REDUCING SPIN TUNE SPREAD BY MATCHING DX PRIME AT SNAKES IN RHIC*

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Abstract

At the Relativistic Heavy Ion Collider (RHIC) at BNL the physics program includes collisions between beams of polarized protons at high beam energies. Maintaining the proton's polarization is vital and preserved primarily by application of a pair of Siberian snakes [1]. Measurements from recent high-energy physics runs indicate polarization loss during acceleration between 100 and 250 GeV [2]. Based on analytic estimations for off-momentum particles and/or beams, a nonzero difference in DX prime - the dispersion function angle - between the snakes can result in a spread in the spin tune [3, 4], or equivalently, the conditions of snake resonances in close proximity to the beam during acceleration. Requiring that DX prime at the two Siberian snakes in RHIC be equal would reduce the spin tune shift for off-energy particles so helping to maintain polarization during the energy ramp. Preservation of half-integer spin tune is also important for future operation of the spin flipper [5] at store. In this report, the matching scheme and simulations using MAD-X will be presented together with a newly applied method based on response matrices to take power supply limitations into account in the minimization procedure.

INTRODUCTION

In order to match the DX primes at the two snakes, one needs to identify the effective knobs in the machine for controlling the horizontal dispersion.

Three types of magnets–dipole, quadrupole and skew quadrupole–have been considered as potential knobs for controlling dispersion. The coupling of the vertical dispersion to the horizontal plane by skew quadrupoles would be very ineffective because the vertical dispersions are zero by design. Dipole magnets can control the dispersion effectively but involves change of circumference and orbit. Controlling the dispersion by the quadrupole feed-down effect will certainly introduce beta-beat and tune change. Fortunately, moderate ($\sim 20\%$) beta-beat can either be tolerated or fixed by optics corrections. Tune changes can be compensated by tune controlling quadrupoles with minimal disturbance to the dispersion functions.

The change in the dispersion function is proportional to the change of quadrupole integrated strength K_j [6]

$$\triangle D_i = -G_x(s_i, s_j) K_j D_j$$

Here,

$$G_x(s_i, s_j) = \frac{\sqrt{\beta(s_i)\beta(s_j)}}{2\sin\pi\mu} \cos\left(\pi\mu - |\phi(s_i) - \phi(s_j)|\right) \quad (1)$$

Apparently, quadrupoles at higher dispersion location are more effective for controlling the dispersion functions.

The beta-beat introduced by altering quadrupole strength is

$$\frac{\triangle\beta}{\beta} = -\frac{\beta(s_j)K_j}{2\sin\pi\mu} \cos\left(2\pi\mu - 2|\phi(s_i) - \phi(s_j)|\right) \quad (2)$$

It is worth to note that there is a factor of 2 difference in the phase term of Eq. 1 and 2. One could select existing π-doublet quadrupoles such that introduced tune change is zero, beta-beat outside the π-doublet range is zero but the dispersion change over the ring is nonzero.

π-DOUBLET SOLUTION

This effort was initiated by E. Courant and D. Trbojevic. The quadrupoles being selected are marked in Fig. 1. The

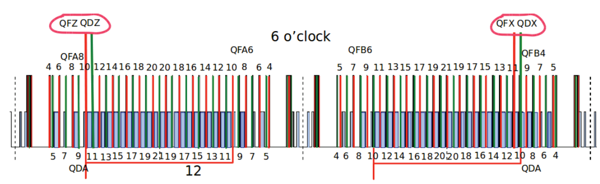

Figure 1: Beamline around IP6, quadrupole QFZ, QDZ, QFX and QDX are used for matching in π-doublet solution.

change of quadrupole strength comply with

$$\begin{cases} KFX = KF * (1.0 + DLTG) \\ KFZ = KF * (1.0 + DLTG) \\ KDX = KD * (1.0 - DLTG) \\ KDZ = KD * (1.0 - DLTG) \end{cases}$$

Here, DLTG is the relative change of the quadrupole strength.

The optics being used in the matching simulation is for Run-12 ramp at time 250 s. The DX prime difference at the two snakes was reduced from 0.05 to 1×10^{-6}, with a relative quadrupole strength change of 7.25%.

The quadrupoles in the simulation are not powered independently. New power supplies are required for implementing this scheme.

QF8+QF9 SOLUTION

In RHIC, quadrupoles in interaction region (IR) and the two ends of the arcs can be controlled individually. The

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dispersion functions are designed to be small in the IRs. Therefore, the QF8 and QF9 magnets with moderate dispersion functions are selected for matching DX prime. The total number of these magnets are 12 [7].

In addition to DX prime at the snakes, there are constraints on other parameters in the matching to minimize the disturbance to the other optical parameters. These parameters are the DX and beta stars at IP6 and IP8, two interaction points for experiments; the global tunes and beta-beat at one of the quadrupole of each arc. The DX prime difference was reduced from 0.05 to 2×10^{-5} by this scheme. The beta-beat is $\pm 30\%$ peak-to-peak in the horizontal plane, $\pm 8\%$ in the vertical plane. No dispersion peak was introduced along the ring.

The introduced beta-beat are shown in Figs. 2 and 3.

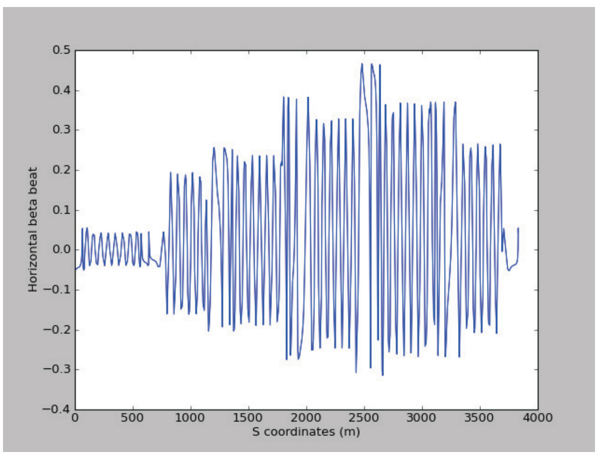

Figure 2: Introduced horizontal beta-beat in QF8+QF9 solution.

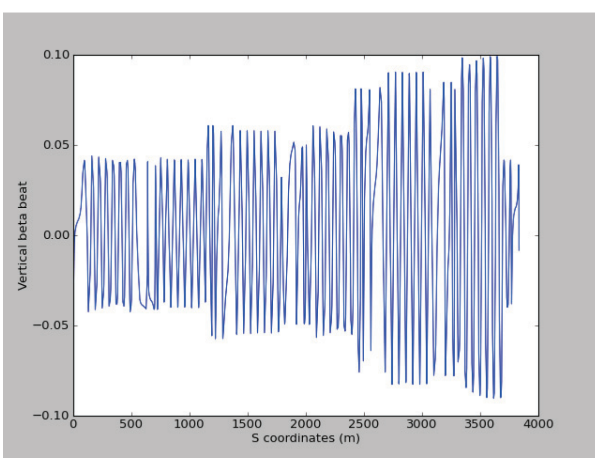

Figure 3: Introduced vertical beta-beat in QF8+QF9 solution.

The horizontal dispersion functions of the ring are shown in Fig. 4.

The initial and final strengths of all the 12 magnets and the relative changes are shown in Table 1.

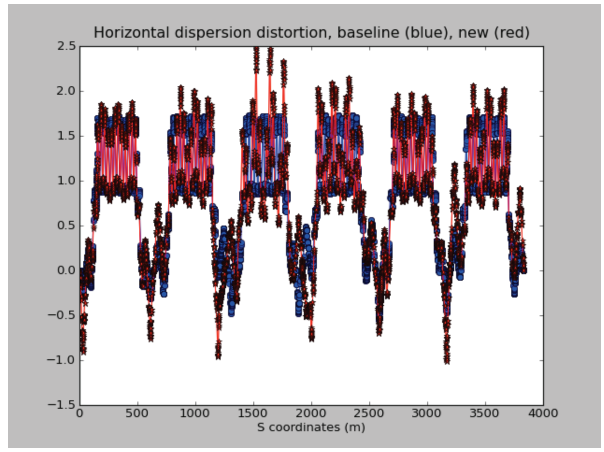

Figure 4: Baseline and new horizontal dispersion functions in QF8+QF9 solution.

Table 1: Initial and Final Strength of QF8 and QF9 Magnets

Magnets	Final	Initial	Relative (%)
qfa6	0.0797930	0.0851501	-6.29
qfa8	0.0875657	0.0851501	2.84
qfa10	0.0862944	0.0807370	6.88
qfa12	0.0826227	0.0807370	2.33
qfa2	0.0843956	0.0823113	2.53
qfa4	0.0823227	0.0807370	1.96
qfb6	0.0840926	0.0845783	-0.57
qfb8	0.0844324	0.0845783	-0.17
qfb10	0.0805808	0.0795547	1.28
qfb12	0.0734157	0.0795547	-7.71
qfb2	0.0839466	0.0812185	3.35
qfb4	0.0758067	0.0795547	-4.71

The allowed relative change of these magnets is -3–0%. There are 5 required magnet strengths exceeding the limits, 7 magnets that need opposite polarity. This scheme would also require certain amount of power supply work.

CONTROLLING REQUIRED STRENGTH CHANGE

In the simulation in the above section, we attempted to put the power supplys' limits in the matching as constraints in order to find a practical solution. No solution could be found by the MAD-X matching module.

A response matrix and SVD (single value decomposition) [8] technique was then employed to match DX prime while being able to control the changes of quadrupole strengths. In this scheme, we first need to check the linearity of the response of parameters of interest to variables (for our case, DPX and tunes to quadrupole strength). The calculation done using MAD-X confirmed the linearity of the response. At the same time, the response matrix for parameters of interest to variables was established and stored.

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Then the response matrix was inverted using the SVD algorithm and the required changes of quadrupole strength and the resulting parameters of interest were calculated. As a confirmation, parameters of interest were simulated by MAD-X as well by putting in the changes of strength calculated in the previous step.

With a regular SVD, 2 of the final quadrupole strengths exceeded their limits. Cutting eigenvalues and Tikhonov regulation [9] have been applied to limit the required quadrupole strengths which would end with less optimal matching result. In addition, one other trick is to set the two magnets to be at the maximum strengths allowed. The last one resulted in the best overall performance. DX prime difference of the two snakes was reduced by a factor of 3 with all magnets within limits.

The corresponding beta-beat are shown in Figs. 5 and 6.

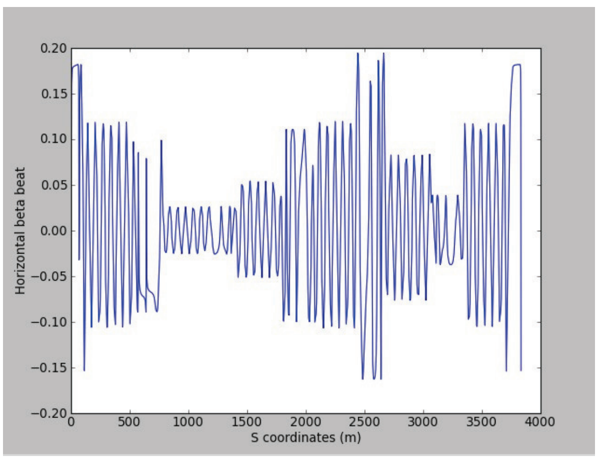

Figure 5: Introduced horizontal beta-beat with controlling required strength change.

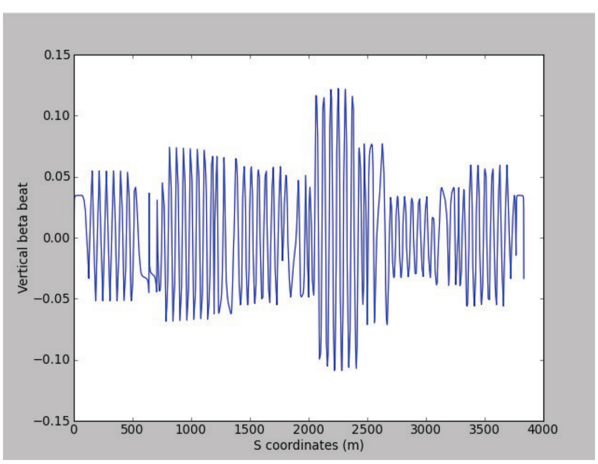

Figure 6: Introduced vertical beta-beat with controlling required strength change.

The horizontal dispersion is shown in Fig. 7.

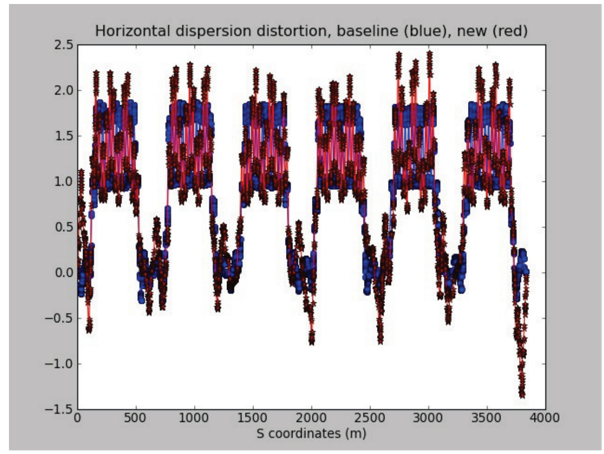

Figure 7: Baseline and new horizontal dispersion functions with controlling required strength change.

SUMMARY

To match DX prime at the two snakes for minimal spin tune spread, the QF8 and QF9 magnets are chosen because of their high dispersion functions. Matching with MAD-X produced good results in terms of DX prime matching, global beta-beat and dispersion. However, the results are not practical because of power supplys' limits. The employment of response matrix and SVD technique is able to keep all magnets within their limits and reduce the DX prime difference by a factor of 3.

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