KEKB LINAC WAKEFIELD STUDIES OF COMPARING THEORETICAL CALCULATION, SIMULATION AND EXPERIMENTAL MEASUREMENT*

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Abstract

For SuperKEKB, in order to achieve designed luminosity, the machine needs to run with a small beam emittance in the injection linac. During the beam propagation in the linac, the short-range wakefield in the accelerating structure will cause the beam instability and emittance growth. In practice, injecting beam with a certain offset could compensate wakefield effect. In this paper, wakefield theoretical calculation, simulation results will be presented. And then the wakefield impact to beam emittance and wakefield compensation will be discussed. Finally, we will show the comparison of the results getting from theoretical calculations and experimental measurements.

INTRODUCTION

KEKB [1] was an electron-positron collider with energy of 8 GeV and 3.5 GeV. After a successfully construction and running, the machine has achieved a peak luminosity of $2.1{\times}10^{34}$ cm^{2}s^{-1}. The scientists in KEK have planned a major upgrade of KEKB to SuperKEKB [2] with the luminosity of 8×10^{35} cm^{2}s^{-1}. It is a challenge to improve the luminosity 40 times from the KEKB. In order to achieve that, a low emittance machine is required so that a nano-beam scheme has been proposed to squeeze the beam as small as possible ($\epsilon_y = 3.2/5.3$ nm). The performance of such nano-bean scheme machine highly depends on injection beam characteristics, requiring a low-emittance beam for the injection linac. When the beam propagates in the linac, the head particles induce a wakefield, which interacts with tail particles causing the beam instability and emittance growth. The longitudinal wakefield gives rise to energy spread and the transverse wakefield can lead to increase of beam emittance. In this paper, we introduce the trajectory of the bunch when there is an offset injection, and then calculate the emittance growth due to the misalignment of accelerating structure. To reduce the emittance growth caused by wakefield, an investigation of using offset injection has been carried out. In the final section the results of beam emittance measurements are presented and comparing with simulation results.

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SHORT-RANGE WAKEFIELD

Offset Injection and Trajectory

When a bunch of electron beam travels off-axis along a perfect aligned accelerating structure, the head particles in the bunch will interact with the beam pipe and leaves a wakefield behind the leading particles [3]. The induced wakefield can deflect the trailing particles further away from the axis. In that case, the projected beam emittance will increase. In Fig.1, the plot shows the displacement x of a point on the bunch as a function of distance.

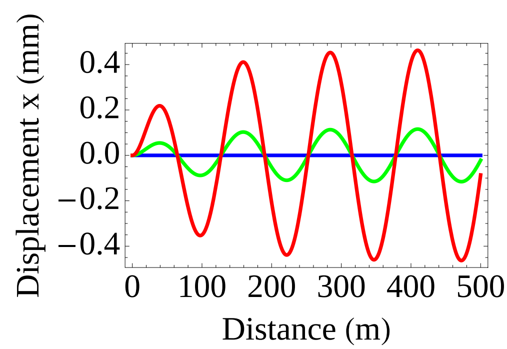

Figure 1: The displacement x of a point on the bunch as a function of traveling distance. The blue, green and red curve corresponds to the position of head, center and tail particles along the beam respectively.

As we can see in Fig.1, x value depends on the position along the bunch. The blue line represents the head position, which vanishes as we expected. And the center and tail of the bunch are shown with green and red curves respectively. The tail particles will suffer a much stronger kick than the particles located in the center of the bunch. The further away from head, the stronger the wakefield will be.

Misalignment Effect

In the previous section, calculation is based on the assumption that all the elements are perfect aligned. The wakefield generated is due to the beam injection with a displacement error. However, in the real world, because of the engineering limitation, there must be some misalignment along the linac, which could also lead to the beam instabilities even the beam is injected with a perfect precision. If we assume a misalignment error d, the x coordinates square will be represented as [4].

$$\left\langle x_{mis}^{(1)2}\right\rangle = \frac{1}{2N_c}\left\langle d^2\right\rangle(\frac{r_0L}{\gamma_f k_0})^2 ln(\frac{\gamma_f}{\gamma_0})R_1^2(z) \quad (1)$$

$$\left\langle x_{mis}^{(2)2}\right\rangle = \frac{1}{24N_c}\left\langle d^2\right\rangle(\frac{r_0L}{\gamma_f k_0})^4 ln^3(\frac{\gamma_f}{\gamma_0})R_2^2(z) \quad (2)$$

where $\left\langle d^2\right\rangle^{1/2}$ is the rms value of the misalignment and the wakefield is assumed to be linear. N_c is the number of accelerating unit, r_0 is the classical radius of the particle, L is the total length of accelerating structure, γ_0 and γ_f are the energy of the beam at position of entrance and exit. The expression of R_1^2 and R_2^2 could be found in [4]. The equations are adopted to calculate the beam emittance growth due to the wakefield produced by misalignment accelerating structure. In the calculation, we assume a misalignment of 0.1 mm, with 240 accelerating units in totally length of 500 m. The results are shown in Fig.2.

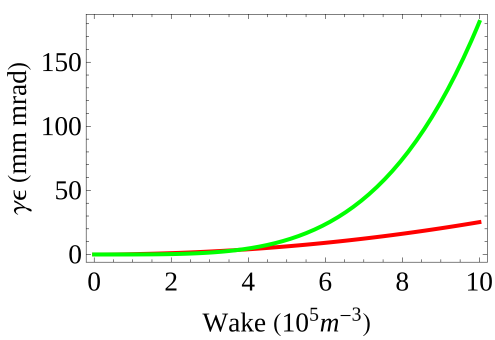

Figure 2: Emittance growth as a function wakefield. The red line and green line corresponds to the 1^{st} and 2^{nd} order contribution to beam emittance growth respectively.

Figure 2 shows that for a fixed total acceleration length, the 2^{nd} order contribution has a much larger effect to the emittance growth when there is a strong wakefield. In other words, for a machine whose wakefield is larger than certain critical value, the 2^{nd} order contribution should be on the top of priority list to compensate. By considering the KEKB parameters and implement them into the formula introduced in [5], we can work out the wakefield is about $4 \times 10^5 \mathrm{m}^{-3}$. In that case, the 1^{st} order and the 2^{nd} order contribution to emittance growth are roughly in the same level.

Offset Injection Compensation

The emittance growth due to wakefield effects can be enhanced by both the initial offset errors and the structure misalignment. In fact, the wakefield induced by misalignment could be cancelled substantially by applying an offset injection. The compensation could be very helpful to our emittance preservation. The 1^{st} order and the 2^{nd} order contribution by an initial offset x_0 could be calculated by equations [4]:

$$x_{off}^{(1)}(z, L) = \frac{1}{(1+GL)^{1/2}}(\frac{r_0}{\gamma_0 k_0}) R_1(z)\frac{ln(1+GL)}{2G}x_0 \sin k_0 L \quad (3)$$

$$x_{off}^{(2)}(z, L) = -\frac{1}{(1+GL)^{1/2}}(\frac{r_0}{\gamma_0 k_0}) R_2(z)\frac{ln^2(1+GL)}{2G^2}x_0 \sin k_0 L \quad (4)$$

where G is the acceleration gradient and L is the total length of accelerating unit. The compensation could apply to either the 1^{st} order or the 2^{nd} order contribution. The offset wakefield effect is represented by Eq.3 and Eq.4, and the misalignment wakefield effect are represented by Eq.1 and Eq.2. In order to reduce the emittance growth, for instance, in the case of the 1^{st} order compensation, we need $x_{mis}^{(1)} = -x_{off}^{(1)}$. By solving this equation, the offset injection position x_0 could be obtained. Then if we substitute x_0 into Eq.2 we can get the emittance growth due to the 2^{nd} order contribution. Similar method could also be used to cancel the 2^{nd} order and then calculate the 1^{st} order contribution.

The results have been compared with the one which gets from misalignment caused emittance growth without cancellation. The results show us that the emittance could effectively reduce to $1/4$ by canceling the 1^{st} contribution. On the other hand, the emittance is about $1/3$ of the case of no offset injection if we compensate the 2^{nd} order contribution. The researches we have done so far implied that an on purposed offset injection could well control the wakefield and minimize the emittance growth. In reality, the beam in the accelerator will be far more complicated than what we have shown in calculations. In the next section, the experimental data taken from KEKB linac has been analysed, which will help to understand how the emittance changes in the accelerator due to the wakefield.

KEKB LINAC DATA FOR WAKEFIELD STUDY

Experiment Data Analysis

In reality, the accelerator elements cannot be perfect alignment. Hence, even the beam is injected without offset, the misalignment will induce the wakefield as we introduced in the previous section. In order to reduce the emittance growth, the offset injection compensation method has been investigated. The purposes are achieved by adjusting the current of steering coil, then the beam can be injected into the next section with certain angle and offset. Figure 3 shows the measured emittance as a function of steering current. From the plot we can observe not only the emittance growth due to the wakefield caused by misalignment, but also the offset injection compensation of the emittance growth.

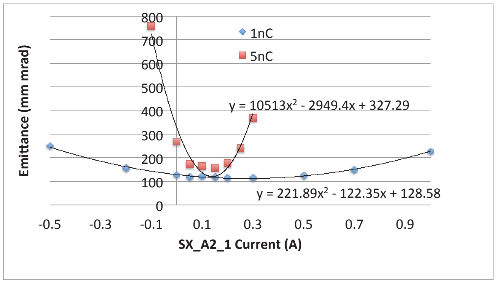

Figure 3: Emittance as a function of steering coil current. The red and blue dots are the wire scanner measured results for 1 nC, 5 nC beam in KEKB linac. The black lines are the data parabolic fitting, and the fitting functions have also been displayed.

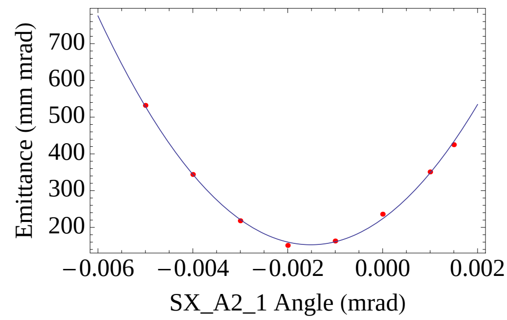

Figure 4: Emittance as a function of kick angle. The red dots are the emittance value of 5 nC beam. The blue line is the parabolic data fitting. The KEKB linac lattice file has been implemented into Elegant, and the components have a random misalignment of 0.5 mm.

Figure 3 shows the emittance measurement of operating 1 nC and 5 nC electron beam in KEKB linac. The steering coil current has been changed in order to control the kicking strength, so that the electron beam could go into next section with an offset and angle. For 1 nC electron beam, when current changes from -0.5 A to 1.0 A, the maximum emittance could reach up to 250 mm mrad, and have a minimum value of 115 mm mrad. Regarding the 5 nC electron beam, it is more sensitive to the steering coil current changes. The emittance could reach up to the 760 mm mrad when a -0.1 A current is applied. The same as the 1 nC run, the minimum emittance can be obtained at the point of using a current of 0.15 A, which is about 160 mm mrad. It is clearer for the 5 nC beam that when there is an offset compensation, the beam emittance could be $1/3$ of the case of without one.

In order to investigate the wakefield effect for imperfect aligned structure, we use Elegant [6] for simulation and results are shown in Fig.4. In simulation, lattice file, changing steering coil and measuring wire scanner are the same as real experiment. The advantage of simulation is the misalignment magnitude could be known and controlled, whereas in the experiment there is no way to monitor the misalignment value. From Fig.3 and Fig.4 we can see that for both of them, the minimum point has been shifted off from the origin, which means the emittance is reduced when the beam is off the axis. In experiment, the 5 nC electron beam has received a kick from steering coil having a current of 0.15 A. The 5 nC electron beam inject into the next unit with a displacement from axis. The displacement caused the beam instability of inducing wakefield. This wakefield combines with another wakefield which is generated due to the imperfect structures. They start to cancel each other, which leads to the emittance reduction. To sum up, both of the simulation and experiment has shown evidence that the compensation method is valid and well sufficient to keep a small emittance when electron beam propagate in the linac.

SUMMARY AND CONCLUSION

The emittance growth due to the wakefield effect in the injection linac appears to be critical to the nano-beam scheme of the SuperKEKB. The structure misalignment will be the main source of wakefield generation, but this is something we cannot avoid. In order to minimize the effect of the wakefield, injecting the beam with certain offset and angle could sufficiently reduce the emittance growth, which has been studied in theory and proved by experiment. With the help of KEKB linac, we have been collecting exciting results of indicating the validation of wakefield compensation using offset injection. The latest experimental results show the emittance could be 1/4 of no compensation, which has a well agreement with the theoretical calculation results and simulation output. For SuperKEKB, the experience we have had so far based on KEKB beam and machine studies will be valuable to the emittance preservation in the linac.

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