PRELIMINARY ORBIT MEASUREMENT FOR BEAM-BASED ALIGNMENT

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ABSTRACT

A part of the excitation current of a quadrupole magnet is shunted through the electronic shunt circuit, then the closed orbit receives the perturbation due to the current reduction. If this method is repeatedly applied to all quadrupoles, the transverse misalignment can be obtained by taking the orbit difference before and after applying shunt. The preliminary orbit measurement for the beam-based alignment (BBA) method was made for the TRISTAN-AR ring to see the validity of this method.

1 INTRODUCTION

So far the accelerator magnets in a modern synchrotron are aligned precisely along the pre-determined orbit with an accuracy of 0.1 mm (rms) by using optical instruments such as level and theodolite and with specially designed device to measure the offset length with an accuracy of 0.01 mm. To attain this accuracy, however, an indescribable effort is required. It includes booking data obtained by measurements down to a unit of μm and subsequent data processing to calculate the magnet displacement which is corrected by using tools and indicators such as micrometer to measure the relative displacements to every direction. Moreover, it requires frequent calibration of instruments. Several years ago the powerful instrument - laser tracking survey system - which utilizes the built-in laser interferometer was introduced. An accuracy of length to the direction of the laser is excellent but poor to its transverse direction due to the resolution of the angle measurement. It is contributing to the great reduction of the manpower for the accelerator survey, but procedure of the precise magnet alignment and attainable alignment accuracy are not so much different from the conventional one.

With the development of the accelerator technologies, the beam orbit can be measured accurately and the slight perturbation applied to the beam distorts the closed orbit which can be detected with the beam position monitors (BPM) installed in the synchrotron. This offers a new alignment method called a beam based alignment (BBA). Even if this method could provide us with more precise magnet positioning, the conventional method mentioned above is not dispensable because all magnets must be aligned precisely before the beam commissioning starts, then the BBA procedures begin.

2 EQUATION OF PARTICLE MOTION

The BBA method imposes a kind of perturbation to a quadrupole magnet such as to reduce the excitation current bypassing a part of current to a shunt attached across the magnet current terminals. If there is an orbit excursion at this magnet, beam senses the change of the deflection strength and travels along the subsequent different closed orbit. The equation of motion of the particle is

$$\frac{d^2\eta}{d\phi^2} + \nu^2\eta = \nu^2\beta^{3/2}F(s), \qquad (1)$$

where $F(s) = \Delta B/B\rho$. Here $B\rho$ is the magnetic rigidity and $\Delta B(= B_z - B_0)$ the deviation from the ideal field. The periodic solution is

$$\eta(\phi) = \frac{\nu}{2\sin\pi\nu}\int_{\phi}^{\phi+2\pi} f(\psi)\cos\nu(\pi+\phi-\psi)d\psi, \qquad (2)$$

where $f(\psi) = \beta^{3/2}F(s)$ [1]. If $\eta = \beta^{-1/2}y$ and $ds = \nu\beta d\psi$ are introduced, the beam position at an azimuthal position s is

$$y(s) = \frac{\sqrt{\beta(s)}}{2\sin\pi\nu}\sum_j \theta_j\sqrt{\beta_j}\cos\nu[\varphi(s) - \varphi_j + \pi] \qquad (3)$$

before applying a current shunt, where $\theta_j = \Delta B l_j/B\rho$ is a kick angle and l_j is the j-th magnet length. If a current shunt is active for the n-th quadrupole, the tune changes from ν to ν' and the betatron function changes,

$$y'(s) = \frac{\sqrt{\beta'(s)}}{2\sin\pi\nu'}\sum_j \theta'_j\sqrt{\beta'_j}\cos\nu'[\varphi'(s) - \varphi'_j + \pi], \qquad (4)$$

where notations with a prime give those while the shunt is active. If $j \neq n$, $\theta'_j = \theta_j$. Otherwise, $\theta'_n \neq \theta_n$. Then,

$$y'(s) = \frac{\sqrt{\beta'(s)}}{2\sin\pi\nu'}\{\sum_{j\neq n}\theta_j\sqrt{\beta'_j}\cos\nu'[\varphi'(s) - \varphi'_j + \pi] + \theta'_n\sqrt{\beta'_n}\cos\nu'[\varphi'(s) - \varphi'_n + \pi]\}. \qquad (5)$$

If the differences of beta-function and phase advance are taken into consideration, the following misalignment equation is obtained in the first order approximation [2] [3].

$$\{\Delta y\} = (B)\{\xi\}, \qquad (6)$$

where {Δy} and {ξ} are column vectors for orbit excursion and quadrupole magnet offset, respectively. (B) is an NxN matrix whose elements are

$$B_{mj} = \frac{\sqrt{\beta_m \beta_j}}{2\sin\pi\nu} \frac{G_j l_j}{B\rho} \{[\frac{\Delta\beta_m}{2\beta_m} + \frac{\Delta\beta_j}{2\beta_j} - \frac{\pi\Delta\nu}{\tan\pi\nu}]$$

$$\cdot \cos\nu\Phi_{mj} - [\Phi_{mj}\Delta\nu + \nu\Delta\Phi_{mj}]\sin\nu\Phi_{mj}\}$$

for $j \neq n$, and

$$B_{mn} = \frac{\sqrt{\beta_m \beta_n}}{2\sin\pi\nu} \frac{G_n l_n}{B\rho} \{[\frac{\Delta\beta_m}{2\beta_m} + \frac{\Delta\beta_n}{2\beta_n} - \frac{\pi\Delta\nu}{\tan\pi\nu}$$

$$+ \frac{\kappa}{100}]\cos\nu\Phi_{mn} - [\Phi_{mn}\Delta\nu + \nu\Delta\Phi_{mn}]\sin\nu\Phi_{mn}\}$$

for j = n, (7)

κ is a percent change of the field gradient of the n-th quadrupole with gradient G_n and length l_n as expressed by

$$\theta'_n - \theta_n = \xi_n \kappa G_n l_n / 100B\rho. \quad (8)$$

If the matrix elements, B_{mj} and B_{mn}, are given numerically for a fixed n, the n-th magnet transverse displacement can be found by solving eq(6). These relations are hold for both horizontal and vertical plane independently when no coupling exists between both planes. As the effect of the current shunt on one quadrupole appears in all BPM, one BPM may be used to monitor the change of the beam orbit.

3 NUMERICAL EXAMPLES IN THE LINEAR FIELD

To get the generalized relation, the (B) matrix must be established numerically. The TRISTAN-AR ring is selected for this purpose. Two optics, with and without a current shunt to one specified quadrupole magnet, are calculated using a modified MAGIC code which has been rewritten for this purpose. If the current shunt allows the current reduction by 5% for QR8-NW quadrupole, every beam position monitor gives different reading. Two typical readings are shown in Fig.1, where BPM's close to QC4-SW and QF10-NW are selected. (QC4 and QF10 are the quad names. SW and NW give their locations.) Beam position changes linearly with the magnitude of misalignment.

If the linear relations at a specified BPM can be established for all quadrupole magnets, misalignments can be predicted by activating the current shunt sequentially. Every quadrupole has alignment errors more or less even if the orbit error is corrected with steering dipoles, however, their effects are piled up and the BPM readings change retaining a linear relation as shown in Fig.1 where are assumed random misalignments to all quadrupoles except for QR8-NW which has a fixed misalignment.

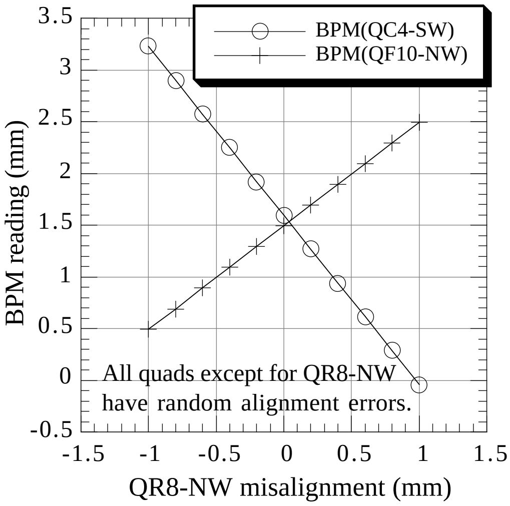

Figure: 1 Estimated beam position monitor readings for κ=5% for misalignment of a quadrupole magnet (QR8-NW) at two points, 1300 deg upstream (QC4-SW) and 270 deg downstream (QF10-NW) of QR8-NW. All quads have random alignment errors in addition to the fixed error of QR8-NW quad.

If the orbit is not corrected with steering dipoles, the BPM readings reflect all quadrupole misalignments. Taking the orbit difference before and after the current shunt is activated, the related quadrupole misalignment can be obtained.

4 IMPROVED MODEL SHUNT CIRCUIT APPLICABLE TO LOW VOLTAGE TERMINAL

A current shunt is a circuit connected parallel to a quadrupole magnet as shown in Fig.2. A part of the exciting current of the quadrupole flows through this circuit while it is conducting. It modifies the quadrupole current and affects the beam orbit if the closed orbit deviation from an ideal one is not zero. Two kinds of shunt is realized, resistive [4] and FET current shunts. In the present study the latter shunt was used because it is easy to control the shunt current accurately for more than 1 min without a fear of drift as in the case of the resistive shunt.

The FET shunt uses the metal oxide semiconductor field-effect transistor (MOSFET) parallel to the magnet coil and the current shared to the shunt is specified by the reference signal from the digital-to-analog converter (DAC). The allowable maximum shunt current is limited by the saturation of MOSFET. The 25A current sharing is attained for the 4.1 V terminal voltage. The sharing duration is 60 sec for this current by using the heat radiating fin. During this period all BPM's can be scanned.

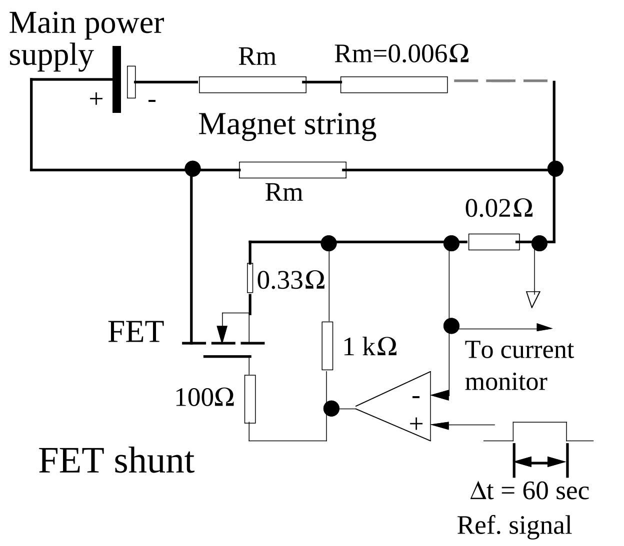

Figure: 2 Simplified model circuit of the FET current shunt.

Either of two types of the current shunt can be incorporated into the beam control system to predict the quadrupole misalignments. Applying the current shunt to every quadrupole sequentially for a short time during the BPM readings can be stored, a complete data set for BBA is obtained. For this purpose, the individual resistive current shunt will be required to every quadrupole because the shunt resistivity differs by the cable length to the quadrupole magnet. While the FET current shunt does not depend on the cable length, so the multiplex system can be economically constructed using only one shunt unit.

To investigate the BBA validity at injection field, an FET shunt is multiplexed to several quadrupole magnets of TRISTAN-AR ring. A terminal voltage of each quad is as low as 1.7V, so an additional voltage source was equipped to the FET shunt so as to feed reverse current to quad as shown in Fig. 3.

5 PRELIMINARY STUDY ON MISALIGNMENT AT TRISTAN-AR RING BY BBA METHOD

The horizontal and vertical closed orbit were measured by applying the FET shunt to a focusing (F-) and defocusing quad (D-quad) separately. Fig. 4 shows the comparison between measurement and calculation for an F-quad (QR6-NW). Local orbit bumps were given at this quad to practice the misalignments and a few percent of its current was reduced by activating the FET shunt. Applied local orbit bump is well large as compared with the actual misalignment, an order of 0.1 mm. From Fig.4 the BBA method can predict the misalignment of 20 μm if the BPM reading is as accurate as 5 μm.

In summary this method will offer an elegant and precise magnet alignment method, but it still requires the further study to get more stringent coincidence between measurement and calculation.

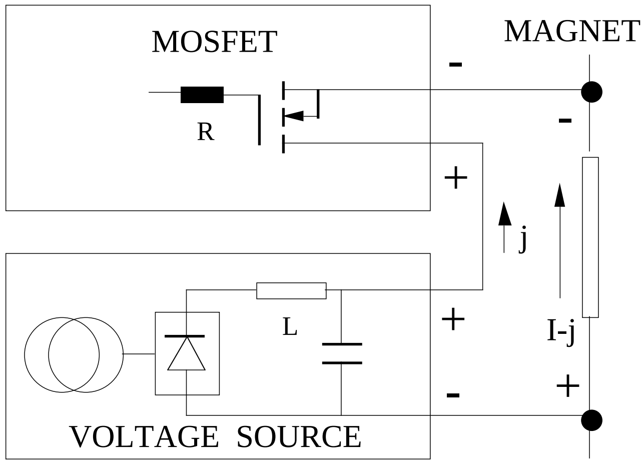

Figure: 3 Voltage source to feed the forced reverse current to the magnet. It produces compensation voltage to the FET shunt of Fig.2 when used at lower terminal voltage.

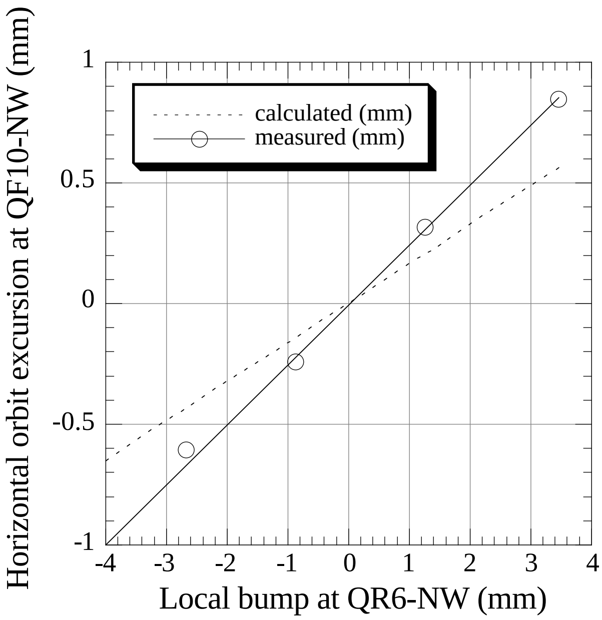

Figure: 4 Comparison between the orbit measurement and calculation for a quad (QR6-NW). Shunt current (10A) is 3% at injection field.

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