WEIGHTED SVD ALGORITHM FOR CLOSED-ORBIT CORRECTION AND 10 Hz FEEDBACK IN RHIC*

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Abstract

Measurements of the beam position along an accelerator are typically treated equally using standard SVD-based orbit correction algorithms so distributing the residual errors, modulo the local beta function, equally at the measurement locations. However, sometimes a more stable orbit at select locations is desirable. In this paper, we introduce an algorithm for weighting the beam position measurements to achieve a more stable local orbit. The results of its application to close-orbit correction and 10 Hz orbit feedback are presented.

INTRODUCTION

The general orbit correction algorithm treats beam positions from all monitors equally, which in turn would result in an orbit whose deviation from the goal orbit is at the same level for all position monitors. However, a local stabilized orbit is required in some special cases, for example, in the interaction region of colliders, or in undulators of FELs. In RHIC [1], two imminent upgrade projects present similar requirement, one is the electron lens [2], in which electron beam colliding with proton beam to partially cancel the beam beam from proton beam collision; the other is coherent electron cooling prototype [3], where electron co-propagate with an ion beam in a line in the undulator to cool the ion beam. Therefore, a weighted SVD algorithm for orbit correction has been proposed to further stabilize the local orbit. The algorithm, offline test and online application are presented.

GENERAL ALGORITHM

Suppose the measured orbit is $(x_1, x_2, \ldots x_m)'$, the goal orbit is $(x_{1g}, x_{2g}, \ldots x_{mg})'$, the general algorithm [4] of orbit correction can be expressed in a matrix form

$$\begin{pmatrix} x_{1g} - x_1 \\ x_{2g} - x_2 \\ \vdots \\ x_{mg} - x_m \end{pmatrix} = \begin{pmatrix} R_{11} & R_{12} & \cdots & R_{1n} \\ R_{21} & R_{22} & \cdots & R_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ R_{m1} & R_{m2} & \cdots & R_{mn} \end{pmatrix} * \begin{pmatrix} \theta_1 \\ \theta_2 \\ \vdots \\ \theta_n \end{pmatrix} \tag{1}$$

here the matrix R is the orbit response of beam positions at BPMs to the strength change of correctors. $(\theta_1, \theta_2, \ldots \theta_n)'$ is the required strength changes for correctors to achieve the goal orbit. The linear equations can be solved using SVD [5] for which the matrix R may be decomposed as

$$R = USV^T \tag{2}$$

here U is an $m \times m$ unitary matrix, S is an $m \times n$ rectangular diagonal matrix, V is an $n \times n$ unitary matrix. The inverse matrix of R is

$$R^{-1} = VS^{-1}U^T \tag{3}$$

The required strength change is

$$\theta = R^{-1}X \tag{4}$$

X is the difference orbit on the left side of Eq. 1.

WEIGHTED SVD ALGORITHM

In order to reduce the final deviation from the goal orbit, different weighting factor can be applied to both sides of Eq. 1,

$$\begin{pmatrix} f_1 \cdot (x_{1g} - x_1) \\ f_2 \cdot (x_{2g} - x_2) \\ \vdots \\ f_m \cdot (x_{mg} - x_m) \end{pmatrix} = \begin{pmatrix} f_1 \cdot (R_{11} & R_{12} & \cdots & R_{1n}) \\ f_2 \cdot (R_{21} & R_{22} & \cdots & R_{2n}) \\ \vdots & \vdots & \ddots & \vdots \\ f_m \cdot (R_{m1} & R_{m2} & \cdots & R_{mn}) \end{pmatrix} * \begin{pmatrix} \theta_1 \\ \theta_2 \\ \vdots \\ \theta_n \end{pmatrix} \tag{5}$$

The equations can be solved in the same way as mentioned in the previous section. The deviation from goal orbit can be evaluated by predicting the orbit with correction for regular and weighted SVD algorithm. Because the real residual orbit will be proportional to the inverse of the weight factor, beam position at monitors with higher weight will be brought closer to the goal.

E-lens

Two additional BPMs in the e-lens main solenoid will be added to monitor the proton and electron beam positions. To better align the proton and electron beam, a weight factor $f > 1$ will be applied to these two e-lens BPMs.

10 Hz Feedback

For 10 Hz global orbit feedback [6], adding weights on BPM data requires additional programming. To simplify the process the matrix is further manipulated.

$$F * \begin{pmatrix} x_{1g} - x_1 \\ x_{2g} - x_2 \\ \vdots \\ x_{mg} - x_m \end{pmatrix} = F * \begin{pmatrix} R_{11} & R_{12} & \cdots & R_{1n} \\ R_{21} & R_{22} & \cdots & R_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ R_{m1} & R_{m2} & \cdots & R_{mn} \end{pmatrix} * \begin{pmatrix} \theta_1 \\ \theta_2 \\ \vdots \\ \theta_n \end{pmatrix} \tag{6}$$

where

$$F = \begin{pmatrix} 1 & 0 & \cdots & 0 & 0\cdots & 0 \\ 0 & 1 & \cdots & 0 & 0\cdots & 0 \\ \vdots & \vdots & \ddots & \vdots & \vdots & \vdots \\ 0 & 0 & \cdots & f & 0\cdots & 0 \\ 0 & 0 & \cdots & 0 & f\cdots & 0 \\ \vdots & \vdots & \ddots & \vdots & \vdots & \vdots \\ 0 & 0 & \cdots & 0 & 0\cdots & 1 \end{pmatrix} \tag{7}$$

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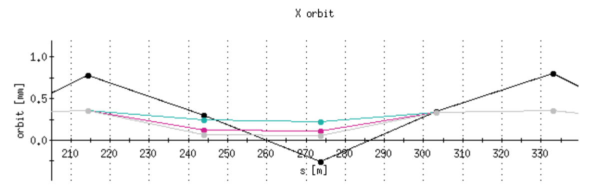

Figure 1: Weighted orbit correction with different weights for bo6-bh16 and bo6-bh18 (f=1 for Cyan, f=2 for Red and f=4 for Gray)

Instead of matrix R, we decompose matrix $F * R$,

$$(F * R) = OPQ^T \tag{8}$$

then invert matrix as follows

$$(F * R)^{-1} = QP^{-1}O^T \tag{9}$$

The difference beam position vector will be multiplied by $(F * R)^{-1} * F$ in the weighted algorithm instead of by R^{-1}.

OFFLINE TEST

Offline test has been carried out for close-orbit corrections to verify the algorithm.

RhicOrbitDisplay

A sub-routine has been added to the existing *RhicOrbitDisplay* application to add weighting on all BPMs and corresponding response matrix rows. For the offline test (Fig. 1), the measured orbit is in black and the goal orbit is zero everywhere. With different weights on two selected BPMs (at longitudinal coordinate $s = 244m$ and $s = 274m$), the program calculates the required strength changes for all available correctors and predicts the final orbit. As evidenced in Fig. 1, orbits with higher weights on the two BPMs are closer to the target.

E-lens Offline Test

An offline code was programmed to simulate the orbit correction for e-lens because e-lens BPMs are not online yet. The closed orbit of proton beam will be distorted by the e-lens components such that orbit rms is on order of mm scale [7]. Correcting global orbit is less demanding than aligning the proton beam with the axis of main solenoid along which the electron beam passes. Some weight factors are applied to demonstrate the effects of the new correction algorithm (Fig. 2). The final orbit with correction by regular algorithm has a 0.08 mrad angle offset with respect to electron beam, which can be reduced by factor of 8 if the weight factors on the e-lens BPMs is increased.

However, local orbit is improved on the expense of deterioration of global orbit, as seen in Fig. 3.

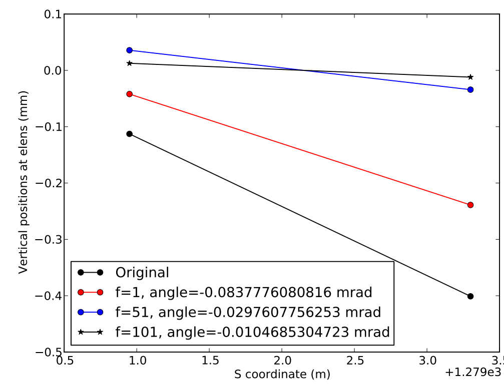

Figure 2: Local orbit for e-lens with different weights

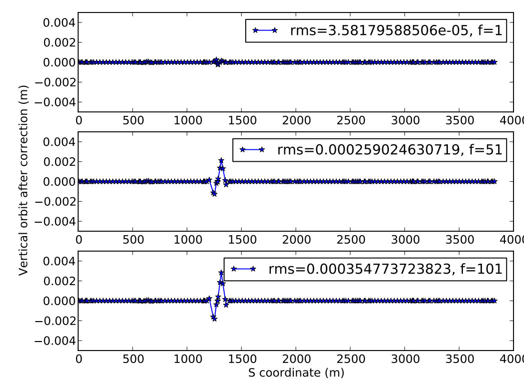

Figure 3: Close-orbit for e-lens with different weights

ONLINE APPLICATION

Closed Orbit

Driven mostly by external temperature variations, orbits tend to drift during the course of a physics store. To combat this, store orbit feedback [8] has been turned on for 10 s every 30 mins during regular stores. In Run-12, the collision rates were observed to occassionally be reduced, which is correlated with changes in difference orbit of two beams at so-called DX BPMs located in the DX magnets used to separate and conbine the beams in the interaction region. The DX BPMs are not included in the existing orbit correction algorithm due to concerns about the reliability of the absolute readings.

A two-step measure was taken to fix the orbit without affecting the collision rates: first the DX BPMs were included in the correction scheme. Then weights were added to the DX BPMs in the algorithm. As a note, two hypothetical BPMs instead of physical BPMs can be used to achieve similar goal provided there are no magnets in between. The choice of DX BPMs is due to convenience. The goal positions for DX BPMs are the measured positions, which means maintaining the same beam positions at location of DX magnets. The goal orbit for IR BPMs are the captured

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Figure 4: Variation of beam positions at DX BPMs (top plot), and arc BPMs statistics (bottom plot) during orbit correction with new algorithm and existing algorithm

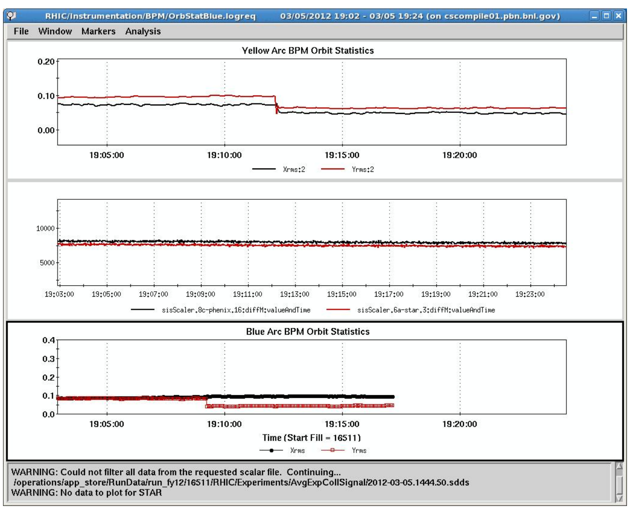

Figure 5: Orbit correction in the yellow (top plot), the blue (bottom plot) ring and collision rates (middle plot) when the new algorithm was tested for a physics store

orbit after IR steering to optimize the collision rates. The goal orbit outside the IR region is zero.

The newly adapted algorithm has been applied online to verify its ability of maintaining collision rates during orbit correction. In Fig. 4, orbit corrections of both horizontal and vertical planes was implemented with the weighted algorithm in the yellow ring around 13:51, the correction was reverted at about 13:57, then orbit was corrected again with existing algorithm around 14:02 and reverted after that. With weight factor $f = 5$, the first variation of beam position at DXs due to correction by new algorithm is less than that of the third, which is due to the correction by existing algorithm.

We have tested the new algorithms 4 times during physics stores to check if any impact on collision rates. All tests showed no sign of collision rate drop (in Fig. 5).

To study the effect of the new algorithm systematically, store orbit feedback using the new algorithm for physics stores is envisioned.

10 Hz Feedback

Weights on BPMs around the physics experiments were added in the online test. No further damping of 10 Hz oscillation has been seen on the same BPMs. This may due to the fact that the weight factor was not optimized by offline simulation for 10 Hz feedback. Further study is planned for 10 Hz feedback in the future.

SUMMARY

A weighted SVD algorithm for orbit correction has been proposed for store orbit correction and 10 Hz feedback. Offline tests verified the validity of the new algorithm for close-orbit case. Offline test for e-lens orbit correction seems promising which apply to CeC as well. Offline simulation with noise for 10 Hz feedback is in process to optimize the weight factor. To relieve the collision rate drop associated with auto orbit feedback at store, weighted SVD algorithm has been applied in online test. The results are as expected and repeatable so far. Online application in 10 Hz feedback needs further investigation.

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