ADJUSTING THE IP β FUNCTIONS IN RHIC

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Abstract

The β-functions at the IP can be adjusted without perturbation of other optics functions via several approaches. In this paper we describe a scheme based on a vector knob, which assigns fixed values to the different tuning quadrupoles and scales them by a common multiplier. The values for the knob vector were calculated for a lattice without any errors using MADX. Previous studies for the LHC [1] have shown that this approach can meet the design goals. A specific feature of the RHIC lattice is the nested power supply system. To cope with the resulting problems a detailed response matrix analysis has been carried out and different sets of knobs were calculated and compared. The knobs were tested at RHIC during the 2004 run and preliminary results are discussed. Simultaneously a new approach to measure the beam sizes of both colliding beams at the IP, based on the tunability provided by the knobs, was developed and tested.

INTRODUCTION

To adjust the β-function at the IP several approaches have been discussed theoretically and simulated for the LHC. As the LHC is under construction and the functionality of the knobs is essential, the work was repeated for RHIC, since it is an excellent testbed for verification. The specific difference of the RHIC to the LHC lattice, which had to be investigated before, is the nested power supply system. This reduced the number of adaptable tuning quadrupoles. Also several quadrupoles which serve as tuning quads are coupled to each other. The lattice which was used for the study was converted from line to sequence format in MADX to rotate the starting point from STAR to IP4. The knobs were calculated for PHENIX, which will be referred to as IP8. In addition the optics constraints were monitored in STAR, which will be referred to as IP6.

CALCULATING AND ANALYZING THE RESPONSE MATRIX.

As mentioned above, the nested power supply system makes the behavior of the coupled tuning quads not easily predictable. For this reason and because of the strongly nonlinear behavior (see Fig.1) of the first knobs calculated by MAD matching the response matrix for all in principle usable quadrupoles was computed with MADX. The nominal strength (for 1m $\beta^{\star}$ at IP6 and IP8) of the different quadrupoles or combinations was varied over ranges of $\pm 5\%$ to $\pm 95\%$ (the maximum range for each quadrupole or combination was chosen so as to correspond to the full region of stability of the matched solution) of the

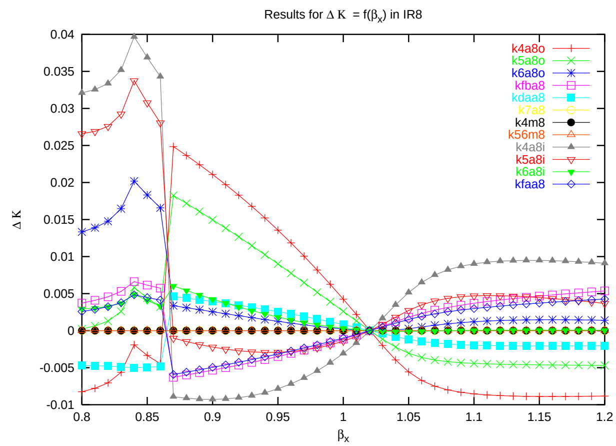

Figure 1: Non linear behavior when matching different values for $\beta_x^{\star}$. The behavior of the quadrupole change ΔK is strongly nonlinear in the range between 0.87 and 1.2 meter. In addition at 0.87 m there is a sudden change of the solution. At this point the function behaves discontinuous. This and the nonlinearity render the solution not applicable in practice.

nominal strength with 40 intermediate steps. The parameters α, β, D and Q for both planes where recorded. These were then plotted as a function of the change of the quadrupole strength. The investigation of $\beta = f(\Delta K)$ shows, that there is a strong difference in the behavior between quadrupoles. Three different cases can be identified: First the β-function is only enlarged, independent of the sign of the applied change, second the change of the β-function depends on the sign of the applied change, but $\beta = f(\Delta K)$ is strongly nonlinear and third the β-function changes over a wide range almost linearly.

In addition the other parameters α, β, D and Q are categorized in the same way, but only as additional information and not as a criterion for selection. Only the third category is adaptable without any additional consideration. The variables for the control of the strengths of the quadrupoles are classified according to this scheme. The number of usable quadrupoles or groups of quadrupoles lies between six and ten on both sides. All ten were used for the construction of one set of knobs, nine for a second set.

CALCULATING KNOBS BY LINEARLY FITTING MAD MATCHING RESULTS.

According to the response matrix analysis, the number of maximum usable quadrupoles, ten in total, is smaller than the maximum number of constraints. These are α, β and dispersion functions, in IP6 and IP8, tune, tune slope and chromaticity (16 in total). Depending on the specific lattice some of these are either not constrainable or do not change or cannot be constrained in certain combinations. First simulations showed, that dispersion could not be controlled with this approach. However, the changes in dispersion do not increase the IP spot size significantly. Several combinations of different quadrupoles and constraints were simulated and the best two results are described below.

For one version (knob version 10) quadrupoles or combinations of them, which are controlled by the following K values, were chosen: K4A8O, K5A8O, K6A8O, KFBA8, K4A8I, K5A8I, K6A8I, KFAA8, KDAA8 and K7A8. The basis for the selection was the response matrix analysis according to the results of the previous section. As constraints for version 10 the α and β-functions at IP8 and IP6 as well as the tune Q were used in MADX to match over the range of $\pm 10\%$ of the nominal $\beta^{\star}$ value. By fitting the slopes for each quadrupole the knob vector was constructed. To characterize the behavior of the knobs, both x and y knobs are applied simultaneously and scanned over the operative range, which is for both planes $\pm 20\%$. The values of the constraints on the four outermost points of the knobs range are computed for IP8 and IP6. The results are all within the given boundaries for the constraints.

For the second version (knob version 11) quadrupoles or quadrupole combinations which are controlled by the following K values were chosen: K4A8O, K5A8O, K6A8O, KFBA8, K4A8I, K5A8I, K6A8I, KFAA8, and KDAA8 (one less than in version 10). As constraints the α_x and β-functions at IP8 and α and β-functions at IP6 as well as the tune Q were used. α_y was not constrained because simulations showed this to be best choice. One constraint of version 10 had to be dropped because one quadrupole less was included. Also here a range of $\pm 10\%$ was used to calculate the knob values.

Both knob sets (Version 10 and 11) fulfill the required condition for the constraints. Compared to version 10 version 11 has the better performance for the dispersion but the confinement of the β-function change to IR8 is slightly degraded. Also the tune change is increased. The choice for either of these knob sets for operation depends on the demands on the constraints.

CALCULATING KNOBS USING THE RESPONSE MATRIX.

Tuning knobs can be obtained deterministically determined by analytically inverting the response matrix. For this purpose specific conditions have to be fulfilled. In the case of the RHIC lattice in the region of IR8 and IR6 the response matrix is well conditioned and the number of constraints was chosen to be equal to the number of tuning quadrupoles whereby a square response matrix is generated. The values of the response matrix are only spread over a range of three orders of magnitude with the exception of one element which deviates by five orders. By inverting the matrix and solving the linear system one obtains a well behaved solution for the knobs. The solution of this calculation for the knobs does not significantly differ from the one obtained by MAD matching. This also holds for the behavior of the constraints when changing the knobs by $\pm$20% in both planes.

Using SVD [2] to invert the matrix gives the same result within machine precision compared to direct inversion. In this case the primary goal of SVD is not to invert but to characterize the condition of the response matrix. For the RHIC case the singular values of the diagonal matrix vary only by one and a half orders of magnitude. Two different cases were studied in which the smallest two (case I) and the smallest four (case II) values of the diagonal or singular matrix were set to zero in the inversion. Again the results do not differ much from the one obtained by MAD matching or from the one obtained by full inversion. The SVD conditioning brought no improvement of the behavior.

In case of nonlinear response of the constraints to the quadrupole increments ΔK, solving the linear system to construct the knobs creates an error which depends on the size of the change and on the response behavior. A method [3][4] to minimize the error is to compromise between the permitted quadrupole increments ΔK and the target values for the constraints. The relation of the maximum changes of different tuning quads to each other can be determined by analyzing the plots which where used to calculate the response matrix. By using the method of the maximum likelihood [5] one derives the penalty function and calculates the optimized solution for a chosen set of weights for the constraints (allowed deviation from target values) and limits on the changes of quadrupole strength (minimizing the change with respect to different linear ranges calculated by response matrix analysis). The χ^2 function for this general approach is

$$\chi^2 = \chi^2_{min} + (\alpha - \tilde{\alpha})^T \, \mathbf{V}^{-1} \, (\alpha - \tilde{\alpha})$$

where χ^2 is the minimum, χ^2_{min} the residual minimum, $\tilde{\alpha}$ the set of calculated parameters (constraints or quadrupole changes ΔK) and $\mathbf{V}$ the weight matrix. $\mathbf{V}$ is a diagonal matrix whose diagonal elements contain weight variables. Integrating the set of constraints with their allowed ranges as weight and the ΔK with their ranges determined by linearity as weight in the penalty function where the constraints and the ΔK are related by the linear response matrix creates a new penalty function with which both quadrupole increments and changes of the constraints can be minimized according to their weights. Taking the derivative and setting it to zero yields the condition for this minimization. The application of this adapted Moore Penrose method for multidimensional optimization to the RHIC lattice brought no noticeable improvement as the nonlinear behavior for the selected set of quadrupoles is not very strong in the range of the applied changes.

RESULTS FROM BEAM EXPERIMENTS

These beam experiments had the goal to prove the validity of the developed knob theory, the range of application and search of possible error sources for malfunctioning of the knobs. The RHIC on-line model [6] gives a much better operational description of the real lattice vs. the design MAD model, the knobs were recalculated using this model. The resulting knobs are similar to the ones described above.

The beam experiments were performed in two major stages. The first was to test the stability of the beam when applying the tuning knobs. For this stage there were only four bunches with low energy injected, accelerated and squeezed. This was to prevent damage to the installation in case of knob induced beam loss. At this stage the knobs were applied and the stability observed. When passing this stage a new batch of bunches (nominal number and intensity) was injected and the procedure above repeated.

In a first attempt the β functions for both beams and planes were squeezed in IP8 by $\approx 12\%$ of its nominal value ($\beta^{\star}_{x,y} \approx 1\text{m}$). The effect on the counting rates in IP8 (blue curve) and IP6 (red curve) is shown in Fig.2. A clear increase in the counting rates in IP8 was observed. No problems concerning beam stability were recorded. The beam loss measurement showed a slight increase in the beam stability. The background in IP8 increased more strongly than in IP6, but it was acceptable for both.

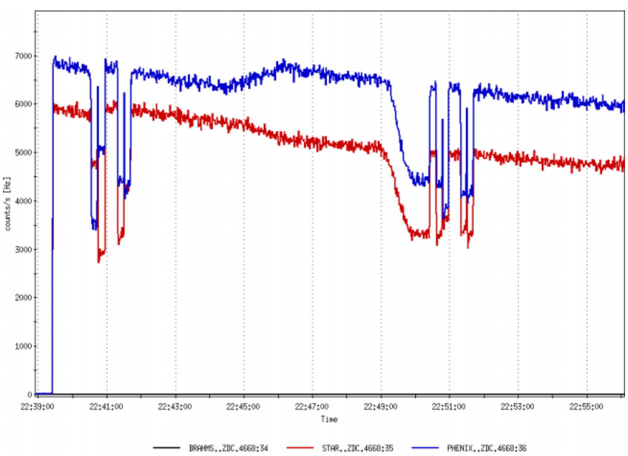

Figure 2: Counting rates during the offset optimization with LISA and when applying the tuning knob by decreasing the horizontal and vertical β-function at the IP for both beams in IP8. The blue graph shows the counting rate in IP8 and the red in IP6.

In addition the dispersion was measured before and after the application of the tuning knobs. The dispersion beat created by the β squeeze was calculated and compared to the one predicted by the on-line model. This is shown in Fig.3. The two curves show an extraordinary agreement around the whole ring in the phase. The amplitudes differ slightly which is caused by the measurement uncertainty. Points of great disagreement are caused by bad BPM readings.

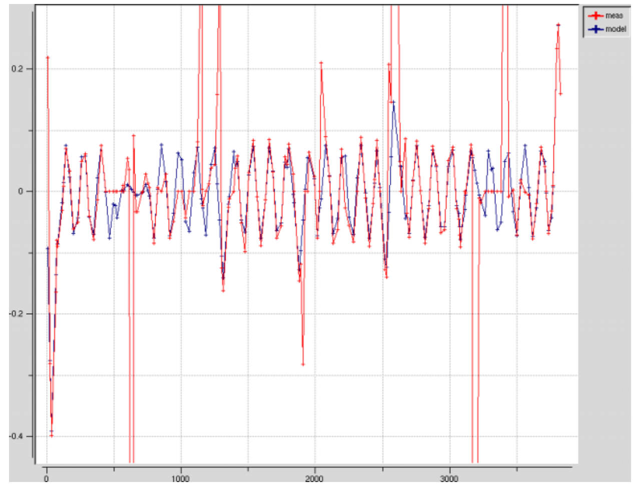

Figure 3: Comparison of the dispersion wave introduced by the tuning knob as predicted by the on-line model (blue curve) and measured (red curve).

In the second attempt both IP6 and IP8 were squeezed simultaneously. For this, a new knob set had to be calculated. Simulations had indicated that this approach would be more successful than squeezing the IPs with separate two knob sets. Also here the β-functions for both beams and planes were reduced by $\approx 12\%$ of their nominal value. Counting rates in both IPs increased approximately by the same factor. However, a steering correction had to be performed in IP6.

SUMMARY AND CONCLUSIONS

Various sets of tuning knobs for IP8 have been calculated with different methods. The results are similar due to the well conditioned system after the response matrix analysis was performed and the tuning quadrupoles were chosen accordingly. For the beam experiments a new set of knobs was calculated using the response matrix extracted from the on-line model. This set was successfully used to squeeze the IP β-functions in IP8 and IP6 by $\approx 12\%$ of its nominal value with negligible effects on dispersion and other constraints.

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