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Minimization of Spin Tune Spread by Matching Dispersion Prime at RHIC

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At RHIC, the spin polarization is preserved with a pair of Siberian snakes on the opposite sides in each ring. The polarized proton beam with finite spin tune spread might cross spin resonances multiple times in two cases, one is when beam going through strong spin intrinsic resonances during acceleration, the other is when sweeping spin flipper' frequency across the spin tune to flip the direction of spin polarization. The consequence is loss of spin polarization in both cases. Therefore, a scheme of minimizing the spin tune spread by matching the dispersion primes at the two snakes was introduced based on the fact that the spin tune spread is proportional to the difference of dispersion primes at the two snakes. The scheme was implemented at fixed energies for the spin flipper study and during beam acceleration for better spin polarization transmission efficiency. The effect of minimizing the spin tune spread by matching the dispersion primes was observed and confirmed experimentally. The principle of minimizing the spin tune spread by matching the dispersion primes, the impact on the beam optics, and the effect of a narrower spin tune spread are presented in this report.

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I. INTRODUCTION

RHIC is the world's only machine capable of colliding high-energy polarized proton beams, a unique tool for studying the spin structure of the proton[1]. The spin polarized proton beam is generated by the OPPIS[2], transported through the Booster, AGS and into the two RHIC rings (Blue and Yellow)[3]. During beam acceleration, spin polarization could get lost due to depolarizing resonances[4,5]. The resonances occur when the spin tune $G\gamma$, the spin rotations in one revolution is equal to an integer (imperfection resonances) or equal to $kP \pm \nu_y$ (intrinsic resonances). Here P is the super-periodicity of the machine, ν_y is the vertical betatron tune and k is an integer. The depolarizing resonances in the injectors (the Booster and AGS) were corrected by the harmonic orbit correction for the imperfection resonances and the tune jump method for the intrinsic resonances. The partial snakes have also been employed to reduce the effect of both resonances in AGS[6]. Two Siberian snakes[7] were placed on the opposite sides of each of the two RHIC rings to reduce the imperfection and the intrinsic depolarizing resonances. The Siberian snakes consist a sequence of superconducting helical dipole magnets which rotate the spin by 180 degrees. The number of spin procession rotation per turn is 1/2 by design with two snakes in RHIC. However, the spin tune of a proton bunch has a finite spread due to the intrinsic energy spread of the beam.

It is desirable to minimize the spin tune spread. Firstly, it would improve the spin flipping efficiency by the spin flipper[8]. The RHIC spin flipper is designed to flip the spin helicity of all RHIC bunches in the Blue ring in order to eliminate systematic errors in the experiments. The spin flipper consists of four DC dipoles with horizontal deflection and five AC dipoles with vertical deflection. The tune of the AC dipoles is swept slowly across the spin tune to flip the spin rotation axis by 180 degrees and the spin of all particles will follow adiabatically. With large spin tune spread, the spin tune of the particles cross the tune of the AC dipoles multiple times (Fig. 1) which would result in polarization loss. The benefit of a narrower spin tune spread on spin flip efficiency were reported in simulations[9,10]. Secondly, it reduces the number of crossings of a depolarizing resonance during beam acceleration due to energy oscillation at the synchrotron frequency. Multiple crossing of resonances is of particular concern when beam is accelerated through strong intrinsic resonances during the later part of the acceleration. The simulation reported in[11] showed the spin transmission efficiency dependency on the spin tune spread.

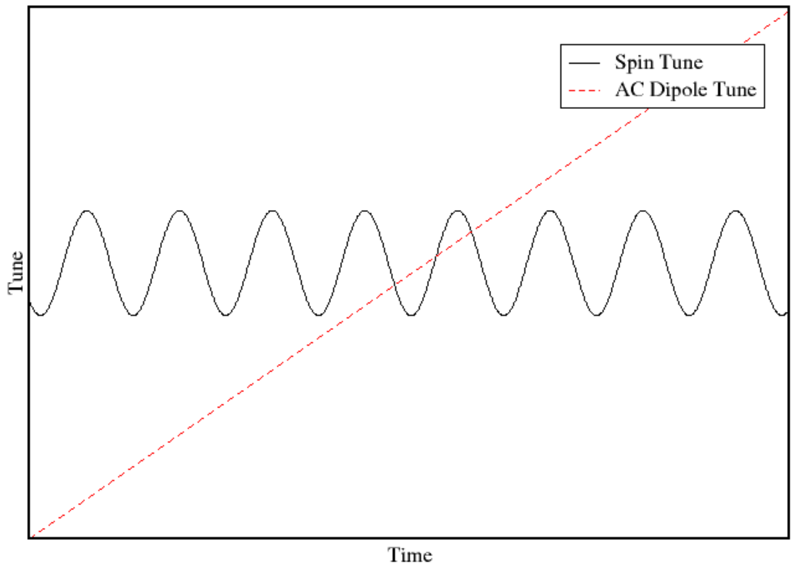

FIG. 1. Mechanism of multiple resonance crossings. The spin tune for an off-energy particle (the solid line) is oscillating with the synchrotron frequency. The AC dipole tune (the dashed line) is ramped across the $\nu = 0.5$ line and intersects with the black line three times.

To the first order, the spin tune is expressed as[12],

$$\nu = \frac{1}{2} + \frac{G\gamma}{\pi}\left[\frac{(D'_1 - D'_2) * \Delta p}{p}\right] \tag{1}$$

The second term shows the spin tune spread is proportional to the difference of the dispersion prime at the two snakes. In principle, one could reduce the momentum spread of the beam for smaller spin tune spread. However, this method is limited by the upper limit of the bunch length and the concern of high intra-beam scattering growth rate. The scheme of reducing $(D'_1 - D'_2)$ by optics modification[9,11] was explored and demonstrated to be effective without significant impact to the dynamic aperture.

II. THE SCHEME OF MATCHING DISPERSION PRIME AT THE SNAKES

The γ_T quadrupoles in the arc were identified as the effective magnet elements for matching the dispersion primes at the two snakes[9]. There is a set of four quadrupoles located in each arc (Fig. 2) and they are used during the acceleration of ion beams to jump the transition γ_T of the lattice across relative beam energy γ . These magnets, with the same polarity and strength, are located in places with identical β-functions. For γ_T jump, the first and third quadrupoles generate a closed bump in the dispersion, and so do the second and forth quadrupoles. Meanwhile, the relative β-function change from the the nearby magnets cancel each other. The perfect cancellation of the dispersion and the β-beat outside of the quadrupoles families is only possible with a ideal 90-degree horizontal phase advance between magnets. These γ_T quadrupoles are not useful to correct the dispersions and its primes at the snakes in their usual configuration. If the polarity of two of the quadrupoles (say the second and third) is reversed, the dispersion distortion is not closed instead it is maximized around the ring. Since the β-functions are the same for all the γ_T quadrupoles the tune does not change dramatically with the quadrupole strength and there is a significant cancellation of the β-beat outside the region of the γ_T quadrupoles. Another pair of jump quadrupoles is located at each end of the arc (Fig. 2), where the dispersion is zero. These are used during the γ_T jump to keep the tunes constant. They are employed in the matching of dispersion prime as well to compensate for the minor tune change caused by the γ_T quadrupoles in the arc.

Since the phase advance between γ_T quadrupoles (82 degrees) is a little deviated from the ideal case, we went through the following procedure to determine the γ_T quadrupoles that need polarity reversal. The 48 γ_T quadrupoles are treated as magnets with individual power supplies first so that individual strength of each quadrupole magnet is generated when matching the dispersion primes at the two snakes. Then, the magnets with negative strength are the ones whose polarity need to be reversed, and the magnets in the same families are grouped so that the absolute strength of them are equal. We then rerun the matching simulation which produces the strength for each family. One other constraint of the matching is that the resultant tune change is zero, which is fulfilled by the alternating polarity of the quadrupoles and compensation from the quadrupoles at non-dispersive locations.

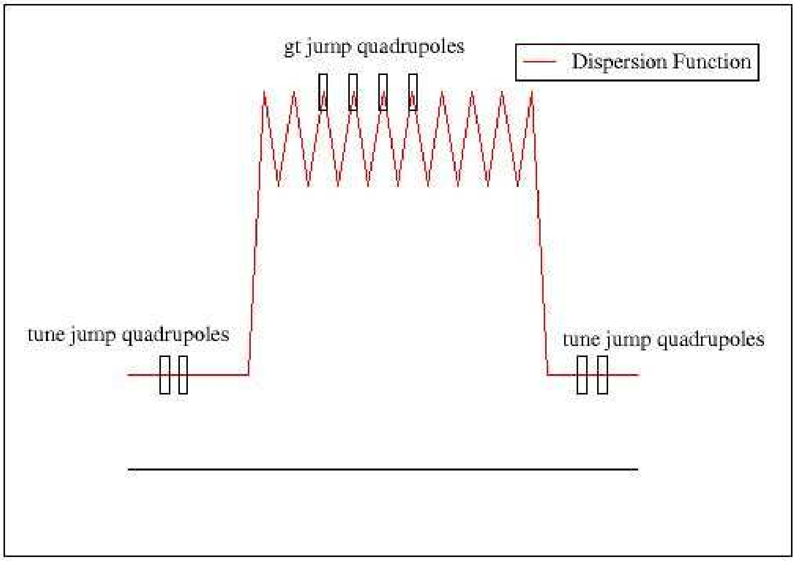

FIG. 2. Layout of the γ_T quadrupoles in each sextant of RHIC. The quadrupoles at the dispersive locations are for generating closed dispersion bump. The quadrupoles at non-dispersive locations are for compensating minor tune change.

The matching of dispersion primes at the two snakes was realized by distorting the dispersion functions in the ring which also causes some distortions to the other optical functions. The following results are for the Blue ring lattice at top energy (255 GeV) in 2017 polarized proton program[13].

The dispersion primes at the snakes were matched in simulation for 20 beam energies during beam acceleration including the injection and top energy. The distortion of the β-functions due to the matching for all the other energies are less compared to the one for the top energy (Fig. 4). The standard deviation of the relative changes of the β-functions at 20 beam energies during beam acceleration including the injection and top energy are shown in Fig. 5.

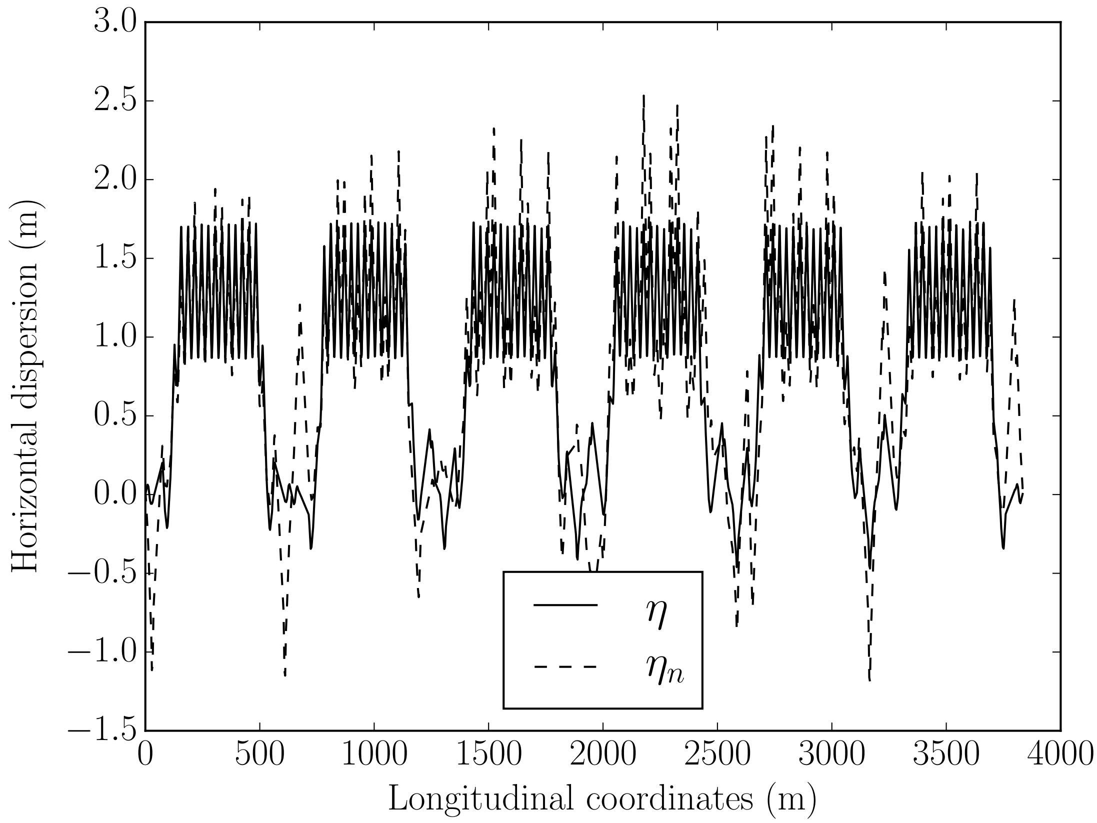

FIG. 3. The design horizontal dispersion functions (the solid line) at top energy and the distorted horizontal dispersion functions (the dashed line) with the dispersion primes matched at the two snakes in the Blue ring. The baseline lattice is the top energy in the 2017 polarized proton program.

III. DISPERSION PRIME MATCHING IMPLEMENTATION AND MEASUREMENT

The dispersion prime matching were implemented in the Blue ring at injection and top energy for the spin flipper studies. The measured baseline dispersion functions before the matching and the one after the matching at injection energy are shown in Fig. 6. The initial difference of dispersion prime at the two snakes was $\delta D' = 0.07396 \pm 0.00011$ at injection energy. The $\delta D' = 0.00345 \pm 0.00016$ with matched dispersion primes. A much narrower spin tune spread was measured with the matching of the dispersion primes at the two snakes. This facilitated the demonstration of 97% spin flip efficiency first time at RHIC[14].

The measured baseline dispersion functions before the matching and the one after the

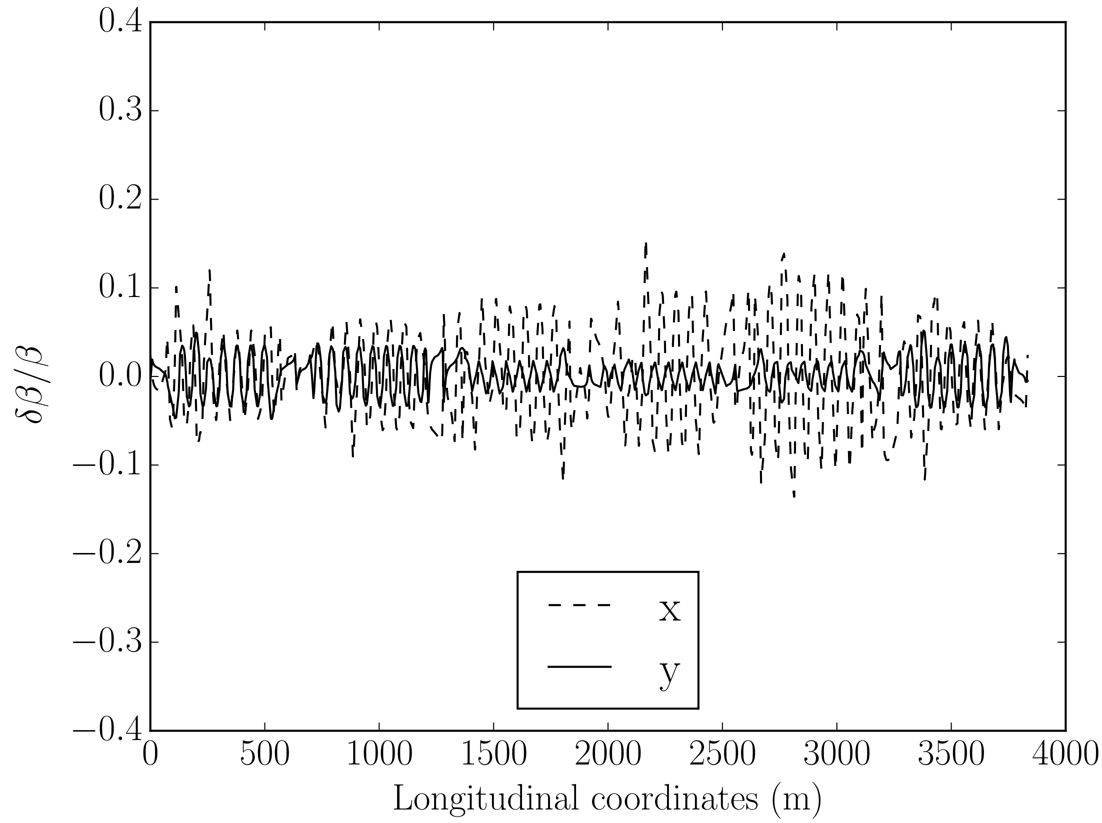

FIG. 4. The resulted relative changes of the β-functions at top energy with the dispersion primes matched at the two snakes in the Blue ring, the horizontal in the dashed line and the vertical in the solid line. The baseline lattice is for the top energy in the 2017 polarized proton program.

matching at top energy are shown in Fig. 7. A second round of the dispersion prime matching was found to be helpful for the spin flip study at top energy. The spin flip efficiency was about 70% with only the first round of dispersion prime matching. The residual difference of the dispersion primes was -0.00297 ± 0.00013. The second round of minimizing the difference of the dispersion prime at the snakes was done by overshooting in the matching simulation with the goal of $\delta D' = 0.00297$, which is the opposite of the residual $\delta D'$ from the first round of matching. The difference of dispersion primes was measured to be -0.00012 ± 0.00024 with the second round of matching. The spin flip efficiency was improved to be about 94% with the second round of dispersion prime matching.

The dispersion prime matching was implemented in the Blue ring lattice during beam acceleration for better spin transmission efficiency. The spin polarization transmission ef-

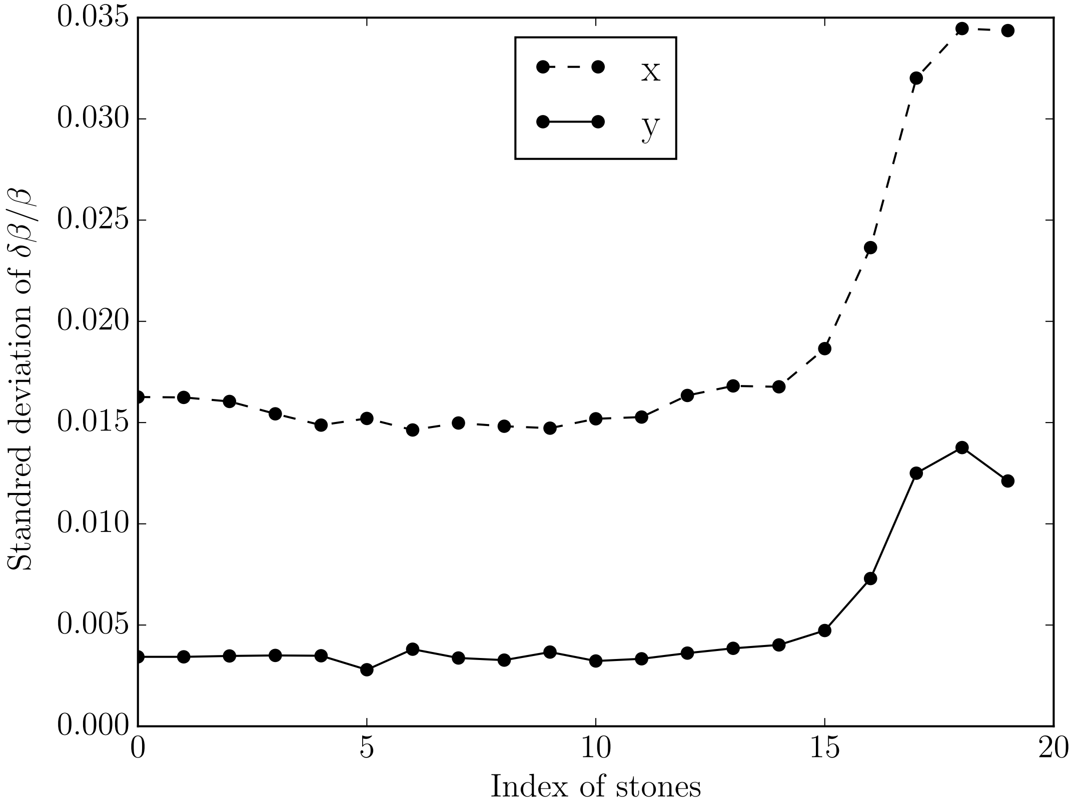

FIG. 5. The standard deviation of the resulted relative changes of the β-functions at 20 beam energies during beam acceleration including the injection and top energy with the dispersion primes matched at the two snakes in the Blue ring. The lattice is for the beam acceleration in the 2017 polarized proton program.

TABLE I. Spin polarization transmission efficiency during beam acceleration in 2017 polarized proton program.

dates	BH target	BV target	YH target	YV target
03/14-04/14	0.954 +/- 0.005	0.979 +/- 0.006	0.915 +/- 0.005	0.905 +/- 0.012
04/14-05/25	1.020 +/- 0.004	0.963 +/- 0.005	0.947 +/- 0.004	0.953 +/- 0.010

ficiency in the 2017 polarized proton program is summarized in Table I. There was no dispersion prime matching during the time period 03/14-04/14. The matching was implmented during the time period 04/14-05/25 in the Blue ring only. The transmission efficiency in the Yellow ring for the same time periods are listed for comparison. There are horizontal

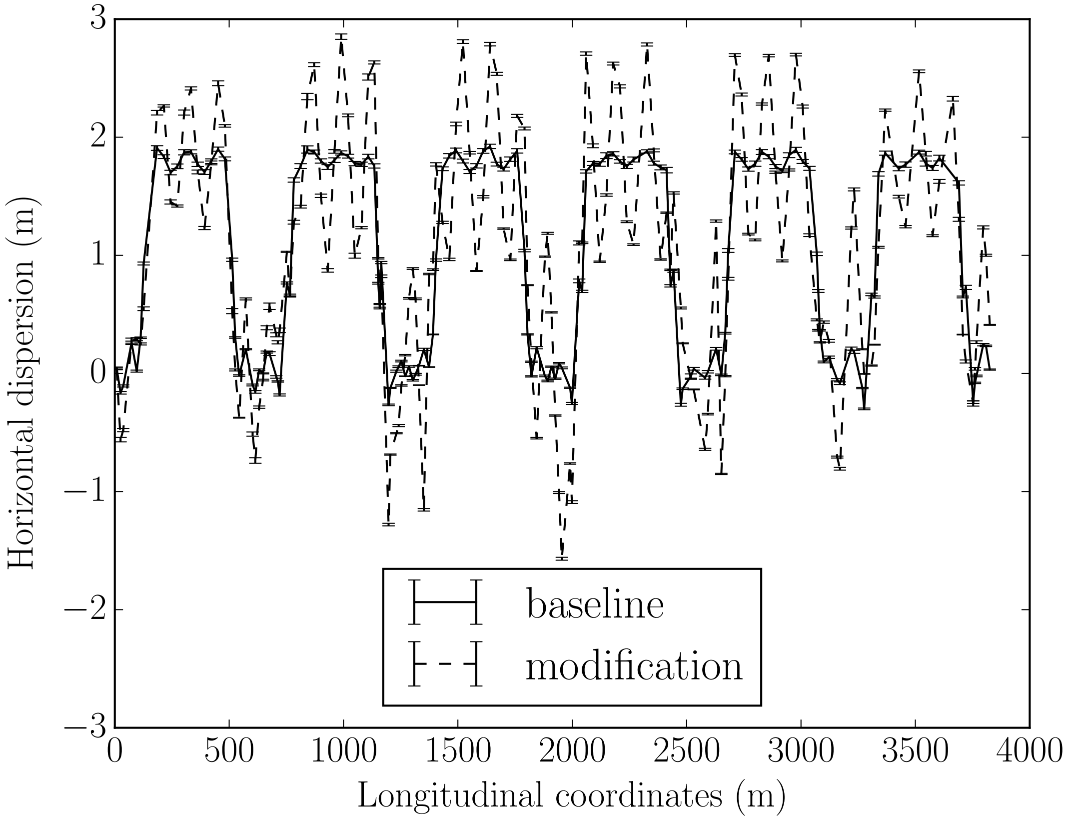

FIG. 6. The measured horizontal dispersion functions at the beam position monitors at injection energy before (the solid line) and after (the dashed line) the matching of the dispersion primes at the two snakes in the Blue ring.

and vertical targets for polarization measurement in each ring. The average transmission efficiency measured by the two targets in Blue ring was higher by 3% with the dispersion prime matched at the two snakes. However, the transmission efficiency in the Yellow ring was higher by 4% in the later time period than the earlier time period. There was no difference of beam emittance to which we can attribute the improvement of the transmission efficiency in either ring. The observation of spin polarization transmission efficiency with dispersion prime matched lattice is not conclusive.

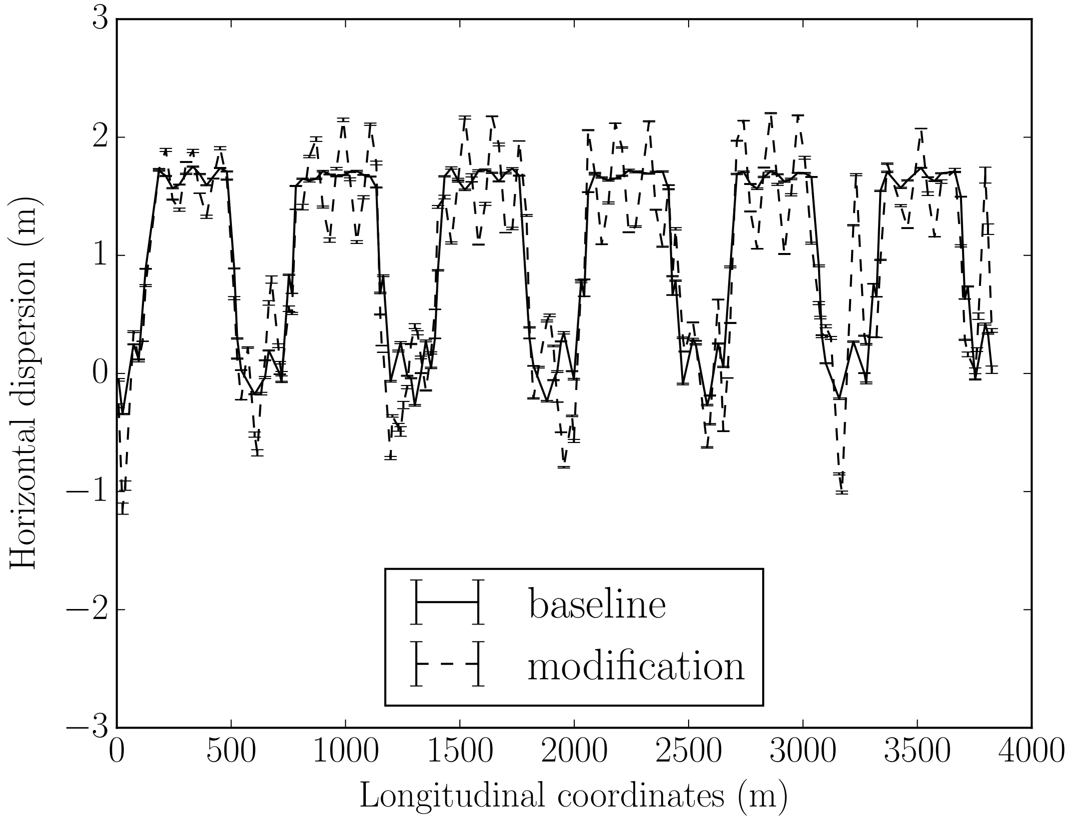

FIG. 7. The measured horizontal dispersion functions at the beam position monitors at top energy before (the solid line) and after (the dashed line) the matching of the dispersion primes at the two snakes in the Blue ring.

IV. SUMMARY

The minimization of the spin tune spread by matching the dispersion primes at the two snakes was demonstrated at RHIC. The effort was mainly motivated by the spin flipper study, and secondly by improving the spin polarization transmission efficiency during beam acceleration. The γ_T quadrupoles, which were designed for jumping γ_T at energy transition of heavy ion beams, were reorganized to match the dispersion prime at the two snakes. The scheme was implemented both at fixed energies and during beam acceleration. The spin flip efficiencies was improved both at injection and the top energy with much narrower spin tune spread. The spin polarization transmission efficiency was improved as well with the dispersion prime matched lattice during beam acceleration, however, it is not certain it was solely contribution from the effect of minimization of the spin tune spread.

The significance of the work reported in this article is in several aspects. It demonstrated that the spin tune spread must be reduced to be on the order of 10^{-3} to achieve satisfactory spin flip efficiency, and that this can be fulfilled by matching the dispersion primes experimentally. Secondly, the scheme of matching dispersion prime by reorganizing quadrupoles has minimal impact on beam optics and beam operations. The principle of reorganizing quadrupoles for dispersion matching purpose can be applied for other facilities. Last but not least, there is potential of improving spin polarization transmission efficiency by perfecting the dispersion prime matching lattice. The spin physics program at RHIC might benefit from this effort of minimizing the spin tune spread in the long run.

V. ACKNOWLEDGMENTS

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