Past, Present, and Future of KEKB

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HISTORY OF KEKB

Table 1 summarizes the brief history of the KEKB B–Factory, the asymmetric collider for B–Physics at KEK. It consists of two rings, the LER and the HER, for e^+ at 3.5 GeV and e^- at 8 GeV, respectively, and the injector Linac.[1, 2]

Table 1: Brief History of KEKB

1989	Design work started; first design with $10^{34}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$
1994	Approval of budget; start of construction
1995	*KEKB Design Report*
Sep. 1997	Commissioning of the injector Linac started as the upgrade completed.
Dec. 1998	Start of injection to the HER
Jan. 1999	Start of injection to the LER
May. 2001	Roll-in of the Belle detector
Apr. 2001	World's highest luminosity (then $3.4 \times 10^{33}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$) was achieved.
Oct. 2002	Integrated luminosity reached 100 /fb as the first machine in the world.
May 2003	Luminosity exceeded the design number $10^{34}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$.

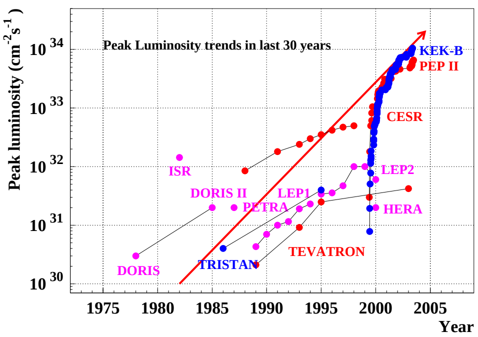

Figure 1: Trends in peak luminosity of the colliders in the world over the past 30 years. The arrow represents 1 order growth in 5 years.

The design work of KEKB started around 1989. The luminosity goal of KEKB was set to $10^{34}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$ from the beginning. As seen in Fig. 1, at the time of the start of KEKB around 1990, the luminosity of colliders in the world barely reached $10^{32}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$ at ISR and CESR. Thus the goal of KEKB might look too ambitious for the majority of the accelerator community in the world. KEKB never compromised on its luminosity goal. On the contrary, the design goal became more and more convincing as the design study advanced. A number of innovations were made by intensive works in theories, simulations, and experimental studies including the high-current operation at TRISTAN–AR. The essential elements of KEKB, such as the interaction region with the finite crossing angle, "sub-micro" β beam optics with 2.5π unit cell, ARES and superconducting cavities, bunch-by-bunch feedback system, beam monitors, vacuum system, electron-cloud effect, and injector J-Linac, etc., were so designed as to satisfy the design goal. Thus the design was comprehensively written in *KEKB Design Report*.[1] The design of KEKB also fully utilizes the existing legacies of TRISTAN, such as the tunnel, utilities, magnets, power supplies, rf system, etc.

Figure 2 shows the progress of the performance of KEKB since Oct. 1999. Though having a number of breaks and slumps, the overall performance has been continuously improved toward the design luminosity. Four years were necessary for KEKB to achieve the design luminosity. Was it too long or not? The period of startup was specified as "100 /fb in the first 3 years" in the *KEKB Design Report*, and KEKB achieved 100 /fb in October 2002, and 150 /fb in 4 years. So the speed of startup actually satisfied the plan very well. The startup speed of KEKB was even remarkable in the history of the colliders (Fig. 1), and now KEKB is driving the trend. Please note that the progress of luminosity in Fig. 2 corresponds to the increase of the beam currents in some periods such as from summer 2001 to summer 2002, but in other periods luminosity improved without the increase of the currents such as in 2003.

Table 2: Machine parameters of KEKB

Date	5/13/2003		Design		
	LER	**HER**	**LER**	**HER**	
Current	1.38	1.05	2.6	1.1	A
Bunches	1265		5000		
Bunch current	1.09	0.83	0.52	0.22	mA
Spacing	1.8 or 2.4		0.6		m
Emittance ε_x	18	24	18	18	nm
β_x^*	59	58	33	33	cm
β_y^*	0.58	0.70	1.0	1.0	cm
Hor. Size @ IP	103	118	77	77	μm
Ver. Size @ IP	2.2	2.2	1.9	1.9	μm
$\varepsilon_y/\varepsilon_x$	4.7	2.9	2	2	%
Beam-beam ξ_x	.093	.068	.039	.039	
Beam-beam ξ_y	.067	.053	.052	.052	
Luminosity	10.57		10		/nb/s
$\int$Lum/day	579		$\sim$ 600		/pb
$\int$Lum/7 days	3876				/pb
$\int$Lum/30 days	12809				/pb

PERFORMANCE

Table 2 compares major machine parameter corresponding to the best peak luminosity, recorded on May 13, comparing to the design. While the luminosity, beam-beam pa-

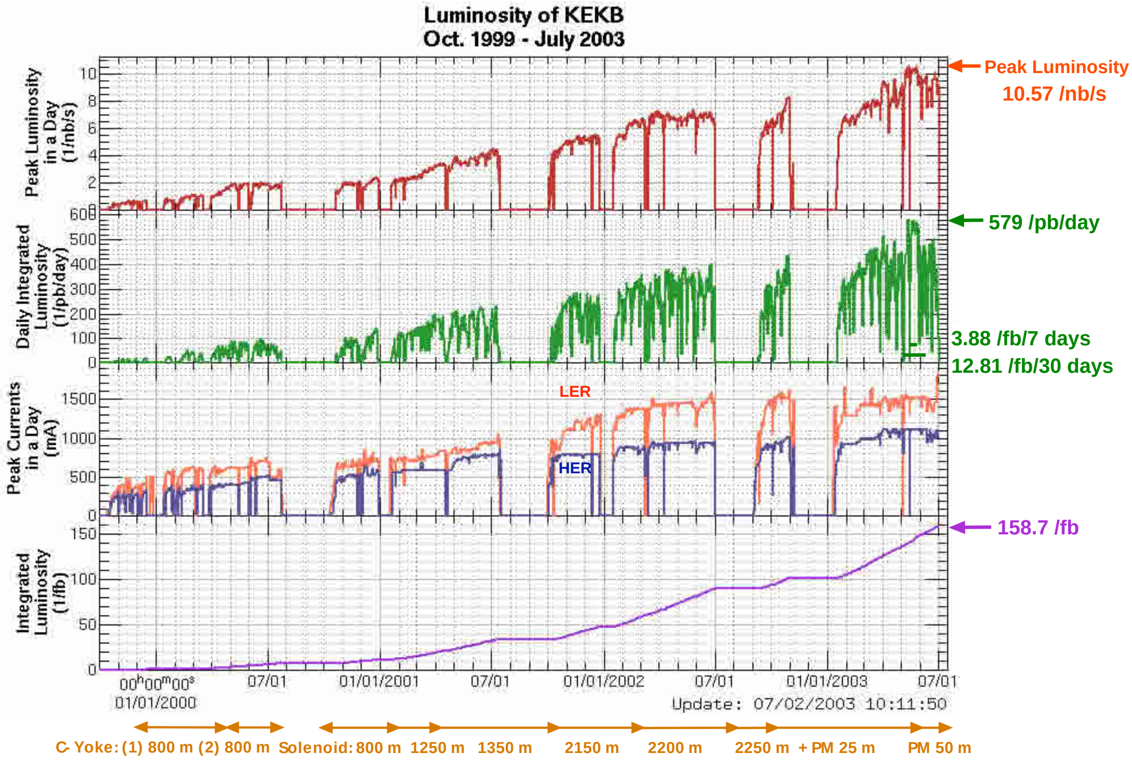

Figure 2: The history of KEKB performance since 1999. The rows are (top to bottom) the peak luminosity in a day, the daily integrated luminosity, the peak stored current in the LER and the HER, and the integrated luminosity in Belle, respectively. The integrated luminosities are the numbers recorded by Belle. The arrows at the bottom show the progress of the length of solenoid/permanent magnets to suppress the electron-cloud instability in the LER.

rameters, and the HER current were more or less equal to the design. The LER had less current than the design, and it was compensated by the smaller β_y^* than the design.

The major differences between the best achieved and the design are in the number of bunches (thus bunch spacing). Although the solenoid windings were so extended as to cover roughly entire drift spaces, the effect of the electron cloud did not disappear completely. The threshold of the vertical blowupblowup was increased to about 1.8 A for near-4 bucket spacing. The threshold was lower for shorter spacings. Even below the threshold, the specific luminosity per bunch still seemed to degrade for shorter spacings. Actually, the average bunch spacing was reduced from 4.08(=49/12) buckets to 3.77(=49/13) buckets during this period, but in a few trials spacing less than 3.5 buckets did not give good specific luminosity. (To utilize the 2-bunch/pulse injection scheme, the bunch fill pattern must have the periodicity of 49 buckets.) The specific luminosity with 3.5 buckets might not be much worse than 3.77 buckets, but it was not usable due to the higher heating of the bellows at the interaction point (IP) until the summer 2003. As the number of bunches were much smaller than the design, the bunch current was so higher than the design, especially in the HER. Such high current caused higher HOM losses in all components. The ferrite HOM absorber in the superconducting cavity (SCC) in the HER now absorbs 10 kW/cavity, which already exceeded the design and the tested power level.

As the beam current of the LER was so limited by the electron-cloud, the ratio of the beam currents of the two rings was quite different from the so-called energy-transparent condition (inversely of the energy ratio). The violation of the transparent condition brought neither disastrous nor pleasant effects on the beam-beam interaction so far.

ISSUES

Luminosity

One of the convenient expressions of a luminosity of a ring collider is

$$\mathcal{L} \approx \frac{\gamma_\pm}{2er_r}\frac{I_\pm \xi_{y\pm}}{\beta_y^*}\frac{R_\mathcal{L}}{R_y}, \tag{1}$$

where $I_\pm$, $\gamma_\pm$, and $\xi_{y\pm}$ are the stored current, the Lorentz factor, and the vertical beam-beam tune-shift parameter for each beam. The vertical β function at the IP (β_y^*) was assumed to be common for both beams. We have assumed flat beams for Eq. (1). The factors $R_\mathcal{L}$ and R_y are geometrical reduction factors for the luminosity and ξ_y, respectively, determined by the hour-glass effect and the crossing angle. It is known that the ratio $R_\mathcal{L}/R_y$ does not differ much from unity if the bunch length is shorter than β_y^*. Thus the luminosity of a ring collider is basically determined by three parameters, β_y^*, ξ_y, and I. Let us discuss issues to achieve higher luminosity by smaller β_y^*, higher ξ_y, and higher I.

Smaller β_y^*

Generally speaking, a small β_y^* reduces both the physical and the dynamical apertures of a ring. A small β_y^* simply means a large β_y at the final focusing lenses. At the present KEKB, to make the world's smallest β_y^* as a ring collider, β_y reaches 1,000 m at one of the final focus lenses in the HER. This requires a large aperture of the final lenses and makes the separation of the two beam more and more difficult. The dynamic effect of a small β_y^* arises from the nonlinearity of the beam optics for chromaticity correction.

A number of ideas are applied to realize the small β_y^* in the design of KEKB:

- Finite crossing angle, 22 mrad to make the beam separation easier and simplify the arrangement of the orbits and components around the IP.
- Combination of normal and superconducting magnets for the final focus lenses.
- Compensation solenoids to cancel the coupling effects of the detector solenoid field.
- A large number (54 in the LER and 52 in then HER) of pairs of sextupoles connected with $-I$ transformation which cancels the transverse nonlinearity.
- 2.5π unit cell of the arc lattice to optimize the location of the sextupole pairs as well as to have good tunability in the emittance and the momentum compaction factor.
- A local chromaticity correction system around the IP in the LER, similar to the final focus system for a linear collider.

No beam optics works without diagnostics and corrections. First of all, all magnets and power supplies were carefully constructed and calibrated within the margins of the errors. The alignments of the magnets were also successful even within a limited period of construction. The beam position monitors (BPMs) were well calibrated too. These are the basis of the orbit/optics correction system. KEKB routinely applies orbit/optics corrections:

- Orbit correction to a reference “golden” orbit (set by the optics correction below), every 15 seconds. The r.m.s. residual was 30–50 μm.
- Circumference correction by chicanes (LER) and rf frequency (HER). Circumference of KEKB drifts by about 2.5 mm in 6 months. Though tidal effects were seen in the drift, the major part was much slower component.
- β, x-y coupling, and dispersion corrections looking at the orbit response on every BPM. The correctors are the fudge factors of normal and skew quadrupoles, and bump orbits at sextupoles. These corrections were applied more than once in 2 weeks. These are quite essential to enable the best operating tunes and to maintain the luminosity.
- Beam-based alignment of all BPMs. Using correction winding of each quadrupole, the beam-based alignments was done periodically. The residual r.m.s. of the alignment error was about 100 μm.
- Beam-based mapping of BPMs. While each BPM were mapped at bench before installation, changes happen in the gains of the electronics, the attenuator, and the connectors. Thus the calibration was necessary. At KEKB an innovative method for mapping using the beam has been developed. The result was remarkable and even better than the mapping at the bench.

The control system of KEKB gave the basic tool of any diagnositics and control of KEKB. It utilizes the EPICS system as one of the largest scale in the world with about 100 input/output controllers (IOCs). The online model SAD, linked with EPICS, is widely applied for control, diagnostics, and correction of the KEKB beam.

Higher ξ_y

One of the major issues in the design of KEKB was the finite crossing angle at the IP. Though the merit of the crossing angle was obvious for the beam separation and reduction of the parasitic crossing, many machines hesitated to use it after the bitter experience at DORIS (except a small crossing angle at CESR). The crossing angle of KEKB, 22 mrad, is as large as the bunch diagonal angle σ_x^*/σ_z, and might have enough scared conservatives. The KEKB design justify the crossing angle as:

- The magnitude of the synchrotron-betatron coupling terms arising from the crossing angle has the same magnitude as the regular synchrotron-betatron terms which are intrinsic to any beam-beam interaction. Thus the crossing angle just increases the number of terms whose effect can be avoided by choosing the operating tunes.
- Simulations showed there are such operating tunes that give $\xi_y \geq 0.05$, the design value of KEKB.
- There is a backup solution, *crab crossing*, to restore the effective head-on collision with crossing angle.[7]
- The problem of DORIS was not the crossing angle itself, but the tune-spread over bunches to relax the transverse coupled-bunch instabilities, making it impossible to choose good tunes for all bunches. KEKB did not need such tune-spread owing to the low-impedance cavities and the bunch-by-bunch feedback.

As shown in Table 2, KEKB actually achieved the design value, ξ_y = 0 .05, as expected. After the completion of the design, the progress in the beam-beam simulation has been remarkable. Now a strong-strong simulation becomes enough reliable at least for electron machines with damping. Such new simulations have been confirming the safeness of the finite crossing angle at least up to the current magnitude of ξ_y.

The most important factor to determine the actual ξ_y is the linear optics of two rings. Tunes, βs, and waists are the most important parameters as well as the relative orbit offsets between two beams. The orbit offset is managed by feedbacks using the beam-beam deflection and beam size response. The interferometer to measure the vertical beam size below the diffraction limit works as an essential tool for the orbit control. The couplings and dispersions between the degrees of freedom must be reduced as small as possible. The optics corrections described in the previous section are necessary but not enough to keep the best condition of collision. Thus a number of coupling/dispersion knobs were applied to find out the optimum. The so-called *dynamic* β effect was also important to increase the luminosity. It requires a horizontal tune ν_x very close to a half integer. Up to now KEKB could operate $\nu_x \sim 0.506$ and $\nu_x \sim 0.511$ in the LER and the HER, respectively. Such tunes require strict optics corrections and control of tunes. KEKB utilizes a tune-feedback system with collision-free pilot bunches for that purpose.

Higher Current

Higher luminosity requires higher current anyway. High current is the toughest issue related to the wide range of the beam dynamics and the accelerator technology. Here we just list up issues on high current experienced at KEKB.

Synchrotron light KEKB has already accumulated 1.5 A in the LER (in regular operation, the maximum was 1.8 A), and 1.1 A in the HER, and these currents are not less than many light sources. If one counts the size of the ring, the stored charge is well higher than them and even comparable to the charge per pulse at the J-PARC. The energy losses of the synchrotron light are 2.6 MW in the LER at 1.5 A and 4.4 MW in the HER at 1.1 A. The synchrotron light has enough energy density to melt down the vacuum chamber if improperly hit it. Such accidents were experienced at KEKB a few times near the IP and the wiggler sections.

High vacuum The average pressure in the KEKB beam pipe is maintained below 100 *nP a* with the stored beam. It was achieved by non evaporative getter pumps (NEGs) with 200 ℓ/s pumping speed placed in every 1 m along the beam pipe. Such good vacuum is necessary to reduce the background for the detector, to increase the beam lifetime, and to avoid the fast-ion instability.

Beam loss The stored high current at KEKB has enough power to melt, evaporate, and destruct the beam pipe and other components if it hits them directly. Such accident happened at KEKB many times as the result of a big change of orbit due to beam instabilities and/or trip of rf system. A system, consisting of beam loss monitors, rf phase detectors, transient data loggers, abort kckers, etc., have been developed at KEK to prevent such accidents by detecting the beam loss as early as possible and to abort the beam immediately. Fragile components such as the movable collimators needed a number of improvements since the beginning of KEKB operation after experiencing such beam losses.

Electromagnetic resonances The accelerating cavities of KEKB were so designed that all higher order or parasitic resonances escape or damp via wave guides, slots, dampers, and absorbers. As the result, no instability, either longitudinal or transverse, has been arisen from rf cavities up to the design current. Resonances at other components such as bellows are avoided in the design, but occasionally resonances start from tiny distortion and grow up catastrophically toward destruction. Such destructions happened a few times per year. Anomalous resonant coupling of bellows or pumping slots via TE-like modes, which usually do not couple to the beam, occurs near the collimators that break the symmetry to excite such modes.

Acceleating mode The accelerating mode of an rf cavity, which is the inevitable resonance, has a problem for high current storage. The beam loading voltage at KEKB is huge enough to cancel all acceleration if the cavities are tuned at the center of the resonance. Thus the detuning of the accelerating mode is necessary, but if the detuning is large, the coupled-bunch modes nearby the accelerating mode becomes unstable. To avoid such instability, KEKB chose a passive stabilization scheme, which reduces the amount of detuning by increasing Q values of the accelerating mode. The normal conducting ARES cavity[3] was so designed that the Q value is one order higher than usual cavities according to the huge storage cavity. The superconducting cavity naturally has a very high Q value.[2] Both cavites has been working successfully until now, and their stabilities are sufficient. The trip rate of the rf system itself is roughly once per day. The passive stabilization scheme does not need a sophisticated feedback system involving the rf and the bunch-by-bunch feedback.

Non-resonant modes Even after the removal of all resonances, wake fields with frequencies higher than the cut-off of the beam pipe (HOM) remain as a problem. Such modes become more important for shorter bunch length. The heating power of such modes roughly scales as

$$W \propto \frac{IN}{\sigma_z} , \qquad (2)$$

where N is the number of particles/bunch. It is interesting that the scaling (2) is very similar to the expression for luminosity, Eq. (1), since $\sigma_z \leq \beta_y^*$ is necessary. This means that for a given environment, a high luminosity means a high heating due to the non-resonant modes. This will impose a very strict constraint on the future upgrade of the machine.

Beam instability Instabilities caused by electromagnetic wakes have been well studied and more or less understood according to the development of the beam dynamics until the design of KEKB. As mentioned before, the design of KEKB basically suppresses all electromagnetic instabilities below the radiation damping without feedback, and it has been so verified in the actual operation. There was some discrepancy, however, in the longitudinal single-bunch impedance and the HOM loss in the measurement and the design. Though it has not yet confirmed quantitatively, additional impedances surely exist at the collimators and the coherent radiation in the wigglers. An idea to suppress a bunch lengthening is to make the momentum compaction factor negative, and it has already been tried at KEKB successfully. The resistive wall effect, especially the tune shift due to the non-circular cross section of the beam pipe in the HER, has been a problem, since the amount is big enough ($\sim$ 0.02/A) to get out of the optimum tune for the luminosity without the tune-feedback as the stored current decays.

Fast ion instability One of the modern instabilities observed at KEKB besides the electromagnetic ones is the fast-ion instability in the HER. The transverse bunch-by-bunch feedback has been quite effective to suppress it. Therefore this instability is practically less problem for the operation except when the vacuum pressure or the tuning of the feedback is bad.

Electron cloud The most serious instability at KEKB has been the electron-cloud instability at the LER. Though the coulped-bunch instability due to electron cloud had been known blowupexperimentally at Photon Factory,[4] and theoretically explained[5] before *KEKB Design Report*. The coupled-bunch effect was actually observed at KEKB and the bunch-by-bunch feedback was again very effective to suppress it as planned. The more serious one was, however, the single-bunch instability by the electron cloud[6] to cause the blowup of the vertical beam size beyond a threshold current. Although such single-bunch effect had been predicted before the start of KEKB operation, but not payed enough attention by the KEKB members.

Since the frequency range of the single bunch effect is as high as 30 GHz, it is not possible to suppress them by a feedback. Then the only possible cure was to apply weak magnetic field at the beam pipe to prevent the cloud to come close to the beam. Such an effort already started in Nov. 1999 by attaching a number of permanent magnets on the beam pipe for about 800 m. Though these magnets were actually as effective as solenoids, it was hard to confirm. The solenoid windings replaced the permanent magnets since Oct. 2000, then their effects were experimentally confirmed easily. The solenoid windings were extended to about 2,300 m before summer 2003 (Fig. 2), to cover the nearly entire free space of the LER.

Though the solenoids were so extended, the electron cloud instability did not remove completely. The threshold current for 4 bucket spacing increased from 0.4 A (no solenoid) to 1.8 A (2,300 m). This means that about 20% of the cloud still remains somewhere in the ring, including the magnets, but their location has not been identified.

Injection Storing high current requires a strong injector. The injector linac was commissioned one year earlier than the rings, and has been operated with good stability since then. One major breakthrough on the injection is the success of the two-bunch injection scheme for positrons. By choosing the bunch separation to 49 ring rf bucket, it was possible to accelerate two positron bunches in the same rf pulse. The energies of the bunches were equalized by adjusting the timing of the rf pulse taking the SLED wave form into account. The two-bunch injection has been regularly used for the operation. The injection rate was actually doubled and achieved higher numbers than the *Design Report*.

FUTURE

KEKB has various upgradability toward 10 to 50 times higher luminosity than the current design. For instance:

- By introducing a crab crossing with crab cavities, the beam-beam parameter can reach 0.1 to 0.25.
- Smaller β_y^* down to 3 mm is possible by redesigning the final quadrupoles and the compensation solonoids.
- Higher beam current up to 9.4 A in the LER and 4.1 A in the HER is possible by new beam pipe, new bellows, more cooling system, more rf systems with improved ARES (LER), couplers, HOM absorbers (SCC), etc.
- Charge switch of the rings with C-band system and a damping ring in Linac will help the needs of positrons and relax the electron-cloud effect.

The present tunnels, facilities, magnets, power supplies will be still usable for the upgrade. For an e^+e^- B–factory with the luminosity range $10^{35} - 10^{36}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$, upgrading KEKB will be the cheapest solution.

ACKNOWLEDGMENT

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