OPERATION EXPERIENCE AND PERFORMANCE LIMITATIONS IN e+e- FACTORIES

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Abstract

Since 1999 three double-ring e+e- colliders have been operating. PEP–II and KEKB are asymmetric B–factories at $\Upsilon(4S)$, and DAΦNE is a Φ-factory. Generally speaking, the two B-factories have more or less common issues, and the Φ–factory has somewhat different issues from the B–factories. This paper first describes two B-factories, then discusses on DAΦN later. The description on DAΦNE owes Dr. M. Preger.

1 ASYMMETRIC B–FACTORIES

1.1 Successful Startup

Figure 1 shows the development of the peak and the integrated luminosities of PEP–II and KEKB since 1999. This figure obviously tells the success of two machines. PEP–II reached its design luminosity, 3 /nb/s, in the fall of 2000, only 15 months after the startup of the BaBar detector. It also exceeded its design luminosity by 50% (4.6 /nb/s) in the fall of 2001. The integrated luminosity is approaching 90 /fb in May 2002. KEKB started the luminosity run in 1999, and the startup speed was somewhat slower than PEP–II's. The main obstacle at that time was the electron-cloud effects and various machine failures due to the high current operation. The peak luminosity of KEKB surpassed PEP–II's in March 2001 and it reached 7.3 /nb/s in May 2002, which is still 30% below its design value, 10 /nb/s. Though the peak luminosity of KEKB has been higher than PEP–II's since 2001, the integrated luminosities of two machines in 2001 through 2002 were roughly equal to each other.

The ratio of the average luminosity to the peak luminosity was about 76% and 62% for PEP–II and KEKB, respectively. The strong injector of SLAC benefits PEP–II pretty much to improve the luminosity efficiency. Also the total running time in 2001 was longer in PEP–II by about 2 months than in KEKB.

Both machines have already produced substantial output of particle physics as planned, including the discovery of CP violation in the B meson system. The quick start of the luminosities in the two machines was remarkable in the history of colliders.

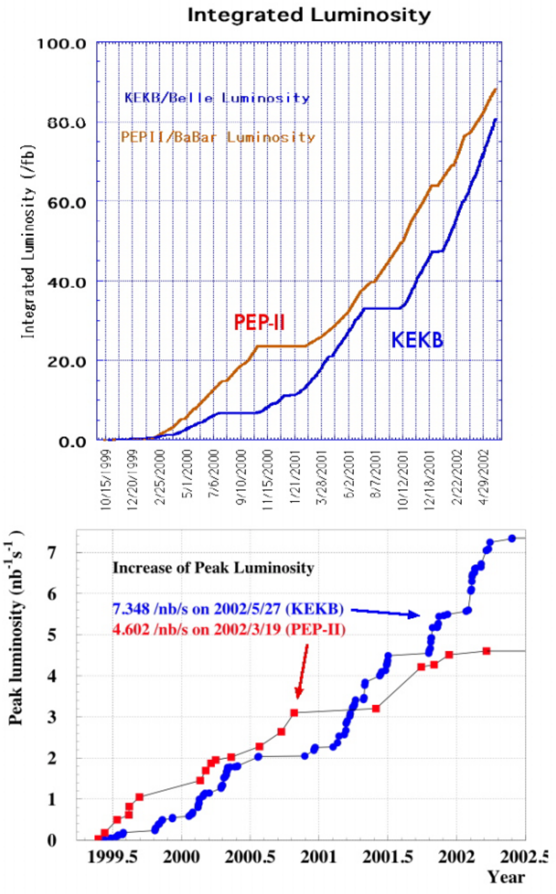

Figure 1: The increase of the integrated (upper) and peak (lower) luminosities of PEP–II and KEKB since 1999.

1.2 Machine Parameters

Table 1: Machine Parameters of Asymmetric B–Factories.

	PEP–II		KEKB		
	LER	**HER**	**LER**	**HER**	
Energy	3.1	9.0	3.5	8.0	GeV
Circumference	2200		3016		m
Current	1.78	1.06	1.37	0.92	A
Bunches	800		1224		
N/bunch	10.2	6.1	7.0	4.7	10^{10}
Spacing	2.5		2.4		m
Cross. Angle	0		22		mrad
Emittance ε_x	50	50	18	24	nm
β_x^*	35	50	59	61	cm
β_y^*	0.9	1.25	0.62	0.7	cm
Hor. Size @IP	132	158	103	121	μm
Ver. Size @IP	7.9	4.5	2.8	2.8	μm
$\varepsilon_y/\varepsilon_x$	14	3.2	7.2	4.8	%
Bunch Length	13	12	5.3	5.5	mm
Beam-beam ξ_x	.062	.070	.080	.074	
Beam-beam ξ_y	.056	.029	.048	.041	
Luminosity	4.60		7.35		/nb/s
$\int$Lum/24 hrs	303		395		/pb
$\int$Lum/7 days	1790		2524		/pb
$\int$Lum/30 days	6666		8783		/pb

Table 1 lists main machine parameters of two B–factories corresponding to their best luminosity.

1.3 *Energy Transparency*

Both machines were designed with the so-called energy transparent condition, which requires the beam currents to be inversely proportional to the beam energy. As shown in Table 1, in the real situation, mainly due to the blow-up of LER beam size by electron cloud, both machines violate the transparent condition. On the one hand this verified that the transparent condition is not so strict to obtain the luminosity, but on the other hand, the non-transparent parameters as Table 1 was still not the optimum for the luminosity. While the luminosity/(LER current) in Table 1 is not better than the transparent one, the luminosity/(HER current) was significantly worse than that of the transparent condition. This means that it was necessary to store HER current as much as possible to recover the luminosity degraded by the blow-up of the LER beam size. Thus for a design of future machines, the energy transparency will be still valid, assuming such external blow-up being solved.

1.4 *Crossing Angle*

One of the big differences between two machines is the crossing angle at IP. KEKB (as well as DAΦNE) has 22 mrad horizontal crossing angle. This angle is roughly equal to the bunch diagonal angle $\sigma_x/\sigma_z = 20$ mrad. Up to now, no serious effect related to the crossing angle has been noticed at KEKB. With the crossing angle their beam-beam tune-shift parameters have exceeded 0.07 and 0.04 in horizontal and vertical planes, respectively. When KEKB was designed, strong-weak beam-beam simulations justified the crossing angle, and later strong-strong ones confirmed that. The experimental results basically agree with these simulations. The crossing angle will help shorter the bunch spacing that is necessary to increase the beam current further.

1.5 *Maintaining Collision*

Number of methods have been applied to collide two beams and maintain high luminosity:

- 4D Orbit feedback measuring beam-beam kick by the IR BPMs (KEKB). Care was needed when the BPMs are moved within a fill by the temperature change at the IR.
- Dithering method with a fast luminosity monitor to optimize the orbit (PEP–II). At KEKB the limited acceptance of the monitor makes it hard to utilize.
- Flip-flop control using either the dispersion bump or horizontal offset of two beams (KEKB).
- Controlling the betatron tunes during a fill looking at the pilot bunches (KEKB: off-collision, PEP–II: on-collision).

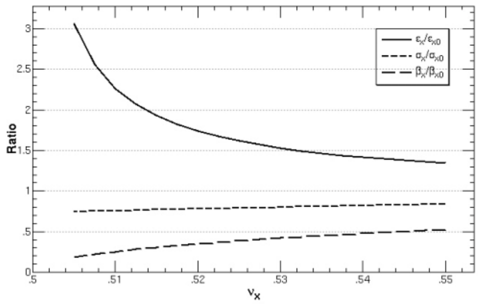

Figure 2: The dynamic β effect. This figure assume ξ_x=0.075 for both rings. By the focusing force of the beam-beam interaction, β_x^*(bottom) shrinks as the horizontal tune becomes close to 0.5. The emittance(upper) diverges and the beam size (middle) stays nearly constant.

1.6 *Access to Half Integer*

The search for good betatron tunes would have been very difficult for a double-ring collider that have four tunes, if simulations did not exist. Beam-beam simulations, either strong-weak or strong-strong, indicate that best luminosity is achieved just over an integer or half-integer horizontal resonances. The half-integer resonance is preferable because the orbit distortion will be more stable than the integer one. KEKB has been systematically pursuing such tunes, starting from 0.56 in 1999, 0.52 in 2000, 0.514 in 2001, 0.510 in 2002. The luminosity actually became better as the horizontal tune came closer to the half integer. This was basically the same result as the prediction of the simulations.

The access to the half integer was made possible by reducing the width of the stop band with optics corrections. At KEKB, optics correction including β, coupling, dispersion corrections have been done regularly in every 2 weeks with an online model by SAD. The residual β-beat is suppressed to below 5% by the correction. Such a correction system is also under development at PEP–II, and whose tune has been set closer to half-integer, 0.52, recently.

A possible explanation of the superiority of half-integer is give by the so-called dynamic β effect. The beam-beam focusing force at the IP changes the beta functions and the emittances for particles at the core where the beam-beam force is nearly linear. This effect becomes stronger at an integer or half-integer resonances. Figure 2 shows the effect of the dynamic β, emittance, and beam size as functions of the horizontal tune above the half-integer. For instance, β_x^* is squeezed down to 25% at $\nu_x = 0.510$ by the dynamic β effect. It is interesting that the horizontal emittance is increased as ν_x comes close to 0.5, resulting that the horizontal beam size at IP stays nearly constant for the tune change. We assume both rings have same tunes. Therefore although the luminosity is not directly affected by the tune, the effective beam-beam parameter, which is inverse of the emittance, will be reduced as the tune comes close to the half-integer. The nominal horizontal tune shift in Table 1

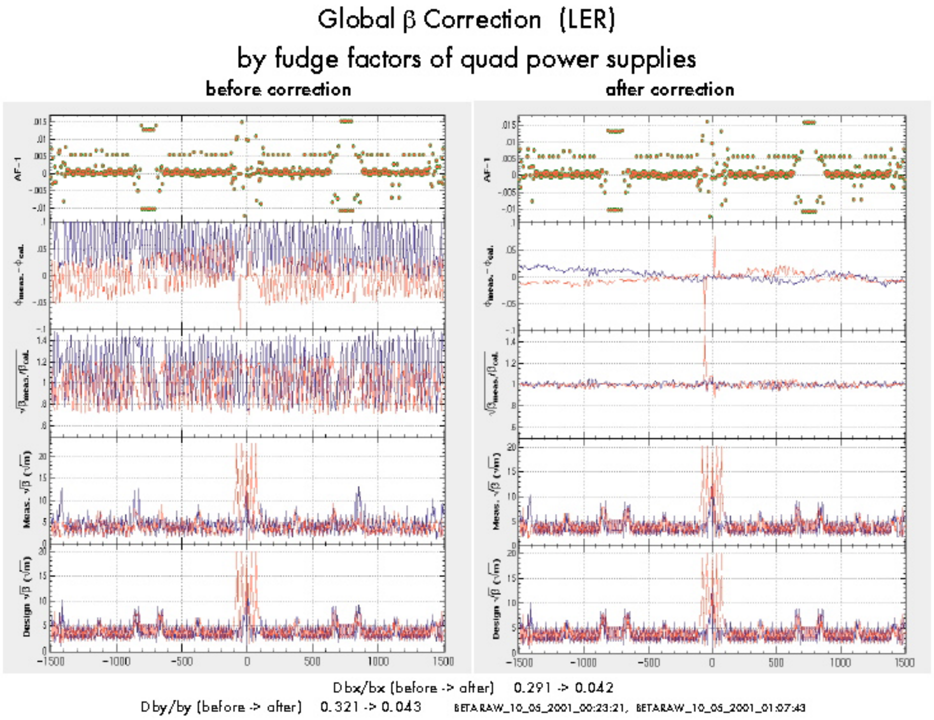

Figure 3: An example of the β correction in KEKB LER. Left is before correction showing the β and phase beats in x and y planes. It was corrected (right) reducing the residual within about $\pm5\%$ after a few iterations. This correction is done by an online model with SAD. A turn around time for the measurement/correction is about 5 minutes (by H. Koiso, et al.).

is as high as 0.075, but the effective value is much smaller due to the dynamic β effect. This should contribute to relax nonlinear effects of the beam-beam interaction.

Squeezing β^* near the half-integer is only valid in the horizontal plane. The reason is that β_y^* has been already squeezed down to the bunch length, and further reduction of β_y^* just increases the hour-glass effect and does not contribute to the luminosity at all. This is also consistent with the result of simulations.

1.7 *Understanding Optics*

Understanding the beam optics was a key issue to achieve the high luminosity. The beam optics around the IP is especially important, because the optics around the IP is quite irregular due to the low-β insertion and the x-y coupled components. At PEP–II, number of measurements were done to analyze the beam optics around IP. As PEP–II does not have a compensation solenoid to cancel the BaBar's solenoid, the handling of the skew components were quite important and not easy. By the help of the compensation solenoid, the beam optics at the IP was relatively easier in KEKB. The x-y coupling was corrected locally by the skew quadrupoles near the IP, as an integrated part of the optical correction system of KEKB. Even with such correction methods, there were a lot of unknown behavior of the orbit and optics remaining around the IP. To solve the issue, more BPMs are necessary not only for every quads, but also for skew quadrupoles.

Optics and the orbit around the ring is also important to squeeze β^*s, reduce ε_y and x-y coupling, and access to the half-integer resonance. The correction must be as local as possible to avoid higher order effects. As a nature of the collider, these machines have strong sextupoles distributed around the ring, and the control of orbit at sextupoles has been very important to keep the beam optics as ideal as possible. The orbit at sextupoles can be used to knobs to correct dispersions, x-y coupling, and β errors as done in KEKB (may be applied at PEP–II also). The local chromaticity correction system applied in LERs of both PEP–II and KEKB was successful to reduce the strength of the arc sextupoles to stabilize the optics.

The beam-based alignment of all BPMsdone in KEKB were also necessary to ensure the optics correction scheme.

1.8 *Electron Cloud*

The LERs of the asymmetric B–factories were the first machines to show the electron-cloud effect, especially the single-bunch blow-up. The coupled-bunch effect of the electron cloud was first seen at the Photon Factory around 1990, and was already known at the design stage of the B–factories. The growth time of the coupled bunch effect was estimated to be below the damping rate by the bunch-by-bunch feedback system in both machines. Such estimation has been verified experimentally in KEKB, and the coupled-bunch effect was actually not the critical issue.

The more striking effect of the electron-cloud was the single-bunch effect. It was actually predicted by F. Zimmermann and T. Raubenheimer around 1997, well before the start of the B-factories, for the bunch compressor of the NLC as well as the fast-ion effect. Unfortunately it was not well noticed by the B-factory people until the blow-up of the LER beam was observed in their rings. The blow-up of the vertical beam size in LER was observed in March 1999 at KEKB, and was explained as a single-bunch effect of the electron-cloud in October 1999 by F. Zimmermann. Sooner or later the blow-up was also observed at PEP–II. After that a number of measurements were done using synchrotron light image/interferogram, gated camera, gated tune meter, gated luminosity monitor, electron-cloud detector, etc. Those measurements basically support the prediction by the single-bunch theory and the simulations.

There are two sources of the electron cloud. One is the photo-electron and the other is the multipacting with the secondary electron at the chamber wall. The first one dominated at KEKB since the vacuum chamber is a simple cylinder, while PEP–II has an antechamber. This difference was one of the factors to make the startup of KEKB slower than PEP–II until the solenoid was fully installed in 2001. The major cure of the electron cloud was the external solenoid field both in PEP–II and KEKB. Both machines have wound solenoids with 20 to 50 Gauss covering more than 95% of the field-free region. As the result the electron cloud is not the critical issue at least up to the present beam current with 4 bucket spacing.

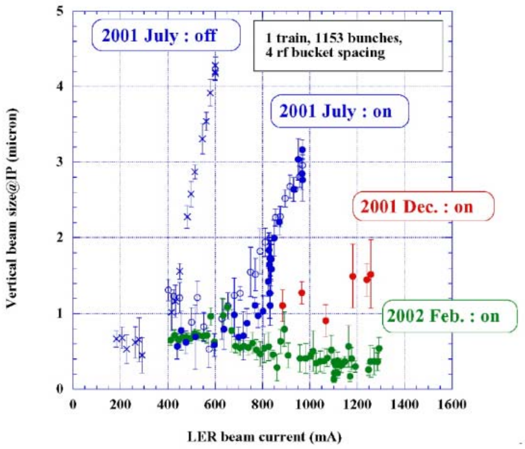

Figure 4: The blowup of the vertical beam size at KEKB LER for various lengths of the solenoid. With the current configuration the blowup is not seen any more up to 1.4 A. (by H. Fukuma, et al.)

Though the effect of solenoid was so remarkable, it is not clear yet the problem was completely solved or not. Number of issues are remaining:

- Measurements by gated-tune and the coupled-bunch growth rate show that there still remains 1/4 to 1/2 of the original cloud even with solenoids (KEKB). Since these measurements are sensitive to the cloud far from the beam core, the cloud at the beam core might be smaller than these measurements.
- If there still remains clouds somewhere in the ring with solenoids, it must be in the magnets. If it is true, special method other than solenoid will be necessary. Also a trapping effect by quad and sextupole fields has been predicted by L. Wang, but its effect on the beam is not known yet.
- Horizontal blow-up was seen at PEP–II, even stronger than vertical. The mechanism is still unknown. It is not observed at KEKB at all.
- The bunch-by-bunch luminosity indicates strong dependence along a train at PEP–II. Also an effect of mini-gap was strong at PEP–II. These are very weak at KEKB.
- Observations suggested a mixed effect of the electron-cloud and the beam-beam interaction as predicted by E. Perevedentsev, et al. Even below the threshold of the single-beam blow-up, the luminosity was degraded by the electron cloud.

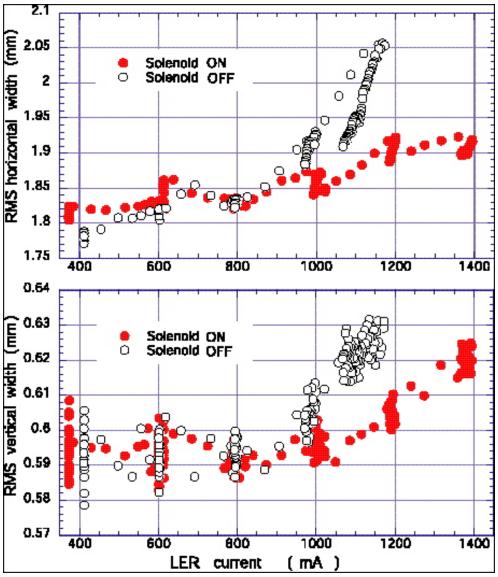

Figure 5: The blowup of the horizontal(upper) and the vertical(lower) beam sizes at PEP–II LER. Effect of the solenoid is seen in both planes (by A. Kulikov, et al.).

1.9 *Acceleration of High Current*

The asymmetric B-factories were also successful just in storing high currents. PEP–II has achieved maximum current higher than 2 A, and KEKB 1.5 A also. These stored currents are even higher than usual synchrotron light sources. It is remarkable that the high current was achieved with complicated beam optics at the IP with number of x-y coupled components. Light source machines may have undulators with short gaps to make injection difficult, but the gap of the vertical masks of B–factories are also very narrow (for instance, ±3 mm for KEKB).

The most difficult problem to accelerate such high current was the stability of the beam with the rf cavities. PEP–II and KEKB took different approach at this issue. PEP–II's rf cavity is a very compact single-mode damped cavity. To compensate the heavy loading of the beam, PEP–II developed a sophisticated feedback system controlling the klystron phase for each bunch together with the bunch-by-bunch longitudinal feedback. In this sense PEP–II took a very active control system. KEKB chose the opposite direction: passive stabilization. KEKB's two types of cavities, the ARES copper cavity and the superconducting cavity(SCC), both have very high stored energy to reduce the beam loading small enough. As the result, KEKB does not need special feedback system for the longitudinal plane. It only uses a slow 0 and -1 mode feekdbacks. Due to the heavily damped impedances of these cavities, KEKB does not need bunch-by-bunch feedback for the longitudinal plane (it is necessary for the transverse planes to suppress the electron-cloud, the fast-ion, and the resistive-wall instabilities).

Though their choices were opposite, both rf schemes worked as expected up to the present stored currents. Remaining issues are:

- The bunch-by-bunch longitudinal phase difference is significantly higher in PEP–II.
- The availability of the SCC at KEK is limited by the regulation for the He refrigerator imposed by the government. It is very hard to extend the running time longer than 40 weeks per year.

1.10 Summary

- Rapid startup, good coopetition. Sufficient for the planned physics.
- Many schemes worked as expected = victory of the accelerator technology and the beam dynamics. Electron cloud was serious, but cured by solenoid up to some extent.
- But, no big breakthrough for future! Is Super B beyond 100 /nb/s to be possible only by a brute force (=higher current, more power, more cost)?

2 DAΦNE

DAΦNE is a high luminosity electron-positron collider designed as a Φ-factory for the production of a high rate of K-mesons from the decay of the F resonance at 1.02 GeV CM. It consists of two rings on the same horizontal plane, crossing at an angle of 25 mrad in two interaction regions (IR). Up to 120 bunches can be stored in each ring The first IR hosts a magnetic detector (KLOE) mainly aimed at the study of CP violation. In the second IR the DEAR experiment studies the properties of kaonic atoms, namely atoms where kaons are captured in the inner shells in place of electrons.

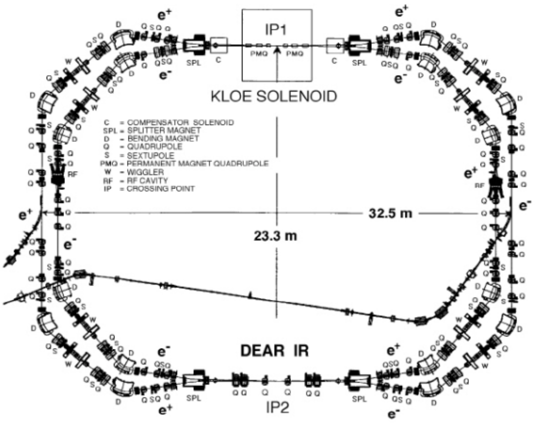

Figure 6: The Layout of DAΦNE (by M. Preger).

2.1 Present Performance

Table 2 shows the present performance of DAΦNE with KLOE and DEAR detectors, respectively. With the luminosity collected in April shifts, the capture of kaons in Argon atoms clearly observed.

Table 2: Present Performance of DAΦNE

	KLOE	DEAR	
Energy	510		MeV
Bunches	47 + 47	45 + 45	
Current	1 + 1	0.8 + 0.8	A
Emittance	1		μm
β_x^*/β_y^*	400/4		cm
Luminosity	51	46	/μb
Int Lum /day	2.5	1.1	/pb
Lum Lifetime	20	30	min.

2.2 Short Term Plans

- Deliver > 300 /pb to KLOE.
- Further improve luminosity performance and signal-to-background ratio in order to observe and measure the properties of kaonic hydrogen in DEAR ($\sim$ 40 /pb required).
- During a long shutdown (from November 2002 to January 2003) install new interaction regions for KLOE and for a new magnetic detector (FI.NU.DA.,aimed at the study of hypernuclear physics on IP2), with modified optic and supports in order to decrease the IP β-functions, optimise background rejection and provide variable quadrupole rotation to operate at different magnetic fields (from 0 to maximum) in the solenoids.

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