Improvements in the RHIC Polarized Proton Operation

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Spin Dynamics

- Spin precession in a planar circular accelerator [in the lab frame]

$$\frac{d\vec{S}}{dt} = \vec{\Omega} \times \vec{S} = -\frac{e}{\gamma m}[G\gamma \vec{B}_{\perp} + (1+G)\vec{B}_{//}] \times \vec{S}$$

- Orbital motion

$$\frac{d\vec{P}}{dt} = \vec{\Omega}_{rev} \times \vec{P} = -\frac{e}{\gamma m}[\vec{B}_{\perp} \qquad\qquad] \times \vec{P}$$

- Spin tune

$$\nu_s = \frac{\Omega}{f_{rev}} = G\gamma$$

G is anomalous magnetic moment, G=1.793 for protons

In the frame which moves with the particle

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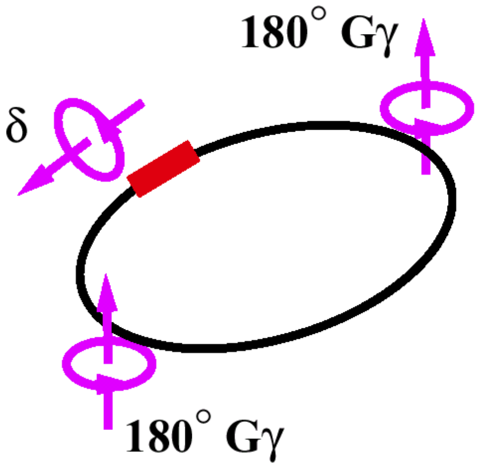
Siberian Snakes (Local Spin Rotators)

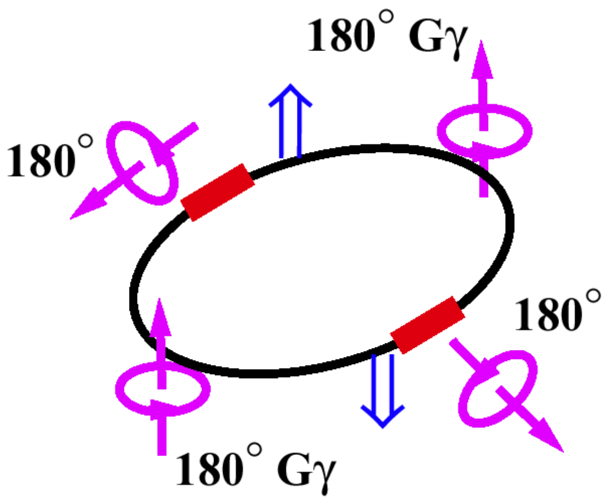


$$\boxed{\cos(180^\circ \nu_{sp}) = \cos(\delta/2) \cdot \cos(180^\circ\, G\gamma)}$$

$\delta \neq 0^\circ \rightarrow \nu_{sp} \neq n$

No imperfection resonances

Partial Siberian snake (AGS)



$\delta = 180^\circ \rightarrow \nu_{sp} = ½$

No imperfection resonances and

No Intrinsic resonances

Full Siberian Snake

Two Siberian Snakes in RHIC

Depolarizing Resonances

Spin tune: Number of 360 degree spin rotations per turn
Depolarizing resonance condition:
Number of spin rotations per turn = Number of spin kicks per turn

Imperfection Resonances

arising from sampling of error fields, fields due to closed orbit errors, etc.

$G\gamma=n$ (integer)

Intrinsic Resonances

arise from sampling of focusing fields due to finite beam emittance.

$G\gamma=kP\pm\nu_y$ P: Superperiodicity [RHIC: 3]

ν_y: Vertical betatron tune [RHIC: ~29.675]

Horizontal Intrinsic Resonances

1. horizontal non-vertical stable spin direction due to strong partial snake interaction with horizontal motion.
2. betatron motion coupled to the vertical betatron motion by coupling elements: solenoid, helical magnet.

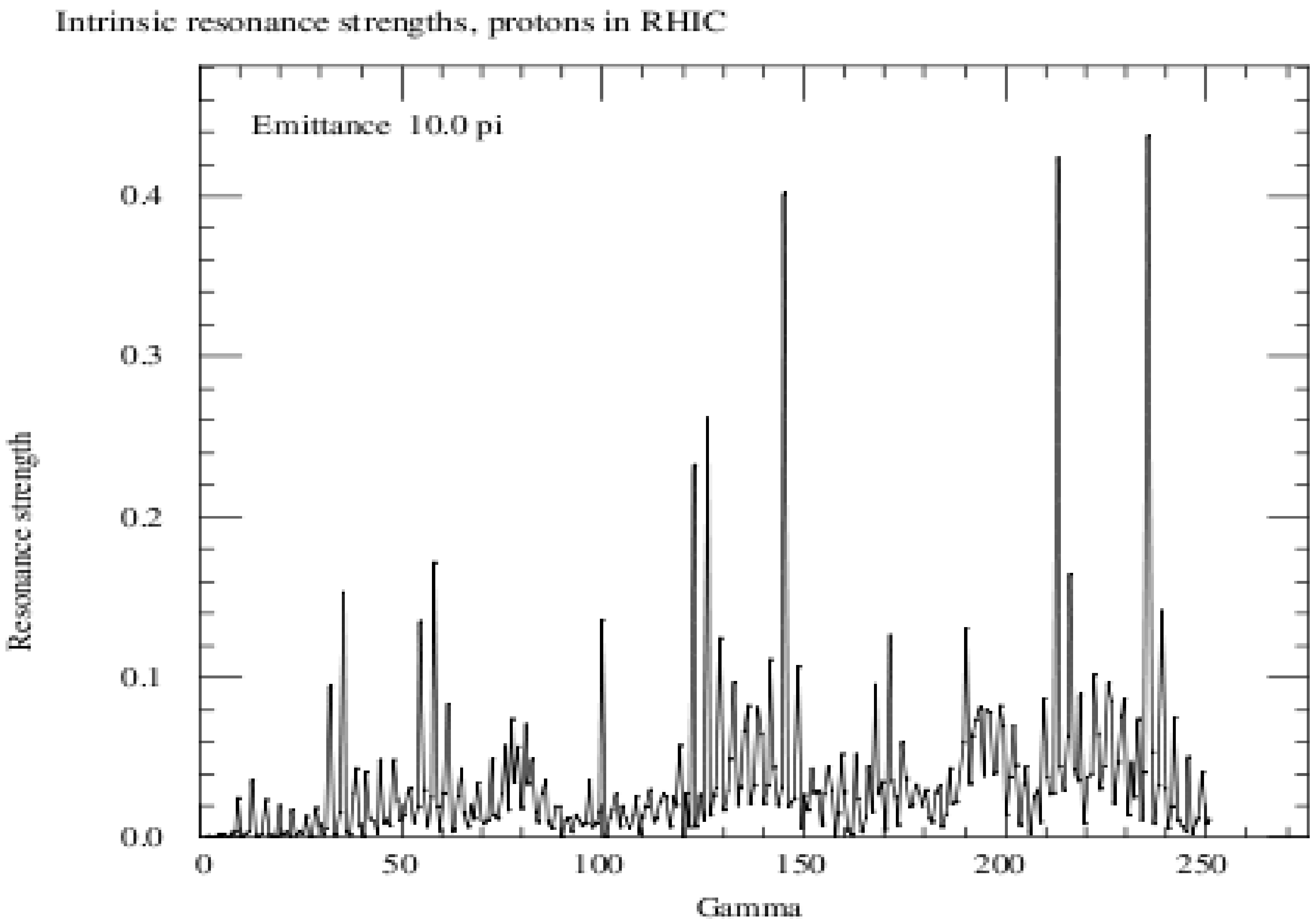
$\nu_s=k\pm\nu_x$

Snake Resonances

$\nu_{sp}=k\pm n\nu_y$ n: integer [snake resonance order]

ν_y: Vertical betatron tune [RHIC: ~29.675]

Vertical Intrinsic Resonance Spectrum in RHIC



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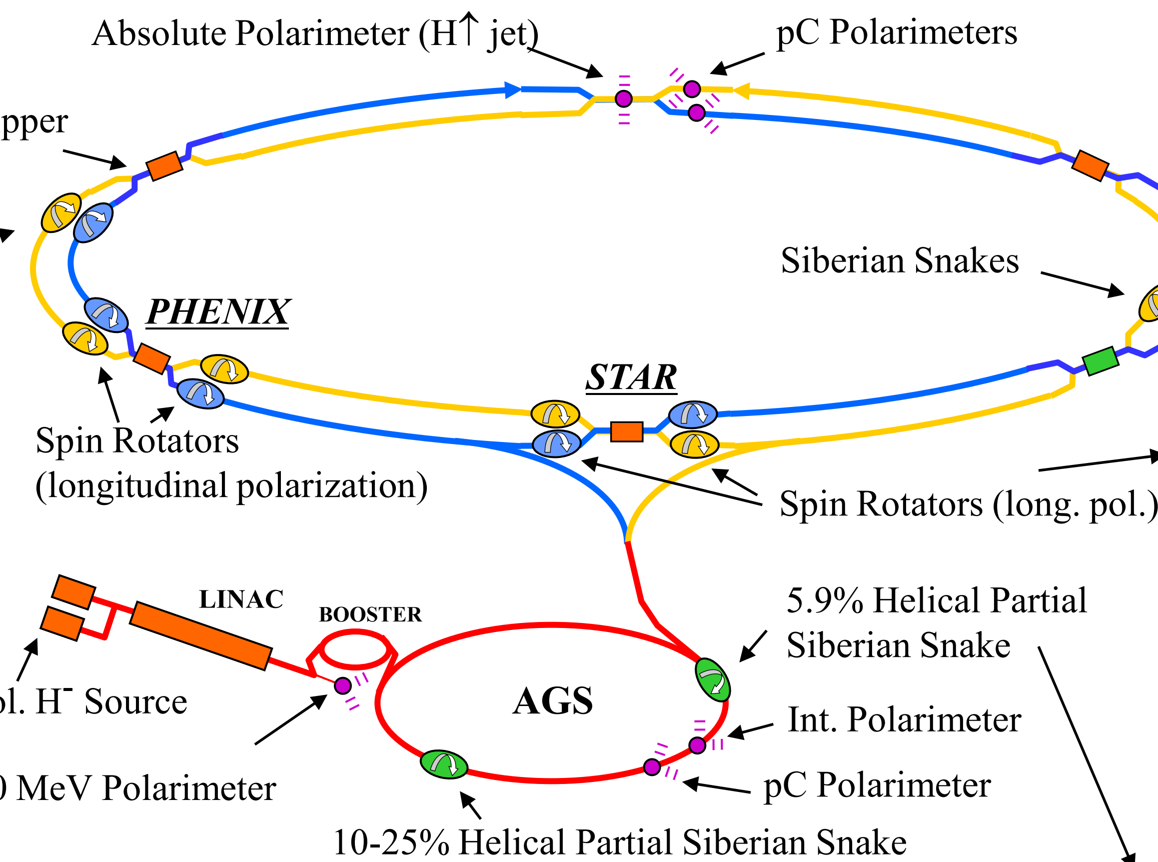
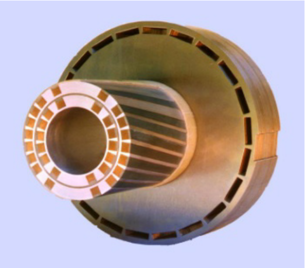
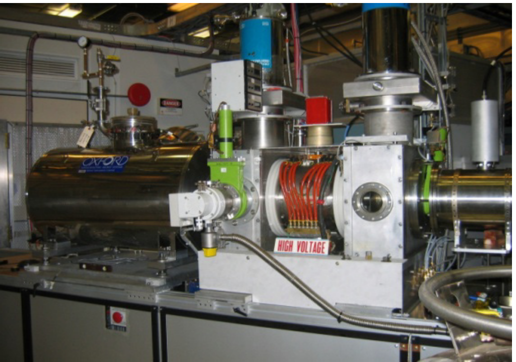
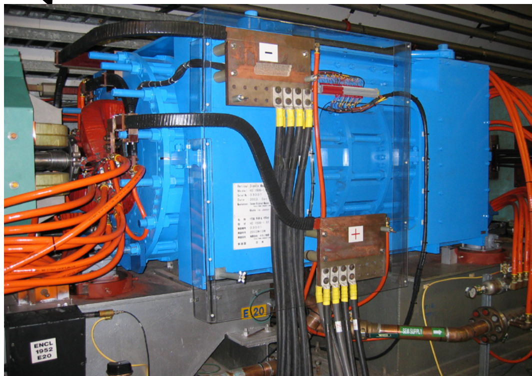
RHIC – First Polarized Hadron Collider

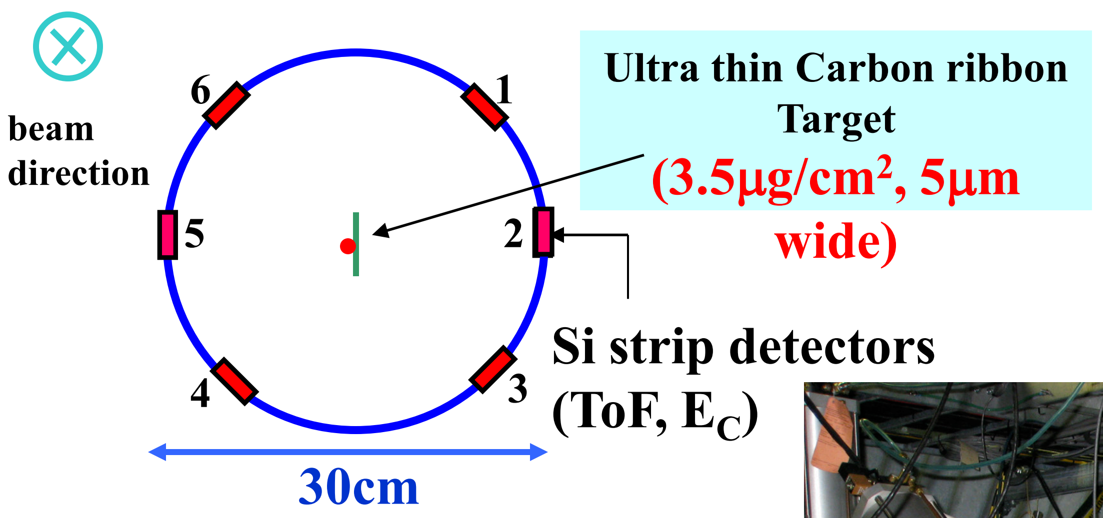






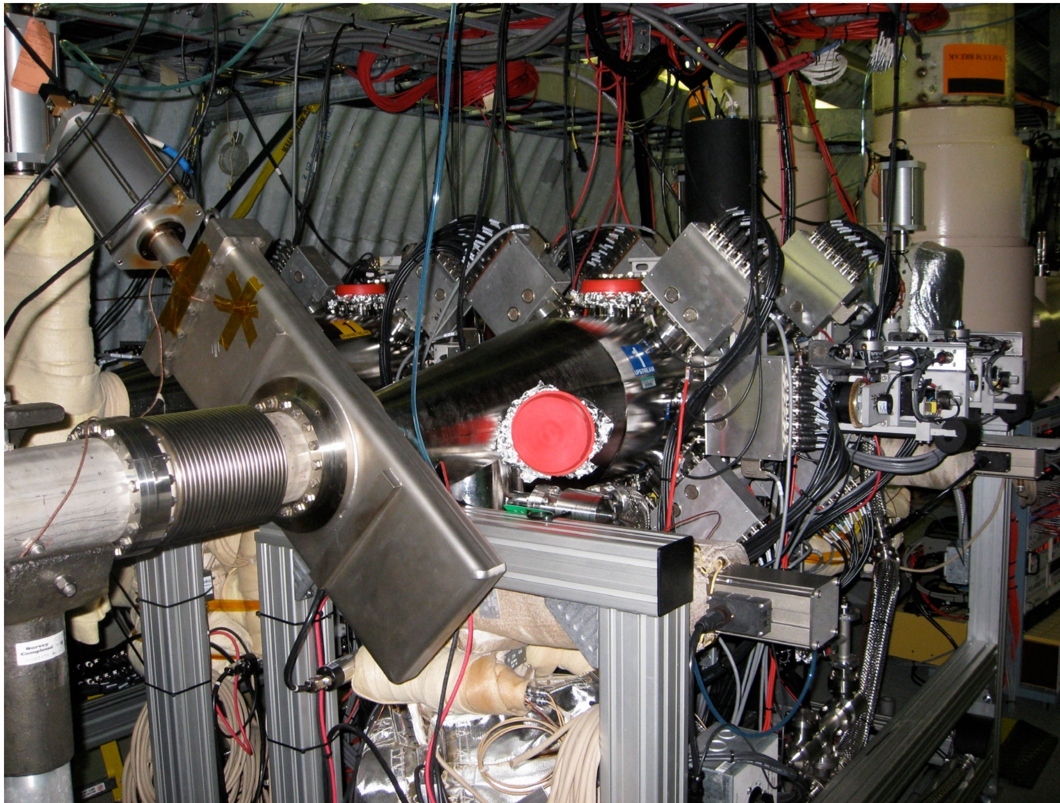


pC Scattering – the RHIC Polarimeters

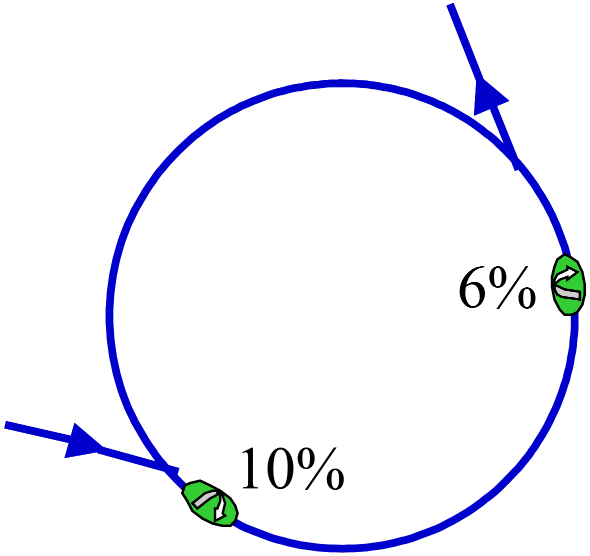


Two polarimeters in each ring, which can provide polarization and beam profiles information quickly.

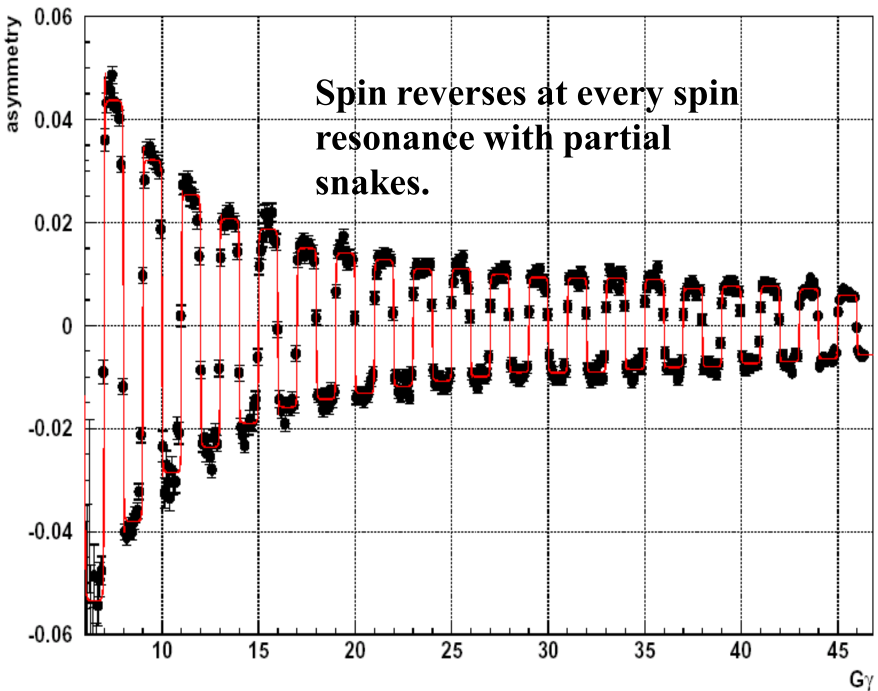
RHIC Beam



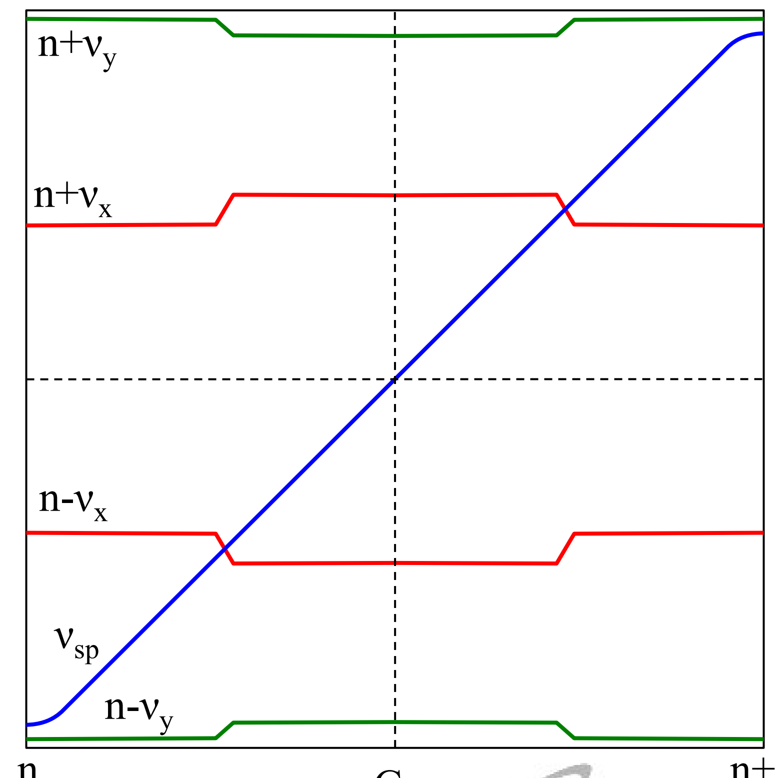
Polarized Protons in the AGS



- Two strong partial Siberian snakes
- Vertical betatron tune at 8.98
- Pulsed quadrupoles to jump across the many weak horizontal spin resonances driven by the partial snakes.



5 16 23 GeV



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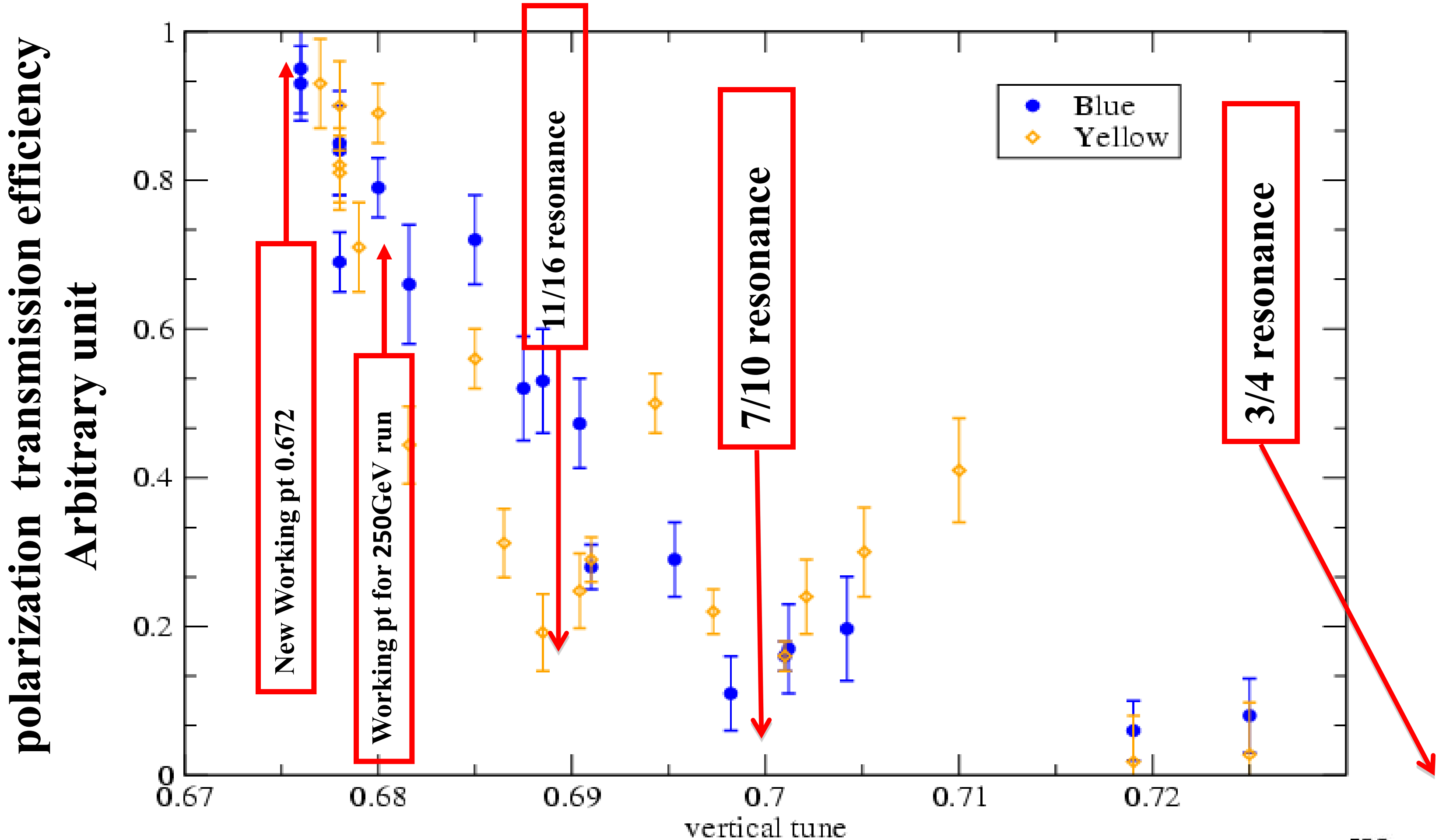
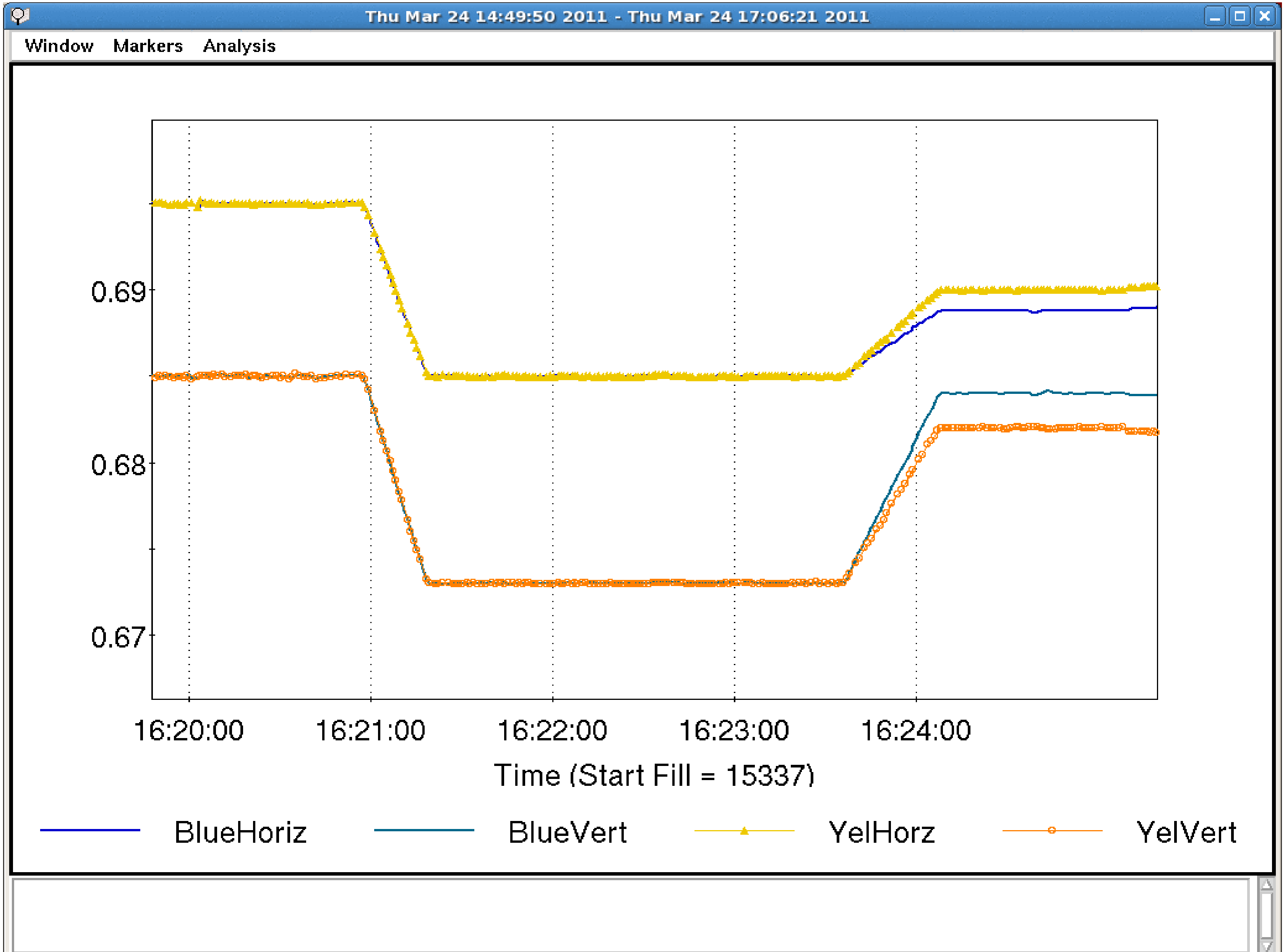
RHIC Polarization Transmission to 250GeV

- The relative gain of polarization by moving Q_y from .68 to .675 is 1.12. The close orbit error reduction gives additional gain.



Betatron Tune on the Ramp



Spin Tune Shift due to the Horizontal Orbit Angle in Snakes

The spin tune shift due to horizontal orbit angles in Snakes and rotators :

$$\delta Q_{sp} = \frac{1+G\gamma}{2\pi}(2\alpha_{sn} + \alpha_{rt\_ip6} + \alpha_{rt\_ip8})$$

$$\alpha_{sn} = x'_{co\_sn9} - x'_{co\_sn3}$$

$$\alpha_{rt\_ip} = x'_{co\_rt\_left} - x'_{co\_rt\_right}$$

At 250 GeV:

	Orbit angle error, mrad	δQ_{sp}, 10^{-3}
Snakes	0.1	15.4
Rotator (in one IR)	0.1	7.7

On the acceleration ramp (the rotators are off) only α_{sn} contributes.

•The variation of snake angles on the (last half of) ramp was maintained within established tolerances during the Run-9: 7/10 resonance shift < ±0.001 => δQ_{sp} < ±0.005 => α_{sn} < ± 30 μrad

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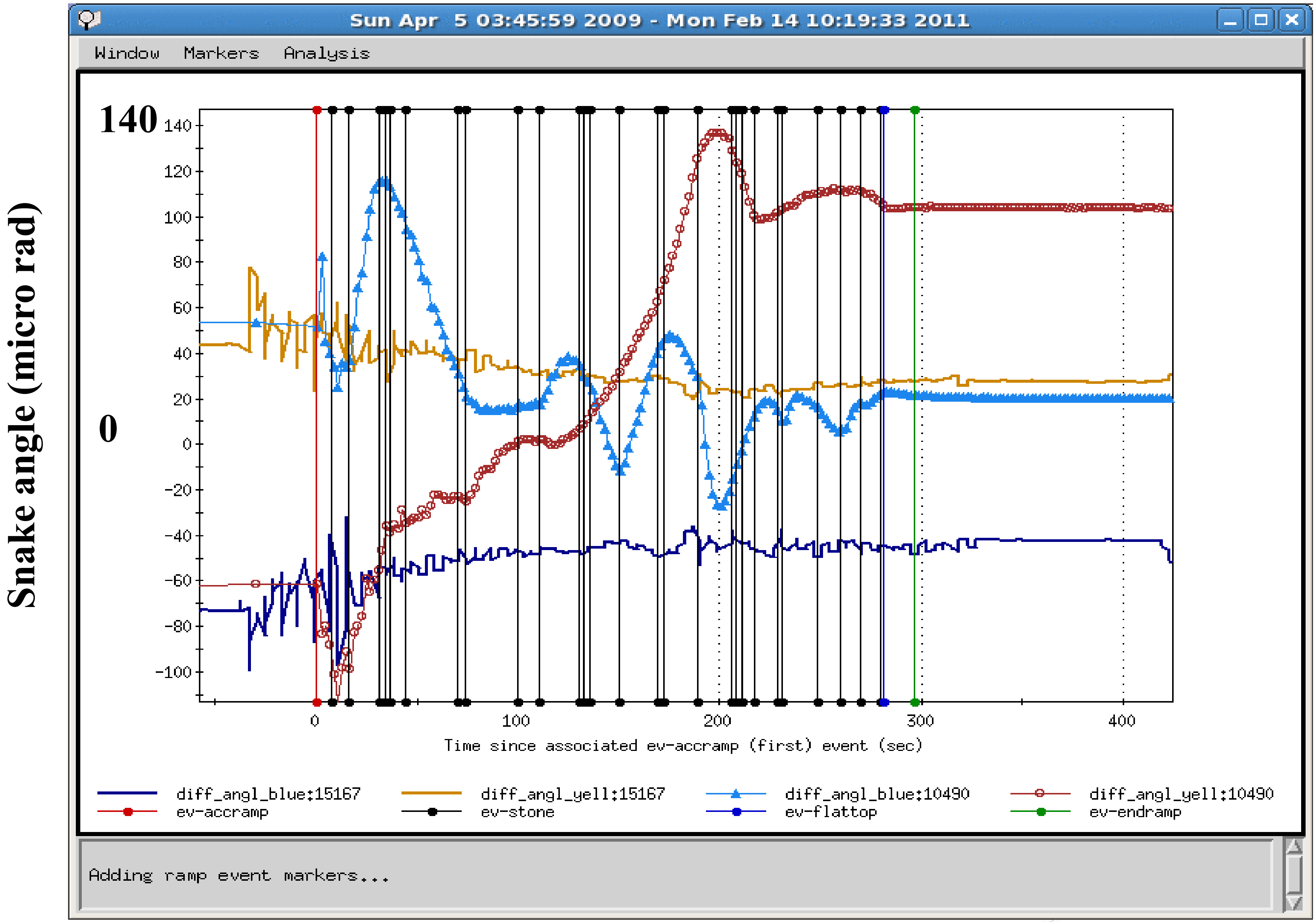
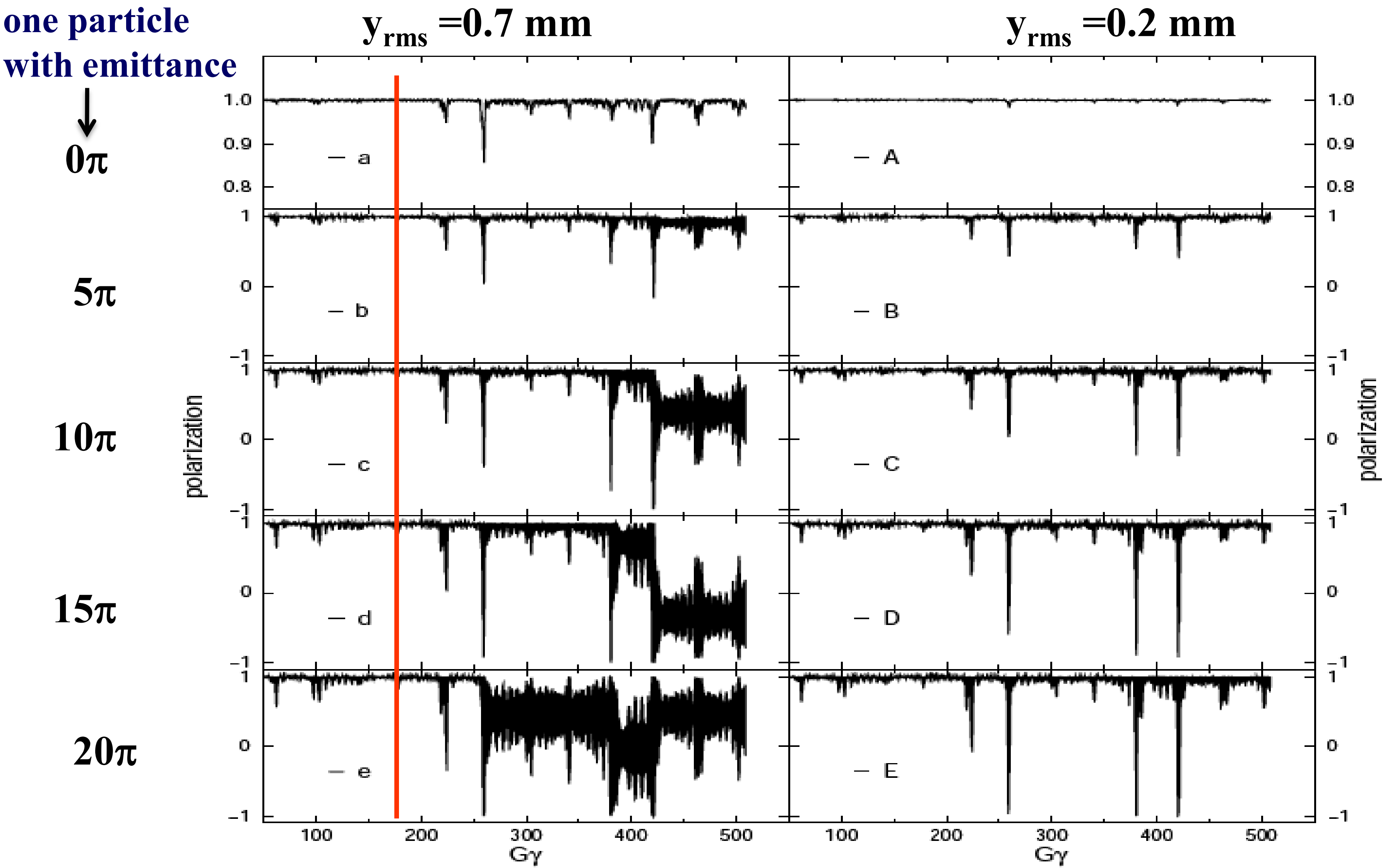
Snake Angle Difference: run11 vs. run9



Polarization Simulations with Orbit Errors



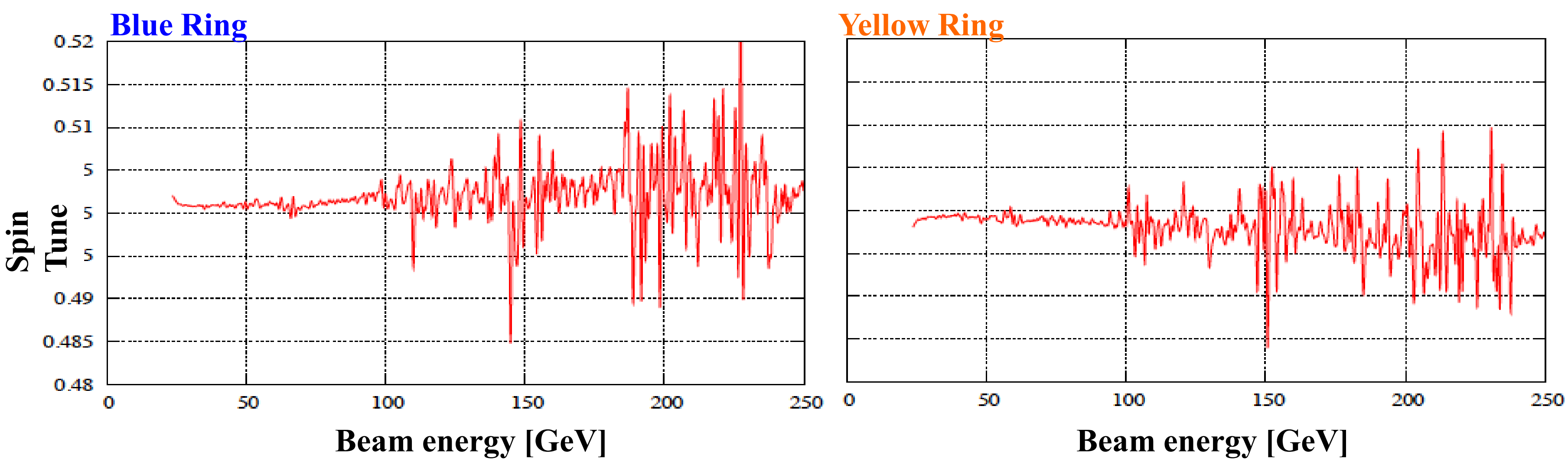
The simulations established the tolerance on vertical closed orbit rms at 0.3 mm, or $|\varepsilon_{imp}| < 0.07$

Spin Tune Shift Caused by Imperfection Resonances

$$|\Delta Q_s| \le \frac{1}{\pi}\arcsin\left[\sin^2\frac{\pi\varepsilon_{imp}}{2}\right]$$ **where ε_{imp} is the resonance strength**

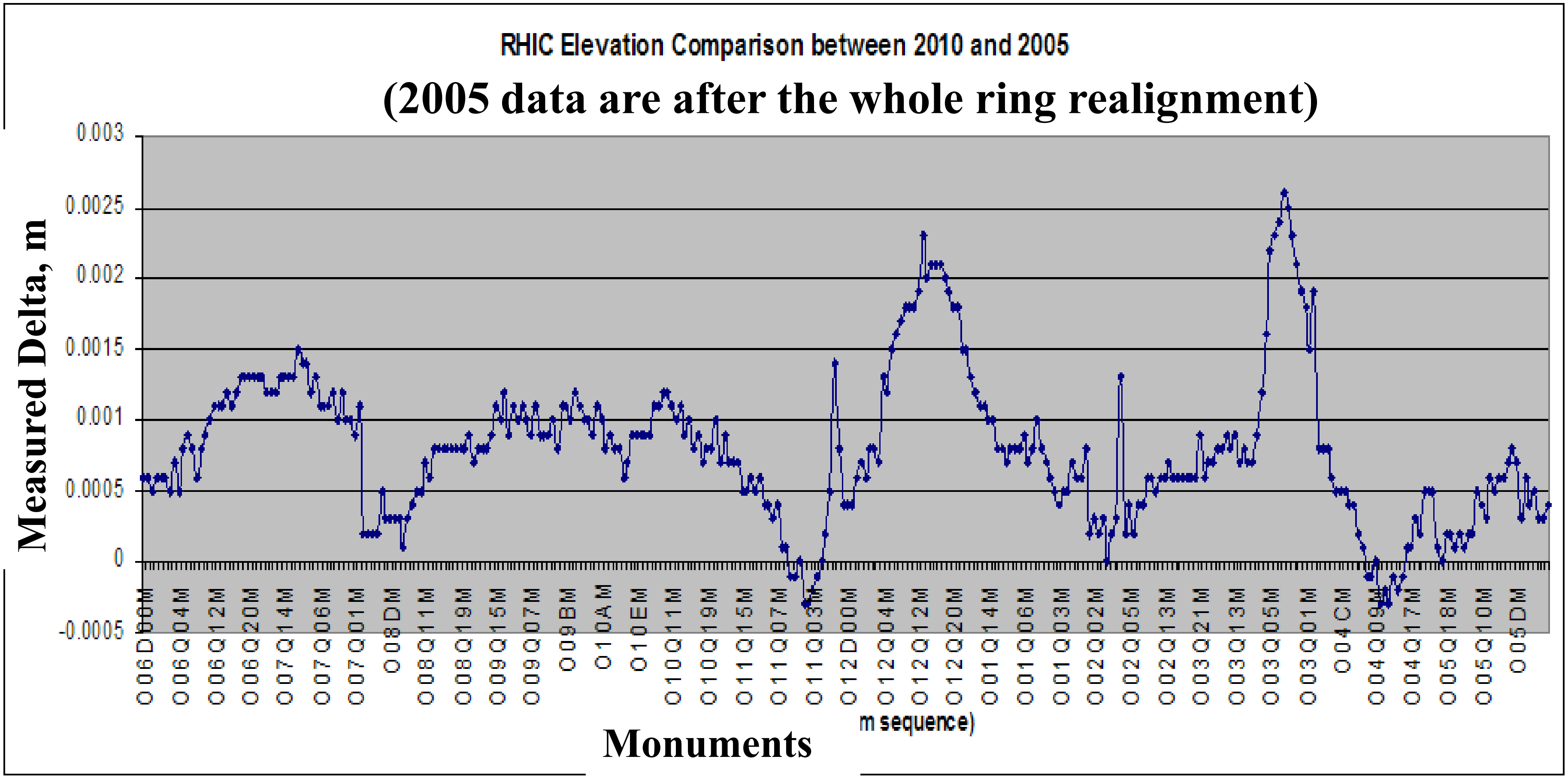
The problem with reversed BPM offsets was found during Run10.
Reversed offsets led to closed vertical orbit rms ~1 mm and the maximum imperfection resonance strength exceeding 0.1.

Corresponding spin tune shift along the acceleration ramp:



Above 100 GeV the spin tune shifts are considerable (>0.02 in Blue ring).
Corresponding 7/10 resonance shift up to 0.004-0.005.

Measured Vertical Misalignments



The realignment of the whole ring is done before run 11.

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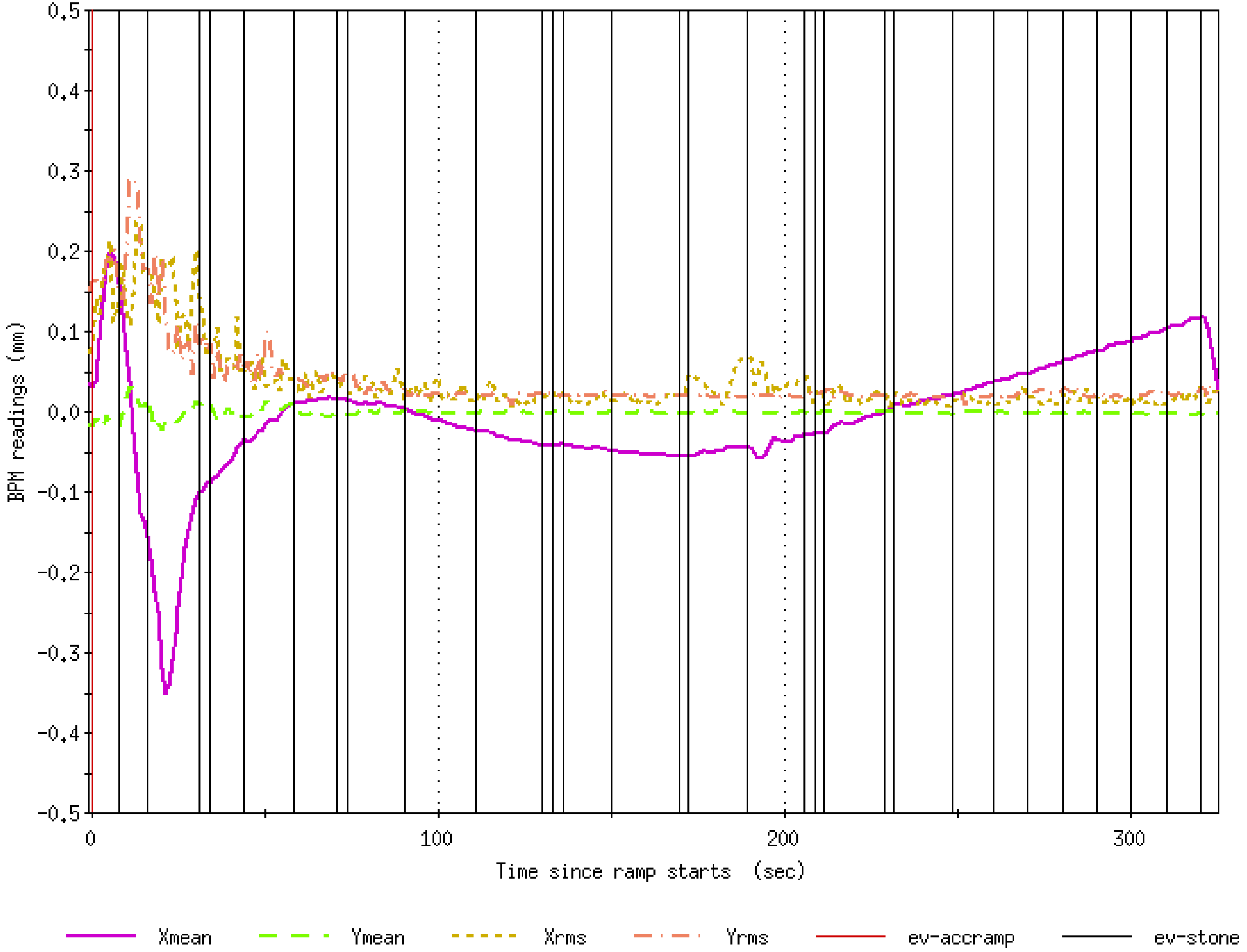
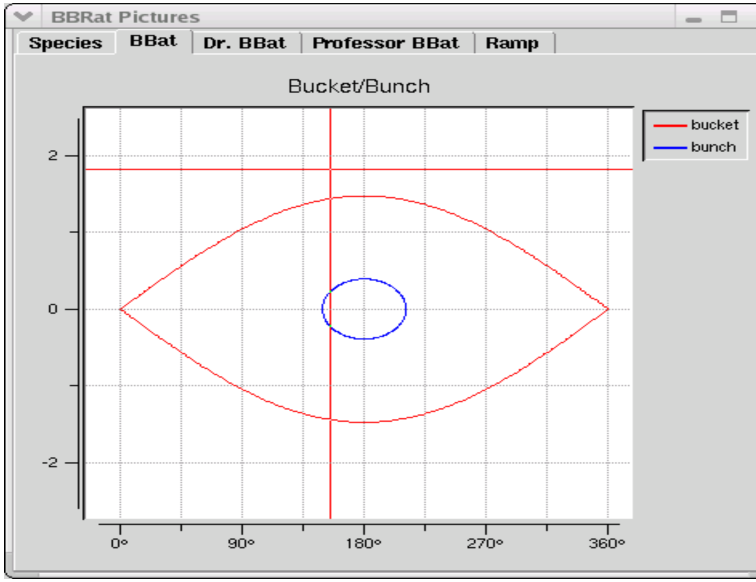
Orbit Statistics on the Ramp



Motivation for 9 MHz

- Short bunches during the ramp result in lower luminosity because of:
  - Transverse emittance growth
  - Instability
- The objective is to have long bunches on the ramp and short bunches during store
- 9 MHz makes long bunches without the emittance blowup
- At store (250 GeV)
  - Emittance preservation
  - Adiabatic damping
  - Rebucketing into 197 MHz



At Store

- **0.66 eVs**
- **250 GeV**
- **300 kV, 28 MHz**

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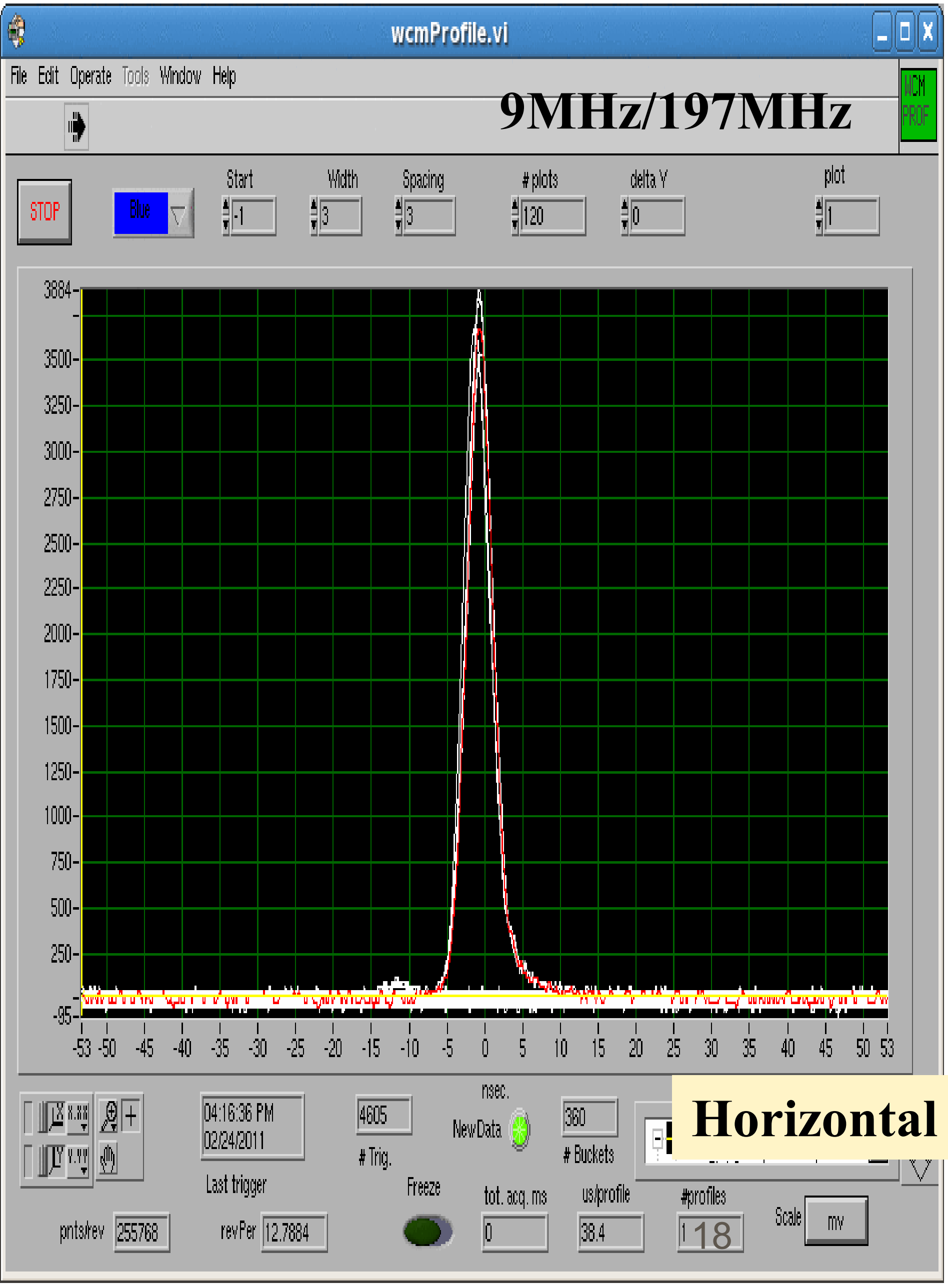
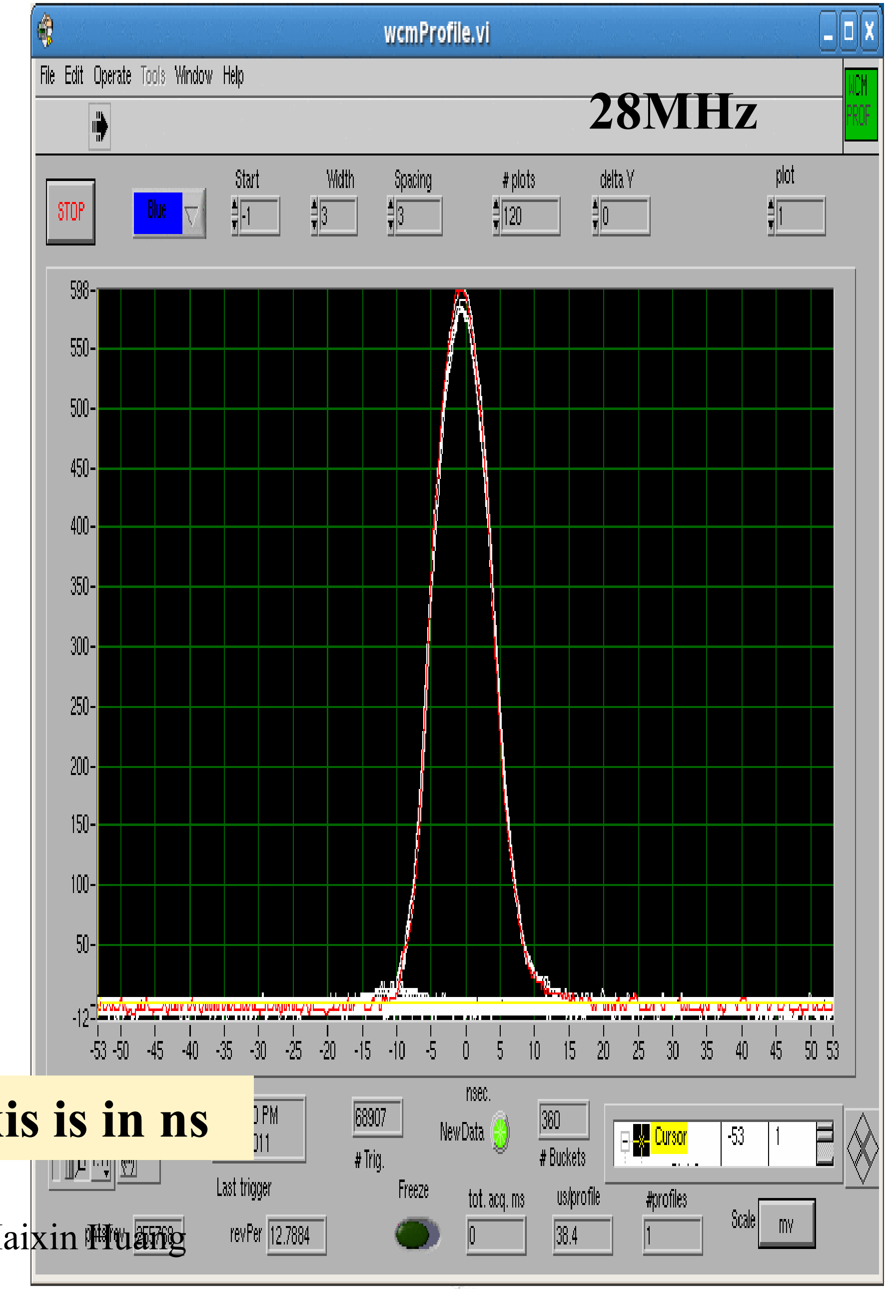
Bunch Shape after 9MHz and 28MHz Ramps

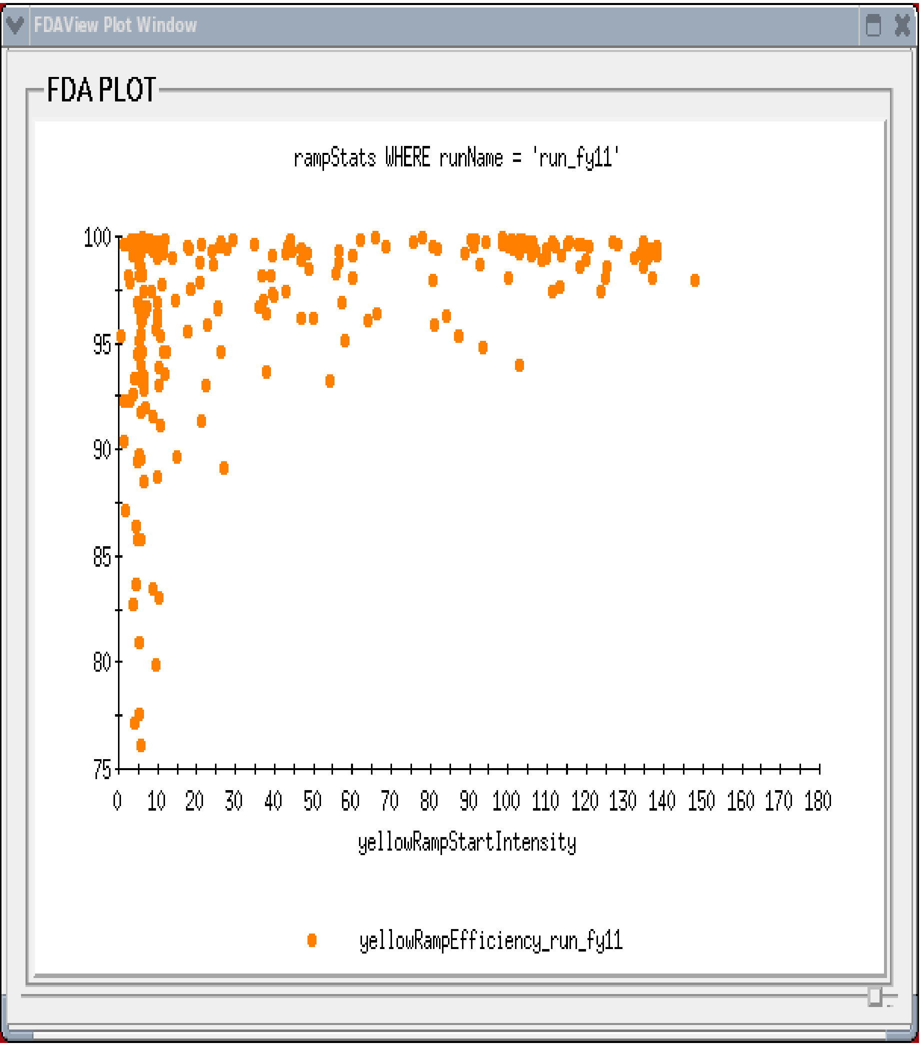




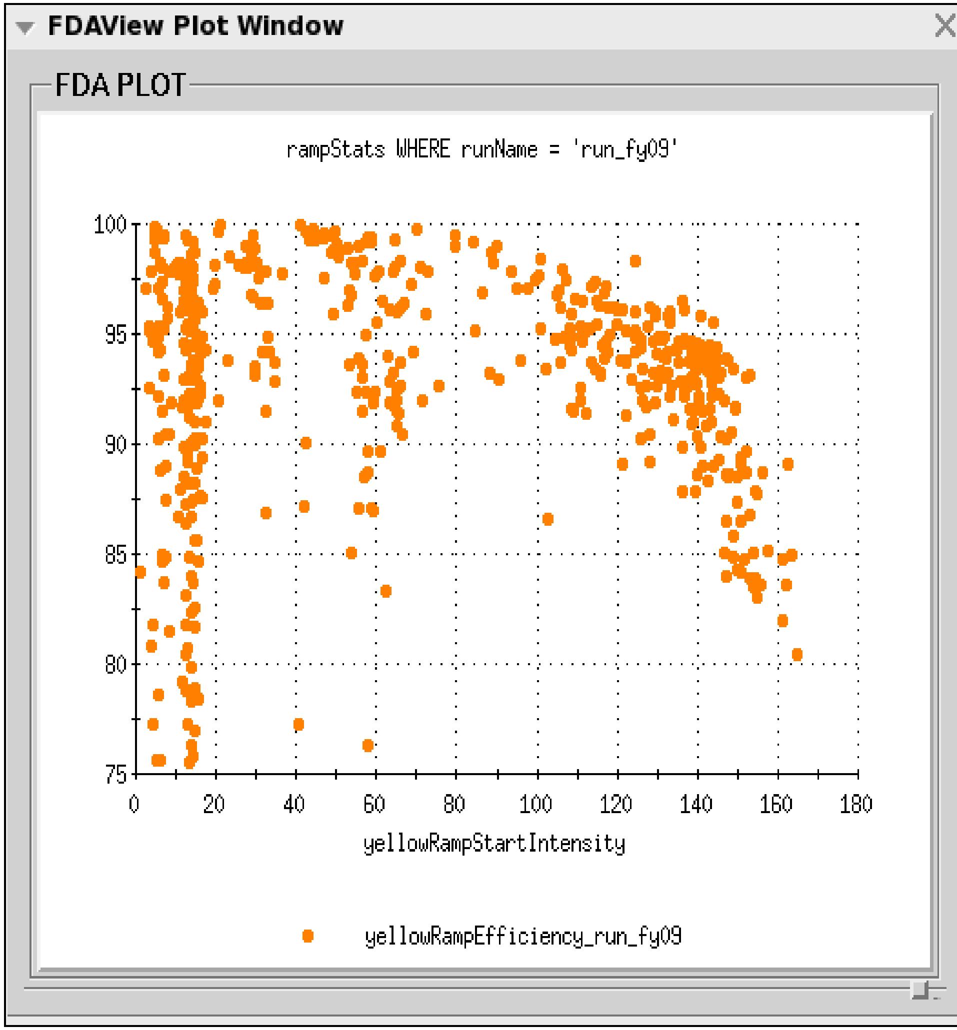
Horizontal axis is in ns

Ramp efficiency in Run9 and Run11

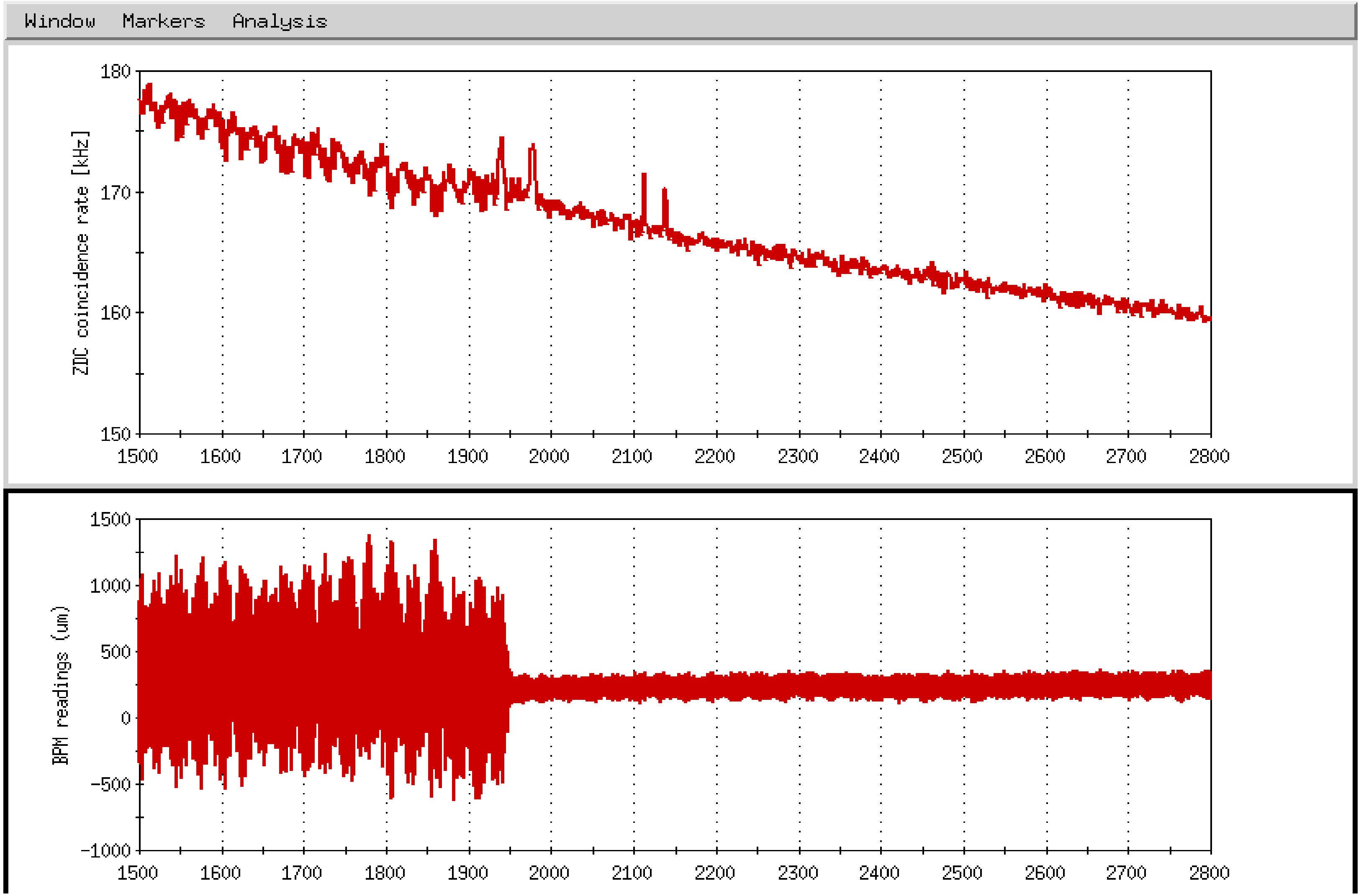
Run11, mostly with 9MHz



Run9, with 28MHz



Benefit of 10Hz Feedback on Luminosity



purpose: stabilize beams against “natural” orbit oscillations at ~ 10 Hz. It also reduced backgrounds for experiment detectors.

RHIC Polarized Proton Parameters

Energy at injection	24.3	GeV/u
Energy at Store	250	GeV/c
Interaction points	6 8 10 12 2 4	clock
β* at injection	7.5 7.5 7.5 7.5 7.5 7.5	m
β* at store	.65 .65 7.5 7.5 3 7.5	m
Working points	ramp: (28.685, 28.675) Store: (28.69, 29.68)	
Snakes current	DC	
Spin rotator current	Ramp up after energy ramp	
Polarization at store	>45%	
Peak bunch intensity	1.4*10^11	
Peak luminosity	10^32	cm^-2s^-1

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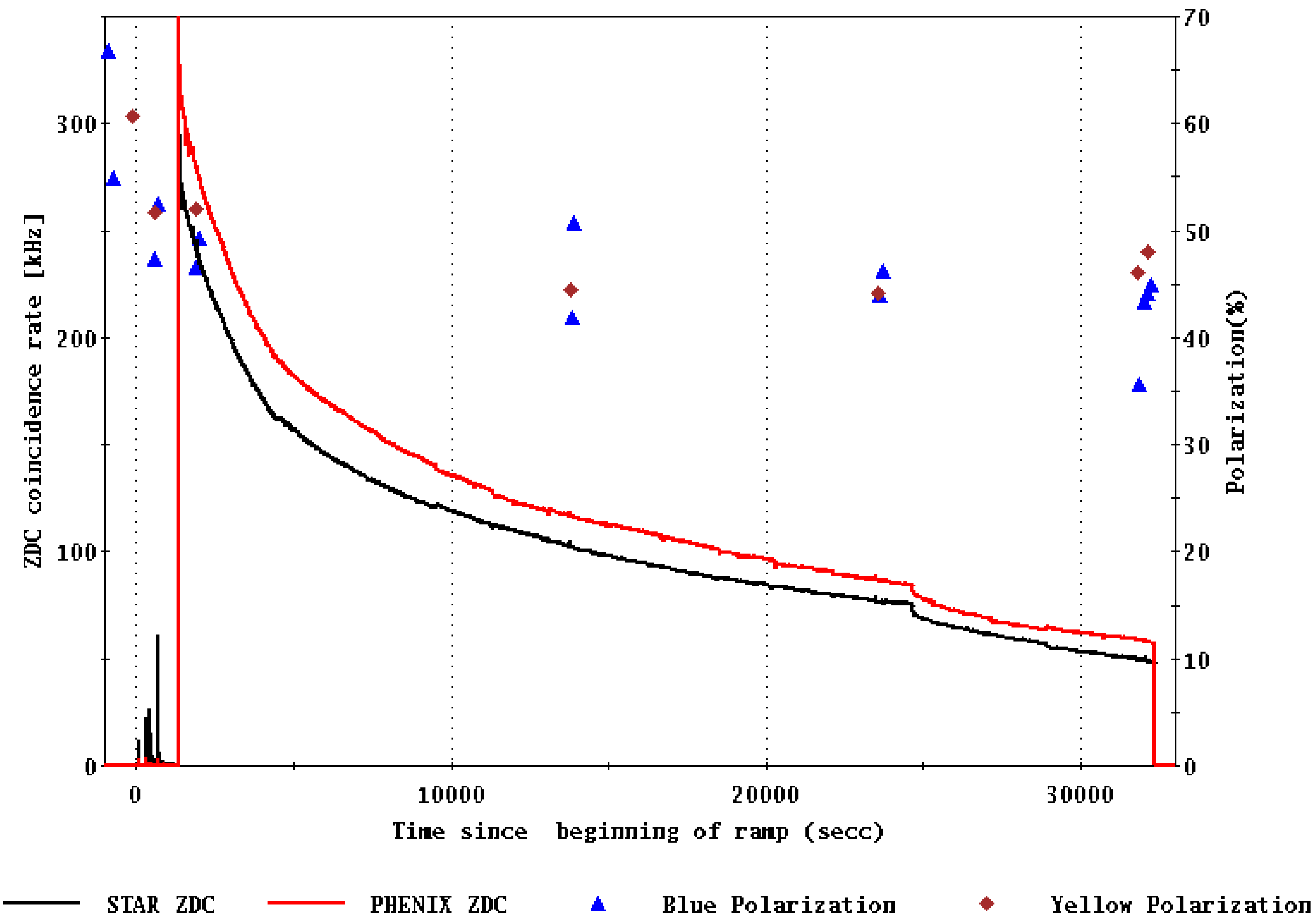
Polarization and Luminosity in a Store



Summary

- The higher polarization during this run comes from several improvements:
  - Much better orbit this run: vertical realignment; excellent orbit control on the ramp; BPM offset sign reversal.
  - Vertical tune moved further away from snake resonance 7/10. This is only possible with precise control of betatron tune.
  - High polarization out of AGS due to tune jump system.
- Higher luminosity is achieved with better ramp efficiency after introducing 9MHz cavity.
- Remaining Tasks:
  - Understand any polarization loss scheme;
  - Careful setup jump quads in the AGS to get full benefit;
  - Control emittance through the whole accelerator chain;
  - Introduce electron lenses to compensate beam-beam effect.