Beam-Profile Measurement in the KEK-PS Booster Using Pulsed Bump Magnets and a Movable Scraper

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Abstract

A system for precise measurements of the beam profile in the KEK-PS Booster has been developed. This system comprises a movable scraper and pulsed bump magnets. Using this system, we measured the intensity dependence of the beam profiles for intensities from 1.8×10^{11} to 2.2×10^{12} particles per bunch.

1. INTRODUCTION

In the KEK-PS Booster, which accelerates a 40-MeV proton beam up to 500 MeV with a repetition rate of 20 Hz, a transverse blow-up of the beam at injection has been known. Especially, the blow-up in the vertical plane becomes crucial as the beam intensity increases. Since a beam-profile measurement gives information on the beam blow-up, some attempts have been made to measure the profile. Those involved the BEAMSCOPE method [1] and a non-destructive profile measurement [2]. Unfortunately, the latter failed to measure the beam profile around injection due to noise from the injection bump magnet. On the other hand, in the former method, the beam profile around injection was measured in the Booster. In this method, a profile measurement is performed using a scraper and pulsed bump magnets. When the bump magnets are excited, the proton beam gets close to the scraper along the bump orbit. Then, a portion of the beam, which passes through the scraper, is lost due to absorption and/or scattering. Since the displacement of the bump orbit is proportional to the bump-magnet current, a beam profile can be obtained as the current dependence of the beam intensity. In order to measure the beam profile precisely, it is essential to calibrate the bump current to the beam displacement with good accuracy. In early measurements, the calibrated values deviated by more than few percent since the value was determined by eye. In addition, the time response of the conventional intensity monitor was not fast enough to monitor a rapid change in the intensity. Recently, the time response of intensity monitoring has been improved by recording each beam-bunch signal in a digital sampling oscilloscope. A scenario for the precise calibration has also been established. In the following sections, we describe this system and the results of the measurements.

2. MEASURING SYSTEM

2.1 System Configuration

The profile measuring system comprises a scraper and pulsed bump magnets which deflect the beam to the scraper in the vertical direction. Figure 1 shows a plan of the Booster Synchrotron. As shown, vertical bump magnets are installed in straight sections S2 and S4. The magnets are connected in series and excited by a pulsed current having the same polarity. The pulse shape is a half-sine and the width is about 200 μsec. We have chosen magnet locations where the betatron phase difference is π radians and the beta-functions are the same, so that a bump orbit is formed from S2 to S4 in the vertical plane. In straight section S3, the scraper is located at the position where the bump orbit has its extremum. The beam profile was obtained by the procedure described below.

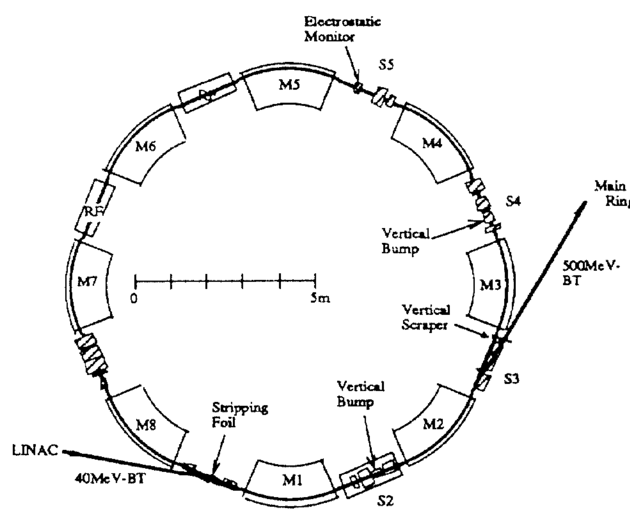

Figure 1. Plan of the KEK-PS Booster Synchrotron.

The displacement of the bump orbit at the scraper from the unperturbed closed orbit is given by

$$y = \theta\sqrt{\beta_0\beta_1}, \tag{1}$$

where y is the vertical displacement from the unperturbed closed orbit and θ is the kick angle of each bump magnet. β_0 and β_1 are beta-functions at the scraper and the magnet, respectively. Using the magnetic field (B) and the length (l) of the bump magnet, the kick angle is given by

$$\theta = Bl / B_0\rho_0. \tag{2}$$

Here, B_0 and ρ_0 are the guiding field, which varies sinusoidally with a repetition rate of 20 Hz, and the bending radius of the Booster main magnet, respectively. Hence, y can be obtained by

$$y = Bl\sqrt{\beta_0\beta_1} / B_0\rho_0 \equiv \alpha\, I / B_0\rho_0, \qquad (3)$$

where I is the current of the bump magnet and α is a beam-independent parameter which depends on the structure of the bump magnet and beta-functions. As shown in eq. (3), the beam displacement is proportional to the magnet current. As the current increases, the beam gets close to the scraper and is shaved more and more. If the beam intensity dependence on the bump magnet current is measured, the instantaneous intensity can be plotted against y in terms of eq. (3). This plot shows half of the profile. A full profile is obtained by folding the mirror image of the half part with respect to the beam center, since this method assumes a symmetric distribution in phase space. If the beam center is unknown, this technique is not available. In this case, we must measure the other half part by alternating the polarity of the bump magnets. We call the thus-obtained complete distribution the 'Beam Profile'. We use the variable Y as a reference coordinate rather than y. Y is the scraper position measured from the beam center, and defined by

$$Y = Y_{scr} - y - Y_{co} = Y_{scr} - \alpha\, I / B_0\rho_0 - Y_{co}, \qquad (4)$$

where Yscr is the vertical scraper position. Yco is the displacement of the unperturbed closed orbit from the central orbit. Figure 2 is a schematic view of the profile measuring system. As shown, the current of the bump magnet and a beam bunch signal were recorded simultaneously using a digital sampling oscilloscope with a sampling rate of 200 MHz. In order to measure the beam intensity, we observed a beam bunch with a fast electrostatic monitor (ESM) rather than an ordinary intensity monitor, since the time response of the intensity monitor is not fast enough to monitor a rapid change in the intensity. The instantaneous intensity was obtained by numerically integrating the bunch signal for each turn.

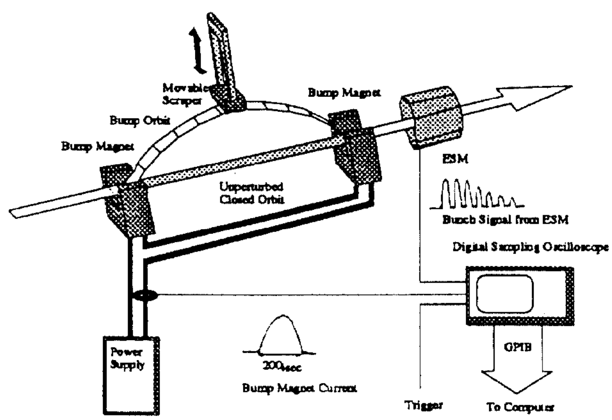

Figure 2. Schematic of the Profile Measuring System.

2.2 Determination of α

The value of α can be evaluated, in principle, by taking account of the beta-functions and the structure of the bump magnet. However, the lattice of a synchrotron comprises so many magnets that it is hard to obtain the value of α with good accuracy. Therefore, we determined the value of α directly by the following method. From eq. (4), we obtain the formula using reference value Y(50%) and the bump magnet current, I(50%), at which the beam survives by 50% of the unscraped beam intensity:

$$Y_{scr} = Y(50\%) + \alpha\, I(50\%) / B_0\rho_0 + Y_{co}. \qquad (5)$$

Since the profile and the closed orbit of the proton beam were stable from pulse to pulse, Y(50%) and Yco were constant. Hence, the relation between Yscr and I(50%) is linear. In our system, the scraper position (Yscr) is movable. Therefore, by measuring I(50%) at several scraper positions (Yscr's), α and summation of Y(50%) and Yco are determined using a least-squares fit without any knowledge of the beta-functions and the bump magnet properties. In order to obtain the value of α with good accuracy, a pencil beam was used. We performed a calibration of α twice at different machine cycles; the results were consistent each other. The resulting value was $\alpha = 0.0444 \pm 0.0006$, and was constant within an error up to 20 msec from injection. From 20 msec to extraction (25 msec), the value becomes small due to saturation of the bump magnet, since the beam momentum becomes very large in this region.

3. PROFILE MEASUREMENTS

Using this system, we measured the intensity dependence of the Beam Profiles in the vertical plane for intensities from 1.8×10^{11} to 2.2×10^{12} particles per bunch (ppp). Figure 3 shows the normalized emittance containing 90% of the beam against a delay time of up to 5 msec from injection for various beam intensities. The lines and dots identify each data group.

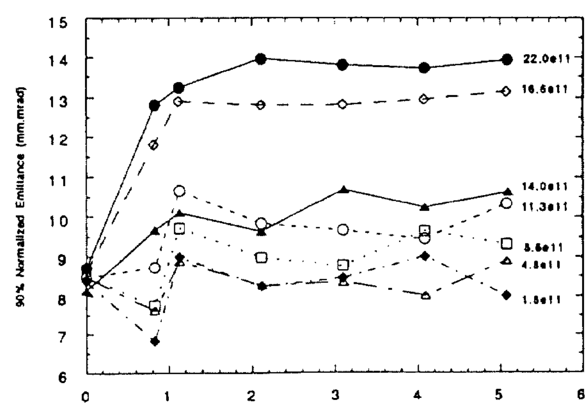

Figure 3. Intensity Dependence of the Normalized Emittance.

The emittance at injection, i.e. delay time = 0, was obtained from the Beam Profile taken by moving the scraper without exciting the bump magnets, since the ESM cannot be available during the injection process, where a bunch structure is not formed sufficiently. In this case, the Beam Profile was obtained as the scraper position dependence of the beam intensity.

In the figure, the beam emittance grows until 1 msec. Such a growth is clearly seen at intensities larger than 1.4×10^{12} ppp. The blow-up rate seems to be saturated at an intensity of 2.2×10^{12}. This may imply that the beam was scraped by a machine aperture at this intensity.

The density (n) in a phase space of the vertical motion is given by

$$n = dN/dY/L, \qquad (6)$$

where N is the intensity of the surviving beam at the scraper position (Y). L is the length of the circumference of the ellipse tangent to the line of Y = constant in phase space. Figure 4 shows a typical density distribution which was taken at a delay time of 3 msec from injection for an intensity of 1.7×10^{12} ppp. Here, the ellipse was evaluated using the design values of the Twiss parameters.

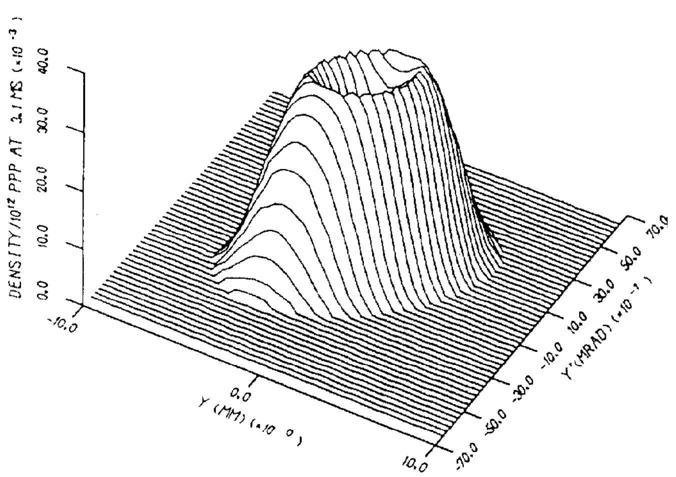

Figure 4. Typical Density Distribution.

We tried to measure the Beam Profile close to a delay time of 0.2 msec from injection. However, definite results have not yet been obtained due to the poor S/N ratio. The reason was that the gain of the ESM at lower frequencies was not sufficiently high to detect an unsufficiently formed bunch with a good S/N ratio. Since the beam is growing at a timing before 1 msec from injection, it is very interesting to investigate the behavior of the beam in this region. Therefore, we are now improving the ESM by compensating its gain at lower frequencies in order to measure the Beam Profiles in this region.

4. Conclusions

We have constructed a beam-profile measuring system of the BEAMSCOPE type in the KEK-PS Booster. In order to conduct precise measurements, improvements were performed for the following items: the intensity measurement by direct observation of the beam bunch and a simple calibration of α without any knowledge of the beam optics and the bump magnet properties. Using this system, Beam Profiles up to a delay time of 5 msec from injection were measured for intensities from 1.8×10^{11} to 2.2×10^{12} ppp. The beam growths were clearly seen at the intensities larger than 1.4×10^{12} ppp.

5. Acknowledgements

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6. References

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[2] T. Kawakubo et al., "Fast data acquisition system of a non-destructive profile monitor for a synchrotron beam by using a microchannel plate with multi-anodes", Nucl. Instr. Meth., A302, pp. 397-405, 1991.