Beam-Based Measurement of Focusing Errors in Quadrupole Magnets by a Local Bump Orbit in ATF-Damping Ring

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Abstract

The strength deviation of the quadrupole magnets from its design values in ATF-Damping ring was measured by the π-bump method. The horizontal phase advance in the arc sections was tuned to its design value with the residual error being less than 0.1%.

1 Introduction

It is essential to establish the beam-based diagnostics of beam in an accelerator to deduce its ultimate performance. Recently the commissioning of ATF-Damping Ring (DR) has been started[1] and work on the beam-based diagnostics of optics has been done[2], in which the optics was checked by the response of the beam orbit under the excitation of a corrector magnet. In this report, we show another method, so-called π-bump method[3], utilizing a local bump orbit to detect the small optics disturbance.

A π-bump is a local bump excited by a pair of orbit correction magnets (correctors) between which the betatron phase advance is designed to be exact π radian (or multiple of π). Due to this special phase advance, the bump orbit by these two correctors can be completely confined in the local region between the correctors (the bump region) and no change of the beam orbit appears in the downstream of the beam line. In other words, if we observe a "leakage orbit" in the downstream, it indicates the existence of the disturbance of optics within the bump region. A possible source of the disturbance is strength deviation of quadrupole magnets. Accordingly, an observation of the leakage orbit allows us to measure the deviation and to tune the local optics to its designed one by compensating the deviation.

Let us describe the basic ingredients of π-bump. Suppose a ring into which the pulsed (bunched) beam is being injected. Let ST1 and ST2 are (thin) correctors in the ring, located at $s = s_1$ and s_2 ($s_1 < s_2$), where s is the azimuthal coordinate along the ring (from the injection point to downstream), and $T(s_2|s_1)$ be the transfer matrix from ST1 to ST2. An excitation of ST1 changes the orbit at ST2 by

$$T(s_2|s_1)\begin{pmatrix} 0 \\ k_1 \end{pmatrix} = k_1 \begin{pmatrix} c_1 \sin\chi \\ c_2\cos\chi + c_3 \sin\chi \end{pmatrix}, \qquad (1)$$

where k_1 is the kick angle of ST1 and χ is the phase advance from ST1 to ST2. The coefficients c_i ($i = 1, 2, 3$) are written by Twiss parameters at s_1 and s_2. From Eq. (1), we see that the orbit in the downstream of ST2, $s > s_2$, does not change at all *if* and *only if* the following two conditions are fulfilled at the same time:

$$\chi = n\pi, \qquad (2)$$

and the kick angle of ST2 is

$$k_2 = (-1)^{n+1} c_2\, k_1, \qquad (3)$$

where n is an integer. The constant c_2 is found to be $\sqrt{\beta(s_1)/\beta(s_2)}$, where $\beta(s)$ is the betatron function.

A localized focusing error within the bump region violates the condition in Eq. (2) and produces a leakage orbit in the downstream. If we have N of such errors, δg_j ($j = 1, \ldots, N$), located at t_j ($s_1 < t_j < s_2$), the resulting leakage orbit, $X(s)$, is

$$X(s) = K\sqrt{\beta(s)} \sum_{j=1}^{N} \delta g_j \beta(t_j) \sin\psi(t_j) \sin(\psi(s) - \psi(t_j)), \qquad (4)$$

where $K = k_1\sqrt{\beta(s_1)}$ and ψ is the phase from ST1.

If ST2 fails to satisfy Eq. (3), we have a leakage orbit too. Let δK be the unbalance between the kicks by ST1 and ST2, then the leakage orbit is

$$X(s) = \delta K \sqrt{\beta(s)} \sin\psi(s). \qquad (5)$$

From Eqs. (4) and (5), $X(s)$ is expected to be a sinusoidal form, $\sqrt{\beta(s)}\,(a \sin\psi(s) + b\cos\psi(s))$, where

$$a = K\sum_{j=1}^{N} \delta g_j W_a(t_j) + \delta K, \qquad (6)$$

$$b = -K\sum_{j=1}^{N} \delta g_j W_b(t_j). \qquad (7)$$

Note that only a includes the contribution originated from the corrector unbalance. Each focusing error is weighted by $W_a(s) = \beta(s)\sin\psi(s)\cos\psi(s)$ in the summation for a while by $W_b(s) = \beta(s)\sin^2\psi(s)$ for b. These weight functions, W_a and W_b, are defined in the bump region.

2 Measurement

ATF-DR consists of two arc sections, West and East Arc, and two straight sections. A specially designed optics was set for our measurement, in which the designed phase advance of the unit cell in the arc sections is tuned to be $3\pi/4$ in the horizontal while $\pi/5$ in the vertical direction. The unit cell is FOBO, where the main horizontal focusing is provided by quadrupole magnets (series QF2R) while the defocusing is provided by combined bending magnets (series BH1R). In Fig. 1, the geometrical shapes of these π-bump orbits are shown. A horizontal π-bump extends over 4 unit cells and the phase advance within the bump region is 3π, while a vertical π-bump covers 5 cells and the phase is π.

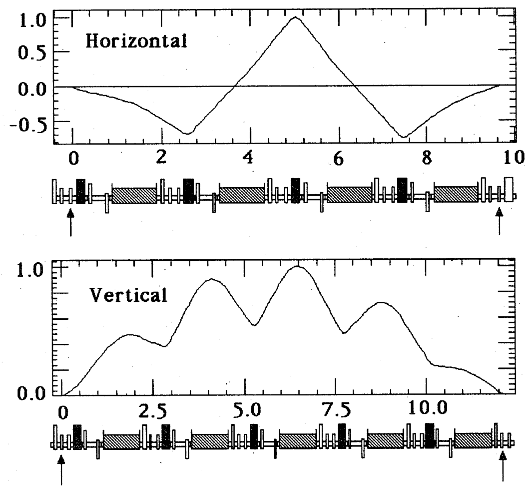

Fig. 1 Geometrical shape of a horizontal (upper figure) and a vertical (lower) bump orbit in the arc. The orbits are normalized by their maximum values. The abscissas are s (meters). The lattice configurations are shown in the bottom of each picture. The correctors to excite the bump are pointed by arrows. The magnets of QF2R (quadrupole, horizontally focusing) in the bump region are painted out and those of BH1R (combined bend, horizontally defocusing) are shaded in the figure.

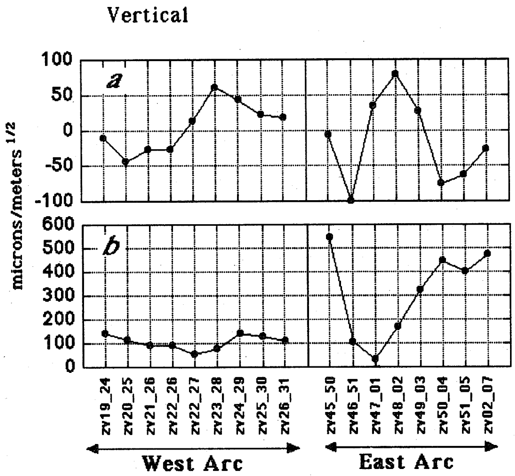

Fig. 3 The observed coefficients a and b of leakage orbits for the vertical bumps in West and East Arc. The bumps are named by the correctors to produce it.

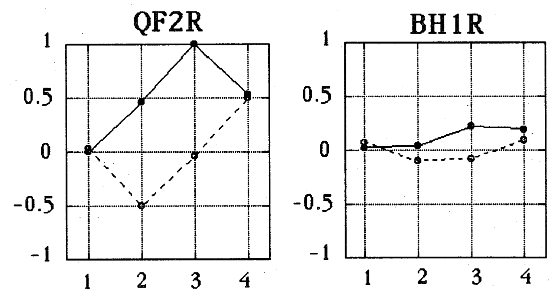

Fig. 4 Values of W_a (dotted line) and W_b (solid line) at QF2R and BH1R magnets in the horizontal π-bump. The magnets are numbered from upstream to downstream. The values of W_a and W_b are normalized by the W_b at the third QF2R magnet. This magnet, which locates almost the center of the bump region, has the maximum weight in the summation for b.

The single-bunched beam was injected from ATF Linac into DR (repetition 0.75 Hz) and the one-turn orbit downstream of the bump region was measured. The orbit was averaged over a few tens pulses to reduce the statistical noise. The leakage orbit is obtained by subtracting the orbit of the bump being off from that of on. We turned off all the sextupole magnets in the ring during the measurement in order to get rid of their effects on the measurement.

The observed leakage orbit is normalized by $\sqrt{\beta}$ and fitted to a sinusoidal function, $a \sin \psi(s) + b \cos \psi(s)$, where a and b are the fitting parameters, linked with the focusing errors through Eqs. (6) and (7), respectively. The resulting a and b are the input data for the

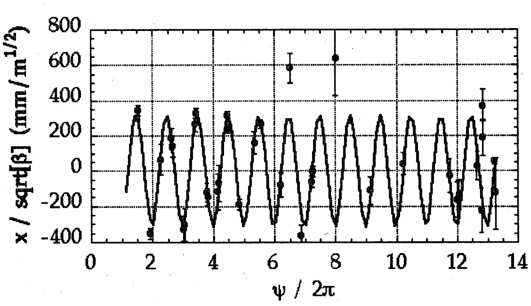

Fig. 2 The fit of a leakage orbit to a sinusoidal curve. The ordinate is the orbit normalized by $\beta^{1/2}$ and the abscissa is the phase advance from ST1 (divided by 2π). The error bars represent the statistical noise in the orbit measurement.

correction of the local optics within the bump region. An example of the fit of the horizontal leakage orbit is shown in Fig. 2. In this particular example, we found $a = 31 \pm 10$ and $b = -311 \pm 9$ (microns/meters$^{1/2}$) for $K = 1.5$ mrad $\times \sqrt{3.75}$ meters$^{1/2}$.

We measured the leakage orbits for 18 horizontal and 17 vertical bumps. We discuss the fitting results of horizontal leakage orbits in the next section. Here we show the result of the fitting for vertical leakage orbits. See Fig.3. We found large b coefficients for the bumps in East Arc, which indicates large strength deviations of the quadrupole magnets there.

3 Beam-Based Correction of the Focusing Error

If we have only a single source of focusing error in a bump region, i.e., $N = 1$ in Eqs. (6) and (7), the error δg and the corrector unbalance δK are uniquely determined. This is not the case since there should be a

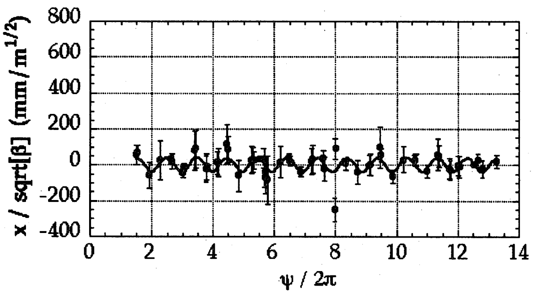

Fig. 5 Observed leakage orbit after correction. Compare this orbit with the orbit before correction, shown in Fig. 2. In this example, the target was QF2R.25. The elimination of b component of the leakage orbit indicates the phase is tuned to be its design value (3π). We find $a = -11 \pm 18$ and $b = -38 \pm 18$(microns/meters$^{1/2}$).

lot of error sources in general. However, if a single error source dominates others in the summation for a or for b, we can know it in good accuracy.

As for a horizontal π-bump in AFT-DR, there are 4 QF2R and 4 BH1R magnets within the bump region (Fig. 1). The values of W_a and W_b at these magnets are shown in Fig. 4. The third QF2R magnet has the largest weight for b although we cannot say this magnet dominates others. At any rate, this magnet is the most important in the summation for b. We call this magnet the target. The target is used for the correction of the local optics in the bump region.

The phase advance within a bump region is tunable by changing the strength of the target. Since W_a is almost zero at the target, only the "b component" of the leakage orbit can be controlled by the target. In fact, as shown in Fig. 5, the size of the leakage orbit in Fig. 2 was significantly reduced by tuning the target. We found the b component was reduced while "a component" almost remained uncorrected. This is actually what we expect.

We applied a simple prescription to tune the local optics in all of the horizontal bump regions: each of the targets is changed at the same time based on the observed data of each leakage orbit. By this prescription, however, the tuning is not perfect, since the regions are overlapped each other, i.e., the target in one bump region is also contained in another (neighboring) bump and there occurs an interference between the actions of targets. The interference is smaller and smaller when the target dominates more and more. Although the target does not dominates other magnets so much in ATF-DR, we tried this simple prescription. The validity of this prescription can be checked easily by remeasuring the leakage orbit. The result is shown in Fig.6. We see that b components of the leakage orbits are reduced much. The typical size of a does not change, although a itself changes due to the interference between the targets. The typical size of the residual b component orbit is the same as that produced by the strength deviation of 0.2% of the target. In conclusion, the phase advance in each bump in the arc section was tuned to $3\pi(1+\delta)$, where the typical size of the residual error is $|\delta| \sim 10^{-3}$.

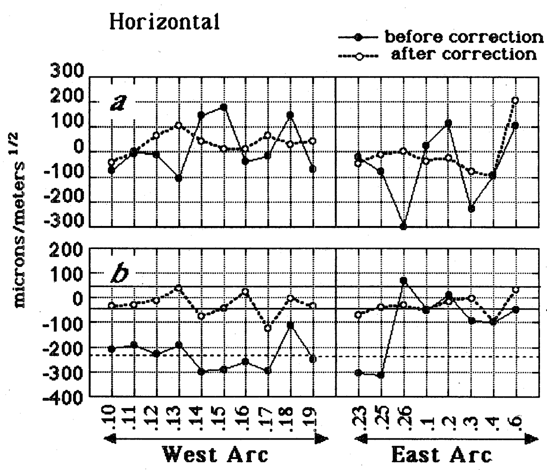

Fig. 6 The coefficients a and b of the fit for the horizontal leakage orbits of the first (before correction) and the second (after correction) measurement. The bumps are named by the target magnets. The strength of the targets was changed by the data fitted b of the first measurement. If the target deviates 0.2%, it produces b component leakage orbit of 50 microns/meter$^{1/2}$. This and the level of 1% target error are shown as the horizontal line in the bottom figure.

4 Conclusion

The correction of the horizontal phase advance in the arc sections was successfully done by the π-bump method, whereas some improvement may be possible, for example, the correction can be better if we take the interference of the targets into account before we set the correction current on the target. At any rate, it was proven that this method is very sensitive and the local phase advance can be tuned precisely by this method.

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