PHASE-SPACE PAINTING OF CHARGE-EXCHANGE INJECTION IN THE KEK BOOSTER

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Abstract

Protons are injected into the KEK booster by means of charge-exchange injection. Phase-space painting of charge-exchange injection in the horizontal plain has been tried using two fast orbit bump magnets, which are placed at the upstream and the downstream positions, respectively. At each position, the phase of the betatron oscillation leads and lags by $\pi/2$ from the injection point. Beams are gradually injected from the center of phase space to the outside by a shift of the closed orbit, which is controlled by these two orbit bump magnets. The waveform of the magnet is adjusted to the optimum gradient to realize a uniform density in real space using a mixed-waveform power supply. The particle distributions of the proton beams in the phase space were measured to examine the effects of the painting method.

1 INTRODUCTION

In the KEK-PS Booster, which accelerates 40 MeV proton beam of up to 500 MeV with a repetition rate of 20 Hz, the injection scheme was converted from orbit-shift multi-turn injection to H^- injection from 1987. H^- injection makes it possible to inject a beam at the center of phase space already occupied by a previously injected beam. Therefore, an intense proton beam can be accumulated into the ring without largely increasing the beam emittance. Beam intensities of the KEK-PS Booster have been obtained up to 2.2×10^{12} ppp.

As the beam intensity was increased, the emittance blow up was also observed. The vertical emittance through the accelerating process under various beam intensities were measured using pulsed orbit bump magnets and a movable scraper system[1]. The emittance growth of the extracted beams was also measured using the beam profiles and transfer matrix of the 500 MeV beam-transport line. Intensity-dependent emmitance growth has actually been observed, which might indicate the existence of a space-charge effect.

The design value of the vertical acceptance of the booster is 49π mm mrad. In the case of a beam intensity of 2.2×10^{12} ppp, the absolute value of the vertical emittance grows to 44π mm mrad which is close to the aperture limit of the booster. It has been thought that blow-up of the vertical emittance is one of the key reasons which restrict the beam intensity.

On the other hand, the design value of the horizontal acceptance of the booster is 294π mm mrad. The actual value of the horizontal acceptance is 275π mm mrad which is measured by studying the orbit-shift multi-turn injection for positive ions, which requires using the full aperture of the ring in the horizontal plane. The horizontal emittance of the circulating beams injected by charge-exchange injection is 47π mm mrad which is only 17% of the measured acceptance (275π mm mrad). To extend the horizontal beam emittance, there is sufficient space in the horizontal plane. The space-charge limit of the booster, which is calculated under the assumption that the envelope of the circulating beam is fully extended to the acceptance was calculated to be 3.2×10^{12} ppp[2].

The beam emittance and the distribution of charged particles in real space can be controlled by phase-space painting during the injection process, which will increase the circulating beam intensity. This paper deals with phase-space painting using fast orbit bump magnets which shift the closed orbit during the injection process.

2 PHASE-SPACE PAINTING BY DISPLACING THE CLOSED ORBIT

The distribution of charged particles in phase space is controllable by changing the injection points. However a change of the injection points is not realistic, because the position of stripping foil are not easily be changeable at high speeds. Actually, changing the injection points for phase-space painting is available by changing the position of the closed orbit or injection angle. In the case of the KEK Booster, we adopt the method of changing the position of the closed orbit, because the KEK Booster was designed to use conventional orbit-shift multi-turn injection and has a rather wide aperture in the horizontal plane.

Here, we note that from the point of view of the space-charge effect that the most favorable distribution in the transverse direction is a uniform distribution. To realize a uniform distribution in one-dimensional case, the orbit shift equation is given as[3][4],

$$x = a\left(1-\sqrt{\frac{2t}{T}-\left(\frac{t}{T}\right)^2}\right) \qquad (1)$$

where x is the shift in the closed orbit from the center of the closed orbit, a is the radius of the beam and T is the injection time.

3 PAINTING DEVICE

3.1 Magnets system

The injection scheme of the KEK Booster is shown in Fig.1. The injection system consist of four closed-orbit bump magnets for charge-exchange injection and two orbit-shift bump magnets for phase-space painting. The position and angle of the injection point for charge-exchange injection are fixed by the closed-orbit bump magnets, and the center of the closed orbit at the injection point can be shifted by two orbit bump magnets which are placed at the upstream and the downstream positions. At the each position of orbit shift bump magnets, the phase of betatron oscillation leads and lags by $\pi/2$ from the injection point. Beams are injected gradually from the center of phase space to the outside by a shift of the closed orbit, which is controlled by the decay pattern of the magnetic field of these two bump magnets.

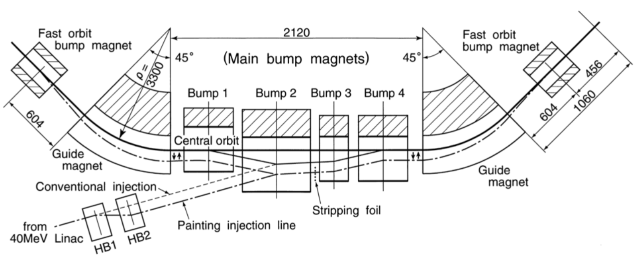

Figure 1: Charge-exchange injection system for phase space painting

3.2 Approximate wave form of orbit shift bump magnet

The magnetic field of the orbit shift bump magnet expressed by Eq. (1), which realize a uniform density of charged particles in real space, is the equation of an ellipse in a t-x coordinate. Actually, the waveform of the orbit-shift bump magnets must be approximated to the Eq.(1). This wave form can be approximated by the composition of a LC harmonic circuit and a LR exponential decay circuit[5].

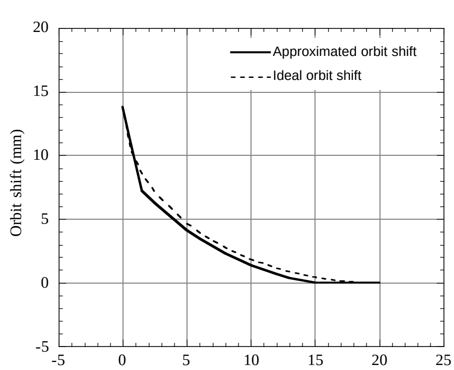

Figure 2: Actual waveform of the orbit shift bump magnet approximated to Equation (1)

The steep inclination at the beginning point of the injection is formed by a half sine, and the gentle inclination at the latter part of injection is formed by exponential descent of the excitation current. The waveform can be easily modulated by three components, which are charging the voltage of C, resistance R and the timing of conversion of the LC harmonic circuit to the LR exponential decay circuit.

In Fig.2, the actual waveform of the orbit shift bump magnet, approximated to Eq. (1), is shown and compared with the ideal waveform of Eq.(1).

4 SIMULATIONS OF THE PARTICLE DISTRIBUTION

In the case of the excitation current given by Eq.(1), the particle density in real space becomes uniform after injection is completed, which has been verified analytically for a beam injected with a small emittance. As for the actual waveform of Fig.2 approximated to Eq.(1) and for a certain amount of emittance, simulations were practiced in order to examine the accuracy of the approximated waveform under the premises of actual beam injection in the KEK Booster.

The assumptions of the simulations were as follows. The horizontal and vertical emittance(2s) of the injected beams are 18πmm mrad and 14π mm mrad, respectively. In the horizontal plane, since the half width of the injected beam is 8mm, and the half aperture of the machine is 30mm (physical aperture), the maximum orbit shift for injection painting is assumed to be 20mm .

The simulation results of the particle distribution in the phase space and the real space is shown in Fig.3. The density in the real space is almost uniform in the middle area.

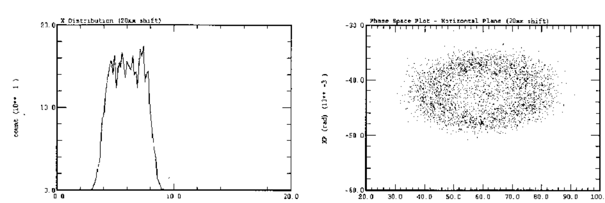

Figure 3: Simulation results of the particle distribution in the horizontal plane. Left; real space;. Right; phase space.

5 EXPERIMENTAL RESULTS OF THE PARTICLE DISTRIBUTION

During charge exchange injection the beam is painted on the horizontal phase space. As shown in Fig.4, by changing the decay current of orbit shift bump magnets, the circulating beam orbit during an injection period was moderately shifted for stacing in desired distribution.

To examine the effects of the orbit shift bump magnet, the particle distributions in the real space were measured using the multi-wire profile-monitors in the extracted beam line. The output signals of the profile monitor are shown in Fig.5. Solid triangles indicate the normal injection overlapped on the central orbit. Open circles indicate the off-center injection by 15mm parallel shift of injection line, which shows hollow beam distribution. Solid squares indicate the painting injection using the orbit shift bump magnet, which show the flat distribution in the middle area.

As shown in Fig.6, the particle distribution in transverse phase space which depends upon the waveform of the orbit bump magnets were estimated using a multi-wire profile-monitors in the extracted beam line[6]. The markers are same as Fig.5. The density distribution in phase space moved to the outside by painting, and the difference between the off-center injected hollow beams and the painted uniform density beams are clearly observed.

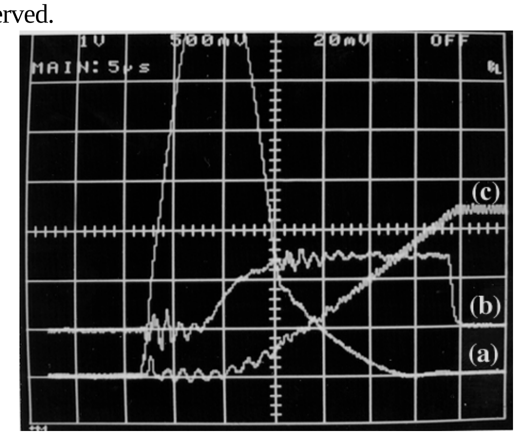

Figure 4: The Booster injection by phase space painting.
(a) Orbit shift bump magnets (3.5mm / div)
(b) linac beam current (5mA / div)
(c) booster beam current (0.1A / div); 9.4×10^{11}ppp

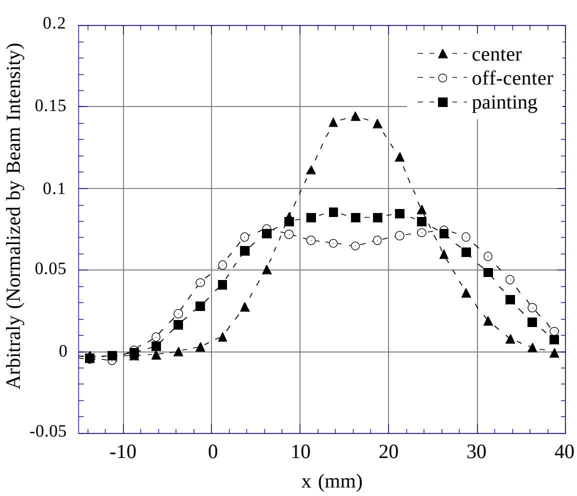

Figure 5: Particle distributions in the horizontal real plane measured by multi-wire profile monitor on the 500 MeV extracted beam line.
40MeV absolute emittance (95%) estimated by $\beta\gamma$:
Center (non paint); 79π mm mrsd,
Off center (hollow); 289π mm mrad
Painting (uniform); 224p mm mrad

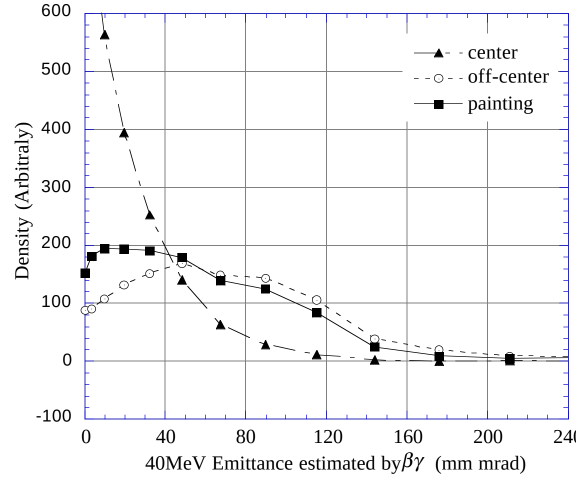

Figure 6: Particle density in the horizontal phase plane estimated from the transvers profiles.

6 SUMMARY

The emittance growth of the extracted beams having an intensity dependence was observed in the KEK Booster, which seems to be the space-charge effect. The particle distribution of the accelerated beams in the horizontal plane is controllable using the orbit-shift bump magnets located at the π-section. The uniform density of charged particles in real space, which is most suitable to reduce the space charge effects, can be realizable by phase space painting using the orbit-shift bump magnets. We are now trying to improve the beam intensity of the KEK PS.

The authors would like to express sincere appreciation to the Director General of KEK, H. Sugawara, as well as Prof. M. Kihara, Y. Yamane and T. Kawakubo for their continuous encouragement. They are also indebted to S. Ninomiya, T. Kurosawa, S. Takano and E. Kadokura for their valuable support of experimental technique.

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