BETA* AND BETA-WAIST MEASUREMENT AND CONTROL AT RHIC

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Abstract

During the course of last RHIC runs the beta-functions at the collision points (β*) have been reduced gradually to 0.7m. In order to maximize the collision luminosity and ensure the agreement of the actual machine optics with the design one, more precise measurements and control of β* value and β-waist location became necessary. The paper presents the results of the implementation of the technique applied in last two RHIC runs. The technique is based on well-known relation between the tune shift and the beta function and involves precise betatron tune measurements using BBQ system as well as specially developed knobs for β-waist location control.

INTRODUCTION

One of the year-to-year improvements, which have provided the substantial increase of the RHIC luminosity, was the reduction of β* at two collision points (IP6 and IP8). Over years the β* in those interaction points has been reduced from 3m to 0.7m. Further plans consider the attempt of the reduction to 0.5m in near future. As β* is reduced the need for its accurate measurement becomes more and more important. The measurement should confirm that the actual optics of the accelerator agrees with the design one and, thus, the machine luminosity is close to what is intended by the design. Besides that at smaller β* values, the control of the longitudinal position of β*, or β-waist, has to be tightened to avoid the reduction of the luminosity.

MEASUREMENT TECHNIQUES

In previous RHIC runs several methods have been developed for the verification of the linear lattice of the machine [1,2]. In Run-8, we have decided to develop an additional method, aimed only at the measurement of the β* and β-waist at the interaction points, in the hope to get more reliable values of those parameters. The method uses the well-known formula for the change of the betatron tune due to a small change of quadrupole gradient:

$$\Delta Q = \frac{\langle\beta\rangle\Delta(Kl)}{4\pi} \tag{1}$$

where *Δ(Kl)* is the change of integrated normalized quad gradient and $<\beta>$ is the beta-function value averaged over the length of a given quadrupole.

* Work supported by Brookhaven Science Associates, LLC under Contract No. DE-AC02-98CH10886 with the U.S. Department of Energy.

To get the information on the value of beta-function at an interaction point, the gradient of a quadrupole, closest to the interaction point, should be changed. In RHIC this is Q1 quadrupole, a part of IR focusing triplet. The distance L from the collision point to the entrance of the Q1 quadrupole is 25.4m. There is Q1 quadrupole on each side of a given interaction point, but the gradients of those quadrupoles are of opposite signs. The linear optics functions ($\beta_0,\alpha_0,\gamma_0$) at the entrance of the Q1 quadrupole are related with the functions at the location (s*) of β-waist by simple relations of transformation through a drift:

$$\beta_0 = \beta^* + \frac{(L-s^*)^2}{\beta^*};\quad \alpha_0 = -\frac{L-s^*}{\beta^*};\quad \gamma_0 = \frac{1}{\beta^*} \tag{2}$$

where the index 0 refers to the entrance of Q1 and the star symbol denotes the values taken at s*.

The average value of β-function at the Q1 can be related with the optical functions at the quad entrance, using the elements (m_{ij}) of the quadrupole transformation matrix:

$$\langle\beta\rangle = \langle m_{11}^2\rangle\beta_0 - 2\langle m_{11}m_{12}\rangle\alpha_0 + \langle m_{12}^2\rangle\gamma_0 \tag{3}$$

The matrix elements m_{ij} are taken from the thick-lens transformation matrix of the Q1 quadrupole.
On the next step, substituting the relations (2) into the equation (3), one gets the expression, which relates the average β-function in the Q1 with β* and s* . With two Q1 quadrupoles, on each side of the IP, we have then the system of two equations, which should be resolved to extract β* and β-waist values. Although those two equations are non-linear in β* and s*, some simplifications can be made. The terms, presented in these equations, have the following hierarchy of the order of magnitude:

$$\frac{L^2}{\beta^{*2}};\quad \frac{L}{\beta^*};\quad 1 \tag{4}$$

Since L=25.4m and expected β* is less than 1m, the terms of the order of 1 can be neglected without noticeable loss of the accuracy. After that the system of the equations becomes linear in β* and s* and can be easily resolved, leading to the following expressions:

$$s^* = -\frac{L(\beta_+a_- - \beta_-a_+) + 2(\beta_+b_- - \beta_-b_+)}{2(\beta_+a_- + \beta_-a_+)}$$
$$\beta^* = \frac{1}{\beta_+}\left(a_+L^2 + 2b_+L - 2a_+L\,s^*\right) \tag{5}$$

where β_+ and β_- are the average β-function taken at left and right Q1 quadrupoles, and *a* and *b* are used to denote the values coming from the averaging of the matrix elements of left and right Q1 quadrupoles:

$$a_{\pm} = \langle m_{11}^2 \rangle_{\pm}; \quad b_{\pm} = \langle m_{11} m_{12} \rangle_{\pm} \tag{6}$$

There two techniques, based on the same set of formulas (1),(3),(5), that have been tried. In one technique, the β_+ and β_- are directly found by making the tune measurements due to independent gradient variations of left and right Q1s and using the formula (1). Thus, for instance:

$$\beta_+ = \frac{4\pi \Delta Q}{\Delta(Kl)_+} \tag{7}$$

After the β_+ and β_- are extracted the values of β* and s* can be calculated, using the formulas (5).

In another technique, the gradients of both Q1 quadrupoles are changed simultaneously. If one looks at the difference and the sum of the averaged β-functions in Q1 quads, the following expressions can be found (on the basis of formulas ((2)-(3) or (5))):

$$\begin{aligned} \beta_+ - \beta_- &= \frac{1}{\beta^*}\left((a_+ - a_-)L^2 + 2(b_+ - b_-)L - 2(a_+ + a_-)L\, s^*\right) \\ \beta_+ + \beta_- &= \frac{L}{\beta^*}\left((a_+ + a_-)L + 2(b_+ + b_-)\right) \end{aligned} \tag{8}$$

Using the formulas (8) and (1), with calculated *a* and *b* parameters, one gets following dependences of the tune shifts on β* and s* for the RHIC case :

$$\begin{aligned} \Delta Q &= \left(4.32 - 8.08\, s^*\right)\frac{\Delta(Kl)}{\beta^*}; \qquad \Delta(Kl)_+ = -\Delta(Kl)_- = \Delta(Kl) \\ \Delta Q &= \frac{108.2\,\Delta(Kl)}{\beta^*}; \qquad \Delta(Kl)_+ = \Delta(Kl)_- = \Delta(Kl) \end{aligned} \tag{9}$$

Here, the first line describes the tune shift when the gradient in left and right Q1s are changed with the opposite sign, while the second line corresponds to the same sign of the gradient adjustment. On the basis of these two expressions both β* and s* values can be obtained.

The values (*a*,*b*) of the averaged products of the matrix elements are calculated assuming the design gradient and length of the Q1 quadrupole. The fact that some design, but not measured, values have to be used in calculations limits the accuracy of both techniques.

Let's note that in the case of a symmetric optics, when the parameters a_+ and a_- , as well as b_+ and b_- would be equal, the difference of β_+ and β_- the expression (8) would be then proportional to s*. In this case, the tune shift due to the gradient change of opposite sign will be also proportional to s*. Unfortunately, this is not the case for the present measurement scheme, since left and right Q1s have opposite gradient. But, as described later in this paper ("Future plans"), the scheme can be modified in the future to allow for simpler measurement of s* in the symmetric scheme.

MEASUREMENT RESULTS

For the betatron tune measurements, the BBQ tune measurement system has been used. It provides very good tune resolution at the level of 10^{-4}. In order to eliminate possible effects of the betatron coupling on the measured tune shifts, the RHIC rings were decoupled to $\Delta Q_{min}\sim 10^{-3}$ and the betatron tune separation was increased above 0.01.

An example of the tune measurements done by the BBQ system during the Q1 gradient changes is shown in Figure 1. Tune shifts exceeded 0.005 for a gradient change of an individual Q1 by 10^{-4} m^{-1}. In the case of simultaneous changes of the gradients of two Q1s with opposite signs the tune shift was at the level of 0.001 for $\Delta Kl_+ = -\Delta Kl_- = 10^{-4}$ m^{-1}. The integrated normalized gradient of Q1 quad is about 0.08 m^{-1}.

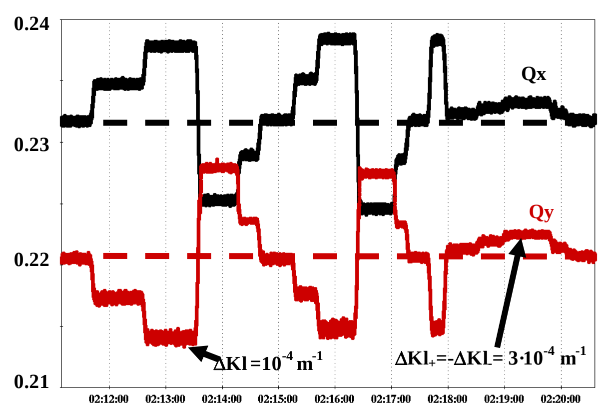

Figure 1: BBQ betatron tune data during the variation of the Q1 gradients. The dashed lines show the measured tunes at Δ(Kl) = 0.

The maximum value of the gradient variation was limited by the shift of s*, caused by this variation. For instance, for $\Delta Kl = 2\cdot 10^{-4}$ m^{-1} the calculated shift of s* is about 8cm. Therefore, to keep the s* measurement error as low as few cm, the variation of the gradient should not exceed 10^{-4} m^{-1}. That gave a preference to the technique which uses individual gradient changes, since lesser gradient variation can be used during the betatron tune measurements.

Table 1 summarizes the results of first round of the measurements in both RHIC rings (Blue and Yellow rings), in both interaction regions (IR6 and IR8) with small β* and both transverse planes. The data were obtained using the technique with the individual gradient changes. According to the design optics one should have β* in [0.7-0.75]m range in both interaction points. In Yellow, the measurements showed large deviations of the measured β* from the design values. In addition, β-waist positions (s*) were found shifted by noticeable amounts. The measurement precision, based on the 10^{-4} accuracy of the BBQ tune measurements, was evaluated to be at the level of +- 6cm for s* and 1.5% for β* values. However, as mentioned before, larger errors possibly come from the imperfection of the design optics (Q1 transport matrix).

Table 1: The results of the measurements of β* and s*, by the technique using individual gradient changes.

	Yellow				Blue			
	IR6 H	IR6 V	IR8 H	IR8 V	IR6 H	IR6 V	IR8 H	IR8 V
b*,m	0.80	0.88	0.85	0.89	0.81	0.73	0.71	0.75
s*,cm	-34	-33	2	30	-5	-3	20	5

MEASUREMENTS WITH BETA-WAIST KNOBS

Since the β-waist location for Yellow ring was found considerably shifted, next step, tested during RHIC Run-8, was an attempt to realize a correction of that location. Specific knobs have been developed, which adjust the gradients of the interaction region and matching section quadrupoles in such way that β-waist shift is produced, while β* changes are minimized and the β-wave distortion does not propagate outside of a given interaction region. Those knobs were tested during another series of the measurements done in two weeks after the first one. This β-waist correction was attempted only in the Yellow ring of RHIC. The results are summarized in Table 2. The knobbing worked mostly as expected, except the horizontal plane in the IR6 region. The quality of the knobs, calculated on the basis of the design optics, was limited by the deviation of the real machine optics from the design. Several iterations of the knobbing correction may be required in such situation.

FUTURE PLANS

The measurements have demonstrated the feasibility and efficiency of tested techniques. But the operational usability of the measurement method and the accuracy of the measurements can be improved with small modifications. The modifications include the installation of additional small quadrupole magnets, close to the Q1 magnets. Those small warm magnets can be used as dedicated hardware for the β* and s* measurements. The gradient of the small magnets will be varied during the measurements (instead of Q1 gradient). In this case, due to the symmetry, we will have: $a_+=a_-$, $b_+=b_-$, providing the simplifications of the formulas (5) and (8). In addition the matrix elements, m_{ij}, in this case, come from the matrix of the drift, instead of the quadrupole, and will be known with greater precision. Also, one will have more precise knowledge of the magnet transfer function, and, therefore, better accuracy of the gradient variations during the measurements.

As already was noted earlier in the paper, this symmetric system can simplify significantly the measurement and control of s*. When changing the gradients of two magnets with opposite signs, but by the same absolute value, the betatron tune shift will be proportional to s*.

Table 2: The measurement of β* and s* in Yellow ring done before and after the applications of β-waist knobs

	IR6 H	IR6 V	IR8 H	IR8 V
β*,m before knobbing	0.80	0.91	0.90	0.94
β*,m after knobbing	0.76	0.96	0.86	0.88
s* ,cm before knobbing	-29	-53	-8	15
s*,cm after knobbing	13	-29	-9	-5
expected Δs*, cm	24	27	0	-28
measured Δs*,cm	42	24	-1	-20

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