Transverse beam transfer functions of colliding beams in RHIC

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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.

1 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

\[
\langle x \rangle(t) = \frac{A}{2\omega_0} \left[ \cos(\Omega t + \phi) \mathcal{P}V. \int d\omega \frac{\rho(\omega)}{\omega - \Omega} + \pi \rho(\Omega) \sin(\Omega t + \phi) \right].
\]  

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 non-zero 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.

2 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 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

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

<table>
<thead>
<tr>
<th>parameter</th>
<th>unit</th>
<th>value</th>
</tr>
</thead>
<tbody>
<tr>
<td>beam energy ( E )</td>
<td>GeV</td>
<td>100</td>
</tr>
<tr>
<td>spin polarization ( P )</td>
<td>%</td>
<td>60</td>
</tr>
<tr>
<td>no of collision points</td>
<td></td>
<td>2</td>
</tr>
<tr>
<td>no of bunches ( N )</td>
<td></td>
<td>111</td>
</tr>
<tr>
<td>bunch intensity ( N_0 )</td>
<td></td>
<td>( 10^{11} )</td>
</tr>
<tr>
<td>rms emittance ( e_{x,y} ), initial</td>
<td>mm-mrad</td>
<td>2.8</td>
</tr>
<tr>
<td>envelope function at IP ( \beta^* )</td>
<td>m</td>
<td>1.0</td>
</tr>
<tr>
<td>hour glass factor ( h ), initial</td>
<td></td>
<td>0.75</td>
</tr>
<tr>
<td>peak luminosity ( \mathcal{L} )</td>
<td>( 10^{30} ) cm(^{-2})s(^{-1} )</td>
<td>35</td>
</tr>
<tr>
<td>avg. luminosity ( \mathcal{L} )</td>
<td>( 10^{30} ) cm(^{-2})s(^{-1} )</td>
<td>20</td>
</tr>
</tbody>
</table>

Possible tune shifts 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 so 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 reproduced the measured tune spectra.

3 SIMULATED TUNE SPECTRA

For simulations we used COMB1 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 different:

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different 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 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 an additional overall tune shift smaller compared to the nominal one.

Tune spectra were also produced with PMPS (Fig. 4). As expected [5] 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 $\Delta Q_y$. Therefore we only expect two peaks at their respective tunes. In the Horizontal plane the beam-beam coupling strength is always bigger or equal to $\Delta Q_x$. Therefore, we have a coupled system of harmonic oscillators, oscillating at two equilibrium $\sigma$ and $\pi$ frequencies with the intermediate modes being suppressed due to Landau damping.

4 BTFS MEASURED AND SIMULATED

BTF measurements are routinely 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 taken before going into collisions is shown in Fig. 5.

To reproduce the BTF measurements, code was implemented which gives a frequency dependent kick to the bunches of the two beams in 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 $2 \times 10^{-4}$ tune units) gives the amplitude and phase of the response.

The measured tune distributions are compared to simu-
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.

BTF measurements will reveal not only the unperturbed tunes but also all coherent modes proper of the beam-beam coupling mechanism. Measurements can be reproduced with numerical simulations that take into account the multibunch beam structure and multiple interaction, although not all features seen in the measurement were reproduced in the simulations.

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7 REFERENCES

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