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Error localization in RHIC by fitting difference orbits

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Error localization in RHIC by fitting difference orbits*

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Abstract

The presence of realistic errors in an accelerator or in the model used to describe the accelerator are such that a measurement of the beam trajectory may deviate from prediction. Comparison of measurements to model can be used to detect such errors. To do so the initial conditions (phase space parameters at any point) must be determined which can be achieved by fitting the difference orbit compared to model prediction using only a few beam position measurements. Using these initial conditions, the fitted orbit can be propagated along the beam line based on the optics model. Measurement and model will agree up to the point of an error. The error source can be better localized by additionally fitting the difference orbit using downstream BPMs and back-propagating the solution. If one dominating error source exist in the machine, the fitted orbit will deviate from the difference orbit at the same point.

ALGORITHM

In either a transport line or a storage ring, the beam trajectory in either transverse plane (neglecting coupling) can be expressed by the transfer matrix and initial conditions,

$$z(s) = \sqrt{\frac{\beta_s}{\beta_i}}(\cos(\phi_s - \phi_i) + \alpha_i \sin(\phi_s - \phi_i)) \cdot z_i + \sqrt{\beta_s \beta_i}\sin(\phi_s - \phi_i) \cdot z_i', \quad (1)$$

where β_s, β_i, ϕ_s, ϕ_i are the beta functions and phase advances at position s and initial position i; α_i is the initial alpha and z represents either the horizontal (x) or vertical (y) motion. The following algorithm may be applied to both beam trajectories in a linear transport line and to closed orbits in storage ring, which afterwards we will refer to as "orbit".

The difference of two orbits complies with

$$\triangle z = M_{11} \cdot \triangle z_i + M_{12} \cdot \triangle z_i',$$

with $M_{11} = \sqrt{\frac{\beta_s}{\beta_i}}(\cos(\phi_s - \phi_i) + \alpha_i \sin(\phi_s - \phi_i))$, $M_{12} = \sqrt{\beta_s \beta_i}\sin(\phi_s - \phi_i)$.

By selecting a fitting range from the mth BPM to the nth BPM, a set of linear equations follows,

$$\begin{cases} \triangle z_m = M_{11}^m \cdot \triangle z_i + M_{12}^m \cdot \triangle z_i' \\ \triangle z_{m+1} = M_{11}^{m+1} \cdot \triangle z_i + M_{12}^{m+1} \cdot \triangle z_i' \\ \vdots \\ \triangle z_n = M_{11}^n \cdot \triangle z_i + M_{12}^n \cdot \triangle z_i' \end{cases} \quad (2)$$

Using a least-square fit for minimizing the merit function $f = \sum_{k=m}^{n} (\triangle z_k - M_{11}^k \cdot \triangle z_i + M_{12}^k \cdot \triangle z_i')^2$, we obtain the initial conditions as

$$\begin{cases} \triangle z_i = \dfrac{\sum_{k=m}^{n} \triangle z_k M_{11}^k \cdot \sum_{k=m}^{n} M_{11}^k M_{12}^k - \sum_{k=m}^{n} \triangle z_k M_{12}^k \cdot \sum_{k=m}^{n} (M_{11}^k)^2}{(\sum_{k=m}^{n} M_{11}^k M_{12}^k)^2 - \sum_{k=m}^{n} (M_{11}^k)^2 \cdot \sum_{k=m}^{n} (M_{12}^k)^2} \\ \triangle z_i' = \dfrac{\sum_{k=m}^{n} \triangle z_k M_{11}^k \cdot \sum_{k=m}^{n} (M_{12}^k)^2 - \sum_{k=m}^{n} \triangle z_k M_{12}^k \cdot \sum_{k=m}^{n} M_{11}^k M_{12}^k}{\sum_{k=m}^{n} (M_{11}^k)^2 \cdot \sum_{k=m}^{n} (M_{12}^k)^2 - (\sum_{k=m}^{n} M_{11}^k M_{12}^k)^2} \end{cases} \quad (3)$$

Once the initial conditions are so determined, the fitted orbit along the ring can be computed based on Eq. 1.

APPLICATION VERIFICATION

This algorithm was integrated into the existing RhicOrbitDisplay application used for viewing orbits and applying corrections. As a demonstration, we used orbit data acquired during measurements made to check the BPM polarities. The automated BPM polarity check works in this way. First the closed orbits before and after making a strength change of a corrector are recorded. The difference between those measurements, the so called difference orbit, is then formed. The difference is also predicted by the on-line model with knowledge of the corrector strength. A BPM polarity error can be identified when the signs of the measured and predicted beam positions do not agree.

As an after-fact test, we applied the algorithm and tried to localize an error source, which in this case was due to the intentionally varied dipole corrector. Shown in Fig. 1

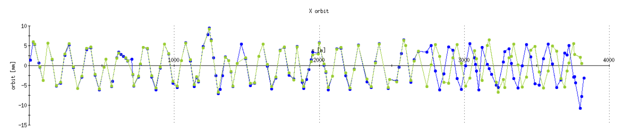

Figure 1: Measured horizontal difference orbit (blue) versus the fitted orbit (cyan) by forwards propagation

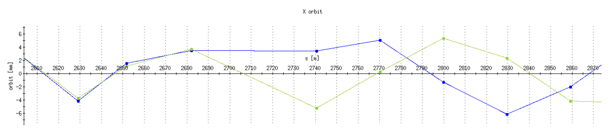

Figure 2: The region (by zooming in Fig. 1) where the fitted orbit starts to deviate from the difference orbit

are the measured horizontal difference orbit (blue) and the fitted orbit (cyan). The fit range was 200 to 800 m and

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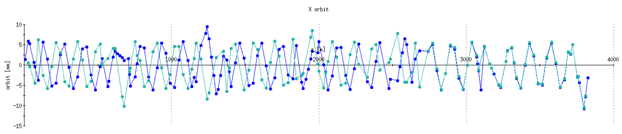

Figure 3: Measured horizontal difference orbit (blue) versus the fitted orbit by backwards propagation

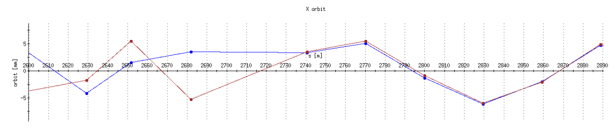

Figure 4: The region (by zooming in Fig. 3) where the fitted orbit starts to deviate from the difference orbit

the fitted orbit was propagated forward. The agreement between measurement and fit is very good upstream of the BPM at 2686 m. The expanded range shown in Fig. 2 reveals that the two orbits begin to deviate between BPMs located at 2683 and 2740 m, which is in agreement with the longitudinal coordinate (2713 m) of the dipole magnet that was used. In order to confirm this result, a different region (3000 to 3600 m) was selected for fitting and the resulting fitted orbit was propagated backwards for the same set of data. The result (Fig. 3 with expanded view shown in Fig. 4) agrees with that obtained by forward propagating the fitted difference orbit (Fig. 1).

In the vertical plane with separation bumps used to separate the beams at 4 interaction regions, this algorithm works equally as well. Fig. 5 shows the fitted orbit (fitting range:

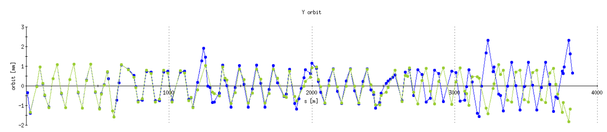

Figure 5: Measured vertical difference orbit (blue) versus the fitted orbit by forwards propagation

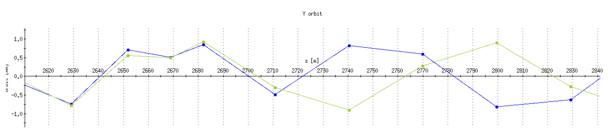

Figure 6: The region (by zooming in Fig. 5) where the fitted orbit starts to deviate from the difference orbit

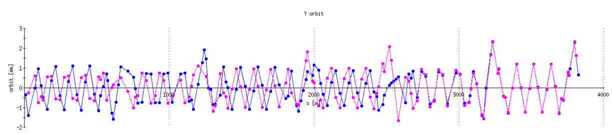

Figure 7: Measured vertical difference orbit (blue) versus the fitted orbit by backwards propagation

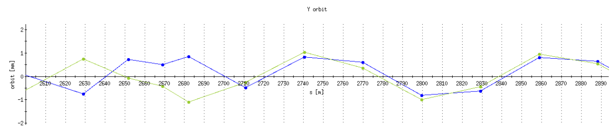

Figure 8: The region (by zooming in Fig. 7) where the fitted orbit starts to deviate from the difference orbit

200 to 800 m) versus measured difference orbit, which start to deviate from one another in between 2710 and 2740 m (in Fig. 6). The backwards propagated fitted orbit versus difference orbit (in Fig. 7 with zoom in Fig. 8) confirms the finding in Fig. 5. This agrees with the fact that the dipole magnet being used was at 2713 m.

We conclude from this analysis that the orbit fit algorithm correctly localized an intentionally introduced perturbation. The localization was accurate with a range given by the distance between the two closest BPMs.

APPLICATION IN OPERATION

The algorithm has been implemented into RhicOrbitDisplay before RHIC Run-12 and proved to be useful both for machine setup and during routine operations.

Localization of diurnal disturbances in RHIC

Diurnal variations in the beam trajectory have long been observed at RHIC. Using turn-by-turn BPM data, the source for vertical deviations was localized [1] to near the IR at the vicinity of the accelerating cavities (IR4). The source was thought to originate near the cryogenic feed lines located there. As a test, these feed lines were mechanically decoupled from the roof of the accelerator tunnel [2], however, this did not seem to mitigate the diurnal perturbation to the beam trajectories.

To confirm this locale of diurnal variations, we applied the orbit fit algorithm to two sets of data. First we used a range from 2000 to 2800 m for the fitting, and forward propagated the fitted orbit along the ring. The difference orbit and the fitted orbit were seen to deviate from one another near the 3 o'clock side of IR4. The details are clearer in Fig. 10 and Fig. 11 which shows the difference of the original difference orbit and the fitted orbit.

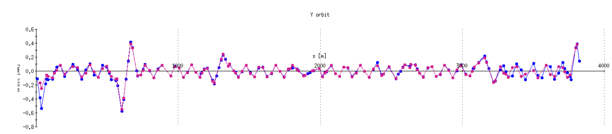

Figure 9: The vertical difference orbit (blue) vs fitted orbit (red) using range from 2000 to 2800 m and forward propagation

Then, a different range (from 3400 to 3800 m) was used for the fitting, and the fitted orbit was backward propagated. The result from forward propagation was confirmed by the backward propagation (Fig. 12 and Fig. 13) since the orbits start to deviate in the same region.

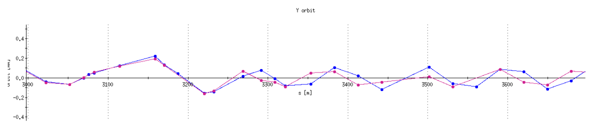

Figure 10: Expaned view of Fig. 9 showing that the deviation originating from IR4

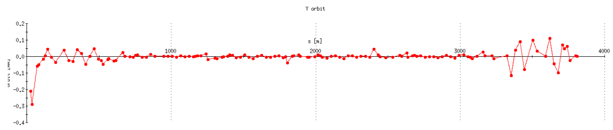

Figure 11: The difference of original difference orbit and forward propagated fit orbit

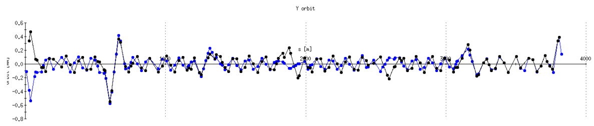

Figure 12: The vertical difference orbit (blue) vs fitted orbit (black) using range from 3400 to 3800 m and backward propagation

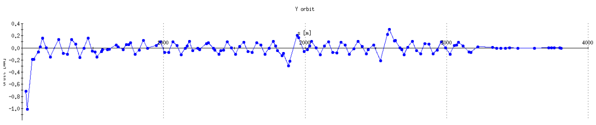

Figure 13: The difference of original difference orbit and backward propagated fit orbit

In this example the orbit fit program confirmed that the source of diurnal variation of RHIC orbit is in the IR4 region, which is suspected to be the cryogenic pipe, however, further narrow down of the longitudinal position of the source is needed. The precision of localizing error sources by orbit fit program is limited by the spacing of BPMs, which is tens of meters at RHIC.

Error localization during operation

The behavior (current, voltage, timing...) of accelerator components sometimes become abnormal due to various reasons, which in turn may degrade machine performance. The process of finding an offensive component can be time-consuming and difficult. For example in RHIC Run-11, a long list of components were turned off one by one to eventually isolate a problem with the RHIC abort kicker [3].

With orbit fit, this process can be much simplified as proven by its application in RHIC Run-12. A DX magnet power supply oscillation was found by operations using orbit fit taking as input the difference between the last orbit and the third to the last orbit before the beam abort. Another example concerns a DC offset of two 10 Hz correctors in IR2. The correctors were settling at -12 A when off, and went back to zero when the 10 Hz feedback was turned on. The orbit was not well controlled when the feedback was turned on. As shown in Fig. 14 and 15, a difference orbit was taken by substracting the orbit before distortion from the orbit after distortion. Both forward orbit fit and backward orbit fit pointed to the error in IR2. Immediately, the check on corrector current revealed the underlying problem.

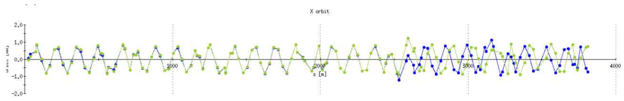

Figure 14: The difference orbit (blue) of the orbit with correctors on and off, and predicted difference orbit (green) by orbit fit, orbits start to deviate from IR2

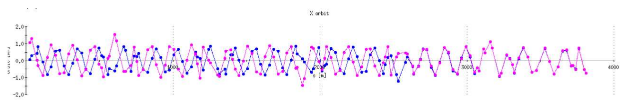

Figure 15: The difference orbit (blue) and its back-propagated fit orbit (red), orbits start to deviate from IR2, which confirms the forward orbit fit

CONCLUSION

An orbit fit algorithm for both transport lines and storage rings was presented. The algorithm has been implemented into RhicOrbitDisplay. Offline tests using BPM polarity check data validated its potential for localizing error sources in RHIC. Its application in RHIC operation has been successful. It is able to localize errors which distort closed orbit quickly. It is also expected to be able to treat intermittent errors which will not perturb closed orbit but turn-by-turn orbits. The resolution of the error localization is given by the spacing between BPMs.

ACKNOWLEDGMENT

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