# BEAM ORBIT, TUNE AND CHROMATICITY IN THE SPRING-8 BOOSTER SYNCHROTRON

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## *Abstract*

Optimization of the excitation pattern of the magnets and a study on the beam energy loss of the SPring-8 booster synchrotron are reported. In order to observe closed orbit distortion (COD), tune, and chromaticity at certain beam energies, an energy-constant period was formed with a time of 100 ms in the region of the energy-ramping period. Using the horizontal COD, energy loss per turn relative to beam energy was observed. Based on the measurements of betatron tunes at the energy-constant period, the excitation patterns of quadrupole and sextupole magnets were optimized for single-bunch operation.

## 1 INTRODUCTION

The SPring-8 synchrotron accepts an electron beam with an energy of 1 GeV from the SPring-8 linac. The beam is accelerated up to 8 GeV and then ejected to stack into the SPring-8 storage ring [1]. The synchrotron consists of a FODO lattice of 40 cells and its circumference is 396.124 m. There are 64 bending, 80 quadrupole, 60 sextupole, and 80 correction magnets.

In the synchrotron, beam energy is changed with some acceleration patterns. In normal operation, the beam energy is kept constant in the injection with a period of about 250 ms (flat-bottom). Then, it is increased linearly in the energy-ramping at about 350 ms and is kept constant in the ejection at about 130 ms (flat-top). The magnets are excited with the cycle pattern (Fig. 1). This acceleration pattern is called normal-pattern in this paper. Eight five-cell rf cavities of 508.58 MHz were installed in the straight section of injection side. The effective rf voltage can be changed by controlling phases of two klystrons outputs. Each klystron drives four rf cavities.

A single-bunch beam is formed in the synchrotron and injected in one or some rf buckets in the storage ring (single-bunch or several-bunch operation) for pulsed-light users. Using an rf knockout system (RF-KO), the single-bunch beam is formed during flat-bottom period [2]. To remove electrons in the other bunches, these were excited by RF-KO with the synchronized frequency toward the vertical tune. At present, the impurity of the single-bunch beam defined as a ratio of another-bunch-beam-current to main-bunch-beam-current is less than $7\times10^{-8}$ [3]. To reduce this impurity, it is necessary to make the betatron tune constant and the chromaticity near zero while forming the single-bunch beam.

To observe the beam orbit, betatron tunes and chromaticities at the beam energy during accelerating, an energy-constant region is formed (flat-middle pattern). The period of the flat-middle was set to 100 ms. This is because the total measuring time of 80 beam position monitors (BPMs) was about 30 ms and it takes about 40 ms to settle the betatron tunes. The energy of the flat-middle period was set from 2 to 7 GeV by 1 GeV.

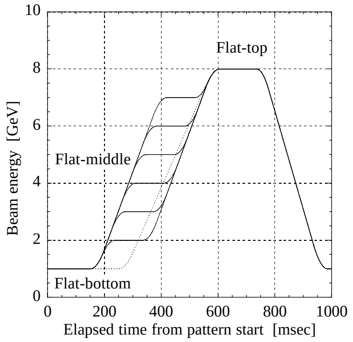

Fig. 1 Flat-middle pattern (solid line) and normal-pattern (dotted line) are shown together. Using flat-middle pattern, energy-constant regions with a time of 100 ms at different energies were prepared.

## 2 MEASUREMENT

Using the BPMs, horizontal and vertical CODs were measured at the flat-bottom, flat-top and flat-middle periods. All correction magnets were turned off to measure CODs without correction.

To measure the betatron tunes of the beam, it was shaken by an RF-KO field. The knockout power was changed in proportion to the beam energy. The horizontal and vertical oscillations of the beams were picked up with a strip-lined monitor. Using a real-time-spectrum-analyzer [Sony Tektronix 3056], frequency analysis was carried out with an interval of 1 ms to obtain the horizontal and vertical tune distributions. To observe the chromaticity distributions, the beam energy was changed by changing the acceleration frequency of the rf cavity. The frequency was increased by 10 kHz up to +30 kHz (•p/p = -0.58 %).

The tunes and the chromaticities during the energy-ramping period depend on the deviations of excitation characteristics of the quadrupole and the sextupole magnets from those of the bending magnets. However, the tunes and chromaticities also depend on the quadrupole and sextupole fields due to the eddy current on the wall of the vacuum chamber. The former and the latter are static and dynamic terms, respectively. It is impossible to separately observe the effects related to either term in the normal-pattern. To observe the static term, tune and chromaticity were measured in the flat-middle pattern.

## 3 EXPERIMENTAL RESULTS

The Horizontal and the vertical CODs without correction at different beam energies are shown in Fig. 2. The vertical CODs agreed with each other at all beam energies with an error of 80 •m. On the other hand, the horizontal COD changed with the beam energy.

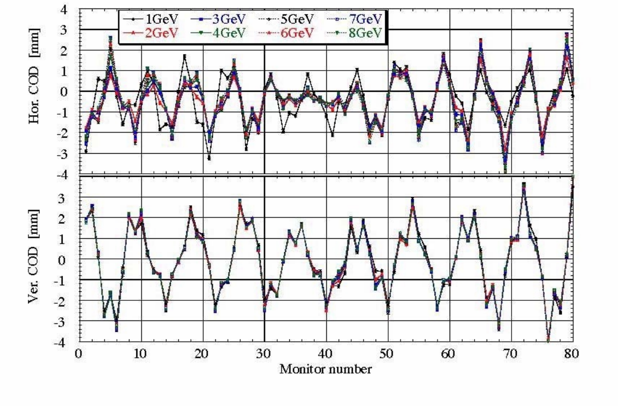

Fig. 2 CODs without correction at different energies are shown together. Error bars indicate the standard deviations of the data on the same condition.

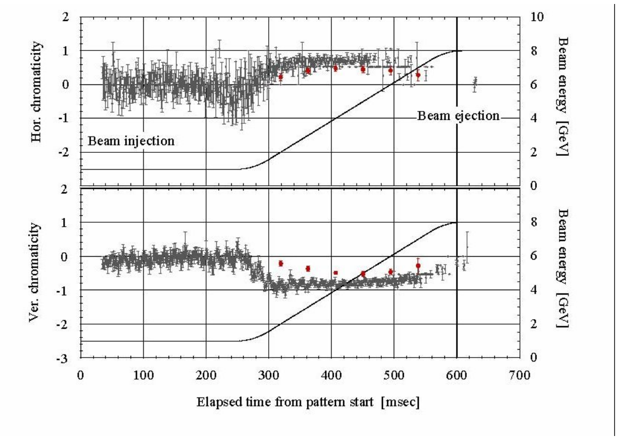

Fig. 3 Chromaticities with normal-pattern (solid circle) and flat-middle pattern (red-closed circle) are shown. Error bars indicate an error of the least-squares fit. Solid lines indicate beam energy.

The Horizontal and the vertical chromaticities are shown in Fig. 3. The solid circle and the red-closed circle indicate the chromaticity distributions with the normal-pattern and the averaged chromaticities at each flat-middle period, respectively. The chromaticities of the flat-middle pattern did not agree with that of the normal-pattern. On the other hand, the tunes at each flat-middle period agreed with that of the normal-pattern having a corresponding energy with an error of 0.005. The error was caused by the difference between the tunes at flat-bottom in the normal-pattern and that in the flat-middle pattern.

## 4 DISCUSSION

### 4.1 Energy loss per turn

The beam energy due to the synchrotron radiation per turn $U$ is expressed by

$$U[keV] = \frac{4\pi r_c E^4}{3(mc^2)^3 \rho} = 88.5 \frac{E^4[GeV]}{\rho[m]} \quad , \qquad (1)$$

where $mc^2$ is the rest mass of an electron, $r_c$ is classical radius of an electron, •• is the bending radius, and $E$ is the beam energy [4]. In the measured COD at several energies below 3 GeV, the COD is not uniquely since the elapsed time from beam injection is not much longer than the energy and the betatron damping time. To estimate the energy loss, the change in the horizontal position from the value at 3 GeV is calculated at several beam energies of more than 3 GeV. About the position data at two kinds of dispersion function of 0.98 m (32 points) and 0.48 m (30 points), the energy loss per turn at these energies were obtained by least-squares-fitting. The energy loss at different beam energies is shown in Fig. 4. Experimental result on the energy loss by the synchrotron radiation was consistent with the theoretical value with an error ratio of 8.4 % to measured value.

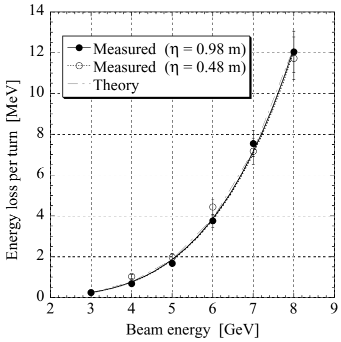

Fig. 4 Measured energy loss per turn at several different beam energies are shown. Error bars indicate standard deviation of measured dispersion functions. Ratio of error to measured value is 8.4 %.

### 4.2 Optimization of excitation pattern of quadrupole and sextupole magnets

Based on the measurements of the tunes and chromaticities of the normal- and flat-middle patterns, the static terms of the quadrupole and the sextupole magnets were obtained (Fig. 5). The strengths of the quadrupole and sextupole magnets during the energy-ramping period were modified to cancel the static terms (modified normal-pattern). The tunes and chromaticities with and without the correction are shown in Fig. 6 and 7, respectively. The tunes at energy-ramping period agreed with those of the flat-bottom and flat-top periods with corrections for only the static terms of the quadrupole magnets. However, the chromaticities at the energy-ramping period did not agree with those of the flat-bottom and flat-top periods. The remaining chromaticities are only dynamic terms. The chromaticities due to the eddy current on the wall of the vacuum chamber in the bending magnets were calculated [5] and results are shown in Fig. 7. Measured values were consistent with the calculation results.

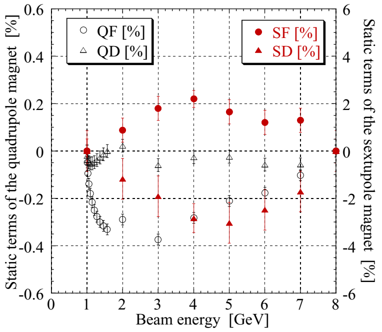

Fig. 5 Static terms of quadrupole and sextupole magnets are shown. Error bars for quadrupole and sextupole magnets indicate standard deviations of measured tune and chromaticity, respectively.

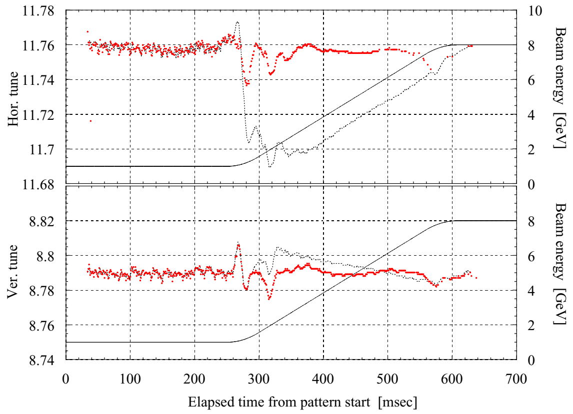

Fig. 6 Tunes with corrections for static terms of quadrupole magnets (red-solid circle) and without corrections (black-dotted line) are shown.

The dynamic terms of the sextupole field are constant during the energy-ramping period if it is assumed that the remaining chromaticities are caused by the eddy current. Therefore, the chromaticities are corrected by adjusting the start time of the ramping pattern of the sextupole magnets. Based on the measured chromaticities, the value of the delay times of the focusing- and defocusing-sextupole magnets were estimated to be +1.0 and -3.7 ms, respectively. The chromaticities for delayed-pattern are shown in Fig. 8. The dynamic terms could be canceled by adjusting the delay times.

## 5 CONCLUSIONS

Using the flat-middle pattern, we obtained the excitation pattern of the magnets that is appropriate to make the betatron tune constant and the chromaticity near zero in all energy regions. The beam energy loss per turn was observed at beam energy during accelerating.

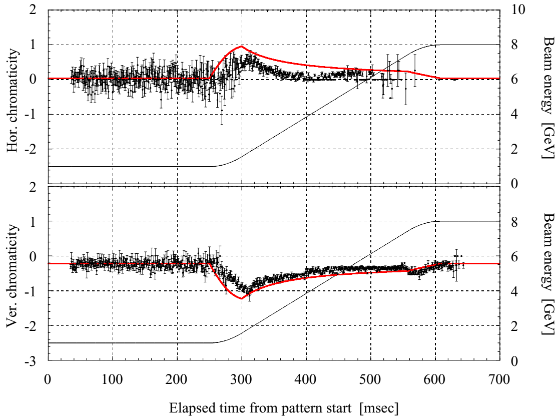

Fig. 7 Chromaticities with corrections for static terms of sextupole magnets (solid circle) are shown. Red-solid lines indicate calculation results for the chromaticities due to eddy current on the vacuum chamber wall in the bending magnets.

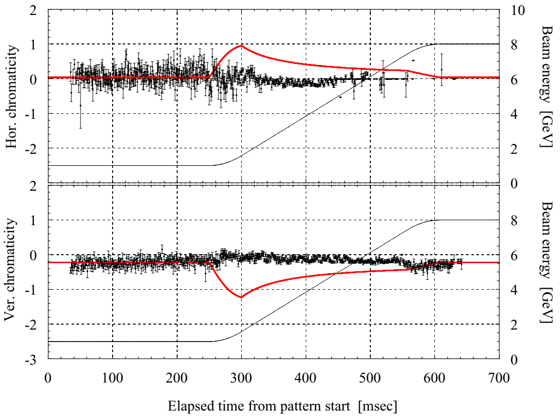

Fig. 8 Chromaticities with corrections for static and dynamic terms of sextupole magnets.

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