SPACE CHARGE EFFECTS DURING THE INJECTION PERIOD OF THE KEK PS MAIN RING

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Abstract

Space charge effects during the injection period of the 12 GeV main ring of the KEK proton synchrotron have been studied. Measurement of the transverse beam profiles using 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 and could not be explained with the injection mismatch. 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 qualitatively reproduced the beam profiles.

INTRODUCTION

The beam intensity of the KEK PS 12 GeV main ring has significantly increased since the K2K neutrino oscillation experiment started. Efforts to minimize beam loss have been continuously made. One of the issues is to reduce the loss during the injection period. Nine bunches of protons with the kinetic energy of 500 MeV are injected with the interval of 50 ms. About 30% of protons are lost during the injection period of 510 ms. The highest operating intensity of the main ring is 1.4×10^{12} protons per bunch at injection. The nominal operational tune has been optimized to be 7.15 and 5.25 for the horizontal and vertical tune respectively. The main ring has a circumference of 340 m and four-fold symmetry. A super period consists of seven FODO cells.

The incoherent tune shift is estimated to be 0.5 for the highest operating intensity without considering the effect of the image field or dispersion. The large value of the space charge tune shift is partly due to a small emittance of the injection beam. Emittance dilution and particle loss would occur under the circumstances. It is empirically known that emittance dilution observed after injection to the main ring depends on the beam intensity and tune.

PROFILE MEASUREMENTS

Flying wire transverse beam profile monitors have been operated at the main ring. An analysis procedure has recently been established to reconstruct the beam profile that quickly changes with a time scale of 1 ms or less [1].

When the injection beam intensity was set to 8.0×10^{11} protons, the beam profile 0.2 ms to 2.8 ms after injection were reconstructed as in figure 1. The horizontal tune in this case was 7.05 which was not the nominal operational value. The vertical tune was 5.22. A significant beam loss was observed within 1 ms after injection under the condition. The reconstructed profile shows a notable change of the distribution. The profile at 0.2 ms after injection consists of a narrow peak and a broad distribution. The narrow peak diminishes in 2 ms and only the broad distribution remains.

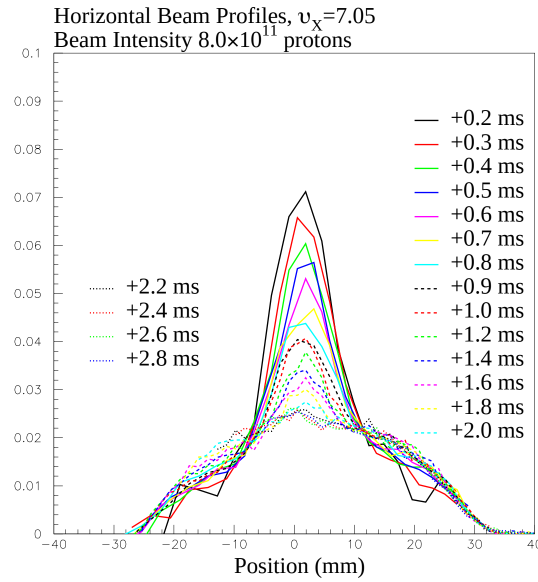

Figure 1: Horizontal beam profiles 0.2 ∼ 2.8 ms after injection when the horizontal tune was 7.05 and the injection beam intensity was 8.0×10^{11} protons.

The same procedure was applied for the horizontal tune of 7.11 and the vertical tune of 5.21 which was near the nominal operational value. The profile at 0.2 ms after injection still consists of a narrow peak and a broad distribution. The narrow peak diminishes in 1 ms, and only the broad distribution remains as in the case of the tune of 7.05. The narrow peak of this case is, however, less significant than that of the previous tune, and the beam loss is not either significant in this case.

Horizontal beam profiles after injection were measured for the injection beam intensity of 2.2, 3.9 and 8.0×10^{11} protons. The measurements were performed for a range of the horizontal tune from 7.05 to 7.26. The vertical tune was maintained to be between 5.23 and 5.32. The trigger was set to initiate the wire scanning to take beam profiles of about 4 ms after injection when the rapid change of the profile was settled. The profiles for the intensity of 8.0×10^{11} protons are shown in figure 2. It was observed to be wide

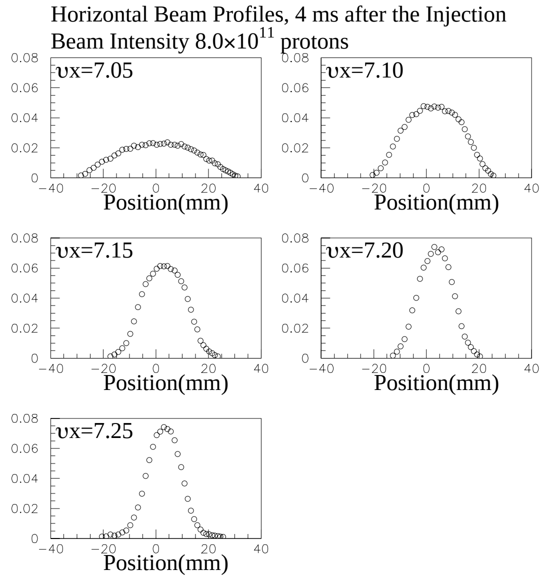

Figure 2: Horizontal beam profiles 4 ms after injection when the injection beam intensity was 8.0×10^{11} protons.

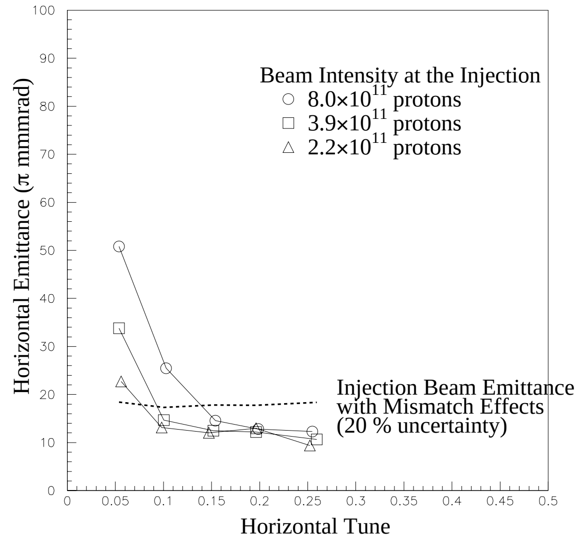

Figure 3: Horizontal 87% emittance as a function of the horizontal tune for the beam intensity of 2.2, 3.9 and 8.0×10^{11} protons.

when the horizontal tune was 7.05, and became narrower as the tune was away from the integer.

The injection beam σ emittance was measured at the beam transfer line to be 3.4 and 2.7 πmmmrad for the horizontal and vertical direction respectively. The emittance did not depend on the beam intensity. The measurement, however, has uncertainty from short understandings of transfer line lattice parameters.

Injection steering error, betatron function mismatch and dispersion function mismatch were measured and the effects to the injected beam to main ring were considered. The mismatch parameters were observed to show little dependence on the horizontal tune between 7.05 and 7.26. Beam emittance with the mismatch effects as a function of the horizontal tune was estimated. Little dependence on the horizontal tune was observed as in figure 3.

Each beam profile was fitted with either a Gaussian or a parabolic function and the emittance that includes the 87% fraction of the density distribution was estimated and plotted in figure 3. Emittance growth was observed when the tune is close to the integer for all the measured intensity settings. The tune dependence can not be explained only with the mismatch effects. A tune range where the emittance growth occurs depends on the intensity. It is inferred that the emittance growth is due to the space charge field.

ACCSIM SIMULATIONS

A multiparticle tracking simulation program, ACCSIM [2], taking account of space charge effects has been performed to understand the observed phenomena. Transverse space charge forces have been calculated for 10000 macro particles with a hybrid fast-multipole technique and grids of 1 mm $\times$ 1 mm every 0.76 m step. Thin lens kicks have been applied to simulate sextupole and octupole magnets. A fringing field from an injection septum magnet was suspected as one source of closed orbit distortion and included in simulations for some cases. Parameters for the injection beam emittance were based on the transfer line profile measurements. Another tracking simulation code, PATRASH [3], has also been applied and the results agreed with the ACCSIM results.

Figure 4 is the $x-p_x$ phase space plot of 20 test particles for 400 turns when the horizontal tune is 7.05. It shows patterns of fourth order resonance that was created by the space charge force. Particles having the tune of 7 by the incoherent tune shift make a resonant condition with the space charge field [4]. Octupole type space charge field creates the resonance. The resonant tune is 7/4 for a super period, because the main ring has a four-fold symmetry.

ACCSIM results of the horizontal beam profiles 0.6 ms after injection is shown in figure 5 for the beam intensity of 8×10^{11} protons. Profiles were fitted with a Gaussian plus a parabolic function for the tune of 7.05 and 7.10, and a parabolic function for the tune of 7.15 and 7.20. Only the parabolic distribution was assumed to remain in each profile after 4 ms and the emittance was evaluated to include the 87% fraction of the density distribution to compare with the measured emittance.

Figure 6 shows the comparison between the ACCSIM results and flying wire measurements for 87% emittance. The ACCSIM results reproduced the tune dependence qualitatively. The agreement is good for the intensity of 4×10^{11} protons. The ACCSIM results, however, are about 1.4 times of the measured emittance for the intensity of 8×10^{11} protons. The discrepancy may be due to uncertainty in the

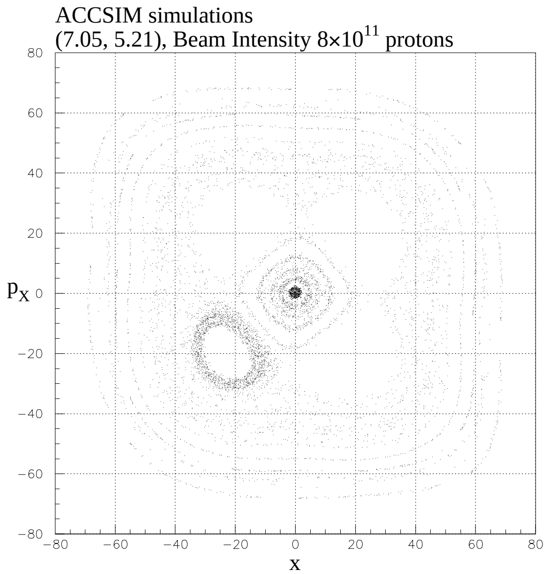

Figure 4: ACCSIM simulation of the $x - p_x$ phase space plots of 20 test particles when the horizontal tune was 7.05 and the injection beam intensity was 8×10^{11} protons.

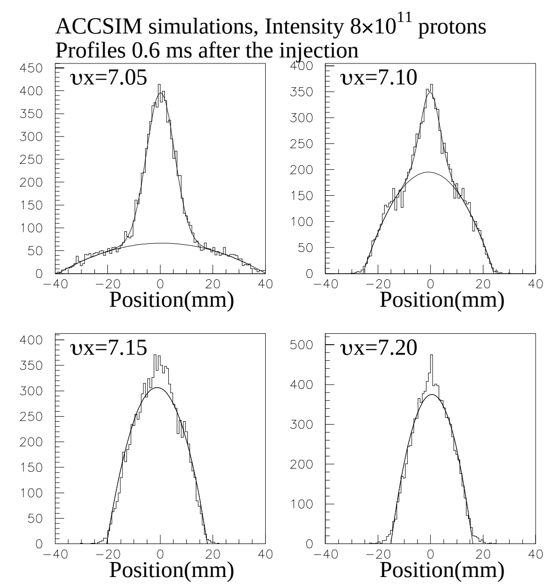

Figure 5: ACCSIM simulation of the horizontal beam profiles 0.6 ms after injection when the injection beam intensity was 8×10^{11} protons and the horizontal tune was 7.05, 7.10, 7.15 or 7.20.

measurement of the injection beam emittance. Mechanism to modify the resonance width, otherwise, has to be considered such as effects of the betatron function modulation.

CONCLUSIONS

Measurement of the transverse beam profiles using flying wires has revealed a characteristic temporal change

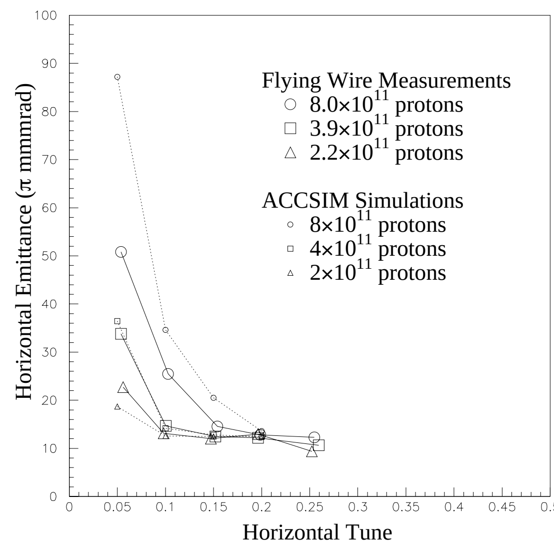

Figure 6: ACCSIM results of the horizontal 87% emittance as a function of the horizontal tune are shown in small symbols and dotted lines. Flyingwire measurement results are shown in large symbols and solid lines.

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. 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 qualitatively reproduced the beam profiles.

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