OBSERVATION OF SPACE-CHARGE EFFECTS IN THE KEK BOOSTER

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Abstract

We have been studying painting injection to increase the beam intensity of the KEK booster. In the low-intensity mode of operation, the extracted beam emittance can be expanded to the full acceptance by the painting injection. But in the high-intensity mode operation, the horizontal emittance of the extracted beams has not exceeded the half value of the full acceptance, aithough the injected beam could be broadened to the full acceptance by painting injection. The experimental results suggest the space-charge effect on painting injection.

1 INTRODUCTION

The features of the 500-MeV KEK booster are rapid cycling (20Hz), very compact and comprising combined function magnets. It supplies proton beams to the 12-GeV main ring (MR) and the neutron and meson science laboratory (NML). The MR demands to control the extracted beam emittance from the booster for optimum injection and the NML demands the high intensity beams as high as possible.

The injection system of the KEK booster consists of four bump magnets for normal H^- injection, two fast orbit-bump magnets for orbit shift painting to form a unifrm distribution and two steering magnets on the injection beam line, which adjust the width of the horizontal painting[1].

The normalized value of the designed acceptance of the KEK booster is 80π mm mrad in the horizontal plane and 18π mm mrad in the vertical plane. The incoherent space charge limit of the booster was calculated to be 3.2×10^{12} ppp assuming the designed acceptance of the machine. Until now, a beam intensity of 2.2×10^{12} ppp was constantly obtained by normal H^- injection. At this beam intensity, the emittance of the extracted beams is 38π mm mrad in the horizontal plane and 27π mm mrad in the vertical. The value of the vertical emitttance already exceeds the designed acceptance of the machine. The increase of the vertical beam size seems to restrict the beam intensity. But the horizontal emittance of the extracted beams is half the value of the full acceptance of the machine. It had been expected that the beam intensity might increase by 25%, if the horizontal emittance is extended to the full acceptance of the machine by painting injection.

In the case of a low-intensity beam ($\leq1\times10^{12}$ppp), the extracted beam emittance is well controlled by the painting injection and fills the full acceptance of the machine. However, regarding high-intensity mode operation ($\geq1.8\times10^{12}$ ppp), the horizontal emittance of the extracted beams dose not exceed the half value of the full acceptance of the machine; nevertheless, the injected beams of the booster were extended to the full acceptance by off-center painting injection. This strange, but interesting phenomenon has been carefully examined and studied from various angles. This paper deals with the relation between painting injection and extracted beam emittance by the experimental results and computer simulation.

2 INTESITY DEPENDENCE OF THE EXTRACTED BEAM EMITTANCE

The extracted beam emittance is measured by multi-wire profile monitors at the dispersion-free points on the extracted beam line. In the case of hollow distribution by simple off-center injection, is performed only by two steering magnets on the injection beam line, the center of the projection of charged particle beams in the horizontal plane is 22% lower than the uniform distribution by precise orbit sift painting[1]. Precise orbit shift painting is replaceable by simple off-center injection for the convenience in experiments.

The extracted beam emittance with the width of off-center injection in the horizontal plane as the parameter of the beam intensity is shown in Fig.1. In the low-intensity mode, the increments of the horizontal emittance give good agreement with the calculated values by the width of the off-center injection, and the vertical emittance is only little affected by the horizontal expansion of the

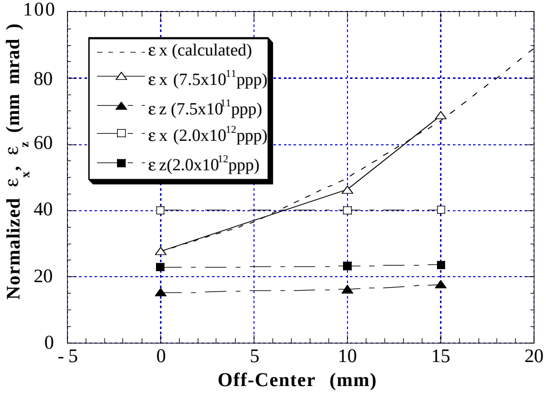

Figure 1: The extracted beam emittance with the width of off-center injection as the parameter of the beam intensity.

emittance. It can be considered that the emittnce is conserving through the accelerating process.

On the other hand, in the high-intensity mode, although the injected beams of the booster were expanded by off-center injection, the horizontal emittance dose not increase.

The intensity dependence of the extracted beam emittance as the parameter of the off-center injection is shown in Fig.2. The injection point was fixed and the beam intensity was changed by the Linac beam intensity. In the case of center injection, both horizontal and vertical emittnce gradually increases with beam intensity. But in the case of 15mm off-center injection, the horizontal emittance decreases with the beam intensity, although the injected beam is expanded by the off-center injection.

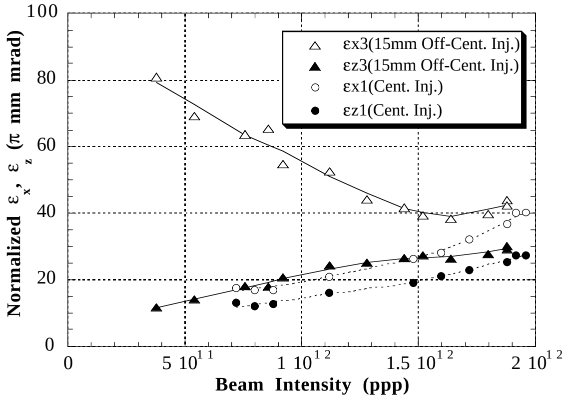

Figure 2: Intensity dependence of the extracted beam emittance as the parameter of the off-center injection.

3 COHERENT TUNE SHIFT

To examine the aperture decrease by the closed orbit distortion (C.O.D.) which might be enhanced by the coherent tune shift by the intensity effects, the intensity dependence of the coherent tune shifts was measured through an accelerating process using the measuring system which is composed of a kicker magnet, transverse pick-up and real time spectrum analyzer.

The coherent tune shift in the horizontal plane was almost zero throughout the accelerating process. The vertical tune shift was 0.04 during the injection period, where the value of the tune decreased from 2.29 (low-intensity mode) to 2.25 (high-intensity mode). The measured values are in rough agreement with the calculating results. In the horizontal plane, the C.O.D. enhancement by coherent tune shift was almost zero. In the vertical plane, the maximum C.O.D. increased 11% due to this coherent tune shift.

The measured value of coherent tune sift is not so large to decreases the aperture of the machine definitely.

4 CIRCULATING BEAM EMITTANCE

To obtain information about shrinkage of the extracted emittance in the horizontal plane, the beam size is measured in the accelerating process using a scraper and bump magnets system. When the bump magnets are excited, the circulating beam becomes closed to the scraper along the bump orbit, and thus the particles which hit the scraper are lost. Since the displacement of the bump orbit is proportional to the exciting current of the bump magnets, the inside or outside beam envelope at the scraper position can be measured as the bump current dependence on the beam intensity. Thus the beam size can be obtained by calibrating the bump current to the beam displacement[2].

The horizontal beam sizes, which are expanded to full acceptance by off-center injection, were measured in a period of 0.06ms to 1.5 ms after injection, where the injected coasting beams were captured in a RF bucket. In this bunching process, the momentum spread and the line charge density increases in an RF bucket. The bunching factor decreases from 1.0 to 0.4 in this period (from 0.06ms to 1.5 ms after injection).

The typical values of the beam size measured by the scraper method are shown in Fig.3 and Fig.4, where the data are 0.06ms and 1.5ms after injection, respectively. In Fig.4, at the 1.5ms after injection, the whole beam size of the high-intensity mode is clearly decreased compared with the low-intensity mode.

Because the momentum dispersion at the scraper position is not zero (1.4m) in the horizontal plane and the

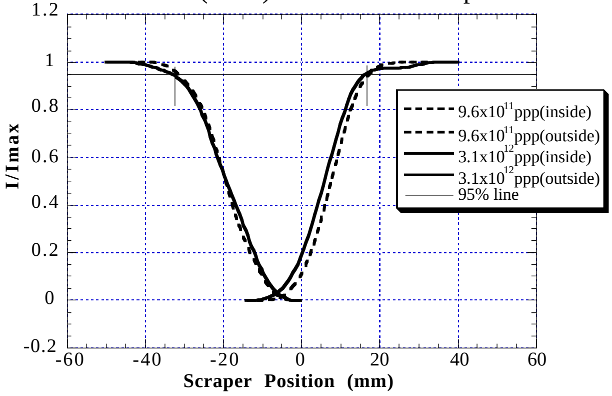

Figure 3: Horizontal beam size measured by the scraper method. (0.06ms after injection)

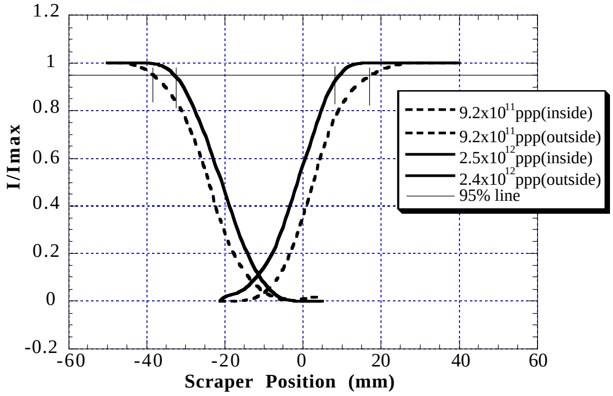

Figure 4: Horizontal beam measured by the scraper method. (1.5ms after injection)

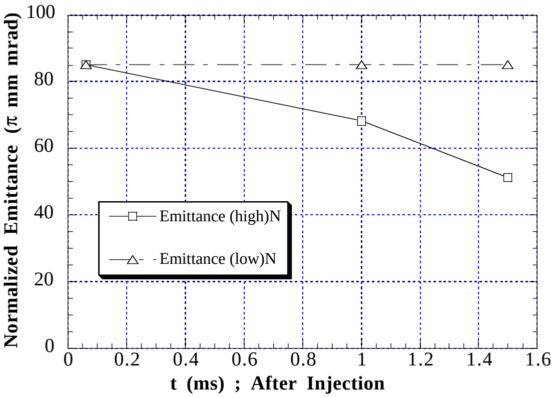

Figure 5: Decrease in the horizontal emitttance after injection.

momentum spread is not constant throughout the accelerating process, we cannot directly calculate the beam emittance from the whole beam size. However, under the assumption that the momentum spread is constant at the same time after injection, irrespective of the beam intensity (neglecting the beam loading in RF acceleration and space charge effect on the RF bucket), the difference in the beam size is considered to be the difference in the emittance due to the beam intensity. The emittance is conserving throughout the accelerating process in the low-intensity mode; that just after injection can be deduced to be the same value as the extracted beam emittance, which is measured by a multi-wire profile monitor. As shown in Fig.3, the emittance of the high-intensity mode and that of low-intensity mode are almost the same at the 0.06ms after injection; the decrease in the horizontal emitttance in the high-intensity mode can be deduced as the solid line in Fig.5. The circulating beam emitttance 1.5ms after injection is close to the extracted beam emitttance

5 SIMULATION RESULTS

In order to clarify the experimental results, multi-particle tracking was performed with self-consistent space-charge forces. The space-charge forces are modeled in the 2D plane (transverse only). Multi-turn injection is simulated by adding a constant number of macro particles turn by turn. As a result, the forces increase linearly as a function of time (or turn) and reach the maximum when injection is completed. In reality, the line density increases further after the injection period, because of a bunching process, that was not included in this study. We assume that the emittance of an incoming beam is 1π mm-mrad in both planes.

When a linac beam is injected off center in the horizontal plane, a resultant distribution in the booster becomes hollow. Thus, the projected profile on the position has a plateau as shown in Fig.6 (H). On the other hand, the beam is injected on axis in the vertical direction and the distribution remains the same as the incoming beam (Fig.6 (V)). That is the case when space-charge effects are turned off. It is no longer true when space charge (2.7×10^{12} ppp) is included. Just as the experimental results show, the horizontal outline of beam size is decreased and the vertical one is increased in turn, indicating an emittance exchange between the two planes (Fig.7 (H) and (V)).

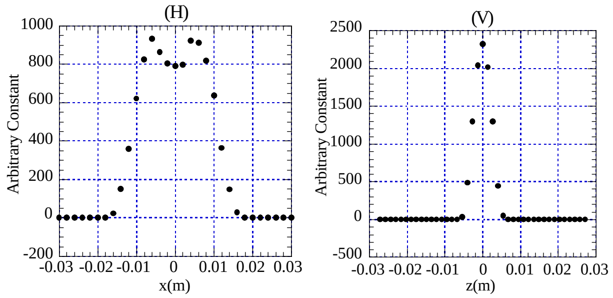

Figure 6: Simulation results of the projected profile (Space-charge effects are turned off)

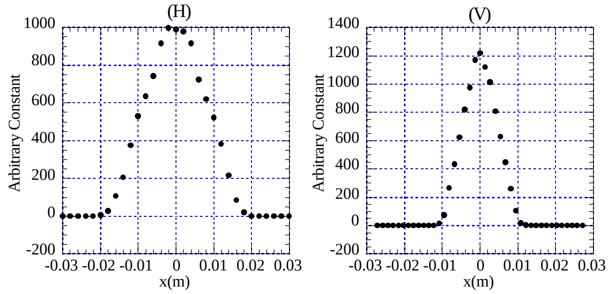

Figure 7: Simulation results of the projected profile (Space charge (2.7×10^{12} ppp) is included)

7 SUMMARY

The above experimental and simulation results imply that the space-charge potential of a beam induces coupling between the horizontal and vertical planes. Although a linear coupling term in the Hamiltonian, namely x z, is not excited by space charge because of the axial symmetry of a beam, the octupole term ,x^2 z^2, exists. In addition, the present bare tune is (2.17, 2.32), slightly above the coupling resonance line of $2Q_x$–$2Q_z$=0, and the depressed tune approaches as the beam intensity is increased.

Above results are in the case of one-dimensional painting. Even in two-dimensional painting to form a uniform charge distribution, the cross section in real space must pass through the flat shape during the initial stage. It may be needed to escape the above effects for designing the injection systems of future high-intensity machines.

REFERENCES

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[2] T.Adachi, et al, “Beam-Profile Measurement in the KEK-PS Booster Using Pulsed Bump Magnet and a Movable Scraper”, EPAC94, London, June 1994.