Available online at www.sciencedirect.com
ScienceDirect
Nuclear Instruments and Methods in Physics Research A 572 (2007) 607–612
NUCLEAR INSTRUMENTS & METHODS IN PHYSICS RESEARCH Section A
www.elsevier.com/locate/nima

Beam-based measurement of skew-quadrupole field distribution along the longitudinal direction in a long undulator

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Received 21 November 2006; received in revised form 23 December 2006; accepted 27 December 2006
Available online 10 January 2007

Abstract

The skew-quadrupole field errors in an undulator were determined from the response of the stored beam. This method used was to measure the change of the horizontal closed orbit distortion produced by two types of vertical local bump orbit in the undulator. In this method, the unknown distribution of the skew-quadrupole field along the longitudinal direction in the undulator was expressed quantitatively by the multipole moments. Therefore, the reliable result is obtained. In addition, this method is faster than the global modelling of a ring, which uses the response matrix of the whole ring, and is not sensitive to skew-quadrupole field errors in sections other than the target section. Therefore, this method is suitable for measuring the gap dependence.

PACS: 07.85.Qe; 29.20.Dh; 41.60.Ap; 41.75.Fr

Keywords: Undulator; Skew-quadrupole field; Beam-based measurement; Local bump; Moment; NewSUBARU

1. Introduction

Recently, top-up operation has been performed in many storage rings [1–5], and it is expected to become a standard for low emittance synchrotron radiation rings. The beam current is maintained by occasional injections; therefore, a long beam lifetime is not an essential parameter for a ring. This enables operation with low transverse coupling, which gives vertically diffraction-limited light. Consequently, the control of the coupling sources becomes more important. One potential problem would be a skew-quadrupole imperfection field in the undulator, because it is not static with respect to its gap dependence. Another issue for top-up operation is injection with the undulator gap closed. This requires extreme control of the beam-loss accompanying the injection, in order to prevent radiation damage to the magnets of the in-vacuum undulator. This could lead to the problem that an unwanted skew-quadrupole field might sometimes reduce the injection efficiency.

In normal cases, skew-quadrupole field errors in the undulator are determined by direct measurement of the magnetic field distribution at a bench. By contrast, for an undulator, which cannot be moved easily, beam-based measurement is useful. One example is 10.8 m long undulator (LU) at NewSUBARU storage ring, which is very long and not designed for frequent replacement. The main parameters of NewSUBARU storage ring [6] are listed in Table 1. This storage ring is a racetrack-type, with two 14 m long straight sections. In one of the long straight sections, a permanent magnet, planar-type, out-of-vacuum 10.8 m LU [7] is in operation. The main parameters of LU are listed in Table 2.

The changes of the horizontal closed orbit distortion (COD) produced by two types of vertical local bump orbits in the undulator give sufficient information about the linear coupling. Generally, various parameters, such as transverse linear and non-linear field and vacuum chamber

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doi:10.1016/j.nima.2006.12.046

Table 1
Main parameters of the storage ring

Electron energy	0.5–1.5 GeV
Injection energy	1.0 GeV
Circumference	118.731 m
Type of bending cell	Modified DBA
Betatron tune ν_x/ν_y	6.30/2.23
Natural emittance at 1 GeV	38 nm
Natural energy spread at 1 GeV	0.047%

Table 2
Main parameters of LU

Type	Planar, our of vacuum
Magnet	Permanent Nd–Fe–B
Number of periods	200
Period length	54 mm
Gap	119–25 mm
K	0.3–2.5
Total length	10.8 m

impedance, are determined from beam response to a local bump [8–21]. These methods assumed a local, which means infinitely thin, error source. On the other hand in the present method, skew-quadrupole field error distributed along the longitudinal direction is determined. The unknown distribution of the skew-quadrupole field errors along the longitudinal direction in an undulator is expressed quantitatively by their multipole moments. In many storage rings, skew-quadrupole field error can be also determined using the response matrix of the whole ring assuming local error, namely three errors in one undulator section [22,23]. Results from these two methods are mathematically identical, however, the meaning of three local errors and their measurement accuracy would not be clear to a member of undulator group. In the present method, the measurement errors for the moments along the longitudinal direction have no correlation. Also, this method is faster than the global modelling of a ring and is not sensitive to skew-quadrupole field errors in sections other than the target section; therefore, the result is simple and clear. This method is suitable for measurements with various undulator gaps, because rapid measurement is possible.

This paper reports analytical formulae for this local bump method, and the measurement of LU at NewSUBARU. Using this method, it was confirmed that the gap-dependent skew-quadrupole field errors had been cancelled by the shimming technique [24] and the correction coils.

2. Analytical formulae for longitudinal moments

2.1. Moments of skew-quadrupole field

The coordinates x, y and s used here are the horizontal and vertical displacements, and the longitudinal coordinate, respectively. In order to express the distribution of the skew-quadrupole field along the longitudinal direction, we use the moments along the s-axis. Assuming that the undulator is located from $s = -s_0$ to $s = +s_0$ and the skew-quadrupole field is distributed along the undulator, the Nth moment M_N is defined by Eq. (1):

$$M_N \equiv \int_{-s_0}^{s_0} s^N K(s)\,\mathrm{d}s. \tag{1}$$

Here, N is a non-negative integer and K is the skew-quadrupole field given by Eq. (2):

$$K \equiv \frac{1}{B\rho}\left(\frac{\partial B_x}{\partial x}\right). \tag{2}$$

Here, B_x is the horizontal magnetic field and $B\rho$ is the momentum of reference electron.

In the following discussions, we assume that K is extremely small and ignore the higher order terms with respect to K. We also assume that the undulator is in free space, and that the beam focusing caused by the undulator is negligible. Analytical formulae considering the natural focusing of the undulator are given in Appendix A.

2.2. Linear transfer matrix with small skew-quadrupole field

When there is a local skew-quadrupole field with strength $K\Delta s$ at $s = s_K$, the 4×4 linear transfer matrix through the undulator is given by Eq. (3):

$$\begin{pmatrix} x(s_0) \\ x'(s_0) \\ y(s_0) \\ y'(s_0) \end{pmatrix} = \begin{pmatrix} 1 & 2s_0 & K\Delta s(s_0 - s_K) & K\Delta s(s_0 + s_K)(s_0 - s_K) \\ 0 & 1 & K\Delta s & K\Delta s(s_0 + s_K) \\ K\Delta s(s_0 - s_K) & K\Delta s(s_0 + s_K)(s_0 - s_K) & 1 & 2s_0 \\ K\Delta s & K\Delta s(s_0 + s_K) & 0 & 1 \end{pmatrix} \times \begin{pmatrix} x(-s_0) \\ x'(-s_0) \\ y(-s_0) \\ y'(-s_0) \end{pmatrix}. \tag{3}$$