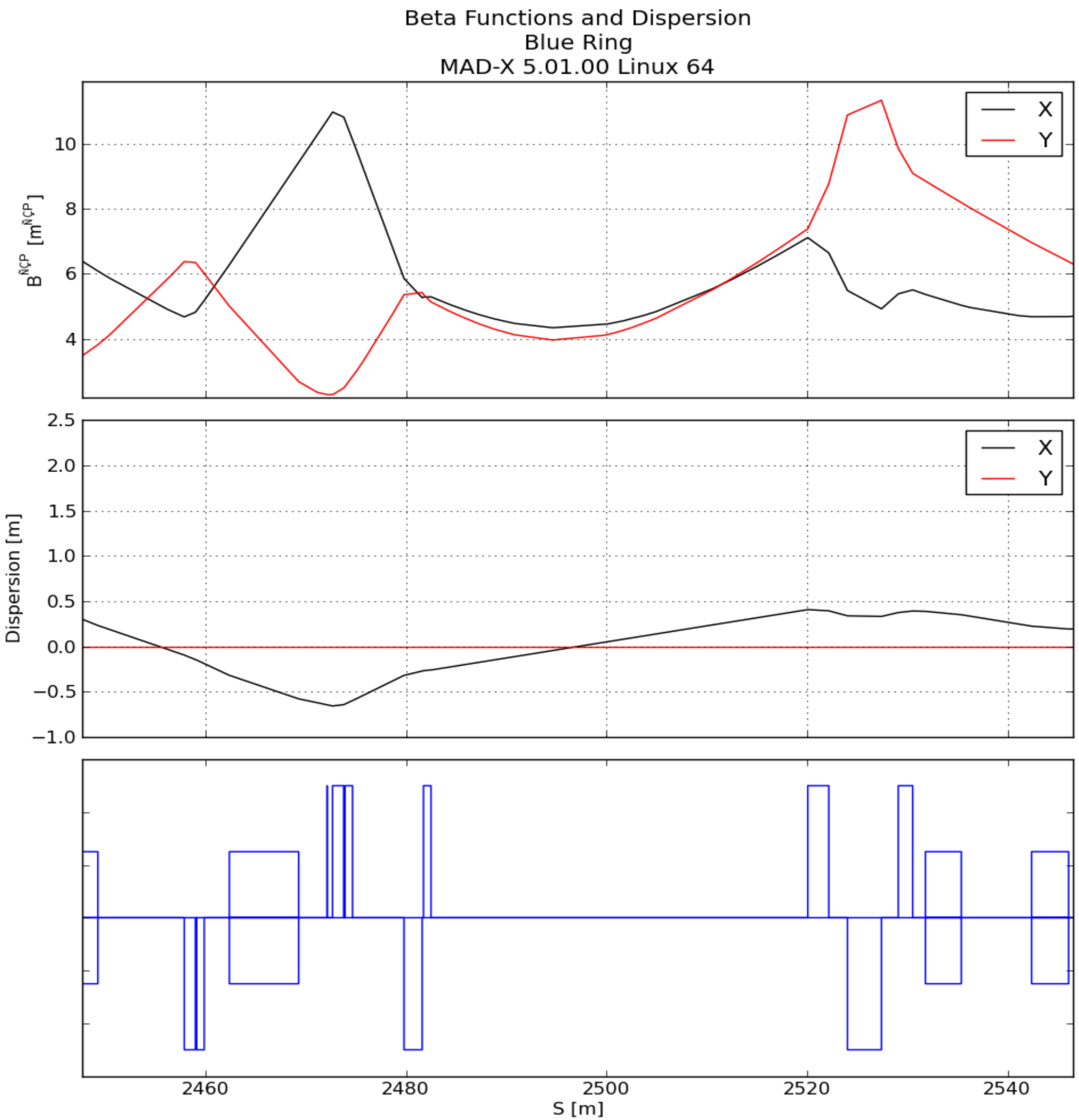
Beam lifetime with collisions

Significant effects on the beam lifetime were observed when beams were put into collisions . For the space-charge tune spread larger than 0.05 it appeared difficult to find sufficient space free from dangerous resonances on the tune diagram to avoid effects of beam-beam on the lifetime.

For heavy ions, an experiment was performed in RHIC with the space-charge tune spreads of 0.02-0.035 (but much smaller beam-beam parameters) by moving the working point close to an integer. Very little effect on beam lifetime was observed after beams were put into collisions.

This is different from RHIC operation with protons, where different regime was studied with a large beam-beam parameter.

RHIC optics in cooling section will be different



IBS redistribution

Below transition energy (in RHIC γ_t is about 23):

If we could shrink bunch length -> increase ion beam momentum spread, we could make longitudinal beam temperature larger than transverse.

This would minimize longitudinal emittance increase due to IBS and prevent beam loss from RF bucket.

For luminosity improvement, the bunch length growth, intensity loss due to debunching, and transverse emittance growth are all important.

from C-A/AP/#339 Tech Note:

Table 5. Initial longitudinal τ_z^{-1} and transverse τ_x^{-1} IBS rates ($\tau_x^{-1} \equiv d\varepsilon_x/(\varepsilon_x dt)$, $\tau_z^{-1} \equiv d\sigma_p^2/(\sigma_p^2 dt)$) for different longitudinal emittance ($S_{95\%}$) for 28 MHz RF with 500 kV total gap voltage. Bunch intensity $N=1\times10^9$, transverse beam emittance $\varepsilon=15\mu m$ (95%, normalized).

γ	h	$S_{95\%}$, eV-s/n	τ_x^{-1}, sec^{-1}	τ_z^{-1}, sec^{-1}
2.7	387	0.1	0.007	0.004
3.2	378	0.1	0.004	0.006
		0.14	0.0044	0.002
4.3	369	0.1	0.0015	0.013
		0.14	0.0018	0.005
		0.2	0.002	0.0016
6.4	363	0.1	0.0002	0.016
		0.2	0.0006	0.003
		0.4	0.0007	0.0006

Work on further improvements

Possible studies

1. **Studies of magnet cycles (can be done on the test bench).**
2. **Studies of DA by tracking.**
3. **Beam lifetime study without collimators.**
4. **Runs with longer bunches and smaller momentum spread.**
5. **Issues with very long bunches and BPM's signals.**
6. **RHIC lattice studies for LEReC. Will show whether relocation of diagnostics like IPM, kickers to other sectors is needed.**
7. **IBS redistribution study.**

Most of these studies could be done during 7.5 GeV run during machine development or APEX.