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correction at RHIC***

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COMMISSIONING OF A BETA* KNOB FOR DYNAMIC IR CORRECTION AT RHIC*

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Abstract

In addition to the recent optics correction technique demonstrated at CERN and applied at RHIC, it is important to have a separate tool to control the value of the beta functions at the collision point (β^*). This becomes even more relevant when trying to reach high level of integrated luminosity while dealing with emittance blow-up over the length of a store, or taking advantage of compensation processes like stochastic cooling. Algorithms have been developed to allow modifying independently the beta function in each plane for each beam without significant increase in beam losses. The following reviews the principle of such algorithms and their experimental implementation as a dynamic β -squeeze procedure.

INTRODUCTION

In high energy physics, the main performance parameters of a collider are the energy of the circulating beams E and the luminosity \mathcal{L} , which corresponds to the amount of events R per second per unit of area ($\text{cm}^{-2} \text{s}^{-1}$). For a given physics process of cross section σ_{event} [1]:

$$\frac{dR}{dt} = \mathcal{L} \cdot \sigma_{\text{event}}. \quad (1)$$

For equal Gaussian beams colliding head-on [1]:

$$\mathcal{L} = \frac{N_1 N_2 f N_b}{4\pi \sigma_x^* \sigma_y^*}, \quad (2)$$

where $\sigma_{x,y}^*$ and σ_s^* are respectively the transverse and longitudinal beam sizes at the interaction point (IP), $N_{1,2}$ is the number of particles per bunch for each beam, f the revolution frequency and N_b the number of colliding bunches. The cross section σ_{event} for rare events is usually very small, which means a larger luminosity \mathcal{L} is required to detect such events. This can be achieved with smaller beam sizes:

$$\sigma_x^* = \sigma_y^* = \sqrt{\beta_x^* \cdot \epsilon_x} = \sqrt{\beta_y^* \cdot \epsilon_y} = \sqrt{\beta^* \cdot \epsilon}, \quad (3)$$

where $\beta_{x,y}^*$ are the betatron functions at the IP and $\epsilon_{x,y}$ the emittances in each plane. For unequal beams, Equation 2 becomes:

$$\mathcal{L} = \frac{N_1 N_2 f N_b}{2\pi \sqrt{(\sigma_{x1}^*)^2 + (\sigma_{x2}^*)^2} \sqrt{(\sigma_{y1}^*)^2 + (\sigma_{y2}^*)^2}}. \quad (4)$$

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Equation 4 shows that reaching higher luminosity can be achieved by reducing either β^* or ϵ for each beam. Table 1 lists the β^* and ϵ values achieved during the last three RHIC high energy heavy ions and the luminosity delivered to the STAR (IR6) and PHENIX (IR8) experiments. One can notice an increase in peak luminosity by roughly 75% from Run7 to Run11. This can be attributed to a larger circulating beam intensity and a smaller beam size (squeezed optics and smaller beam emittance), as well as significant improvements in the RHIC feedback systems along the energy ramp. For Run10, a stochastic cooling system was implemented and commissioned: it allowed limiting the emittance blow-up in Run10 and reducing the transverse emittance by more than 30% over the length of a store in Run11. Figure 1 shows the evolution of the transverse emittances for the Blue and Yellow beams during one of the 100 GeV Au⁷⁹⁺ ions stores of Run11.

Table 1: Overview of performance parameters for the three most recent 100 GeV RHIC Au⁷⁹⁺ runs. Run11 data is preliminary.

Run	Run7	Run10	Run11
Intensity [10^9]	113.3	122.1	144.3
β^* (IR6/8) [m]	0.83/0.77	0.75/0.75	0.70/0.70
ϵ [μm]	17 \rightarrow 35	17 \rightarrow 20	15 \rightarrow 10
$\mathcal{L}_{\text{peak}}$ [$\text{cm}^{-2} \text{s}^{-1}$]	30.0×10^{26}	45.3×10^{26}	52.6×10^{26}

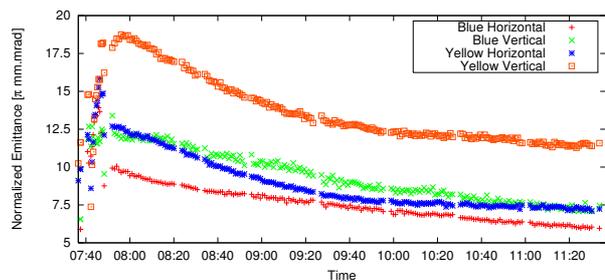


Figure 1: Transverse emittances for the Blue and Yellow beam during Fill #16027 of Run11 for 100 GeV Au⁷⁹⁺ ions.

The progress shown on the control and reliability of the RHIC stochastic cooling system allows developing a new procedure that would dynamically reduce β^* as the emittance is reduced, taking advantage of the increase of available aperture in the triplet quadrupoles. Based on the data shown in Figure 1, it is clear that squeezing β^* can only be done in the later part of a store: the transverse emittances first have to be significantly reduced to not risk los-

ing the beam in the machine aperture due to increasing β functions in the triplets while the current is ramping in the quadrupoles selected for the squeezing scheme.

β -SQUEEZE ALGORITHMS

The RHIC Control System includes a pair of calculation servers, RampManager and OptiCalc, that make the online numerical model of RHIC and service the various requests sent to that model, such as optics calculations and changes to the magnets strengths. OptiCalc already contains an algorithm to modify the value of β^* at any IP of the machine, which can be used to test the hardware limitations of the machine (limit in magnet currents relative to the requested β^* change) and the beam response to the modified optics.

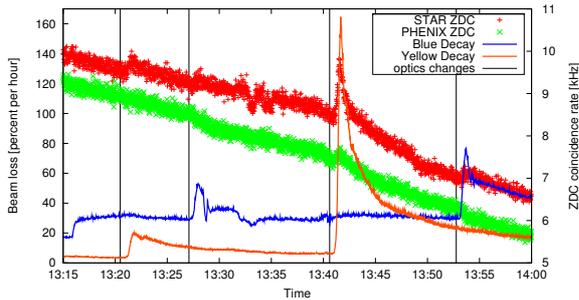


Figure 2: Changes in STAR and PHENIX ZDC collision rates and Blue and Yellow beam decay during a β^* -squeeze experiment with OptiCalc at the end of a Au+Au physics store during RHIC Run11. A vertical line marks the time when new optics are sent.

The tune, coupling and orbit feedback systems are used in an attempt to minimize beam losses while the new magnet settings are sent to the machine. Beam conditions are those of the end of a regular Au+Au physics store of RHIC Run11 with the Au11v1 100 GeV energy ramp along with operational stochastic cooling in all planes for both Blue and Yellow rings [2]. The OptiCalc β -squeeze algorithm is used to reduce the initial β^* of 0.70 m down to 0.60 m in the STAR experimental insertion (IR6) using 5 cm steps. This method only allows to squeeze one ring at a time, but the RHIC feedback systems still have to be engaged for both beams since they are in collisions during the optics change. Figure 2 shows the evolution of the collision rates at the STAR and PHENIX experiments and the variations in beam decay for each β -squeeze step during that first test. The requested changes for β^* in IR6 are $\beta^* = 0.65$ m in Yellow ($t = 13:20:29$) then Blue ($t = 13:27:05$); later, $\beta^* = 0.60$ m in Yellow ($t = 13:40:36$) then Blue ($t = 13:52:46$).

One can clearly notice the rise of the beam decay signals with every optics change. Despite the use of the RHIC feedback systems, setting the STAR β^* to 0.60 m in Yellow makes beam losses rise to a peak rate of 165% per hour, a factor 30 increase from the stable conditions before the optics change. Figure 3 shows the background rates in STAR for each beam. The sharp peak around the 13:40 mark corresponds to the rise in ZDC rates observed for the same

time in Figure 2, meaning that most of the measured increase in collision rate is in fact induced by background events. The RHIC collimators were then adjusted to new positions to minimize the impact of background to the ZDC rates: this is shown in Figure 3 around 13:48 with the drop in both Blue and Yellow background signals. This new setup allowed measuring the sole effect of a β^* -squeeze on the collision rates. When the final optics change is sent to the machine, Figure 2 and 3 clearly show a jump in the STAR ZDC signal without any significant change to the STAR background rates (when compared to the three previous optics changes).

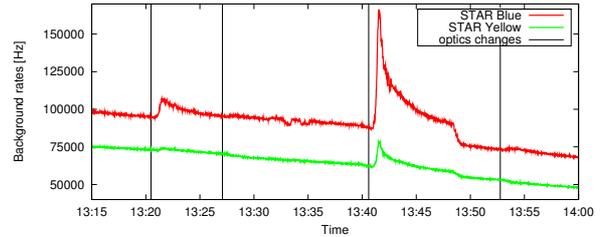


Figure 3: Changes in STAR background rates for the Blue and Yellow beams during a β^* -squeeze experiment at the end of a Au+Au physics store during RHIC Run11. Each squeezing attempt is marked by a vertical line at the time the new optics were sent.

As seen in Figure 2, there is a significant level of losses experienced even when controlling the tune, coupling and orbit in both rings. The issue is two-fold: if the measured tune spectrum is too wide, the tune and coupling feedback systems might not be able to lock on the correct tunes; also, changes in chromaticity are not being compensated for in the OptiCalc algorithm, causing the beams to get lost in the off-momentum aperture.

Generating a MAD-X algorithm

To lessen the workload to the feedback system, one might look at the constraints set in the squeezing algorithm used. In OptiCalc, β^* -squeeze is actually performed using all available power supplies (PS) in the considered insertion, including the bus for the main quadrupoles in the arcs. The generated β -bumps are thus not closed and the changes in phase advance cannot be localized to the squeezed insertion. This explains the large tune changes that had to be compensated by the tune feedback system. Figure 4 describes the wiring scheme of the quadrupole power supplies in the RHIC IR6 insertion region. This scheme, with the information on the PS limits for each quadrupole, can be modeled in MAD-X [3] and used in a β^* matching algorithm that would use only the individual PS, i.e. all quadrupoles from Q9 upstream to Q9 downstream and all trim quadrupoles (QT4, QT5, QT6). The advantage of this algorithm is that it keeps the phase advance constant across the insertion, leaving the rest of the machine unperturbed. Changes in chromaticity are also calculated, allowing for compensation as the new optics are sent.

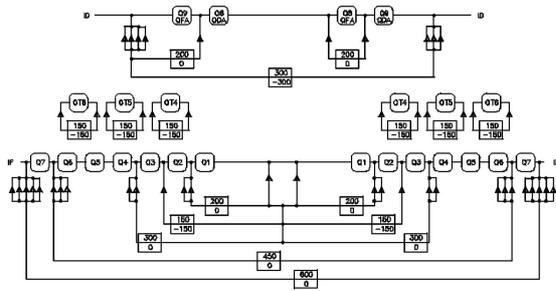


Figure 4: Wiring scheme of the quadrupole power supplies in RHIC IR6 (STAR) insertion. Upper and lower current limits are included. From [4].

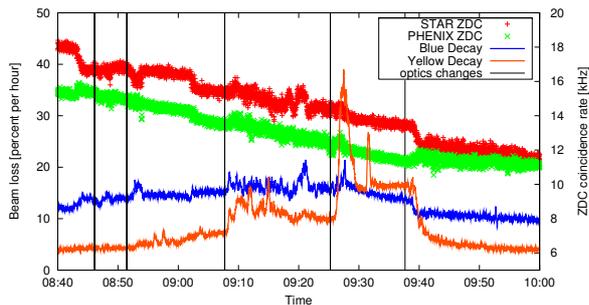


Figure 5: Changes in STAR and PHENIX ZDC collision rates and Blue and Yellow beam decay signals during a β^* -squeeze experiment with MAD-X at the end of a Au+Au physics store during RHIC Run11. A vertical line marks the time when new optics are sent.

The MAD-X algorithm gives the required changes in quadrupole gradients to be sent to RampManager to squeeze IR6 and/or IR8 for both lattices to the requested β^* value. Figure 5 shows the results of successive squeezing attempts using the MAD-X algorithm: compared to the experiment with the OptiCalc algorithm, fewer beam losses are observed, with a peak at 39% for the Yellow beam. For this test, β^* (IR6) was sent to 0.66 m ($t = 08:46:07$), 0.62 m ($t = 08:51:28$) and 0.58 m ($t = 09:07:43$) successively. An attempt was made at $t = 09:25:15$ to squeeze β^* (IR8) to 0.66 m, which caused the peak in Yellow decay signal. The last optics change at $t = 09:37:39$ was sent to reset the β^* in IR6 and IR8 to their design value of 0.70 m. The necessary chromaticity corrections are applied after each optics change using the regular knob for RHIC operations. It allowed reducing beam losses after each squeezing attempts, as seen in Figure 5 after the second attempt for the Blue beam ($t = 08:51:28$), and more noticeably for the Yellow beam after the attempt in IR8.

To get a quantitative measurement of the effective change in β^* in IR6, one can calculate the change in specific luminosity. It is defined as the luminosity from Equation 2 normalized by $N_1 N_2$, and is inversely proportional to the product of the horizontal and vertical convolved

beam sizes at the IP. Figure 6 plots the inverse of the specific luminosity as a function of time during the MAD-X β^* -squeeze experiment.

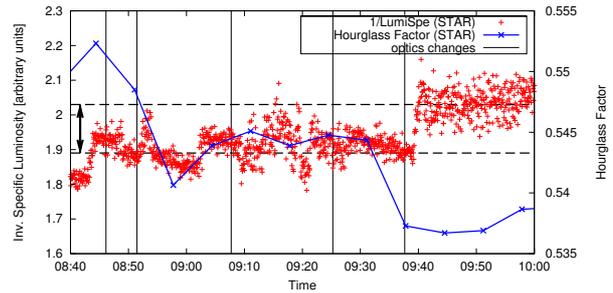


Figure 6: Inverse specific luminosity during a β^* -squeeze experiment with MAD-X at the end of a Au+Au physics store during RHIC Run11. A vertical line marks the time when new optics are sent.

The jump in inverse specific luminosity at $t = 09:37:39$ can be attributed to β^* (IR6) reverting to 0.70 m. With the last squeezing attempt in IR6 being for $\beta^* = 0.58$ m, the expected change was 17.14%. From Figure 6, the amplitude of that change (estimated between the two dashed lines) is calculated to be 7.41%; with a measured STAR hourglass factor of about 0.54, this would imply a 13.72% change in β^* , i.e. in good agreement with the theoretical predictions.

CONCLUSION

The potential for a luminosity increase for the RHIC experiments STAR and PHENIX by taking advantage of its fully operational stochastic cooling system to reduce the transverse β function at the considered interaction point, β^* , was reviewed. When testing the existing β^* -squeeze algorithm, part of the RHIC online model, it was determined that a new method had to be commissioned that would maintain the phase advance constant along the squeezed insertion and also take care of the changes in chromaticity.

A new MAD-X knob was created and tested, showing a better control of beam losses through the squeezing process. It also allowed getting a measurement of the actual change in β^* , demonstrating the qualitative and quantitative efficiency of this new method. An extension of the MAD-X algorithm to control the longitudinal location s^* of the interaction point is also possible, as it would rely on the same principle of controlling the optics functions over the length of the considered experimental insertion.

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