OBSERVATION OF EMITTANCE GROWTH AT THE INJECTION OF THE KEK PS MAIN RING

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Abstract

Emittance growth and beam loss mechanism have been studied during the injection period of the 12 GeV main ring of the KEK proton synchrotron. Measurement of the transverse beam profiles using flying wires has revealed a characteristic temporal change of the beam profile within a few milliseconds after the injection. Horizontal emittance growth was observed when the horizontal tune was close to the integer. The effect was more enhanced for higher beam intensity and could not be explained with the injection mismatch. A resonance created by the space charge field was the cause of the emittance growth. A multiparticle tracking simulation program, ACCSIM, taking account of space charge effects has successfully reproduced the beam profiles.

INTRODUCTION

The KEK proton synchrotron was operated successfully and provided proton beams to elementary and nuclear physics experiments until March of 2006 for 30 years. A continuous effort was being made to achieve higher intensity and to improve the beam loss. One of the issues was the beam loss during the injection period of the 12 GeV main ring. When the highest operating intensity was 1.4×10^{12} protons per bunch (ppb), about 30 $\%$ of the beam was lost during the injection period of 510 ms. The transverse beam profile has been measured using the flying wire profile monitors [1] to understand the beam loss mechanism.

The injection kinetic energy of the main ring was 500 MeV. The typical horizontal 4 rms emittance of the injection beam was measured to be 14 π mm mrad. The bunching factor was typically 0.3. The incoherent tune shift was then estimated to be 0.4 for the beam intensity of 8×10^{11} ppb. Strong space charge effect to the beam profile was therefore predicted [2].

PROFILE MEASUREMENTS

Horizontal beam profiles were measured for the horizontal tune of 7.05 to 7.25. The vertical tune was about 5.25. In the normal operating condition the horizontal tune was 7.15 and the vertical tune was 5.25. The beam intensity was set to 2×10^{11}, 4×10^{11} or 8×10^{11} ppb at the booster extraction.

Figure 1 shows the horizontal beam profile from 0.2 ms to 2.8 ms after the injection when the intensity was 8×10^{11} ppb and the horizontal tune was 7.05. The profile at 0.2 ms after the injection had a narrow peak and a broad distribution. The component of the narrow peak gradually diminished and only the broad distribution remained 2 ms after the injection. There was large beam loss in this case.

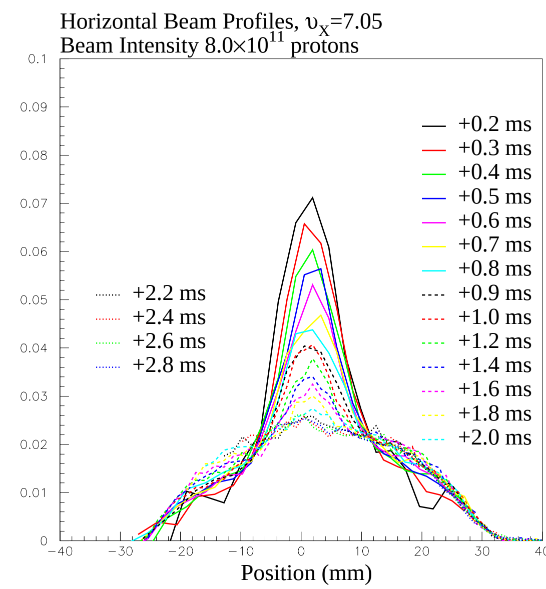

Figure 1: The horizontal beam profile $0.2 \sim 2.8$ ms after the injection when the intensity was 8×10^{11} ppb and the horizontal tune was 7.05.

Figure 2 shows the horizontal beam profile from 0.2 ms to 2.8 ms after the injection when the intensity was 8×10^{11} ppb and the horizontal tune was 7.11. The profile at 0.2 ms after the injection had a narrow peak and a broad distribution. The component of the narrow peak was small unlike the profile at the tune of 7.05 and only the broad distribution remained 0.6 ms after the injection. The beam loss was small in this case.

Horizontal beam profiles at 4 ms after the injection were measured for the horizontal tune of 7.05 to 7.25 as shown in figure 3 for the intensity of 8×10^{11} ppb. The distribution was broad and parabolic when the tune was close to the integer. The distribution meanwhile was narrower and becomes Gaussian when the tune was not close to the integer. The measurements were repreated for the lower intensity of 2 and 4×10^{11} ppb. The modification of the beam profile was less enhanced for the lower intensity.

INJECTION BEAM PROFILE AND INJECTION MISMATCH

The beam profile of the injection beam was measured using multiwire profile monitors at the beam transfer line from the booster to the main ring. Data were taken from

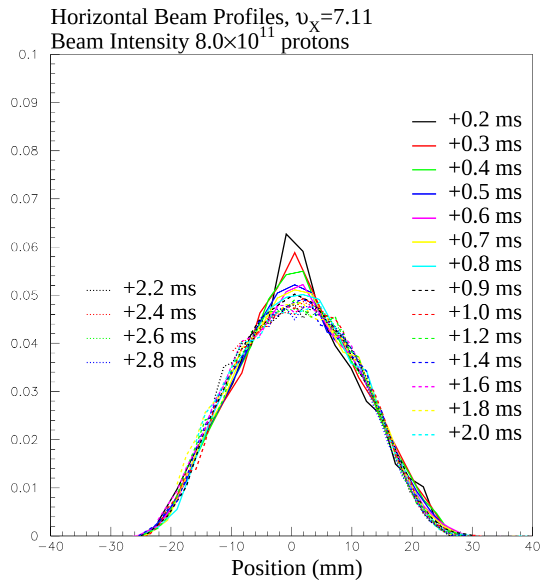

Figure 2: The horizontal beam profile $0.2 \sim 2.8$ ms after the injection when the intensity was 8×10^{11} ppb and the horizontal tune was 7.11.

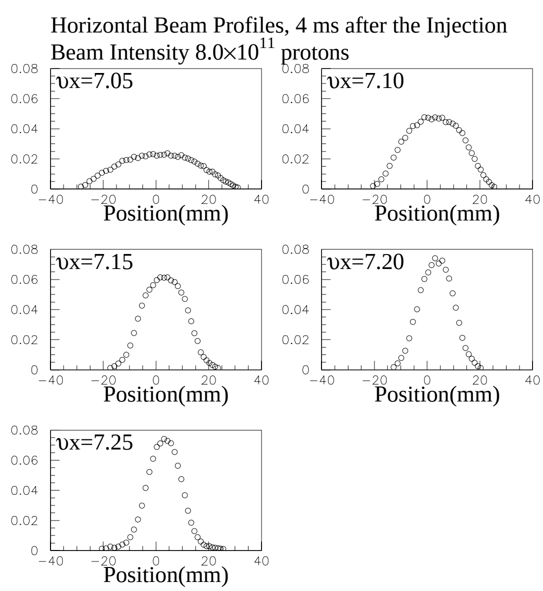

Figure 3: The horizontal beam profile 4 ms after the injection when the intensity was 8×10^{11} ppb and the horizontal tune was $7.05 \sim 7.25$.

six profile monitors. Distributions of the horizontal and vertical profiles turned out to be Gaussian functions. Results of the fitting and the twiss parameter calculation using DIMAD were then used to estimate the injection beam emittance. The horizontal 4 rms emittance was measured to be 14 π mmmrad, and the vertical 4 rms emittance was measured to be 12 π mmmrad. They did not depend on the beam intensity between 2×10^{11} and 8×10^{11} ppb. The uncertainty of the estimated emittance was 15 % which was the deviation of the esitimates from the six profile monitors.

Steering errors at the injection were measured using two beam position monitors. Phase space positions of x and x' at the injection point were calculated from the position data using the twiss parameter calculation. The mismatch did not depend much on the horizontal tune.

The betatron amplitude function was measured for the horizontal tune of $7.05 \sim 7.25$. A steering magnet pattern was changed to make a single kick at the point of interest. The closed orbit distortion was measured and the betatron amplitude function was then obtained. The dispersion function was measured by changing Δr, an rf parameter to adjust the horizontal beam position. The closed orbit distortion was measured and the dispersion function was then obtained. Either of the betatron amplitude function or dispersion function did not depend on the horizontal tune much for the horizontal tune of $7.05 \sim 7.25$.

ACCSIM SIMULATIONS

The injection process was simulated with a multiparticle tracking program ACCSIM [3]. The input to the initial beam distribution and mismatch condition were based on the measurements. The distribution of the bunch shape and the bunching factor were also reproduced with the longitudinal parameters. The transverse space charge force was calculated every step of 0.7575 m. The grid was set to 1 mm $\times$ 1 mm. A typical number of the multiparticles was $10,000$. The sextupole and octupole magnets were simulated as thin lenses. Random rotation of the quadrupole magnets were also taken into account with the standard deviation of 2 mrad. The horizontal and vertical position of each particle was checked once per turn whether it was in a preset aperture or not.

Figure 4 shows the horizontal phase space plot of 20 test particles for 400 turns when the beam intensity was 8×10^{11} ppb and the horizontal tune was 7.05. The pattern of the fourth order resonance was observed. The incoherent tune shift by the space charge force was large enough to cross the tune of 7 under this condition.

The horizontal beam profile from the ACCSIM simulation for the intensity of 8×10^{11} ppb and the horizontal tune of 7.05 had a broad distribution and a narrow peak. Diminishing of the narrow peak as shown in figure 1 was reproduced up to 400 turns.

A comparison was made between horizontal emittances from the flying wire measurement and those from the ACCSIM simulation. The beam profile at 4 ms after the injec-

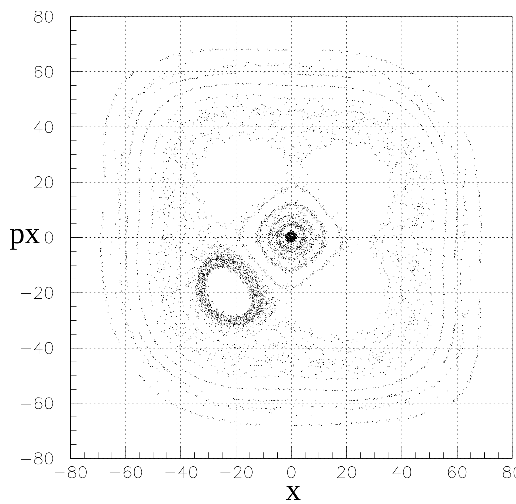

Figure 4: A horizontal phase space plot of 20 test particles for 400 turns when the intensity was 8×10^{11} ppb and the horizontal tune was 7.05.

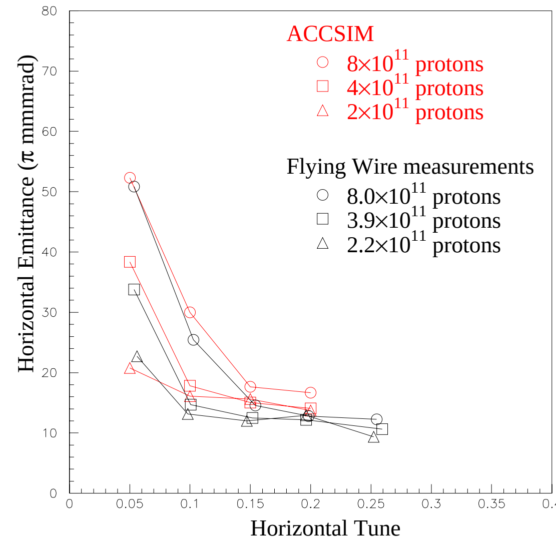

Figure 5: Horizontal 87 % emittance as a function of the horizontal tune when the intensity was 2, 4 and 8×10^{11} ppb Flying wire measurements are shown in black symbols and results from the ACCSIM simulation are in red symbols.

tion had a Gaussian distribution when the tune was away from the integer. Horizontal emittances were defined as 2σ for these cases and 87 % of the particles in the phase space of x and x' were included in the emittance. When the tune was close to the integer, the beam profile did not have a Gaussian distribution but a parabolic distribution. The beam profiles were fitted with parabolic functions and the 87 % emittance were defined for these cases. Because the ACCSIM simulation was performed only for 0.6 ms, the profile was fitted with the combination of a Gaussian and a parabolic function when the intensity was 8×10^{11} ppb and the horizontal tune was 7.05. The comparison was made with an assumption that only the part of the parabolic function would remain after 4 ms.

Figure 5 shows the horizontal 87 % emittance as a function of the horizontal tune for the intensity of 2, 4 and 8×10^{11} ppb. Results from the ACCSIM simulation shows very good agreement with the flying wire measurements.

CONCLUSIONS

Measurement of the trasverse beam profiles using the flying wires has revealed a characteristic temporal change of the beam profile within a few milliseconds after injection. Horizontal emittance growth was observed when the horizontal tune was close to the integer. The effect was more enhanced for higher beam intensity. Fourth order resonance created by the space charge field was the cause of the emittance growth. A multiparticle tracking simulation program, ACCSIM, taking account of space charge effects has reproduced the beam profiles.

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