# TRANSVERSE BEAM TRANSFER FUNCTIONS OF COLLIDING BEAMS IN RHIC*

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*Abstract*

We use transverse beam transfer functions to measure tune distributions of colliding beams in RHIC. The tune has a distribution due to the beam-beam interaction, nonlinear magnetic fields – particularly in the interaction region magnets, and non-zero chromaticity in conjunction with momentum spread. The measured tune distributions are compared with calculations.

## INTRODUCTION

In a beam transfer function (BTF) measurement, the beam response $\langle x \rangle$ is measured as a function of the excitation frequency $\Omega$. If particles with a transverse tune distribution $\rho(\omega)$ are excited by a driving force $A\cos(\Omega t + \phi)$, the beam response after transient effects is [1]

$$\begin{aligned} \langle x\rangle(t) &= \tfrac{A}{2\omega_x}[\cos(\Omega t+\phi)\mathrm{P.V.}\int d\omega \tfrac{\rho(\omega)}{\omega-\Omega} \\ &\quad +\pi\rho(\Omega)\sin(\Omega t+\phi)]. \end{aligned} \quad (1)$$

By scanning the frequency $\Omega$ the distribution $\rho(\omega)$ can be obtained from the second, out of phase, term in the brackets. We have taken such BTF measurements of colliding proton beams during the RHIC Run-6 in 2006 [2], and compare the measured tune distributions with calculated ones.

The tune distributions of colliding proton beams are dominated by the beam-beam interaction, but other effects such as nonlinear magnetic fields and nonzero chromaticity in conjunction with the momentum distribution also contribute. The main beam parameters are listed in Tab. 1. In RHIC, there are nominally no long-range beam-beam interactions. The head-on beam-beam interaction couples 3 bunches in the Blue ring to 3 bunches in the Yellow ring through collisions in the interaction points IP6 and IP8 (Fig. 1). Due to the abort gaps in the two rings some of the groups have less than 3 bunches.

## CALCULATED TUNE DISTRIBUTIONS

The tune distribution can be calculated in the following way: points in $(x, y, dp/p)$ are randomly generated within a Gaussian distribution using the transverse emittances and momentum distribution. The tune of each point is calculated with coefficients for the amplitude dependent tune shift, and the nonlinear chromaticity. The tune points can then be sorted into a histogram. The coefficients for the amplitude dependent tune shift up to second order in action were determined in a tracking program with individual nonlinear magnetic magnet errors in the interaction region magnets DX, D0, Q1, Q2, and Q3; a local nonlinear correction; and randomized sextupole errors in the arc dipoles. The nonlinear chromaticity was calculated up to third order in $dp/p$. Fig. 2 shows the calculated tune distributions for beam-beam only (top), and including field errors and nonlinear chromaticity (bottom). Comparison with measured spectra (Figs. 5- 8) shows that such a simple model does not reproduce the measured tune spectra.

Table 1: Maximum achieved beam parameters during the 2006 polarized proton run.

| parameter | unit | value |
|---|---|---|
| beam energy $E$ | GeV | 100 |
| spin polarization $\mathcal{P}$ | % | 60 |
| no of collision points | ... | 2 |
| no of bunches $N$ | ... | 111 |
| bunch intensity $N_b$ | $10^{11}$ | 1.35 |
| rms emittance $\epsilon_{x,y}$, initial | mm·mrad | 2.8 |
| envelope function at IP $\beta^*$ | m | 1.0 |
| hour glass factor $h$, initial | ... | 0.75 |
| peak luminosity $\mathcal{L}$ | $10^{30}\mathrm{cm}^{-2}\mathrm{s}^{-1}$ | 35 |
| avg. luminosity $L$ | $10^{30}\mathrm{cm}^{-2}\mathrm{s}^{-1}$ | 20 |
| beam-beam parameter $\xi$/IP | ... | 0.006 |

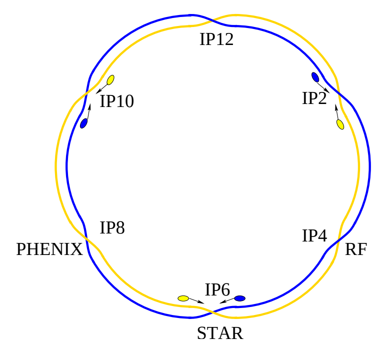


Figure 1: The head-on beam-beam interaction couples groups of 3 bunches in Blue to 3 bunches in Yellow through collisions in IP6 and IP8. There are no long-range beam-beam interactions.

## SIMULATED TUNE SPECTRA

For simulations we used the COMBI code [3,4] with two different models: the Rigid Bunch Model (RBM) and the Parallel Multi Particle Simulations (PMPS). Simulations are compared to fill 07915 of the RHIC polarized proton Run 2006 where the two beams were operated at two dif-

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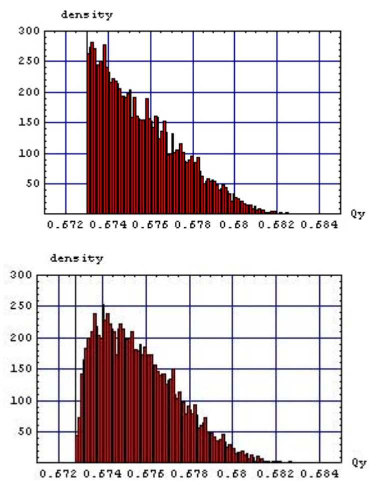


Figure 2: Calculated tune distribution with beam-beam only (top), and including nonlinear magnetic field errors and nonlinear chromaticity (bottom).

ferent working points. Schottky and BTF measurements from this store show tune differences of $\Delta Q_y \approx 0.01$ and $\Delta Q_x \approx 0.0035$.

Due to the abort gap (out of 120 possible buckets 111 are filled and 9 are empty), the orientation of the collision pattern (Blue bunch 1 meets Yellow bunch 1 in IP2 and IP8), and the choice of two asymmetric IPs (IP6 and IP8) 2 classes of bunches are created: 102 nominal bunches (which collide head-on in both IPs) and 9 SuperPacman bunches which collide only in IP6.

In the rigid bunch model 4 eigen-frequencies are expected for the RHIC configuration. This can be derived analytically and also from the RBM mode in COMBI. Fig. 3 shows the differences between nominal and SuperPacman bunches. For the SuperPacman bunches we find an intermediate mode which is a signature of a single head-on collision with a tune shift smaller compared to the nominal one.

Tune spectra were also produced with PMPS (Fig. 4). The coherent motion is completely suppressed in the vertical plane (Fig. 4 bottom) while still visible in the horizontal (Fig. 4 top). In the vertical plane the two beams are decoupled because the relative beam-beam strength ($\xi \approx 0.0041$ per IP) is always smaller than $\Delta Q_y$ [5]. Therefore we only expect two peaks at their respective tunes. In the horizontal plane the beam-beam coupling strength is always larger or equal to $\Delta Q_x$. Therefore, we have a coupled system of harmonic oscillators, oscillating at two frequencies with the intermediate modes being suppressed due to Landau damping.

## BTFS MEASURED AND SIMULATED

BTF measurements are rountinely made during the course of a store. A measurement involves sweeping the kicker frequency across the tune spectrum in steps of approximately $10^{-4}$ tune units and recording the amplitude response in a downstream pickups. A BTF measurement

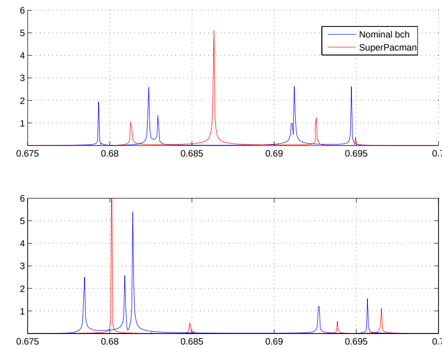


Figure 3: Horizontal (top) and vertical (bottom) tune spectra reproduced with RBM for nominal and SuperPacman bunches.

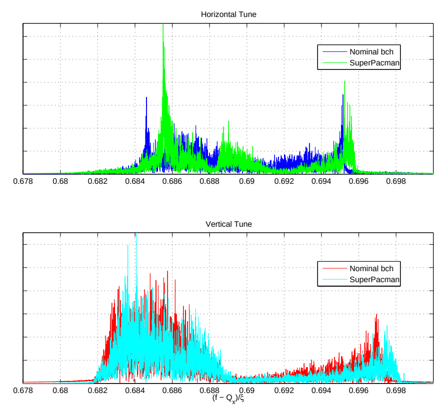


Figure 4: Horizontal (top) and vertical (bottom) tune spectra reproduced with PMPS for nominal and SuperPacman bunches.

taken before going into collisions is shown in Fig. 5.

To reproduce the BTF measurements, the COMBI code was modified to give a frequency dependent kick to the bunches of the two beams at a defined location, while the amplitude response is measured in another. A Fourier analysis of the amplitude response for the different excitation frequencies (made in steps of $2\times10^{-4}$ tune units) gives the amplitude and phase of the response.

The measured tune distributions are compared to simu-

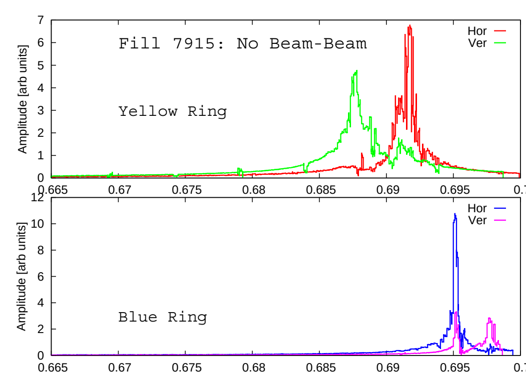


Figure 5: Measured tune distributions in the Yellow and Blue rings before going into collisions.



 

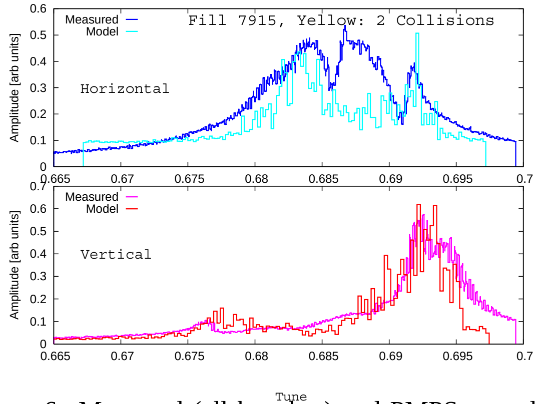


Figure 6: Measured (all bunches) and PMPS tune distributions of nominal bunches in the Yellow ring. The BTF measurements were taken at the beginning of the store.

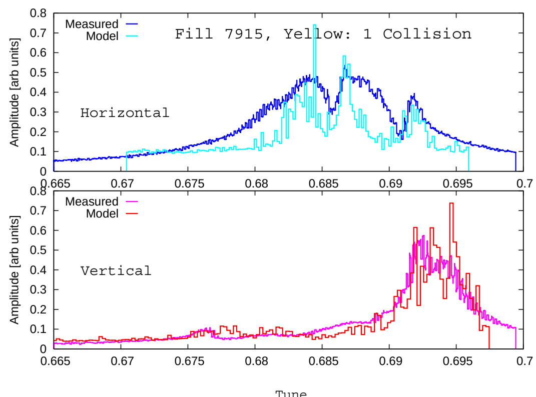


Figure 7: Measured (all bunches) and PMPS tune distributions of SuperPacman bunches in the Yellow ring.

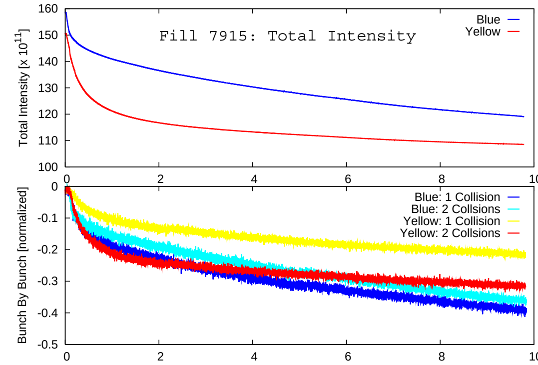


Figure 8: Total (top) and bunch intensity (bottom) evolution during a store. The bunch intensity evolution depends on the working point (different in Blue and Yellow) and the number of collisions.

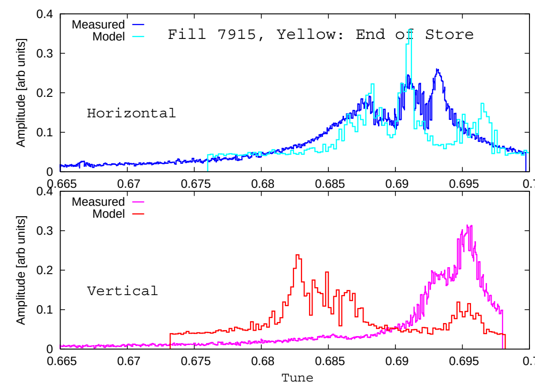


Figure 9: Measured (all bunches) and model tune distributions of a normal bunch in the Yellow ring. The BTF measurements were taken at the end of the store.

lations of nominal and SuperPacman bunches as shown for the Yellow beam in Figs. 6 and 7. For nominal bunches in the horizontal plane (Fig. 6 top) only the two extreme $\sigma$ and $\pi$ modes appear in simulations. The other two eigenfrequencies are too close to be distinguishable. For the SuperPacman bunches (Fig. 7 top), the intermediate mode, suppressed by Landau damping appears in the simulation. The measured spectrum agrees better with simulated spectrum of SuperPacman bunches.

In the vertical plane, Figs. 6 and 7 (bottom), the tune distributions from measurements and simulations agree for both nominal and SuperPacman bunches. The SuperPacman bunches show a shift of the centroid distribution to higher tunes as in the case of the measurements.

To study the intensity dependence, the BTF measurements were compared to simulations at the end of the physics store for the Yellow beam. The bunch intensity decreased from $1.32\times10^{11}$ to $1.06\times10^{11}$ protons (Fig. 8). Simulations and measurements show a good qualitative agreement in the location of the peaks as seen in Fig. 9. Due to coupling the location of the eigen-frequencies are swapped between the two planes.

## SUMMARY

Due to the abort gaps and the asymmetric collision patters, different bunches show different tune distributions. BTF measurements will reveal not only the unperturbed tunes but also all coherent modes due to the beam-beam coupling mechanism. Measurements can be reproduced with numerical simulations that take into account the multi-bunch beam structure and multiple interaction, although not all features seen in the measurement were reproduced in the simulations.

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