# BEAM PROFILE MEASUREMENT DURING TOP-UP INJECTION WITH A PULSED SEXTUPOLE MAGNET

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*Abstract*

A beam injection scheme using a pulsed multipole magnet is suitable for the top-up injection because a disturbance to the stored beam is much smaller than that of the conventional scheme using several kicker magnets. At the Photon Factory storage ring, the top-up injection with a pulsed sextupole magnet (PSM) has been used for the user operation since January 2011. In order to ascertain the effect of the PSM injection, we measured turn-by-turn stored beam profiles following the injection kick by using a fast-gated camera. As a result, it was demonstrated that the PSM injection dramatically decreases not only the coherent dipole oscillation but also the beam profile modulation, as expected from the beam tracking simulation.

## INTRODUCTION

In recent synchrotron radiation (SR) sources, it has become mainstream to keep a stored beam current constant with a top-up injection [1]. In the top-up injection using the conventional injection scheme with several kicker magnets, coherent dipole oscillations of the stored beam are inevitably excited by the magnetic field errors, timing jitters, and nonlinearities within the injection bump orbit. It is crucial to suppress the stored beam oscillation during the top-up injection because it modulates the SR intensity and interferes directly with the user experiments.

A new injection scheme using a pulsed quadrupole magnet (PQM) has been developed at KEK as a solution of this problem [2]. In this scheme, the horizontal kick to the injected beam has little disturbance to the stored beam dynamics because the stored beam always passes through the magnetic center of the PQM. Since several kicker magnets are replaced by the single quadrupole magnet, the scheme has an additional advantage of being able to make effective use of crowded space around the injection point. In the feasibility experiment conducted at the Photon Factory Advanced Ring (PF-AR), it was demonstrated that the dipole oscillation of the stored beam could be greatly reduced compared with the kicker injection. On the other hand, a beam profile modulation of the stored beam, like a quadrupole mode oscillation, was clearly observed in the optical measurement [3]. This profile modulation can be attributed to a linear field gradient along the horizontal axis of the PQM. Using a sextupole magnet whose field gradient has a parabolic dependence instead of a quadrupole magnet, the profile modulation is expected to reduce because of its smaller field around the magnetic center. In order to confirm this expectation, a pulsed sextupole magnet (PSM) for the beam injection has been installed in the Photon Factory storage ring (PF-ring) and examined the basic performance [3]. In the machine studies conducted thus far, although it has been observed that the dipole oscillation of the stored beam was reduced to almost the same level as the PQM injection, whether the profile modulation was also reduced has yet to be proved.

In this paper, we measure the turn-by-turn profiles of the stored beam following the injection kick by using a fast-gated camera and experimentally confirm that the disturbance to the stored beam in the PSM injection is smaller than that in the PQM injection.

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## SETUP

### *Optical Layout*

The turn-by-turn stored beam profiles are measured by observing the SR emitted from a bending magnet BM27. BM27 is located within the injection bump orbit of the PF-ring. The optical layout of the profile measurement is shown in Fig. 1. The visible light components of the SR are extracted from a vacuum chamber by a water-cooled mirror made of beryllium (Be) and fed to the optical hatch

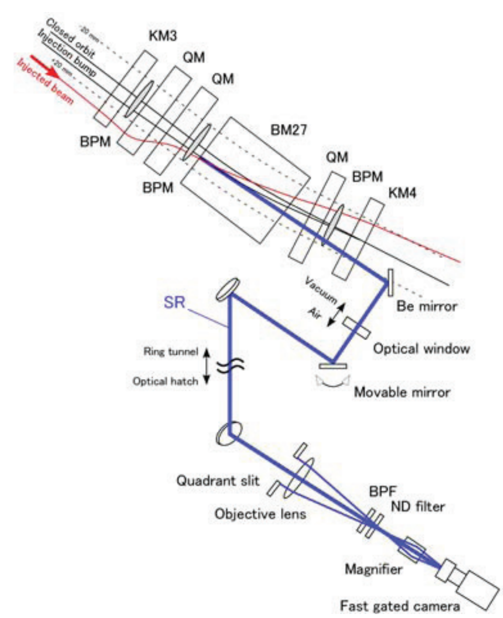


Figure 1: Optical layout of the turn-by-turn profile measurement. Blue bold line corresponds to the SR orbit. The SR source BM27 is located within the injection bump orbit produced by 4 kicker magnets KM1-KM4.

where the fast-gated camera is installed. An apochromatic lens having a diameter of 80 mm and focal length of 500 mm is used as an objective lens. A quadrant slit is applied just in front of the objective lens to define the entrance aperture. The distance from the source point in BM27 to the slit is approximately 8 m. The focus image of the beam profile enters an image intensifier (I.I.) of the gated camera (Hamamatsu, C4078-01) via a magnifying lens. A band pass filter (BPF) to select the light whose wave length is 500±5 nm and a neutral density (ND) filter to adjust the light intensity are inserted in a space between the objective and the magnifying lenses. A conversion factor from pixels on CCD to meters at the source point has been calibrated by using a displacement of the source point associated with an error of the acceleration frequency of the ring. As described in Ref. [3], the PSM is located about 30 m downstream from BM27. The main parameters of the PF-ring and some beam parameters at the source point are listed in Table 1.

Table 1: Main parameters of the PF-ring and some beam parameters at the source point in BM27.

| | | |
|---|---|---|
| Beam energy $E$ | 2.5 | GeV |
| Circumference $C$ | 187 | m |
| Betatron tune $\nu_x$ / $\nu_y$ | 9.60 / 5.28 | |
| Revolution period $\tau_{rev}$ | 624 | ns |
| Natural emittance $\varepsilon_x$ / $\varepsilon_y$ | 35.8 / 0.358 | nm rad |
| Energy spread $\sigma_\varepsilon$ | $7.29\times10^{-4}$ | |
| Betatron function $\beta_x$ / $\beta_y$ | 2.17 / 22.8 | m |
| Dispersion function $\eta_x$ | 0.179 | m |
| Beam size $\sigma_x$ / $\sigma_y$ | 308 / 90.3 | μm |

### *Timing System for Turn-by-Turn Measurement*

The profile measurement is performed with a single bunch of 10 mA stored in the ring. The kicker magnets or the PSM are fired using tentative triggers without the injection beams. A block diagram of the timing system is shown in Fig. 2. The tentative injection triggers are distributed to the CCD camera (Hamamatsu, C9164-01) and a pulse generator (Agilent, 81101A) via a digital delay module which uses the revolution frequency of the beam (1.6 MHz) as a clock. This delay module enables us to acquire the beam profile at any turn number following the injection kick. However, each profile measurement is performed for the stored beam kicked with another injection trigger because the maximum repetition frequency of the gated camera is much smaller than the revolution frequency. A gate/delay generator inserted in front of the CCD camera is used to increase the width of the trigger pulse and to carry out the CCD exposure and the readout of charges steadily. The pulse generator shapes the trigger pulse into the gate signal for I.I. The exposure time and the gate width are set to 20 ms and 50 ns, respectively.

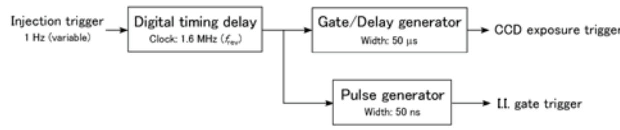


Figure 2: Block diagram of the timing system.

## MEASUREMENT OF TURN-BY-TURN STORED BEAM PROFILE

### *Tracking Simulations*

Before proceeding to experimental observations, we simulate the turn-by-turn profile measurements in the kicker, PSM, and PQM injections, employing the particle-tracking simulation code SAD [4]. The stored beam is represented by 1000 particles with Gaussian distributions in the 6-D phase space. The horizontal emittance and the emittance coupling are assumed to be 35 nmrad and 1%, respectively. Each profile is calculated at the entrance of BM27. The upper picture in Fig. 3 shows the turn-by-turn stored beam profiles in the kicker injection. To emulate a leakage of the injection bump, we introduced a field error of 7% to one of the kicker magnets KM4. At the first turn when the bump orbit is produced (turn number = 1), the beam profile is scaled out from the window because of a large horizontal displacement. Before the first turn the beam profiles are observed at the same position stably, while after the first turn, the profiles are oscillating in the horizontal plane at the betatron frequency. The amplitude of the betatron oscillation is proportional to the amount of field errors of the kicker magnets. The middle picture shows the beam profiles in the PSM injection. Almost no fluctuations in the beam position and the beam profile are observed after the injection. As mentioned in the previous section, since the PSM is located downstream of the observation point at BM27, it must be noted that the effect of the horizontal kick by the PSM appears after the second turn. The lower picture is the beam profiles in the PQM injection at the PF-ring, which was simulated by virtually-installing the PQM at the same point as the PSM. Although there is no dipole oscillation of the stored beam as well as the PSM injection, the modulation of the beam profile is excited by the horizontal kick of the PQM. This result is qualitatively consistent with the experimental observation at the PF-AR.

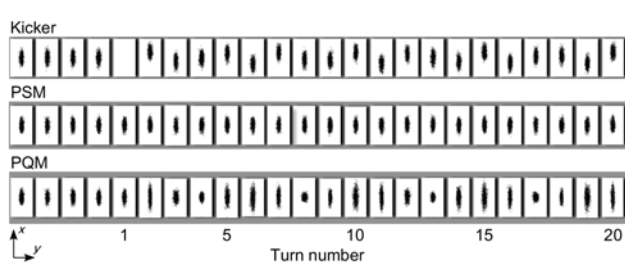


Figure 3: Turn-by-turn stored beam profiles in the kicker, PSM, and PQM injections simulated by SAD code.

According to more detailed simulations, whereas the disturbance to the stored beam in the pulsed multipole magnet injection is nearly independent of the magnetic field errors, that increases with the alignment errors; namely, the misalignment between the stored beam orbit and the magnetic center without fields. The PSM injection has a greater tolerance for the alignment errors than the PQM injection.

### *Experimental Results*

The turn-by-turn stored beam profiles measured in each injection scheme are displayed in Fig. 4. All profiles are single-shot images (not integrated) applied a background correction. The upper and middle pictures correspond to the results of the kicker and PSM injections, respectively. For reference, the result of the PQM injection obtained at the PF-AR is shown in the lower area of Fig. 4. Large horizontal displacements observed at the first and second turns of the kicker injection result are due to the injection bump orbit [5]. Slight distortions of the beam profiles are also observed at the turns with a large oscillation amplitude. These are considered nonlinear effects caused by field distortions of the ring components.

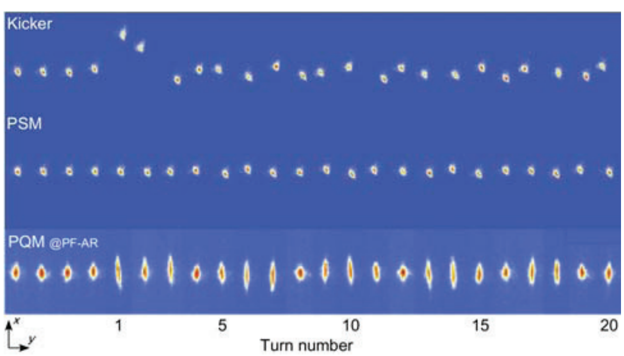


Figure 4: Turn-by-turn stored beam profiles in the kicker, PSM, and PQM injections measured by using a fast-gated camera.

The beam positions in the kicker and PSM injections have been plotted against the turn number in Fig. 5. The origin of the vertical axis was set to the average beam position before the first turn. The amplitude of the stored beam oscillation observed in the PSM injection has been suppressed to approximately $\pm 400$ µm which is less than half of that in the kicker injection. The residual oscillation is expected to be minimized by tuning so that the stored beam precisely passes through the field center of the PSM. As also shown in Fig. 3, the stored beam oscillation excited by a leakage of the injection bump should appear almost only in the horizontal plane. However, the same level oscillation as the horizontal plane was observed in the vertical plane. We suspect the alignment errors of the kicker magnets and the skew quadrupole fields produced by the recently-installed undulator [6] as possible candidates coupling the horizontal and vertical motions strongly. Further studies are required to identify the coupling source.

The RMS beam sizes in the PQM injection at the PF-AR and the PSM injection are plotted in Fig. 6 as a function of the turn number. The RMS beam size was estimated by fitting a Gaussian function with an offset to the image projections on the horizontal and vertical axes. In addition, the beam sizes shown in Fig. 6 were converted to the change ratio from the average beam size before the first turn for the sake of comparison. In the PQM injection the horizontal beam size grows up to twice the size before the kick, while in the PSM injection, that is maintained almost constant. These results are qualitatively in good agreement with the simulation results shown in Fig. 3 and proves clearly that the PSM injection has a superior performance compared with the PQM injection.

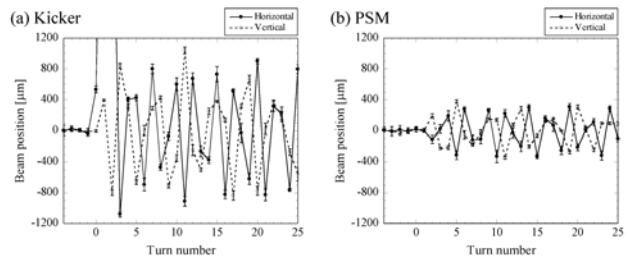


Figure 5: Beam positions of the stored beam in the kicker injection (a) and PSM injection (b). The horizontal displacement observed at the first turn of (a) is 5.5 mm.

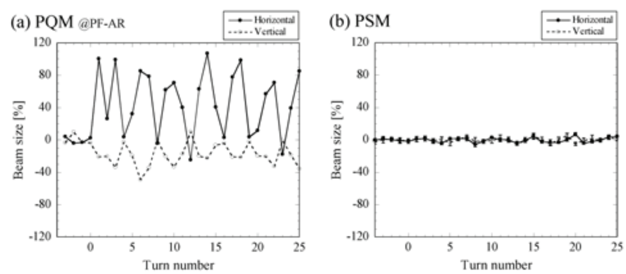


Figure 6: Beam sizes of the stored beam in the PQM injection at the PF-AR (a) and PSM injection (b).

## CONCLUSIONS

We measured the turn-by-turn stored beam profiles using a fast-gated camera and investigated the effect of the PSM injection on the stored beam. The experimental results are qualitatively in good agreement with the expectation from the tracking simulation, it has been demonstrated that the PSM injection can realize an ideal top-up injection which both the stored beam position and profile do not fluctuate at every injection.

At the PF-ring, the PSM injection has been introduced in the user operation instead of the kicker injection since January 2011. In the near future, we plan to make machine studies to minimize the residual stored beam oscillation and to improve the injection efficiency.

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