COHERENT BEAM-BEAM EFFECTS OBSERVATION AND MITIGATION AT THE RHIC COLLIDER*

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Abstract

In polarized proton operation in RHIC coherent beam-beam modes are routinely observed with beam transfer function measurements in the vertical plane. With the existence of coherent modes a larger space is required in the tune diagram than without them and stable conditions can be compromised for operation with high intensity beams as foreseen for future luminosity upgrades. We report on experiments and simulations carried out to understand the existence of coherent modes in the vertical plane and their absence in the horizontal plane, and investigate possible mitigation strategies.

INTRODUCTION

Colliding beams with equal brightness and close tunes in either plane can give rise to coherent dipole motion through beam-beam coupling. In the simplest case of one interaction point (IP) two main modes arise corresponding to the two bunches oscillating in phase (σ-mode) or out of phase (π-mode). The σ-mode will oscillate at the betatron frequency and the π-mode will be shifted, negatively for equally charged beams, with respect to the σ-mode by an amount $Y \cdot \xi$ where Y is the Yokoya factor, $Y \approx 1.21$ for round beams, and ξ the beam-beam parameter [1]. Coherent beam-beam modes where already measured at RHIC in a dedicated experiment with one colliding IP in 2003 [2].

RHIC is currently operating with two interaction points located asymmetrically around the ring. The bunches will therefore couple in groups of three in each ring leading to six coherent dipole modes. This is illustrated is Fig. 1 where simulations of the RHIC collision pattern are shown using two different models.

In the rigid bunch approximation, the force is calculated assuming a fixed Gaussian transverse distribution. It allows to understand how the different bunches couple together by showing all the possible dipole modes but can only give qualitative results as it does not take into account the Landau damping and the frequency of the modes is incorrect due to the Gaussian approximation. In Fig. 1 the data was rescaled in order to match the Yokoya factor simulated with the multi-particle model.

The multi-particle simulations were performed with the tracking code BeamBeam3D [3]. In this model no assumption is made on the beam distribution and the field is recomputed every turn from the macro-particles distribution. This model allows for a more realistic approach which includes Landau damping and gives the correct frequency of the modes. In Fig. 1, with $Q_x = 0.691$ and $Q_y = 0.689$, two of the six modes lay inside the incoherent continuum and are fully damped. Out of the four remaining modes only two are well separated from the incoherent tune spread and are expected to be observable in the machine.

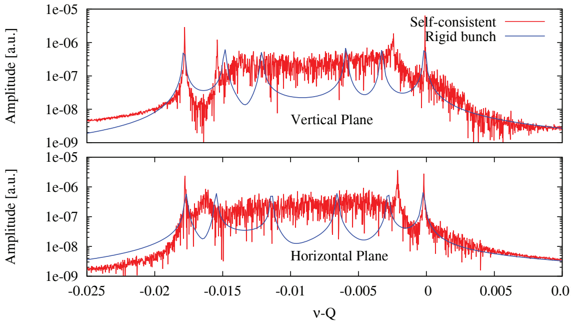

Figure 1: Simulated spectrum for 3 bunches colliding in IP6 and IP8 with the rigid bunch model and a self consistent model.

COHERENT BEAM-BEAM OBSERVATION

At RHIC the coherent beam-beam modes are routinely measured with the Beam Transfer Function (BTF) [4]. This technique consists of measuring the amplitude and phase response of the beam as a function of an excitation frequency. By scanning the excitation frequency one can measure the beam tune distribution. In case the frequency of a dipole mode is excited the beam will oscillate coherently and this will appear as a peak in the BTF spectrum.

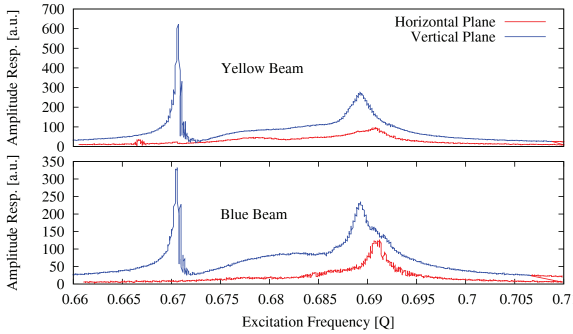

Figure 2: BTF measurements for 12 bunches colliding in 2 IPs at 100 GeV.

Figure 2 shows an example of BTF measurements taken

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during a store with 12 bunches colliding at the two IPs during the 100 GeV polarized proton run. The vertical plane clearly shows the two coherent modes as expected from the simulations. In the horizontal plane only the σ-mode is present. A tentative explanation for this feature will be given in the following section.

ABSENCE OF π-MODE IN THE HORIZONTAL PLANE

Past studies and beam experiments at the CERN PS [5] showed that Landau damping could be transfered from one plane to the other via coupling. Strong local coupling sources in the IR originating from the triplets roll alignments have been identified at RHIC [6]. In addition, the beam-beam force also provides local coupling.

The 2003 experiment [2] where π-modes were observed in the two planes was done with small beam-beam parameters and tunes well separated, i.e. the incoherent tune spreads were not overlapping. Each plane featured four modes also indicating a non-negligible coupling. During the 2011 proton run, RHIC was usually operating with the horizontal tune higher than the vertical one, the horizontal π-mode would therefore lay inside the incoherent continuum of the vertical plane and could therefore experience Landau damping through coupling mechanism. This effect is already observed to some extend in Fig. 1 where the beam-beam force is the only coupling source. Even though well present the horizontal π-mode is weaker than the vertical one.

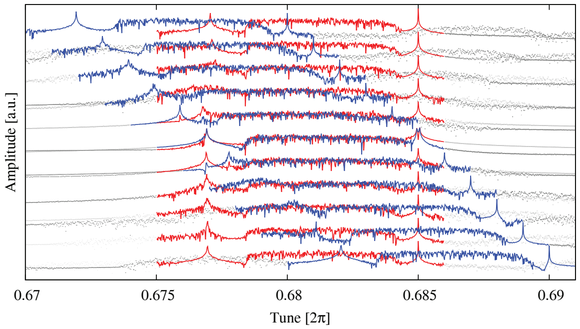

Figure 3: Simulated tune scan. The vertical spectrum is in red and the horizontal one in blue.

Figure 3 shows a tune scan where the horizontal tune, in blue, is swept across the vertical one, in red, with one IP colliding. We can see that as the horizontal π-mode approaches the tune region, where the vertical particle density is the highest, it experiences Landau damping. As the tune is moved away from this region the horizontal π-mode re-appears and the vertical one is damped. These simulation were performed with the beam-beam force as the only source of coupling. Adding linear coupling the model with a skew quadrupole at the IP did not significantly affect the damping effect. The major change observed was a transfer of the coherent modes from one plane to the other.

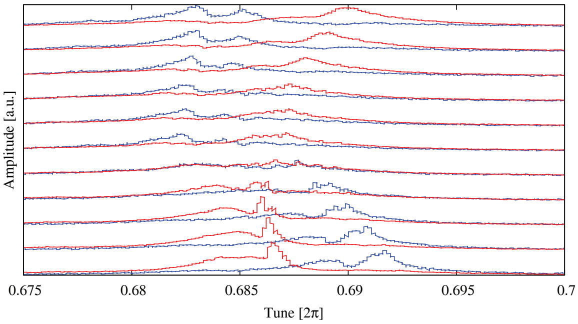

Figure 4: Mesured tune scan with BTF. The vertical spectrum is in red and the horizontal one in blue.

The simulations were verified in a dedicated experiment with only one IP colliding. Unfortunately, the Blue vertical emittance was significantly blown up introducing a large mismatch between the beams. This could explain the absence of π-mode in the vertical plane. We can however see, that as the horizontal tune is swept across the vertical one the coherent modes, to the right of the vertical tune spread, first disappear and then re-appear to the left once the tunes are fully crossed. This is consistent with the simulations shown in Fig. 3. In the measurements we can see that the σ-mode also appears to be affected, which was not seen in simulations. This is not yet fully understood but the model used for tracking uses linear transfer map where the beam-beam force is the only non-linearity. Additional sources of tune spread, such as chromaticity and triplets field errors, could provide additional Landau damping.

COHERENT MODES SUPPRESSION

The RHIC luminosity upgrade includes the installation of an electron lens for head-on beam-beam compensation [7]. It was shown that the head-on compensation will reduce the beam-beam tune spread, allowing for more bunch intensity, but will not affect the coherent beam-beam modes. The distance between the coherent modes and the incoherent tune spread will therefore be increased which could possibly compromise the beam stability [8].

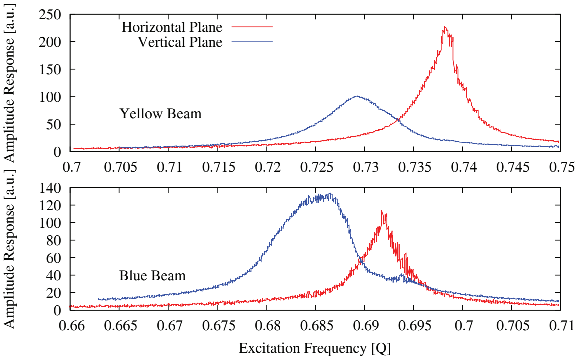

Figure 5: BTF measurement with split tunes.

When operating with the two beams on sufficiently different tunes, the coherent modes will cluster inside the incoherent continuum and experience Landau damping [9]. In preparation for operation with the electron lenses, this technique was tested at RHIC with tunes of about (0.691,0.689) for the Blue beam and (0.74,0.73) for the Yellow beam. Figure 5 shows an example of a BTF measurement with the beams on different tunes. The coherent modes are completely suppressed as expected from the theory.

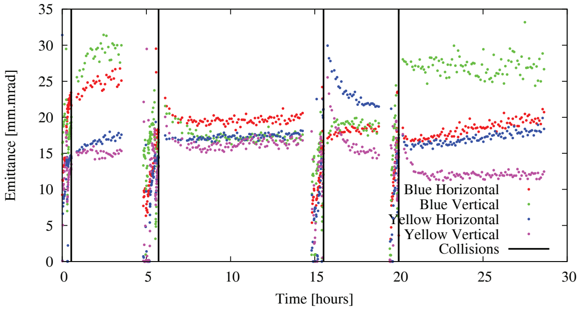

Figure 6: Emittance measurements during fills with split tunes.

Figure 6 shows emittance measurements over four consecutive stores with split tunes. A strong emittance blow-up is observed in three fills out of four as soon as the beams are brought into collision. This behavior for colliding beams with unequal tunes had been predicted in past simulations and theoretical analysis [10], where it was stated that operating a collider with unequal tunes could lead to coherent beam-beam resonance excitation and, providing the modes lay inside the incoherent continuum, emittance blow-up.

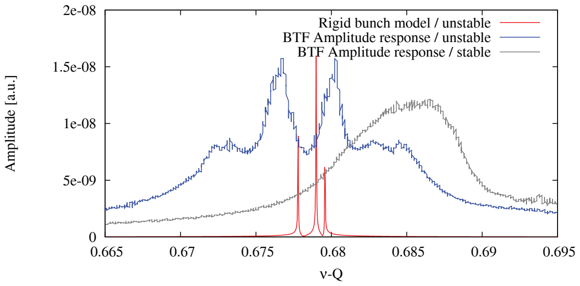

Figure 7: BTF data take during stores with emittance blow-up (blue) and without emittance blow-up (gray). The rigid model simulation are based on the beam parameters from the store with emittance blow-up.

Figure 7 shows a comparison of BTF data taken during two stores, one where a strong emittance blow-up was observed and one where emittance blow-up was not observed. Coherent modes excitation inside the incoherent spectrum appears to be associated with the emittance blow-up. During the store where no emittance blow-up was observed the tunes were significantly different, indicating a tune dependent effect as predicted in [10].

The closest coherent beam-beam resonances is in our case of odd order and should be excited only by beams colliding with an offset. We performed strong-strong simulations with beams colliding head-on and with an offset in order to verify that the blow-up was originating from the collisions with unequal tunes.

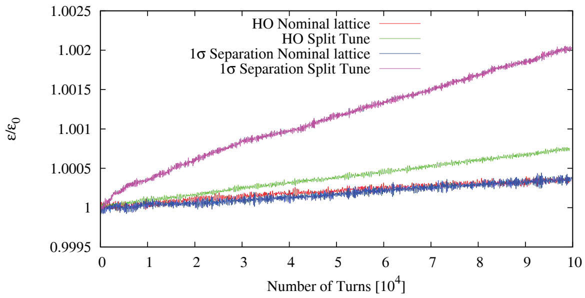

Figure 8: Simulated emittance growth rate for different tune and orbit settings.

Figure 8 shows the results of these simulations for head-on collisions and offset collisions. As a first test collisions with both beams close to 0.75 tunes were simulated without significant changes with respect to the case below 0.7 tunes. The growth rate is slightly increased in the case of unequal tunes and head-on collisions. For separated beams the growth rate becomes very large which would be consistent with excitation by an odd order resonance.

SUMMARY

Coherent beam-beam effects were studied in dedicated experiments. The absence of horizontal π-modes could be explained by a transfer of the Landau damping from one plane to the other. More detailed analysis and simulations would be required to understand this mechanism, more specifically the effect on the σ-mode which was not observed in simulations. The coherent modes were suppressed by operating RHIC with beams on different tunes. Large emittance blow-up was observed in most of the cases. This blow-up is consistent with what was predicted by past studies [10] and could be reproduced in simulations.

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