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# SIMULATION OF BEAM-BEAM TUNE SPREAD MEASUREMENT WITH BEAM TRANSFER FUNCTION IN RHIC*

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*Abstract*

Head-on beam-beam compensation had been successfully implemented routinely in the 2015 polarized proton operation in the Relativistic Heavy Ion Collider at Brookhaven National Laboratory. Two electron lenses have been used to reduce the incoherent beam-beam tune spread to allow a larger proton bunch intensity and therefore a higher luminosity. Beam transfer function was used to determine the beam-beam incoherent tune spread. In this article, we carry out numeric simulations to compare the tune spreads derived from tune histogram and the beam transfer function. Then we present the experimental beam transfer function measurements and extract the tune spreads due to beam-beam interaction and electron lens. Experimental results show that the electron lens reduced the beam-beam tune spread.

## INTRODUCTION

The luminosity is limited by the beam-beam interaction in the polarized proton operation operation in the Relativistic Heavy Ion Collider (RHIC) at Brookhaven National Laboratory. To have good beam and polarization lifetimes, the working point is constrained between 2/3 and 7/10 in the tune space. To minimize the head-on beam-beam tune spread and to compensate the nonlinear beam-beam resonance driving terms, two electron lenses (e-lenses) have been installed in RHIC, one for each ring. In 2015, head-on beam-beam compensation had been implemented routinely for the first time in the RHIC 100 GeV polarized proton operation [1–3]. With beam-beam compensation, both the peak and integrated luminosities had been doubled comparing to the previous energy proton operation in 2012.

In the article, we present a fast and efficient way to experimentally determine the incoherent beam-beam tune shift with beam transfer function (BTF) measurement. We first carry out numerical simulations to compare the tune spreads from the BTF calculation and from the tun histogram and the beam-beam parameter. Then we present the BTF measurements during electron current scans without and with beam-beam interaction. The tune spreads introduced by the e-lens are extracted. The experimental results show that the e-lens reduced the beam-beam tune spread.

## NUMERICAL SIMULATION

We developed both weak-strong and strong-strong beam-beam codes to numerically calculate BTF and tune histogram [4]. The advantage of weak-strong code is that the particles can be tracked element-by-element through the ring and all the lattice nonlinearities can be included. In the RHIC operation, coherent beam-beam modes can only be detected with external excitation. In the following, we will use the weak-strong beam-beam interaction model. The proton bunch is represented by macro-particles while the other beam by a rigid Gaussian charge distribution. The e-lens is modeled as 4 segments with each one represented by a drift – a 4-d beam-beam kick – a drift.

In one test, the 2015 100 GeV blue ring lattice is used. The lattice tunes are set to (0.69, 0.685). To minimize the tune spread from the chromatic effect, the linear chromaticities are set to (0, 0). The proton bunches collide at IP6 and IP8. The e-lens is switched off. The proton bunch intensity is scanned up to $2.0 \times 10^{11}$ or a total beam-beam parameter of -0.02.

Figure 1 shows the calculated imaginary part of BTF and the tune histogram with a beam-beam parameter of -0.01. The imaginary part of BTF is wider than that directly calculated tune histogram since BTF is related to the amplitudes of particles. In the following, to compare the width of tune spreads derived from the imaginary part of BTF and the tune histogram, we define the tune spread as the full width of 10% maximum [5]. We choose the full width of 10% maximum other than the well-known full width of half maximum (FWHM) because the former is close to the full span of the tune distribution, and also 10% maximum is a practical choice for experimental BTF measurements to overcome the noise floor.

Figure 2 shows the correlation between the tune spreads derived from the imaginary part of BTF and tune histogram. The horizontal and vertical axises are the tune spreads from the tune histogram and BTF respectively. The tune spread derived from BTF can be fitted linearly with that from the tune histogram, although the tune spread from BTF is about 8% larger than that from the tune histogram in this test. We also found that both the tune spreads from BTF and from the tune histogram can be fitted linearly with the beam-beam parameter, too. They are about half of the beam-beam parameter within a relative error of 12%.

The linear correlations between the tune spreads from the imaginary part of BTF and the tune histogram and the beam-beam parameter provide us a fast and convenient way to estimate the tune spread experimentally based on the high signal-to-noise BTF measurement.

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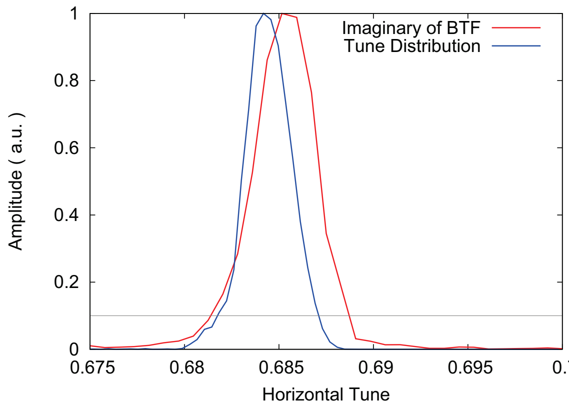


Figure 1: Simulated tune histogram and imaginary part of BTF with a beam-beam parameter of -0.01.

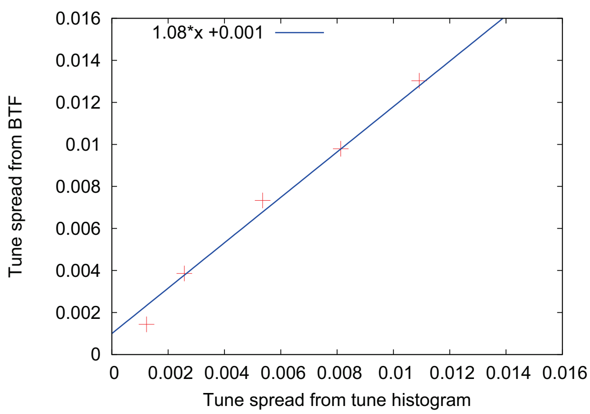


Figure 2: Correlation between the tune spreads derived from BTF and tune histogram.

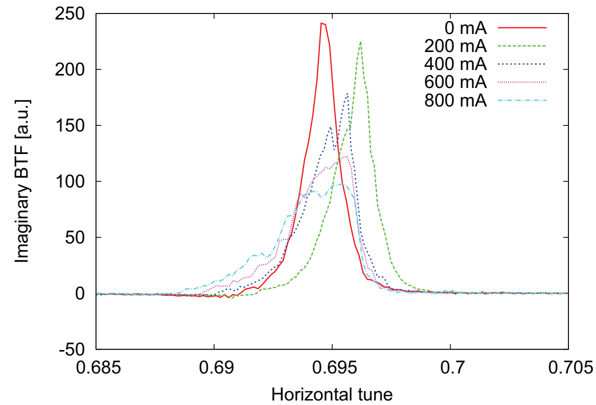


Figure 3: Measured imaginary parts of BTF without beam-beam interaction.

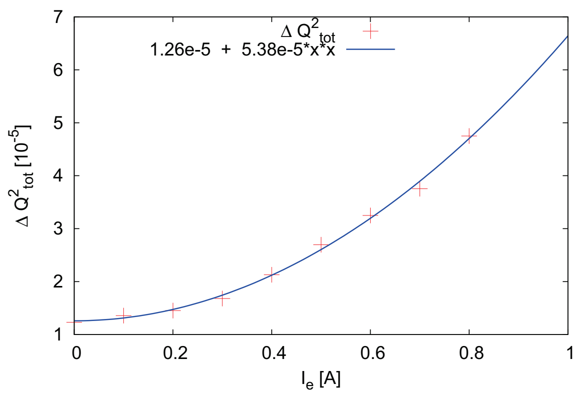


Figure 4: The total tune spread fitted with the electron current according to Eq. (1).

## MEASUREMENT RESULTS

### *Without Beam-beam*

Figure 3 shows the measured imaginary BTFs of the proton beam in the Yellow ring during the 2015 100 GeV proton-proton operation. During this experiment, there was no beam-beam interaction. The electron current of the e-lens was scanned from 0 up to 800 mA with a step size of 100 mA. The electron beam size in the interaction region is 0.74 mm, while the proton beam size was 0.60 mm at the same location.

For RHIC, without beam-beam interaction, the main source of tune spread is from the chromatic effect. Since the tune spread generated from the chromatic effect and the tune spread generated from the e-lens are uncorrelated, we have

$$\Delta Q^2_{tot} = \Delta Q^2_{resid} + \Delta Q^2_{elens}, \quad (1)$$

where $\Delta Q_{tot}$, $\Delta Q_{resid}$, and $\Delta Q_{elens}$ are the total tune spread, and the residual tune spread, and the tune spread contributed by the e-lens. If the electron beam shape and size were well maintained during the electron beam current scan, the tune spread from the electron lens should be proportional to the electron current $I_e$. Therefore,

$$\Delta Q^2_{tot} = \Delta Q^2_{resid} + (k * I_{elens})^2, \quad (2)$$

where $k$ is an unknown constant.

Figure 4 shows $\Delta Q^2_{tot}$ as a function of $I_{elens}$ . $\Delta Q^2_{tot}$ can be fitted very well according to Eq. (1). After knowing $\Delta Q^2_{resid}$, we extract the tune spread contributed by the electron lens $\Delta Q_{elens}$ and fit them to a linear function of electron current. Figure 5 shows the result. The tune spread from the e-lens is $\Delta Q_{elens}/\Delta I_e$= 0.0072/A. The incoherent tune shift from the e-lens can be numerically calculated based on the electron beam 's size and current. For 1000 mA electron current, the incoherent tune shift from the e-lens is 0.011.

### *With Beam-beam*

In the proton-Aluminum ion collision, the proton beam's tunes are (0.695, 0.685) while the Aluminum ion beam's tunes are around (0.235, 0.225). There is no coherent beam-beam interaction. In this experiment, we scanned the electron current from 0 up to 1030 mA with proton-Alumimum ion collisions at IP6 and IP8. The total beam-beam parameter from the proton-Alumimum ion collision is about -0.014.

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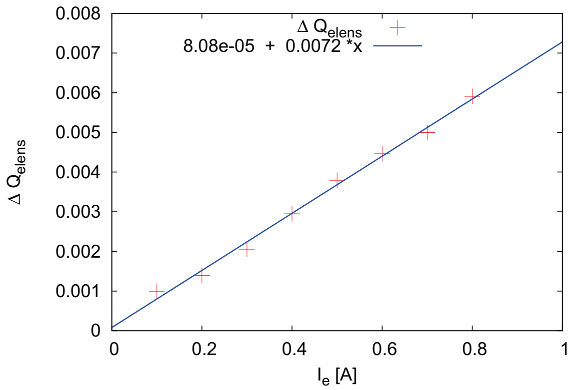


Figure 5: The tune spread from e-lens linearly fitted with the electron current.

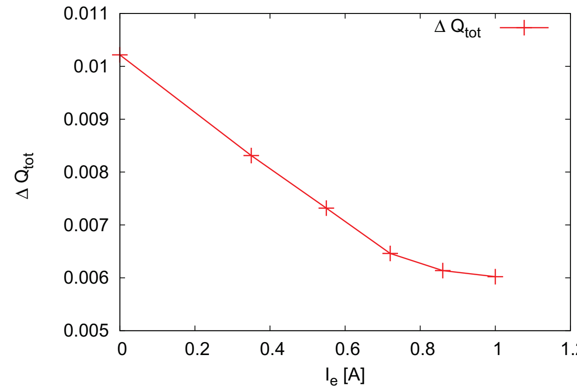


Figure 6: Measured total BTF tune spreads with beam-beam interaction.

The electron bunch size was 0.65 mm. The proton beam size at the e-lens was about 0.60 mm.

Figure 6 shows the measured BTF tune spreads versus the electron current. The total tune spread drops fast at the beginning with a small electron current. Then it drops much slower after the electron current reached 750 mA. A minimum of the total tune spread was reached around 1000 mA. When both the tune spreads from beam-beam interaction and electron lens appear, the total tune spread is given by

$$\Delta Q_{tot}^2 = \Delta Q_{resid}^2 + (\Delta Q_{p\text{-}Al} + \Delta Q_{elens})^2, \qquad (3)$$

where $\Delta Q_{p\text{-}Al}$ is the beam-beam tune spread contributed by the proton-Aluminum ion collision. Note that $\Delta Q_{p\text{-}Al}$ and $\Delta Q_{elens}$ have different signs. For simplicity, we define $\Delta Q_{p\text{-}Al} + \Delta Q_{elens}$ as the 'beam-beam like' tune spread.

Again we assume that $\Delta Q_{elens}$ is proportional to the electron current. Then we have

$$\Delta Q_{tot}^2 = \Delta Q_{resid}^2 + (\Delta Q_{p\text{-}Al} + k * I_{elens})^2, \qquad (4)$$

The measured $\Delta Q_{tot}$ can be fitted very well with Eq. (4). Knowing $\Delta Q_{resid}$, we further fit the beam-beam like tune spread as a linear function of the electron current. Figure 7 shows the results.

With zero electron current, the total beam-beam like tune spread is solely from the beam-beam interaction $\Delta Q_{p\text{-}Al}$, which is about 0.0083. The tune spread due to the e-lens increases linearly with the electron current with a different sign to $\Delta Q_{p\text{-}Al}$. The slope of the fitting line shows that $\Delta Q_{elens}/\Delta I_e$= 0.0073/A. When the electron current reaches about 1100 mA, the e-lens almost completely compensates the beam-beam tune spread. Therefore the total measured tune spread reached its minimum. The minimum is actually the residual tune spread $\Delta Q_{resid}$ from the nonlinear lattice. The lattice tune spread can not be compensated by the e-lens. If we continue increasing the electron current, the total tune spread is expected to grow, which is confirmed by off-line numerical simulation.

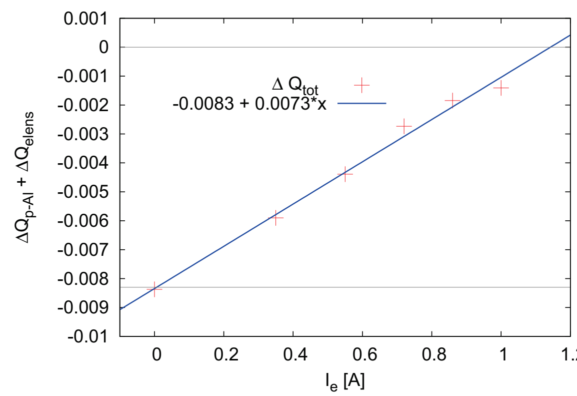


Figure 7: Beam-beam like tune spread linearly fitted with with electron current.

## SUMMARY

In this article, we carried out numeric simulations to compare the tune spreads derived from BTF and tune histogram and a linear correlation between them is found, although the tune spread from BTF is slightly larger than that from tune histogram. Both tune spreads also linearly scale with the beam-beam parameter. We extracted the tune spreads from BTF measurements without and with beam-beam interaction. The tune spread from e-lens is a linear function of electron current. Simulations reproduced the similar tune spreads per 1 A. Experimental results show that the beam-beam tune spread could be compensated by the e-lens.

## REFERENCES

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