

# Coherent beam-beam experiments and implications for head-on compensation

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Thanks to M. Bai, M. Blaskiewicz, Y. Luo  
A. Marusic and W. Fischer



## **Electron lenses at RHIC**

*layout, motivations*

## **Impact of 2/3<sup>rd</sup> order resonance**

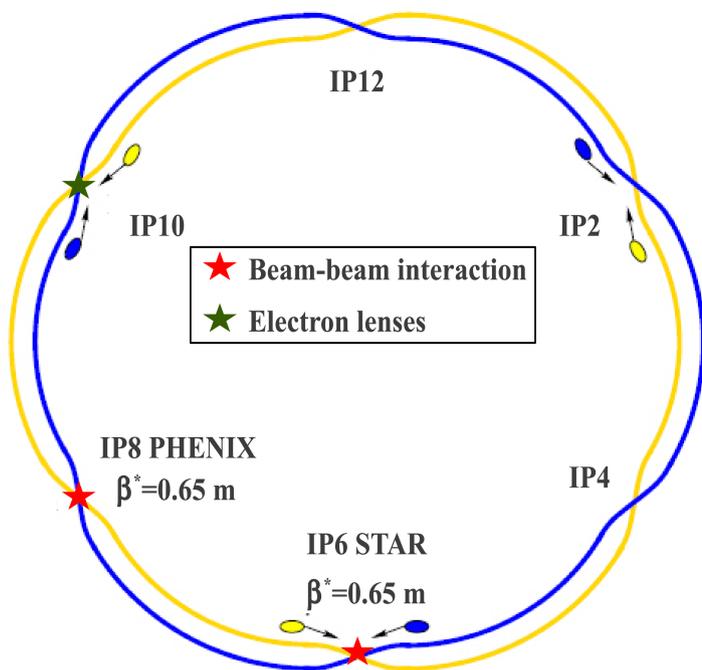
*stability, tune scans*

## **Coherent modes suppression**

*simulations, tune split experiment*

## **Beam stability with electron lenses**

*machine impedance, electron lens driven TMCI*



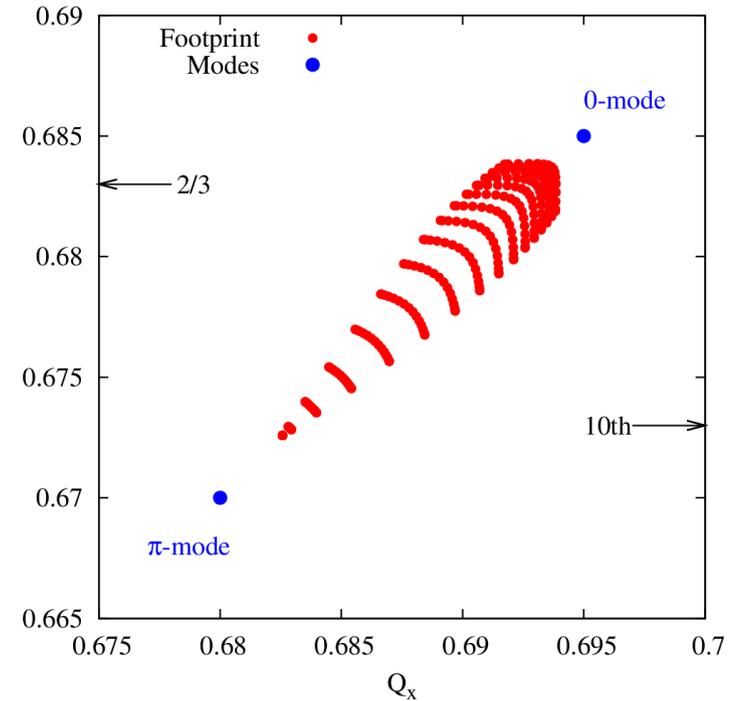
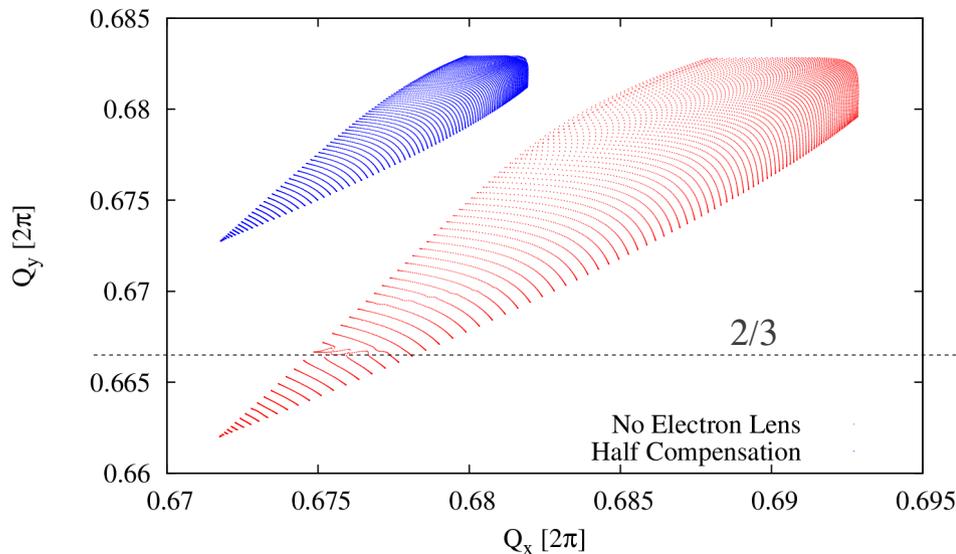
	2012	Upgrade
Energy [GeV]	250	100 - 250
$N_p$ [ $10^{11}$ p/bunch]	1.8	2.5 - 3.0
$\beta^* / \beta_{el}$ [m]	0.65	0.65 / 10.0
$\epsilon_N$ [ $\mu\text{m}$ ]	3.0	2.5
$\xi$	0.015	0.024 - 0.03
$Q_x / Q_y$	28.695 / 29.685	28.695 / 29.685
$Q_s$	0.0005	0.0005
$\sigma_s$ [m]	0.44	0.44
$\delta p/p$	1.4e-4	1.4e-4

- The beam collide head-on (no crossing angle) in IP6 and IP8 at  $\beta^* = 0.65$  m
- Head-on compensation with electron lenses located in IP10 at  $\beta^* = 0.10$  m
- Compensate half the beam-beam parameters: design - luminosity gain of a factor 2

→ RHIC is operated between the 2/3<sup>rd</sup> and 7/10<sup>th</sup> resonances. 7/10<sup>th</sup> is also a spin resonance, remain as far as possible

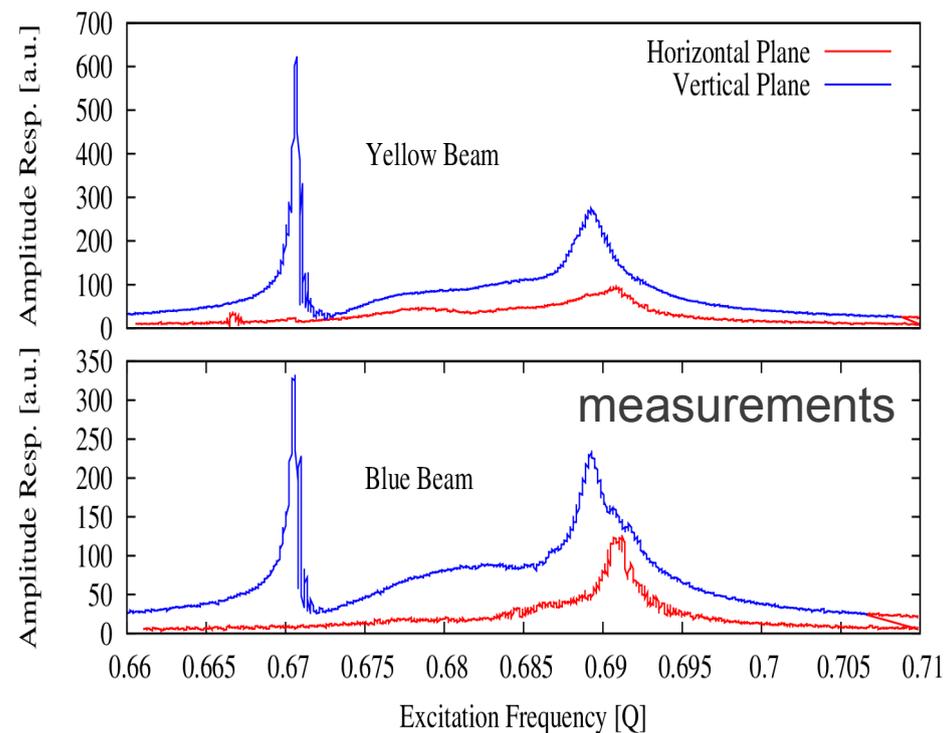
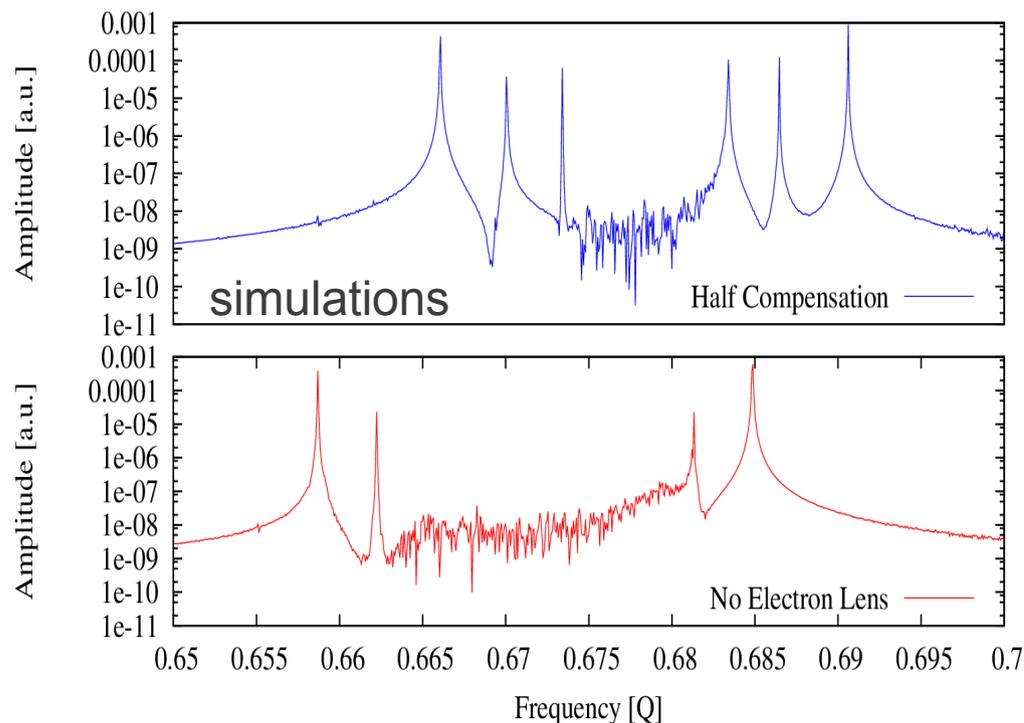
→ Regularly operated with a total head-on tune shift of  $\sim 0.016$

→ Very limited space available for further increase in luminosity



→ With RHIC luminosity upgrade parameters the tune spread would cross the 2/3<sup>rd</sup> resonance

→ Head-on compensation with electron lenses allows the reduce the tune spread and therefore accommodate more intensity



→ Due to the symmetry of collision points bunches couple 3x3 → expect 6 coherent beam-beam modes – without electron lens Landau damping acts on the inner modes

→ Head-on compensation reduces the tune spread and Landau damping is lost for all modes → coherent modes will be far outside the tune spread and overlap the 2/3<sup>rd</sup> resonance: stability?

→ To be noted:  $\pi$ -mode is generally not observed in the horizontal plane – a possible explanation could be an exchange of Landau damping between planes

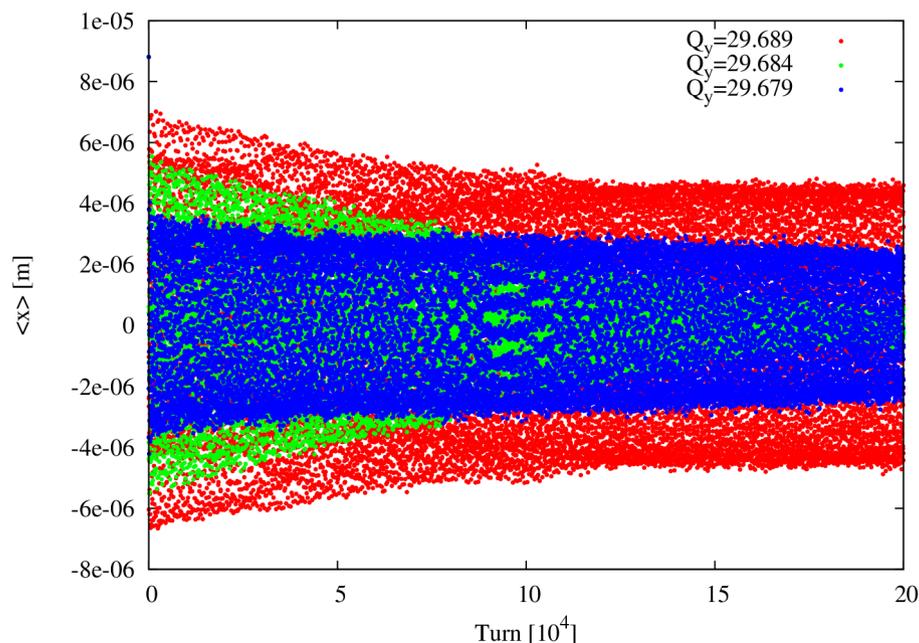
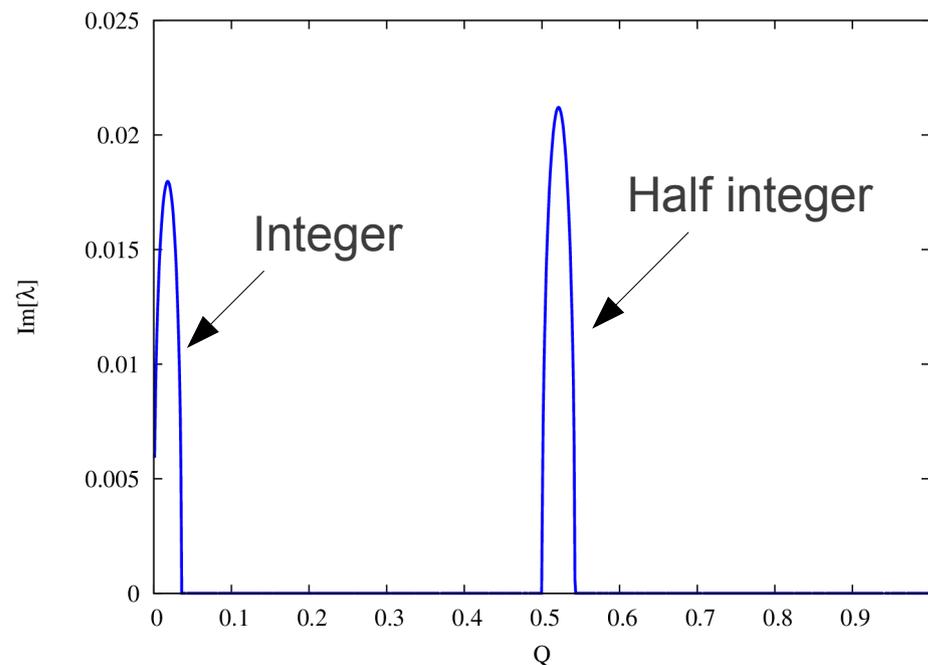
# Impact of the 2/3<sup>rd</sup> resonance



→ Coherent modes stability versus the tune can be evaluated with linearized model

→ Shown here the case of 3 bunches colliding in 2 IPs with  $\xi/IP = 0.012$  ( $Y=1$ )

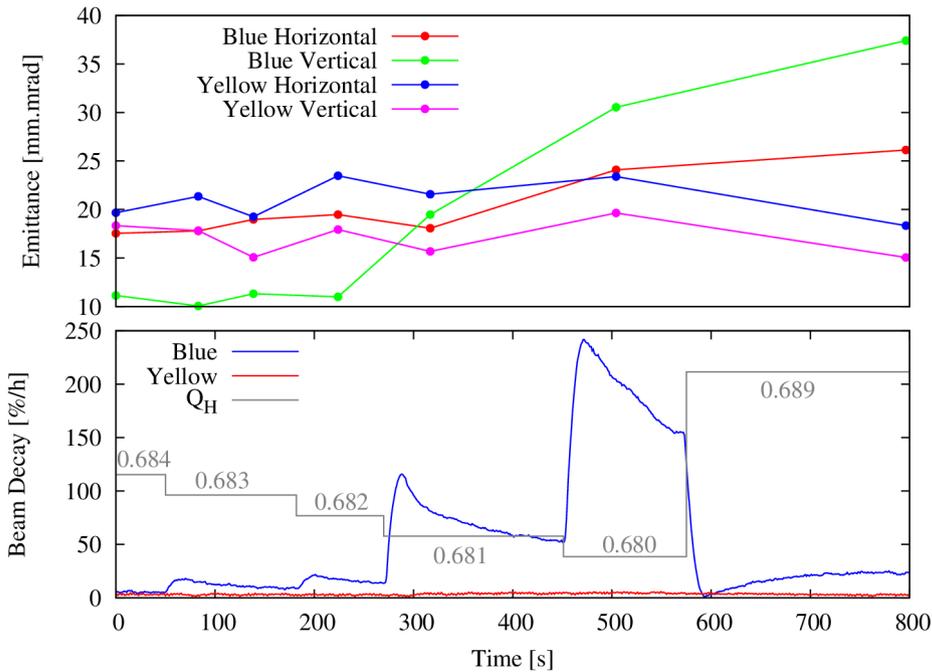
→ Only the integer and half integer resonances should be harmful



→ Strong-strong simulations with  $\pi$ -mode Crossing the 2/3<sup>rd</sup> resonance

→ No sign of instability

→ Although simulations and theory show no detrimental effects for stability we checked it experimentally



→ Start with  $\pi$ -mode close to the resonance and slowly move the blue beam towards the resonance

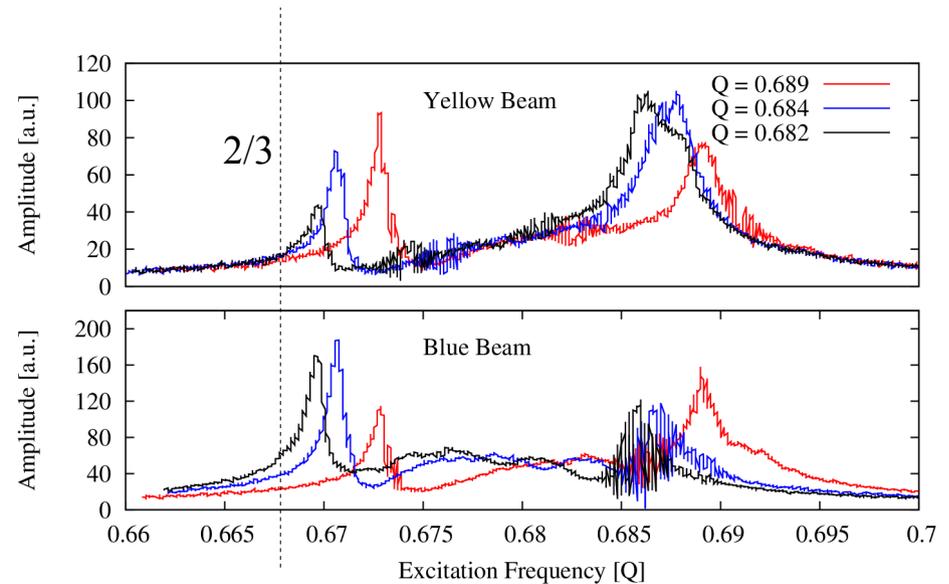
→ As we approach the resonance losses and emittance blow-up observed. Mostly in the vertical plane of the Blue beam ( $Q_y < Q_x$ )

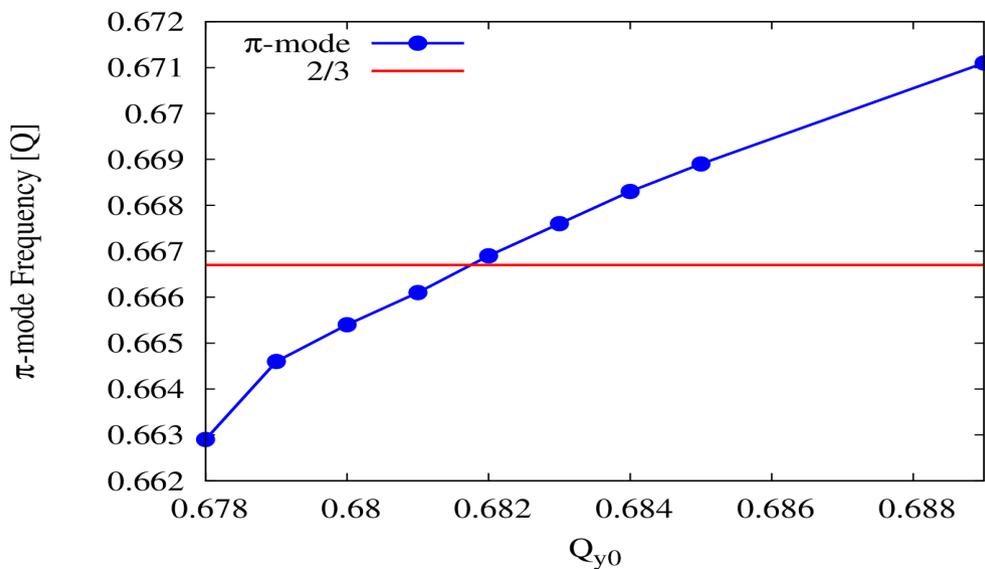
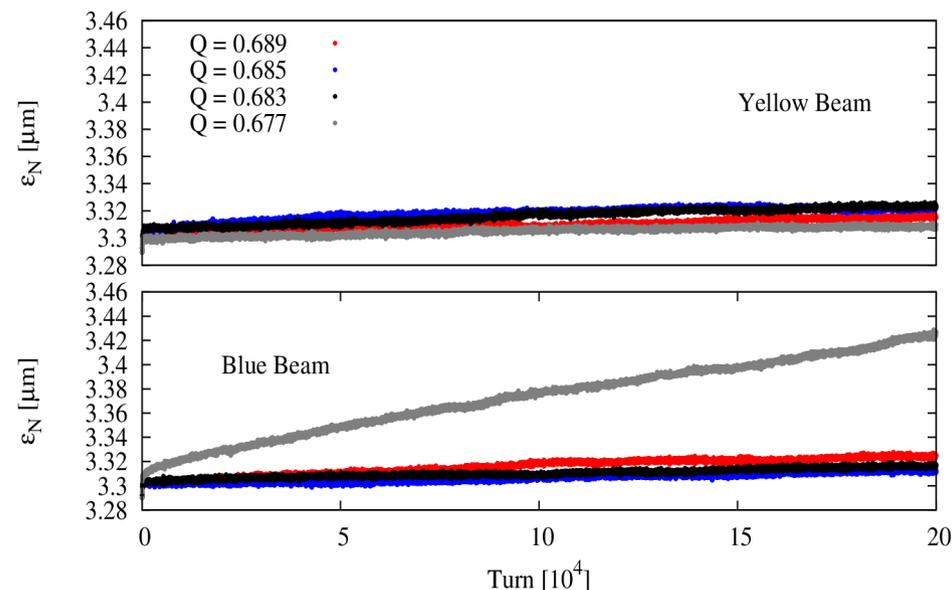
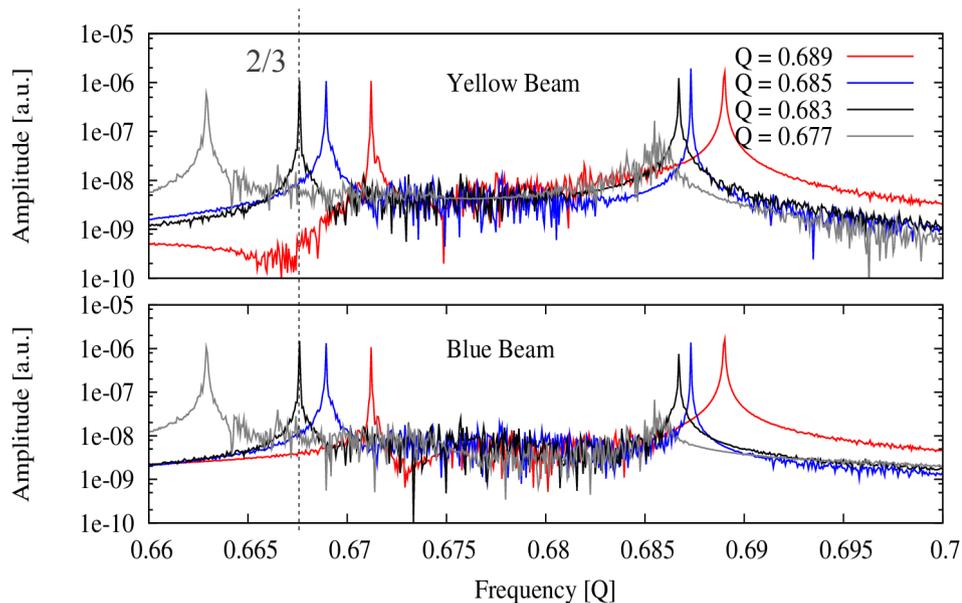
→ No sign of coherent instability. The Yellow beam shows no sign of losses or blow-up

→ Moving one beam only introduces a small tune split. Amplitude of the modes affected

→ Onset of losses appears before the  $\pi$ -mode touches the resonance

→ Losses and blow-up most likely not related to coherent effects





→ Even when right on resonance the  $\pi$ -mode does not appear to be excited and its frequency is not repulsed nor attracted by the resonance

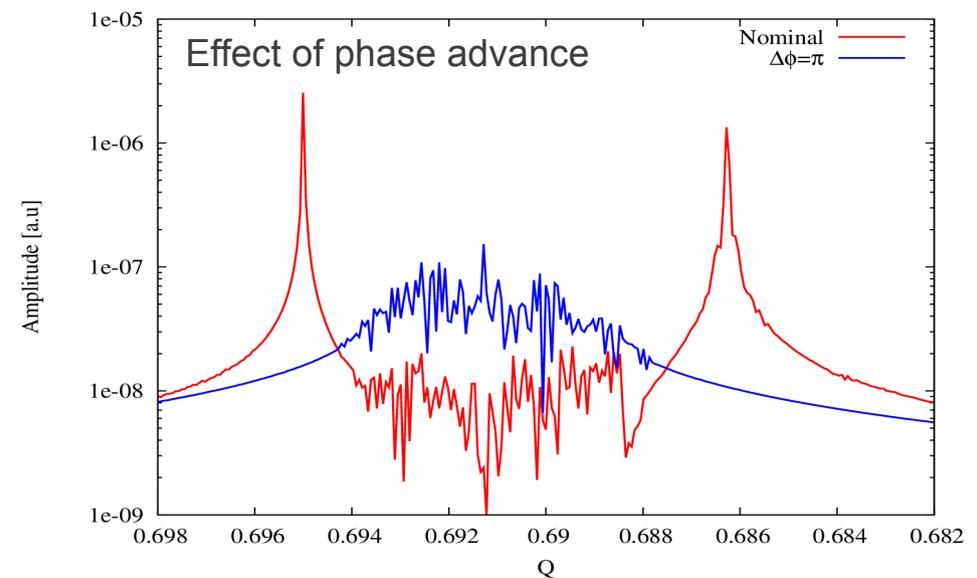
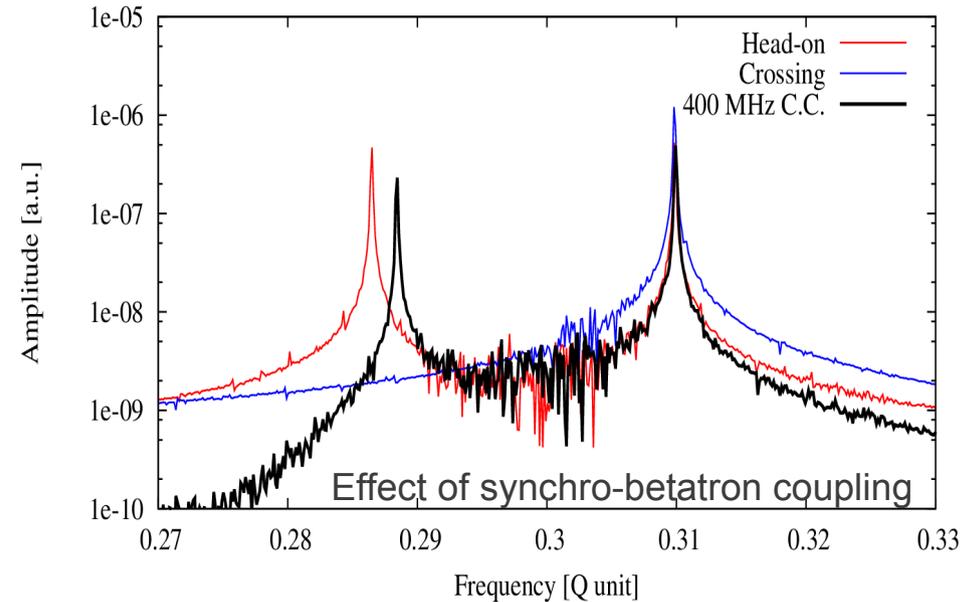
→ Emittance blow-up only observed when the resonance hits the tune spread. No sextupoles in simulations: could explain the sharper resonance

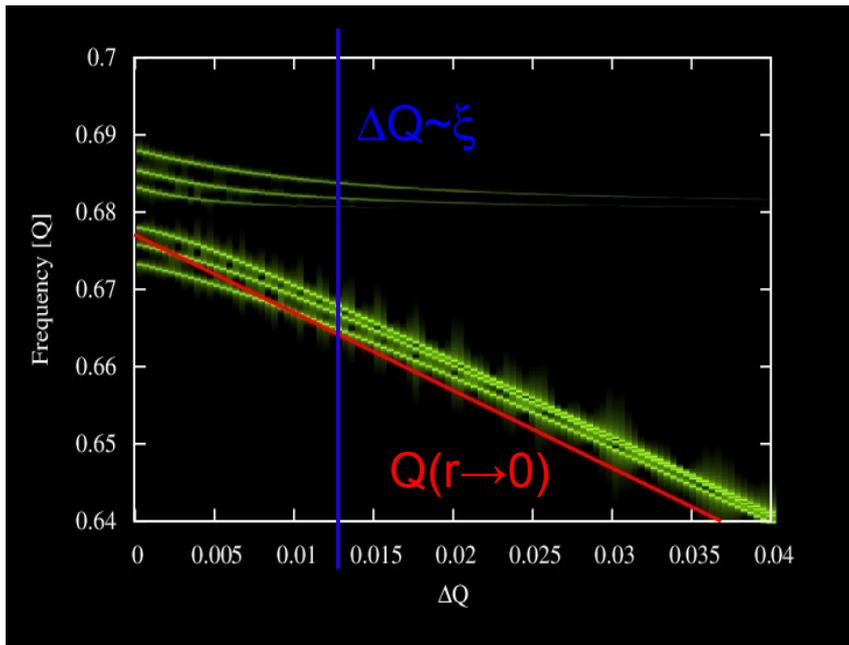
- Several possibilities have been investigated in the past to suppress coherent beam-beam modes (*Y. Alexahin, NIM A 480, (2002)*):

→ Make use of the synchro-betatron coupling with crossing angle: for  $Q_s \sim \xi$ , the synchrotron sidebands of the continuum can overlap the  $\pi$ -mode and damp it

→ A proper arrangement of the phase advances between IPs can also remove the modes

- However at RHIC there is very little flexibility to adjust phase advances and  $Q_s \ll \xi$  is making it difficult to profit from synchro-betatron coupling
- Another well known technique is to split the tunes of the two beams





→ When the tunes of the two beams are split the modes cluster inside the tune spread and are damped

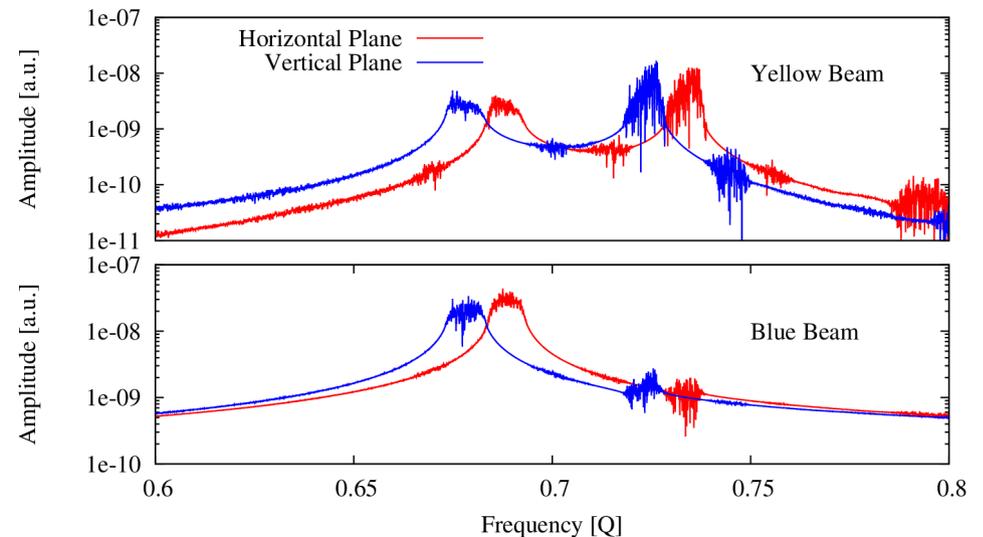
→ The modes are fully damped when  $\Delta Q > \xi$

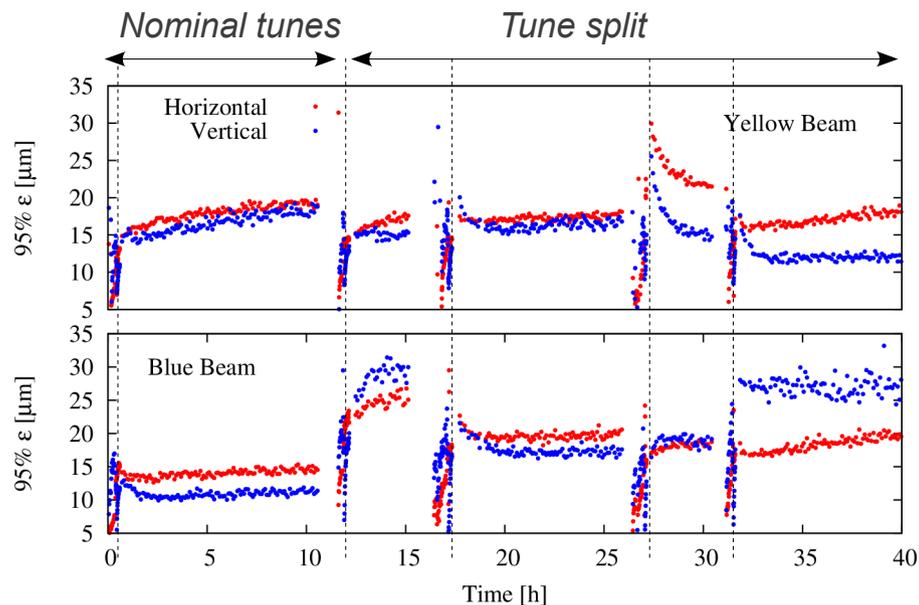
→ At RHIC  $\xi \sim 0.016$ . It was then decided to have one beam one nominal tune (0.695, 0.685) and one above the 7/10 resonance (0.74, 0.73)

→ Strong strong simulation with split tunes

→ Blue was kicked explaining the observation of the blue tune spread in the yellow spectrum

→ As expected the coherent modes are fully suppressed



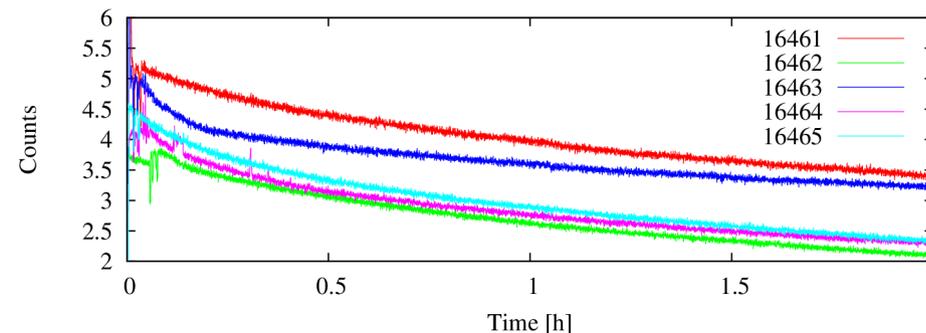
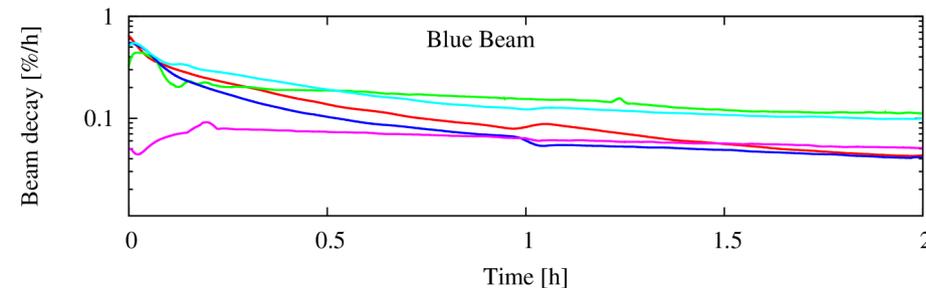
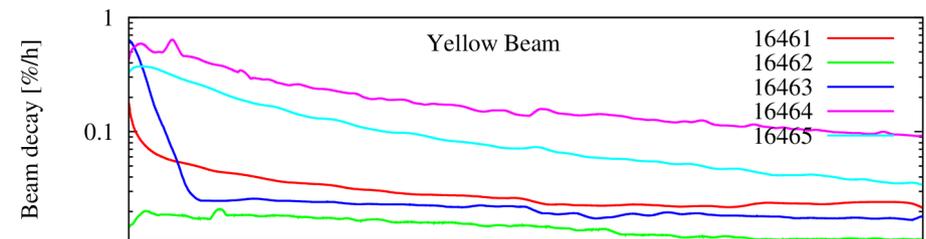


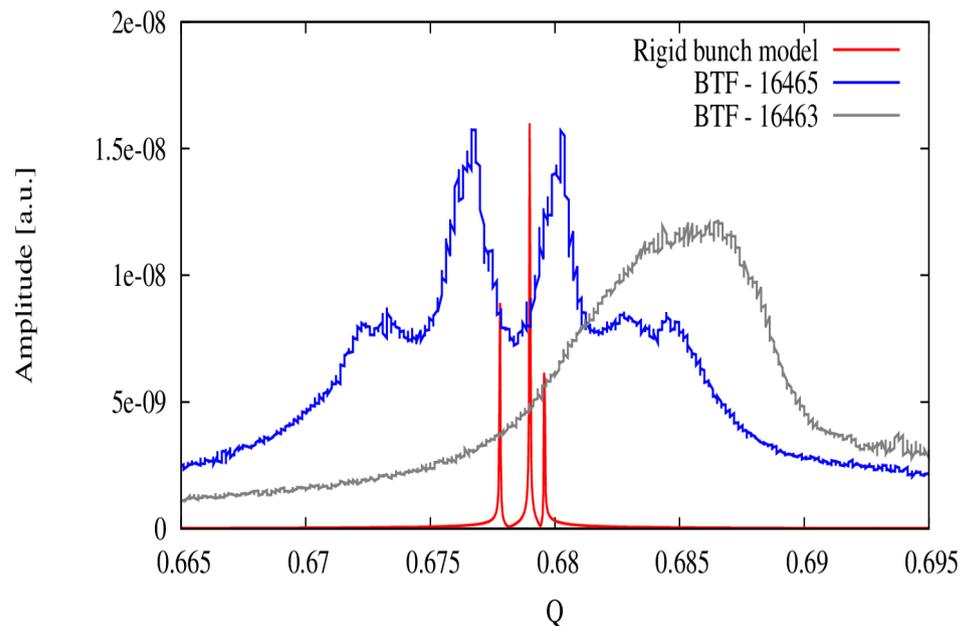
→ Four fills with tune split, significant blow-up of emittance when bringing beams into collision (dashed line)

→ Significant degradation of lifetime and luminosity due to this initially large emittances

→ Reasonable performance achieved for fill 16463 – initial losses due to tune adjustments – but still below nominal

→ Both blue and Yellow show degradation. although the performance seem to be tune dependent a DA issue at ~0.74/0.73 should affect Yellow only





→ Vertical BTF data for split tunes fills

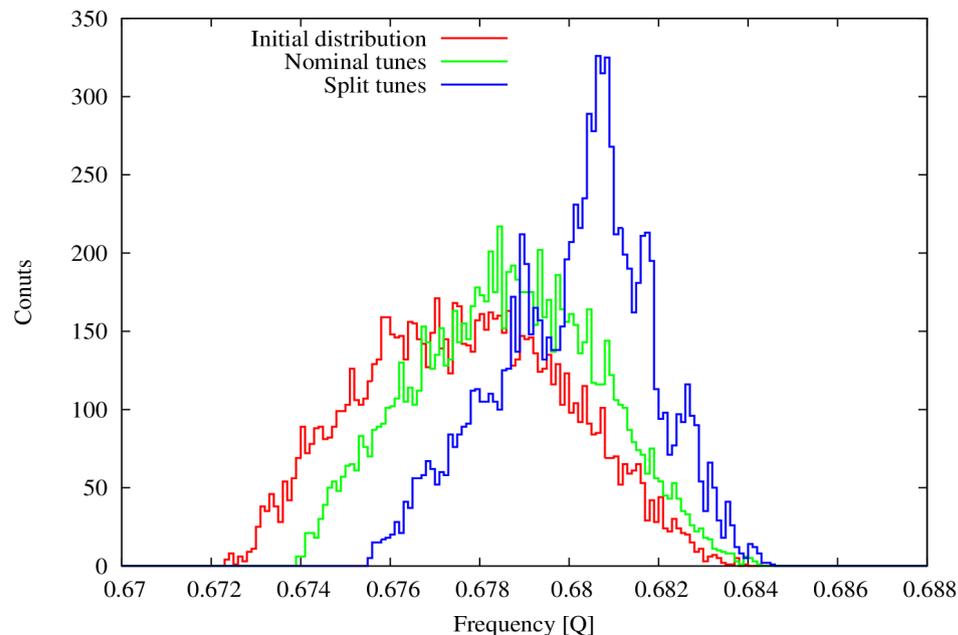
→ Fill 16465 – strong emittance blow-up in the vertical plane. Fill 16463 best fill with split tunes reasonable blow-up

→ Possibly a consequence of the coherent modes laying inside the tune spread. Appears to be correlated to the tune

→ Artificially blow-up the emittance with white noise (single IP)

→ For equal tunes the distribution remains well behaved

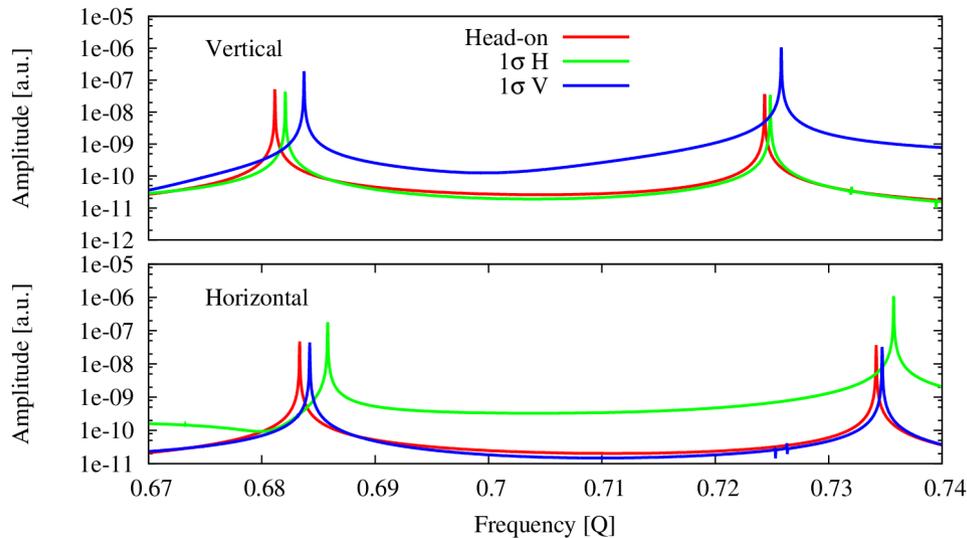
→ For split tunes the multiple peaks structure appears



- A study of coherent effects related to collisions with unequal tunes can be found in: *Y. Alexahin et al. "Excitation of coherent beam-beam resonances for beams with unequal Tunes", LHC-project-report-226 (2000)*  
This paper introduces coherent beam-beam resonances derived from the frequencies of the modes of the two beams:

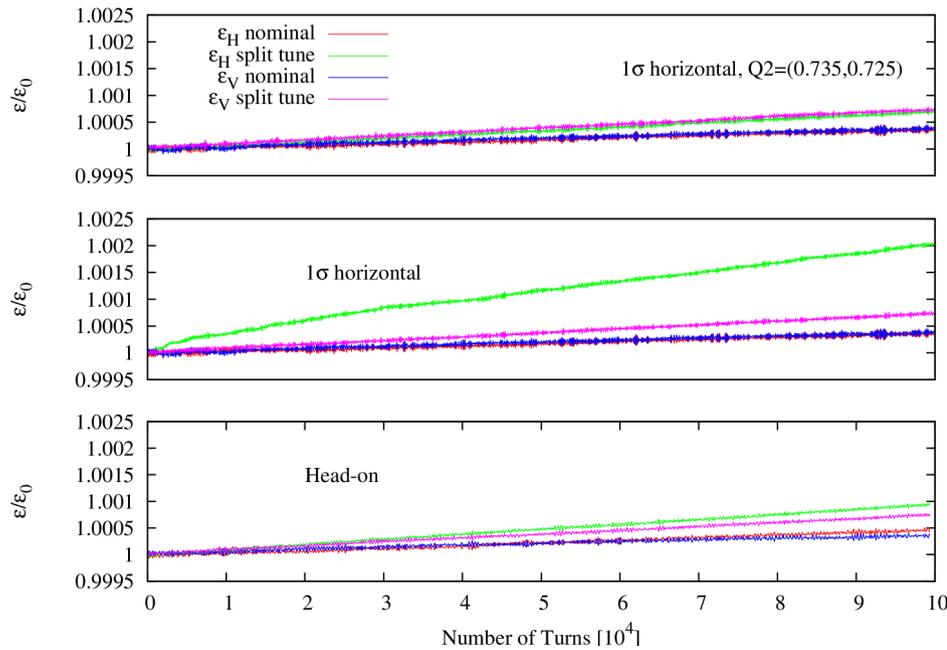
$$m \cdot Q_1 + n \cdot Q_2 = \text{integer}$$

- Taking the estimated W.P. for fill 16465 (0.689/0.691, 0.74/0.73) and  $\xi \sim 0.013$ :



*Modes frequency calculated with rigid bunch model (single IP)*

- Head-on:  $Q_1=(0.683,0.681)$ ,  $Q_2=(0.734,0.724)$   
 $\rightarrow 4 \cdot Q_{1x} - Q_{2x} = 1.998$ ,  $4 \cdot Q_{1y} - Q_{2y} = 2.000$
- $1\sigma$  H:  $Q_1=(0.686,0.682)$ ,  $Q_2=(0.736,0.725)$   
 $\rightarrow 4 \cdot Q_{1x} - Q_{2x} = 2.008$ ,  $4 \cdot Q_{1y} - Q_{2y} = 2.003$
- $1\sigma$  V:  $Q_1=(0.683,0.684)$ ,  $Q_2=(0.735,0.726)$   
 $\rightarrow 4 \cdot Q_{1x} - Q_{2x} = 1.997$ ,  $4 \cdot Q_{1y} - Q_{2y} = 2.01$
- 5<sup>th</sup> order should be excited by offset collisions

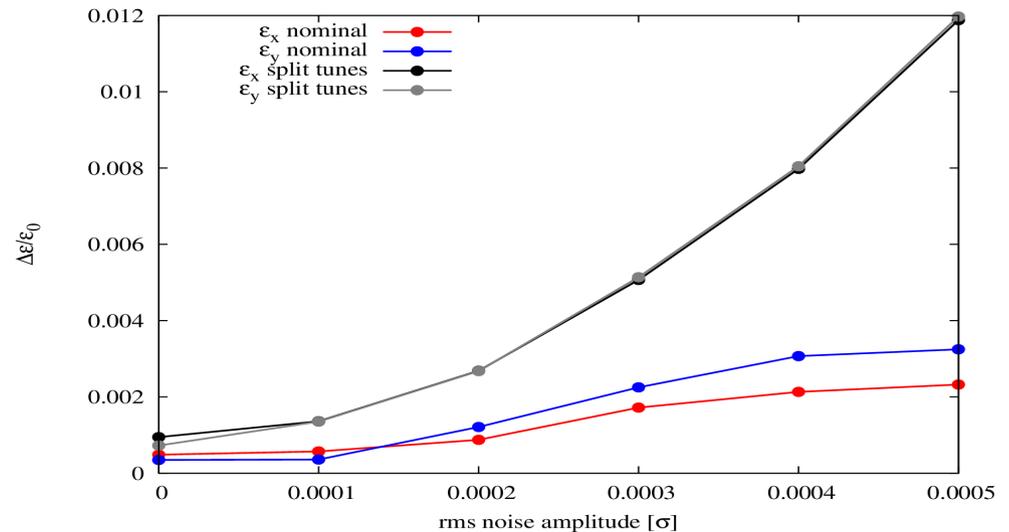


- Three cases considered (single IP):
- Head-on: slightly worse in both planes with the tune split in
- 1 $\sigma$  horizontal separation: strong blow-up in the horizontal plane, slightly worse in the vertical
- 1 $\sigma$  horizontal separation and tunes away from the resonance: similar to head-on - different  $\xi$  would have similar impact

→ White noise amplitude scan for both for nominal and split tunes

→ Tunes were set to be far off any resonances

→ Colliding with unequal tunes makes the beams much more sensitive to external noise



- The electron lenses reduce the tune spread without affecting coherent beam-beam modes. This may compromise the beam stability under external excitation such as impedance
- Experiments were conducted to understand how coherent modes could affect the beams stability:
- Impact of 2/3<sup>rd</sup> resonance:
  - Theory predicted no impact on stability and this was confirmed experimentally
- Coherent modes suppression:
  - Investigated at RHIC in case modes become a problem
  - Only option at RHIC is a tune split
  - Strong emittance blow-up observed for collisions with unequal tune, most likely related to the modes laying inside the tune spread
  - Careful choice of the working point could fix this issue, but very poor polarization was measured above 0.7 and it seems the beams become more sensitive to external noise → Not an option for RHIC
- If coherent beam-beam modes really become a problem, the implementation of a bunch by bunch damper could help

- The reduction of tune spread from electron lenses is not possible to study experimentally without the actual device

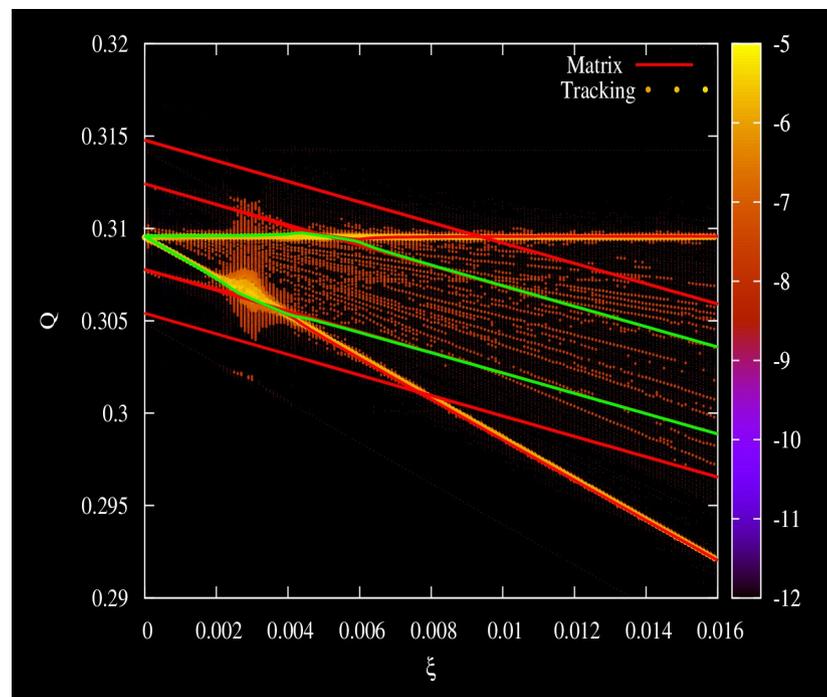
- Interplay with impedance and stability issues had to be studied numerically

- Interplay with machine impedance. Shown here an example with LHC parameters:

→ When the coherent beam-beam  $\pi$ -mode overlaps the headtail mode -1 they can couple and lead to instabilities similar to classical TMCI

→ For details see talk “*Beam-beam and impedance*”, this workshop

→ Unlikely to become a problem at RHIC:  
 $Q_s \sim 5.0e-4$ ,  $\xi \sim 0.024-0.03$  with electron lenses



- Electron lens driven instabilities can become non-negligible for RHIC parameters, see following slides

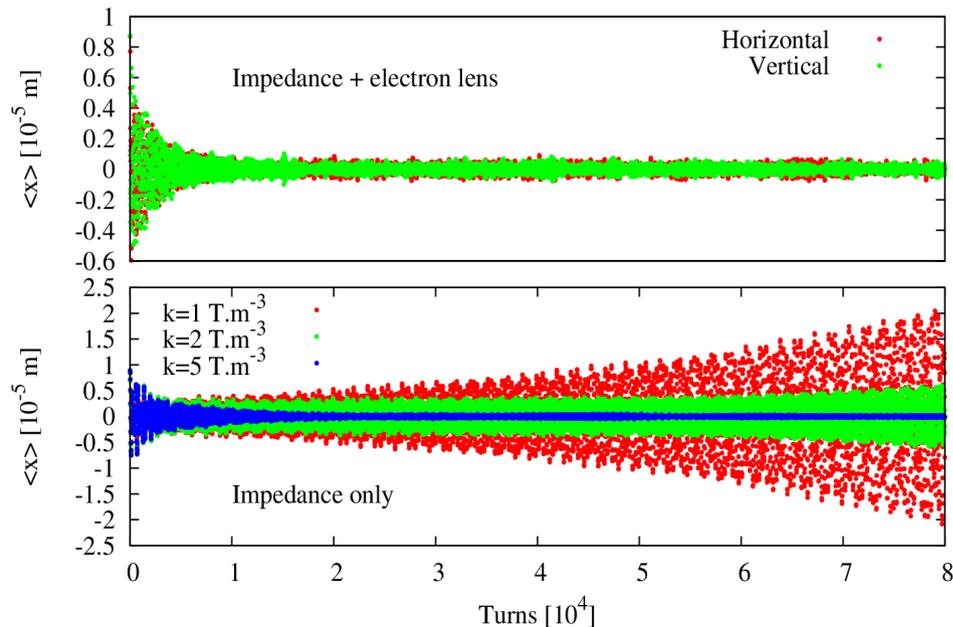
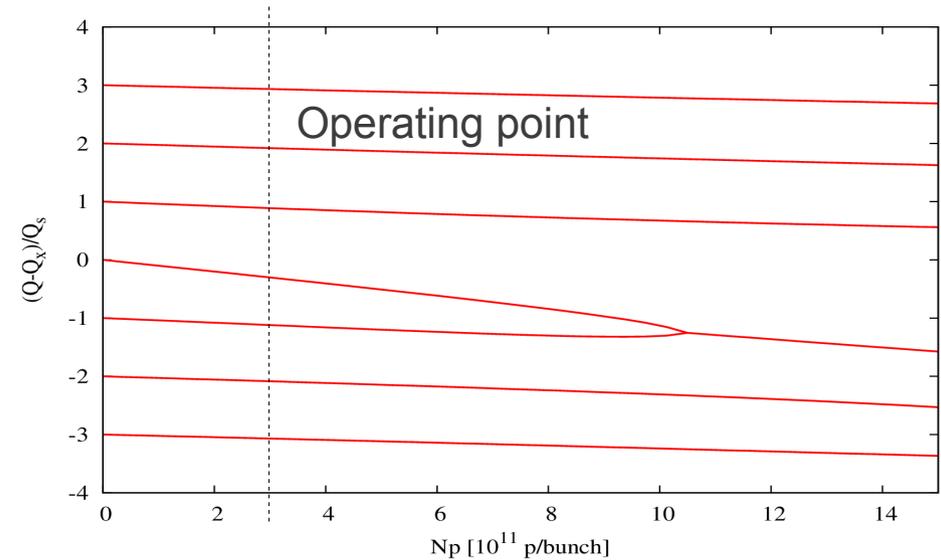
# Machine Impedance



→ RHIC impedance model includes BPM, bellows and resistive wall contributions computed from analytical formulas

→ Using this model one can compute the TMCI threshold at  $Q'=0.0$  for a longitudinal airbag Distribution

→ RHIC operates far off the threshold (250 GeV)



	$\delta Q_x/\delta J_x$	$\delta Q_y/\delta J_y$	$\delta Q_x/\delta J_y$
Tracking	607	607	417
NL model	314	387	463

→ Stabilizing octupolar detuning found to be close to what is provided by machine non-linearities: with electron lens fully stable

→ This year instabilities were observed, new measurements are foreseen to assess the situation

- Low energy electrons acquire a transverse momentum when interacting with the protons and as a result will start spiraling around the solenoid field lines. The kick received by the protons will therefore depend on their longitudinal position. This electron lens transverse impedance was introduced in: *A. Burov et al. "Transverse beam stability with an electron lens", Phys/Rev. E, 59.*

- The s-dependent momentum change of the protons can then be modeled using a wake function:

$$\Delta p_{x,y} = W [\Delta_{x,y} \sin(ks) + \Delta_{y,x} (1 - \cos(ks))], k = \frac{\omega_L}{(1 + \beta_e) c}$$

$W$  is a constant and  $\omega_L$  is the Larmor angular frequency which depends on the field. The kick depend on both the horizontal and vertical displacement of preceding slices.

- Using a linearized model (no Landau damping or chromaticity) one can derive a threshold field required to provide stability:

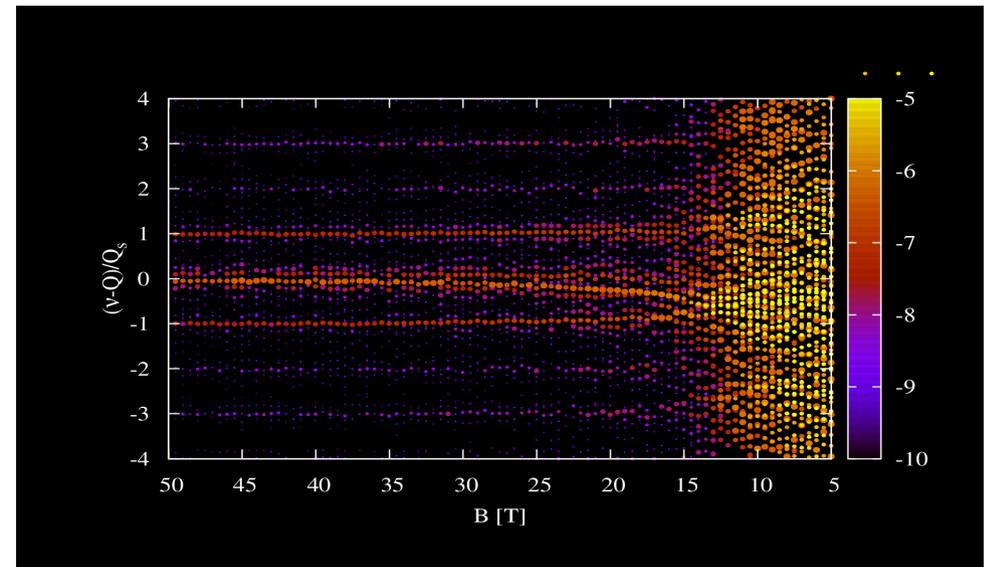
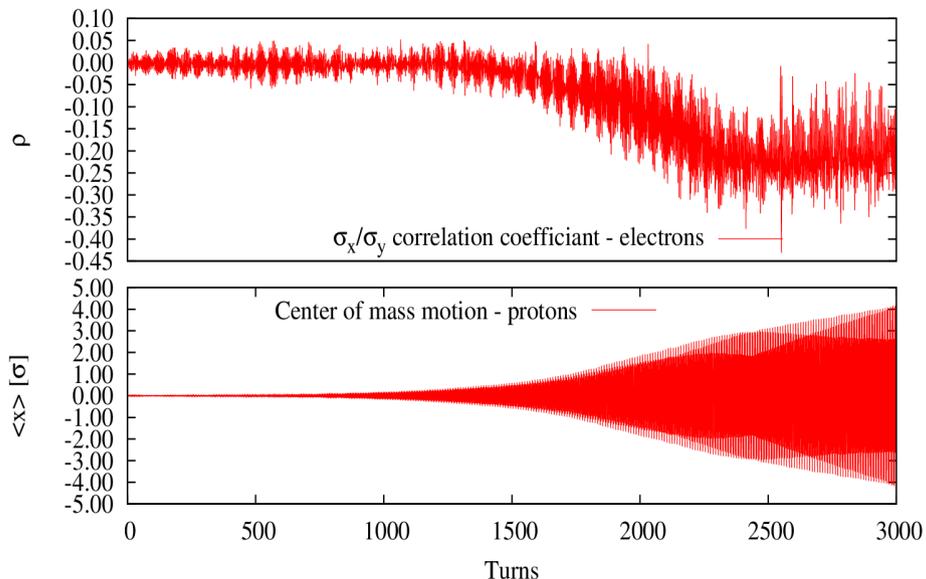
$$B_{th} = \frac{1.3 e N_p \xi_{el}}{r^2 \sqrt{\Delta Q Q_s}}$$

- For RHIC parameters ( $N_p = 3.0e11$ ,  $\xi_{el} = 0.011$ ,  $\Delta Q = 0.011$ ,  $Q_s = 5.0e-4$ ,  $r = 2\sigma$ ) we find a threshold of about 14T. Well above the design field of 6T.

- The electron lens is now modeled by a zero length electron beam going against the 6D proton beam sliced longitudinally. At each interaction the kicks are computed either from linear or 4D Gaussian approximations, the electron beam coordinates are then updated by the solenoid field when moved to the next proton slice and reinitialized every turn.

→ Solenoid field scan with Gaussian distributions and linear beam-beam kicks (electron lens only)

→ The mode coupling (defined as the threshold) occurs around 14T which is in agreement with theory



→ Motion inside a solenoid introduces x/y coupling

→ When the instability is rising it can distort the electron profile: taken into account with “tilted” Bassetti-Erskine formula when  $\rho$  is above statistical noise

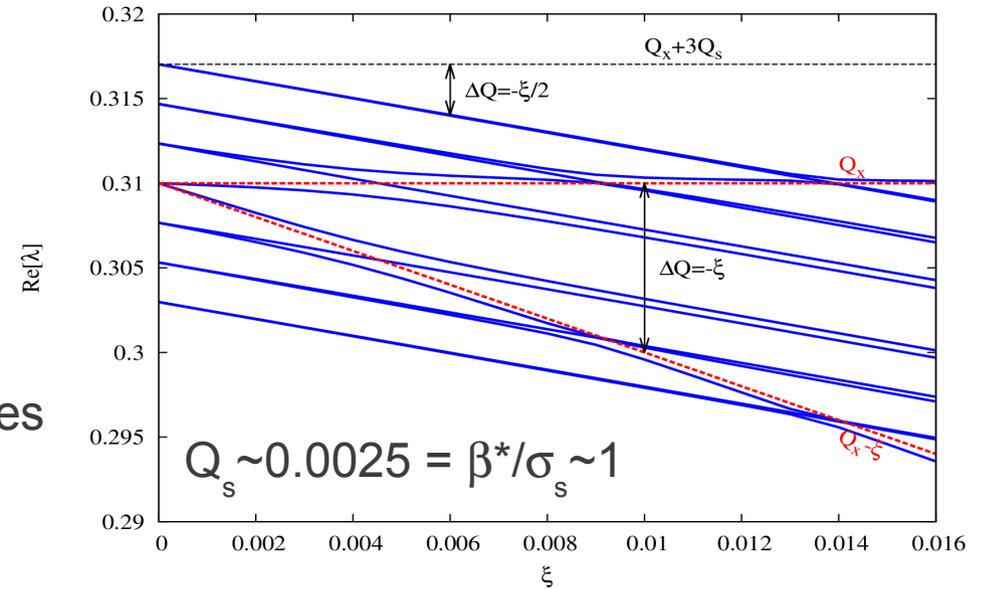
# Coherent beam beam



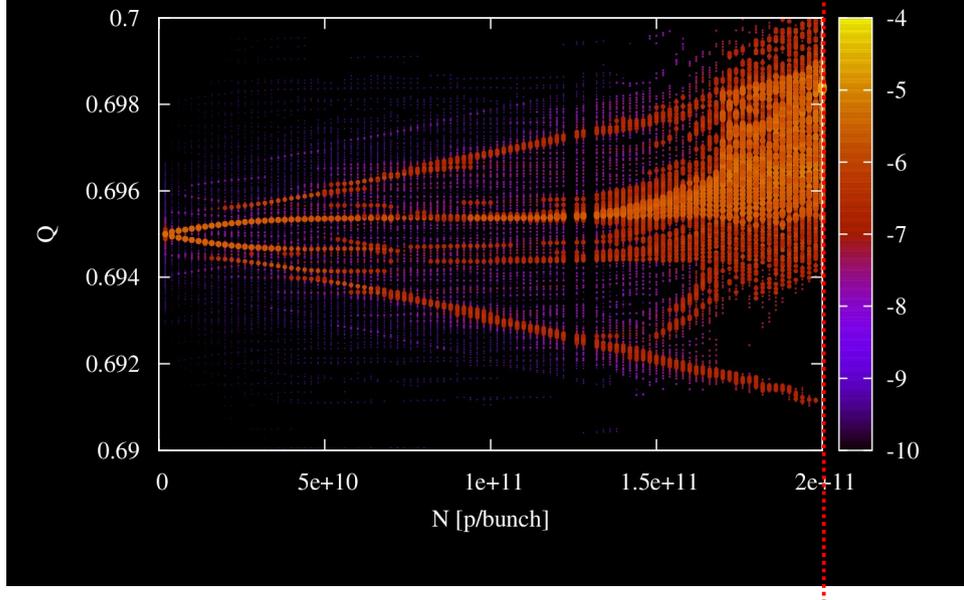
→ Proton-proton interactions give rise to the  $\sigma$ -mode and  $\pi$ -mode at  $Q_0$  and  $Q_0 - Y.\xi$

→ The sides bands are shifted

→ The distance between the respective modes is modified: change in TMCI threshold?



**B=6.0T – single IP**      **Expected threshold**

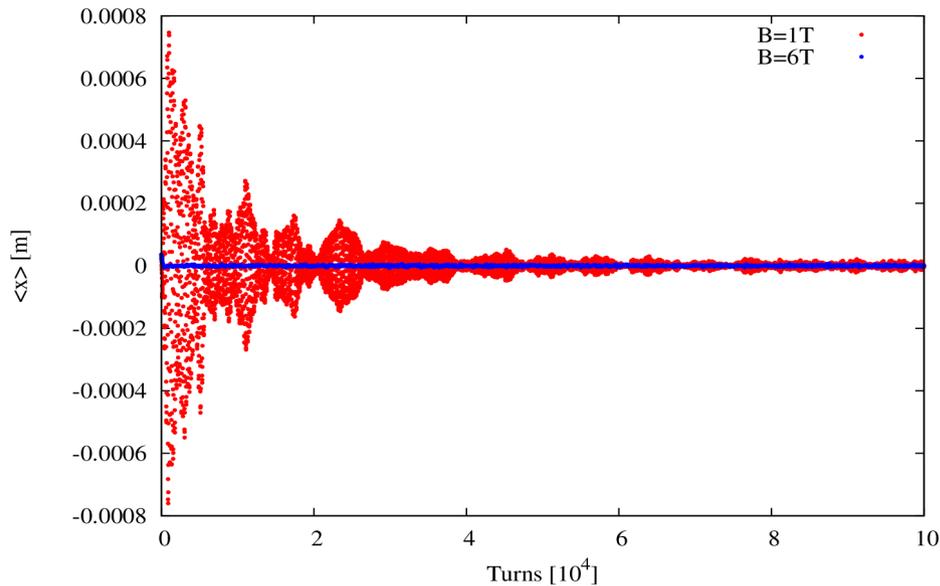


→ Scan in proton intensity. Electron lens scales accordingly to provide full compensation. The positive tune shift is introduced by the electron lens

→ B=6T: expected threshold at  $2.0 \times 10^{11}$  p/bunch. With beam-beam it goes down to  $\sim 1.0 \times 10^{11}$  (field threshold goes in  $N.\xi \rightarrow N^2$ )

→ Coherent beam-beam significantly degrades the situation but here Landau damping was not included

# Including Landau damping



→ Electron lens only: tune spread is provided by the electron beam (opposite sign as p-p)

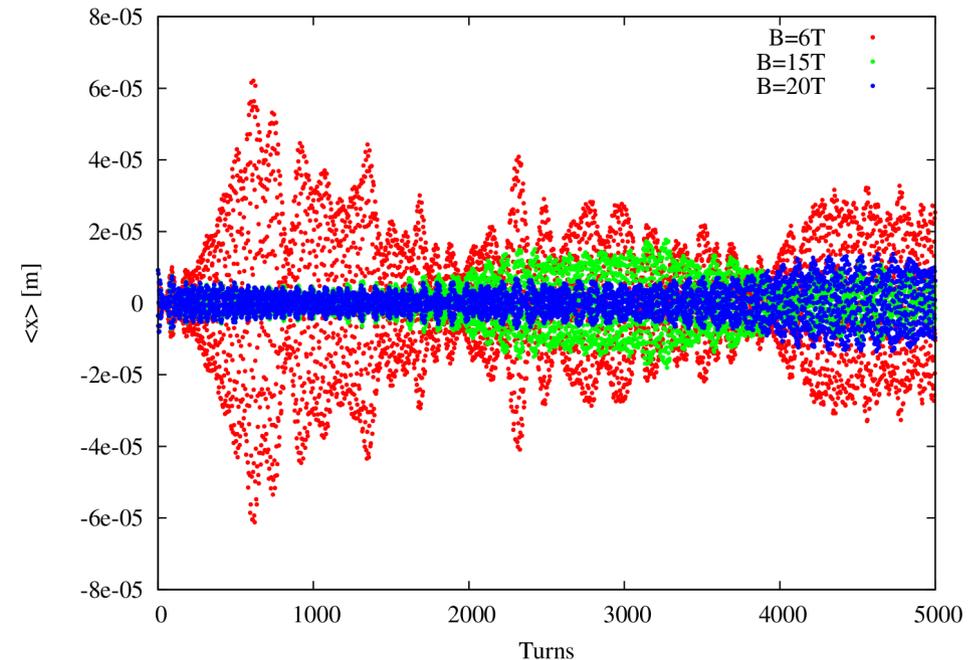
→ Same beam parameters as the ones used in the previous slides

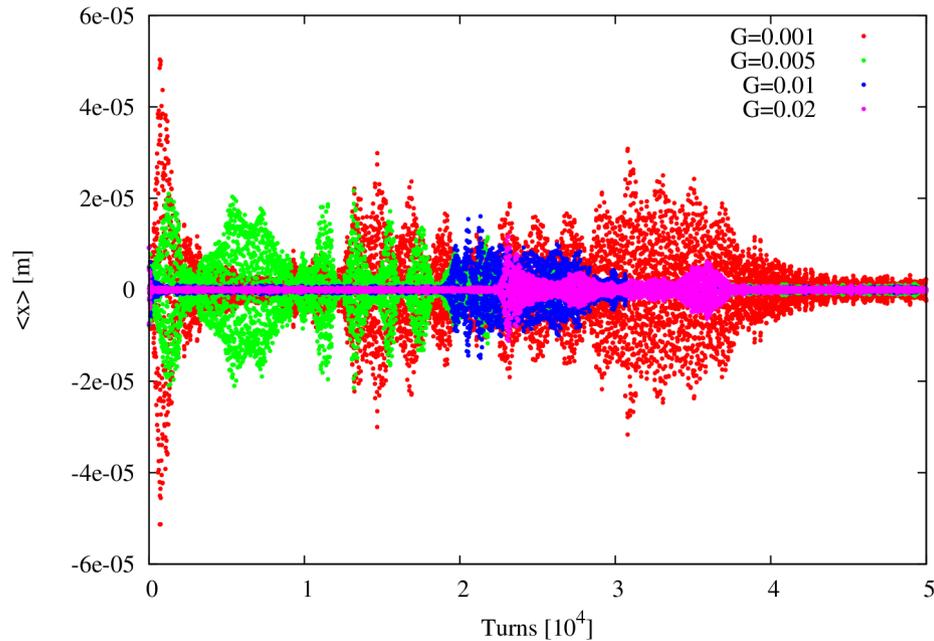
→ Appears stable for 6T solenoid field unstable for 1T

→ Electron lens and a single proton-proton interaction with twice the intensity to reproduce RHIC tune spread

→ Even with Landau damping the situation is much worse as soon as coherent beam-beam modes are included

→ Although a clear improvement is observed the beam is still unstable at 20T





→ Increasing the chromaticity to  $Q'=5.0$  allows to fully damp the instability with a damping time of 100 turns

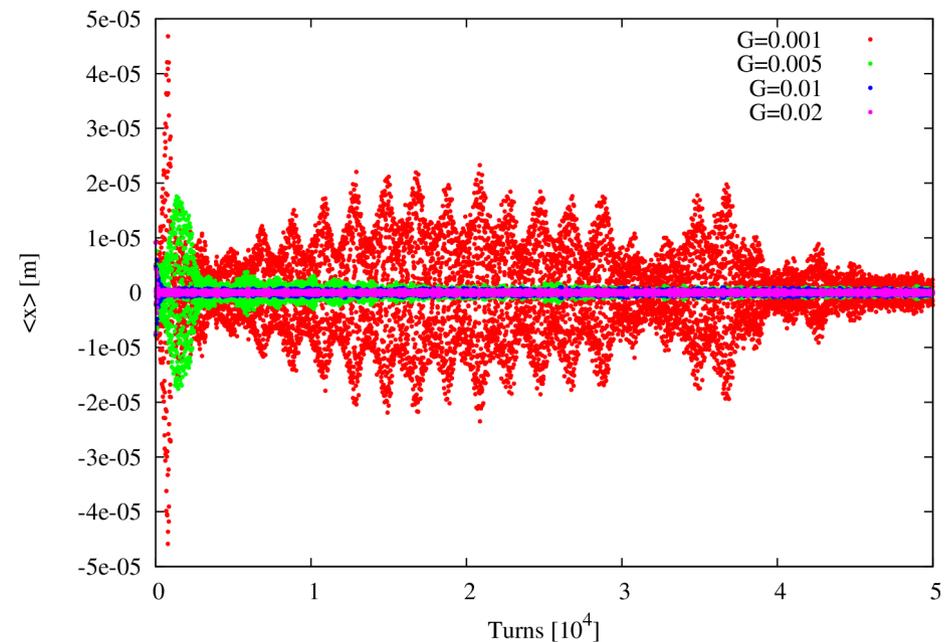
→ Unfortunately RHIC is not currently equipped with a bunch-by-bunch damper

→ Other knobs exist to rise the threshold which are currently under investigation

→ Same beam parameters as the previous slides

→ RHIC is generally operated with  $Q' \sim 2.0$ : first look at this case

→ Although a clear improvement is observed the instability eventually rises

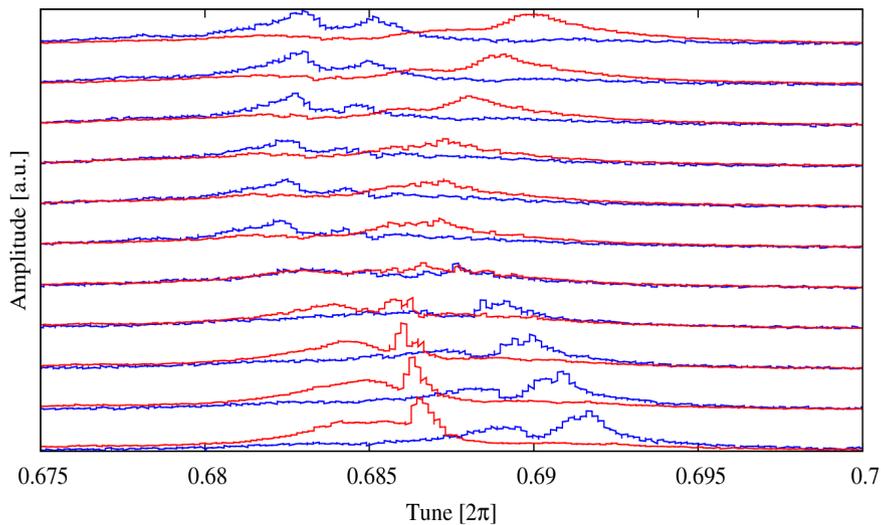
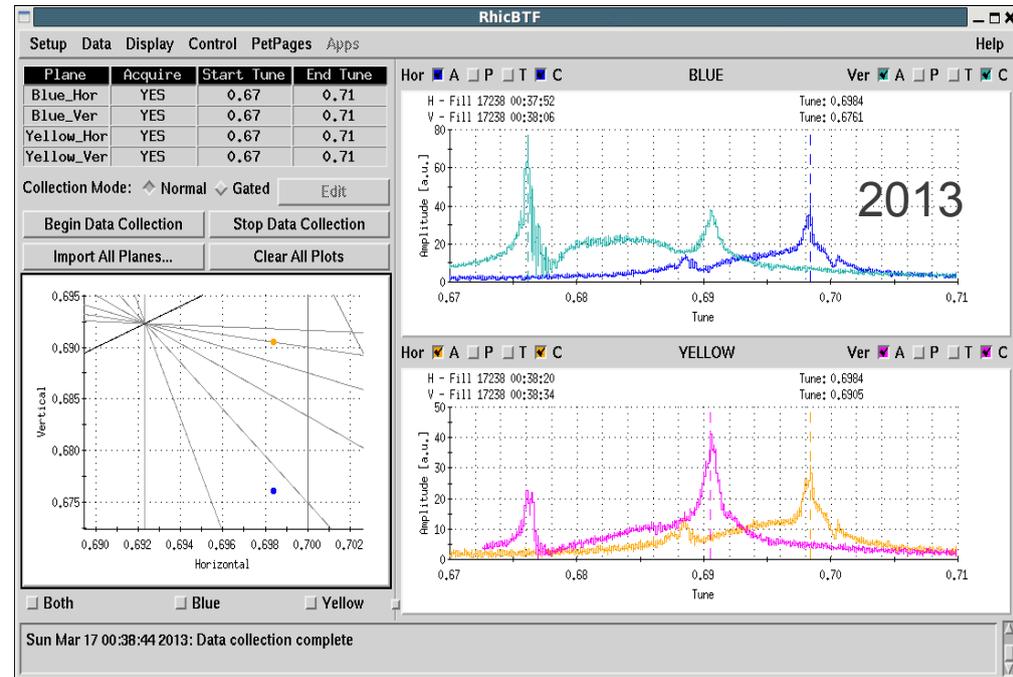
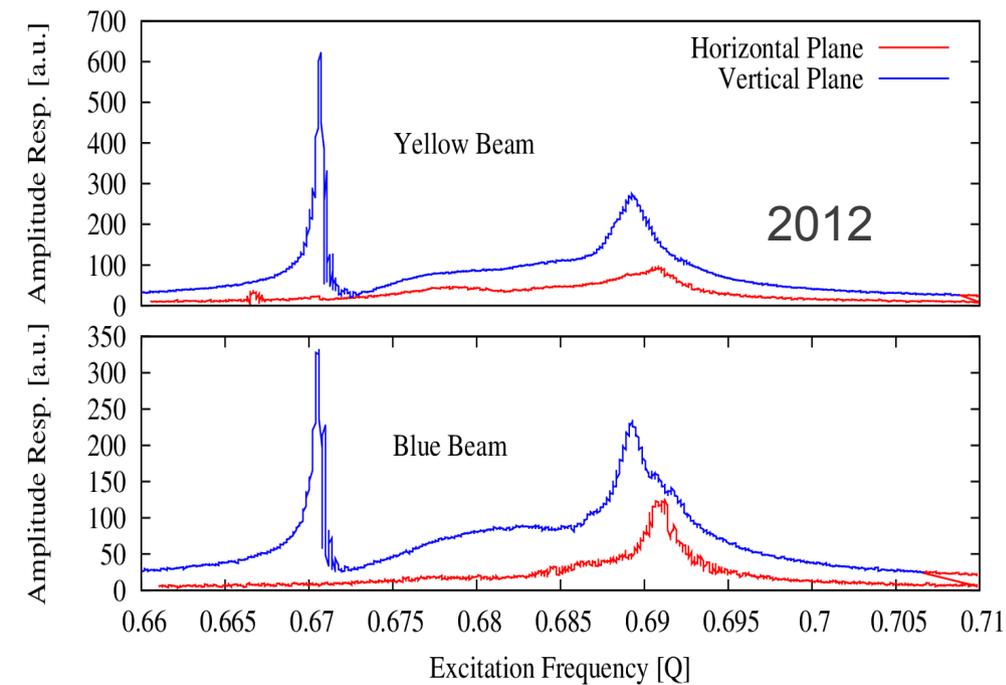


- Beam stability with electron lens was studied in multi-particle tracking. Although they seem to match the theory these results came up very recently and need to be confirmed. Open questions:
  - Poisson solver for electron lens (already the case for pp) – most likely the beams do not remain Gaussian
  - Sampling rate of the electron beam – in this talk  $\sim 10\lambda_L$  (50 proton slices)
  
- Machine impedance:
  - RHIC operates far below TMCI
  - Although this year some instabilities were observed this is generally not the case. New impedance measurements are planned this year to assess the situation
  - Simulations with electron lenses show no issues related to machine impedance
  
- Electron lens driven TMCI:
  - The RHIC design solenoid field is about a factor 2 below theoretical expectation with nominal beam parameters
  - This threshold was verified in tracking with linearized model and seem to be confirmed
  - Coherent beam-beam effects moves the modes around and significantly degrades the situation
  - Landau damping stabilizes the beams with electron lens only (no beam-beam modes) but not when beam-beam is included
  - The only cure that was found to be working so far is to use a transverse damper with chromaticity
  - Some beam parameters can change the threshold without affecting the luminosity reach – they are currently under investigation

**Thank you for your attention!**

# SPARES

# Absence of horizontal $\pi$ -mode



→ 2012: operation almost on diagonal, horizontal  $\pi$ -mode not observed

→ 2013: tunes well separated  $\pi$ -mode observed in both planes

→ Tune scan: although the data is not very clean it looks like the modes are damped when crossing the diagonal – should be repeated this year