OPERATION OF HIGH-LUMINOSITY MESON FACTORIES AND THE CHALLENGE TO GO TO THE NEXT GENERATION

K. Akai*, KEK, Tsukuba, Japan

Abstract

This paper presents an overview of the operational status of B- and Φ-factories, and discusses their present luminosity performance and limitations. It also presents upgrade plans, new ideas, R&D and machine experiments in view of the next generation of meson factories with ∼100-times more luminosity.

INTRODUCTION

Recent high-luminosity e^+e^- colliders, providing particular particles such as B, τ-charm or ϕ mesons at a very high rate of production, are called “factories”. In the last 30 years the peak luminosity of e^+e^- colliders in the world has increased on average by a factor 20 every 10 years. CESR had been operating at the world highest luminosity for many years until 2000, and reached above 10^{33} /cm^2/sec. In 2003 it was converted to CESR-c by lowering its energy from the Υ resonances to the τ-charm region. Two asymmetric energy double-ring B-factories, KEKB and PEP-II, were commissioned in 1998. The two B-factories are operating well above 10^{34} /cm^2/sec, and an integrated luminosity of 1 fb^{-1} is accumulated in one day. The only Φ-factory, DAΦNE, has been delivering luminosity to three experimental detectors at two interaction points. It has reached a peak luminosity of 1.53×10^{32} /cm^2/sec. Two other factories are under construction, and will be commissioned soon. One is BEPC-II, which is a τ-charm factory with a target luminosity of 10^{33} /cm^2/sec; the other is VEPP-2000, which is a unique round beam collider.

As a result of successful operation of KEKB, PEP-II and DAΦNE, extended upgrades of them to next-generation factories are being investigated, aiming at nearly two orders of magnitude higher luminosity than the present factories. Fig. 1 shows the luminosity and energy of e^+e^- colliders, including those under construction or being planned. In this paper we mainly discuss the operation status of the factories, KEKB, PEP-II and DAΦNE, their performance limitation and measures as well as next-generation Super-factories.

REQUIREMENTS AND CHALLENGES

From the standard expression of luminosity for a flat beam, short bunch collider, a common path for those factories to realize high luminosity is to have: (1) a large beam-beam parameter, ξ_y, (2) a small β_y^*, and (3) high beam currents, $I_\pm$, with many bunches, N_b. In addition, (4) a short bunch length of $\sigma_z \le \beta_y^*$ is needed to avoid the hourglass

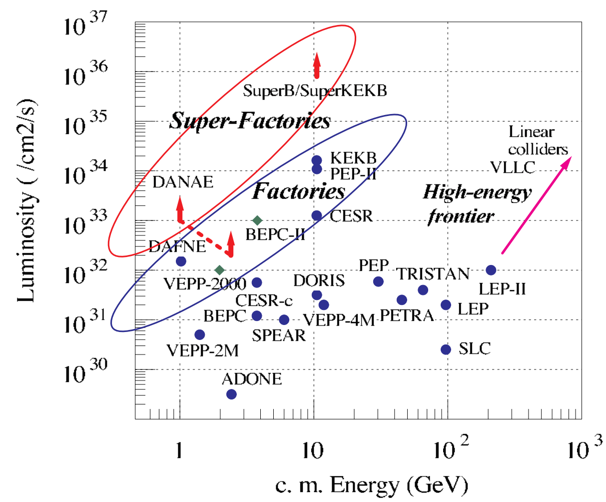

Figure 1: Luminosity and energy of e^+e^- colliders.

effect due to the small β_y^*. The higher is the luminosity, the more stringent are the demands placed to achieve these parameters, which require big challenges in various aspects of accelerator physics and technology.

To obtain a large beam-beam parameter, ξ_y, with a small β_y^*, high performance of the beam optics and precise control of the linear optics and orbits as well as the optimum collision conditions are vital. A sufficiently long lifetime should be maintained by a wide dynamic aperture. It should be noted that many of these conditions are more stringent for a lower energy beam. Wigger magnets are usually needed to increase the radiation damping rate while controlling the horizontal emittance and the energy spread. Furthermore, a lower beam energy results in a lower luminosity at the same values of ξ_y, β_y^* and $I_\pm$. On the other hand, the annihilation production cross section in e^+e^- collisions scales with the energy E_b as $1/E_b^2$.

Besides single bunch instabilities, a high beam current, $I_\pm$, with many bunches gives rise to a high growth rate of coupled-bunch instabilities due to conventional impedances $\propto I_\pm$ as well as of two-stream type instabilities due to an electron cloud or fast ions. A high beam current with a short bunch length, σ_z, gives rise to a large HOM power $\propto I_\pm^2/N_b/f(\sigma_z)$. In addition, coherent synchrotron radiation (CSR), which has not addressed performance limitations to the present factories, will be a serious concern for Super-factories [1]. Large AC plug power is needed to provide the beam to compensate for the losses due to synchrotron radiation $\propto I_\pm$ and the HOM power. These issues require big challenges in many aspects, including heavily HOM-damped cavities with a stable high-

* kazunori.akai@kek.jp

Table 1: Main parameters of high-luminosity e^+e^- meson factories presently in operation or under construction.

	CESR	**DAΦNE**	**PEP-II**	**KEKB**	**BEPC-II**†	**VEPP2000**†
Commissioning year	1979	1998	1998	1998	(2006)	(2006)
Present status	running††	running	running	running	construct	construct
Physics	B	Φ	B (asym.)	B (asym.)	τ-c	Φ
Ring	single	double	LER HER	LER HER	double	single
Particles	e^+ + e^-	e^+ e^-	e^+ e^-	e^+ e^-	e^+ e^-	e^+ + e^-
Beam energy [GeV]	4.7∼6.0	0.51 0.51	3.1 9.0	3.5 8.0	1.0∼2.1	1.0
Circumference [m]	768.43	97.69	2200	3016	237.53	24.38
Harmonic number	1281	120	3492	5120	396	14
RF frequency [MHz]	499.765	368.26	476	508.89	499.8	172.09
RF voltage, operating [MV]	5	0.15 0.12	4.04 15.5	8.0 15.0	1.5 1.5	0.12
Cavity type	SC	NC	NC	NC+SC	SC	NC
Crossing angle [mrad]	±2.5∼3.3	±10∼15	<0.1	±11	±11	0
Beta function at IP, β_x^* [cm]	125	160	35∼49	59 56	100	10
Beta function at IP, β_y^* [cm]	1.9	1.7	1.1	0.65 0.59	1.5	10
Emittance, ε_x [nm]	205	340	31∼59	18 24	144	129
Emittance, ε_y [nm]			1.4	0.4	2.2	129
Betatron tune, ν_x^*	10.53	.11 .09	.504 .506	.505 .511	6.53	4.05
Betatron tune, ν_y^*	9.61	.19 .167	.58 .64	.535 .577	7.58	2.05
Bunch length, σ_z^* [mm]	20	10∼25	11∼12	6∼7	13∼15	
Beam-beam parameter, ξ_x^*	0.028	0.026	.053 .055	.110 .073	0.04	
Beam-beam parameter, ξ_y^*	0.062	0.025	.064 .046	.092 .056	0.04	
No. of colliding bunches	45	110	1722	1389	93	1
Abort/ion clearing gap [%]		0.083	0.9	5		
Beam current, operating [A]	0.37+0.37	1.4 2.0	2.7 1.78	1.7 1.35	0.91 0.91	0.1+0.1
Beam current, achieved [A]	0.78	1.5 2.4	3.0 1.78	2.0 1.36		
Luminosity [10^{32} /cm^2/sec]	12.5	1.53	108.8	162.7	10	1.0 (per IP)
Int. Lum. /day [pb^{-1}]	73	10	786.3	1201.7		
Total Int. Lum. [fb^{-1}]		2.3	375	620		

† Numbers for BEPC-II and VEPP-2000 are design values. Colliding mode of BEPC-II is shown.
†† CESR was converted to CESR-c in 2003. The numbers listed are those for CESR.

power CW RF system, low impedance and robust vacuum components, bunch-by-bunch feedback system providing a high damping rate, and minimization of beam background to physics detectors.

LUMINOSITY PERFORMANCE AND LIMITATIONS

Hardware with High Beam Currents

To store a high beam current of several amperes in the factories, the RF cavities are required to provide a large amount of RF power to the beam as well as to have a very low parasitic impedance so as to avoid coupled-bunch instabilities due to HOMs. Heavily-HOM-damped single-cell cavities are commonly used in the factories, either normal-conducting (KEKB-LER and HER, PEP-II, DAΦNE) or superconducting (KEKB-HER, CESR, BEPC-II) cavities. Typically, each cavity should deliver several hundred kW of RF power to the beam, while extracting or absorbing the HOM power of several kW, or even more than 10 kW. In addition, in the case of B-factories, the accelerating mode, itself, can cause a very strong longitudinal coupled-bunch instability at a coupled-bunch mode of -1, -2, and so on. This instability arises from a large detuning frequency required to compensate for the reactive component of the beam loading, which can even exceed the revolution frequency for a large circumference ring. KEKB uses high stored-energy cavities that reduce the detuning frequency. PEP-II suppresses the instability by RF feedback loops with a comb filter.

Reliable operation has shown that the RF system for a high-current beam of several amperes has come to be standard technology. The factories have recorded the world highest beam currents: e^+ beam current of 3 A (PEP-II LER) and e^- beam current of 2.4 A (DAΦNE). In addition, the world records in superconducting cavities of beam current (1.36 A), power delivered to the beam (400 kW/cavity) and HOM power absorbed by HOM dampers (15 kW/cavity) go to the KEKB-HER cavities.

High-current beams have also placed great challenges on the vacuum components. In particular, masks (collimators), bellows and HOM absorbers often have experinced damages caused by HOM, synchrotron light or even a direct hit of the beam. Elaborate work to solve the problems and to improve these components has continued at KEKB, PEP-II and DAΦNE.

At DAΦNE and PEP-II both transverse and longitudinal bunch-by-bunch feedback systems are used. At KEKB a transverse bunch-by-bunch feedback system only is used; no longitudinal one is needed so far. These feedback systems have been working successfully to suppress the beam instabilities. The transverse and longitudinal damping time by the feedbacks are typically on the order of 100 μs and 1 ms, respectively. The DAΦNE feedback system is operating at the shortest bunch spacing of 2.7 ns.

Single-Bunch Current and More Bunches

The single-bunch current can be limited by a saturation of the beam-beam parameters, bunch lengthening or blow up due to microwave instability, or from the point of view of HOM power. Since the HOM power increases as $\propto I_{\pm}^2/N_b$, more bunches are desired at a given total beam current, $I_{\pm}$, to mitigate stress on the vacuum components caused by the large HOM power. On the other hand, a shorter spacing between the bunches can degrade the specific luminosity, mainly due to positron beam size blow up caused by an electron cloud. The requirements for the bunch-by-bunch feedbacks will also be severer.

KEKB had been operated for several years at a bunch spacing of 4 rf bucket. A shorter bunch spacing significantly degraded the specific luminosity. The harmful effects of the electron cloud seem to be more serious in KEKB than in PEP-II, where ante-chambers are used in the arc sections. From a machine study, a clear correlation between the degradation of the specific luminosity, vertical blow up of the beam, and synchrotron sidebands of betatron tune was observed [2]. In order to mitigate the problem, the length of solenoid windings on the beam ducts has been increased year by year, and the specific luminosity has been improved. In 2004 the specific luminosity at a 3.5 bucket spacing was still lower by about 15% than that at a 3.77 spacing (14 bunches or 13 bunches filled in 49 rf buckets, respectively). It was improved after more solenoids were added in 2005 [3]. KEKB is currently operating at a 3.5 bucket spacing without blow up of the positron beam up to 1.8 A. However, a shorter bunch spacing of 3.27 rf bucket (15 bunches in 49 buckets) still shows a clear degradation of the specific luminosity. Additional solenoids in Q-magnets were wound, but the effect is not obvious [4]. The effect of increasing the solenoid length now seems to be saturating.

The number of bunches in PEP-II has increased by more than double over the years, and almost filled up: by changing from a by4 to by3 pattern, and finally to a by2 pattern, and also by reducing the length of mini gaps [5]. The mini gap was needed to reduce the electron cloud build up that causes a luminosity drop along the positron bunch trains. The effect of the electron cloud has been reduced by winding solenoids of 30 Gauss in the straight sections and later in the arc sections. The electron cloud does not seriously limit the present performance of PEP-II. Improvements of machine tuning and better working points may also have contributed to increase the number of bunches.

DAΦNE fills all rf buckets with bunches, except for the ion-clearing gap. After the 2003 shutdown the maximum positron beam current has been limited at 1.4 A by a very fast horizontal instability. The suspect that the instability is caused by an electron cloud is supported by many observations, such as a large positive horizontal tune shift, anomalous pressure rise, the effect of solenoids and the dependence on the fill pattern as well as by an agreement with simulations [6]. Another issue that degrades the luminosity is bunch lengthening and vertical blow up due to microwave instability. The effect is much more serious in the e$^-$ ring, where ion-clearing electrodes significantly increases the beam coupling impedance [7].

Optics and Beam-Beam Issues

Large beam-beam parameters and small β_y^* have been achieved in the factories, as shown in Table 1. They are mainly attributed to the following features: (1) precise measurement and correction of linear optical functions, such as beta function, dispersion function and coupling correction, (2) improvements of non-linear dynamics with sextupoles and octupoles, particularly, a local chromaticity correction scheme to effectively correct the chromaticity generated at the IP, and (3) continuous tuning of the machine conditions and working points. It is noted that non-interleaved sextupole pairs with a 2.5π lattice (KEKB [8]) and moving close to a half integer horizontal tune (KEKB and PEP-II) have proved to be significantly beneficial to B-factories.

The tuning procedure used to maintain and improve the beam conditions is described for the case of KEKB, as an example. (a) The global optical functions, such as x-y coupling, dispersion function, and global beta-functions, are measured and corrected, typically once in a week. (b) Better optical functions and beam orbit at the IP are constantly searched by scanning parameters with minimum disturbance to the luminosity performance, called adiabatic tuning. Betatron tunes and sextupole settings are also thus optimized. (c) The optimum beam conditions, such as closed orbit distortion, betatron tunes, transverse and longitudinal collision point, are maintained by continuous measurements and feedbacks in a non-invasive way to the luminosity performance. The positron beam size is controlled from the view point of beam-beam effects.

Near-Term Upgrade

Table 2 summarizes the major limitations of the present performance of the factories and measures to be taken or planned for the near-term upgrade.

Table 2: Present performance limitations and near-term upgrade of the e^+e^- factories.

Factories	Present limitations	Cause	Near-term improvements	Expected results
KEKB	spec. lum. drop (e^+ >1.8 A)	e^- cloud + beam-beam?	ante-chambers? more solenoids?	
	e^- current (1.3 A)	heating	improve beam duct components	e^- current $\nearrow$
		crossing angle	crab crossing or crab waist	$\xi_y \nearrow$
PEP-II	beam currents	rf power HOM heating	more RF stations repair & improve BPMs replace IR vacuum components	e^+ current $\nearrow$ to 4 A e^- current $\nearrow$ to 2.2 A
			improve optics/orbit correction	$\beta_y^* \searrow$ to 8.5 mm $\xi_y \nearrow$ by 10 %
DAΦNE	e^+ current (1.5 A)	fast inst. by e^- cloud	scrubbing?	
	$\sigma_z \nearrow$ and $\sigma_y \nearrow$ (e^- beam)	microwave inst.	remove ion-clearing electrodes negative alpha?	reduce impedance $\sigma_z \searrow$
			new injection kickers (5.4 ns)	beam currents $\nearrow$ stable beam at injection

A further increase of the KEKB luminosity highly depends on mitigating the electron-cloud in LER, more beam current in HER, and crab crossing or crab waist. The installation of ante-chambers is considered for the future upgrade. As the first step, a part of the arc section chambers will be replaced with the ante-chambers next year [9]. There is a clear tendency to improve luminosity by a further increase of the HER beam current, presently limited by troubles due to heating of the beam duct components. The crab crossing and crab waist will be discussed later.

PEP-II has a plan to increase the luminosity by a factor of two to reach 2×10^{34} /cm^2/sec. This improvement will come from: increasing each beam current by 40%, lowering β_y^* to 8.5 mm, and increasing the beam-beam parameters by 10%. This scenario will go with more RF stations, replacing IR vacuum components, repair and improvement of BPMs to solve problems caused by HOM heating as well as improving the optics and orbit measurement and correction scheme [10].

At DAΦNE the ion-clearing electrodes in the wiggler sections will be removed so as to reduce the ring impedance to mitigate the bunch lengthening and vertical blow up due to the microwave instability. Also, new injection kickers are planned to be installed, which have a much shorter pulse of 5.4 ns instead of 150 ns for the present ones [11].

Integrated Luminosity

A high ratio of the average to peak luminosity is also important for the factories: it gives more integrated luminosity to physics detectors at the same peak luminosity. Issues related to this direction include: (1) continuous injection, (2) less number of beam aborts, and (3) long-term stable operation.

The continuous injection (trickle-charge) scheme, injecting beams continuously to keep almost constant beam currents without switching off the detector, was brought in operation in KEKB and PEP-II around 2003∼2004 [12] [13]. PEP-II injects the electron and positron beams continuously at the same time. KEKB needs to switch between the two beams, typically every five minutes, injecting one beam at a time. The average luminosity was increased by 20-40% at the same peak luminosity in both B-factories. DAΦNE operates in the topping up mode for one of the experiments (KLOE), while the other two experiments not. For different reasons, including the topping up but also different machine performances and degree of optimization, the daily integrated luminosity for KLOE was about a factor three higher with respect to the other experiments [14].

Thanks to continuous efforts made to reduce the number of beam aborts as well as to avoid any kind of troubles, the factories have been operating quite stably. As an example, long-term statistics of the operation of KEKB is described below. The average number of beam aborts during the last three years from Jan. 2004 to Jun. 2006 is about twice in LER and three times in HER per day. The cause of every abort is analyzed immediately. About 60% of them is caused by any kind of beam loss, and 28% by RF trips [15]. About 80% of the scheduled time of operation has been dedicated to physics runs. The downtime due to any accelerator trouble was only 3.9% in FY2004 and 4.5% in FY2005 (detector trouble is excluded).

NEXT GENERATION FACTORIES

For Super-factories, various kinds of challenges for high beam currents, a small β_y^* and a large beam-beam parameter are also required, as for the present factories, but should be pushed to in a much more extreme regime.

Innovative ideas and experiments

Several innovative ideas have been investigated to drastically increase the luminosity. Experiments are being conducted or proposed at the factories to prove these ideas or to utilize them in the real operation.

The crab crossing [16] restores the luminosity loss due to the finite-angle crossing, and greatly increases the beam-beam parameter. The luminosity is expected to increase by several times [17]. It is one of the key issues for the KEKB upgrade as well as for the next-generation factories. The first experiment of the crab crossing will be conducted at KEKB in FY2006. Two superconducting heavily-damped crab cavities [18], one for each ring, are in the final stage of fabrication [19]. A horizontal test of the first one has been conducted and a kick voltage of 1.67 MV was achieved, well beyond the required kick of 1.4 MV.

Recently, a novel colliding scheme, the crab waist, was proposed [20]. It is an x-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. An experimental test of the crab waist is being considered at DAΦNE in the SIDDHARTA run with a new dedicated IR design [14], and also at KEKB.

Strong RF focusing (SRFF) [21] will make a short bunch at the IP, while keeping a longer bunch at places where RF cavities and other high-impedance components are located. A negative α_c lattice was tested at DAΦNE [7]. A strong decrease of the bunch length as well as a reduction of the microwave instability threshold were observed.

Super Φ-factory

DAΦNE will complete the scheduled operation for the high-energy and nuclear physics program in a few years. Upgrading of DAΦNE to DANAE (DAfne New Adjustable Energy) has been proposed [22]. The DANAE energy will be able to be changed for two major purposes: one is up to 2.4 GeV c. m. for n-$\bar{n}$ production at a design luminosity of $>2\times10^{32}$ /cm^2/sec; the other is at the same energy as DAΦNE, while upgrading its luminosity to 10^{33} /cm^2/sec, to be a Super Φ-factory. The existing infrastructures and buildings as well as a large part of the magnets and injection system will be reused. New dipole magnets for the energy upgrading, new vacuum chambers, wigglers, and RF system at 500 MHz for the luminosity upgrading, and a new IR are required. Crab crossing, crab waist, or the SRFF may be implemented for a further DANAE upgrade [14].

Super B-Factories

Super B-factories are being investigated at KEK, SLAC, and INFN-LNF. The target luminosities are about, or close to 10^{36} /cm^2/sec, which is two orders of magnitude higher than that of the present B-factories.

The accelerator design of SuperKEKB [23] is based on the crab crossing scheme. The present 508 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 recent simulations, the luminosity of SuperKEKB exceeds 8×10^{35} /cm^2/sec at beam currents of 10.1 A in LER and 4.4 A in HER [24]. In addition, the discussion is going on as to whether the crab waist could be implemented instead of the crab crossing to further increase the luminosity.

A study of Super B-factory is also going on at INFN-LNF [25] and SLAC [26]. The present design concept is based on the crab waist with a very low emittance, $\varepsilon_x \leq 1$ nm, similar to the ILC Damping Rings, and very small $\beta_y^* \leq 0.1$ mm by adopting the Final Focus system of the ILC. Extensive simulation work is progressing to study the dynamic aperture and the beam-beam effects with this scheme and to make a set of design parameters. The beam current is about 2.5 A in LER and 1.4 A in HER, comparable to the present B-factories.

ACKNOWLEDGEMENTS

The author wishes to thank T. Agoh, C. Biscari, F.-J. Decker, A. Gallo, H. Koiso, C. Milardi, K. Shibata and M. Zobov for providing materials and helpful discussions.

REFERENCES

[1] T. Agoh, Ph. D. theses, Univ. of Tokyo (2004).
[2] J. Flanagan *et al*., PAC05, p. 680.
[3] Y. Funakoshi *et al*., PAC05, p. 1045.
[4] H. Fukuma, this conference.
[5] F.-J. Decker *et al*., EPAC04, p. 842.
[6] M. Zobov, private communication.
[7] M. Zobov, PAC05, p. 112.
[8] H. Koiso and K. Oide, PAC95, p. 2780.
[9] Y. Suetsugu, private communication.
[10] J. Seeman, PEP-II MAC06, SLAC, January 2006.
[11] D. Alesini *et al*., this conference.
[12] Y. Funakoshi *et al*., EPAC04, p. 707.
[13] U. Wienands, PAC05, p. 149.
[14] A. Gallo, private communication.
[15] H. Ikeda *et al*., this conference.
[16] K. Oide and K. Yokoya, Phys. Rev. A40, 315 (1989).
[17] K. Ohmi *et al*., PAC03, p. 353.
[18] K. Akai *et al*., HEACC92, p. 757.
[19] K. Hosoyama *et al*., APAC98.
[20] P. Raimondi, SuperB Meeting, Frascati, March 2006.
[21] A. Gallo *et al*., EPAC04, p. 683.
[22] C. Biscari *et al*., “DANAE Letter of Intent”.
[23] “SuperKEKB Letter of Intent”., KEK Report 2004-4, June 2004.
[24] K. Ohmi *et al*., SuperB workshop, SLAC, June 2006.
[25] 1st and 2nd SuperB workshop, LNF, November 2005 and March 2006.
[26] 3rd SuperB workshop, SLAC, June 2006.