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INTRODUCING TWO ENERGY-CORRECTION SCHEMES AT DELTA

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Abstract

At DELTA, a 1.5 GeV synchrotron light source operated by the TU Dortmund University, two methods to correct the beam energy of the storage ring have been tested. The first one is capable of maintaining the current beam energy. The second method is used to find the optimal orbit length. Here, the ideas behind both methods are explained and first test results are presented. Numerical studies are shown together with measurement results.

INTRODUCTION

The beam energy of a storage ring varies in the sub-percent range. Orbit lengthening and shortening due to thermal effects and magnetic field errors are the reason for this. Some synchrotron light sources, such as BESSY and the Metrology Light Source (MLS), both located in Berlin/Germany, use a modified orbit feedback to stabilize the beam energy [1]. This prevents undulator spectra from shifting during operation. DELTA, which is currently comissioning a new orbit correction software [2], has tested this method as well.

A variation of this method developed at DELTA has been used to minimize the orbit length and thereby reduce orbit deviations. This is useful when changing the orbit during machine studies. In such situations, it may prevent stray radiation heating the vacuum chamber and may improve the beam lifetime.

Both methods alter the rf frequency to affect the beam energy.

Equilibrium Energy

The beam energy of a storage ring is an equilibrium state constrained by the strength of the bending magnets, the energy loss per turn and the rf frequency. Within these constraints, the beam answers orbit lengh variations with a relative energy deviation δ to keep the revolution time in synchronization with the rf cavity.

Field errors and thermal effects divert the beam from its ideal path. This alters the path length by Δs_r and hence changes the revolution time by

$$\Delta T_r = \frac{\Delta s_r}{c}$$

where c is the electron velocity in ultrarelativistic approximation.

The beam compensates with a dispersive change in revolution time

$$\Delta T_\delta \approx \frac{L\alpha\delta}{c}$$

which is predominantly determined by a dispersive change in orbit length $\alpha\delta$. Here, α is the momentum compaction factor and L is the design orbit length. The impact of the beam energy on the electron velocity and the revolution time is neglected.

The sum of a dispersive change in revolution time and a change in revolution time following from thermal and magnetic-field-error induced orbit lengthening therefore matches the rf frequency [3]

$$\Delta T_\delta + \Delta T_r = \Delta T = \frac{1}{f} - \frac{1}{f + \Delta f}. \tag{1}$$

when the beam is on a closed orbit. Here, Δf is a deviation from the design revolution frequency f whose inverse is the design revolution time T.

ENERGY CORRECTION

The equilibrium energy is reflected in the horizontal orbit [4]

$$x_j \approx \tilde{x}_j + \frac{\theta_k\sqrt{\beta_j\beta_k}}{2\sin(q_x)}\cos\left(|\psi_j - \psi_k| - \pi q_x\right) + D_j\delta \tag{2}$$

where $\tilde{x}$ is the orbit displacement due to field errors and thermal effects, β is the beta function, ψ the betatron phase, q_x the horizontal tune, θ the steerer strength and D the dispersion function. The horizontal orbit therefore reacts dispersively if the energy deviation changes. Beam position monitors (BPMs) are indexed with $j = 1 \dots J$. Steerers are indexed with $k = 1 \dots K$.

Method I: Maintaining the Current Energy

An orbit feedback can detect and compensate a dispersive orbit drift by varying the rf frequency [5]. Firstly, an additional column and an additional row are added to the orbit response matrix R yielding

$$R_\mathrm{I} = \begin{pmatrix} & & & \mathcal{D}_1 \\ & R & & \vdots \\ & & & \mathcal{D}_J \\ 1 & \cdots & 1 & 0 \end{pmatrix}.$$

The additional column contains a rf frequency response $\mathcal{D}$ at all BPMs obtained by shifting the rf frequency and measuring the orbit shift. Secondly, a set of steerer strength corrections for all K steerers and a rf frequency correction

$$\left(\Delta\theta_1, \cdots, \Delta\theta_K, \Delta f\right)^\mathrm{T} = R_\mathrm{I}^\dagger \cdot \left(\Delta x_1, \cdots, \Delta x_J, 0\right)^\mathrm{T},$$

can be estimated by calculating the product of the pseudo-inverted orbit response matrix $R_\mathrm{I}^\dagger$ and the deviation from the reference orbit Δx. This method steers the orbit towards the reference orbit and "locks in" the current energy deviation. A shift in beam energy, noticable as a dispersive orbit

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drift, will then be compensated via rf frequency correction and hence keep the energy deviation at its locked-in value. At the storage ring BESSY, the energy stabilization capabilities of this approach are regularly checked via compton backscattering [1].

Method II: Minimizing the Path Length

An orbit feedback can also invoke a dispersive orbit drift to shorten the orbit length [6]. Firstly, a set of steerer strength corrections

$$\Delta\vec{\theta} = R^{\dagger} \cdot \Delta\vec{x}$$

is guessed via pseudo-inversion of the orbit response matrix [4]. These steer the orbit towards the reference orbit without considering the orbit length. Secondly, the orbit response matrix is extended by adding the frequency response as an additional column

$$R_{\mathrm{II}} = \begin{pmatrix} & \mathscr{D}_1 \\ R & \vdots \\ & \mathscr{D}_J \end{pmatrix}.$$

Thirdly, the absolute steerer strength $\vec{\tilde{\theta}}$ is minimized

$$\min_{\vec{\tilde{\theta}}} \vec{\tilde{\theta}}^{\mathrm{T}} \vec{\tilde{\theta}} \quad \textbf{subject to}$$

$$R_{\mathrm{II}} \cdot (\tilde{\theta}_1, \cdots, \tilde{\theta}_K, \Delta f)^{\mathrm{T}} = R \cdot \left(\vec{\theta} + \Delta\vec{\theta}\right)$$

while maintaining the already optimized orbit position via equality constraints. If less steerer magnets then BPMs are available ($K < J$), inequality orbit constraints have to be used. This method reduces steerer strengths at the cost of a frequency shift and thereby facilitates a dispersive orbit drift towards a shorter orbit length. Similarly to method I, method II combines path length and transverse orbit correction.

SIMULATION

Method II was tested in a storage ring simulation to show that it indeed finds the shortest orbit. The simple storage ring model is implemented in Python and uses the momentum compaction factor, the linear orbit response without dispersion, the dispersion function and the length of all elements from a MAD-X [7] model of DELTA [8] as input. For a given rf frequency and a given set of steerer strengths, the storage ring model then calculates energy deviation and closed orbit. It proceeds like this:

1. select δ;
2. calculate closed orbit according to Eq. (2);
3. calculate path length;
4. test if δ is the equilibrium energy according to Eq. (1) and start over if not.

The path length is calculated by tracking the orbit through a 2D lattice model. The simulation cannot be done solely in MAD-X because it ignores the path length constraint imposed by the rf frequency in the closed orbit calculation. Changing the rf frequency therefore does not change the MAD-X orbit.

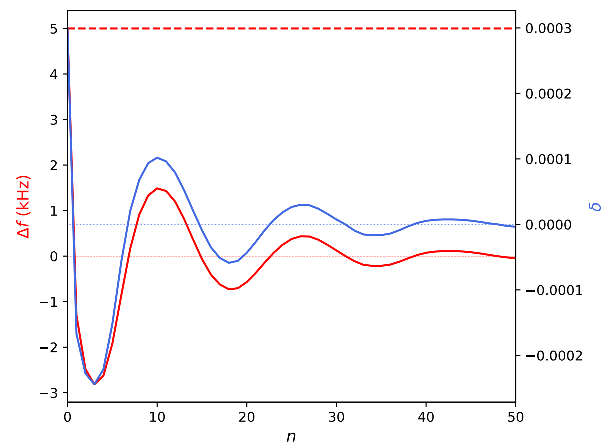

Figure 1: Simulated relative energy deviation δ for an applied frequency shift Δf in step n of method II.

Results

The storage ring simulation was initialized with a frequency shift of 5 kHz and randomly excited steerer strengths. The results of applying method II to this situation are displayed in Fig. 1. The minimization scheme corrects the frequency shift and the energy deviation both to zero as intended. Method II therefore indeed finds the shortest orbit. Due to the shortcomings of the simulation (no non-linear magnetic fields, no higher orders of dispersion), a quantitative analysis of the simulation result is not given here.

MEASUREMENTS

The rf frequency of DELTA in user operation is

$$f_0 = 499.834\,\mathrm{MHz}.$$

Method I

The method was tested by altering the frequency of the storage ring in user operation by up to ±5 kHz expecting the minimization scheme to correct it. As shown in Fig. 2, the results are as expected: when the frequency is perturbed, the root mean square (RMS) of the transverse orbit deviations increases. The orbit correction then corrects the orbit and returns the frequency to

$$499\,833.94\,\mathrm{kHz} \pm 0.04\,\mathrm{kHz}$$

which is very close to f_0. The test was conducted without BPM weights. These are normally used in user operation at DELTA to increase the orbit correction quality at some BPMs located in the injection area and around insertion devices.

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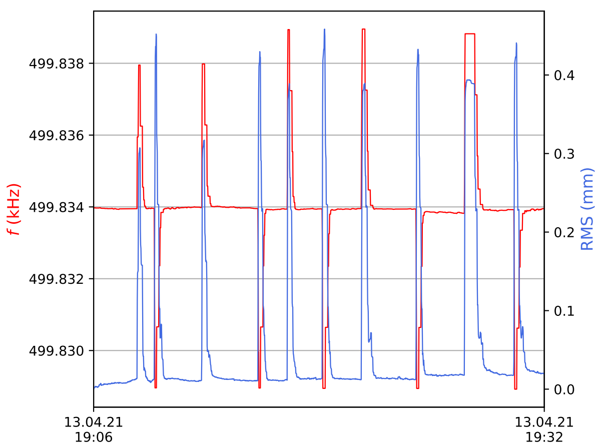

Figure 2: Measured rf frequency f and RMS orbit deviation while applying method I.

Method II

Two experimental tests were conducted. Firstly, the user orbit was optimized. The result is given in Fig. 3. The orbit correction increases the rf frequency until it converges at about 499 835.24 kHz while decreasing the total horizontal steerer currents by about 4.5%. This happens without altering the orbit correction quality (not visible from the figure). It shows the working principle of this method: Replace as much steerer strength with a frequency shift as possible without altering the orbit.

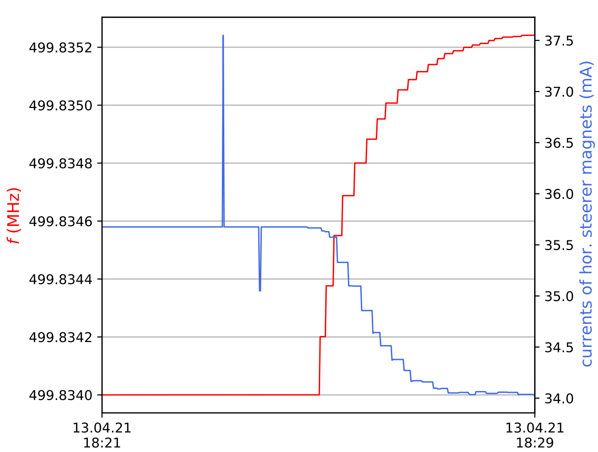

Figure 3: Measured rf frequency f and total horizontal steerer currents while applying method II at user orbit. The two spikes are measurement artifacts.

Secondly, method II was applied in a practical use case. The storage ring at DELTA is operated with a static injection bump in the injection area which can be removed to conduct machine studies. Switching between both modes of operation required manual control of frequency, orbit correction and tune correction up to now. Orbit correction with method II automates part of the process as the measurement presented in Fig. 4 shows.

Back and forth optic switching was conducted about three and a half times. The upper frequency limit

$$499\,835.31\,\mathrm{kHz} \pm 0.07\,\mathrm{kHz}$$

belongs to the optic setting for user operation and the lower frequency limit

$$499\,817.62\,\mathrm{kHz} \pm 0.05\,\mathrm{kHz}$$

belongs to the optic setting for machine studies. Both are reproduced well after each switch. The optimal frequency decreases without bump because removing it increases the orbit length. The injection is located in the east arc of the storage ring where the bump works like a shortcut for the beam. The total horizontal steerer currents also behave as expected. They peak while the orbit switching is conducted and rest at local minima when the correction has converged. Without bump, the total horizontal steerer currents are about 50% smaller.

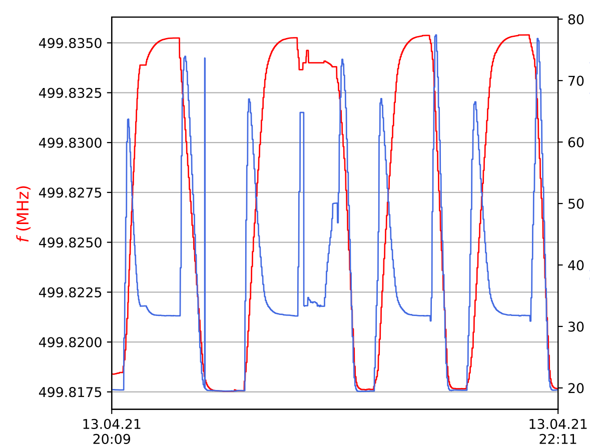

Figure 4: Measured rf frequency f and total horizontal steerer currents while switching between optic settings with method II.

SUMMARY

Two energy correction methods have been tested at DELTA. The first one keeps the beam energy constant and is also used at other storage rings. The second method finds the shortest orbit and was developed at DELTA. It simplifies switching between different optic settings.

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