INVESTIGATION OF BEAM VARIATION AND EMITTANCE GROWTH SIMULATION WITH BOTH MISALIGNMENTS AND THE BEAM JITTER FOR SuperKEKB INJECTOR LINAC*

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Abstract

The SuperKEKB is e+/e- circular collider for high luminosity, 8×10^{35} as a target value. For the high luminosity, the injector linac is required to transport low emittance high-charged electron beam and positron beam to the ring. A charged beam with an offset from a center of cavity is affected by the wakefield depending on both the offset size in the cavity and longitudinal particle position in the beam. The wakefield causes emittance growth. This growth can be suppressed by appropriate orbit control so as to cancel the wakefield effect of the cavities in total. On the other hands, the beam variation in 6-dimensional phase space also induces the emittance growth. Emittance growth by both misalignments and 6-dimensional beam jitter was evaluated by particle tracking simulation. Investigation of beam jitter and drift was also performed by correlation analysis between beam position and measured parameter, charge or temperature.

INTRODUCTION

SuperKEKB is e+/e- collider for high energy particle physics in KEK. Design luminosity of the SuperKEKB is 8×10^{35}, which is 40 times higher than that of KEKB achieved [1]. This high luminosity can be realized by twice current and one-twentieth beam size compared with that of KEKB. For the high luminosity, high intensity low emittance beam is necessary for the injector linac. If beam phase space is larger than SuperKEKB ring acceptance, the particles over the acceptance are lost and lifetime of the beam in the ring become short and luminosity go down. Therefore, we have to transport high charged low emittance beam to SuperKEKB ring.

Phase 1 of SuperKEKB project started from Feb. 2016. Various devices check, software operation check, and vacuum scrubbing were done successfully. Last run of the linac before DR (Damping Ring) commissioning was finished as mentioned reference [2]. DR commissioning will start from Autumn 2017 and phase 2 will start from 2018 for tuning to low emittance beam and low background with Belle II detector, which was installed April 2017. Physics run is planned in the phase 3 from Winter 2018. Low emittance beam tuning has to be established in the phase 2.

Schematic layout of the linac is shown as Fig. 1. The linac is composed of sector A, B, J-ARC, C, and 1∼5. Normalized horizontal/vertical emittance less than 40/20 µm at the end of linac is required in the phase 3. The linac has two kinds of electron gun: thermionic gun for high-current electron beam for positron generation and photocathode RF gun for low emittance electron beam. Positron beam is accelerated up to 4 GeV and transported to LER (Low Energy Ring). Low emittance electron beam is accelerated up to 7 GeV and transported to HER (High Energy Ring). Two-bunch operation will be performed at 50 Hz with 96 ns bunch space. Positron beam emittance for LER is reduced by DR, which is placed between sector 2 and sector 3. There is not major emittance reduction mechanism about electron beam for HER because there is not DR for electron beam. Emittance preservation of the electron beam in the SuperKEKB injector linac was studied by Ref. [3–5]. A charged beam with an offset from a center of cavity is affected by the wakefield depending on both the offset size in the cavity and longitudinal particle position in the beam. The wakefield causes emittance growth. This growth can be suppressed by appropriate orbit control so as to cancel the wakefield effect of the cavities in total. However not only misalignments of accelerator components but also beam variation cause emittance growth statistically, which simulation was performed after ARC section in the reference [6]. In this paper, we evaluate the emittance growth from after electron gun (merged point of two electron gun precisely) to the end of linac by as follows: misalignments of quadrupole magnets and acceleration cavities, magnetic jitters of quadrupole and steering magnets, 6-dimensional beam jitter. We also investigate the reason of the beam variation (jitter and drift).

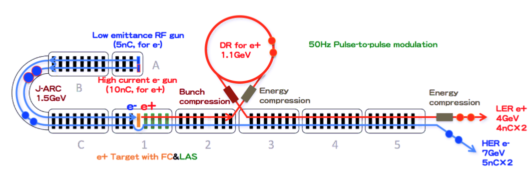

Figure 1: Schematic layout of the SuperKEKB injector linac.

WAKE FUNCTION AND POTENTIAL

We performed particle tracking simulation for SuperKEKB linac. Transverse and longitudinal wake field in acceleration cavity were taken into account. Short range wake functions were derived K. Yokoya [7]. Analytical wake function and numerical wake function in short-range were also derived by K. Bane [8]. These wake functions and the wake potentials are shown as Fig. 2, 3, respectively. Beam distribution is gaussian and σ = 3 mm/2.35, which is typical bunch length in the linac, was assumed in wake potential calculation, which is normalized by charge (nC) in this paper. In Fig. 3, wake potential calculated by CST studio [9] is also plotted. Though the CST wake potential is less than others

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by about 20%, these behaviors are almost same. In this paper, Yokoya wake was used in particle tracking simulation. Only short-range wake field is treated because bunch space of two-bunch operation is 96 ns and the space is long enough to ignore middle-range wake field in our S-band accelerator cavity.

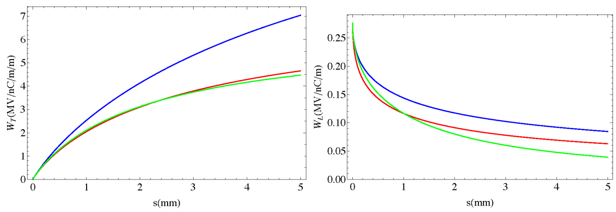

Figure 2: Comparison of wake functions. Right and left figures show transverse and longitudinal wake function, respectively. Green, red, and blue lines show K. Yokoya, K. Bane, and analytical wake function, respectively.

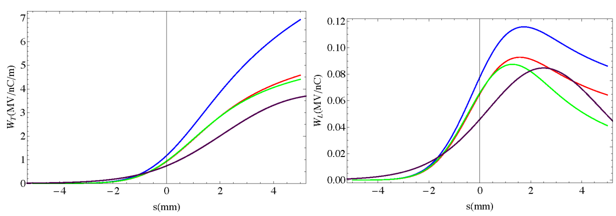

Figure 3: Comparison of wake potentials. Right and left figures show transverse and longitudinal wake function, respectively. Green, red, blue, and purple lines show K. Yokoya, K. Bane, analytical, and calculated wake function (CST), respectively.

PARTICLE TRACKING SETUP

Particle tracking simulation was performed by the Strategic Accelerator Design program [10]. Procedure of low emittance tuning is as following. First, orbit correction is performed so as to minimize beam position measured by BPM. Second, offset injection, which is one of emittance control method by 4 steering magnets [11], is performed. In the linac, reference point of BPM is calibrated to center of quadrupole magnet by Quad-BPM method [12]. In our simulation, we assume that BPM have same misalignment as that of nearest quadrupole magnet. We also assume that doublet or triplet quadrupole magnets have same misalignment values and acceleration cavities on same frame have same misalignment from A sector to ARC sector. Standard deviation of these gaussian misalignments is 0.2mm at from A to B sector and 0.1mm at ARC sector. Since emittance growth at the end of linac is more sensitive to misalignment at ARC section than that at other sectors, misalignment requirement at the sector is higher. From after C sector, misalignments measured by laser PD [13] were used. Realistic limited steering magnetic force was taken into account. Table 1 is basic parameters of our simulation. Offset injection was performed both at after merged point of sector A for thermal&RF gun and at the start of sector C. Emittance was evaluated at the end of linac where wire scanner is placed. In this paper, definition of emittance is RMS emittance.

Table 1: Basic Parameter Set. Aperture values indicate the radius. δ is relative momentum deviation.

Parameter	Value	Unit
Initial emittance	10	μm
Initial σ_z	3/2.35	mm
Initial δ	0.004	–
# of initial particles	10000	–
Distribution	Gaussian	–
S-band accelerator aperture	10	mm

EMITTANCE GROWTH

One of the simulation result for low emittance is shown as Fig. 4 under the conditions we mentioned previous section without magnetic and beam jitters. Blue and red show horizontal and vertical parameters, respectively. From the top of the figure, emittance, the number of transported particles, beam orbit, misalignments of quadrupole magnets, misalignments of acceleration cavities, and K value of steering magnet, respectively. Horizontal emittance increases temporally in ARC sector since there is large dispersion in the place. In the result, normalized horizontal/vertical emittance at the end of linac is about 24/10 μm, which is less than target value, 40/20 μm.

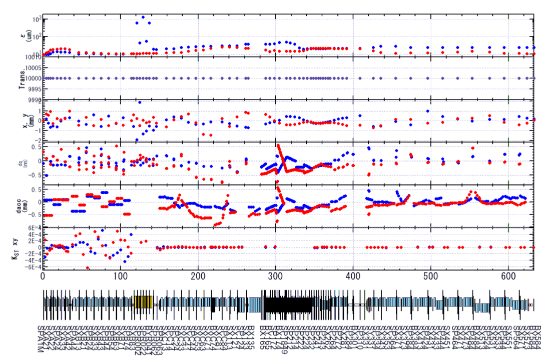

Figure 4: An example of simulation settings and results.

Jitter simulation was performed on the base of this setting. 6-dimensional beam jitters are $\{x, x', y, y', z, \delta\}$ = {10 μm,1 μ, 10 μm, 1 μ, 0.03 mm, 0.03%}. Transverse position jitters are consistent with measured jitter at start point of this simulation. Angle jitters are expected to be about one-tenth the position jitters since BPMs are placed at about 10 m interval. Longitudinal position jitter is roughly corresponded to required phase jitter of acceleration cavity. Longitudinal momentum deviation is corresponded to that at ARC sector. Quadrupole and steering magnetic have relatively 8×10^{-4} and 10^{-4} jitters to peak magnetic force of these magnet, respectively. These jitters have gaussian distributions. Emittance growth by these jitters are described by Fig. 5. The figure shows steering jitter is most sensitive to emittance growth. Total horizontal/vertical emittance, which is described as an emittance about all particles of injected

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beam, is 27/15 µm only with beam jitter , 37/16 µm only with quadrupole jitter, 54/22 µm only with steering jitter, and 74/28 µm with all jitters.

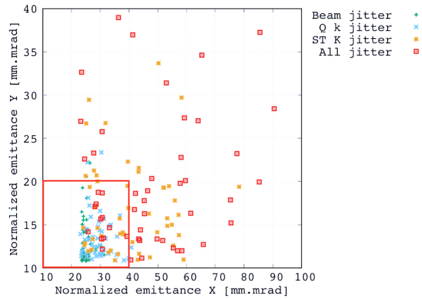

Figure 5: Emittance growth by beam, quadrupole, and steering jitters.

INVESTIGATION OF BEAM VARIATION

Beam position jitters influence directly total emittance. Therefore, reduction of the beam position jitters is important for low emittance tuning. Measured beam position jitters are shown at top of Fig. 6 and correlations between beam positions and charge are shown at bottom of Fig. 6. From the start of linac to before ARC section, averaged beam position jitter was about 25 µm (BPM resolution is about 10 µm). Horizontal beam position jitter was enlarged at ARC section (around 150m point in the figure). Longitudinal momentum jitter in the presence of horizontal dispersion induces horizontal beam position jitter. If dispersion is leaked, beam position jitter is enlarged as shown top of the Fig. 6. SP15T and SP165 are placed at before and after target where beam position jitters increase. Electron beam for HER passes through tungsten target hole, which diameter is 2 mm. In the correlation plot, correlations also increase at these points. This result suggests beam lost at the small hole and beam position jitters are enhanced. To reduce the beam position jitters, dispersion suppression and momentum jitter reduction have to be done. If the beam position jitters after ARC section, beam loss at the target hole should be small and enhancement of the beam position jitters should be also small after the target. The operation for the position jitter reduction will be done at the next run of linac.

Temperature drifts at upstream of A sector and at HV station for electron gun were measured as top of Fig. 7, colored green and red, respectively. In the same time, beam positions were also measured as middle of Fig. 7. From the shape of these figures, it can be found that these temperatures have correlations to beam position (BPM picked up randomly). In fact, correlations between temperature and beam positions are large as shown at bottom of Fig. 7. These three figures show the correlations at BPMs in one-third of the time taken in temperature measurement of HV station. Blue and red show horizontal and vertical correlations, respectively. Time passes from the left to right figure. Temperature of HV station was stable at the first one-third time, and correlation value is not large. However, at the second and third one-third time, temperature of HV station drift, and correlation value

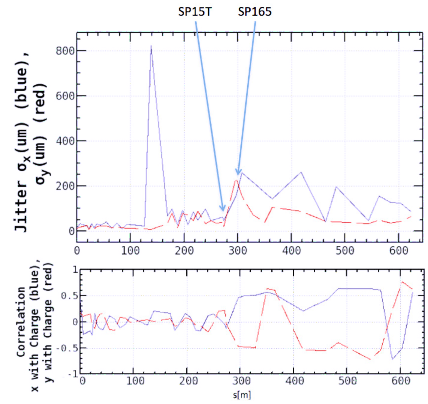

Figure 6: Beam position jitter in the linac and correlations between beam positions and charge. Blue and red show horizontal and vertical correlations, respectively.

became large. This result shows temperature drift around electron gun influence beam position drift.

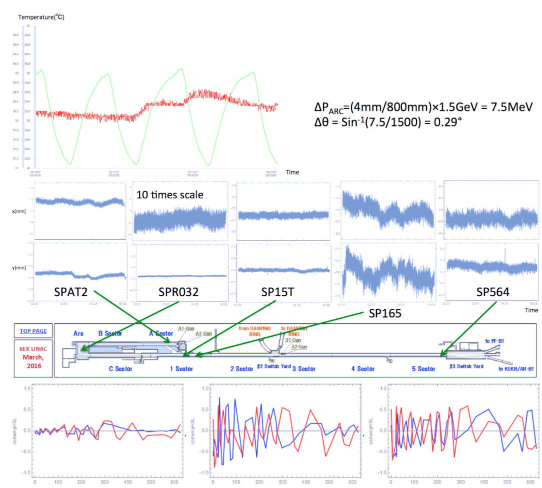

Figure 7: Temperature around electron gun, beam position jitter, and these correlations.

CONCLUSION

Particle tracking simulation for HER electron beam was performed. In this simulation, 0.2 mm RMS misalignments between sector A to B, 0.1 mm RMS misalignments at ARC sector, measured misalignment between sector C to 5, 0.01% steering magnetic jitter, 0.08% quadrupole magnetic jitter, and {10 µm, 1 µ, 10 µm, 1 µ, 0.03 mm, 0.03%} as 6-dimensional beam jitter were included. In these conditions, steering magnetic jitter is dominant for emittance growth. Low emittance tuning method could be developed so as to reduce sensitivity of steering jitter to emittance growth, for example optimization of dispersion suppression, otherwise power supply with higher precision is necessary. Beam position jitter affects growth of total emittance directly; therefore investigation of beam jitter was also performed. Dispersion after ARC section has to be suppressed to reduce beam jitter for high charged low emittance beam. Temperature drift also affects beam position drift. Air conditioning with more performance is desired in linac.

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