A FEW ISSUES ON THE UPGRADE OF KEKB B–FACTORY

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Abstract

A few issues on the path of the luminosity upgrade of KEKB B–Factory is described, including coherent synchrotron radiation, design of the interaction region, crab crossing, and high current operation. These issues will raise more obstacles on the upgrade with the *High-Current Scheme*. As an alternative, *Nano-Beam Scheme* should be considered as a possible option for the upgrade.

KEKB B–FACTORY

KEKB B–Factory[1] has been operating since 1999 for the collision experiment mainly at the Υ(4S) resonance. KEKB consists of the low energy positron ring (LER) at 3.5 GeV, the high energy electron ring (HER) at 8 GeV, and the injector linac. Two beams collide at the Belle detector. The highest luminosity, $\mathcal{L} = 1.93 \times 10^{34}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$, was recorded in May 2009. The peak luminosity became higher than the design by 90% mainly due to smaller β_y^* (6 mm vs. 10 mm) at the interaction point (IP), horizontal betatron tune closer to a half integer (LER: 0.505 / HER: 0.511 vs. 0.52), and crabcrossing. The daily integrated luminosity is as twice high as the design due to the Continuous Injection Mode as well as acceleration of two bunches per an rf pulse at the linac. The electron cloud in the LER, which was much more severe than thought in the design, has been mitigated up to 1.8 A with nearly 3 bucket spacing by solenoid windings for 2,200 m.

UPGRADE PATH

SuperKEKB, which is an upgrade project of the present KEKB to achieve a luminosity ~ 50 times higher than now, has been considered with three main methods:

- Increase the stored beam currents I to 9.4 / 4.1 A (LER / HER).
- Reduce β_y^* to 3 mm, together with bunch length $\sigma_z =$ 3 mm, which is ~ 6 mm at the present KEKB.
- Increase the vertical beam-beam parameter ξ_y up to ~ 0.3 with crab crossing[3, 4], which recovers an effective head-on collision with a crossing angle at the IP.

The resulting luminosity will be $8 \times 10^{35}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$ if these methods work as expected. Let us call the upgrade path based on above the *High-Current Scheme*. Studies have been made on each of them for years until today, and revealed a few issues on the High-Current Scheme as described below.

COHERENT SYNCHROTRONN RADIATION

It has been pointed out by T. Agoh and K. Yokoya[5] that the coherent synchrotron radiation (CSR) can be a show stopper of the High-Current Scheme, causing heavy microwave instability in the LER for the bunch length $\sigma_z = 3$ mm. T. Agoh calculated the wake function with the bending radius of the LER arc bends for various sizes of the beam pipe, which had square cross section. He also developed a simulation code to predict the microwave instability associated with the CSR together with the resistive-wall impedance. He presented the results at the KEKB Accelerator Review Committee[6], which was rather pessimistic. The remaining issues were to apply to a realistic shape of the cross section of beam pipe, which was a round pipe with antechambers at the both sides, and to include the wakes of other components in the ring such as shielded bellows and the gaps between the beam pipes, etc.

An independent estimation of the CSR effects was done in 2008. The essential physics of the Agoh-Yokoya method was to drop the second-order derivative in s, the coordinate along the beam orbit, from the Maxwell equations for Fourier components of the fields. Thus the equation reduces to

$$\frac{d\boldsymbol{f}}{ds} = \boldsymbol{b} + A\boldsymbol{f}\ , \tag{1}$$

where $\boldsymbol{f}$ is the vector of the Fourier components of the electric fields, *i.e.*,

$$(E_z, E_x) = \boldsymbol{f}(x, y, s)\exp(iks - i\omega t)\ . \tag{2}$$

The other components of the electromagnetic field are derived from E_z and E_x. The beam is assumed to move along the orbit with the speed of light, creating the source term $\boldsymbol{b}$. The matrix A in Eq. 1 is a transverse differential operator which reduces to the transverse 2D Laplacian $\frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2}$ when the curvature of the orbit becomes zero. The shape and the boundary condition of the beam pipe determines the actual form of A. Although Agoh-Yokoya solved Eq. 1 in the s-domain with an implicit finite difference method, we have used an analytic solution instead:

$$\boldsymbol{f}(s) = \exp(As)\boldsymbol{f}(0) + \int_0^s \exp\left[A(s - s')\right]\boldsymbol{b}ds'\ , \tag{3}$$

assuming the shape of the beam pipe and the curvature of the orbit constant along s. In such a case, both A and $\boldsymbol{b}$ become constant. Thus the solution 3 can be obtained quickly for any distance without worrying about a possible accumulation of numerical errors in the finite difference method.

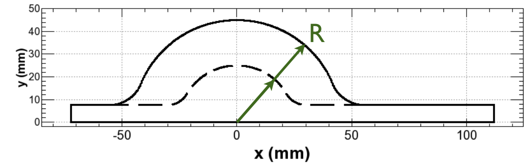

Figure 1: Cross section of the beam pipe with antechambers for SuperKEKB. Two possible shapes with different radii, $R = 45$ mm (solid) and $R = 25$ mm (dashed) are shown. The pipe is symmetric to the horizontal plane. The beam is at the origin.

The caculated fields and the wake functions of the new code agreed with Agoh's very well for square beam pipes, then we applied it to the actual shape of the beam pipe of SuperKEKB. Figure 1 shows the cross sections. We tried three possibilities of different radii, $R = 45, 35, 25$ mm.

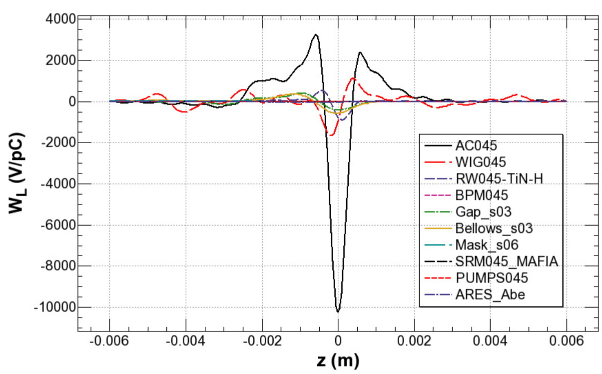

Figure 2: The calculated logituinal wake functions for various impedances of SuperKEKB LER for $R = 45$ mm beam pipes. The highest peak is given by the CSR in the arc (black). The CSR in the wigglers (red-dashed), resistive wall with TiN coating (purple), bellows (gold), and gaps between beam pipes (green) follow.

Figure 2 shows a collection of wake functions of various componens in the LER. The wake function was calculated for a bunch as short as 0.3 mm. For some components including an rf cavity, such a short bunch was not possible due to limitations in computation, then a longer bunch, 0.6 mm, was used. Anyway the CSR obviously dominates all the wakes as shown in Fig. 2. The other impedances hardly interferes the instability caused by the CSR.

The situation did not change for a smaller beam pipe with $R = 25$ mm as shown in Fig. 3. The CSR still dominates, even its peak is reduced by half and the resistive-wall impedance becomes as twice large as $R = 45$ mm.

We surveyed the microwave instability caused by the wakes in Fig. 2 by particle-tracking simulations. The results for the $R = 45$ mm beam pipe with antechambers are shown in Fig. 4. These were obtained with 400,000 particles in the tracking, and the convergence was checked by doubling the particles. We tracked for 25,600 turns, while the radiation damping was 2,800 turns. These wakes were applied twice in a turn, but such a distribution did not affect the result. Other parameter are listed in Table 1. Figure 4 shows the threshold of the instability at $N = 2 \times 10^{10}$, which is 1/6 of the design intensity. At the design intensity, the bunch lengh and the momentum spread blow up by 80% and 60%, respectively. The former degrades the luminosity via the hour-glass effect, and latter also harms the luminosity effectively, as it is much larger than the width of the resonance of B–meson. The instability was also examined by looking at the stability of Vlasov equation[7, 8] and the result was consistent with the tracking as shown in Fig. 5.

Generally speaking, such a microwave instability becomes weaker, when the initial bunch length becomes longer. Figures 6, 7, and 8 show such effects for $R =$ 45 mm, 25 mm, and $R = 45$ mm with a negative momentum compaction factor, respectively. A smaller pipe

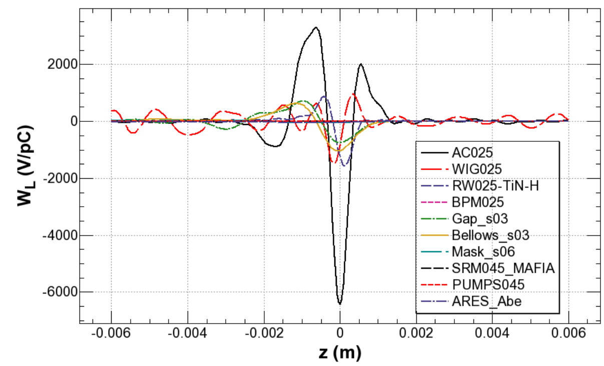

Figure 3: The calculated logituinal wake functions for various impedances of SuperKEKB LER for $R = 25$ mm beam pipes with antechambers. The highest peak is still given by the CSR in the arc (black). Then the resistive wall with TiN coating (purple) becomes comparable to the CSR in the wigglers (red-dashed). Bellows (gold), and gaps between beam pipes (green) follow.

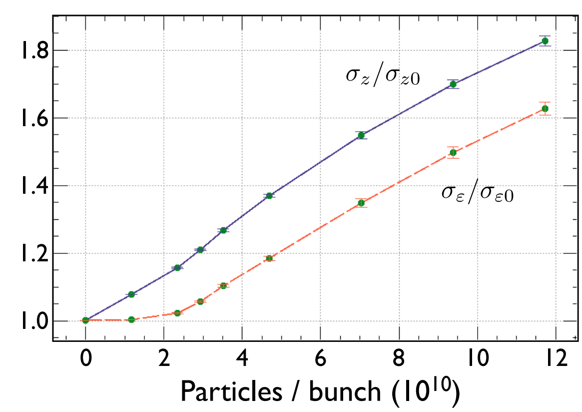

Figure 4: The results of particle tracking simulation with all calculated wakes with the $R = 45$ mm beam pipe with antechambers, showing the bunch length σ_z and the energy spread σ_ε relative to their zero-intensity values σ_{z0} and $\sigma_{\varepsilon 0}$, plotted against the number of particles per bunch N. The right most points correspond to the design intensity of the SuperKEKB LER.

Table 1: Longitudinal parameters of the SuperKEKB LER to evaluate the CSR effects.

N (design)	11.7	10^{10}
σ_{z0}	3	mm
$\sigma_{\varepsilon 0}$	7.1	10^{-4}
ν_z	-0.022	

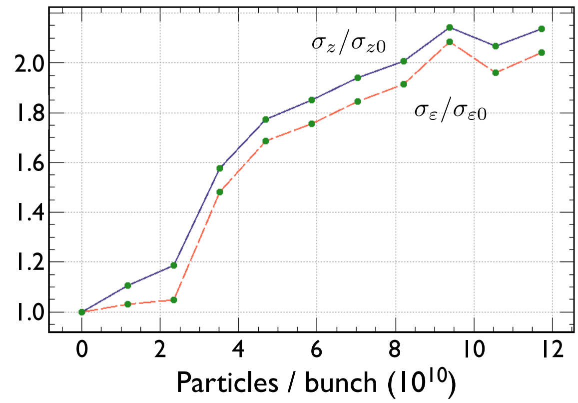

Figure 5: The microwave instability estimated by examining the stability of the Vlasov equatiuon with the same condition as the tracking in Fig. 4, showing the bunch length σ_z and the energy spread σ_ε relative to their zero-intensity values σ_{z0} and $\sigma_{\varepsilon 0}$, plotted against the number of particles per bunch N. The threshold of the instability, $N \sim 2\times 10^{10}$ is consistent with tracking.

$R = 25$ mm surely weakens the instability and thus the blow up of the momentum spread becomes less. A negative momentum compaction factor to switch the polarity of the synchrotron motion is also effective to reduce the blow up. Such choices of the beam pipe radius and momentum compaction factor, however, do not improve the situation drastically.

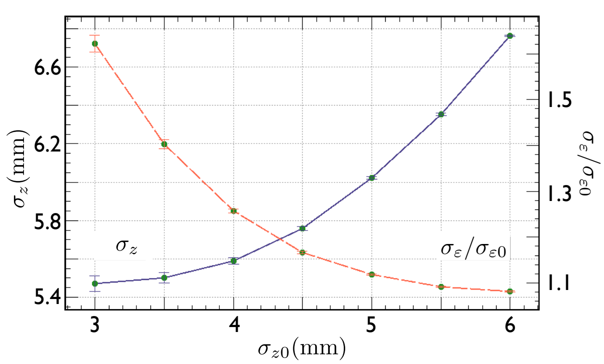

Figure 6: The bunch length (bule, left axis) and the relative momentum spread (red, right axis) at the design intensity as functions of the bunch length at zero intensity. The radius of the beam pipe is $R = 45$ mm.

According to these simulations, a bunch length shorter than 5 mm will not be possible at the design intensity in the LER of SuperKEKB. It almost confirmed the earlier prediction by Agoh for square beam pipes. In the HER, however, 3 mm bunch length will be possible, because the bunch intensity is small and the energy is high. As the bunch length becomes longer, one has to increase β_y^* to match the bunch length to avoid an hour-glass effect. Therefore the resulting luminosity can be reduced to 3/5 of the original value, if both beams have the same β_y^*.

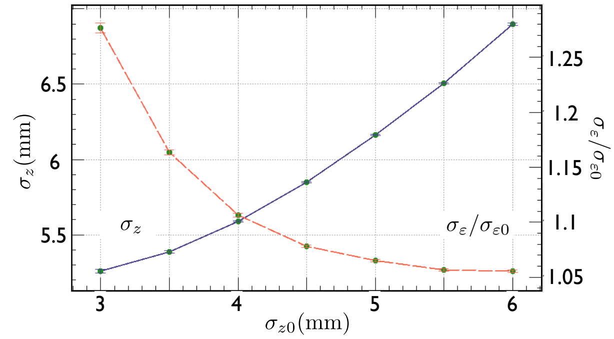

Figure 7: The bunch length (bule, left axis) and the relative momentum spread (red, right axis) at the design intensity as functions of the bunch length at zero intensity. The radius of the beam pipe is $R = 25$ mm.

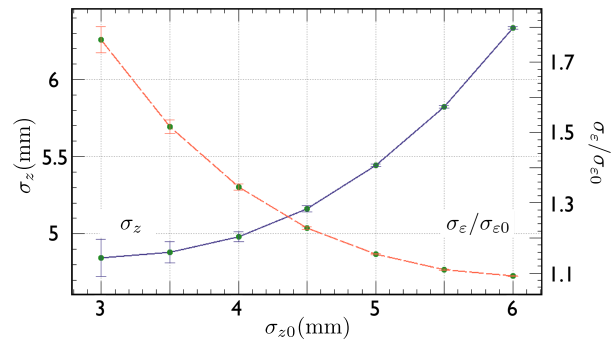

Figure 8: The bunch length (bule, left axis) and the relative momentum spread (red, right axis) at the design intensity as functions of the bunch length at zero intensity. A negative momentum compaction factor is assumed to set $\nu_s = +0.022$. The radius of the beam pipe is $R = 45$ mm.

INTERACTION REGION

As the High-Current Scheme operates at a horizontal tune very close to a half integer resonance, which is necessary to achieve a very high vertical beam-beam parameter, the induced dynamic-β effect on the horizontal plane becomes very strong. The original SuperKEKB assumed $\nu_x = 0.503$ and $\beta_x^* = 20$ cm corresponding to $\mathcal{L} = 8\times 10^{34}$ cm^{-2}s^{-1}. On the other hand, the design of the interaction region becomes more difficult with such a tune and small β_x^*, as the required physical at the final focusing quadrupoles becomes huge. Note that the dynamic-β effect reduces β_x^* while increasing the equilibrium horizontal emittance ε_x, thus the beam size at the final quadrupoles increases as two effects add up. With the orignal parameters, β_x^* dynamically reduces to less than 1/10 of the lattice setting. The horizontal beam sizes at the final quadrupoles increase by more than factor 10. These huge beam sizes also arise the issue of associated synchrotron radiation near the IP to hit the detector components.

Thus the design of the interaction region becomes difficult, and no solution has been found with the original ν_x and β_x^*. Then we relaxed the parameters to $\nu_x = 0.505$ and $\beta_x^* = 40$ cm, and the associated luminosity reduced to $\mathcal{L} = 5 \times 10^{35}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$ with $\sigma_z = 3$ mm in both rings. The luminosity is further reduced to $\mathcal{L} = 3 \times 10^{35}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$, when we include the longer bunch in the LER, $\sigma_z = 5$ mm, due to the CSR described above.

TRAVEL FOCUS

A technique called *Travel Focus* (TF) has been known to mitigate a collision with a bunch length longer than β_y^*, especially for linear colliders[9]. In the case of a ring collider, it is not difficult to introduce TF by combining crab cavities and sextupole magnets. The minimum configuration of TF needs two crab cavities in a ring to shift the waist as a function of z while keeping the betatron tune. Each crab cavities must be placed in the middle of a pair of sextupoles connected by $-I$ transformation to cancel the nonlinear terms of the sextupoles. Thus four additional sextupoles are needed in a ring. In the case of SuperKEKB, such an arrangement is only possible for the LER, as the HER does not have enough space to accommodate them. A lattice design for the LER TF was actually done with sufficient dynamic aperture. The luminosity is recovered to $\mathcal{L} = 4 \times 10^{34}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$ with TF.

Table 2 summarizes luminosities of the High-Current Scheme with the compromised parameters to mitigate the issues described above. The solution of the IR with $\nu_x = 0.503$ and $\beta_x^* = 20$ cm has not ben found.

CRAB CROSSING

The luminosities in Table 2 assume that the crab crossing works as well as expected by simulations. Crab crossing has been tested at KEKB since February 2007 for nearly two years. The specific luminosity per bunch achieved in these periods is plotted in Fig. 9 against the product of bunch currents. A major progress in 2008 is the improvement in beam life time by rearranging the beam optics at the crab cavity in the LER. As a result, the product of bunch currents could reach the design value of SuperKEKB, $I_b^2 \sim 1.5\ \mathrm{mA}^2$ with holding the crab collision. It also provided some improvement of luminosity at $I_b^2 \sim 1.1\ \mathrm{mA}^2$. Although there is a gain in the specific luminosity by about 25% at the desing intensity over the collision without crab, it is still less than the prediction of simulations, which is $\sim 20 \times 10^{30}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}/\mathrm{mA}^2$. The achieved specific luminosity with crab crossing roughly lies on a curve $\xi_y \sim 0.09$[10]. The simulation itself is independently confirmed by Y. Cai[11].

The reason why the luminosity did not reach the predicted value has not been identified yet, despite various machine studies performed for two years considering a number of hypothesis[12, 13]. A few possibilities such as a chromatic x-y coupling at the IP still remain until now, and will be studied this year with new equipments such as skew sextupole magnets. We have to say, however, that the huge gain in the luminosity by crab crossing needs further efforts, which have not been experienced yet. If crab crossing works only at the present level at KEKB, the resulted luminosities in Table lums will be decreased to about 1/3.

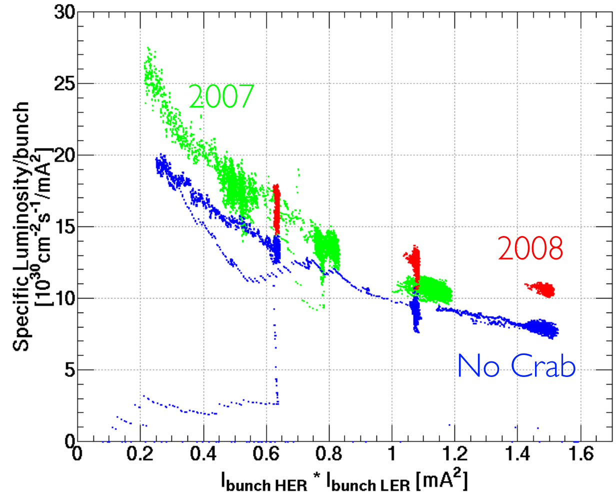

Figure 9: The specific luminosity per bunch vs. the product of bunch currents, I_b^2 comparing the results with crab crossing in 2007 (green), in 2008 (red), and without crab crossing (blue). Parameters are equal in all cases. The product of the bunch currents for SuperKEKB is about $I_b^2 \sim 1.5\ \mathrm{mA}^2$.

HIGH CURRENT

Storing high beam current is an essential part of the High-Current Scheme as the name tells. The required wall-plug power is 90 MW, which is twice as large as the present KEKB. Although the Tsukuba campus of KEK can handle the power as it is still less than the power once supplied for TRISTAN, the yearly running hours should be limited by the electric bill, if the operation budget does not increase. Besides the operation budget, the High-Curent Scheme requires substantial upgrade on the existing rf accelerating system as well as the cooling plant for the beam pipes. Their estimated cost may reach about 40% of the total upgrade.

AN ALTERNATIVE: NANO-BEAM SCHEME

As described above, it has been evident that the High-Current Scheme has more unavoidable issues than expected when the design started in around 2002. Since then an alternative idea, hereafter we call the *Nano-Beam Scheme*, has been developed by P. Raimondi and the SuperB Group[14]. Instead of increasing the beam current, the Nano-Beam

Table 2: Expected luminosity of the High-Current Scheme by accumulating the issues considered.

ν_x	β_x^* (cm)	$\sigma_{z,\mathrm{LER}}$ (mm)	$\mathcal{L}$ (10^{35})	
0.503	20	3	8	Original
0.505	40	3	5	+ Possible IR design
0.505	40	5	3	+ CSR
0.505	40	5	4	+ Travel Focus
0.503	20	5	5.5	+ Recovery of the IR design

Scheme squeezes the beam sizes at the IP as small as possible by reducing the emittances and β-functions. The bunch length is kept as long as the present KEKB, and the crossing angle is made even larger, and no crab crossing is necessary. The Nano-Beam Scheme does not demand very high vertical beam-beam parameters as in the High-Current Scheme. Even though the Nano-Beam Scheme has nontrivial issues on the control of collision with tiny beam size and preservation of emittance against vibration and drifts in the ring components, they may have technical solutions which are less fundamenal than the issues for the High-Current Scheme.

Table 3 compares parameters of two schemes. The parameters for the Nano-Beam Scheme in Table 3 have not yet been optimized. The beam currents for the Nano-Beam Scheme can be still handled by the existing rf accelerating system of KEKB without substantial extension. The parameters in Table 3 does not assume the crab-waist scheme, so the vertical beam-beam parameter is set conservative at $\xi_y = 0.07$, which is even smaller than the value already achieved at KEKB.

Table 3: Comparison of parameters of the High-Current and Nano-Beam Schemes. The half crossing angle at the IP is denoted by ϕ_x. The High-Curent Scheme corresponds to the second last row of Table 2.

	High-Current (LER / HER)	Nano-Beam (LER / HER)	
I	9.4 / 4.1	3.3 / 1.9	A
ε_x	24 / 18	2.8 / 1.6	nm
$\varepsilon_y/\varepsilon_x$	1 / 0.5	0.84 / 0.46	%
ν_x	0.505	0.530	
β_x^*	400	44 / 25	mm
β_y^*	3 / 6	0.21 / 0.37	mm
ϕ_x	15	30	mrad
σ_z	5 / 3	6	mm
ξ_y	0.2 / 0.3	0.07	
$\mathcal{L}$	~ 4	~ 6	10^{35}

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