BEAM ENERGY VARIATION WITH DIPOLE FAULT*

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Abstract

Motivated by top-off safety analysis, we consider the case of single dipole faults and study how large an error can be compensated by the closed orbit correction system before the beam is lost.

INTRODUCTION

In NSLS-II, existence of stored beam current will be interlocked in order to assure personal safety during top-off injection. Therefore we need to understand how much dipole field loss due to a shorted coil or power supply failure can be tolerated before the stored beam is lost. In this paper, we study beam energy change with dipole faults and discuss the impact of orbit correction on determining how large a dipole field error can be tolerated before the stored beam is lost.

MODELING OF SHORTED DIPOLE

A shorted coil inside a dipole can create a continuous kick all along the magnet. In the work reported in this paper, we model the extended dipole kick produced by the short using the numeric dipole model in the ELEGANT code with fractional strength error $FSE = \frac{B-B_0}{B_0}$ [1]. Here B is the actual field value, and B_0 the nominal value. This approach allows proper treatment of nonlinear elements – sextupoles.

BEAM ENERGY AND CORRECTOR MAGNET

A thin horizontal kick on the beam at position s_0 creates orbit distortion is given by

$$u_{co}(s) = \theta(s_0)\frac{\sqrt{\beta_x(s)\beta_x(s_0)}}{2\sin(\pi\nu_x)}\cos[\varphi(s) - \varphi(s_0) - \pi\nu_x]. \quad (1)$$

Here all notations are commonly used in all accelerator literatures. The kick can change closed orbit path-length, therefore the beam energy is changed because the RF frequency is fixed. Wenninger [2] studied the influence of such kick on the beam energy for the LEP ring by using simple models as well as simulations with the MAD program. He found an interesting phenomenon: the energy shift due to the second-order orbit lengthening is almost perfectly compensated by the sextupoles when chromaticity has been corrected to zero at LEP. In his paper [2], Wenninger didn't explain this observed compensation. In the following, we will explain the reason for this compensation.

The path-lengthening Λ (up to 2nd order) can be expressed as [2]

$$\Lambda = \Lambda_1 + \Lambda_2 = \oint \frac{u}{\rho} ds + \frac{1}{2}\oint \left(\frac{du}{ds}\right)^2 ds$$

Here u is the closed orbit offset and ρ the dipole radius. The 1st order contribution can be expressed in terms of the dispersion function

$$\Lambda_1 = \eta(s_0)\theta$$

Which means the beam energy deviates linearly with the kick strength if the kick is located in the non-dispersion region. Here η is dispersion function.

Next we calculate the 2nd order contribution. Let's start by neglecting the effect of the sextupoles and use Hill's equation with a thin-lens kick at s_0

$$u \ + K(s)u = \theta\delta(s - s_0).$$

Consider the derivative of the quantity uu

$$\frac{d}{ds}(uu\ ) = u^{\ 2} + uu$$
$$= u^{\ 2} + u[\theta\delta(s - s_0) - K(s)u]$$

Integrating this equation around the whole ring and applying the boundary condition $\Delta u \ = \theta$ at $s = s_0$, we get

$$u(s_0)\theta = \oint u^{\ 2} ds + u(s_0)\theta - \oint K(s)u^2 ds$$

which implies

$$\Lambda_2 = \frac{1}{2}\oint u^{\ 2} ds = \frac{1}{2}\oint K(s)u^2 ds$$

The path-length change due to the orbit off-set inside sextupoles is

$$\Lambda_2 = -\frac{1}{2}\oint \eta K_2(s)u^2 ds$$

K_2 is the normalized sextupole strength. The phenomenon of perfect compensation observed by Wenninger will occur if

$$\frac{1}{2}\oint \eta K_2(s)u^2 ds = \frac{1}{2}\oint K(s)u^2 ds$$

If the sextupole strengths are adjusted to achieve zero chromaticity, the above equation will hold if $u(s)^2$ is proportion to $\beta(s)$. Since the closed orbit depends not only on the beta-function, but also on the betatron phase, the compensation won't be accurate unless

$$\oint \cos^2[\varphi(s) - \varphi(\bar{s}) - \pi\nu]ds \cong \frac{1}{2}$$

The LEP ring is large and has a lattice structure such that the above relation is well satisfied. We have also checked the NSLS-II lattice, which is also sufficient big, such that this relation holds quite well. But for a small ring, such as the NSLS-VUV ring, the compensation isn't so perfect (see Figure 1).

If the kick is located at non-zero dispersion section, beam energy change is proportional to the dispersion function and kicker strength. The energy change plays important role in determining the existence of stored beam because beam tunes change with it. Stored beam may be lost due to large tune change. In the next section we will study beam energy change with gradual field loss of a single dipole in the cases of w/o automatic closed orbit correction.

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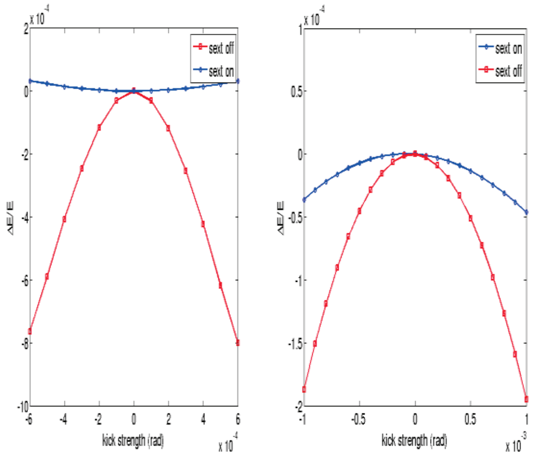

Figure 1: Beam energy changes with a horizontal kick in dispersion-free region. In NSLS-II ring (left) the cancelation is quite accurate (see blue curve), but for the small NSLS-VUV ring (right), the cancelation not so perfect (blue curve).

EXISTENCE OF STORED BEAM WITH SHORTED DIPOLE

The kick from a dipole short is always located in a non-zero dispersion region; therefore beam energy change is proportional to the kick strength and the dispersion function at the kick's location. A simulation using the ELEGANT code [2] was carried out to study the correlation between the strength of the dipole field error and beam loss in the NSLS-II ring. In our analysis, we changed the field in a single dipole gradually to simulate a continuous field drop-off from a shorted coil. Here we discuss two scenarios: with and without automatic closed orbit correction:

Without Orbit Correction

Since RF frequency constrains the path-length of the closed orbit to remain constant, the beam must change its average radial orbit to compensate this path lengthening by changing its energy. The new closed orbit with a single shorted dipole has two contributions: an orbit distortion due to the kick given by Eq. 1, and a dispersive orbit due to energy change. Tunes can be shifted by (1) linear or nonlinear chromaticities, and (2) orbit displacement at the sextupoles. As the example shown in Figure 2 demonstrates stored beam is lost when the horizontal tune approaches a half integer with the reducing dipole field strength. Figure 3 illustrates the beam energy changes during this process.

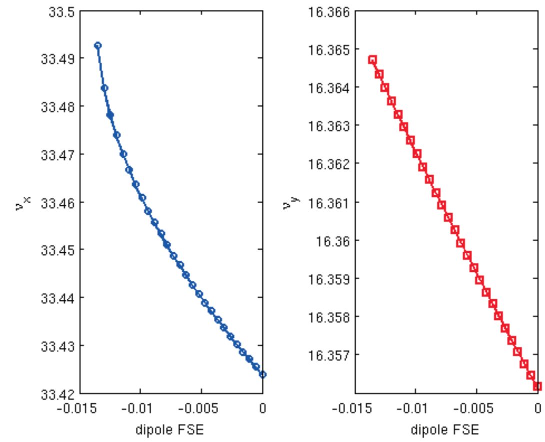

Figure 2: Beam tune-shifts with a single dipole field loss without orbit correction.

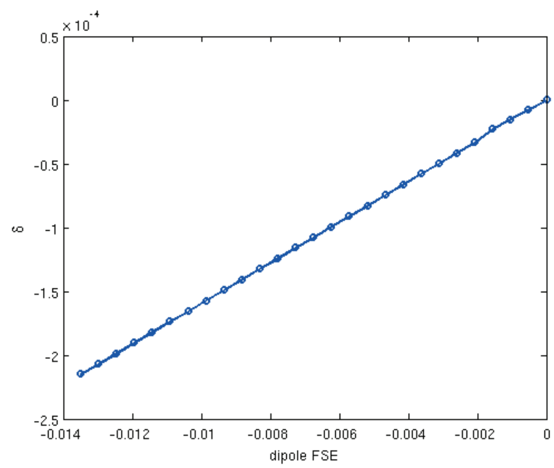

Figure 3: Beam energy change with a single dipole field loss without orbit correction.

With Orbit Correction

Initially closed orbit distortion will be corrected automatically in modern storage rings. SVD algorithm is widely adopted to minimize corrector strengths. As we mentioned before, the closed orbit with a single shorted dipole is composed of a dispersive orbit and a distortion given by Eq. 1. An orbit correction system doesn't distinguish between these two contributions and tries to correct them together. Simulation shows that, after some iteration, corrected orbit is composed of a closed bump to compensate the shorted dipole and a dispersive orbit due to beam energy change (Figure 4). The correction of dispersive orbit inside sextupoles will thwart the cancellation of linear chromaticities by sextupoles (Figure 5). This, in turn, drives tunes to drift significantly even with small beam energy offset. Simulation with the ELEGANT code shows tune-shift increases exponentially with the dipole field loss if automatic orbit correction system is switched on (Figure 6). Therefore, orbit feedback without considering beam energy change does not act to maintain the beam but can actually accelerate its loss at smaller dipole field error.

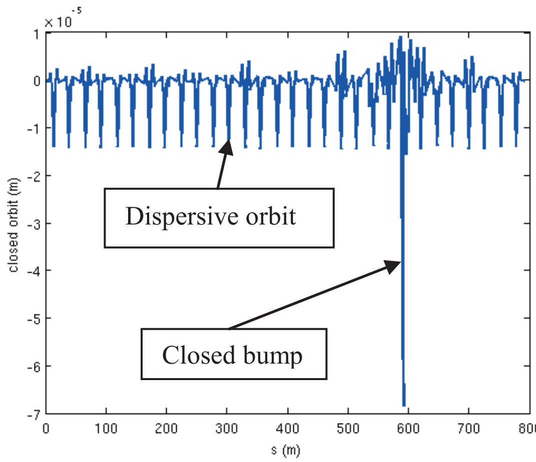

Figure 4: Closed bump to compensate the shorted dipole and dispersive orbit due to beam energy change.

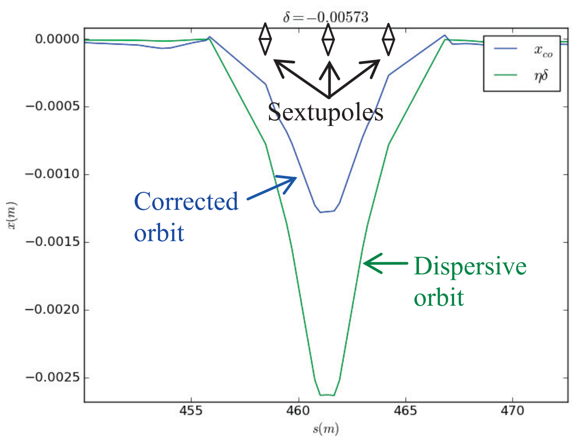

Figure 5: The correction of dispersive orbit inside sextupoles thwarts the cancellation of linear chromaticities by sextupoles.

The rapid increase of tune-shift stops once corrector strengths are saturated. All corrector magnets are designed and manufactured with a limit (0.8mrad in the NSLS-II ring). If a corrector's set-point is larger than the limit, it can't be set properly. Therefore, if any corrector reaches its limit, the local bump to compensate the shorted dipole is no longer closed (Figure 7). Beam energy offset will stop increasing suddenly because second-order orbit lengthening stops (Figure 6). In this case, stored beam will eventually be lost somewhere for the reason that tunes approach some resonance lines or a stable optic solution no longer exists.

SUMMARY

By studying the beam energy change with a thin kick, we provide a simple analytic explanation of why the second-order orbit lengthening is almost perfectly compensated by the sextupoles set for zero chromaticity in large rings. Carrying out an ELEGANT simulation study, we investigated the mechanisms responsible for dipole field errors to result in beam loss. We have found that the automatic orbit correction system without considering beam energy change often doesn't help maintain stored beam. This is because beam energy change is increased due to interference of orbit correction.

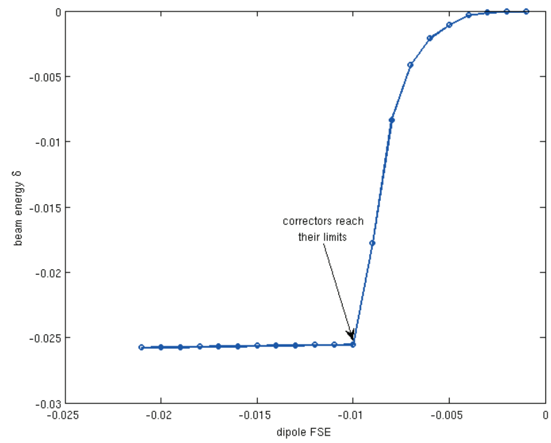

Figure 6: Beam energy change with orbit correction to compensate a shorted dipole. Beam energy change stops once corrector magnets are saturated.

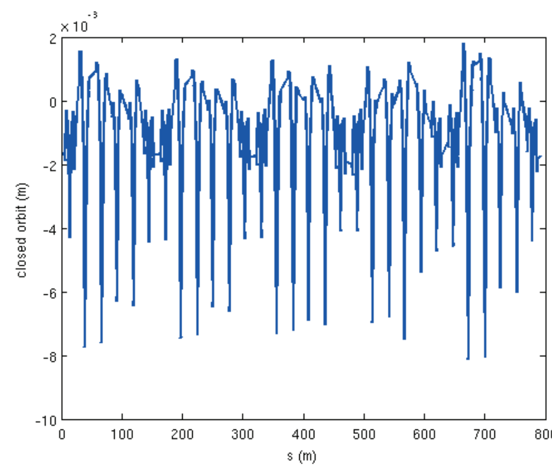

Figure 7: Closed orbit loses the pattern of dispersion function after some correctors are saturated.

ACKNOWLEDGMENT

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REFERENCES

[1] M. Borland, "elegant: A Flexible SDDS-Compliant Code for Accelerator Simulation", Advanced Photon Source LS-287, September 2000

[2] J. Wenninger, Orbit Corrector Magnets and Beam Energy, SL-Note 97-06 OP