Interplay of space-charge and beam-beam effects in a collider

A. Fedotov, M. Blaskiewicz, W. Fischer,

T. Satogata, S. Tepikian

Collider-Accelerator Department

Brookhaven National Laboratory

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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.

- 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.

- Motivation for Low-Energy RHIC: proposed luminosity upgrade with Electron Cooling.

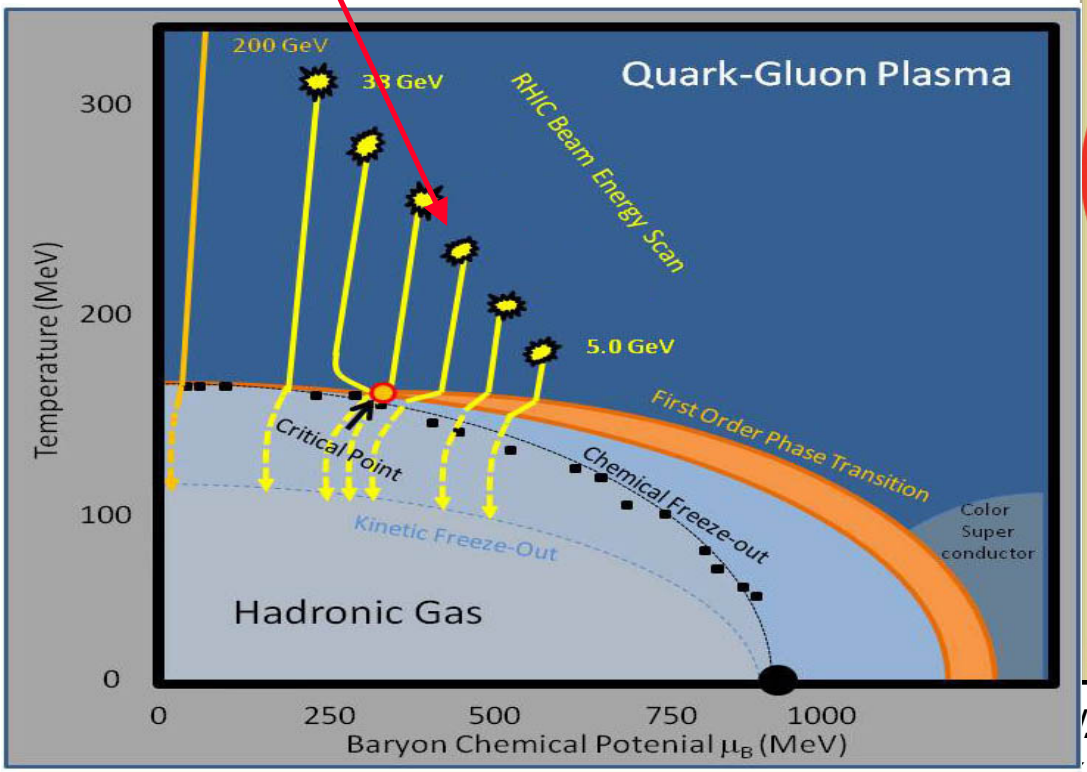
Low-Energy RHIC:

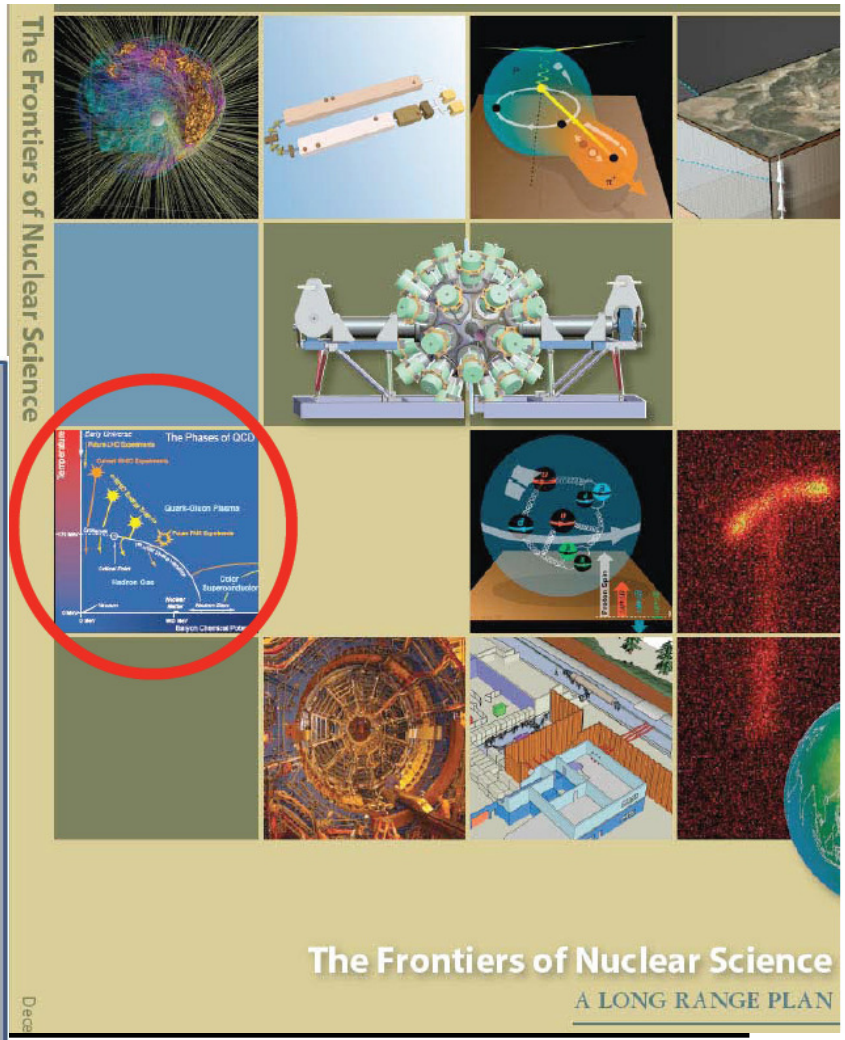
Operation with heavy ions to search for QCD phase transition Critical Point.

Low-Energy scan:

center of mass energies $\sqrt{s_{NN}}$ = 5, 6.3, 7.7, 8.8, 11.5, 18, 28 GeV/n

(May-June, 2010)





'Interplay' of space charge and beam-beam, HB2010, Sep. 27-Oct. 1, 2010

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:

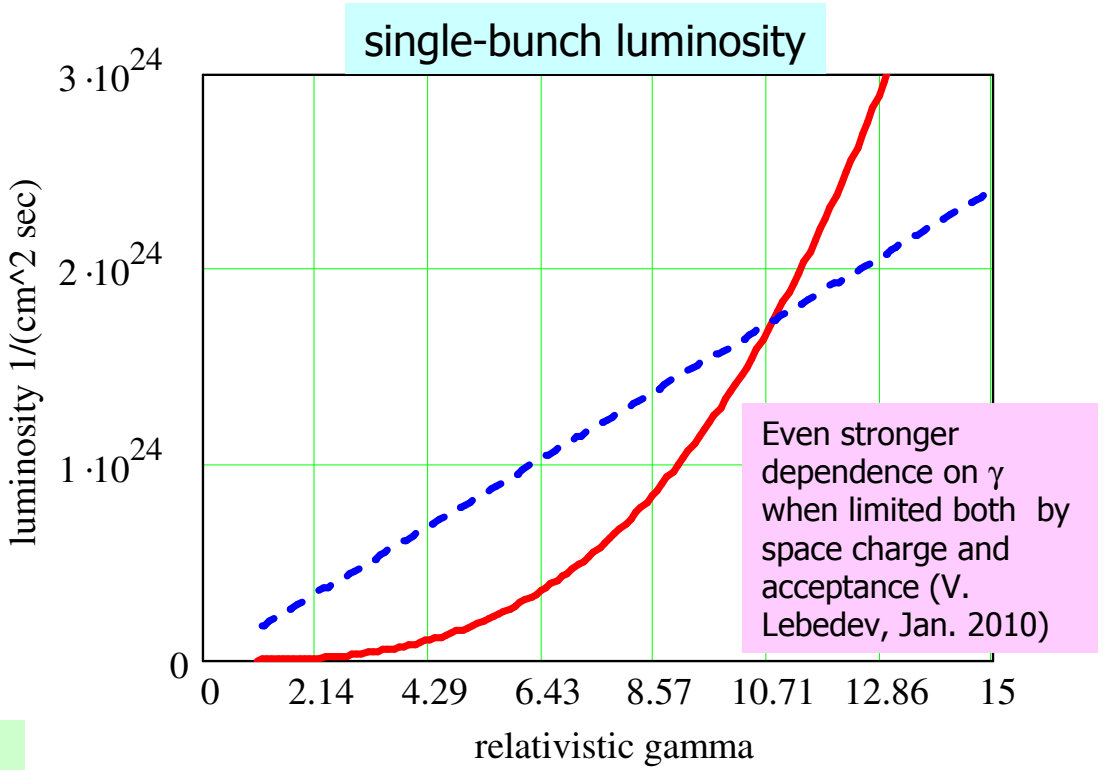
$$L = \frac{A}{Z^2 r_p}\frac{N_i c}{\beta^* C}\frac{2\gamma\beta^2}{1+\beta^2} f\left(\frac{\sigma_s}{\beta^*}\right)\xi$$

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

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:

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

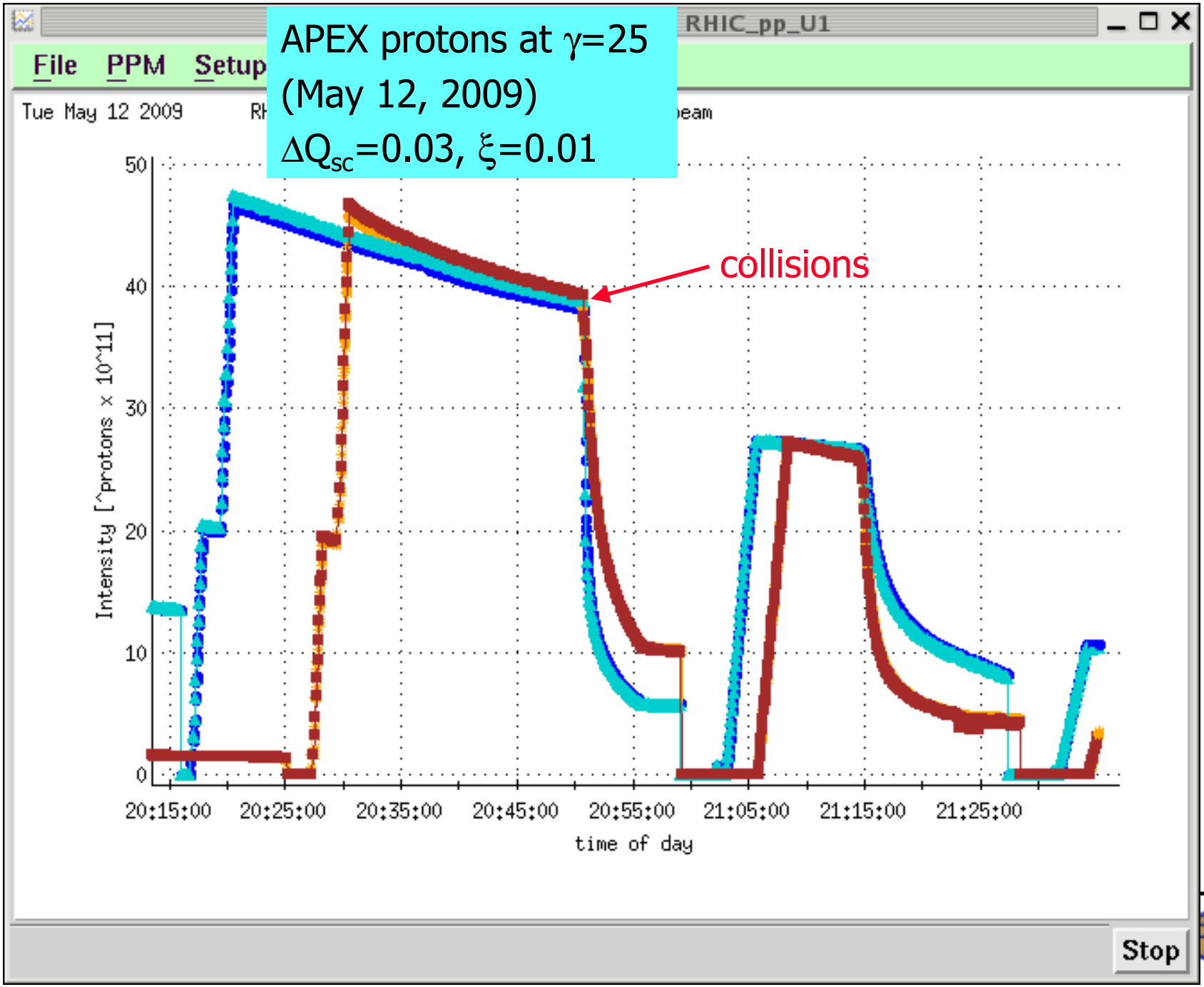
p+p: at beam γ=25 (modest space-charge, large beam-beam)

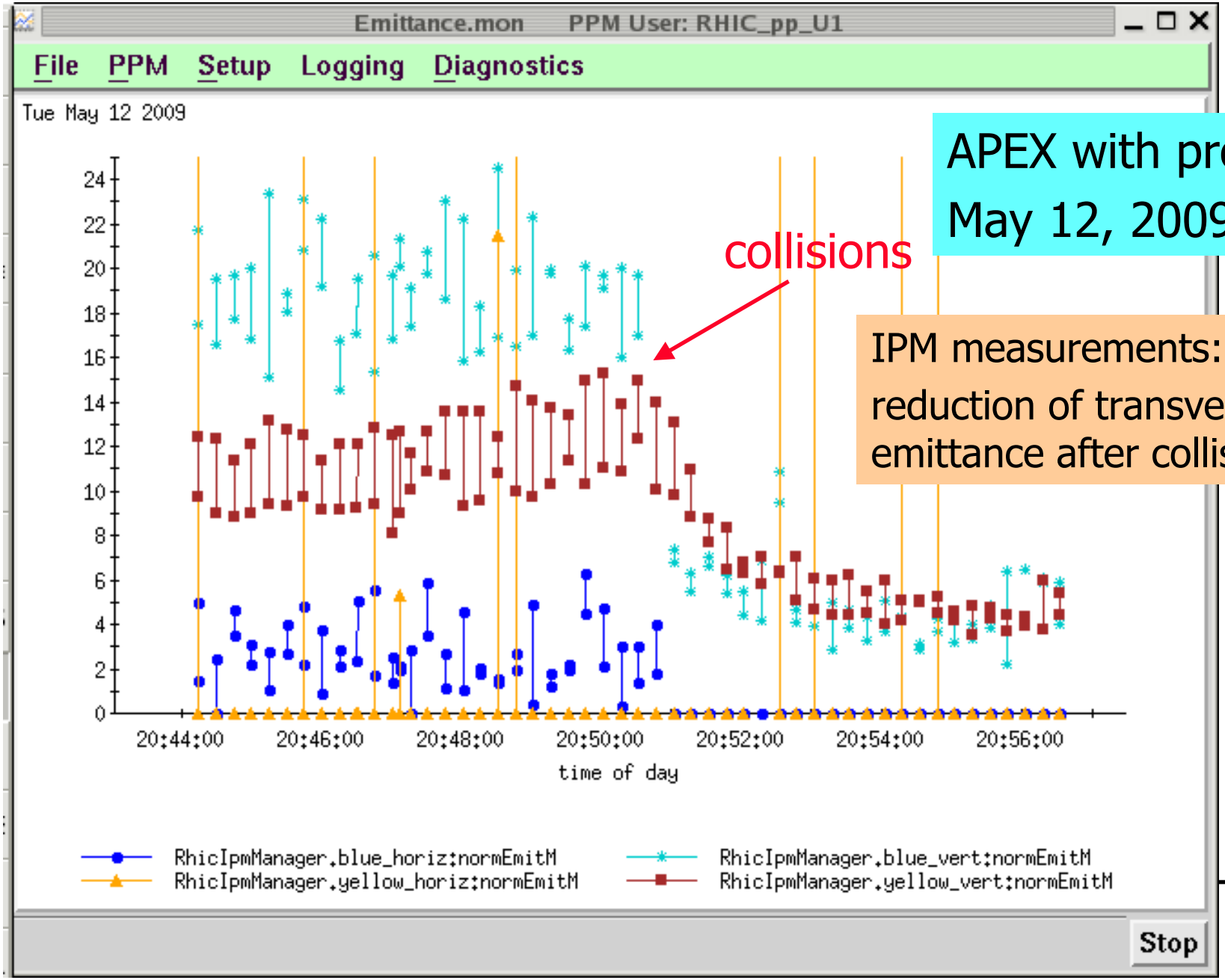
- **APEX March 2010:**

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)
ΔQsc=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

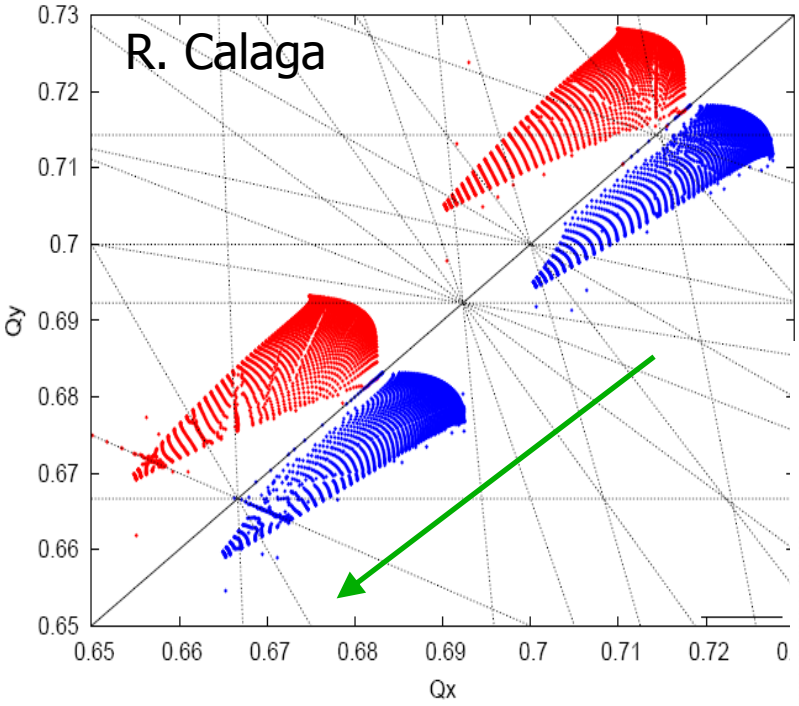


collisions

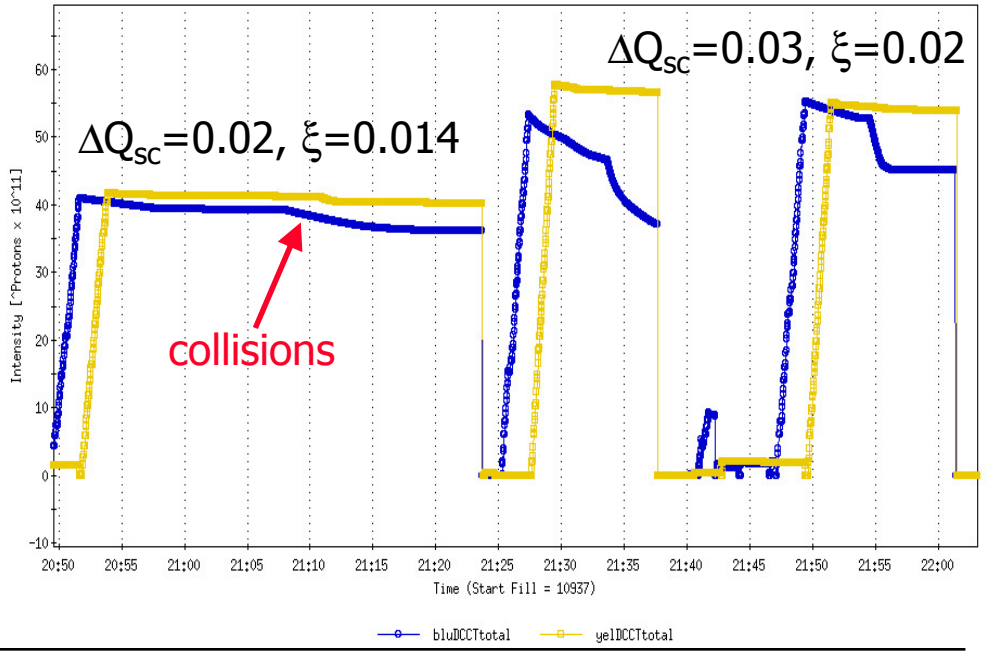
APEX with protons
May 12, 2009

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

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

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

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

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

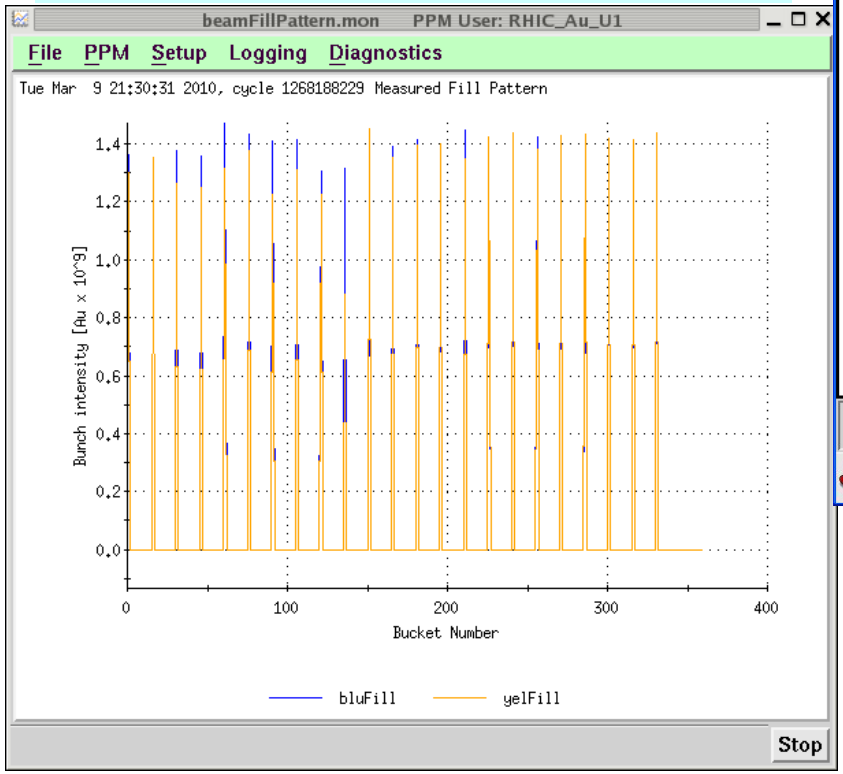
For Low-E RHIC we are interested in the regime:

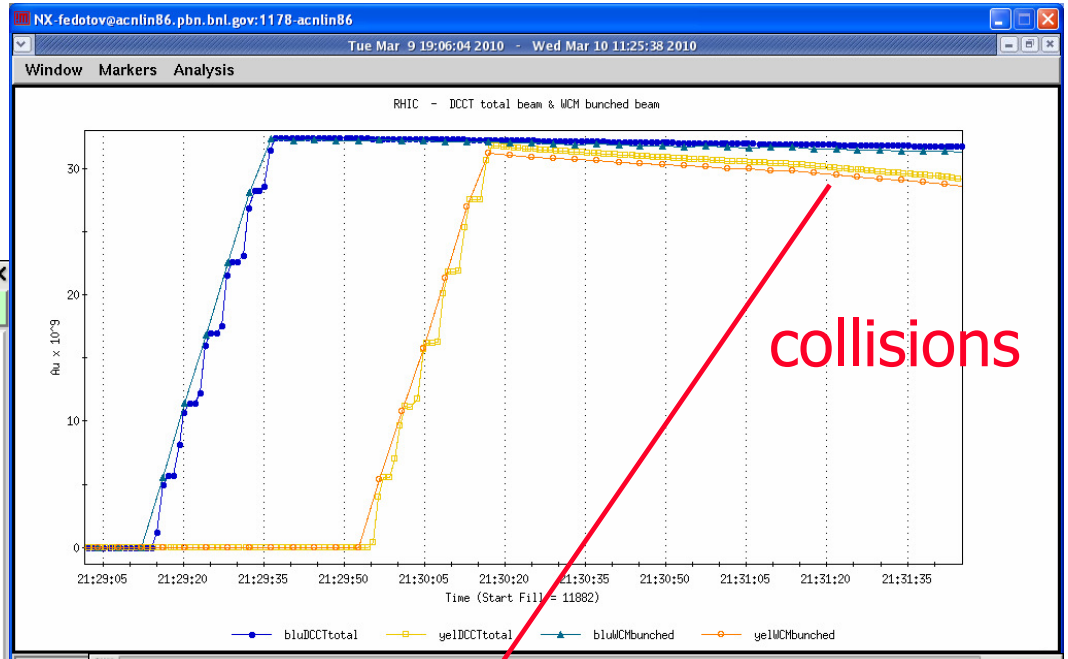
$\Delta Q_{sc} >> \Delta Q_{bb}$

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

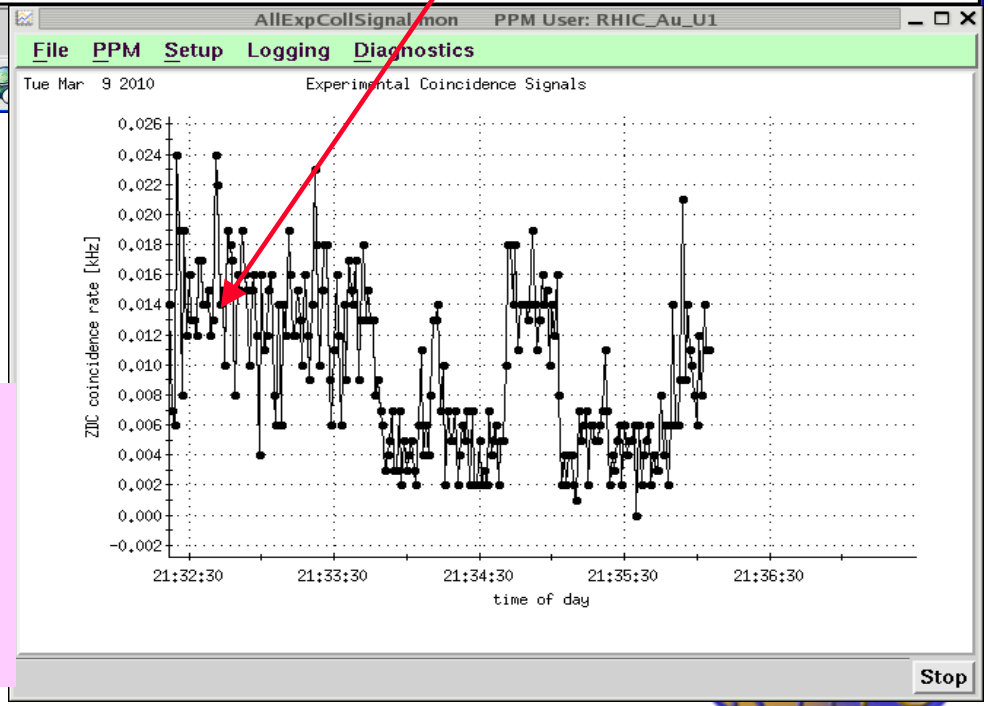
APEX with Au ions at γ=10.5 (March 9, 2010)

ΔQ_{sc}=0.03, ξ=0.002





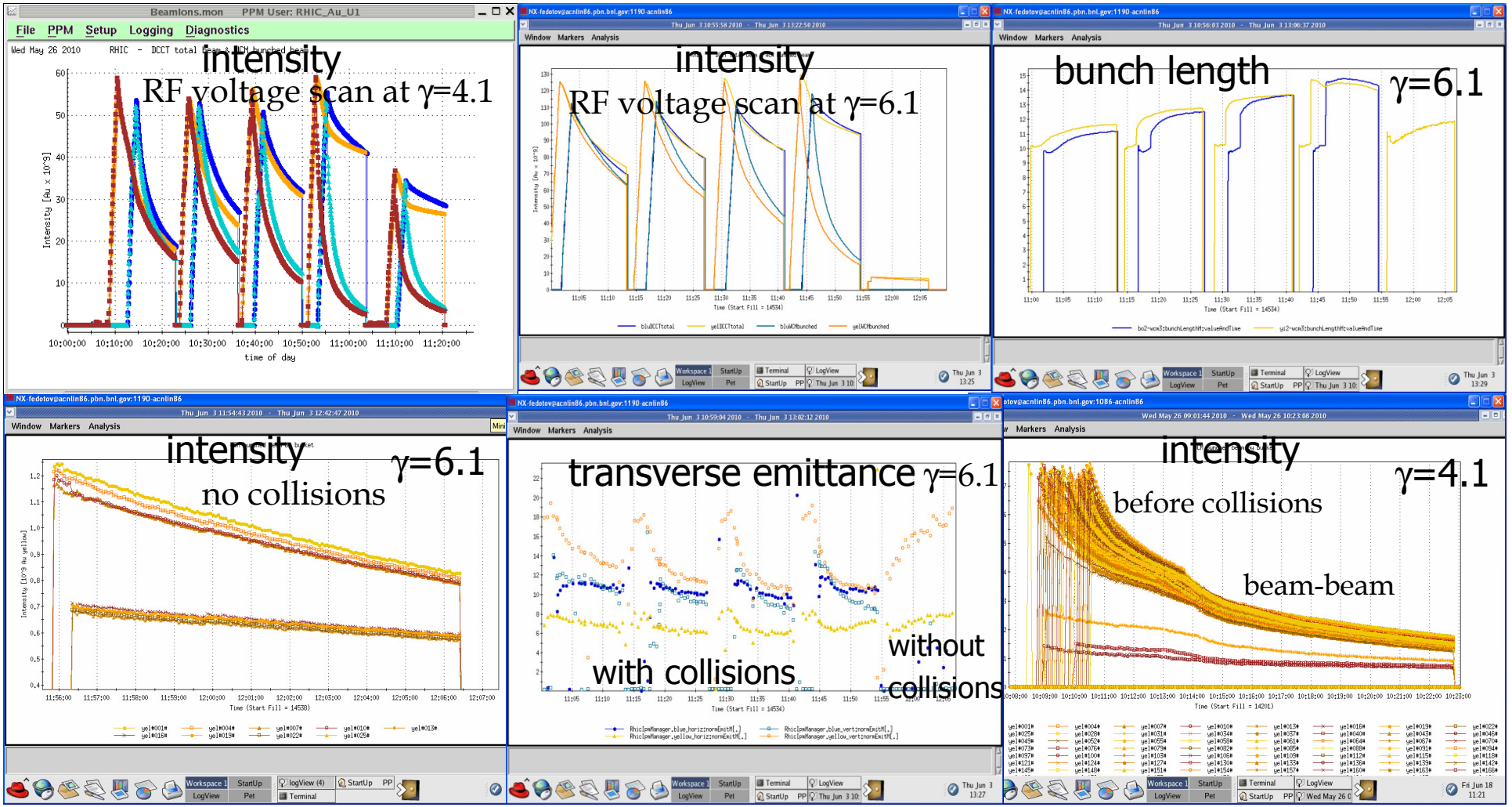
collisions



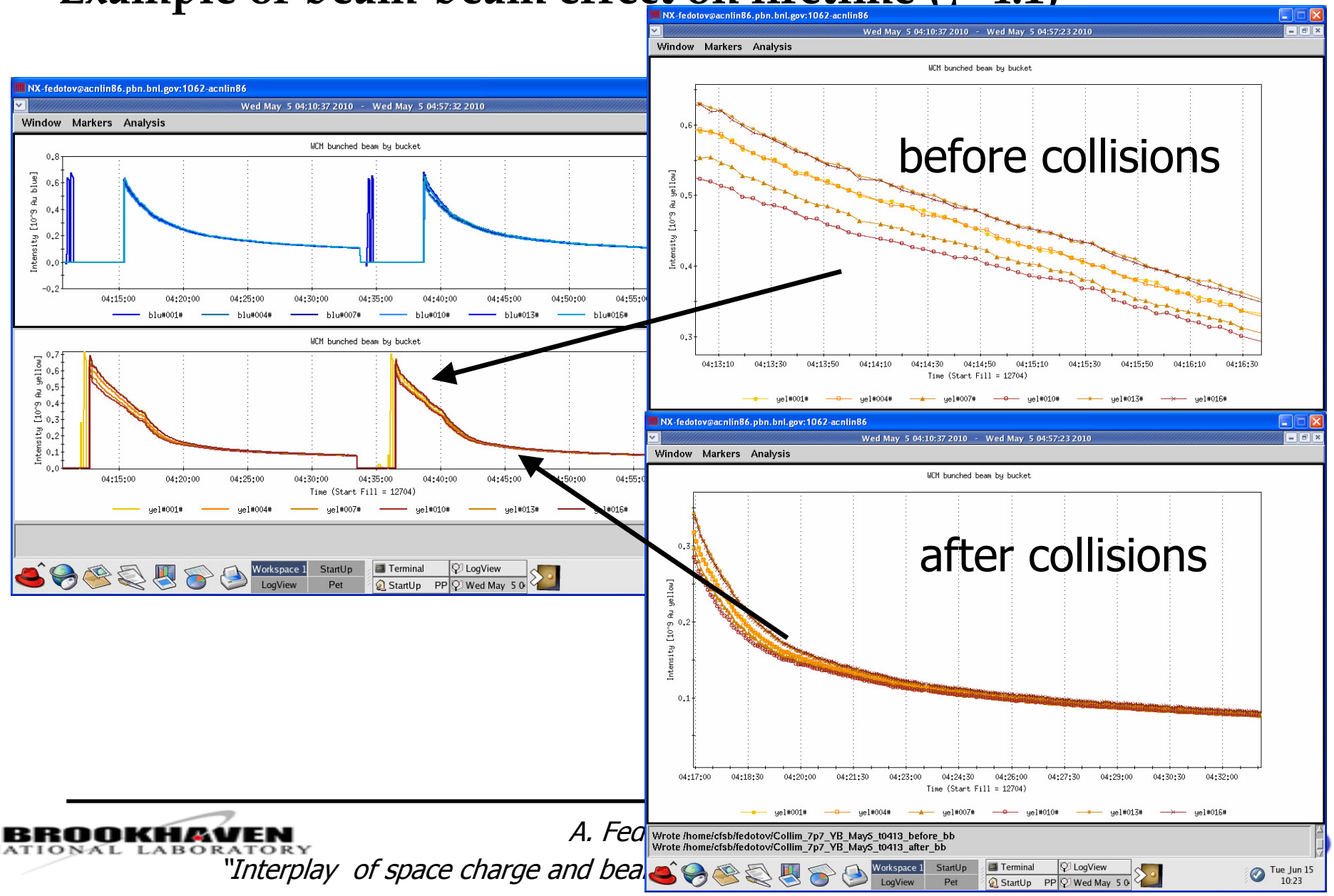
Much better than in 2009 with large beam-beam. But beam lifetime is still affected by beam-beam even for small space charge.

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

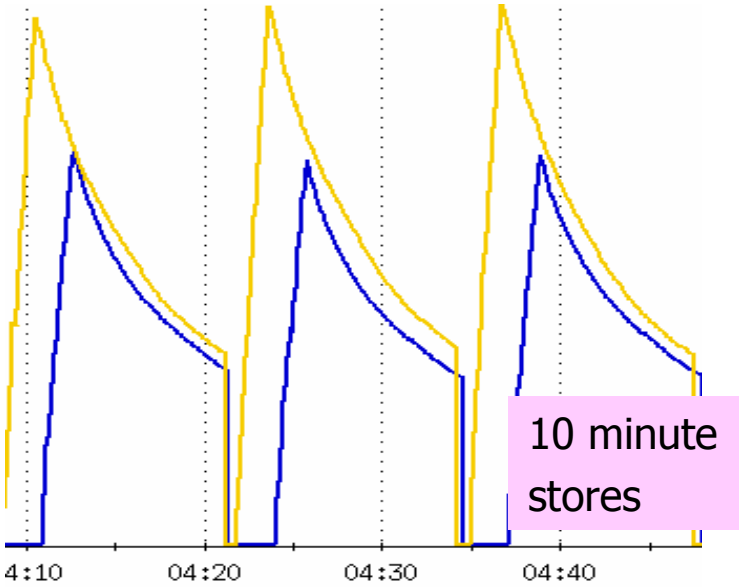
- **Series of APEX studies were done to understand beam lifetime at low energies.**



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 ΔQ_{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.

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.

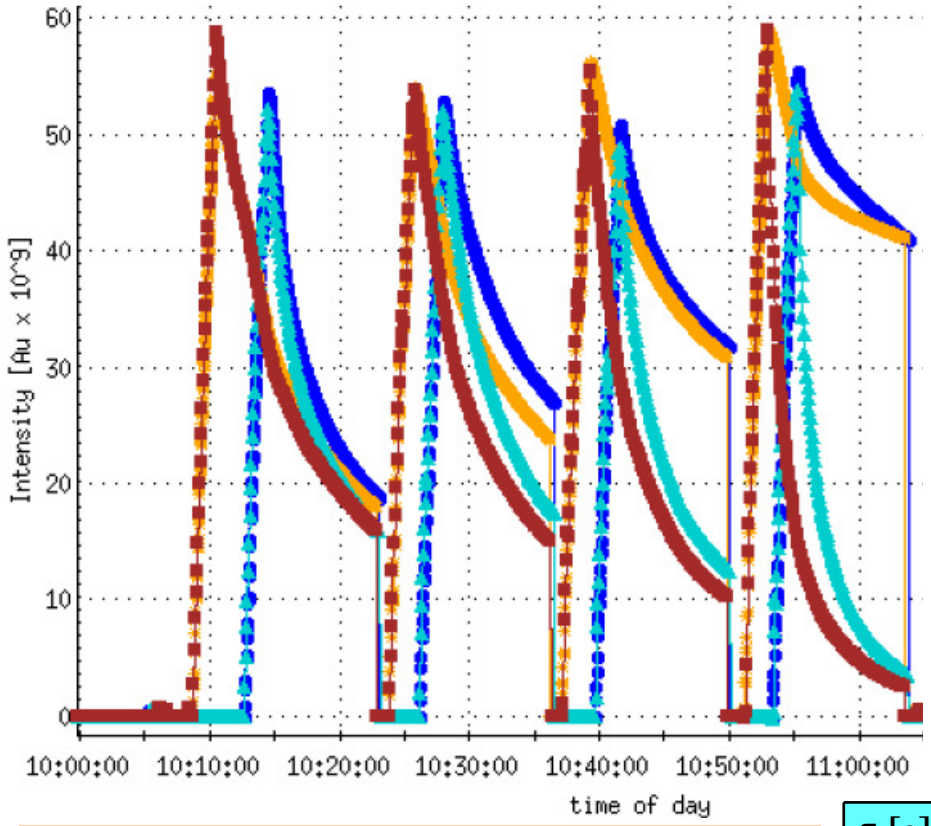
Significant limitation of dynamic aperture at γ=4.1 was expected

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

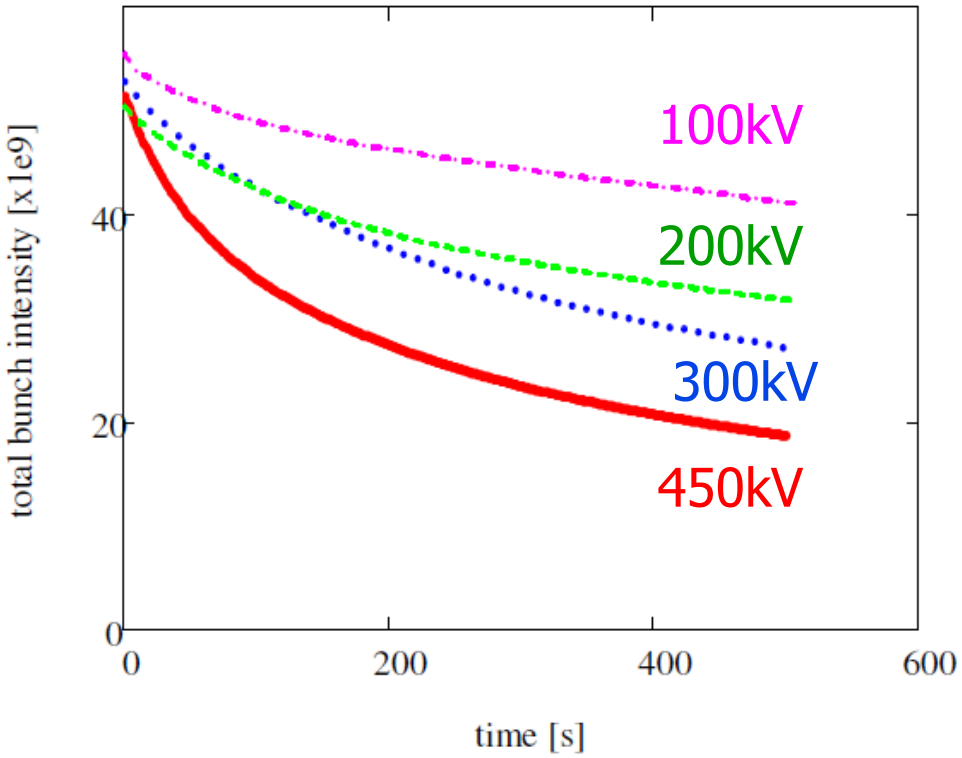
Beam-beam parameter ξ=0.001-0.002

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

Summary

Motivated by Low-Energy RHIC program and proposal to use electron cooling for low energy RHIC operation, a series of measurements were performed in RHIC in order to understand what beam lifetime can be expected for different values of the space-charge tune shift with and without beam-beam effects.

Acknowledgements

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Thank you