STATUS OF KEKB AND UPGRADE PLAN TO SUPERKEKB

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Abstract

KEKB is an electron-positron two-ring collider for the leading B meson factory. It consists of an 8 GeV electron ring (HER) and a 3.5 GeV positron ring (LER) and their injector linac. It has been operated since December 1998, and has recently marked the peak luminosity of 17.12 /nb/s. This peak luminosity is obtained under the crab-ready beam optics having the robust operating condition by some efforts to solve the optics problems. We are aiming more luminosity improvement after the crab cavity installation. Further the major upgrade plan for SuperKEKB is expected to achieve 400 /nb/s keeping the baseline of the original proposal. This paper describes the recent status of KEKB and upgrade plans for SuperKEKB.

OVERVIEW

The 8 GeV electron and 3.5 GeV positron rings are built in the 3 km-long TRISTAN tunnel. This collider aims to make a detailed study of the B-meson. Especially the CP violation effects are measured in its decay. The energy difference between the electron and positron beams gives a boost to the produced B-meson pairs. This boost makes it possible to measure the time dependent features of B-meson decay due to the large CP asymmetry predicted in B-meson system.

Since the construction of KEKB started in 1994 and the first event was observed by Belle detector in June 1999, the KEKB continuously accumulate its integrated luminosity for 7 years. Figure 1 shows 7-year's history of the KEKB luminosity and beam currents. The KEKB has recently marked the peak luminosity of 17.12 /nb/s (= 1.712×10^{34} /cm^2/s) which is 70 % higher luminosity than the designed peak luminosity of 10 /nb/s. Not only the peak but also the integrated luminosity of 710 /fb has been accumulated with the peak increasement of 1.232 /fb/day which is obtained in the continuous injection mode operated after 2004.

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RECENT STATUS OF KEKB

The recent status of KEKB mainly in 2006 is summarized. A status report before this was written in the previous report [1, 2]. Table 1 shows present machine parameters of KEKB compared with those of about one year ago and the design parameter. The performance progress in the past one year is not very remarkable compared with earlier years. We describe the recent status of KEKB including causes of the present performance limitations.

Table 1: Machine parameters of KEKB

	Design		**Dec. 2005**		**Dec. 2006**	
	LER	HER	LER	HER	LER	HER
Energy [GeV]	3.5	8.0				
Circumference [m]	3016.26				3016	
I_{beam} [mA]	2600	1100	1719	1347	1662	1340
# of bunches	5000		1388		1388	
I_{bunch} [mA]	0.52	0.22	1.23	0.97	1.20	0.965
Bunch Spacing [m]	0.59		1.8 - 2.4		2.1	
Emittance [nm]	18	18	18	24	18	24
β_x^* [cm]	33	33	59	56	59	56
β_y^* [cm]	1.0	1.0	0.65	0.62	0.65	0.59
Ver. Size@IP [μm]	1.9	1.9	2.1	2.1	1.9	1.9
RF Voltege [MV]					8.0	15.0
ν_x	45.52	47.52	45.506	44.512	45.505	44.509
ν_y	46.08	43.08	43.531	41.578	43.534	41.565
ξ_x	0.039	0.039	0.117	0.073	0.117	0.070
ξ_y	0.052	0.052	0.096	0.055	0.105	0.056
Lifetime [min.@mA]			135@ 1719	222@ 1347	110@ 1600	180@ 1340
Luminosity [/nb/s]	10		16.27		17.12	
Lum/day [/fb]	~ 0.6		1.183		1.232	
Lum/7 days [/fb]	-		7.358		7.809	
Lum/30 days [/fb]	-		29.018		30.21	

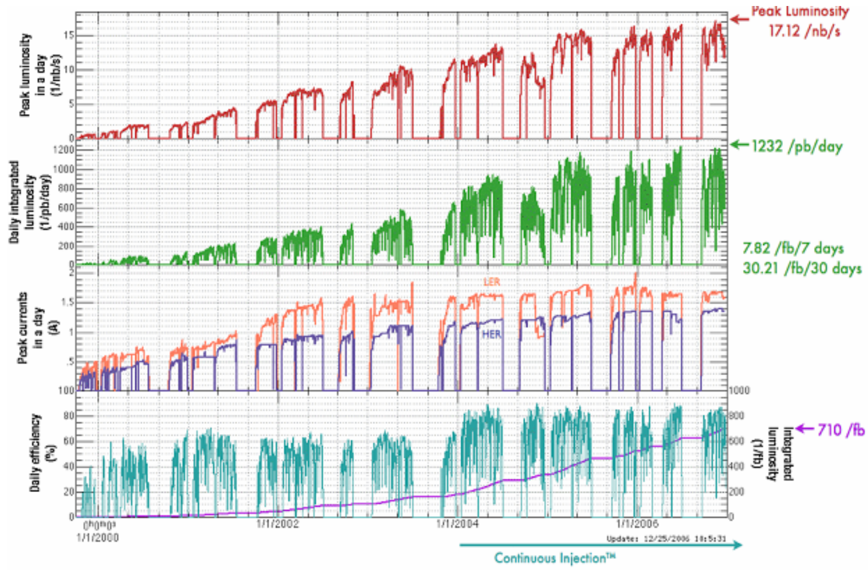

Figure 1: History of KEKB (Oct. 1999 – Dec. 2006).

Beam parameter modifications for luminosity

The luminosity for the ring collider is given as

$$L \approx \frac{\gamma_\pm}{2er_e}\frac{I_\pm \xi_{y\pm}}{\beta_y^*}\frac{R_L}{R_y} \quad (1)$$

Higher currents $I_\pm$, larger vertical beam-beam parameter ξ_y, and smaller β_y^* are necessary to obtain higher luminosity. R_L, and R_y are reduction factors of the luminosity and ξ_y, respectively, due to the hour-glass effect and the finite crossing angle (22 mrad at KEKB). The ratio R_L / R_y is close to unity when the bunch length σ_z is well smaller than β_y^*.

The beam parameters are summarized in Table 1. In actual parameters of HER, I_- and ξ_{y-} are a little larger, and $\beta_y^*{}_-$ is much smaller than design values. Consequently, the luminosity reaches to 1.71 times higher than the design value.

Bunch spacing and effects of electron clouds

The averaged bunch spacing is 3.5 rf buckets at present KEKB, while in the original design we planed to fill all RF buckets except for the abort gap. The longer bunch spacing causes larger bunch currents which generate higher HOM heating power. And the HOM power is one of the present limitations of the stored beam currents. It is desirable to increase the number of bunches and decrease HOM power from the viewpoint of hardware protection against the high beam currents.

Since the beginning of KEKB, effects of electron clouds have been strictly limiting the KEKB performance. To solve their effects, more than 95 % of the drift space in the LER ring, which is equivalent to 75 % of the total circumference, is covered by solenoid fields of higher than 20 Gauss. The blow-up of the vertical beam size in the LER ring has been suppressed after the installation of solenoid coils, and the luminosity saturation at high current is reduced in the present bunch spacing of 3.5 rf buckets.

However, even with the solenoid coils, the evidences of the effects of the electron clouds are observed. The most direct evidence of the effects is vertical betatron sidebands appeared in the transverse beam spectra of the positron bunches [3]. The sidebands seem to be signals of the fast head-tail instability due to short-range wake fields within the electron clouds. In case of the only positron single beam, a beam size blow-up was observed associated with the upper sidebands above a threshold beam current of the instability. With the collisions of the electron and positron beams, the luminosity saturation was observed at the condition of the LER beam current of higher than approximately 1700 mA and the HER beam current fixed to around 1300 mA. Further in the measurement of bunch-by-bunch luminosity, the degradation of the luminosity was also observed for the bunches after the shorter bunch spacing.

From these observations, it seems that the degradation in the specific luminosity depending on the bunch spacing is originated from the effects of the electron clouds. The remaining problem is where in the ring do the electron clouds exist. In the summer shutdown 2005, we installed solenoid coils in the inside of 88 quadrupolemagnets out of 461. However, we observed no effects of these additional solenoids on the luminosity. And in this winter shutdown, we installed the ante-chamber in the drift space with high synchrotron radiation density following after the wiggler section.

Sextupole tuning

We observed that the sextupole tuning occasionally increased the luminosity after the luminosity was saturated by tuning the betatron tunes and the beam optical parameters between the two beams, such as a beam orbit offset at the IP, a vertical crossing angle, beam x-y coupling parameters at the IP, collision timing, waist points. Recently new sextupole tuning panel was developed to tune with toggling the constraints of the tilt at the IP. After new sextupole tuning was optimized, it makes possible to reach the lower horizontal betatron tune of the HER ring of 0.509, and the luminosity becomes approximately 5 % higher than before.

Betatron tune

The horizontal betatron tune ν_x is one of the most important parameters to achieve high luminosity at KEKB. When ν_x is coming closer to a half-integer resonance, the luminosity is being significantly improved. The present values of the fractional part of ν_x are 0.506(LER) and 0.509(HER). The merit of ν_x closer to the half-integer is larger dynamic emittance which should decrease effective beam-beam parameter and then should improve the luminosity. Recent beam-beam simulations reproduce well this tune dependence. The simulations say that the luminosity will be much improved by getting ν_x close to the half-integer in HER same as in LER. In HER, however, the synchro-betatron resonance $2\nu_x + \nu_s$ = integer is much stronger than in LER, so stable operation at lower ν_x is difficult. Optimization of beam parameters is planed to avoid the synchro-betatron resonance to make better chromaticity correction to weaken effects of the resonance and changing the synchrotron tune by adjusting.

Lower Emittance

The beam-beam simulation predicts the higher luminosity in the lower emittance operation. We changed the optics settings for the low emittance operation only for the LER ring in this October. However the beam abort due to the horizontal beam oscillation was frequently occured, and we cannot confirm the effect of the lower emittance operation.

Horizontal beta function

The horizontal beta function β_x^* is once reduced from 59 cm and 56 cm for the LER and HER ring respectively to 50 cm for both rings. Although it aims to obtain the higher luminosity, the betatron tunes of LER ν_y and HER ν_x cannot reach to the previous values due to the short beam lifetime. Thus we cannot distinguish whether this is effective or not.

PLANS FOR 2007

The plans for 2007 to improve the KEKB luminosity against the present luminosity limitations are described.

Crab cavity

The choice of a finite beam crossing angle in the horizontal plane at the IP, 22 mrad, is a notable feature of KEKB. This scheme eliminates parasitic collisions and makes it much easier to optimize the lattice near IP for two beams of different energies, and reduce the beam background to the Belle detector. Currently the finite crossing angle causes the degradation of the beam-beam parameter.

To recover this degradation due to the crossing angle, The crab cavity was developed to rotate the beams to provide head-on collision. Figure 2 shows the crab crossing scheme. Simulations [4] predict that head-on collision may bring the larger beam-beam parameter of ξ_y = 0.19, which means that the luminosity may be doubled.

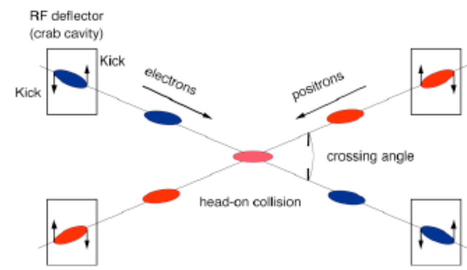

Figure 2: Schematic view of the crab-crossing scheme.

Figure 3: Installed crab cavity.

In this winter shutdown, the crab cavity was installed. Figure 3 shows the photo of the installed crab cavity. On the contrary of the original plan, only one cavity in each ring was installed. Though the crabbing orbit propagates over the rings, any problem has not yet been pointed out.

We already succeeded to operate for the optics which meets conditions required for realizing the crab crossing scheme. The conditions are horizontal phase advances from the crab cavities and IP, large horizontal beta functions at the crab cavities and horizontal phase advances from SR monitors to IP. The last condition is required to measure the crab angle with streak camera systems. Thus we can just start the beam commissioning with the crab cavity.

Higher current

A further increase of the KEKB luminosity depends on mitigating the electron-cloud in LER, more beam current in HER. The drift space of the LER ring is almost covered by solenoid fields to reduce the electron-cloud. To find and reduce the remaining electron-cloud, the ante-chambers is locally installed to the arc section after the wiggler section. On the other hand, there is a clear tendency to improve luminosity by a further increase of the HER beam current. For this purpose, one more RF station for the ARES cavity in HER was installed during the summer shutdown in 2005, since the HER beam current was limited by available RF power. With this new RF station, the target HER beam current was 1500mA. However, troubles with vacuum bellows at the level of 1350mA are frequently occured. These troubles are caused by the lost of the spring finger contact of vacuum bellows due to the horizontal deformations. The vacuum bellows will be replaced to newly developed comb-type bellows according to the budget.

SUPERKEKB

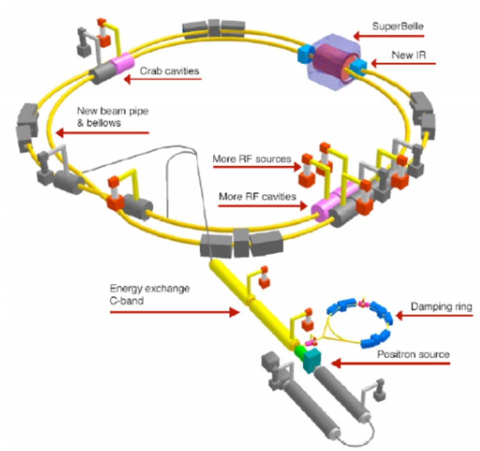

Figure 4: Schematic layout of SuperKEKB.

Table 2: Machine parameters of SuperKEKB compared with KEKB

	KEKB Design		**KEKB Dec. 2006**		**SuperKEKB**	
	LER	HER	LER	HER	LER	HER
Energy [GeV]	3.5	8.0			3.5	8.0
Circumference [m]	3016.26					
I_{beam} [mA]	2600	1100	1662	1340	9400	4100
# of bunches	5000		1388		5000	
I_{bunch} [mA]	0.52	0.22	1.20	0.965	1.88	0.82
Bunch Spacing [m]	0.59		2.1		0.59	
Emittance [nm]	18	18	18	24	24	
β_x^* [cm]	33	33	59	56	20	
β_y^* [cm]	1.0	1.0	0.65	0.59	0.3	
Ver. Size@IP [μm]	1.9	1.9	1.9	1.9	0.73	
ξ_x	0.039	0.039	0.117	0.070	0.152	
ξ_y	0.052	0.052	0.105	0.056	0.215	
Luminosity [/nb/s]	10		17.12		400 (~ 800)	

SuperKEKB is an upgrade to the KEKB machine. Figure 4 shows the schematic layout of SuperKEKB. Table 2 shows the machine parameters of SuperKEKB compared with KEKB in order to achieve over 20 times higher luminosity (400 /nb/s). Smaller β_y^* (3 mm), larger ξ_y (0.19) and higher currents (9.4 A in LER and 4.1 A in HER) are pursued. Further it is based on the crab crossing scheme which will be tested in recent upgrade of KEKB. Existing resources such as tunnel, facilities, magnets, power supplies will be reused as much as possible. The present 509 MHz RF system will be reused, but with twice the number of RF stations. It will also be necessary to reinforce the HOM dampers and further increase the stored energy of the cavities to store much higher beam currents. According to another recent simulations, the luminosity of SuperKEKB exceeds 800 /nb/s at beam currents of 10.1 A in LER and 4.4 A in HER [5].

KEKB Ring Upgrade

Items to be upgraded for KEKB rings are as followings.

(1) New IR with redesigned final quadrupoles and compensation solenoids.

The superconducting final focusing quadrupole magnets (QCS) should be moved toward the IP in order to squeeze the vertical beta function at the IP. To conserve the detector region and to move both QCS's toward the IP for the IR layout, we make the compensation solenoids overlaid on the QCS in the longitudinal direction.

(2) New beam pipes and bellows.

The main issues arise from the intense synchrotron radiation (SR) due to the large beam current. In order to cure the heating from SR and/or the effect of the photoelectron cloud, an ante-chamber scheme will be used. The ante-chamber consists of a beam channel and an SR channel. The beam goes through the beam channel and the SR passes through to the SR channel. The SR is absorbed by a photon stop inside the SR channel. Also we have to replace to the newly developed comb-type bellows for high current beam.

(3) More rf systems with improved ARES cavities, couplers, and HOM absorbers of superconducting cavities.

The present 509 MHz RF system for KEKB employs two types of the damped cavities: a normal conducting cavity (NC) coupled with an energy storage cavity (ARES) and a single-cell superconducting damped cavity (SCC). We will increase the number of ARES cavities from 32 to 40 and SC cavities from 8 to 12. The modification to the RF units at Super KEKB is that one 508 MHz 1 MW CW klystron feeds power to one ARES cavity, as opposed to two ARES cavities which is the current scheme at KEKB. The RF unit is one to one for the SC cavities. Therefore, the total number of RF units increases from 24 to 52, including the klystrons, power supplies, high power system and control system. Also the damper structure and the dummy load should be much improved for the high current.

(4) Reinforced cooling system.

The total power loss at Super KEKB is 83.4 MW, which is three-times larger than at KEKB. If we give up on wigglers in LER, the total power loss becomes 66.5 MW. This number is twice that of KEKB. However, we obtain a simulation result that the luminosity is degraded as the damping time increases. The cooling system must be upgraded for Super KEKB whether wigglers exist or not.

Linac Upgrade

The KEKB injector linac is also planned to upgrade as following items.

(1) Exchange of beam energy

The C-band accelerating structure and the 1.0 GeV damping ring are planned to aim for the efficient injection and to cure the electron cloud problem. The KEKB injector linac has provided 8 GeV electrons and 3.5 GeV positrons to inject those rings directly. In the SuperKEKB project, energy exchange of beams has an important role to escape the influence of electron clouds for the positron ring (LER). To exchange the beam energy of the LER and the HER, the energy of a positron beam has to be raised from 3.5 GeV to 8 GeV However the acceleration length after generating positrons is restricted because a positron is a secondary particle. One of solutions is to double an acceleration field. Thus the C-band (5712 MHz) accelerating unit [6] has been developed to obtain the higher acceleration field over 40 MV/m. Figure 5 shows the layout of one layout of the upgrade plans using the C-band accelerating units. In this layout, three sectors are replaced to the C-band accelerating units. A C-band accelerating unit consists of one 50 MW klystron and four accelerating structures. And a sector consists of 16 accelerating units whose klystron RF inputs are driven by a 150 kW sub-booster klystron.

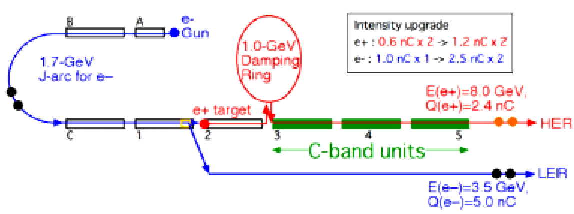

Figure 5: Layout of the linac upgrade for SuperKEKB.

(2) Fast beam mode switch

The KEKB injector linac has to inject 8 GeV electrons and 3.5 GeV positrons to KEKB ring, 2.5 GeV electron to PF ring and PF-AR ring. The multiple beam modes are currently switched at intervals of five minutes. It takes 30 seconds to switch the beam mode and the repetition of the bunched beam is usually only 10 pps inspite of the maximum repetition of 50 pps. In the present condition, the continuous injection can be performed for either LER or HER at once and the injection for KEKB is stopped when the injection for PF or PF-AR is required. Thus the upgrade for the fast beam mode switch is advanced [7]. The upgrade items for the fast beam mode switch are the construction of the new PF BT-line to bypass the ECS magnet, the fast low-level rf phase switch, the installation of the pulse bend and the positron target with a electron bypass hole.

(3) Multi bunch acceleration

The KEKB injector linac is usually operated to accelerate only two 10 nC electron bunches to generate positron, since more bunch cannot be equalized the beam energy using the conventional pulse compressor (SLED) and the simple phase modulation. We tested some way to accelerate more bunches without any modification of high power RF distribution [8]. One way to realize the multi-bunch acceleration is compensating the beam loading. This beam loading compensation method is usually realized by combining the output power of two or more klystrons. However our linac system consists of one 50 MW klystron in one acceleration unit, and eight klystrons are driven by a 100kW klystron. One way to realize the beam loading compensation in our linac is using the amplitude modulation of the klystron. This is realized using the I-Q modulation of the low level RF considering the non-linear characteristics of the total amplification system including klystrons.

Consideration for higher luminosity

Recently, a novel colliding scheme, the long bunch and the crab waist, was proposed [9]. It is an horizontal dependent vertical focus at the IP, which is generated by a pair of sextupole magnets. This scheme may allow beams with a very small horizontal size and a relatively long bunch length to collide at a large finite angle crossing with a small β_y^*. The relatively long bunch length is also attractive from the view point of the CSR and HOM power. Extensive simulation work is progressing to study the possibility to apply this scheme to the present factories or Super-factories.

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