Beam-Beam Effects in the Relativistic Heavy Ion Collider

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1 Introduction

The beam-beam interaction is a major consideration in the operation of the Relativistic Heavy Collider (RHIC). It can lead to emittance growth and particle loss, and is a source for experimental background. Machine parameters, close to the maximum parameters achieved so far, are presented in Table 1. The p-p parameters used in operation differ from those shown in the Table. So far the bunch intensity was limited to $0.7 \cdot 10^{11}$ due to polarization requirements.
RHIC consists of two superconducting rings, Blue and Yellow, and has produced gold-gold, proton-proton and deuteron-gold collisions. With RHIC's interaction region design (Figure 1) and with 4 experiments beams experience 4 head-on, and 2 long-range collisions per turn. The long-range interactions are with at least 7 rms beams sizes separation. With 120 or less bunches per ring (the current limit), sets of 3 bunches in one ring and 3 bunches in the other ring are coupled through the beam-beam interaction.

Table 1: Latest machine parameters relevant to beam-beam interactions, for Au-Au and p-p collisions.

Parameter	Unit	Au-Au	p-p
relativistic γ, injection	…	10.5	25.9
relativistic γ, store	…	107.4	106.6
no of bunches, n_b	…	45	28
ions per bunch, N_b	10^9	1.1	170
emittance $\varepsilon_{N\ x,y\ 95\%}$	mm·mrad	10	20
chromaticities (ξ_x,ξ_y)	…	(+2,+2)	
harmonic no h, store	…	7×360	360
synchrotron tune Q_s	10^{-3}	3.0	0.5
rms bunch length σ_z	M	0.3	0.7
rms momentum spread σ_p/p		0.15	0.3
envelope function β^* at IP	M	1-10	
beam-beam ξ/IP	…	0.0025	0.007
head-on collisions	…	4	2
parasitic collisions	…	2	4

Two beam splitting DX dipoles are the magnets closest to the interaction point (IP). They are each 10m away from the IP (Figure 1). Beams collide nominally without a crossing angle. With rf manipulations, the crossing point can be moved longitudinally. If the bunch spacing is large enough (with 60 or less bunches per ring), it is possible to separate the beams longitudinally and switch off all 6 beam-beam interactions.

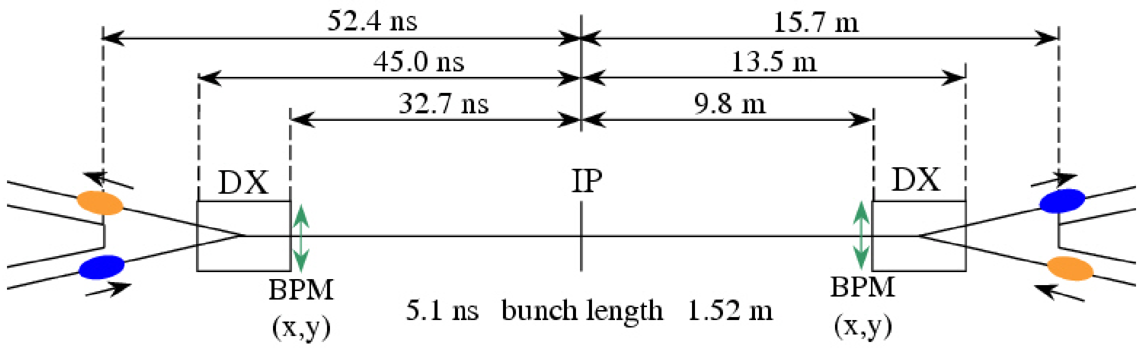

Figure 1: RHIC interaction region. Beams share a common beam pipe between the splitting DX dipoles. The bunch spacing shown corresponds to a fill pattern of 120 symmetrically distributed bunches.

Beam-beam phenomena observed in other hadron colliders [1] can also be seen in RHIC. In addition, with bunches of equal intensity the beams are subject to strong-strong effects. To accommodate acceleration of different species, the two RHIC rings have independent rf systems. With different rf frequencies the beam-beam interaction is modulated and can have a visible impact on the beam lifetime. The overview presented here is a summary of material presented in Refs. [2,3].

2 Quest for a new Working Point

Changing the working point is a strategy to alleviate the beam-beam effect and improve the performance of the machine. We considered as candidates for a new working point those of other hadron colliders. Those working point not suitable to host polarized beams were discarded.

Testing new working points at top energy represents a very significant effort since it requires the set-up of an energy ramp, which can take shifts of dedicated operation. Since the beam-beam parameter does not depend on the energy or the β-functions at the interaction point, the beam-beam effect can also be studied at injection.

The beam-beam interaction is not the only effect that strongly affects the beam dynamics. The magnetic non-linearities present in the interaction regions considerably reduce the dynamic aperture of the lattice. The dynamic aperture was estimated for these different working points by tracking particles for one million turns including the beam-beam interaction in the weak-strong approximation. Experiments to assess beam-beam effects at injection were performed with gold ions during the 2004 gold operation. Each beam consisted of 56 bunches with about $0.7 \cdot 10^9$ Au^{79+} ions. The beam decay rate was measured with and without collisions by fitting the wall current monitor intensity curve at the different tunes. Collisions were set at two interaction points (the STAR and PHENIX experiments). The results for the two most relevant working points are shown in Figure 2.

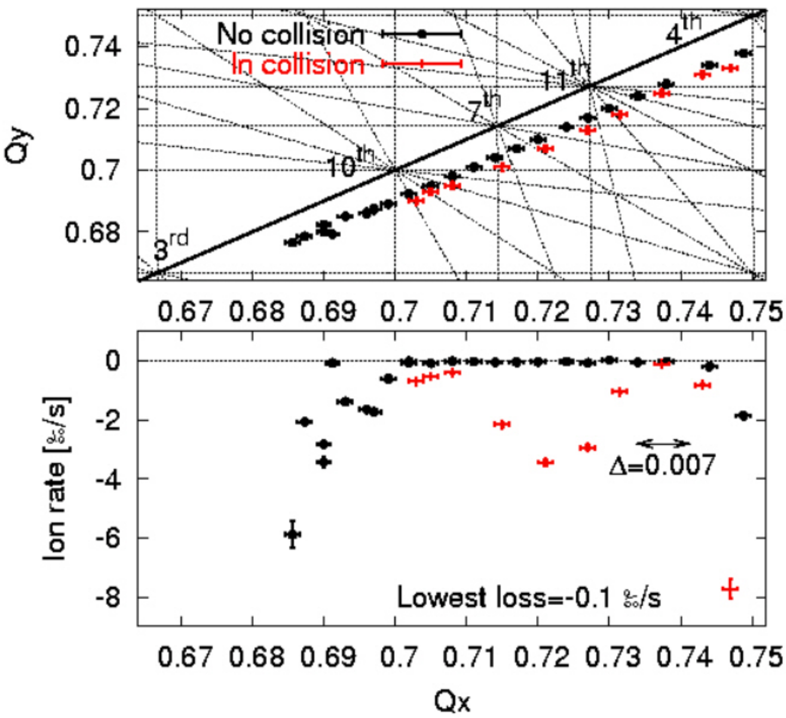

Figure 2: Tune scan at injection.

The beam lifetime near the SPS collider tunes of 0.68 is very short due to the proximity of the third order resonance. Instead a good working range around 0.73 was found at injection. This does not imply that at store the SPS tunes are worse than the other. Indeed the prediction of the dynamic aperture at store is shown in Figure 3.

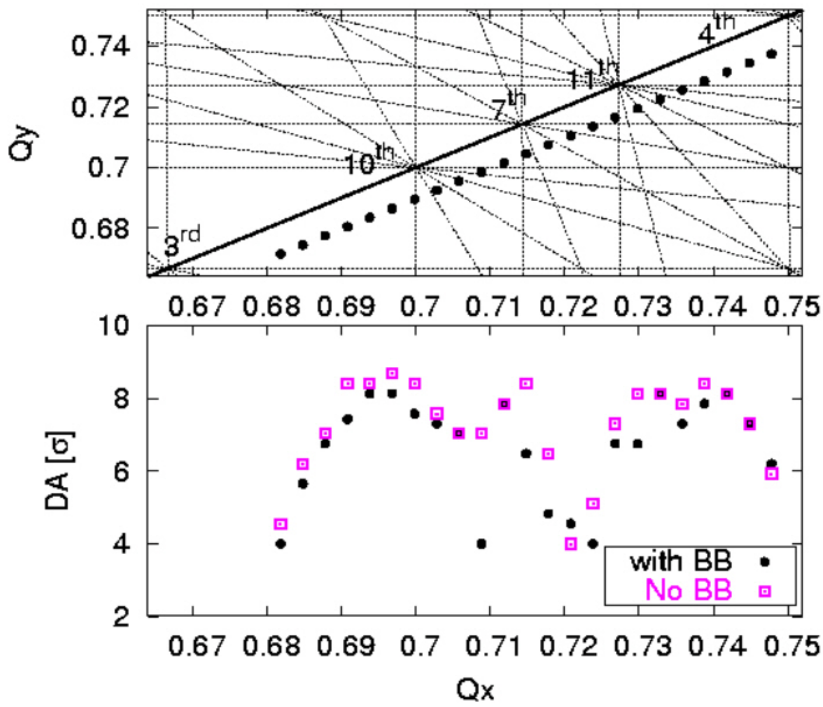

Figure 3: Tune scan and simulation at store.

With the beam-beam interaction, the dynamic aperture of the two possible working points is slightly larger than 8 transverse rms beam sizes. Therefore both tunes should be suitable for operation. During the 2004 proton operation both tunes were used. The SPS collider tunes performed slightly better in terms of beam lifetime, and significantly better in terms of beam polarization.

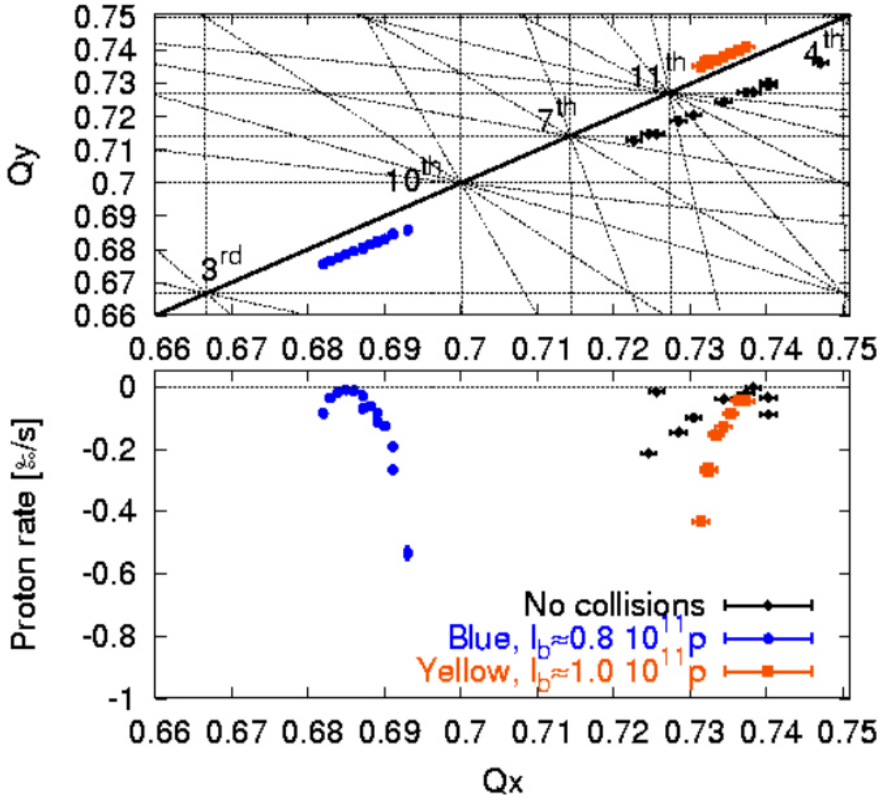

Figure 4: Tune scans at store with 4 head-on collisions.

During the proton run, a beam-beam parameter of ξ = 0.004/IP was reached with 4 head-on collisions, and a beam-beam parameter of ξ = 0.007/IP with only 2 head-on collisions.

3 Strong-Strong Observations

RHIC sees strong-strong beam-beam effects. In addition to the tune (σ-mode) a new transverse oscillation mode (π-mode) occurs. For a single collision per turn the π-mode is at a tune $Y\xi$ below the σ-mode, where $Y \approx 1.2$ for round beams [4]. If the beam-beam interaction is the dominant nonlinear effect, the π-mode can be outside the continuous spectrum and thus be undamped [5].

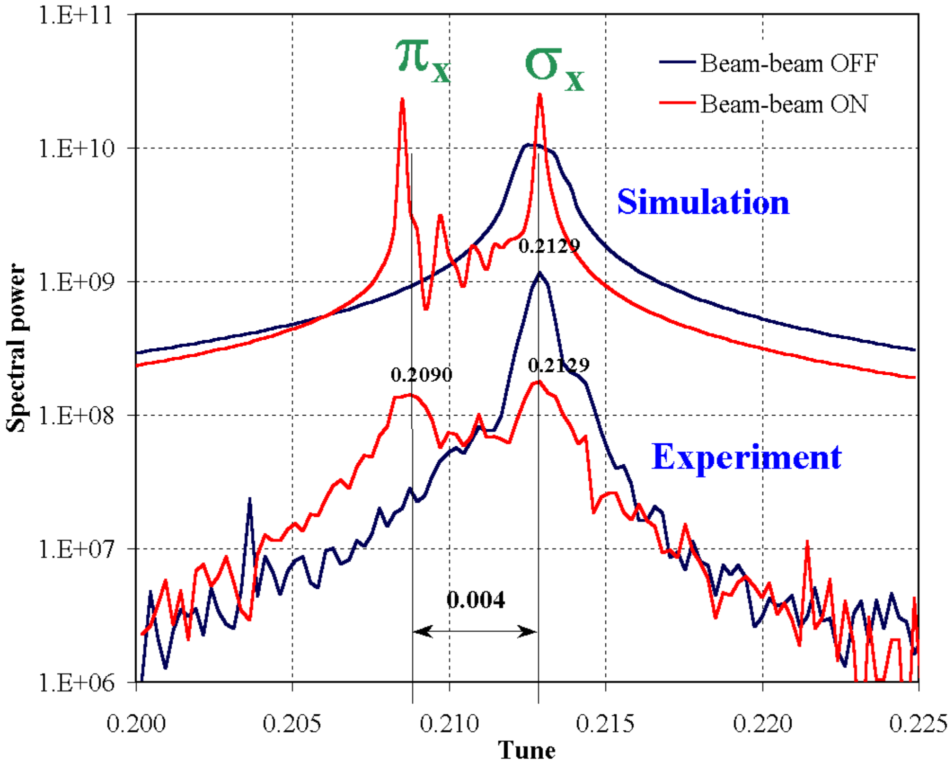

Figure 5: Coherent dipole modes in an experiment with a single proton bunch per beam, and a corresponding simulation [7]. $\xi = 0.003$, spectra from 4096 turns.

Coherent beam-beam modes were observed in an experiment with proton beams, with a beam-beam parameter $\xi = 0.003$ and a single collision per turn (Figure 5). The measured difference between the σ- and π-modes is consistent with a Yokoya factor of $Y \approx 1.2$. The locations of the π-modes were reproduced in a strong-strong simulation [7]. π-modes were also observed in routine operation with a beam-beam parameter $\xi = 0.0015$, four collisions per turn and linear coupling (Figure 5). The π-modes could be suppressed by small changes in one of the tunes. So far, coherent modes have not negatively impacted the collider operation.

4 Unequal RF Frequencies

When the two RHIC beams have different radio frequencies $f_{\rm rf}$ the beam crossing points move longitudinally with the speed

$$v_{CP} = \frac{c}{2}\frac{\Delta f_{rf}}{f_{rf}}$$

where c is the particle speed. Values of $\Delta f_{\rm rf}$ = 5Hz and $v_{\rm CP}$ = 27m/s were typical with gold beams in both rings, during the ramp. When deuteron and gold beams were injected with the same rigidity in 2002 [8], $\Delta f_{\rm rf}$ = 44kHz is needed and $v_{\rm CP}$ = 3m/turn. Beams experience the beam-beam interaction only when the crossing point is between the DX magnets (Figure 6). With slowly moving crossing points (gold-gold case) the beam-beam interaction is modulated, with fast moving crossing points (deuteron-gold case) beams experience pseudo random interactions in time.

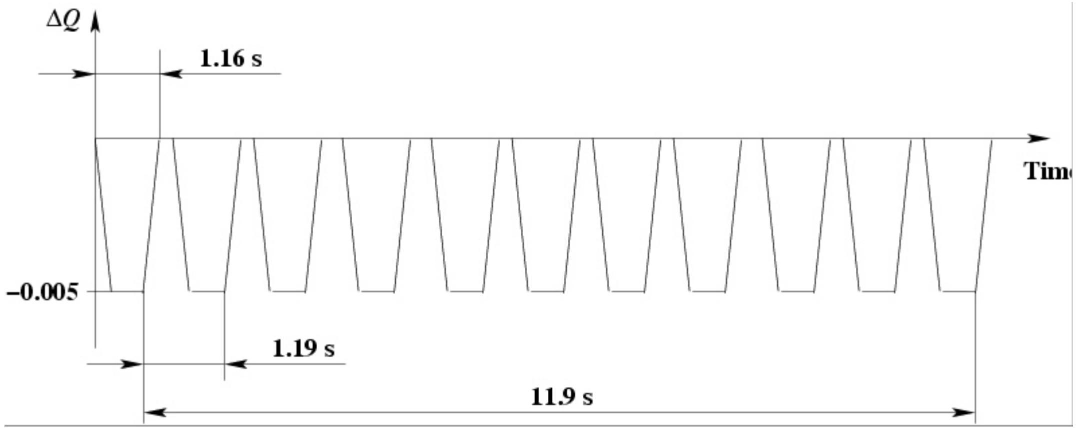

Figure 6: Tune modulation of particles in the centre of a bunch due to moving collision points, for Δf_{rf} = 5Hz, no crossing angle, 60 bunches and a total beam-beam tune shift of ΔQ_{tot} = -0.005.

Slowly moving crossing points and head-on collisions lead to tune modulation and to unacceptable beam lifetime [9]. The tune modulation depth is determined by the beam-beam parameter, the modulation waveform by the crossing angle, and the modulation frequency by the fill pattern and the difference in the rf frequencies Δf_{rf}. Figure 6 shows a case typical for gold-gold operation. To avoid this unwanted effect, the rf frequencies are now locked during ramps. This is challenging for ion beams that have to cross the transition energy.

5 Spin Effects and Future Upgrades

The effect of the beam-beam interaction on the beam polarization of proton beams was studied earlier with simulations of up to 10000 turns [10,11,12]. In these studies, no detrimental effect of the beam-beam forces on the proton beam polarization was found.
This is in agreement with observations so far.

Studies are under way to implement electron cooling in RHIC [13]. To enhance the luminosity, electron cooling may create a dense beam core that is surrounded by beam of lesser density, forming a bi-Gaussian transverse distribution. The beam-beam interaction under these conditions is being studied. A possible way to mitigate beam-beam effects may be to shape the transverse beam profiles of the colliding beams with variable profiles of the electron beams used for cooling.

The proposed electron-ion collider eRHIC [13] would be a collider with two rings of different circumference. In the electron ring a beam-beam parameter of up to 0.08 needs to be accommodated. Studies to date indicate that this can be done [14].

An increase in the RHIC luminosity by an order of magnitude may be implemented with superbunches [15]. Superbunches, however, would require a major upgrade in the timing system of the detectors. This may be easier to accommodate with a new detector [16]. A number of effects that are associated with superbunches need to be studied in more detail.

6 Summary

The beam-beam interaction has a significant impact on lifetime and emittance of the RHIC beams. Recent work shows that a change of the working point from (0.22,0.23) to (0.68,0.69) would allow the accommodation of a larger beam-beam parameter.

In addition to beam-beam effects observed in other hadron colliders, coherent beam-beam modes were seen for the first time. With independent rf systems for both rings, differences in the rf frequencies can lead to tune modulation and emittance growth. Beam-beam work relating to future upgrades, electron cooling and eRHIC, has started.

7 Acknowledgements

The author would like to acknowledge discussions with and support from Y. Alexahin, M. Bai, M. Blaskiewicz, M. Brennan, M. Furman, C. Montag, S. Peggs, J. Qiang, T. Roser, T. Sen, S. Tepikian, J. van Zeijts, and F. Zimmermann.

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