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KEKB B-Factory,*) The Luminosity Frontier

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The experiment at the KEKB B-Factory [*KEKB B-Factory Design Report,* National Laboratory for High Energy Physics, KEK Report **95–7** (1995)], as well as PEP-II, brought the final blow on the 2008 Nobel Prize in Physics for the Kobayashi-Maskawa theory. A few key issues will be described on the design and performance of KEKB to make the world's highest luminosity possible.

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§1. TRISTAN, KEKB, and PEP-II

As an introduction, let us begin with a brief introduction of particle colliders related to KEKB. There have been two colliders. The first one was TRISTAN,[1)] a single ring electron-positron collider with a circumference of 3 km, at the center-of-mass energy up to 64 GeV. TRISTAN was approved in 1981, and experiments started in 1987. Its main object was the discovery of the t-quark, whose mass was not known when it was started.

The second collider in Japan is KEKB, a double-ring collider with asymmetric energy 3.5 GeV positrons and 8 GeV electrons, built in the same tunnel as TRISTAN. KEKB was approved in 1994, experiments started in 1999, and then have continued through 2009. KEKB's energy is tuned around the resonance $\Upsilon(4S) \approx 10.56$ GeV to observe the asymmetry in the decay of B- and $\overline{B}$-mesons. KEKB's luminosity reached 1.96×10^{34} cm^{-2} s^{-1} in 2009, which is twice as high as its design luminosity.

PEP-II[2)] is also a double-ring collider with 3.1 GeV positrons and 9 GeV electrons built in the same tunnel as PEP, which was a single-ring collider with 2.2 km circumference at SLAC. It was a peculiar situation in the history of colliders in the world that the two machines, KEKB and PEP-II were designed, constructed, and operated at the same time in parallel, with the same scientific goal. This was a severe head-to-head competition. At the beginning PEP-II made a good start in the luminosity, but KEKB has taken a lead since 2001. PEP-II ended its operation in 2008, with the highest luminosity 1.2×10^{34} cm^{-2} s^{-1}.

The competition between the two machines provided various benefits to both. It was not hostile but rather cooperative. Most information was open to each other via meetings, web, and visiting people. Both sides invited reviewers from the other to participate in machine review committees.

*) "KEKB B-Factory" is the formal name of the accelerator, although it has been sometimes mistakingly written as "KEK B-Factory" or "KEK-B Factory", etc.

§2. Experimental verification of Kobayashi-Maskawa theory

Two B-factories, KEKB and PEP-II, discovered CP violation in the decay of B-mesons, which was consistent with Kobayashi-Maskawa (KM) theory.[3] The final decisive factor for their Nobel Prize in Physics was these experiments in the B-factories. KM theory proved that at least three generations of quarks are necessary to explain the CP violation in the decay of kaons within the framework of the gauge theory of the weak interaction. It was an extraordinary prediction talking about six quarks, as only three of them had been known in 1972 when the KM theory appeared. Although such third generation quarks, b and t, were actually discovered later, it was not enough to verify the KM theory experimentally. An extreme view was that even if TRISTAN[1] had discovered the t-quark, it would not have lead to a Nobel prize for the KM theory. Of course the discovery of t itself could have got a Nobel prize, but a B-factory would have not been even possible if the mass of t had been so light as to make the lifetime of B-mesons too short.

Anyway the experimental verification of the KM theory required B-factories, and that is the most important results of the B-factories up to today. Especially for KEKB, this has become the first Japanese accelerator experiment which directly contributed to a Nobel prize.

§3. Issues on the design and performance of KEKB

When its design started around 1990, the KEKB B-Factory[4] had several design characteristics beyond the world level of colliders, whose highest luminosity had barely reached 10^{32} cm^{-2} s^{-1}, which is less than 1/100 of the present luminosity of KEKB. It is needless to say that an accelerator is a part of science which makes anything obvious once it is performed. When the design started, KEKB also had such unsolved issues which are now common to everybody but required stunning efforts to be realized. Below let us pick a few issues among them. Please note that these will not cover everything, and those which will not be described here can be as important as these.

The history of the luminosity performance of KEKB is shown in Fig. 1. Table I lists recent machine parameters of KEKB, in comparison with its design.

3.1. *Energy asymmetry*

It is not true that people at KEK expressed some refusal on the idea of a collider with energy asymmetry of two beams, which was required to detect the complex phase of the KM matrix. When the design of B-factories started around 1988, everybody knew that a fixed-target experiment is the ultimate energy-asymmetric collision, and also an e-p collider HERA had been under construction with much higher energy asymmetry than a B-factory. At least among accelerator scientists no doubt was expressed on the energy asymmetry itself. In the beam-beam interaction, which is the most important effect on colliding beams, what one beam sees is the electromagnetic field created by the other beam, not the energy of the other beam. Although the idea of an energy-asymmetric collision was essential for the experiment,

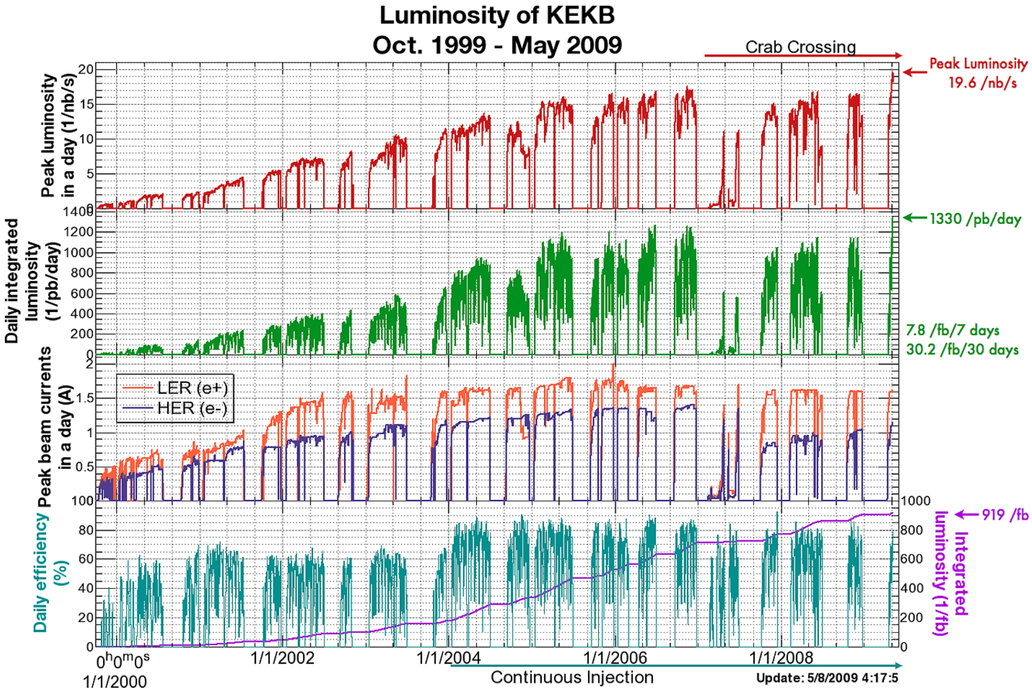

Fig. 1. History of the performance of KEKB from October 1999 until May 2009. The rows represent (top to bottom) the peak luminosity in a day, the daily integrated luminosity, the peak stored currents in the LER and HER in a day, the daily efficiency, and the total integrated luminosity at Belle, respectively. The integrated luminosities are the numbers recorded by Belle. The daily efficiency is defined as (Daily integrated luminosity)/(Peak luminosity × 1 day), and was boosted in January 2004 by the Continuous Injection Mode. The crab crossing scheme has been applied since February 2007.

it did not need any innovative beam physics or technology.

3.2. *Finite crossing angle*

KEKB has a horizontal crossing angle by $\theta_x = 22$ mrad between two beams at the interaction point (IP). This angle is comparable to the horizontal diagonal angle of the bunch, $\sigma_x^*/\sigma_z \sim 17$ mrad, where σ_x^* and σ_z are the horizontal beam size at the IP and the bunch length, respectively. Historically such a large crossing angle was once tried at DORIS in the 1970s, but the achieved vertical beam-beam parameter*) was $\xi_y \sim 0.01$, which had been considered unsuccessful and dangerous since then. That was the reason why PEP-II sticked to a traditional head-on collision scheme.

On the other hand, KEKB included a finite crossing angle in the design from the beginning. The merits of a finite crossing angle were so obvious: it is just easy to separate two beams near the IP before/after the collision without placing strong deflecting dipole magnets, which was permanent magnets in the case of PEP-II. Then the number of necessary components becomes much less than in a head-on scheme to

*) A parameter to represent the strength of the beam-beam interaction. Luminosity is proportional to it.

Table I. Progress of machine parameters of the KEKB B-Factory. The left, center, and right correspond to the highest with/without crab crossing, and the design, respectively. 1/nb = 10^{33} cm^{-2} s^{-1}.

Date	**5/6/2009**		**11/15/2006**		**Design**		
	LER	**HER**	**LER**	**HER**	**LER**	**HER**	
Eff. Crossing angle	0 (crab)		22		22		mrad
Beam current	1.60	1.13	1.65	1.33	2.6	1.1	A
Bunches	1584		1389		5000		
Bunch current	1.01	0.71	1.19	0.96	0.52	0.22	mA
Bunch spacing	mostly 1.8		1.8–2.4		0.6		m
Hor. emittance ε_x	18	24	18	24	18	18	nm
β_x^*	150	150	59	56	33	33	cm
β_y^*	0.59	0.59	0.65	0.59	1.0	1.0	cm
Hor. size @ IP	164	190	103	116	77	77	μm
Ver. size @ IP	0.85	0.85	1.9	1.9	1.9	1.9	μm
Beam-beam ξ_x	0.120	0.099	0.115	0.075	0.039	0.039	
Beam-beam ξ_y	0.123	0.088	0.104	0.058	0.052	0.052	
Luminosity	19.6		17.6		10		/nb/s
$\int$Lum./day	1330		1260		~ 600		/pb
$\int$Lum./7 days	7.17		7.82		–		/fb
$\int$Lum./30 days	23.02		30.21		–		/fb

make room for compensation solenoids used to cancel the detector solenoid field in order to reduce the horizontal-vertical (x-y) coupling effects. Also the generation of synchrotron radiation due to deflection of beams can be removed from the near region of the IP to weaken the detector background. It also eliminates beam-beam effects due to parasitic collisions, which occur at other locations besides the IP depending on the bunch separation along the orbit. Then at KEKB, the parasitic collision is negligible even when every rf bucket*) is filled, while PEP-II cannot ignore that at two-bucket separation.

Although these merits had been known, what people hesitated on a finite angle crossing was *synchrotron-betatron coupling* induced by the beam-beam interaction, which DORIS had encountered. With a finite horizontal crossing angle, the horizontal position of a particle at collision shifts as $x \to x + \theta_x z$, where z is the longitudinal position (i.e. difference of the arrival time) of a particle. Then the transverse beam-beam force depends on z, introducing synchrotron-betatron coupling. On the other hand, a synchrotron-betatron coupling already exists even for a head-on collision. That is due to the fact that the collision point s of each particle shifts by $z/2$ along the orbit. It plays an important role in the vertical plane, as the vertical position of a particle shifts as $y \to y + y'z/2$ at the collision, and $\sigma_{y'}^*\sigma_z$ is comparable to σ_y^*. This intrinsic synchrotron-betatron coupling term has the same magnitude in the Hamiltonian of the interaction as the horizontal crossing angle term, at least in the case of KEKB. Therefore the synchrotron-betatron coupling is not a completely new issue induced by a crossing angle; it is just a matter of quantity.

*) The length of one rf bucket is the wavelength of the accelerating rf. It is about 60 cm for both KEKB and PEP-II.

Generally speaking, such effects caused by a synchrotron-betatron coupling depend on the choice of tunes, which is the oscillation frequency of a particle around the equilibrium orbit in three dimensions. In other words, it is possible to avoid the effects if one can choose good tunes. Then at the design of KEKB, intensive simulations with beam-beam interaction were performed to find out such tunes. Then it actually found areas of tunes, which were sufficiently large for operation, considering the stability and controllability of the machine. As only one of such tunes is needed for the machine operation, a large area is not necessary anyway. By the way, the method of the beam-beam simulation done at the design stage of KEKB was *weak-strong model*, which fixes the particle distribution of one beam and then tracks the orbits of particles of the other beam. Of course, as both beams deform in the real collision, it is not complete unless with *strong-strong model*. As the limited computing power given at the design stage, it was not possible to perform a strong-strong model which needs a sufficiently large number of particles ($\gtrsim 10^6$ for KEKB) to be tracked within a reasonable computing time. Actually such a strong-strong model has become available since more than 5 years ago,[5] and confirmed that the results of both models are not different in the regime of a modest beam-beam parameter, $\xi_y \lesssim 0.05$, where KEKB was designed.

Then it was natural to ask why DORIS could not manage the finite crossing angle successfully. As suggested by Prof. G. Voss, the chair person of the KEKB Accelerator Review Committee (KEKB-ARC), KEKB team invited Prof. A. Piwinski from DESY to discuss the issue. The conclusion was that when DORIS was operated, it was not possible to suppress the beam instability without introducing bunch-by-bunch tune spread, as no sufficiently fast electronics were available at that time. Then the entire beam which consists of about a hundred bunches had tune space larger than the area of good tunes. Also they could not reach the good area near a half integer, which is $0.5 < \nu_x < 0.52$ in the case of a horizontal crossing. It was thought at the design stage, and then actually was verified in its operation, that KEKB could clear these conditions with less impedance design, enough faster beam feedback, more precise control of beam optics, etc. Even if these predictions failed, it was already known that an effective head-on could be restored by *Crab Crossing*,[6),7),*)] and therefore KEKB-ARC finally approved the finite crossing angle.

By the way, there was a short period in the design stage of KEKB, when the goal luminosity was compromised at 2×10^{33} cm^{-2} s^{-1}, 1/5 of the design, by extending the bunch separation to 5 buckets to enable a head-on collision, with opportunism. Then an R&D for a permanent magnet to separate two beams near the IP was actually tried similarly to PEP-II. As a result, the prototype of such magnets did not satisfy the requirement, and thus that direction was given up. If such effort had been as successful as PEP-II's magnets, a head-on collision could have got momentum, and then the competition between PEP-II and KEKB would have been performed differently.

If we compare the achieved performance of the finite crossing angle at KEKB to

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*) A technique to restore an effective head-on collision while keeping the crossing angle itself, by tilting the bunches in both beams by half the crossing angle at the IP.

the head-on at PEP-II, the luminosity per products of bunch currents of two beams was twice higher in KEKB than PEP-II. The finite crossing angle brought a lot of merits including the compensation solenoid, better x-y coupling, and smaller β_y^* [*)] to contribute to higher luminosity.

Moreover one more important merit, which was not well conceived at the design stage, was realized for crossing angle through the beam operation of the B-factories. If there is a strong dipole magnet near the IP, a particle that lost its energy due to a radiative Bhabha event at the collision is bent by the magnet to hit the detector. As the event rate is simply proportional to the luminosity, the detector comes to have a background proportional to the luminosity in this case. As a result, the Babar detector was dominated by such luminosity-dependent background. On the contrary, no such luminosity-dependent background has been observed at Belle, showing a hidden power of the finite crossing angle.

After KEKB, the finite crossing angle scheme has been applied at DAΦNE, LHC, and BEPC-II, and established as a standard for future colliders. This is a frontier opened or reopened by KEKB.

3.3. *TRISTAN*

If TRISTAN had never existed at KEK, how would KEKB have been? Of course a lot of accelerator scientists at KEKB grew up through the experience of TRISTAN, and many of the components, such as magnets, the rf system, and injectors, were reused at KEKB and helped in its success. One important thing, however, to be picked here is the tunnel of TRISTAN. As we know, TRISTAN was a collider with beam energy 30 GeV with 3 km circumference, so most people may think that its tunnel is too large for a B-factory at 3.5 GeV + 8 GeV. Actually in some period of the design stage, a new ring with shorter circumference, 1,400 m, was considered. People thought that the length was just sufficient at that time. Fortunately or not, it was realized that the cost for the construction of such a tunnel was not cheap, and thus the new tunnel scheme had gone forever. If there had been no TRISTAN, or if the short tunnel had been cheap, such a new tunnel scheme could survive, and then it would be an obstacle for the performance later. At a glance, the tunnel of TRISTAN looks too long. It actually brought enough room and flexibility to install various ideas such as 2.5π cell structure, local chromaticity correction, a long wiggler sections,[**)] etc.

As the tunnel of TRISTAN was so designed as to add a proton ring later, the width of the arc section was just suitable to install two rings of KEKB with horizontal separation. The horizontal separation of two rings is sufficient to suppress the vertical emittance as small as possible, which cannot be done at PEP-II that places two rings vertically. The straight sections of TRISTAN had the width and the height enough to involve spin rotators. Then the tunnel at the straight section was adequate to install the Accelerator Resonantly-coupled Damped cavities (ARES) as well as superconducting acceleration and crab cavities at KEKB. As discussed later, these

[*)] The β-function at the IP, β_y, represents the depth of focusing the IP, and is equal to the ratio of the beam size and the angular divergence of the beam at the IP, i.e, $\beta_y^* = \sigma_y^*/\sigma_{y'}^*$.

[**)] KEKB's wiggler sections are about 200 m long in total, the longest in the world.

cavities represented one of the keys of the success of KEKB. If KEKB had started with a small tunnel as PEP-II, the fate of such cavities would not have been clear.

At least in Japan, there is a tendency to seek smaller sizes of accelerators or devices, as a goal of R&D. The important thing is the total performance of such devices, so the size is just one of many factors to achieve the performance. A small size without considering total performance does not make sense, for instance, a small accelerator which needs a large power source, unnecessary interference between devices by making the distance too short, eliminating necessary components due to the small size, etc. The experience of KEKB using the TRISTAN tunnel may suggest that a large size brings more efficiency in total in some cases.

3.4. *Lattice*

The design of the arc section is called 2.5π *cell structure*,[8] which has been quite unique to KEKB. It is characterized as:

- Placing 4 dipoles within 5 cells of 90° FODO structure.
- Pairs of identical sextupoles, one pair for each plain per cell, connected by a $-I$ transformation.*) The horizontal dispersions η are set equal at both sextupoles of the pair.
- Two more additional quadrupoles per cell to have more flexibility.

The transformation of the $-I'$ pair of sextupoles is written as

$$e^{:k'((x+\eta\delta)^3+3(x+\eta\delta)y^2)/6:}e^{:k'((-x+\eta\delta)^3+3(-x+\eta\delta)y^2)/6:} = e^{:k'\left((x^2+y^2)\eta\delta+\eta^3\delta^3/3\right):}, \quad (3\cdot1)$$

where k' and δ are the strength of the sextupole and the relative momentum offset of a particle, respectively. Equation (3·1) shows that only a chromatic quarupole term $(x^2+y^2)\eta\delta$ and a pure longitudinal nonlinearity $\eta^3\delta^3/3$ remain. The latter is usually less harmful compared to transverse nonlinearities. As a result, this cell structure obtains various merits:

- The transverse nonlinearity of the sextupoles is almost cancelled between the $-I$ pair. The measured damping rate of a coherent betatron oscillation by $\sim 10\sigma_x$ due to the nonlinearity was about 1/10 of the radiation damping. It confirmed the high linearity of the KEKB lattice:
- The low-energy positron and high-energy electron rings (LER and HER) have 54 and 52 independent pairs of sextupoles.**) The tuning of such a large number of sextupoles is done without being bothered by the transverse nonlinearity to provide large dynamic aperture.
- It is possible to set the momentum compaction factor and the equilibrium emittance independently within a certain range. Negative momentum compaction is also possible.
- Either by putting horizontal and vertical, symmetric and antisymmetric bump orbits through the sextupole pairs, it is easy to control x-y coupling, horizontal

*) Actually components R_{21} and R_{43} are nonzero, thus called $-I'$ transformation in this case.

**) The number of sextupole families at KEKB is the largest in the world.

and vertical dispersions and β functions of the ring. Also it is easy to enlarge the vertical emittance by such a bump orbit.

Although this cell structure has a lot of merits and potential to apply to other rings such as the ILC damping ring and light sources, somehow no application has been known up to now except for a model ring of a muon collider.

By the way, the idea of using $-I$ transformation between identical sextupoles is old,[9)] and it was applied to the Arc and the Final Focus of SLC, in an imperfect way, which interleaved the pairs to each other. A perfect non-interleaved $-I$ pair was first applied for the Final Focus Test Beam (FFTB).[10)] No ring has been known before KEKB to have installed this idea. Probably the reason was that the distribution of the sextupoles becomes sparse and inevitably needs a large number of pairs, which require a good computer model to determine their strengths as well as a large number of arc cells. Such an optimization of sextupoles was made possible at KEKB with a finite-amplitude method. In a usual machine, the issue of chromaticity correction and dynamic aperture is handled in terms of a Taylor expansion around the equilibrium orbit. If one needs a sort of ultimate performance, however, such a Taylor expansion becomes unsuitable, because of bad convergence at large amplitudes. Thus in the design of KEKB, an optimization was done for a large number of sample orbits with finite amplitudes, instead of a Taylor expansion. This method leads to a good solution at least on a computer.

Another strong point of the KEKB lattice is the local chromaticity correction system (CCS) around the IP. Only the LER, which requires a large dynamic aperture to relax the reduction of the lifetime due to intrabeam scattering, has such a system at KEKB. Two vertical $-I$ pairs of sextupoles are placed in both the straight sections around the IP to suppress the transfer of the chromaticity of the IP to the arc. This scheme further enlarged the dynamic aperture, gave the basis to squeeze β_y^* smaller, 6 mm, than the design, 10 mm, and let the horizontal tune access a half integer down to $\nu_x \sim 0.505$ in the actual operation, while the design was $\nu_y = 0.52$. Both have contributed to increase the luminosity beyond the design, under the restriction of the beam current in the LER due to electron cloud.

3.5. *Injector*

Before the operations of KEKB and PEP-II started, it was thought that "the competition between PEP-II and KEKB will eventually become a competition of the injectors, which KEK can never win". It is true, even for today, the performance of KEKB Injector Linac is behind SLAC's, especially in its production/injection of positrons, as shown in Table II.

Table II. Comparison of positron injection in 1999, when two B-factories began operation.

	KEK	SLAC	
Particles per pulse	0.4	2	10^{10}
Repetition rate	50	≤ 120	Hz
Invariant horizontal/vertical emittances	$\sim 10^4/10^4$	3/0.3	μm
e^+/e^- switching time	5	0 (simultaneous)	min

As PEP-II inherited the SLC Linac, it can inject more intense positrons to PEP-II with better quality at a higher repetition rate than KEK. Thus many people expected that when the rings were tuned up with high luminosity, the competition should be in the refilling speed of positrons, and then SLAC must win.

What happened was, however, completely different from their expectation. The most important factor was a continuous injection mode (CIM), where the detector continues data-taking during the injection of beams. This mode has been utilized in light source rings since around the year 2000, called “top-up”. Both KEKB and PEP-II started the CIM almost simultaneously in 2004 as the first such experiments for high-energy physics. The CIM just requires to supply particles lost by the lifetime of the rings, and thus it does not need full injection power of the injector at all, even at KEKB. Then the difference between the injectors of KEK and SLAC became irrelevant. Although the difference still exists at injection from scratch after a beam abort, the frequency of the beam abort was much less in KEKB, due to the stability given by the ARES and superconducting cavities. The typical rate of beam aborts per day at KEKB was 1/4 of PEP-II. Then the difference of the injectors did not contribute to the luminosity competition. The CIM brought another merit that as the beam currents in the rings became nearly constant, the beam conditions became quite stable as the temperature of components became constant. Then the tuning of the luminosity became far easier than before the CIM, improving the peak luminosity as well as the integrated one.

Prior to the CIM, the KEKB Injector Linac has made another success in 2003 to accelerate two bunches of positrons within an rf pulse. This technique utilizes both slopes of the output of the pulse compressor for the acceleration of two bunches, equalizing the energy gains. Thus the amount of charges was doubled and reduced the difference between KEKB and SLAC. Also the switching time between electron- and positron- modes has been reduced year by year, and finally reached 20 msec, which is a pulse-to-pulse switching, in April 2009. It also enabled a pulse-to-pulse switching between two KEKB rings and the Photon Factory (PF) ring. Thus the KEKB Injector Linac has conquered the initial handicap with at least two new technologies which were not written in the original design. It made KEKB possible to continue to run at the highest luminosity ever achieved.

The progress at the KEKB Injector described above, however, did not close the gap between it and SLAC completely. For instance, the positron production rate and the small emittance generated by the two damping rings have been the remained differences. These issues must be solved for a future upgrade of KEKB, which will require more intense beam with higher quality than today.

3.6. *Storing high current*

Storing high currents in the rings is not the goal of KEKB. Actually its currents were lower than PEP-II and some other rings. For instance, the ISR or even the Booster of the KEK Proton Synchrotron stored or accelerated higher currents than KEKB. In the case of electron-positron rings, however, synchrotron radiation and higher-order mode (HOM) electromagnetic field are associated with the beam to bring completely different difficulties with high current. In that sense, the maximum stored currents of KEKB, 2.0/1.4 A (LER/HER) are much higher than most rings for light sources, and even compared to PEP-II's currents (3.0/1.5 A), the problem of HOM can be more serious, as the bunch length is shorter in KEKB (6 mm vs 12 mm).

The first issue for a high current is the design of the accelerating cavity and the beam pipe. PEP-II and KEKB chose different strategy in both of them. KEKB chose cavities, ARES[11] and superconducting,[12] which could store huge electromagnetic energy compared to usual ones. On the other hand, PEP-II chose a more or less conventional HOM-damped cavity. The size of the tunnel should have affected the choice, as mentioned above. The main difference of KEKB and PEP-II cavities was the amount of detuning of the resonant frequency of the main accelerating mode. At high current, the frequency of the accelerating mode must be detuned from the rf frequency to weaken the reaction from the beam current. If the amount of the detuning is too large, the detuned impedance tends to excite coupled-bunch oscillation of a large number of bunches in a ring. KEKB's cavities could avoid this with the high stored energy to reduce the amount of detuning, to less than 1/10 of conventional ones. As a result, the accelerating cavities never excite any instability up to the design current, without a fast longitudinal feedback system. The beams in KEKB are just stable by itself.[*] On the contrary, PEP-II's accelerating cavities need a sophisticated feedback system to stabilize the beam at high current, to create an artificial impedance to compensate the largely detuned mode. Their system was a sort of high-tech, involving the cavity, and the klystron, and a longitudinal bunch-by-bunch feedback system. Although PEP-II's system actually worked, the resulting stability was much worse than KEKB. The number of beam aborts due to trips of the accelerating cavities was much higher in PEP-II than KEKB.

In the case of the beam pipes, KEKB basically applied simple copper pipes in two rings, while PEP-II used a similar one at the HER and an aluminum pipe with an antechamber. The difference in the design of the LER beam pipe produced a huge difference in the production of *electron cloud*, which became the main reason that PEP-II preceded in the luminosity in 1999–2000.

The formation of the electron cloud had been already known at the design stage of KEKB, through the experience at the PF.[13),14] Actually a similar phenomenon had been also seen in other rings such as the ISR since old days. What had been observed and anticipated was, however, a transverse coupled-bunch instability due to the electron cloud. It was thought that such a instability would be well suppressed by a bunch-by-bunch feedback system, and actually it was also true. Even solenoids are proposed in the *Design Report* of KEKB to suppress the electron cloud, but they were not installed during the construction. KEKB was too optimistic on this issue.

Electron cloud was not the reason why PEP-II applied a design of a beam pipe with an antechamber in their LER. As the production of their LER beam pipe was assigned to LBL, they simply transferred the design of the ALS light source that was then operating at Berkeley. Right after they got information of the issue of

[*] Transverse bunch-by-bunch feedback system was necessary at KEKB to suppress fast-ion, electron-cloud, and resistive-wall instabilities, which are irrelevant to the accelerating cavities.

electron cloud from KEK, they decided to apply TiN coating inside the beam pipes in the LER. This was another factor to have reduced the electron cloud in PEP-II. Although PEP-II responded to the issue reminded by KEK, KEKB did nothing effective on this issue before the start of operation.

What was actually caused by the electron cloud was much serious than expected coupled-bunch instability. Beside the coupled bunch oscillation, a *single-bunch head-tail instability* blowed up the vertical beam size drastically at high current. Such a head-tail instability causes oscillation of particles within a bunch, whose length is 6 mm. Thus the oscillation frequency is as high as 10 GHz, and then no feedback is available to suppress the head-tail motion once appeared. Actually such a head-tail motion had been predicted by Raubenheimer and Zimmermann[15)] for the next linear collider (NLC) before the commissioning of KEKB, but nobody at KEKB had noticed it. That was why Zimmermann quickly identified the phenomenon as a head-tail motion when he visited KEKB in late 2000. Such a head-tail motion was also directly observed later by looking at the sidebands in the spectrum of bunch oscillation.[16)]

As the cause of the blowup of the beam size was identified as electron cloud, mitigations such as permanent magnets or solenoids were quickly applied. Although the amount of electron cloud was greatly reduced by those, but the cloud still remains in the LER, especially inside of dipole and quadrupole magnets where solenoids are not applicable. Thus the luminosity drops due to the electron cloud when the bunch spacing is less than or equal to 2 buckets, 1.2 m. Then storing currents higher than 1.8 A in the LER does not contribute to the luminosity. That is why the LER current has not reached the design current, 2.6 A.

Anyway the electron cloud appeared at KEKB in a large scale with a new type of instability, reminded all accelerator scientists in the world who handle positive charge beams. After the experience at KEKB, it has become one of the very common fields, which is critical to any kind of accelerators, including the LHC, the International Linear Collider (ILC), J-PARC, etc. This is also a frontier KEKB has opened or reopened.

§4. Future

So far KEKB has accumulated the luminosity up to 0.9 ab^{-1}. If physicists need more events, it is not efficient to operate the present KEKB as it is now with the luminosity $\sim$ 0.2 ab^{-1}/year. An upgrade by more than a factor of 10 in the luminosity will be necessary. The luminosity $\mathcal{L}$ of a ring collider is written using three main parameters:

$$\mathcal{L} \propto \left(\frac{I\xi_y}{\beta_y^*}\right) , \qquad (4\cdot1)$$

where I is the stored current. So far two options have been considered to boost the luminosity at KEKB. One is *High Current Option* and the other *Nano-Beam Option.* The former relies on a high beam-beam parameter expected by crab-crossing and stores high currents as much as possible. The latter maintains the beam currents

Table III. Comparison of options of KEKB upgrades as well as the present KEKB.

		Present KEKB LER/HER	High-current LER/HER	Nano-beam LER/HER	
Stored currents	I	1.8 / 1.4	9.4 / 4.1	$\sim 3/1.5$	A
Vert. beam-beam param.	ξ_y	$\lesssim 0.09$	~ 0.3	~ 0.1	
Vert. β at the IP	β_y^*	6	3 / 5	~ 0.2	mm
Hor. emittance	ε_x	~ 18	~ 18	~ 1	nm
Vert. beam size at the IP	σ_y^*	~ 1	~ 1	~ 0.05	μm
Crossing angle	θ_x	22	0 (crab)	~ 60	mrad
Luminosity	$\mathcal{L}$	1.8	~ 50	~ 80	10^{34} cm^{-2} s^{-1}

and the crossing angle, while squeezing the beam size at the IP toward nano-meter scale. Their typical parameters are compared in Table III.

The high-current option is more or less a simple extension of the present KEKB, while difficulties are in the beam-beam parameter as high as 0.3, and the currents 3 to 5 times higher than today. The nano-beam option is a relatively new idea brought by P. Raimondi at INFN, Italy to squeeze the beam size by reducing the equilibrium emittance and β_y^* while keeping the beam currents and the crossing angle.[17)] The nano-beam option requires precise control of the beam at the collision and stability to maintain the small emittance.

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