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Centering of quadrupole family

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Abstract

A procedure for finding the individual centers for a family of quadrupoles fed with a single power supply is described. The method is generalized for using the correctors adjacent to the quadrupoles. Theoretical background is presented as well as experimental data for the NSLS rings. The method accuracy is also discussed.

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1. Introduction

RF beam position monitors (BPM) utilizing signals from pick-up electrodes (PUE) provide good resolution and precision. The absolute accuracy (i.e. position of an orbit in a vacuum chamber) suffers due to various reasons, such as different attenuation in the coaxial cables, deviations in sensitivity of PUE, or unmatched gain in the front end of the receivers.

To improve the absolute accuracy, it was suggested to use the magnetic centers of the quadrupoles for calibration of the BPM [1]. The method is based on varying individual quadrupole strengths by a few percent. If the center of the beam does not pass through the magnetic center of a particular quadrupole, then the beam experiences a deflection θ due to the non-zero field integral. The defection angle is proportional to the orbit deviation from the center (x in the horizontal plane and y in the vertical plane), the quadrupole strength $K1$, and the magnetic length of the quadrupole L_Q:

$$\theta_{x,y} = \pm x, yK1L_Q. \tag{1}$$

The positive sign is used for the vertical plane and the negative sign for the horizontal plane (assuming $K1>0$ for the focusing quadrupoles, $K1<0$ for the defocusing quadrupoles, where positive angles are outwards and upwards). With the change of the quadrupole strength $K1$, the kick changes and the equilibrium orbit varies. The beam position where the orbit does not change with the quadrupole strength corresponds to the magnetic center of the quadrupole.

The orbit deviation caused by a kick can be found from the equations below [2]:

$$x(s) = \frac{\theta_x}{2}\sqrt{\beta_x(0)\beta_x(s)}\frac{\cos[|\phi_x(s)-\phi_x(0)|-\pi\nu_x]}{\sin \pi\nu_x} - \frac{\eta_x(s)\eta_x(0)}{\alpha_c C},$$
$$y(s) = \frac{\theta_y}{2}\sqrt{\beta_y(0)\beta_y(s)}\frac{\cos[|\phi_y(s)-\phi_y(0)|-\pi\nu_y]}{\sin \pi\nu_y}, \tag{2}$$

where $\beta_{x,y}$ are the betatron functions, $\phi_{x,y}$ are the betatron phase advances, s is the longitudinal coordinate with $s=0$ corresponding to the quadrupole location, $\nu_{x,y}$ are the betatron tunes, η_x is the dispersion function, α_c is the momentum compaction factor, and C is the ring circumference. We neglect vertical dispersion because its value is close to zero.

A variation of the quadrupole strength by $\delta K1$ will give two first-order terms for the change in the kicks $\Delta\theta_{x,y}$ [3]. The first is associated with the focusing strength and the

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second is due to a shift of the closed orbit:

$$\Delta\theta_x = -L_Q(K1\delta x + x\delta K1),$$
$$\Delta\theta_y = L_Q(K1\delta y + y\delta K1). \quad (3)$$

For quadrupoles located in a dispersion-free region, Eq. (2) can be simplified by dropping the dispersion term. The formula for the change in kick value induced by the quadrupole strength modulation was obtained in Ref. [3] by solving Eqs. (2) and (3):

$$\Delta\theta_{x,y} = \frac{\pm x, yL_Q\delta K1}{1 - K1L_Q\beta_{x,y}/(2\tan\pi\nu_{x,y})}. \quad (4)$$

By varying the orbit at a particular quadrupole, using local bumps or nearby correctors, one can find the beam position, which provides minimal closed orbit variations with changing quadrupole strength. This procedure allows determination of the offset of the quadrupole magnetic center relative to the BPM center. The method can be easily implemented for accelerators with individually powered quadrupoles. For a storage ring with a quadrupole family fed by a single power supply, it was suggested to utilize the current shunts which allow variation of the current in a single quadrupole without affecting strength of the others [1,4].

2. Quadrupole family centering

In Ref. [5], it was suggested to compensate the variation of the kick of a quadrupole by a built-in or adjacent corrector. The method is based on the orbit "smoothing" algorithm for finding the settings of the adjacent correctors which restore the reference orbit. For the built-in corrector the orbit deviation from the quadrupole center can be found from the change in its strength using Eq. (1). For a stand-alone adjacent corrector one should consider the difference in the values of betatron functions, β, and the betatron phases, φ.

The closed orbit deviation along the storage ring $\varsigma(s)$ caused by the kick $\Delta\delta K1L_Q$ placed at the quadrupole location can be found from the formula below:

$$\zeta_Q(s) = \pm\frac{\Delta\delta K1L_Q}{2}\sqrt{\beta_Q\beta(s)}\frac{\cos(|\phi(s) - \phi_Q| - \pi\nu)}{\sin\pi\nu}. \quad (5)$$

Here Δ is the orbit displacement from the quadrupole center, $\delta K1$ is the change in the quadrupole strength, L_Q is the quadrupole length, ν is the betatron frequency, s is position along the ring. The same formula applies for the trim with the kick α_t.

$$\zeta_t(s) = \frac{\alpha_t}{2}\sqrt{\beta_t\beta(s)}\frac{\cos(|\phi(s) - \phi_t| - \pi\nu)}{\sin\pi\nu}. \quad (6)$$

By a proper choice of the position where $s = 0$, it is possible to remove the absolute value in the cosine argument and thereby simplify further analysis. For the trim strength shown in the formula below:

$$\alpha_t = \mp\frac{\Delta\delta K1L_Q}{\cos(\phi_Q - \phi_t)}\sqrt{\frac{\beta_Q}{\beta_t}}, \quad (7)$$

the uncompensated orbit deviation is the following:

$$\zeta(s) = \pm\frac{\Delta\delta K1L_Q}{2}\sqrt{\beta_Q\beta(s)}\frac{\sin[\phi(s) - \phi_Q - \pi\nu]}{\sin\pi\nu} \times \tan(\phi_t - \phi_Q). \quad (8)$$

The found trim value should provide a least-squares deviation of the orbit because the oscillations are in quadrature with those induced by the quadrupole change. The experimental results can also depend on the distribution of the BPMs along the ring. By inverting Eq. (7), it is easy to obtain the following formula for the orbit offset:

$$\Delta = \frac{\pm\alpha_t\cos(\phi_Q - \phi_t)}{L_Q\delta K1}\sqrt{\frac{\beta_t}{\beta_Q}}. \quad (9)$$

With correctors built into the quadrupoles ($\phi_Q = \phi_t$ and $\beta_Q = \beta_t$), Eq. (9) becomes Eq. (1).

The operation of the orbit-smoothing algorithm [5] is similar to the orbit feedback systems stabilizing beam trajectory in storage rings. Modern orbit feedback and correction systems utilize multiple trims and allow the global orbit in the storage ring to be maintained with high accuracy in real time.

In Ref. [5] it was proposed to use an equal number of trims to the number of quadrupoles in the family. However, during experiments with the NSLS storage rings it was found that the orbit feedback system with the number of trims significantly exceeding the number of quadrupoles in the family also performs adequately. Moreover, there may be an advantage to this configuration because such an approach eliminates systematic errors caused by the orbit variation due to the tune shift. Rotations of the elements about the beam axis of the trim magnets (rolls) introduce an additional source of error in the measurements. These errors can be suppressed by steering the beam to the obtained "centers" and repeating the measurements. The rolls and nonlinearities of the BPMs are of less significance because they are used as "zero" indicators.

Noise in the orbit monitoring system leads to errors in the measurement of the BPM offsets. Improving accuracy through increasing the deviation of the quadrupole strengths may be not an option due to the possible loss of beam stability, especially if there are a significant number of quadrupoles in a family. The tune shift due to the variation of a single quadrupole with β-function β^* can be found from the well-known formula [4]:

$$\Delta\nu = \frac{1}{4\pi}\beta^*\delta K1L_Q. \quad (10)$$

For a quadrupole family, the tune shift is multiplied by the number of quadrupoles in the family N_Q. Let us consider the situation where the orbit deviates by Δ from the center