Interplay of space-charge and beam-beam effects

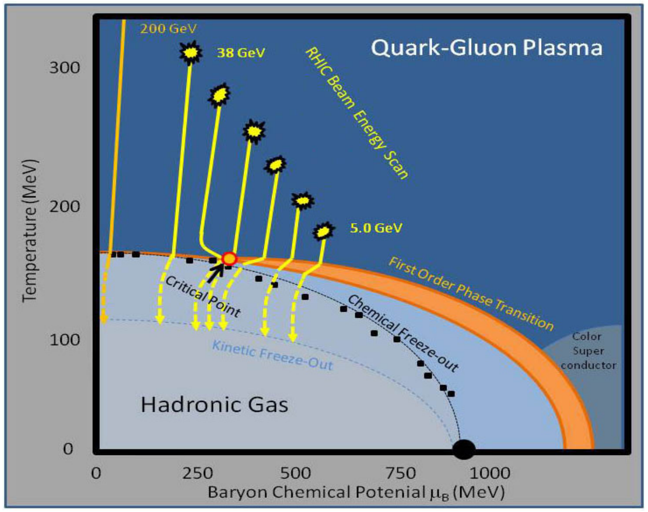
RHIC APEX Workshop

Stony Brook University, October 18-19, 2010

Space-charge limitations in a collider:

• Operation of collider at low energy or use of cooling techniques to increase beam density may result in luminosity limitation due to the space-charge effects.

• 2009-10 APEX studies were motivated by proposal of luminosity upgrade for Low-Energy RHIC with Electron Cooling.



• Becomes important for several projects under design such as NICA at JINR, Electron-Nucleon Collider at FAIR, eRHIC, ELIC, as well as Low-Energy RHIC.

Beam dynamics luminosity limits for RHIC operation at low energies

The beam lifetime observed during lower energy test runs (before 2010) was limited by machine nonlinearities.

Other (high intensity) limitations come from:

Intra-beam Scattering (IBS):

- IBS growth at lowest energies - can be counteracted by Electron Cooling

Beam-beam:

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

Space-charge:

- At lowest energies, ultimate limitation on achievable ion beam peak current is expected to be given by space-charge effects.

What luminosity improvement can we have with E-cooling?

Depends on the question:

To what space-charge tune shift value can we cool and what will be the resulting beam lifetime?

Luminosity limitation by space-charge or beam-beam

Luminosity expressed through

beam-beam parameter ξ:

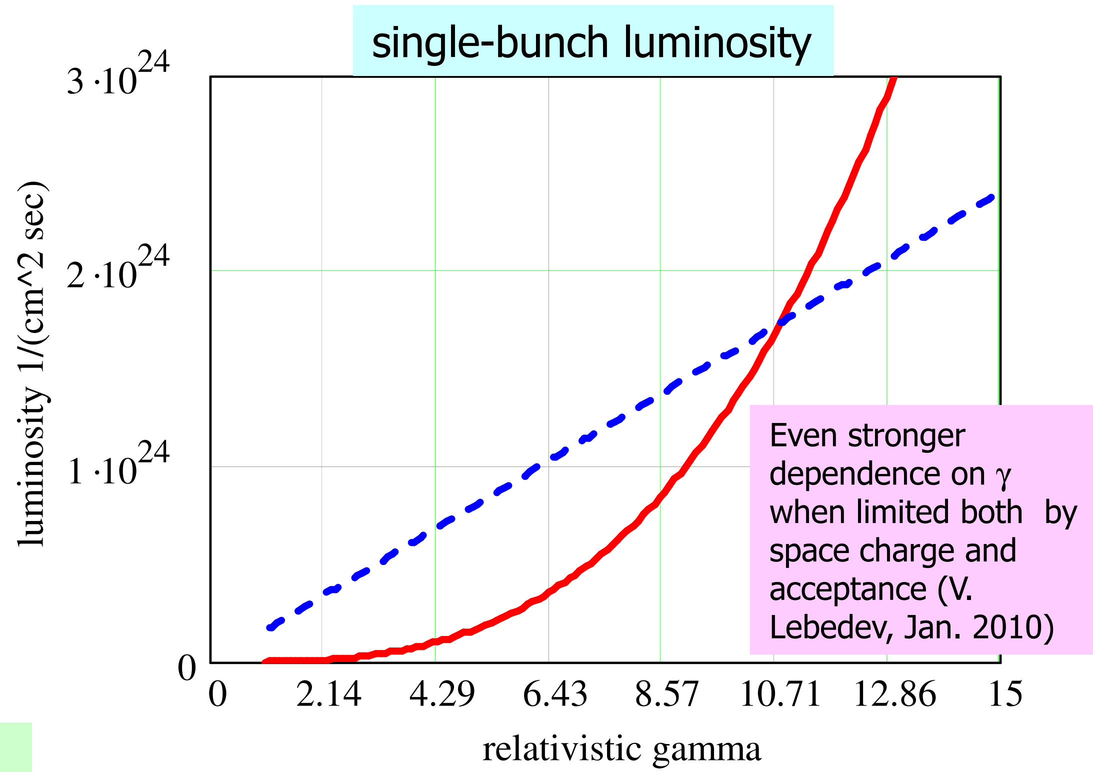
$$L = \frac{A}{Z^2 r_p} \frac{N_i c}{\beta^* C} \frac{2\gamma\beta^2}{1+\beta^2} f\left(\frac{\sigma_s}{\beta^*}\right)\xi$$

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

Luminosity expressed through
space-charge tune shift ΔQ:

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

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



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

Red: space-charge limitation with ΔQ=0.05.

Available theoretical and experimental knowledge about independent limitation due to the space-charge or beam-beam effects is extensive and provides useful guidelines, but interplay of both effects is largely unexplored.

What is acceptable space-charge tune shift for long beam lifetime with collisions?

Experimental studies in RHIC: $\Delta Q_{sc} > \xi$

- **Accelerator Physics Experiments (APEX) May and June 2009:**

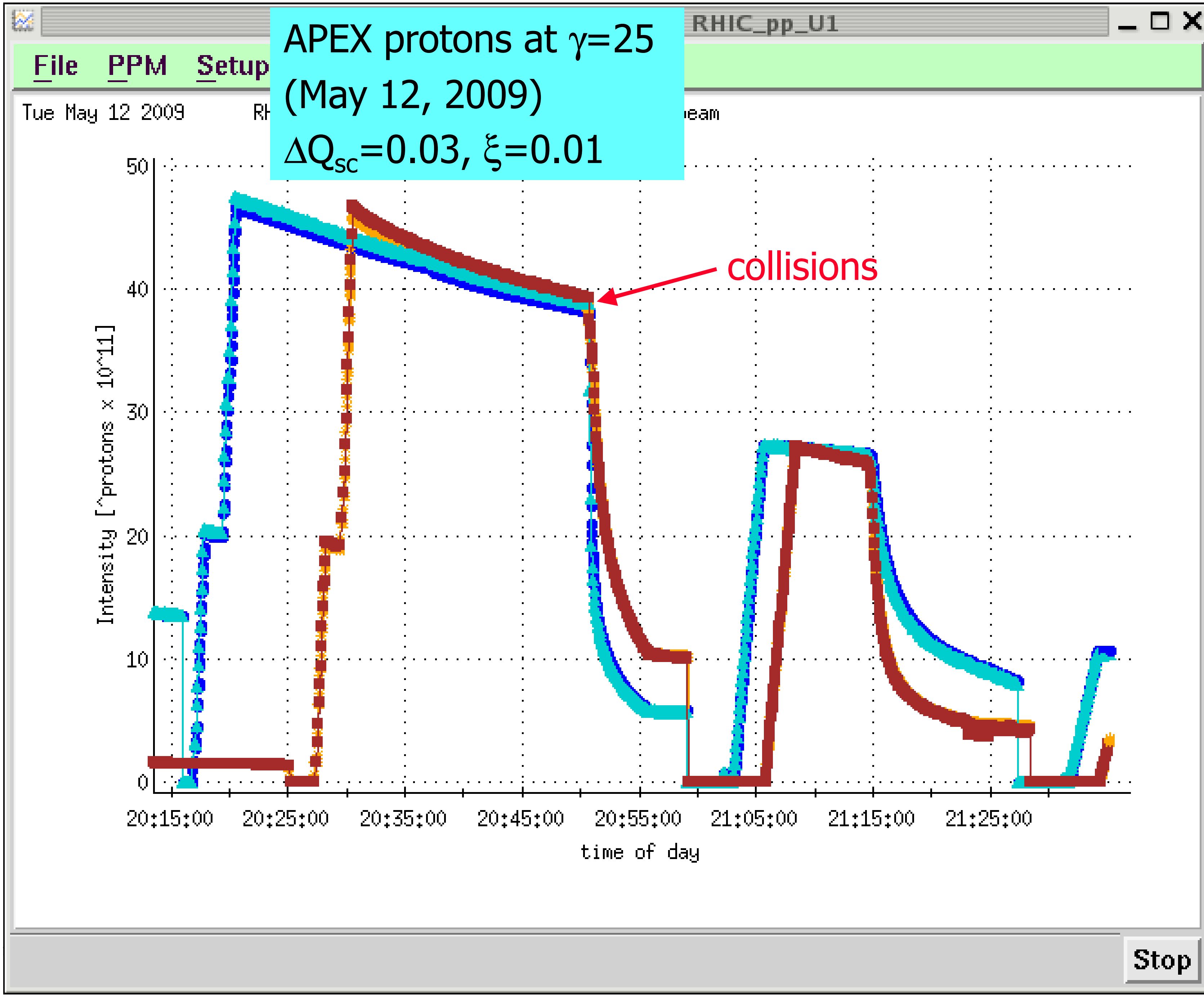
p+p: at beam γ=25 (modest space-charge, large beam-beam)

- **APEX March 2010:**

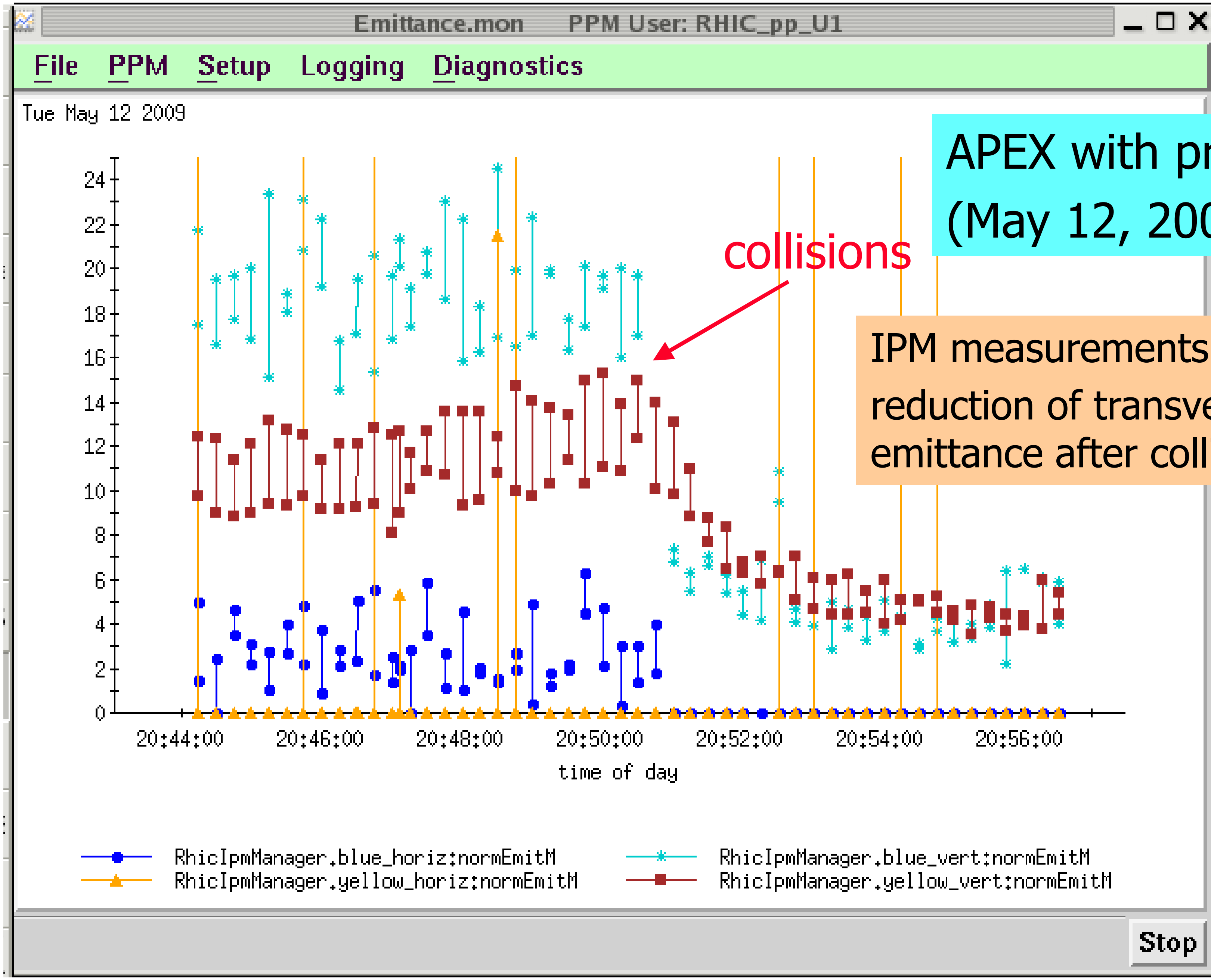
Au+Au ions: γ=10.5 (modest space-charge, small beam-beam)

- **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)

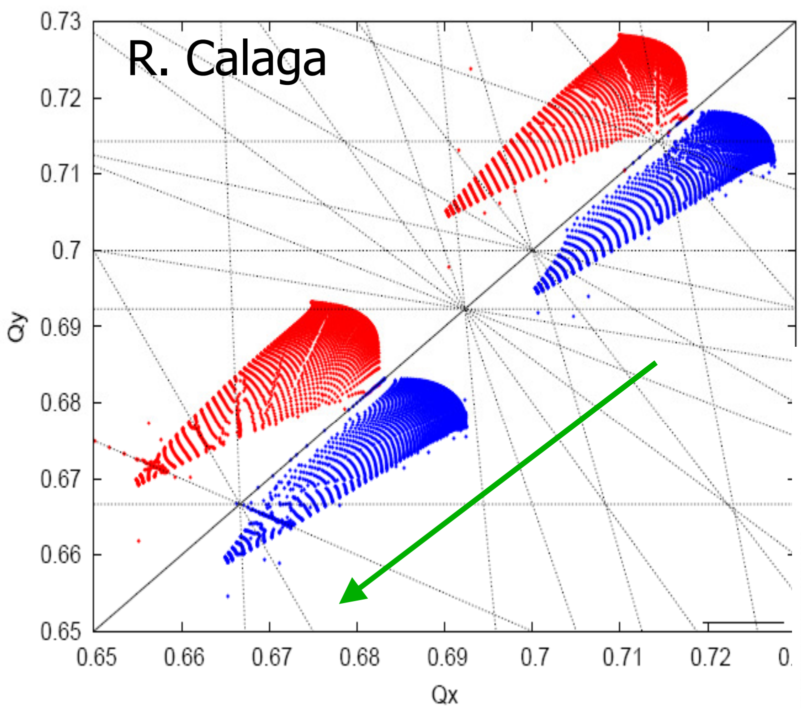

RHIC_pp_U1
File
PPM
Setup
Tue May 12 2009
APEX protons at γ=25
(May 12, 2009)
ΔQ_{sc}=0.03, ξ=0.01
collisions
Intensity [^protons x 10^11]
50
40
30
20
10
0
20:15:00
20:25:00
20:35:00
20:45:00
20:55:00
21:05:00
21:15:00
21:25:00
time of day
Stop

APEX with protons (May 12, 2009)

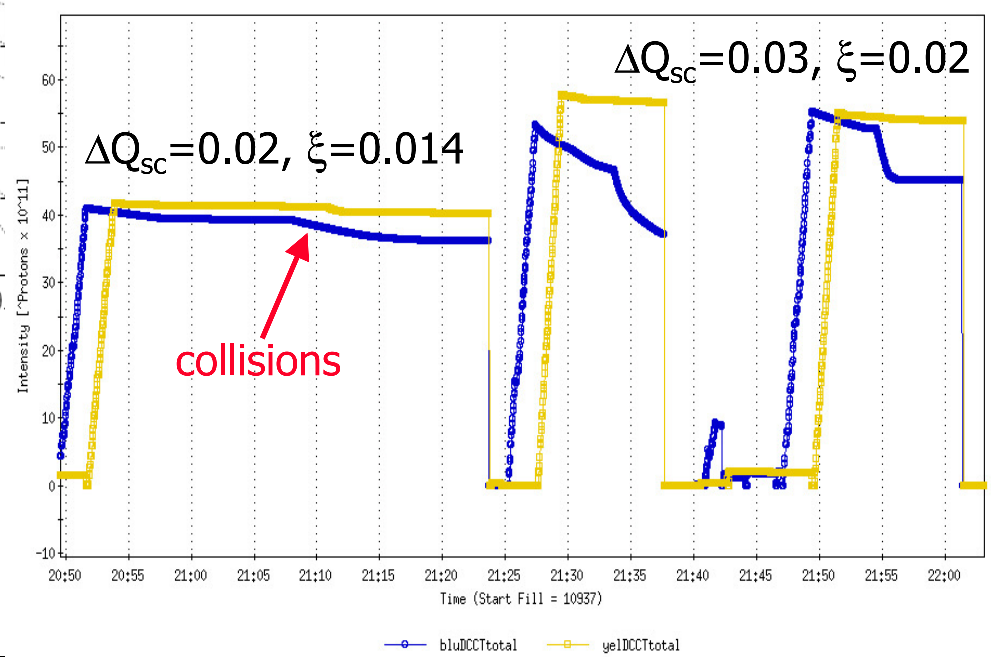


IPM measurements:
reduction of transverse emittance after collisions.

June 17, 2009 experiment with new working point



APEX with protons (June 17, 2009)



Choosing different working point for regime with large beam-beam.

Low-Energy RHIC regime of interest

$$\Delta Q_{sc,G} = -\frac{N_b Z^2 r_p}{4\pi A \beta \gamma^2 \varepsilon_{n,rms}} \frac{C}{(2\pi)^{1/2} \sigma_z}$$

$$\Delta Q_{bb,G} = \xi = -\frac{N_b Z^2 r_p}{4\pi A \varepsilon_{n,rms}} \frac{(1+\beta^2)}{2\beta}$$

$$\frac{\Delta Q_{sc,G}}{\Delta Q_{bb,G}} = -\frac{1}{\gamma^2} \frac{C}{(2\pi)^{1/2} \sigma_z}$$

Example:

Low-E RHIC lowest energy point
Au ions γ=2.7 (sqrt[s]=5 GeV/n)

when limited by space charge
ΔQ_{sc}=0.05

beam-beam tune shift is very small ΔQ_{bb}=0.00057

$\Delta Q_{sc}/\Delta Q_{bb}$=88

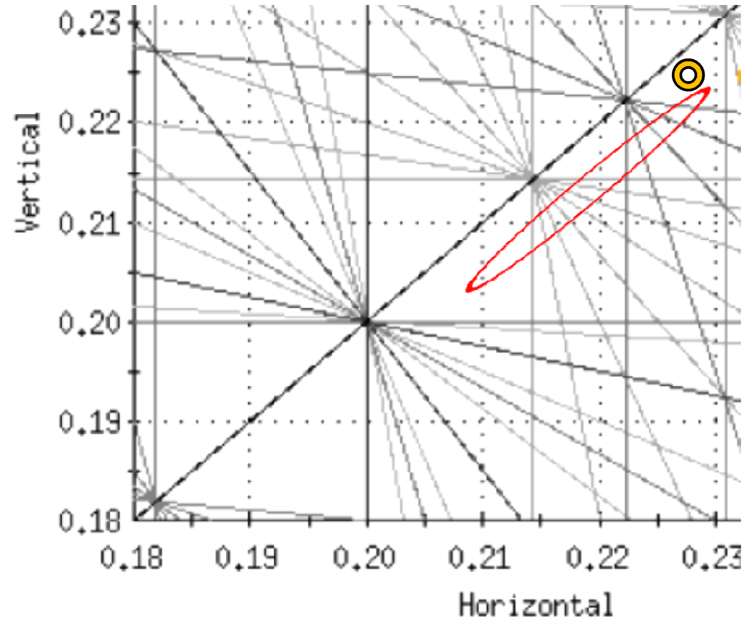
For Low-E RHIC we are interested in the regime:

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

Should we expect beam lifetime limitation mostly due to resonance crossing with a large tune spread?

APEX Au ions at γ=10.5
(March 9, 2010)
maximum ΔQ_{sc}=0.03, ξ=0.002

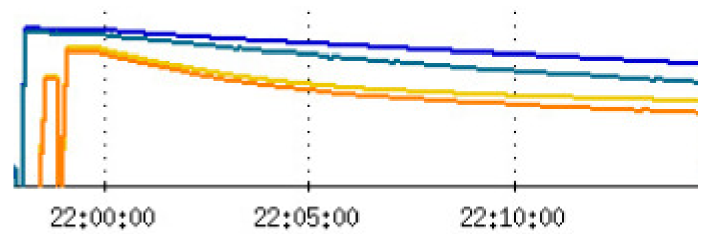
$\Delta Q_{sc} >> \xi$

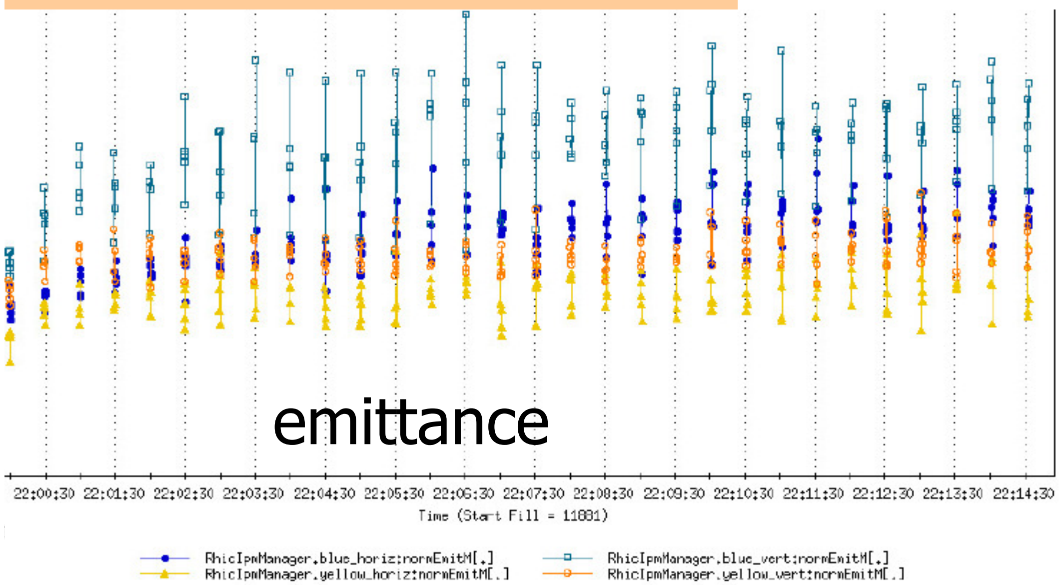


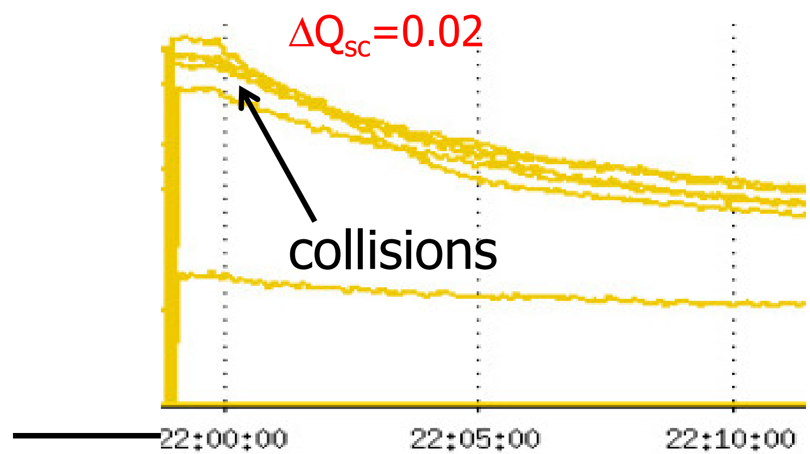
Better than in 2009
with large beam-beam.

The goal of this APEX was to achieve large space-charge tune-shifts. We were NOT able to produce large space-charge tune spread at this energy (insufficient RF voltage).

Working point good for space-charge, is not good enough for space-charge tune spread with beam-beam.

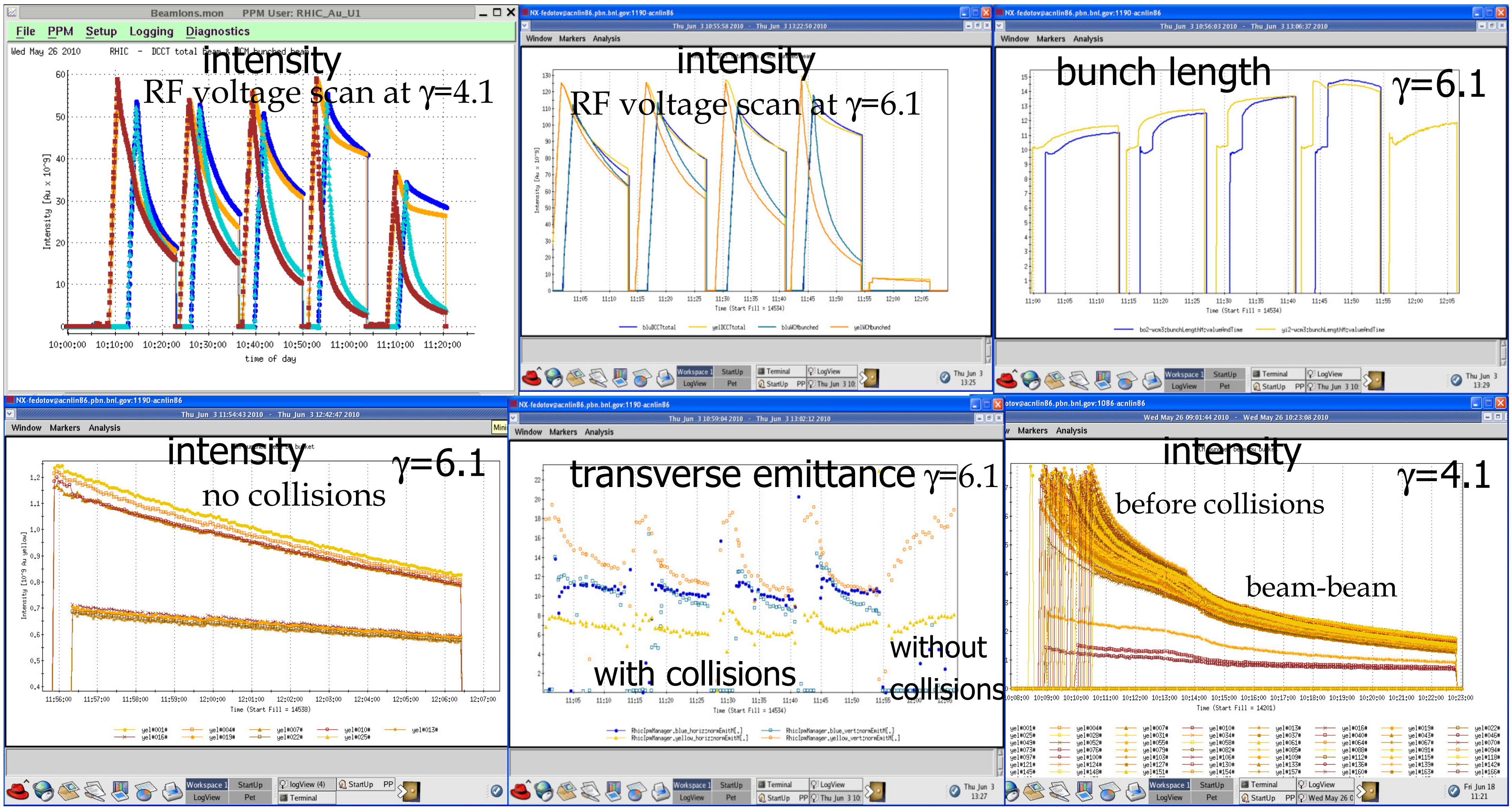




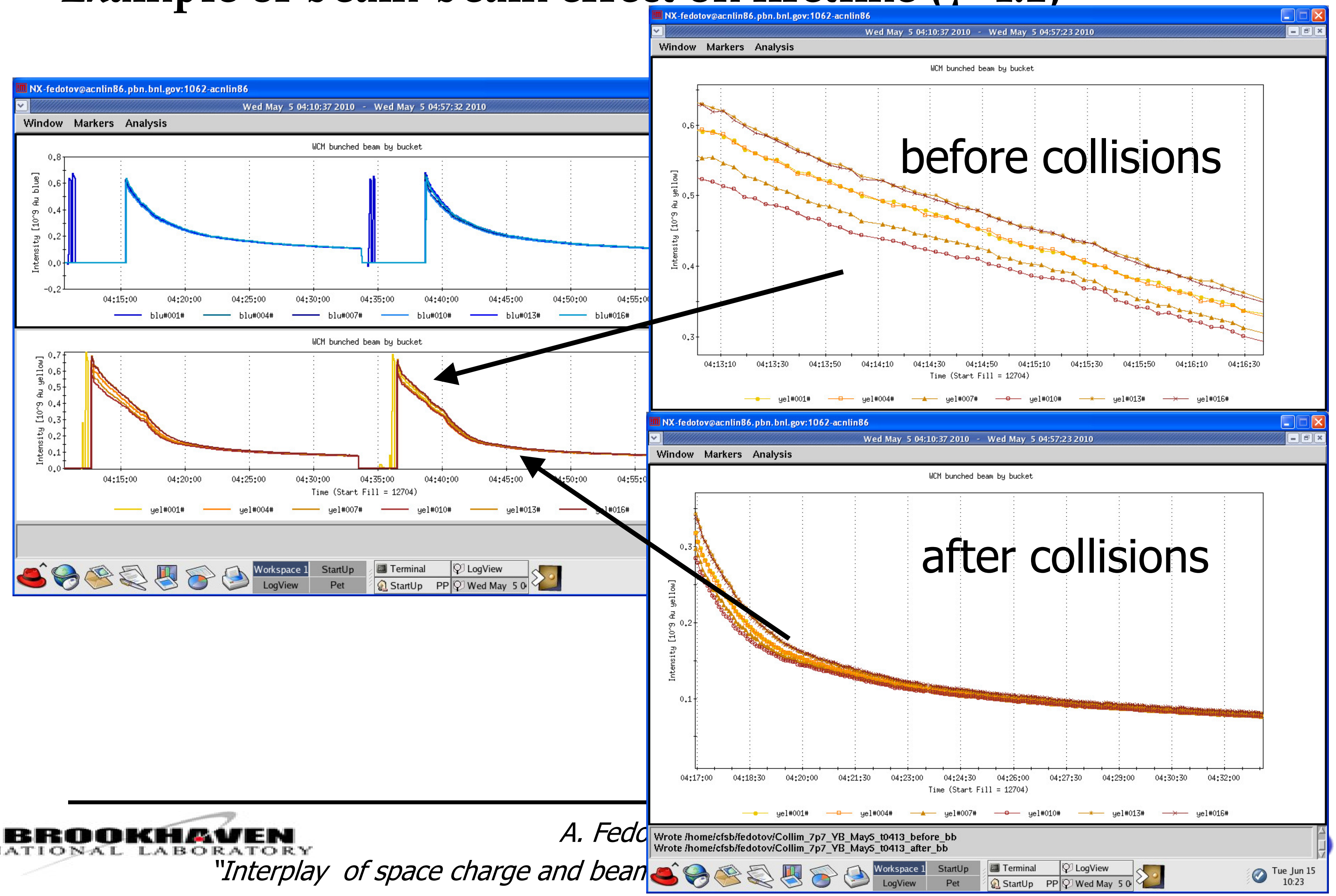


2010 Low-E RHIC runs: sqrt[s]=7.7 (γ=4.1) & 11.5 (γ=6.1) GeV/n

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



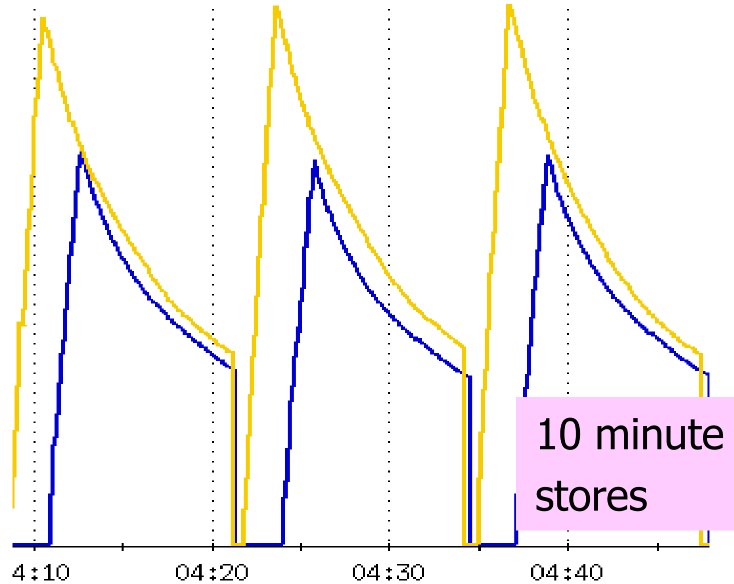
Example of beam-beam effect on lifetime (γ=4.1)



Beam lifetime at center of mass energy sqrt[s]=7.7 GeV/n (γ=4.1)

- Large b2 (sextupole errors) in dipoles, other nonlinearities
- Octupoles were introduced as well to compensate for amplitude-dependent tune spread
- Space charge
- Beam-beam
- Collimators

All of these effects contribute to beam lifetime.



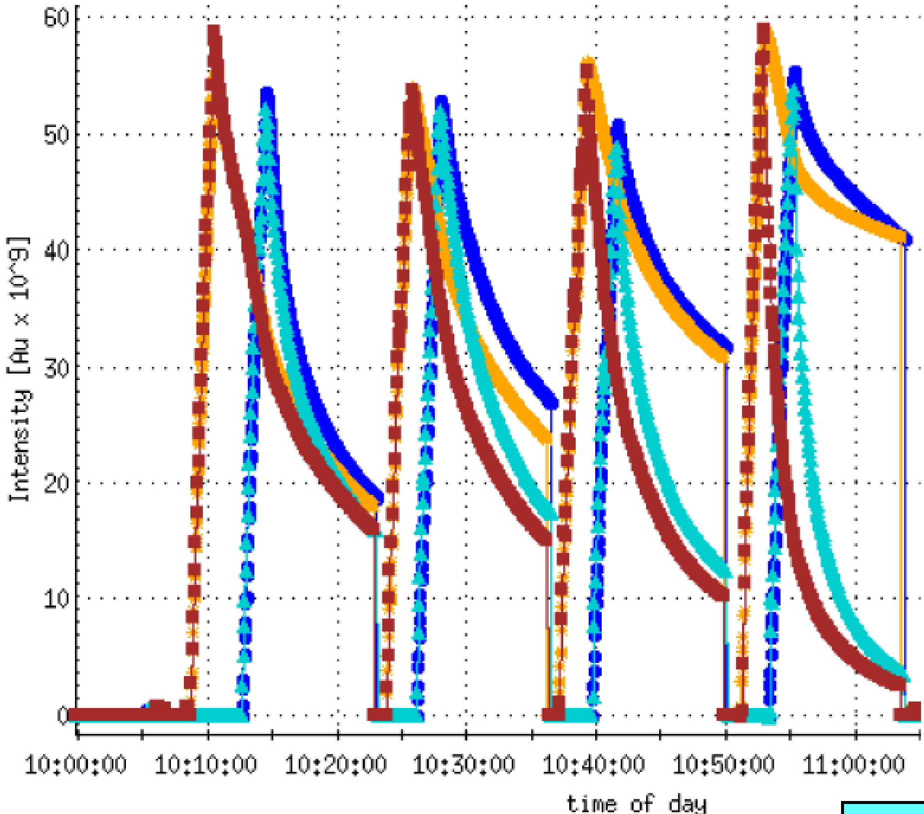
Low-E RHIC γ=4.1 (sqrt[s]=7.7 GeV/n)

Space charge up to $\Delta Q_{sc}=0.1$

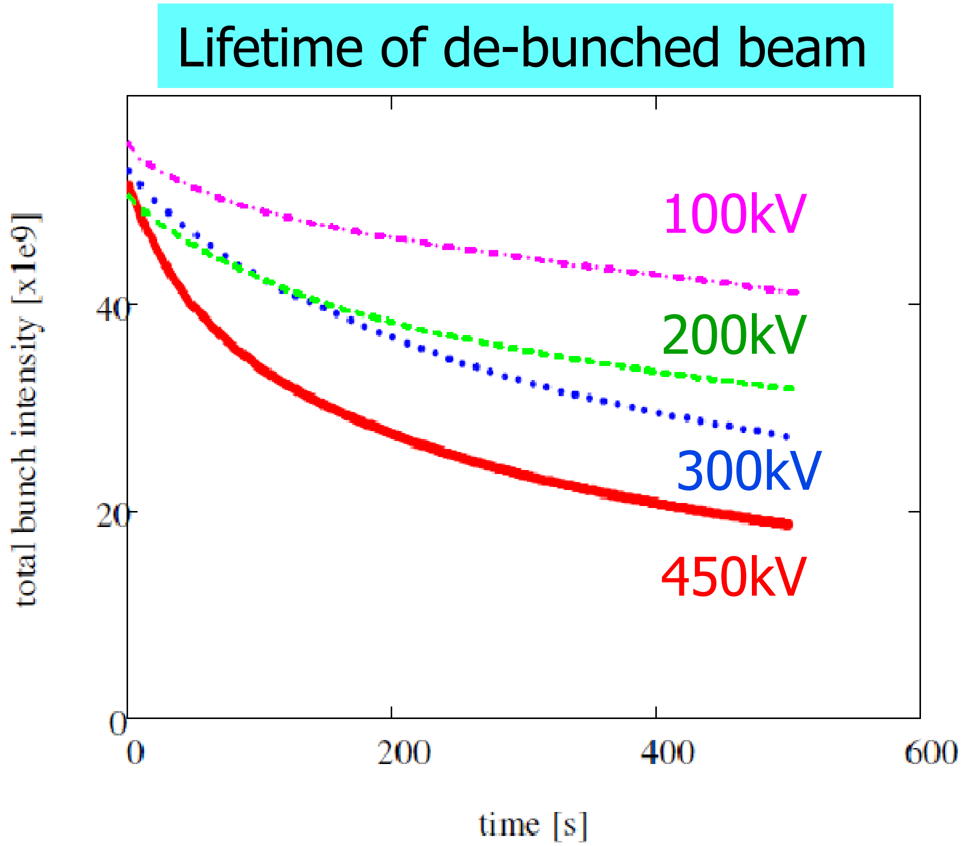
beam-beam $\Delta Q_{bb}=\xi=0.0014$

At sqrt[s]=7.7 GeV/n for highest intensities beam lifetime was limited by a fast component of about 100 sec. At higher energy sqrt[s]=11.5 GeV/n, lifetime was much better for the same space-charge tune shifts.

RF voltage scan at γ=4.1



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



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 for different space charge

no collisions

ΔQ_{sc} (x,y)	τ [s]	γ	Comments
0.03	2000	10	5σ acceptance
0.05, 0.04	1600	6.1	3σ acceptance
0.09, 0.06	700	6.1	3σ acceptance, Q_s=0.006
0.1	70	4.1	2.2σ acceptance, Q_s=0.013

Caution: This is an overview of several experiments with different conditions.

Significant limitation of dynamic aperture at γ=4.1 was expected

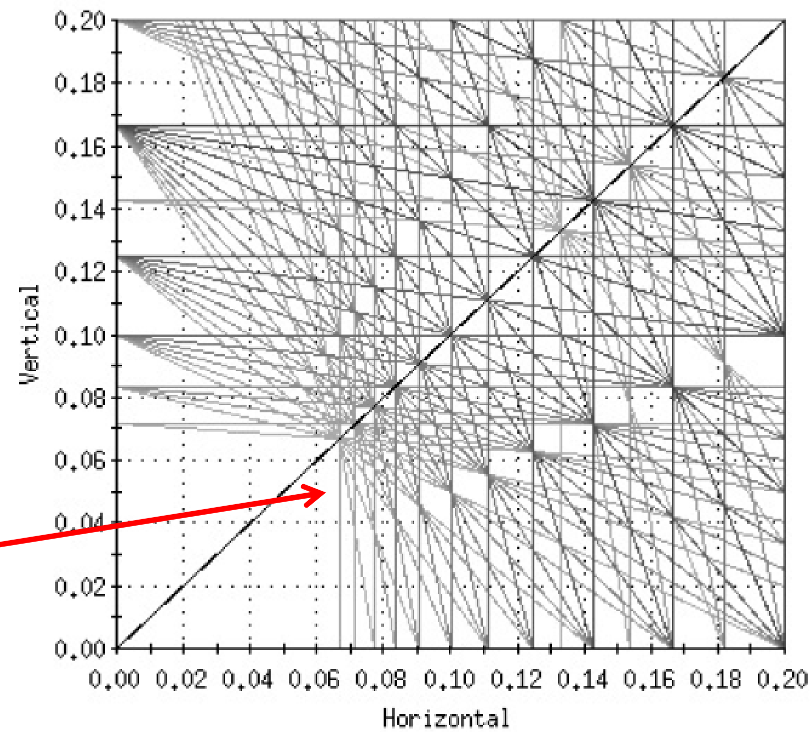
with collisions

ΔQ_{sc}	τ [s]	γ	Comments
0.03	600	10	5σ acceptance
0.05	400	6.1	3σ acceptance
0.1	260	6.1	3σ acceptance, Q_s=0.006
0.1	70	4.1	2.2σ acceptance, Q_s=0.013

Beam-beam parameter ξ=0.001-0.002

We observed effect of beam-beam on lifetime for any space-charge tune spread (when $\Delta Q_{sc} > \xi$), even in the regime with very small ξ.

resonances to 15th order



For Low-Energy RHIC:

It is hard to find working point where effect of beam-beam is minimized due to large (ΔQ_{sc} ~0.1) tune spread.

For small ΔQ_{sc} (~0.03), eRHIC:

We should be able to find better working point.

Possible approach to improve beam lifetime for Low-Energy RHIC

- **Effect of space-charge and beam-beam can be reduced by running at slightly large emittances (at least for higher energy points when there is enough acceptance)**

$$L = \frac{A}{Z^2 r_p} \frac{N_1 c}{\beta^*} \frac{\sqrt{2\pi}\sigma_s}{C^2} \gamma^3 \beta^2 f\left(\frac{\sigma_s}{\beta^*}\right) \Delta Q$$

$$\Delta Q_{sc} = -\frac{Z^2 r_p}{A} \frac{N_1}{4\pi\beta^2\gamma^3\varepsilon_1} \frac{C}{\sqrt{2\pi}\sigma_s}$$

- This should improve beam lifetime.

- It should make easier to find better tune space.

- Peak luminosity is not necessarily reduced.

$$L \propto \sqrt{2} N_1 \frac{\sqrt{2} N_1}{2\varepsilon_1}$$

This was tried during last day of Run-10 on June 7. Unfortunately, it did not work because of strong acceptance limitation due to collimators, which was not realized until the end of the run. Should be repeated without collimators.

Future APEX studies:

Protons at standard injection energy (γ=25):

Finding working point where effects of beam-beam are minimized for regime ΔQ_{sc}=0.03, ξ=0.01-0.02 (this is regime of interest for eRHIC).

Au ions at injection energy (γ=10.5):

Finding working point where effects of beam-beam are minimized for regime ΔQ_{sc}=0.03, ξ=0.002 (to cross check with large beam-beam)

Low-Energy RHIC:

Dedicated measurements (without collimators) are needed either at γ=6.1 (sqrt[s]=11.5 GeV) or γ=4.1 (sqrt[s]=7.7 GeV) to understand possibility for future improvement (very limited room for improvement at γ=4.1).