Simulation and Correction of the Closed Orbit in the Cooler Synchrotron COSY-Jülich

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Abstract

The problem of closed orbit control at COSY-Jülich is discussed. The results of a simulation of the COSY closed orbit and its correction are given using different correction methods. The interactive computer program ORBIT will be described. This code was developed to study the simulation as well as to do the correction. Different correction methods are used. These methods are compensating the orbit deviations with and without identification of perturbations. In order to estimate the necessary corrector strengths and the expected maximum orbit deviations for COSY-Jülich, the orbit correction for more than 200 machine settings with different distributions of the random errors (based on measurements) has been simulated. The maximum orbit deviation is less than 2 mm, whereas the maximum kick strength is less than 1.7 mrad. In 95 % of the cases the maximum kick strength is less than 1.0 mrad.

I. INTRODUCTION

The COoler SYnchrotron COSY-Jülich [1] is a synchrotron and storage ring intended to accelerate protons and light ions up to an energy in the range 200 MeV – 2.5 GeV. The upgraded cyclotron JULIC will be used as an injector.

The transverse motion of the particles in a cyclic accelerator is a superposition of a motion along a closed trajectory (equilibrium or closed orbit) and betatron and radial phase oscillations around this curve. In a real magnetic structure both the closed orbit and the oscillations around it are distorted due to errors in the magnetic fields, displacements and tilts of the elements from their designed positions, stray fields, and ground movements. As far as the closed orbit is concerned, perturbations cause its deformation.

II. MATHEMATICAL OUTLINE

Particle oscillations in an accelerator can be described using the TWISS function $\beta(s)$:

$$x(s) = a\sqrt{\beta(s)}\cos\left(Q\int_0^s \frac{ds}{Q\beta(s)}\right)$$

where Q is the number of betatron oscillations per turn. With two new variables, a generalized azimuth φ , and a normalized deviation η ,

$$\varphi = \int_0^s \frac{ds}{Q\beta(s)}, \quad \eta = \frac{x}{\sqrt{\beta(s)}}$$

the oscillations can be written as

$$\eta(\varphi) = a\ \cos(Q\varphi)$$

In the matrix approach, the normalized deviation at the position of the i-th beam position monitor (BPM) can be written as a linear function of the generalized perturbations:

$$\eta_i = \sum_{\substack{j=1 \\ \varphi_i \le \varphi_j \le \varphi_i + 2\pi}}^{M+L} A_{ij}\delta_j$$

where:

$$A_{ij} = \cos Q(\varphi_i + \pi - \varphi_j)$$

and:

$$\delta_j = -\frac{Q\beta_j^{3/2}}{2\sin\pi Q}\cdot\begin{cases} \Delta B_j + \eta_j\Delta x_j/\rho_j^2\ , & for\ dipoles \\ B_{cj}\ , & for\ correctors \\ g_j\Delta x_j/B\rho\ , & for\ quadrupoles \end{cases}$$

III. ERROR SOURCES

The linear perturbations causing the closed orbit distortion can be summarized as follows

1. constant errors:
   - (a) errors in the coercive force; these kind of errors can be estimated approximately by

     $$\Delta B \approx -\mu_0\frac{\ell_{st}}{\ell_a}\Delta H_c$$

     where ℓ_{st} is the magnet core length and ℓ_a is the aperture
   - (b) errors due to eddy currents
   - (c) stray magnetic fields
   - (d) earth magnetic field
2. errors proportional to the main magnetic field:

(a) permeability errors; approximately

$$\Delta B/B \approx (\ell_{st}/\mu_r^2\ell_a)\Delta\mu$$

(b) errors due to eddy currents

$$\Delta B/B \approx -(1/(\mu_r\ell_a + \ell_{st})\Delta\ell_{st}$$

(c) aperture errors

$$\Delta B/B \approx -(\mu_r/(\mu_r\ell_a + \ell_{st})\Delta\ell_a$$

(d) adjustment errors —
element misalignments, median plane displacements, dipole tilts, quadrupole magnetic center displacements, errors in the coil positions, etc.

(e) ground movement

3. errors appearing only in high fields — these are errors due to saturation.

In the case of the COSY cooler synchrotron the first magnetic measurements [2] showed that random relative field errors with a standard deviation

$$\sigma_{\Delta B/B} = 2 \times 10^{-4}$$

can be expected.

According to the machine design the misalignment errors are going to be

$$\sigma_{\Delta x} = \sigma_{\Delta z} = \sigma_{\Delta s} = 0.25\ mm\ ,\quad \sigma_{\Theta} = 0.3\ mrad\ .$$

IV. ORBIT SIMULATION TOOLS THE COMPUTER PROGRAM ORBIT

Many of the widespread computer codes designed for accelerator design such as MAD, DIMAD, PETROS, etc. have features for closed orbit simulation and correction.

For the case of COSY orbit treatment we used MAD, which possesses features for orbit simulation under the influence of misalignment and field errors, and uses the MICADO algorithm for orbit correction.

Besides MAD, an interactive computer program called ORBIT [3] was developed by one of us, especially intended for closed orbit simulation and correction. ORBIT is designed for PCs running under DOS and was, in its first version, written as a Pascal program. Version 2.0 was rewritten in C. In the meantime, a C version without graphics was adapted to run on a UNIX host. The PC version has a menu driven interface and enhanced graphical capabilities. The initial data about the accelerator – elements, β-functions, phases, lengths, and strengths – can be given either by a user written file or by the MAD output file TWISS.

Given the random errors in field and position, ORBIT is able to simulate the closed orbit, the Fourier spectrum of the orbit, and to prepare a histogram of the maximum orbit deviations for 200 accelerators with different random error distributions. ORBIT can estimate analytically the standard deviation of the orbit and of the orbit maximum. Given the orbit displacements read by the BPMs, ORBIT is able to produce an orbit draft, to interpolate the orbit deviations between the BPMs, and to approximate the orbit spectrum. The interpolation is done using Lagrange and cubic spline methods. For the calculation of the Fourier spectrum of the orbit, Bessel coefficients, broken line and parabolic approximations are used. ORBIT includes six methods for orbit correction: harmonic correction, beam-bump, LSQ method, Bacconier's method, DINAM, and LSQ method with coupled correctors.

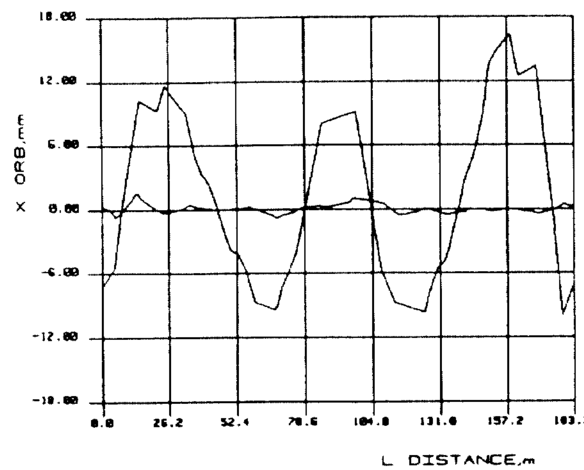

Figure 1. DINAM correction of the COSY horizontal orbit (small amplitudes) compared with the initial orbit (large amplitudes).

V. THE DINAM CORRECTION ALGORITHM

Other orbit correction algorithms described and discussed in detail in [4] strive to compensate orbit deviations in the points where BPMs are situated by the means of some number of orbit correctors. As a result, the corrected orbit will have approximately zero deviations in the BPMs, but non-zero deviations between the BPMs. During the computer simulations it was noticed that in some particular error distributions the deviations of the corrected orbit were out of control in some points. Therefore it is important to correct the orbit over the whole accelerator ring and not only in the BPMs. This leads to the criterion of correction quality as a functional $q = (1/2\pi)\int_0^{2\pi} \eta^2(\varphi)d\varphi$ [5] and, because the orbit $\eta(\varphi)$ is a random function of the generalized azimuth, to an improved criterion by taking the mathematical expectation of the functional

$$q = M\left\langle \frac{1}{2\pi}\int_0^{2\pi} \eta^2(\varphi)d\varphi \right\rangle$$

which is the final form of the correction quality criterion in the DINAM algorithm.

After several substitutions and evaluations described in detail in [4] the quality criterion reads

$$q = \frac{1}{2N}\sum_{i=1}^{2N}\eta_i^2 + \frac{1}{2}\sum_{p=1}^{2N}\sum_{q=1}^{k} A_{pq}\eta_p\delta_q^{Bc} + \frac{1}{2}\sum_{q=1}^{k}\sum_{r=1}^{k} B_{qr}\delta_q^{Bc}\delta_r^{Bc} + 2\sum_{k=n+1}^{\infty}\left(\frac{Q^2}{Q^2-k^2}\right)D$$

The coefficients A_{pq} and B_{qr} describe the optical parameters of the correction system and depend on φ_p, the azimuths of the BPMs, and φ_q, φ_r, the azimuths of the correcting dipoles.

The strengths of the correcting dipoles are determined by the condition for a minimum of q to occur:

$$2\sum_{p=1}^{k} B_{sp}\delta_p^{Bc} = -\sum_{p=1}^{2N} A_{ps}\eta_p \qquad (s = 1, 2, \ldots, k)$$

Introducing the matrices $\mathbf{A} = \{A_{ij}\}$ and $\mathbf{B} = \{B_{ij}\}$ and the vectors $\vec{\delta}^{Bc}$ for the corrections and $\vec{\eta}$ for the BPM readings, this condition can be written in matrix form:

$$2\mathbf{B}\vec{\delta}^{Bc} = -\mathbf{A}^T\vec{\eta} \ .$$

With the matrix

$$\mathbf{R} = -\frac{1}{2}\mathbf{B}^{-1}\mathbf{A}^T$$

which depends only on the azimuths of the BPMs and on the correctors and which, for the given accelerator, can be calculated prior to the correction, the required strengths of the correcting dipoles are determined by the matrix expression

$$\vec{\delta}^{Bc} = \mathbf{R}\vec{\eta} \ .$$

So this algorithm is relatively fast. Computer simulations showed that it works reliably and is free from the undesirable effects mentioned in the beginning of this section. Some results of DINAM corrections on simulated perturbed COSY orbits are shown in Fig. 1 and Fig. 2.

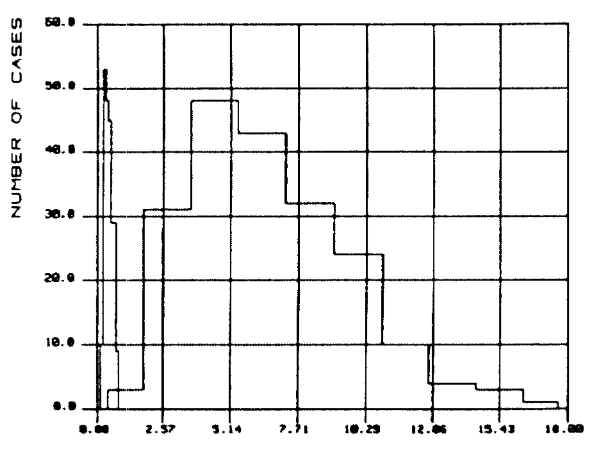

Figure 2. Distributions of maximum horizontal orbit deviations in COSY before and after DINAM correction for 200 machines with randomly distributed errors.

VI. ACKNOWLEDGEMENTS

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