# A GRAPHIC INTERFACE FOR FULL CONTROL OF THE RHIC OPTICS\*

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### Abstract

A high level application has been developed for the RHIC collider to provide a complete package for optics control. Optics can be measured using three different algorithms to process turn-by-turn (TBT) beam position monitor (BPM) data from either free (tune meter) or driven (AC dipole) betatron oscillations, and corrected via SVD on a response matrix built around specific sets of quadrupoles. The following reviews the details of those methods, and includes the first results of the operational commissioning of the application.

### **INTRODUCTION**

One of the methods to measure the linear RHIC optics for any of its high energy heavy ions or polarized protons runs relies on AC dipoles (ACD's). In a particle accelerator, ACD's are designed to adiabatically drive coherent betatron beam oscillations with a frequency close to the beam tune. For RHIC, a GUI application called loptics was built to control the amplitude and frequency of the dipole field of a given ACD when measuring the optics of the corresponding beamline. Once the ACD is triggered, all BPM's around the considered ring record the beam oscillations over 1024 turns; linear optics are then derived using fitting algorithms on each BPM dataset [1]. With the recent successful developments of  $\beta_z$ -beating correction methods at RHIC in Run12 and Run13 [2], a major upgrade of loptics was to turn the application into a complete tool for measurement, correction as well as control of linear optic functions.

# LINEAR OPTICS MEASUREMENTS

#### Fitting Driven and Free Oscillations

For coherent oscillations driven by an ACD at a tune  $\nu_{AC}$ , the beam actually "sees" both  $\nu_{AC}$  and  $1 - \nu_{AC}$  driving tunes according to the Nyquist sampling theorem. The transverse beam position  $z_i^s(N)$  (for either plane) measured at the *i*th BPM and Nth turn at the longitudinal coordinate s in RHIC can then be derived as:

$$z_{i}^{s}(N) = A_{m} \cos\left(2\pi\nu_{AC}N + \psi_{m}(s)\right)$$

$$-A_{p} \cos\left(2\pi\nu_{AC}N - 2\pi\nu_{AC} + 2\chi_{AC} - \psi_{m}(s)\right),$$
with  $\psi_{m}(s) = -\pi\left(\nu_{AC} - \nu_{z}\right) + \chi_{AC} - \psi_{z}(s)$  and:
$$A_{m} = \frac{B_{m}L}{4\sin\left(\pi\left(\nu_{AC} - \nu_{z}\right)\right)B\rho}\sqrt{\beta_{z}(s)\beta_{z}^{0}},$$
(1)

$$A_p = \frac{B_m L}{4\sin\left(\pi\left(\nu_{\rm AC} + \nu_z\right)\right) B\rho} \sqrt{\beta_z(s)\beta_z^0}.$$

where  $B_m L$  is the integrated strength of the ACD field,  $B\rho$  the magnetic rigidity,  $\beta_z(s)$  and  $\psi_z(s)$  the betatron function and phase advance at the *i*th BPM,  $\beta_z^0$  the betatron function at the ACD, and  $\chi_{AC}$  the ACD initial phase. Eq. (1) can be written in both a compact form [3] (Eq. (2)) and a tune-phase dissociated form [4] (Eq. (3)):

$$z_i^s(N) = A_d \sqrt{\beta_d(s)} \cos\left(2\pi\nu_{\text{AC}}N + \left[\psi_z(s) + \chi_{\text{AC}}\right]\right), \quad (2)$$

$$z_i^s(N) = A_m \left[ \cos(\psi_m(s)) F_N \cdot \sin(\psi_m(s)) G_N \right]; \quad (3)$$

with  $r = \sin \left( \pi \left( \nu_{AC} + \nu_z \right) \right) / \sin \left( \pi \left( \nu_{AC} - \nu_z \right) \right)$  one gets:

$$F_N = \cos \left(2\pi\nu_{\rm AC}N\right) - r\cos\left(2\pi\nu_{\rm AC}(N-1) + 2\chi_{\rm AC}\right),$$
$$G_N = \sin\left(2\pi\nu_{\rm AC}N\right) + r\sin\left(2\pi\nu_{\rm AC}(N-1) + 2\chi_{\rm AC}\right).$$

The compact form from Eq. (2) is then solved using the nonlinear Levenberg-Marquardt [5] fitting method on the three variables  $A_{tot}(s) = A_d \sqrt{\beta_d(s)}$ ,  $\nu_{AC}$  and  $\psi_{tot}(s) = \psi_z(s) + \chi_{AC}$ . The dissociated form in Eq. (3) can be solved with a linear fitting algorithm for the variables  $A_m \cos(\psi_m(s))$  and  $A_m \sin(\psi_m(s))$  once the driving tune  $\nu_{AC}$  is found using a fast Fourier transform (FFT) on the TBT data at the considered BPM. The ratio of amplitudes  $A_{tot}$  or  $A_m$  between two BPM's are then directly proportional to the ratio of the  $\beta_z(s)$  functions at the BPM's locations. The phase advance  $\psi_z(s)$  can only be calculated from  $\psi_{tot}(s)$  or  $\psi_m(s)$  with a precise knowledge of the initial ACD phase  $\chi_{AC}$ ; instead, *loptics* provides the phase difference  $\Delta \psi_z(s)$  between two consecutive BPM's, which is independent of  $\chi_{AC}$ .

The  $\beta_z(s)$  and  $\Delta \psi_z(s)$  derived from fitting Eq. (2) are actually the "driven" amplitude and phase of the beam oscillation. Results from the nonlinear fitting will therefore carry some artificial  $\beta_z$ -beating with an amplitude [6]:

$$\frac{\beta_d(s) - \beta_z(s)}{\beta_z(s)} \approx \frac{2\pi \left(\nu_{\text{AC}} - \nu_z\right)}{\sin\left(2\pi\nu_z\right)} \cos\left(2\psi_z(s) - 2\pi\nu_z\right).$$
(4)

For typical ACD operations at RHIC, this amplitude is estimated at about 7% for  $\nu_{AC}$ - $\nu_z = \pm 0.01$ . For a linear machine, the artificial  $\beta_z$ -beat can be reduced experimentally to about 0.3% by driving the beam oscillations with  $\nu_{AC} > \nu_z$  in one measurement and  $\nu_{AC} < \nu_z$  in another, and averaging the fitted optics.

Free oscillations can be generated from beam injection oscillations or a coherent excitation by a single turn kicker magnet (e.g. for tune measurements), with  $z_i^s(N)$  defined as:

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$$z_i^s(N) = A_{calc}^s \cos\left(2\pi\nu_{calc}N + A_3^s\right),$$
  
with:  $A_{calc}^s = A_1^s \exp\left(-2.0\left(\frac{\pi N}{A_2^s}\right)^2\right).$  (5)

The three variables  $A_{1,2,3}^s$  are fitted similarly to driven oscillations using Levenberg-Marquardt. This allows the application to analyze any TBT oscillations dataset acquired during RHIC operations and derive the linear optics. Like in the nonlinear case,  $\nu_{calc}$  is calculated for each BPM dataset via FFT and should be close to the machine tune  $\nu_z$ .  $\beta_z(s)$  and  $\Delta \psi_z(s)$  are then determined from the fitted values  $A_1^s$  and  $A_3^s$  at each BPM.

#### Data Analysis in loptics

Figure 1 shows the graphical interface (GUI) of *loptics* with the ACD control options on the right hand side. Users can provide initial guesses for all parameters to be fitted in the bottom right side. The measured  $\beta_z(s)$  and  $\Delta \psi_z(s)$  are plotted against their respective design values as calculated by the RHIC online model. The corresponding  $\beta_z$ -beat and phase-beat plots are displayed in a separate tab and saved for further use with the optics correction algorithms.  $\beta_z^*$  and  $s^*$  at all IP's are also interpolated and displayed in a dedicated table. One of the upgrades to *loptics* is the calculation of horizontal and vertical phase advances between each IP, providing valuable information when commissioning the new RHIC lattices with e-lens compensation schemes [7].

More than one dataset can be analyzed at a time, with error bars calculated accordingly. Another recent upgrade to the application allows users to analyze datasets acquired with different  $\nu_{AC}$  in order to get rid of the artificial  $\beta_z$ -beat when using the linear fitting method. Each driving tune setpoint makes for an independent measurement, and all related datasets are grouped in the same data analysis process; all calculated average values and error bars are then recombined using the rules of propagation of uncertainty.



Figure 1: *loptics* graphic interface showing the results of data analysis of AC dipole driven Yellow polarized protons beam oscillations for 255 GeV optic functions (black dots) and phase advance (blue dots) measurements, compared to expected values from the RHIC online model (red and green traces respectively). Both horizontal (top) and vertical (bottom) planes were measured.

### **CORRECTION ALGORITHMS**

In addition to new fitting methods, *loptics* now features a correction algorithms package for the RHIC linear optic functions. The first method is based on a singular value decomposition (SVD) of a response matrix R built around the machine settings as defined in the RHIC online model. Based on the wiring scheme of the RHIC insertions [8], one can find a group of n quadrupoles with individual power supplies to operate as a  $\beta_z$  knob for optics corrections. For all m BPM's in a given beamline, the online model can calculate  $(\Delta \beta_z / \beta_z)_p$ ,  $p = 1 \dots m$  at the *p*th BPM resulting from a small gradient error  $\Delta k_j$ ,  $j = 1 \dots n$  at the *j*th selected quadrupole. The matrix  $R_{m,n}$  is then built as:

$$\begin{pmatrix} (\Delta\beta_z/\beta_z)_1\\ \vdots\\ (\Delta\beta_z/\beta_z)_m \end{pmatrix} = R_{m,n} \cdot \begin{pmatrix} \Delta k_1\\ \vdots\\ \Delta k_n \end{pmatrix}.$$
 (6)

Following the data analysis and optics calculations previously described, *loptics* can solve Eq. (6) for  $\Delta k_i^{err}, j = 1 \dots n$  by inverting  $R_{m,n}$  with SVD:

$$\begin{pmatrix} \Delta k_1^{err} \\ \vdots \\ \Delta k_n^{err} \end{pmatrix} = -\left(R_{m,n}^{-1}\right) \cdot \begin{pmatrix} (\Delta \beta_z / \beta_z)_1 \\ \vdots \\ (\Delta \beta_z / \beta_z)_m \end{pmatrix}_{meas}$$
(7)

The correction strengths derived from Eq. (7) can be tested in the online model before being applied to the machine, in full or in incremental steps. Figure 2 shows the calculated gradient errors and the corresponding predicted  $\beta_z$ -beat derived from a measurement of the RHIC Yellow lattice optic functions during a beam experiment with polarized protons at 255 GeV. One can notice that all quadrupole magnets selected for the optics corrections are located in all six RHIC interaction regions (IR's) to allow for the maximum number of power supplies to be used, therefore increasing the efficiency of the SVD package. Figure 3 presents the corrected  $\beta_z$ -beat from the optics shown in Figure 1 once 100% of the calculated correction strengths are applied to the Yellow lattice. There is a significant improvement especially in the vertical plane, where the peak-to-peak amplitude of the beating is reduced to about  $\pm$  20%. One should note that in *loptics* the size of  $R_{m,n}$  takes into account the status bit of each BPM prior to SVD: any status other than "good" and the entire corresponding row in the response matrix is discarded. Another filter could be implemented that would discard BPM data (and matching  $R_{m,n}$  row) if the measured  $\beta_z$ -beat appears to be too unrealistic (e.g. very large reported amplitude compared to other BPM's).

A segment-by-segment method (SBST) [2] is also currently being added to *loptics*. SBST can be used to determine significant gradient errors in individual IR magnets and would allow correcting optics locally, reducing the global  $\beta_z$ -beat to be corrected via SVD. Experiments with beam to test this two-pronged method are being discussed for the coming Run14 of RHIC.

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Figure 2: Strength of the gradient errors  $\Delta k_j^{err}$ ,  $j = 1 \dots n$  (left) calculated using the global SVD correction scheme newly implemented in *loptics* for the optics shown in Figure 1 and the selected quadrupole knob. The  $\beta_z$ -beat from these  $\Delta k_j^{err}$  as predicted by the RHIC online model (right, red trace) is compared to the measured one (right, black trace) to determine the quality of the determined solution.



Figure 3: Measured (top) and corrected (bottom) Yellow 255 GeV polarized protons beam optics using the global SVD correction algorithm described in Figure 2.

### CONCLUSION

*loptics* has been upgraded to allow for linear optics measurement using either free or driven turn-by-turn oscillations, with a graphic interface displaying all relevant parameters. Additionally, a correction algorithm based on SVD calculations on a response matrix built with the RHIC online model is now part of the application after being tested with beam as a standalone procedure. Its use in *loptics* allows predicting the accuracy of the correction before sending the knob values to the machine.

Further improvements include the combination of SBST and SVD correction methods, as well as adding an Independent Component Analysis (ICA) model for optics calculations [9]. ICA allows splitting the beam oscillations

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measured at each BPM into their betatron and synchrotron motions components, as well as filter out any background noise inherent to the electronics involved, leading to a more precise determination of  $\beta_z$  and  $\Delta \psi_z(s)$  before corrections.

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