Simultaneous orbit, tune, coupling and chromaticity feedback in RHIC

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Each and every ramp at RHIC is executed with simultaneous orbit, tune, coupling and energy (radial loop) feedback.

Proof-of-principle for additional chromaticity feedback has also been shown.

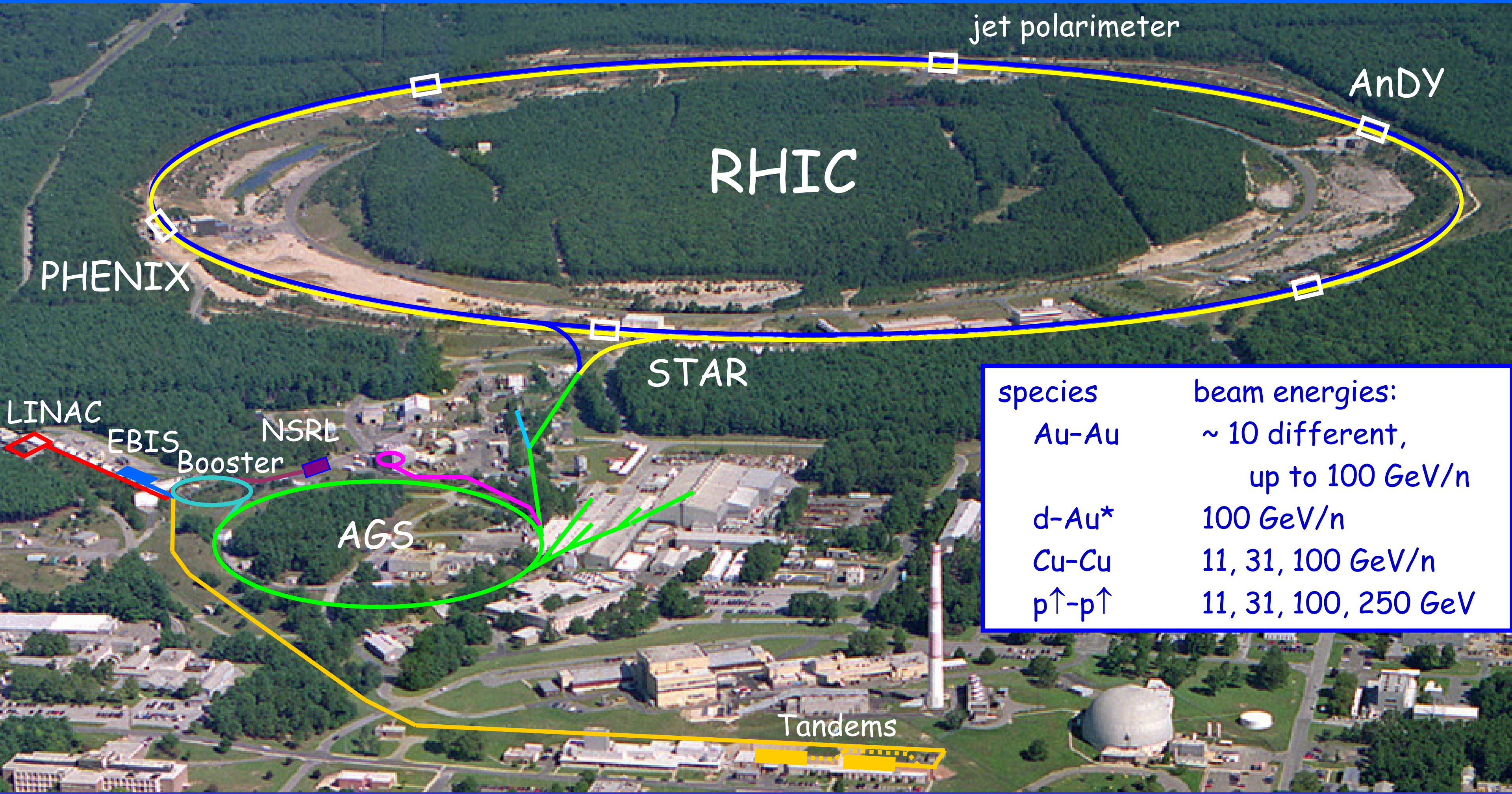
ORIGINAL MOTIVATION

improved ramp development efficiency
polarization preservation

WITH CONTINUOUS APPLICATION

improved reproducibility of accelerator conditions
more precise measurement (and control) of beam parameters
error signals useful for monitoring changes in accelerator and beam properties

Relativistic Heavy Ion Collider (RHIC)



species	beam energies:
Au-Au	~ 10 different, up to 100 GeV/n
d-Au*	100 GeV/n
Cu-Cu	11, 31, 100 GeV/n
p↑-p↑	11, 31, 100, 250 GeV

consists of two ~3.8 km independent superconducting accelerators
operates with a wide range of particle species and beam energies

TUNE AND COUPLING FEEDBACK AT RHIC

measurement

based on direct-diode detection (BBQ = base-band tune) for precision measurements - M. Gasior , R. Jones (2005)

feedback design

uses methodology of coupling angle measurement – Y. Luo (2004)
distinguishes between eigenmodes - R. Jones, P. Cameron, Y. Luo (2005)

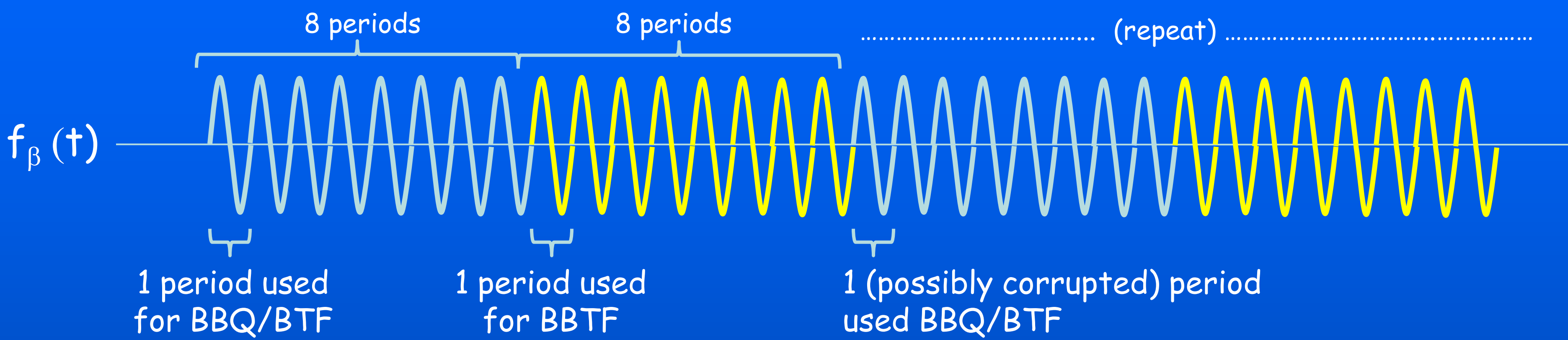
history

demonstrated at RHIC in 2006 - P. Cameron et al (2006)
successfully applied for all ramp developments in 2009
used regularly by operations for ramp development in 2010
used together with orbit and energy feedback for all ramps in 2011

Most significant changes allowing routine application of tune/coupling feedback:

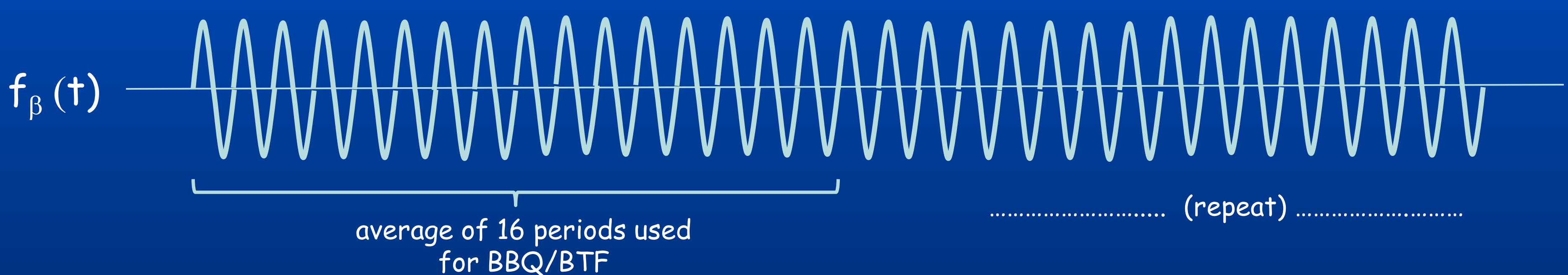
(1) use of all available data

before:



⇨ 1 in 16 periods of data used for BBQ/BTF

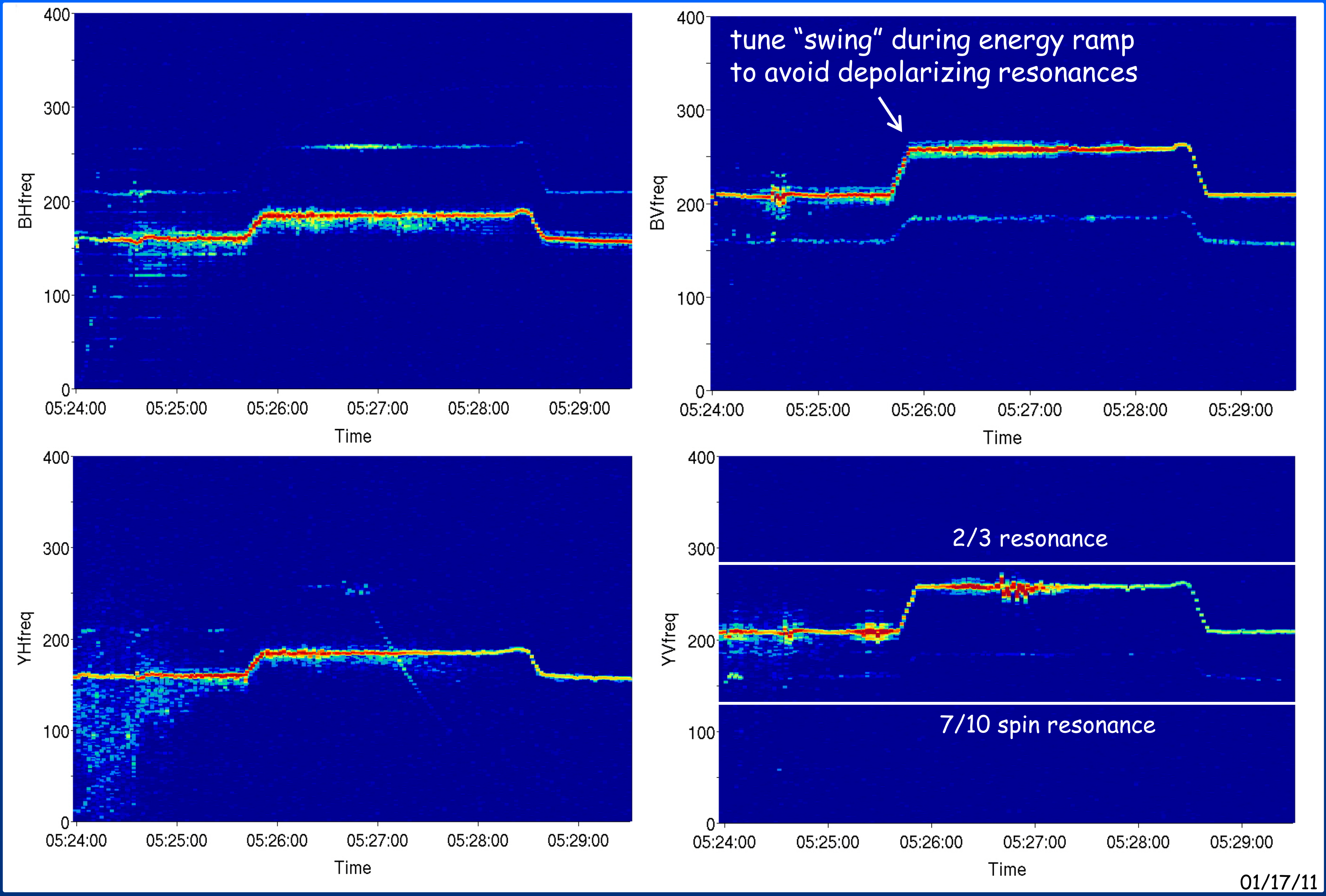
after:



⇨ averaged data (I and Q) delivered at same rate as before

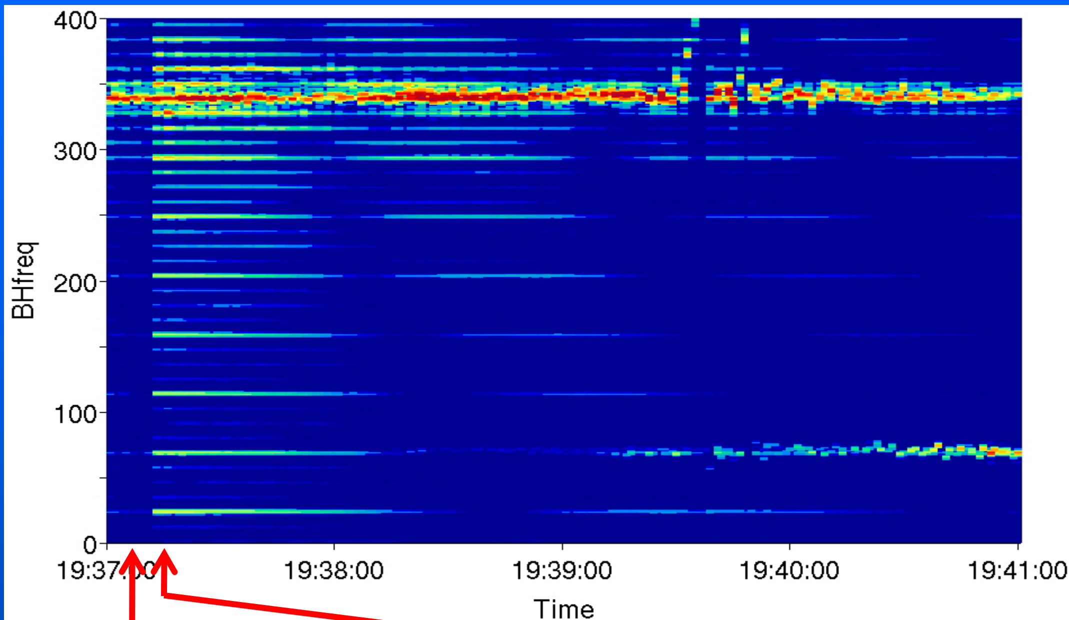
(2) improved integration to main control room

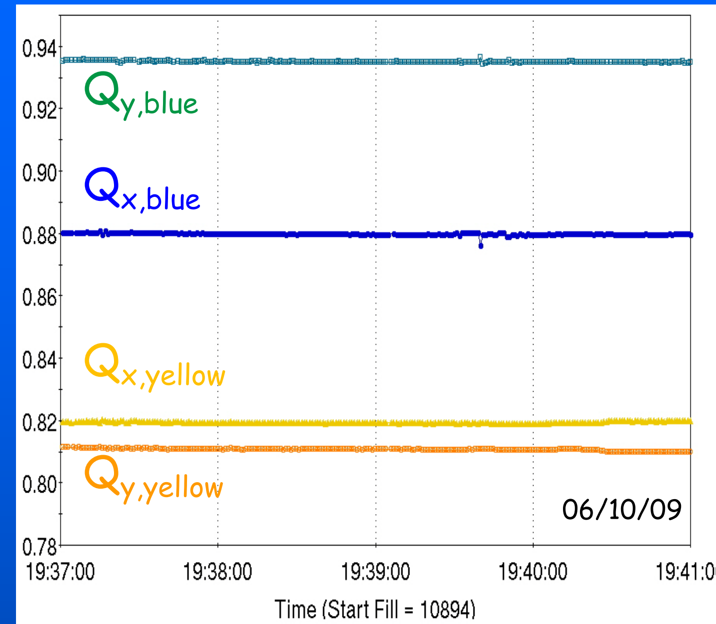
beam spectra in the blue (top) and yellow (bottom) accelerators in first ramp to 250 GeV in run-11

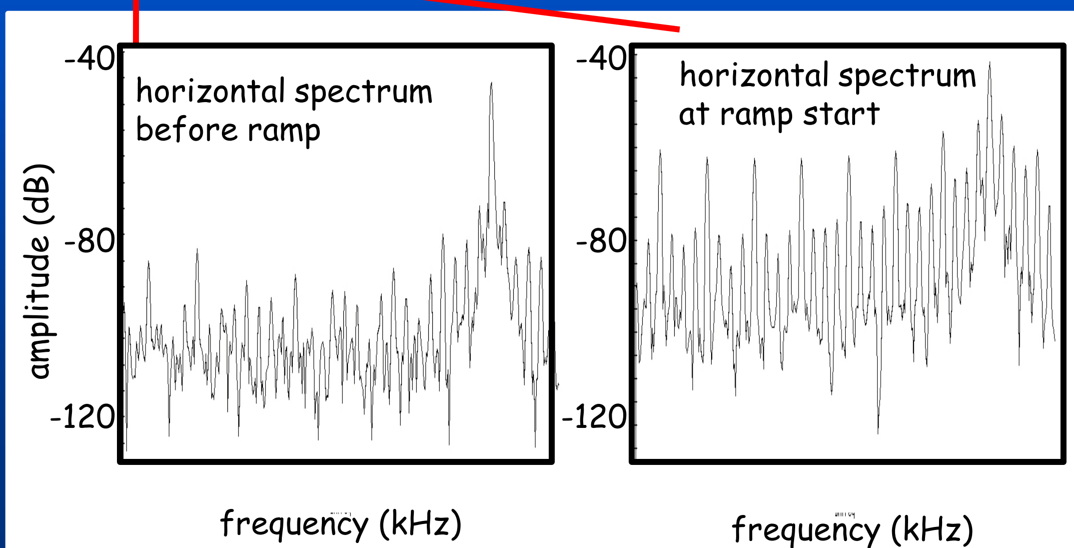


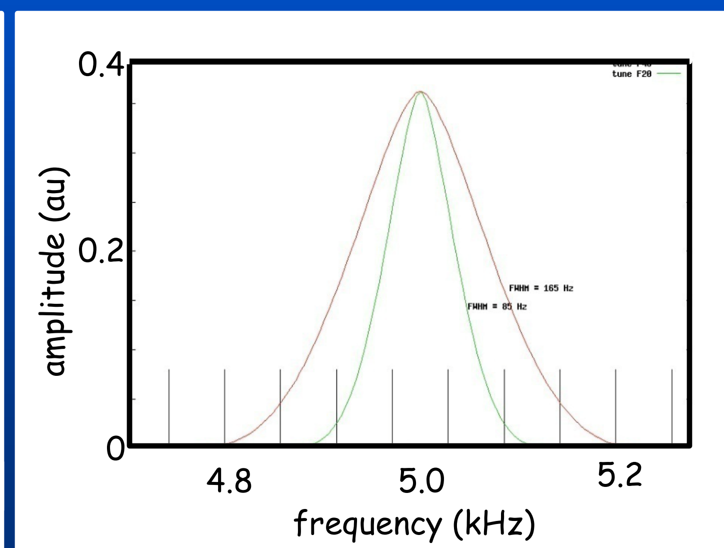
(3) digital filter for immunity to 60 Hz harmonics (not a problem at nominal working point)

horizontal beam spectrum blue during near-integer tune studies



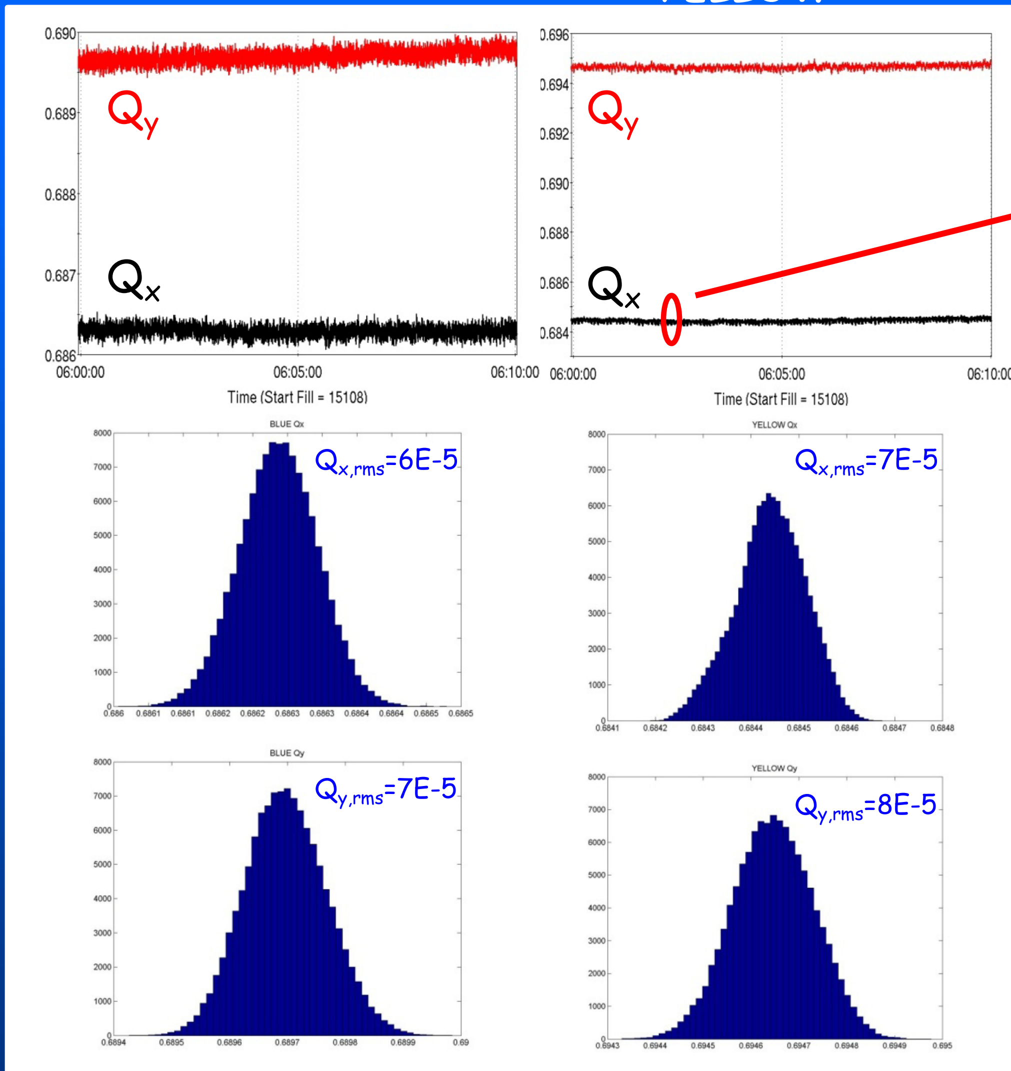


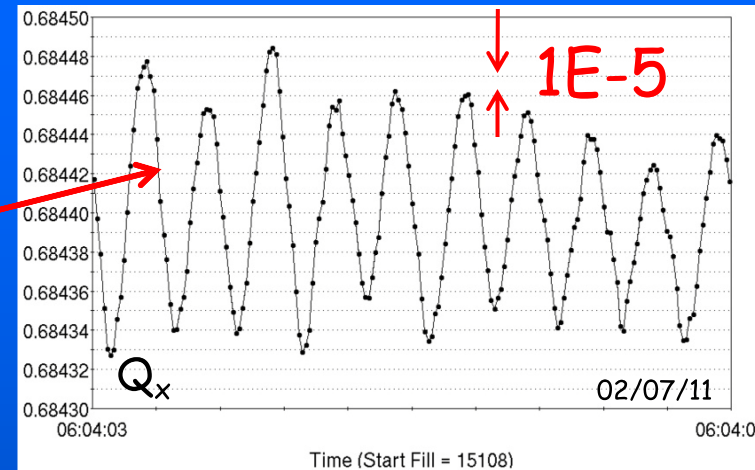




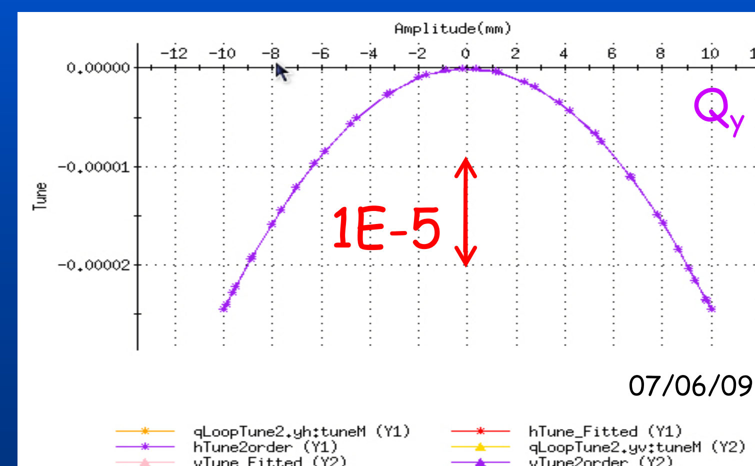
TUNE MEASUREMENTS

BLUE YELLOW





tune measurements during nonlinear field corrections



⇒ precision of tune measurements improved by > factor 10

⇒ now dominated by presence of ~10 Hz variations

COUPLING MEASUREMENTS

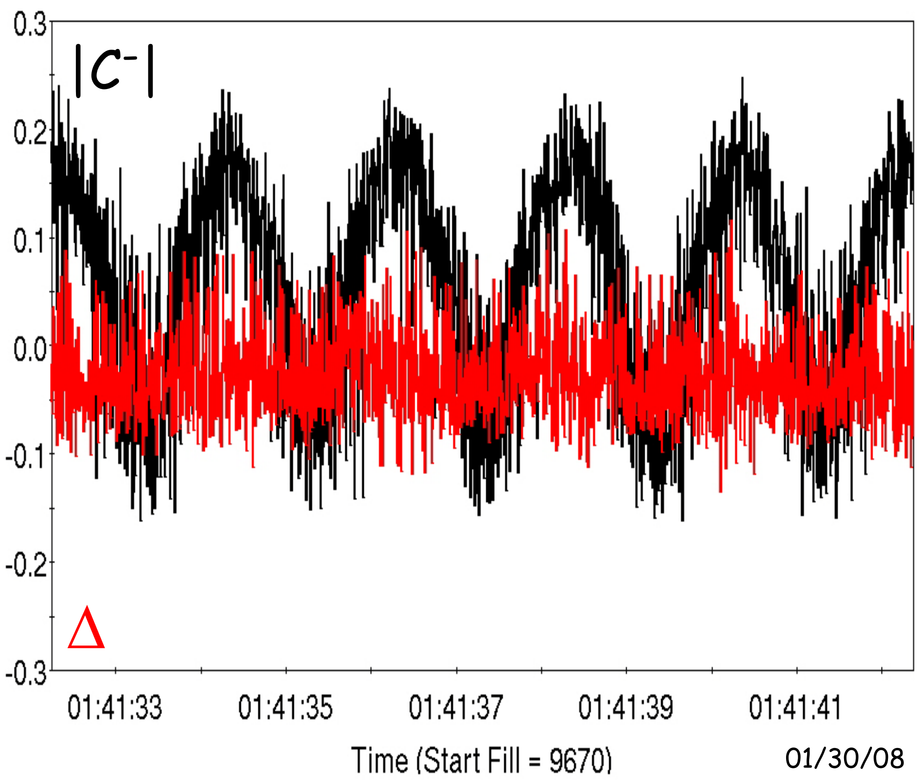
coupling coefficients:

$$|C^-| = \frac{2\sqrt{r_1 r_2}|Q_x - Q_y|}{1 + r_1 r_2}$$

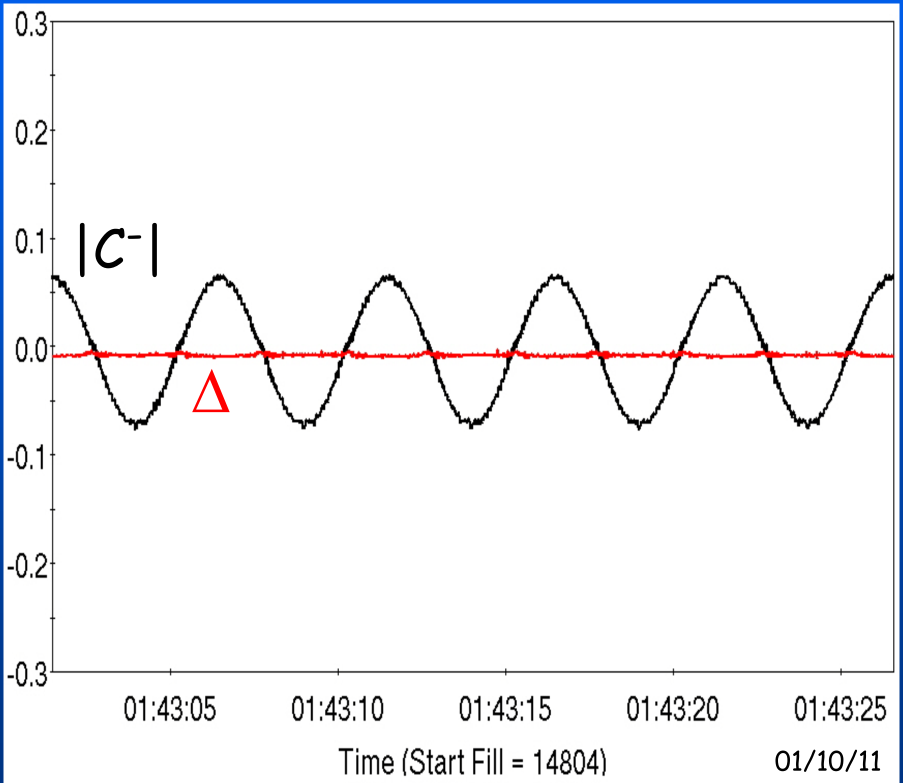
$$\Delta = \frac{|Q_x - Q_y|(1 - r_1 r_2)}{1 + r_1 r_2}$$

with $r_1 = \frac{\tilde{A}_{1y}}{\tilde{A}_{1x}}$ and $r_2 = \frac{\tilde{A}_{2x}}{\tilde{A}_{2y}}$

run-08



run-11



⇒ precision of coupling measurements improved by > factor 10

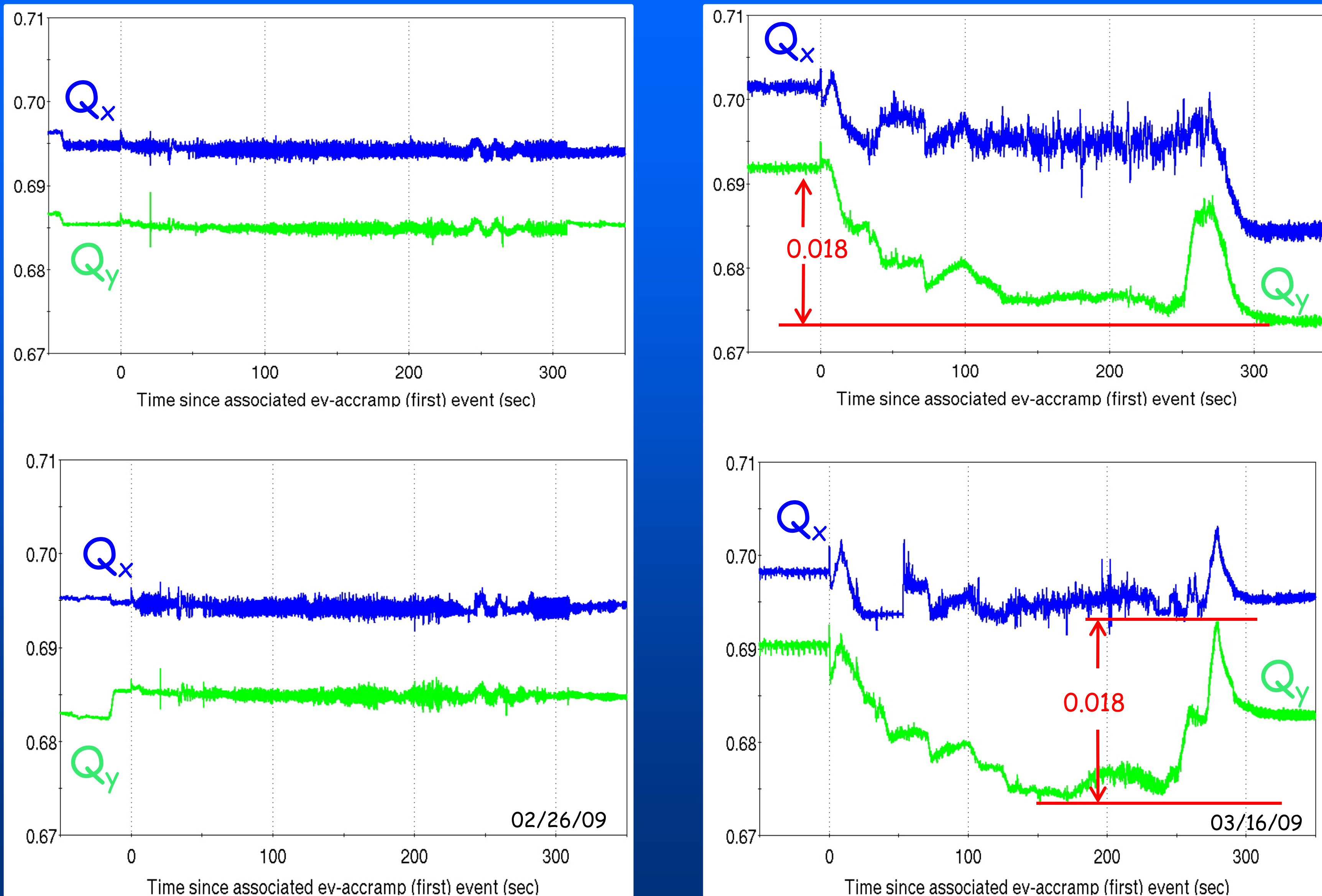
TUNE FEEDBACK

ramp with tune/coupling feedback (run-09)

later ramp with replay (run-09)

BLUE

YELLOW

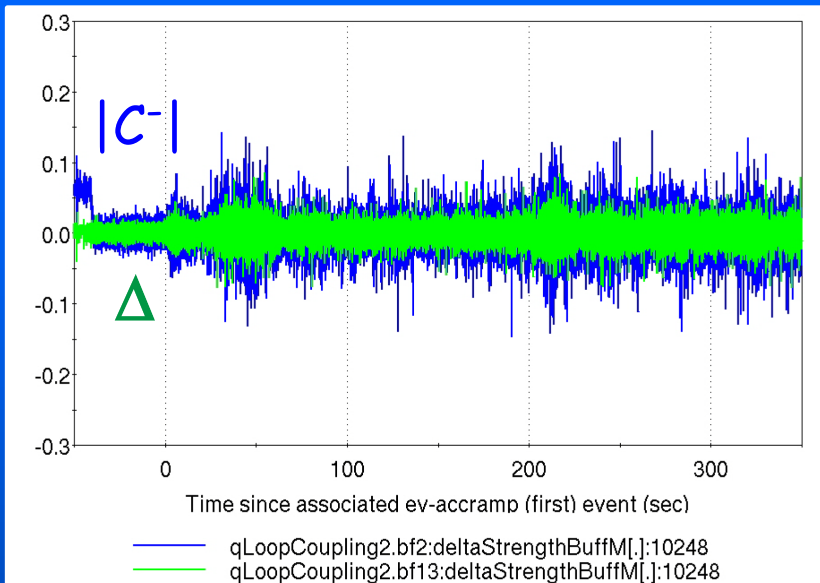


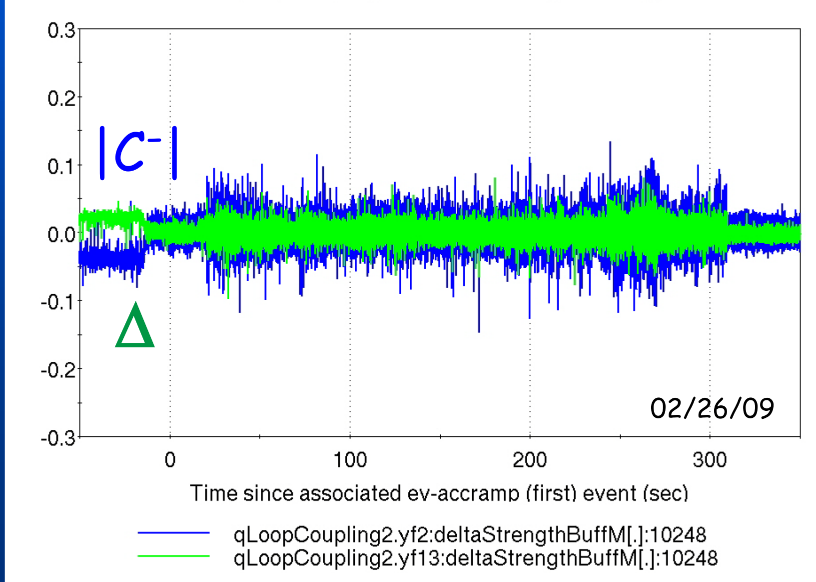
COUPLING FEEDBACK

BLUE

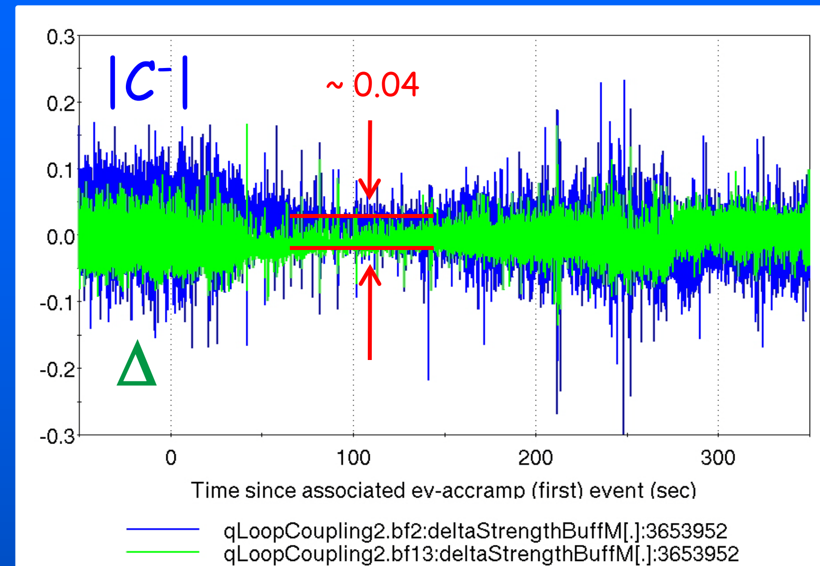
YELLOW

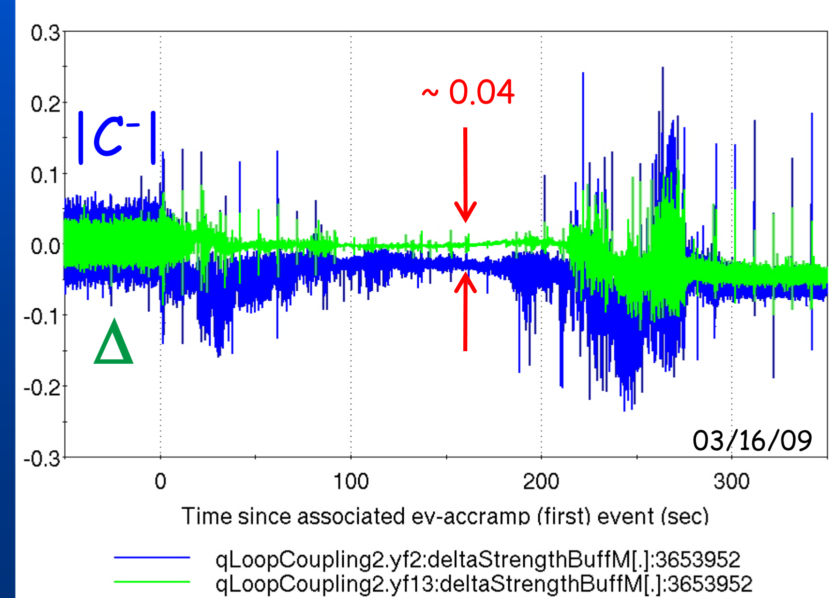
ramp with tune/coupling feedback (run-09)





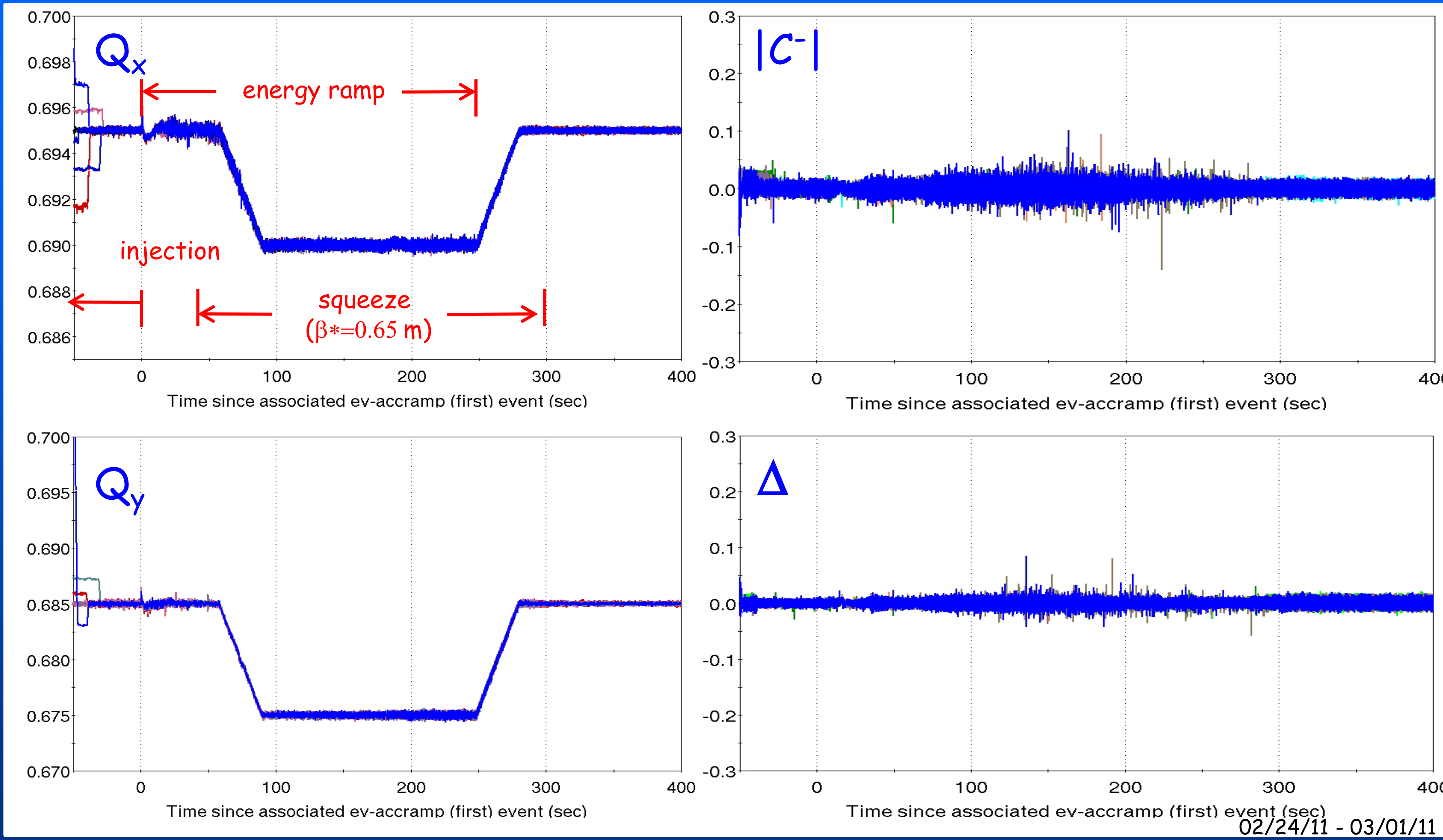
later ramp with replay (run-09)





TUNE AND COUPLING FEEDBACK AT RHIC

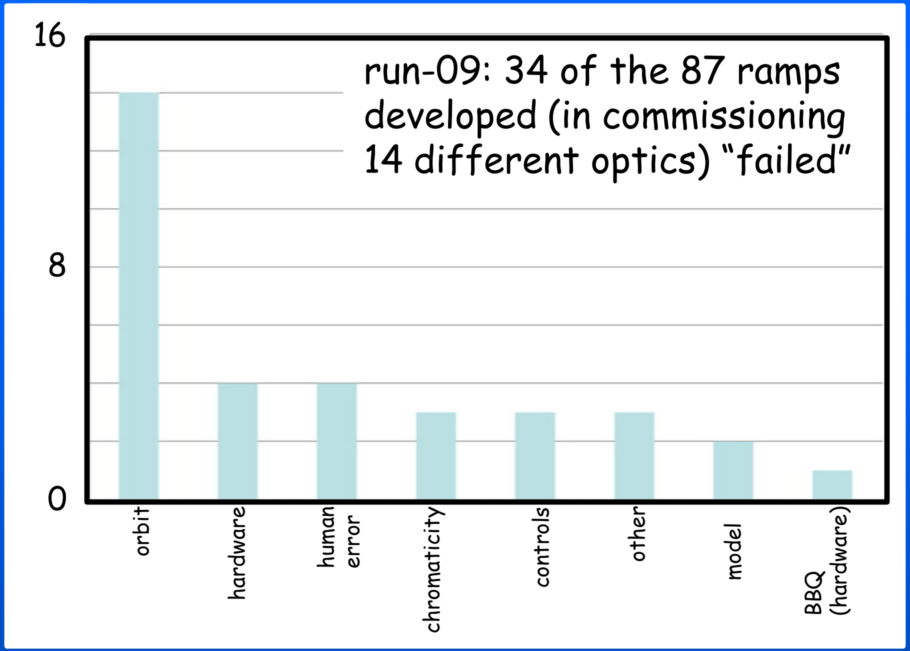
multiple superimposed ramps, run-11:



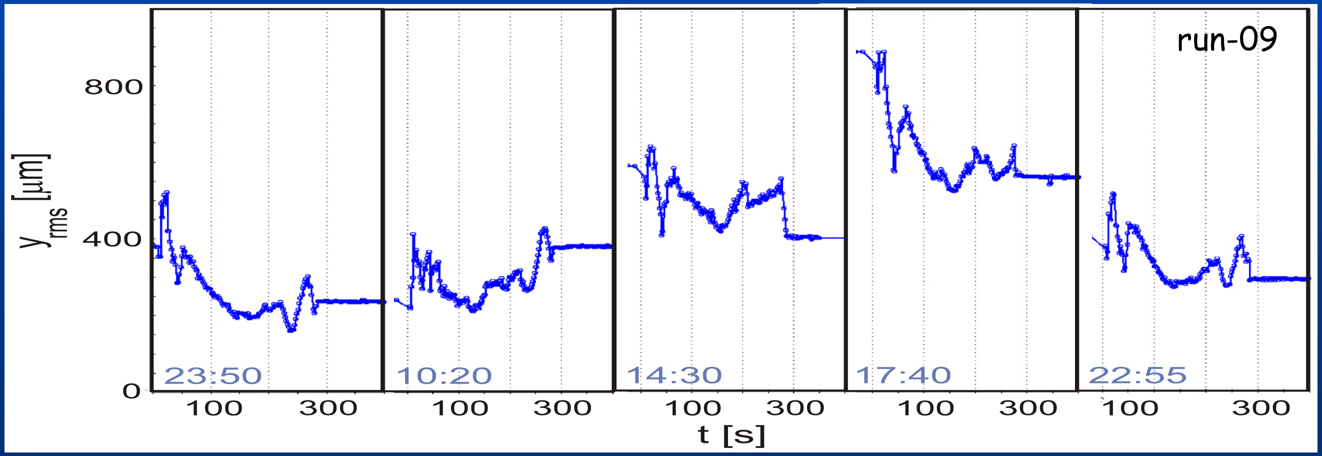
- tunes and coupling well controlled, reproducibility is excellent
- tune/coupling feedback now essential for polarized proton operations

ORBIT FEEDBACK AT RHIC

In run-09 poor orbit control was leading cause of "failed ramps " (ramps which did not end with files suitable for use as replay files)

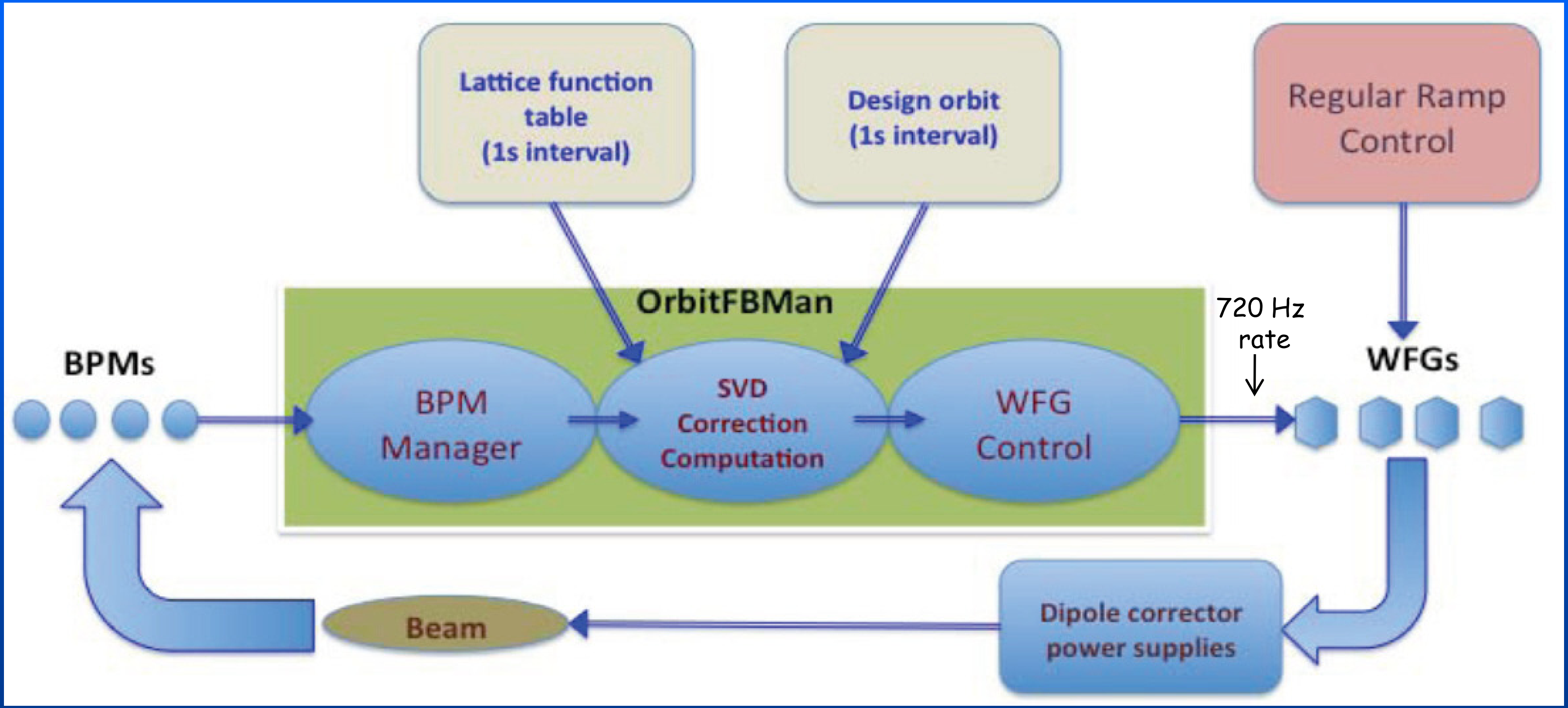


Shortly before run-10, an ambitious program to develop global orbit feedback was initiated with first successful demonstration ~ 4 months later. Orbit feedback was motivated additionally to combat diurnal drift which is important particularly in the context of polarization preservation.



ORBIT FEEDBACK AT RHIC

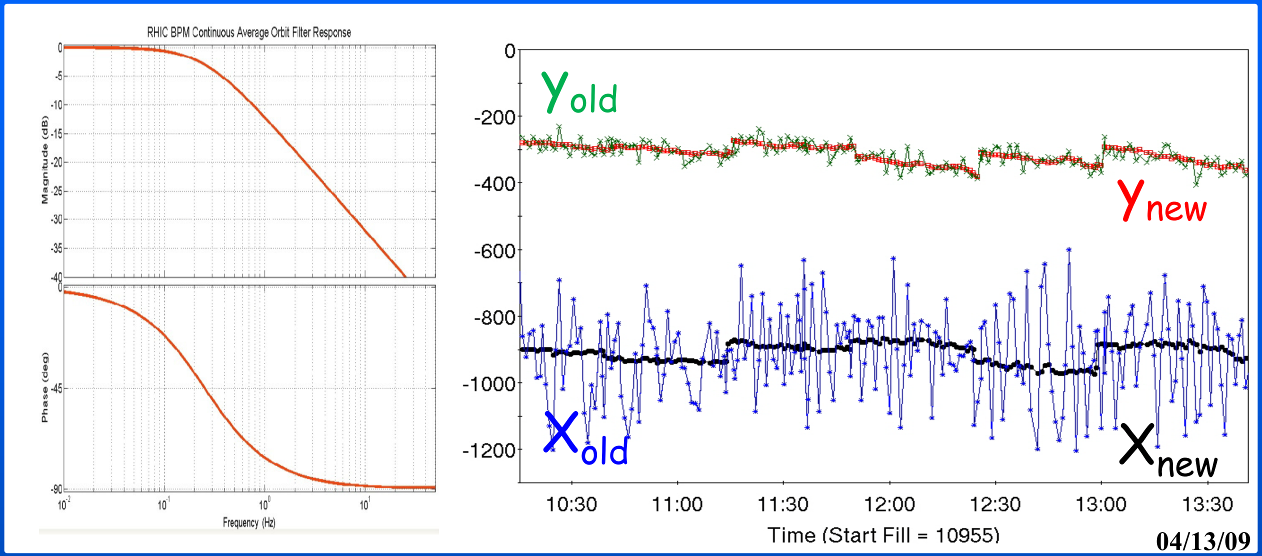
- developed entirely within the framework of existing infrastructure
- 4 months from inception to online demonstration



key features: includes ~ 300 BPMs and ~230 correctors per accelerator
based on SVD algorithm and online model (tabulated, updated once per second)
corrects to specified or measure reference trajectory
excludes dispersive orbit
operates at 1 Hz rate

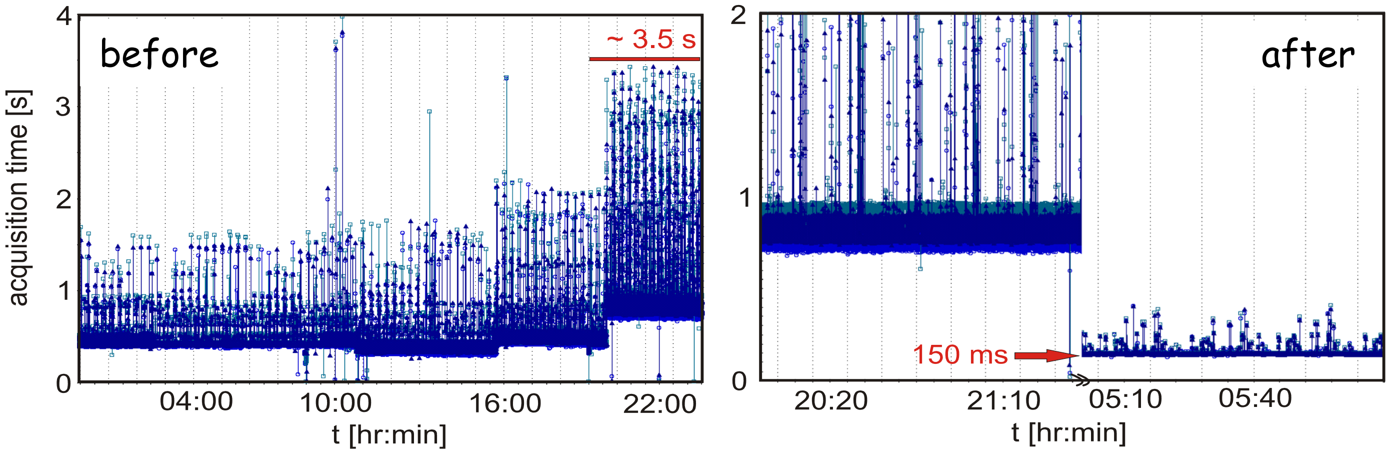
ORBIT MEASUREMENTS

uses digital equivalent of a single-pole, low pass filter (IIR filter) to effectively average out predominantly ~ 10 Hz variations in the closed orbit



precision of average orbit measurements improved by > factor 10

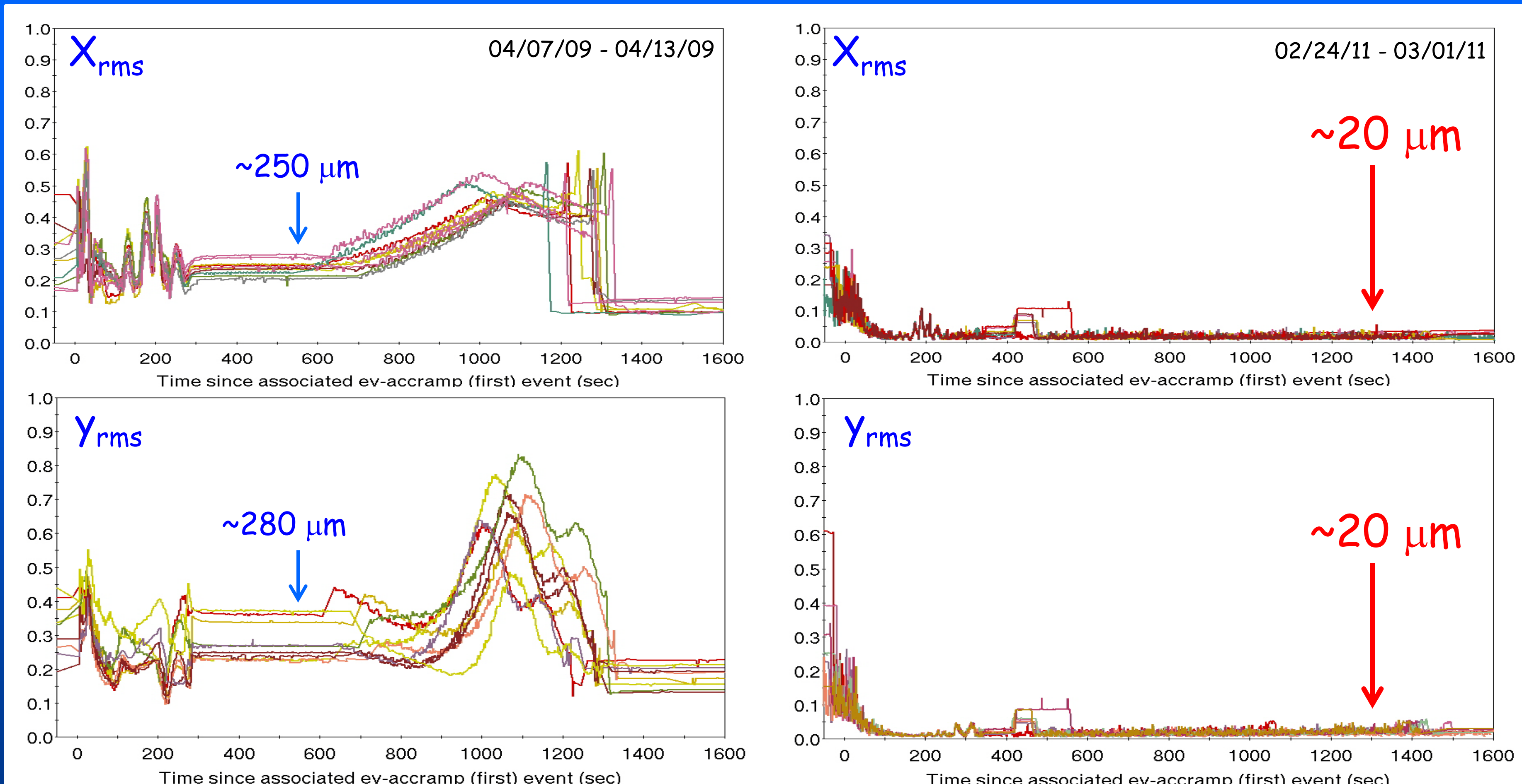
improvements to data acquisition - faster and deterministic data delivery from BPMs



ORBIT FEEDBACK AT RHIC

BLUE RING

run-09 run-11

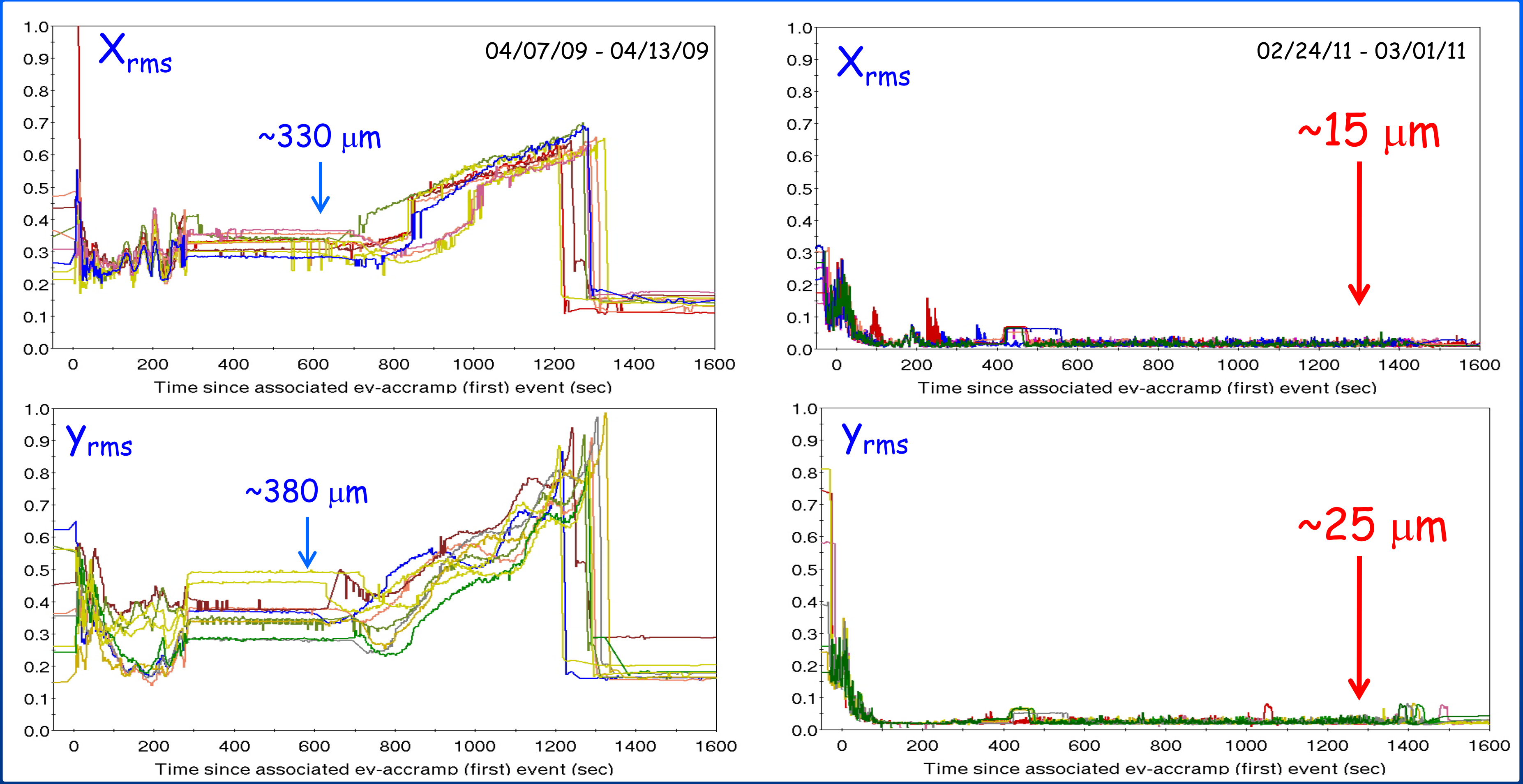


- orbits well controlled, reproducibility is excellent
  orbit feedback now essential for polarized proton operations

ORBIT FEEDBACK AT RHIC

YELLOW RING

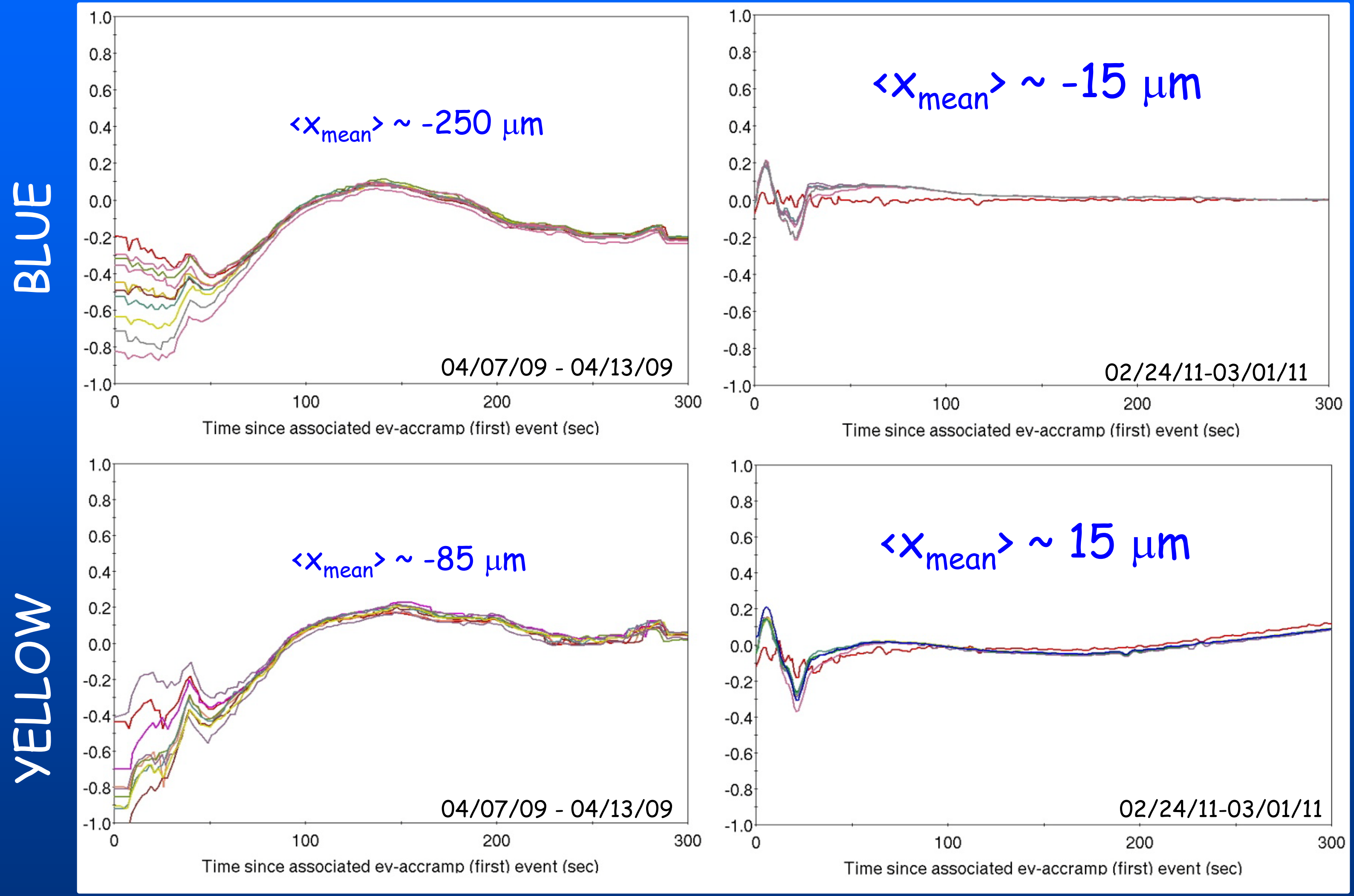
run-09 run-11



- orbits well controlled, reproducibility is excellent
- orbit feedback now essential for polarized proton operations

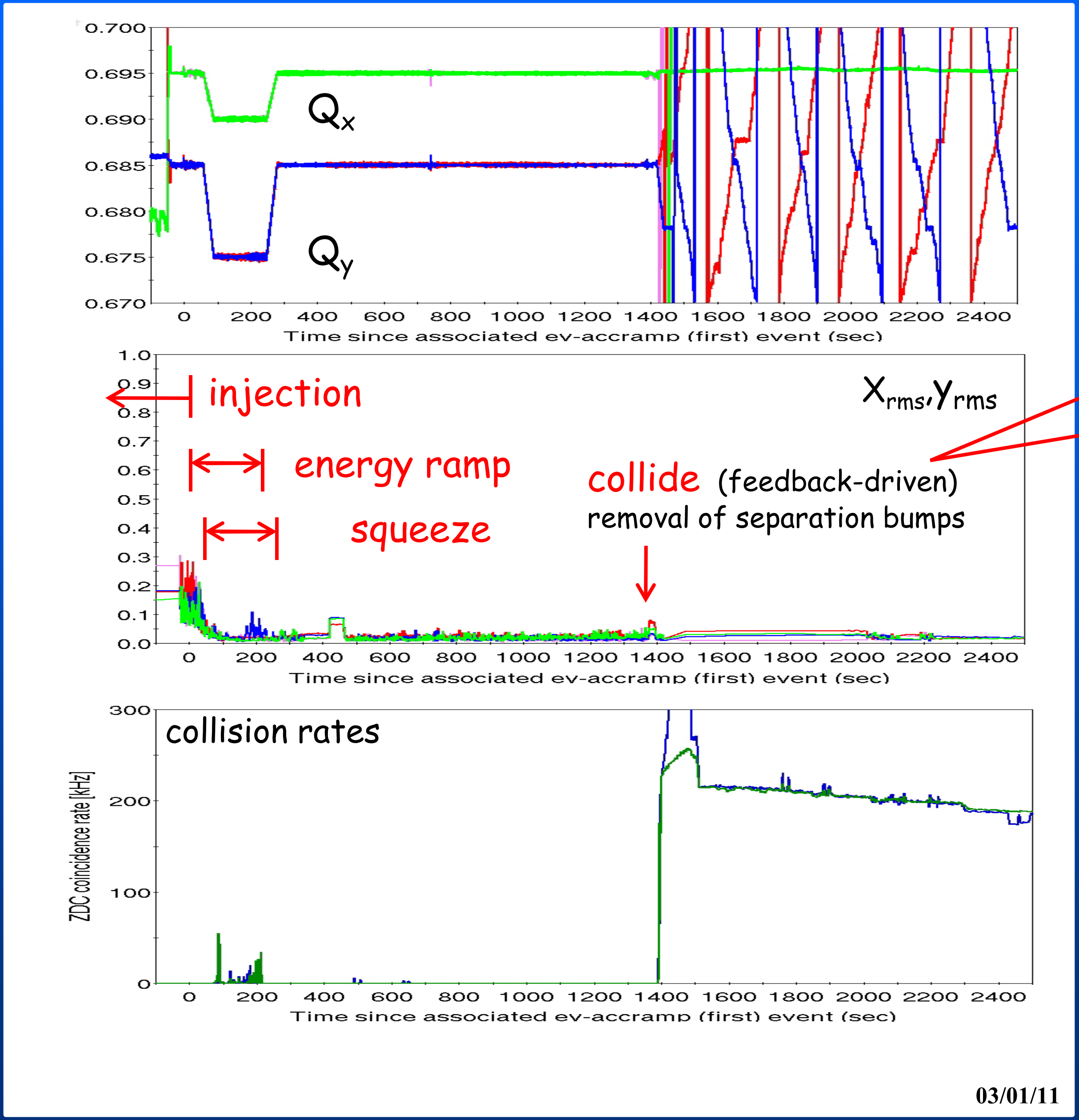
ENERGY (radial loop) FEEDBACK AT RHIC

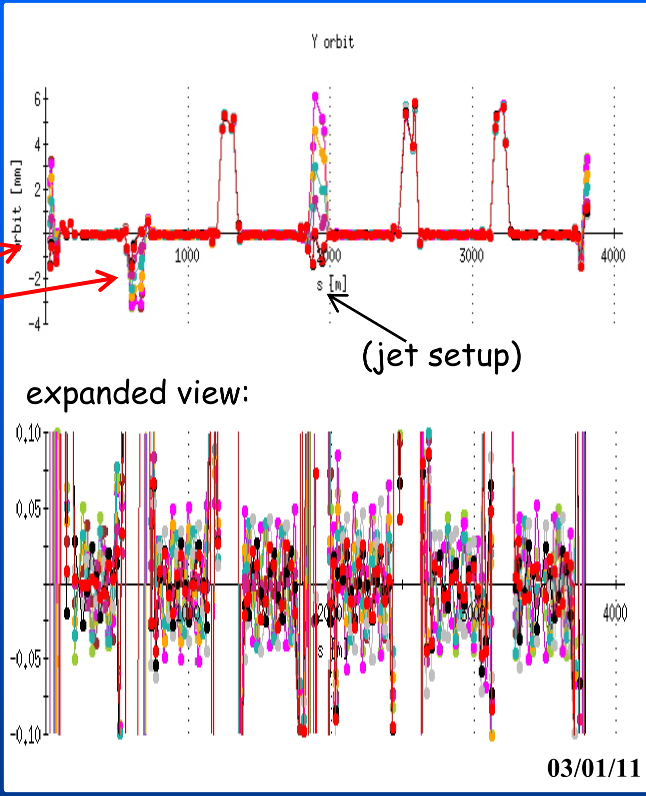
now uses x_{mean} derived from all arc BPMs, as opposed to only 2 BPMs with ~ pi phase advance, to (as before) adjust rf frequency



⇒ profits from higher precision estimate of energy deviation
profits from application of orbit feedback at injection energy

TYPICAL STORE SETUP





CHROMATICITY FEEDBACK AT RHIC

measurement

based on existing tune measurements + rf frequency modulation

history

measurements along the energy ramp at RHIC demonstrated already in 2002
implementation architecture (PID loops) similar to that for tune/coupling feedback
hardware limit (23-bit limit of RTDL) identified in late 2009
first successfully demonstrated in 2010

major challenges encountered during commissioning of chromaticity feedback

(1) sensitivity of algorithm to (intentional and unintentional) tune variations
(2) susceptibility to 60 Hz harmonics with modulated tunes

aside: determined not to be a prerequisite for tune/coupling feedback

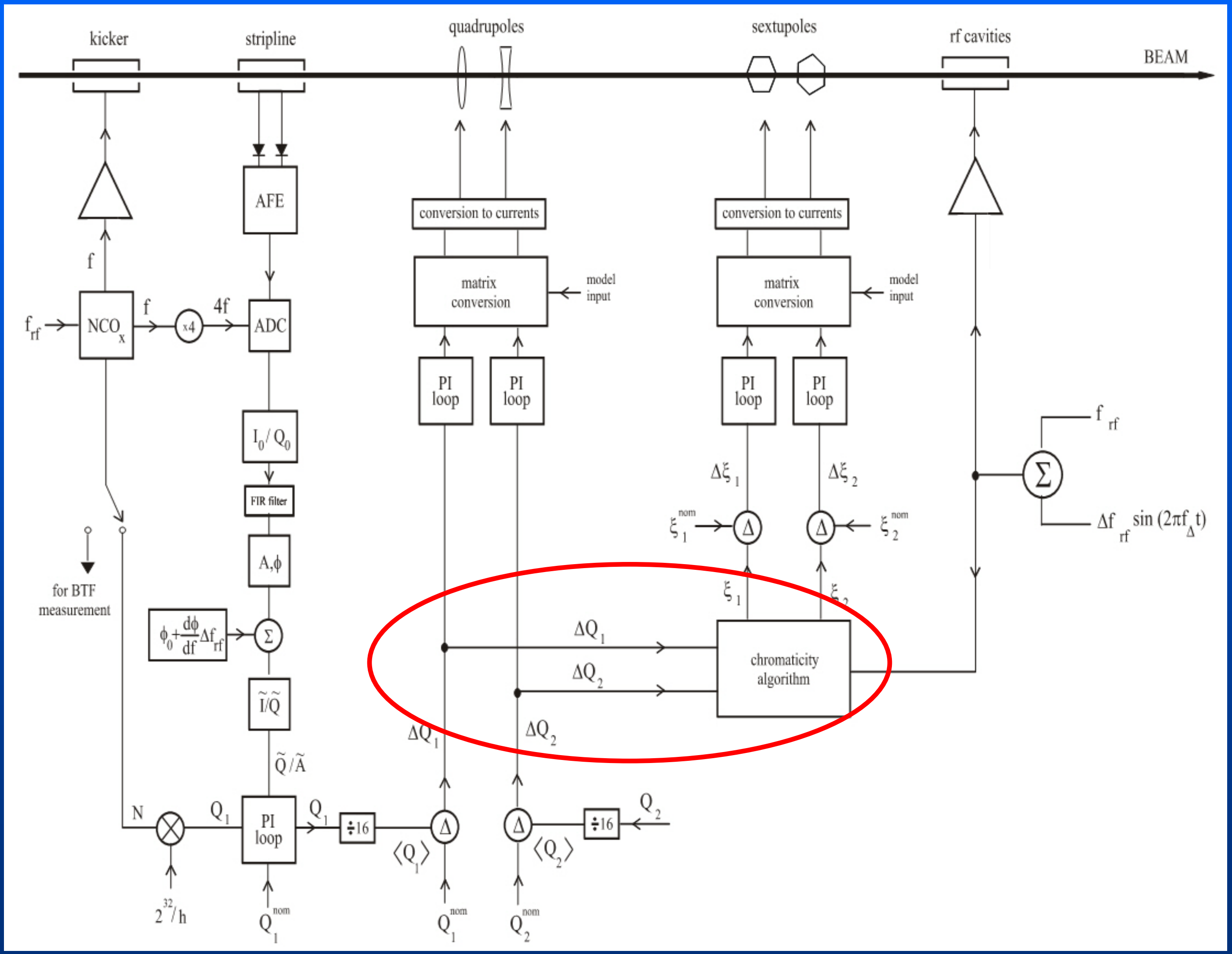
interaction with orbit feedback

nominally none: with rf frequency modulation at 0.5 Hz, BPMs sampled at zero crossing of rf frequency modulation; now (run-11) using input to energy feedback loop to modulate rf frequency

interaction with tune/coupling feedback

the corrections from the tune/coupling feedback loop sent to the quadrupoles are used as input to the chromaticity measurement algorithm

tune feedback chromaticity feedback

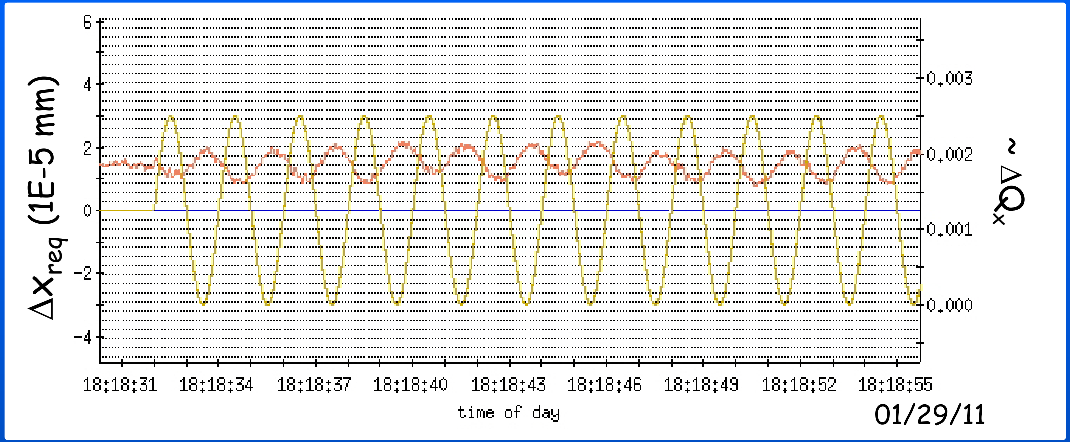


⇒ chromaticity feedback is dependent on the gain and bandwidth of the tune/coupling feedback loop

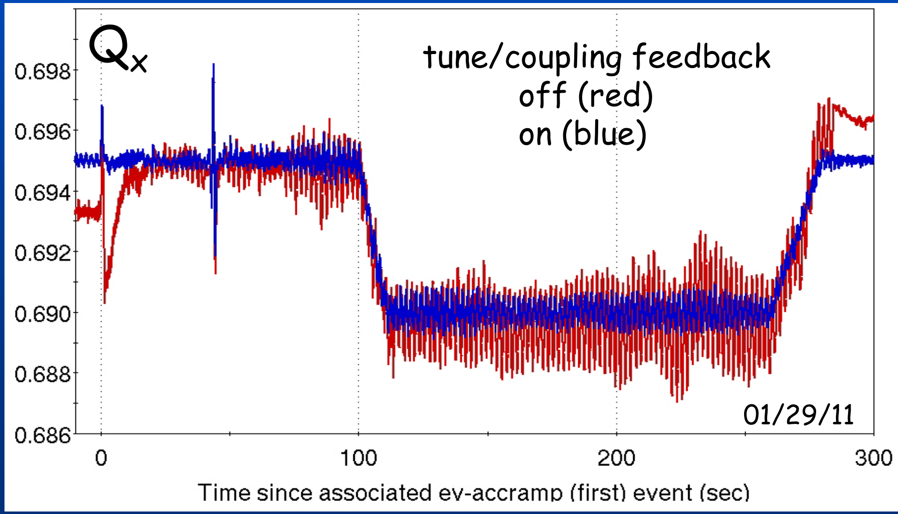
CHROMATICITY MEASUREMENT

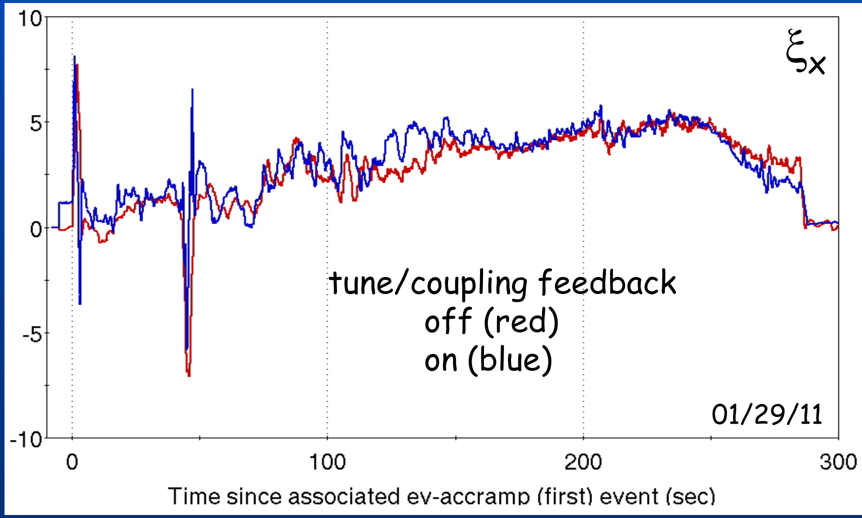
The chromaticity algorithm must be calibrated for use with tune feedback

(1) tune/coupling feedback bandwidth produces a phase shift - determined by comparing the tune and rf frequency modulations measured with tune/coupling feedback engaged



(2) tune/coupling feedback gain results in a scaling factor - determined by comparing the measured chromaticity with and without tune/coupling feedback

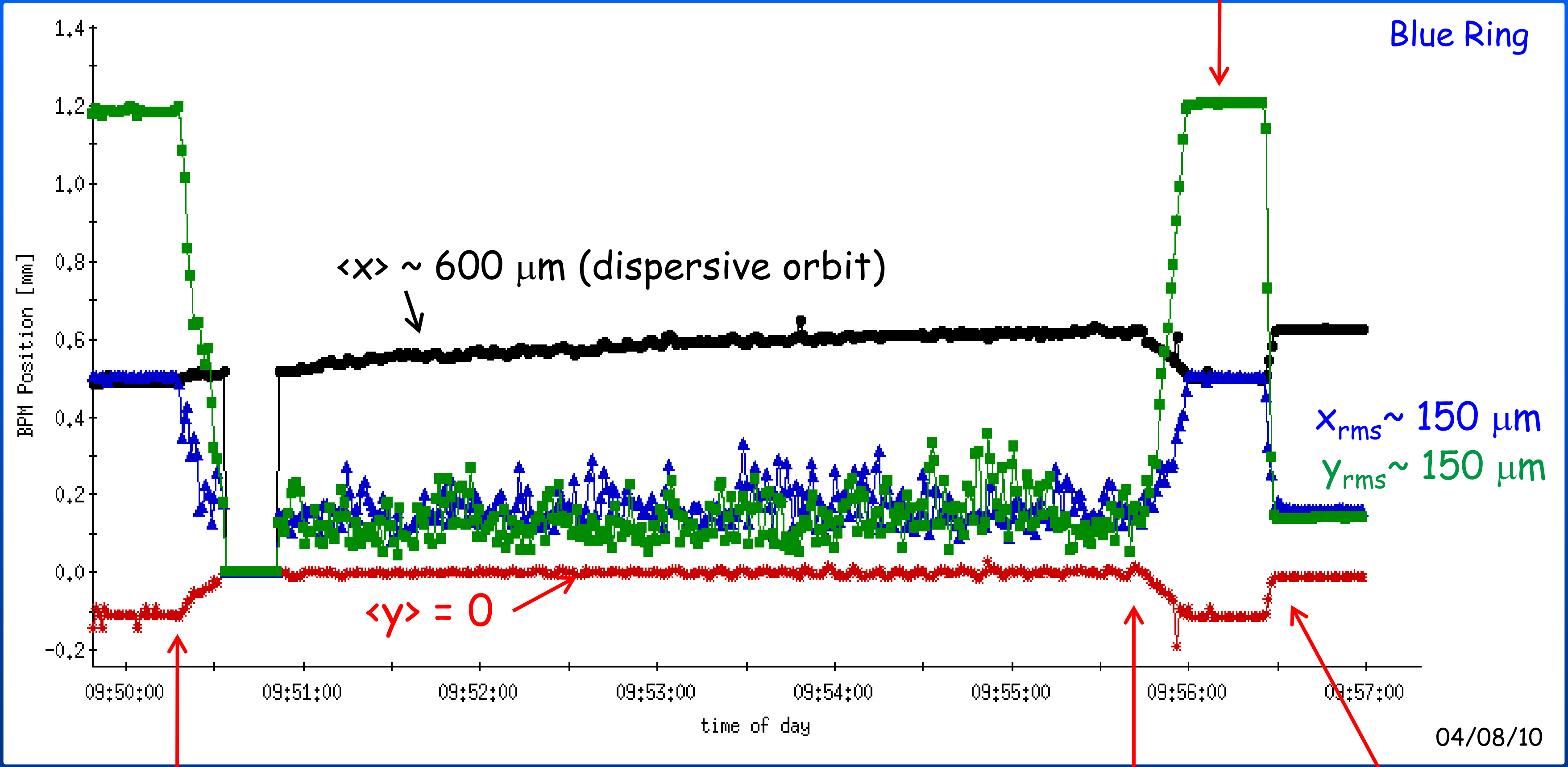




SIMULTANEOUS ORBIT, TUNE, COUPLING, AND CHROMATICITY FEEDBACK AT RHIC

09:50 – prepare orbits at injection energy

feed-forward feedback settings



initial conditions for energy ramp

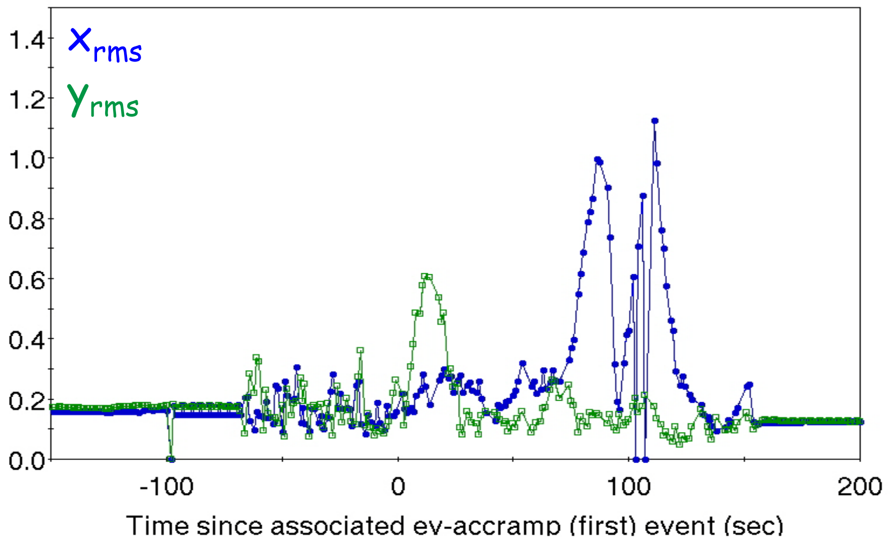
engage orbit feedback

disengage orbit feedback and ramp down

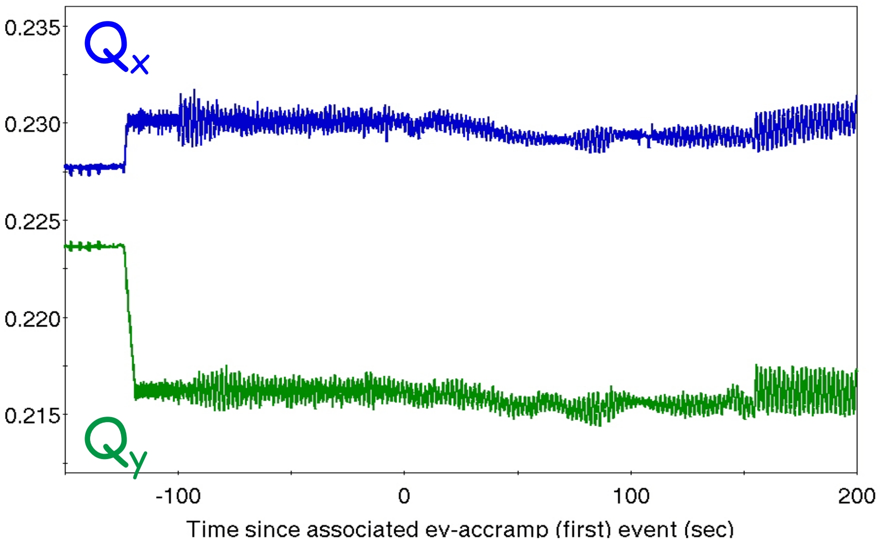
activate

10:40 – first ramp of both beams to store energy with all feedbacks

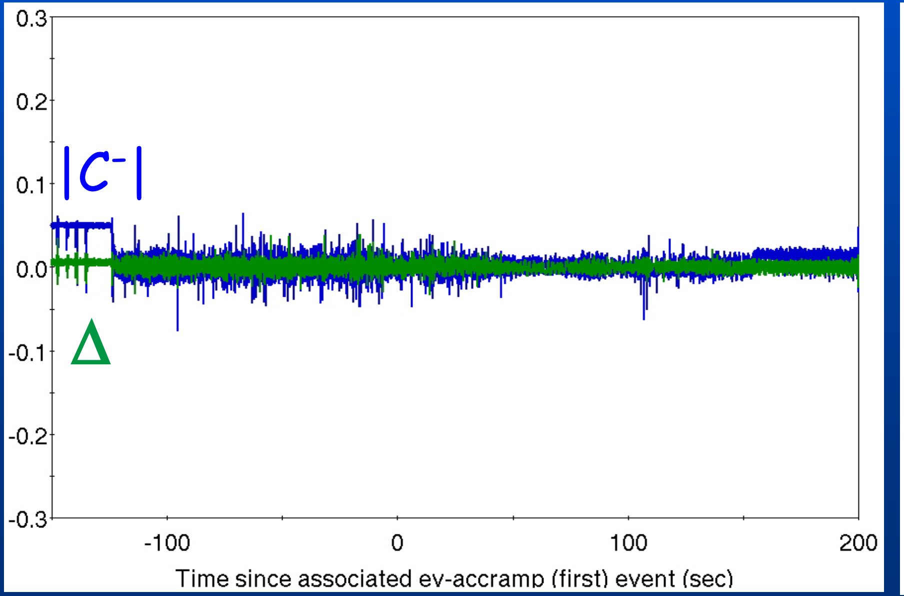
ORBITS



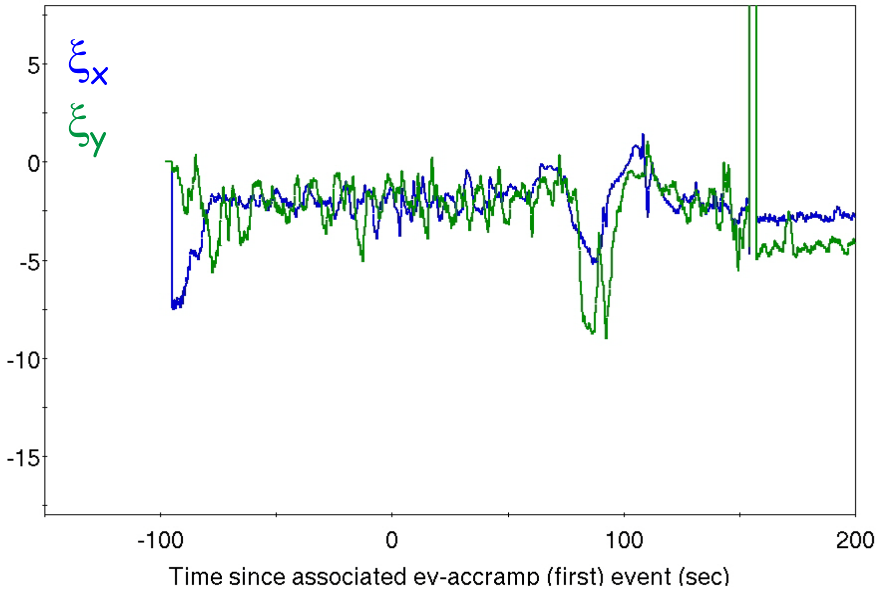
TUNES



COUPLING



CHROMATICITY

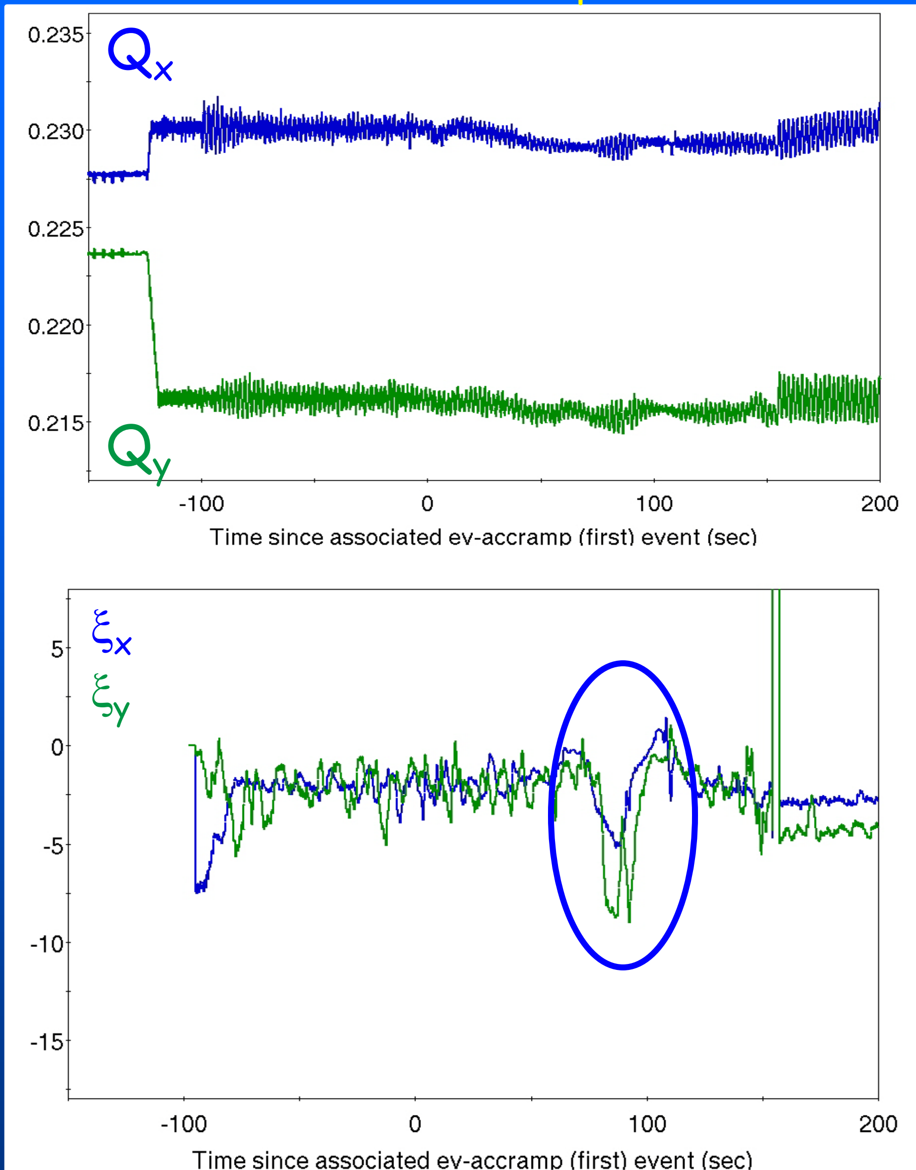


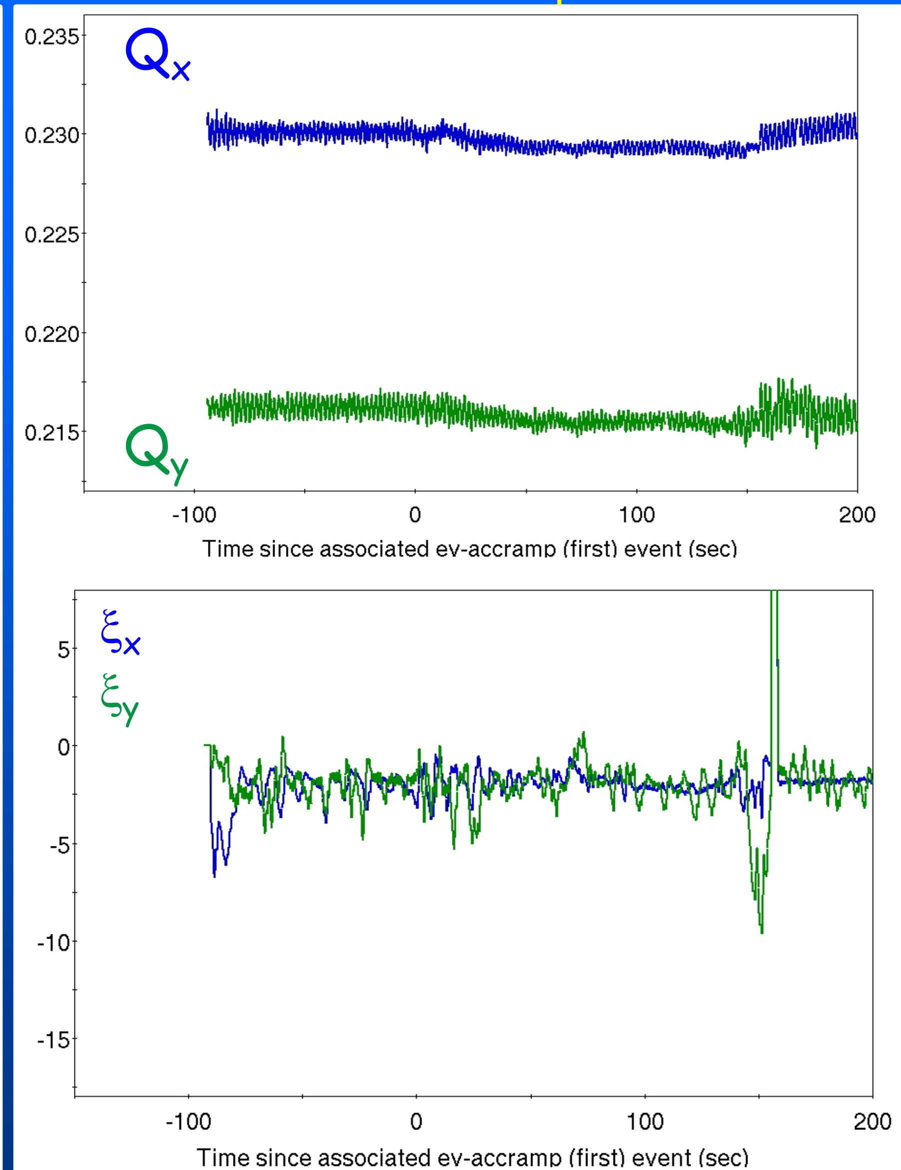
10:40 – first ramp

11:46 – second ramp

TUNES

CHROMATICITY





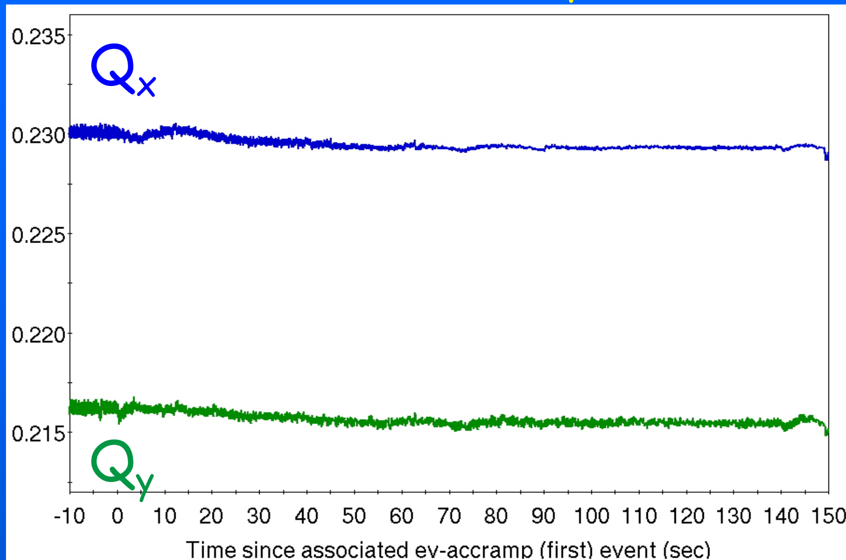
ramp efficiencies:
33% blue (6 bunches)
99% yellow (6 bunches)

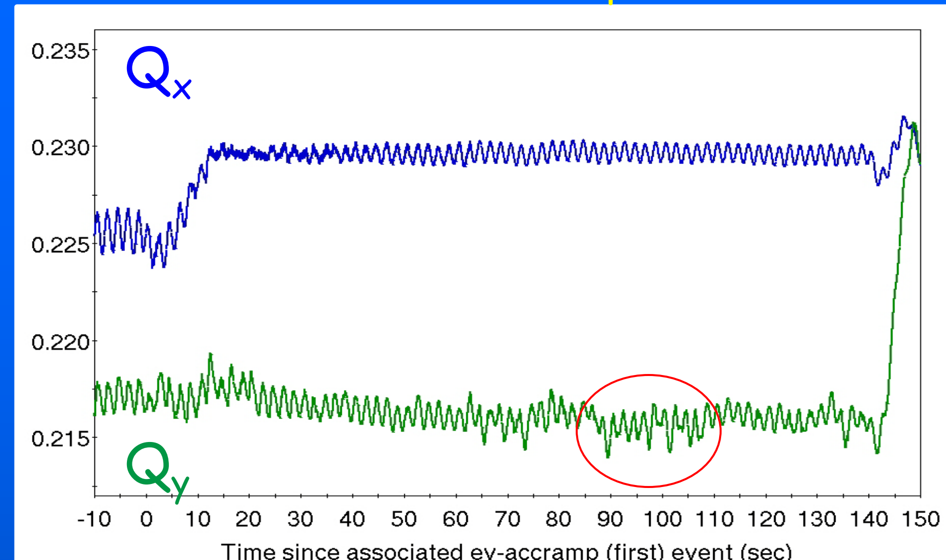
ramp efficiencies:
98% blue (6 bunches)
98% yellow (6 bunches)

12:32 – third ramp

13:36 – fourth ramp

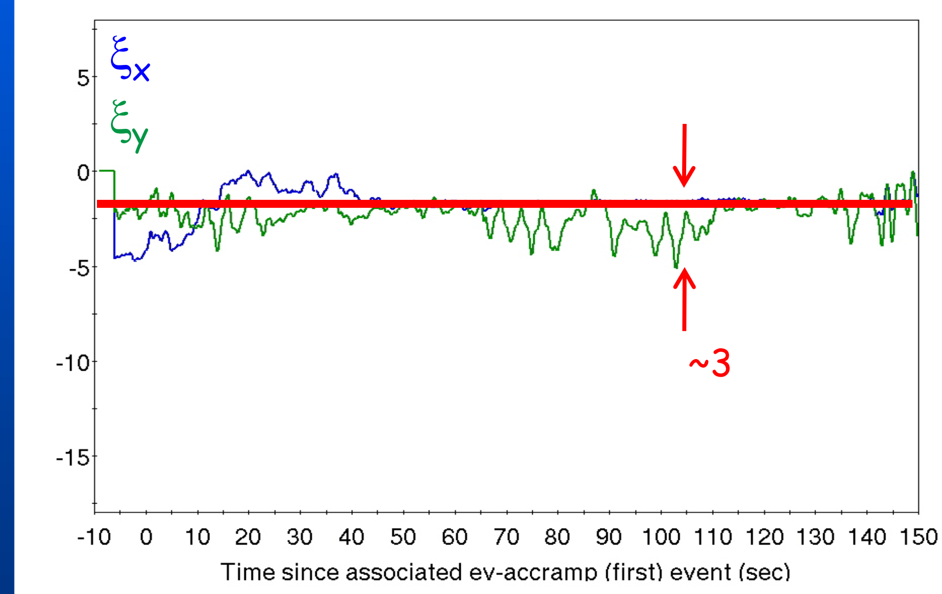
TUNES





CHROMATICITY

rf frequency modulation
intentionally off



ramp efficiencies:

100% blue (17 bunches)

100% yellow (23 bunches)

ramp efficiencies:

91% blue (111 bunches)

99% yellow (111 bunches)

STABILITY COMPARISON WITH AND WITHOUT FEEDBACK

parameter	stability no feedback	stability with feedback	used in normal operations
ORBIT X_{rms} Y_{rms}	~ 1 mm	~20 μm	YES
TUNE Q_x Q_y	~ 0.1 ("first" ramp) ~ 0.018 (with replay)	~ 0.001	YES
COUPLING $\|C-\|$ Δ	~ 0.1 ("first "ramp) ~ 0.04 (with replay)	~ 0.01	YES
ENERGY, X_{mean}	~ 250 μm	~15 μm	YES
CHROMATICITY ξ_x ξ_y	~ 10	~ 3 (with as yet limited experience)	NO

CONCLUSION

Control of the parameters affecting beam properties during acceleration in RHIC has transitioned from being pre-programmed to based on measurements of the beam's properties

The resolution of all such measurements (beam position, energy deviation, tune, coupling, and chromaticity) has been improved by more than a factor of 10 and is nearing the limitations of the instrumentation

At RHIC all ramps (including those for physics) are now executed using orbit, tune, coupling, and energy feedback. Precision control of these parameters has expanded the parameter space accessible during acceleration . They allow for more extreme operating conditions and are now essential for polarized proton operation.