DESIGN STUDY ON KEK INJECTOR LINAC UPGRADE FOR HIGH-CURRENT AND LOW-EMITTANCE BEAMS

H. Sugimoto, M. Satoh, M. Yoshida, KEK, Tsukuba, Japan

Abstract

Injector linac at KEK is now under upgrading to produce high current and low emittance beams to a SuperB factory, named SuperKEKB. Emittance growth resulted from both wakefield and dispersive effects at the linac are troublesome in keeping the beam quality during the acceleration. In this paper, we report recent simulation study for the emittance preservation issue. As a candidate for mitigation of the emittance dilution originated from the transverse wakefield, a bunch compression using an existing bending section is considered. It is demonstrated that the bunch compression remarkably improves the emittance preservation through the linac.

INTRODUCTION

SuperKEKB is a 7 GeV electron and 4 GeV positron collider based on a nano-beam scheme[1]. The target luminosity is $8\text{x}10^{35}$ cm^{-2} s^{-1}, which is 40 times higher than that of KEKB[2]. In the interaction point, a nano-scale sized beam is essential for the design luminosity. SuperKEKB main ring therefore requires a high current and low emittance beam (5nC, 20 mm mrad for electron, 4nC, 6 mm mrad for positron). To meet the requirement, new photo-cathode rf guns will be installed to the injector linac for the electron beam. For the low emittance positron beam, a damping ring is now under construction.

Since the target emittance required by SuperKEKB is very small compared to that of KEKB main ring, much more attention should be paid to emittance growth through the linac. Short-range wakefield and dispersive effects are considered to be the major source of emittance dilution.

In this paper, we report design study on SuperKEKB injector for high current and low emittance beams. We mainly report numerical simulations on the emittance preservation. All simulation presented in this paper is performed by an accelerator simulation code, named "SAD"[3].

EMITTANCE PRESERVATION

The word "emittance" has many definitions in accelerator physics, thus it sometimes causes confusion when the emittance preservation is discussed. The definition of the emittance in this paper is $\varepsilon_x = \gamma\beta\sqrt{\langle x^2\rangle\langle p_x^2\rangle-\langle xp_x\rangle}$, where γ and β are the Lorentz factors. The canonical variables x and p_x are sum of betatron motion and motion related to the momentum dispersion, namely, longitudinal beam dynamics. Therefore the emittance is, in general not preserved and increased by unexpected dispersion due to magnet misalignment even when wakefield is absent.

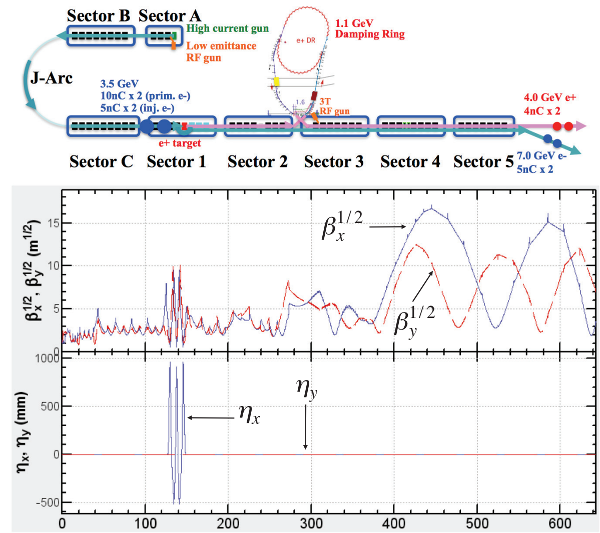

Figure 1: Schematic of SuperKEKB injector linac (upper figure) and beam optical functions (lower figure).

In the case of high current beam, the wakefield cause serious emittance dilution. The longitudinal wakefield induces energy spread to the beam and enhances emittance growth due to the dispersive effect. The enhanced energy spread also involves nonlinear dynamics. The nonlinear force increases the beam emittance due to the filamentation of the beam distribution. The transverse wakefield is excited when a beam passes through off-axis of an acceleration structure and deflects tail particles. This process cause serious beam instability in the high current beam.

Therefore, in order to keep beam quality during the acceleration through the linac, the beam optics including operation parameters should be carefully chosen to minimize these unexpected emittance degradations.

TRACKING SIMULATION

Figure 1 shows a schematic of SuperKEKB injector linac and linear beam optics used in the tracking simulations. The linac is mainly composed of 9 sections. A one unique feature related to this paper is that there is a bending section, named J-Arc. An application of this existing bending section to the emittance preservation is the main topics of this paper.

Simulation Condition

The initial particle distribution is a rectangular pulse of 10 ps bunch length (FWHM) with 5nC charge assuming an electron beam. Gaussian distributions are employed to the transverse phase space and energy spread. The initial

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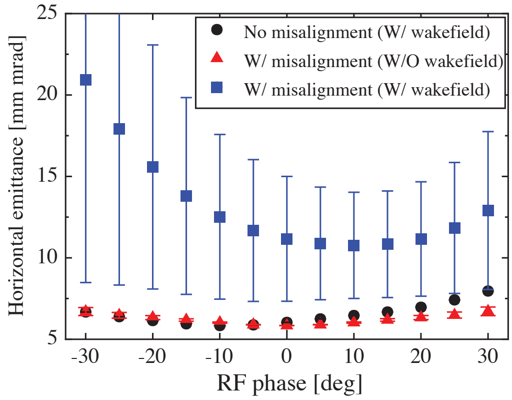

Figure 2: Horizontal emittance at the end of Sector B as a function of rf phase of the acceleration tubes. Each dot and vertical bar represents mean value and standard deviation of 100 simulations, respectively. On-crest is defined by 0 degree, and positive phase means bunch head gains higher energy from the rf wave compared to bunch tail.

emittance is 6 mm mrad for both horizontal and vertical directions, and the energy spread is 0.4 %. These parameters are chosen from a numerical simulation for a photo-cathode rf gun to be installed.

Longitudinal monopole and transverse dipole wakefield are incorporated in the simulation by using an analytical expression of the wake functions[4]. Long-range wakefield effects are not taken into account. The beam is approximated by 10^5 macro particles.

Alignment error of quadrupole magnet and acceleration tube is considered. All alignment errors are Gaussian distributed with rms 0.3 mm without particularly noted. Global orbit correction is carried out with singular value decomposition using 81 BPMs and 194 steering magnets. Each BPM is attached to the quadrupole magnets. Therefore the orbit correction is done not by minimizing actual beam offset to the design beam line, but by minimizing the BPM readings. The jitter error of BPM and beam is not included.

From SectorA to B

Before proceeding simulation including whole linac sections, emittance preservation from the Sector A to B is examined. The emittance at the end of Sector B as a function of acceleration phase is shown in Fig. 2, where 3 different simulation conditions are assumed to find out the most dominant source of the emittance growth.

The emittance is well preserved if linac is perfectly aligned or wakefield is turned off. When the misalignments are introduced to the linac, resultant orbit distortion induces the transverse wakefield and causes emittance degradation. Considering that the orbit correction is done so that the beam passes through the quadrupole center, the dispersive effect due to quadrupole misalignment is minimized after the optics correction. On the other hand, the beam may passes through the off-axis of the acceleration tubes, thus the transverse wakefield is inevitably excited. These simulation results indicate that the most dominant source of the emittance growth is wakefield as long as orbit correction is performed by the presented procedure.

To mitigate the wakefield effects, an application of BNS damping[5] has been considered. BNS damping, however, results a relatively large energy spread at the end of Sector B and leads to serious beam losses at a vertical slit installed to the following J-Arc bending section. One of other possible solution is offset injection scheme[6]. Both experimental and numerical simulation studies at KEKB injector shows that the offset injection effectively reduces the emittance dilution[7].

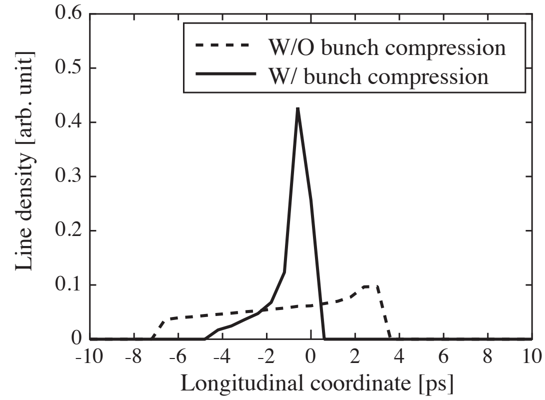

Figure 3: Longitudinal beam profile with and without bunch compression.

Bunch Compression Using J-Arc Section

As a possible way for mitigation of the emittance degradation due to transverse wakefield, we here consider a bunch compression using J-Arc section.

Our linac has a bending section named J-Arc as already mentioned. J-Arc currently is an isochronous bending section and the (5,6) element R_{56} of the transfer matrix is 0. The transverse wakefield effect can be reduced if shorter bunch length is attained. A bunch compression system with non-isochroous J-arc has been investigated.

Longitudinal phase space plot at the end of J-arc section with and without the bunch compression are shown in Fig. 3. It is confirmed from Fig. 3 that the non-isochronous J-arc works well as a bunch compression system. The bunch compression in J-Arc reduces the emittance dilution after J-Arc section as shown in the next section.

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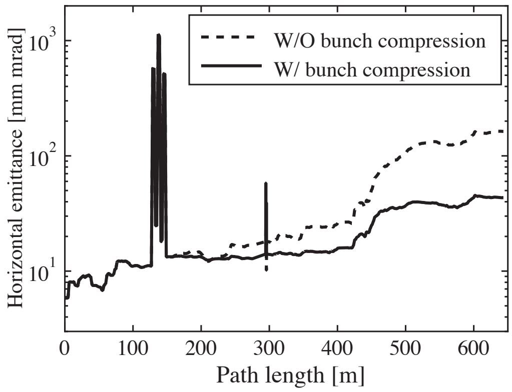

Figure 4: Horizontal emittance history along the linac.

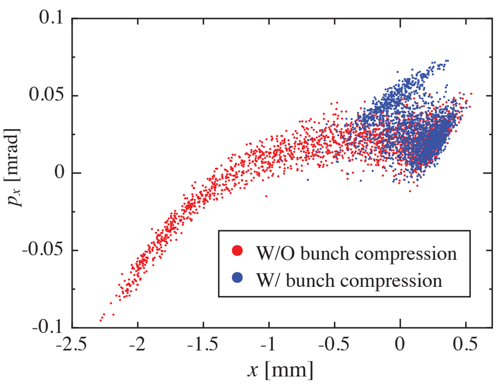

Figure 5: Horizontal phase space plot at the end of the linac with and without the bunch compression.

From Sector A to Sector 5

We finally perform simulations of emittance preservation through the whole linac section to see how effective the bunch compression is. In the presented simulation, we assume that J-Arc section is perfectly aligned in order to focus on the emittance dilution originated from the transverse wakefield. J-Arc imperfection leaks a large dispersion to the downstream and causes emittance growth. The effect on the emittance dilution from the dispersion leakage will be investigated in the near future.

Figure 4 shows the horizontal emittance history along the linac with and without bunch compression. The emittance rises at J-Arc section due to the energy dispersion. A huge emittance growth is observed after 400 m. This is simply because that betatron function is large compared to that of before 400 m and the large betatron function enhances the transverse wakefield effect. The emittance dilution after J-Arc section dramatically improved when the bunch compression is preformed as expected. Transverse phase space plot shown in Fig. 5 clearly shows that the phase space distortion is improved.

The relation between the final emittance and R_{56} value of J-Arc is shown in Fig. 6, where 3 different amplitudes of alignment errors are considered. Since the final emittance may strongly depend on the seed of random number used in the generation of misalignment, we use a

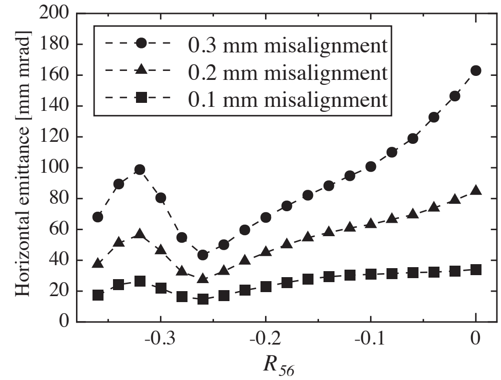

Figure 6: Horizontal emittance at the end of the linac as a function of transfer matrix element R_{56} of J-arc Section, where 3 alignment precisions are considered.

same seed of random number in the all simulation shown in Fig. 6. The non-isochronous J-Arc remarkably improves emittance preservation.

SUMMARY

Design study on the KEK injector linac upgrade is reported focusing on numerical simulation for the emittance preservation through the linac.

The simulation revealed that the most dominant source of the emittance degradation from Sector A to B is the transverse wakefield rather than dispersive effect from quadrupole misalignment. This is because the orbit correction is performed so that the beam passes though the quadrupole center.

As a candidate for the mitigation of the transverse wakefield effects, a bunch compression system using an existing bending section is considered. It is numerically shown that the beam is successfully compressed with the non-isochronous J-Arc.

The tracking simulation of the emittance preservation is carried to see effectiveness of the bunch compression. The simulation shows that the emittance dilution is dramatically improved owing to the shorter bunch length. More systematic and comprehensive study on the emittance preservation issue is under study.

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