HIGH INTENSITY ISSUES FOR SUPER B-FACTORIES

K. Akai, KEK,Tsukuba, Japan

Abstract

The present B-factories, KEKB and PEP-II, have achieved or exceeded their design luminosities. A luminosity of 10^{34} cm^{-2} s^{-1} has become a reality. As upgrading of these machines to increase the luminosity further by ten times or more to extend the physics coverage, Super B-factories are being considered. Beam current should be about 10 A in the Low Energy Ring (LER) and 4 A in the High Energy Ring (HER), or even much higher, with a short bunch length of about 3 mm. It is very challenging for various hardware components, especially for RF system and beam-line vacuum components, to store such an extremely high beam current. Crab crossing is also considered to drastically increase the beam-beam tune shift limit, that results in a further increase of the luminosity. In this paper, high intensity issues for the Super B-factories are discussed.

INTRODUCTION

KEKB and PEP-II are asymmetric-energy, double-ring, electron-positron colliders aimed at producing B and anti-B mesons at high rate as in factories. They were commissioned in 1998 and have been operating for physics experiment. Their performances have been improving steadily and already achieved or exceeded their design luminosities: KEKB and PEP-II achieved remarkable luminosities of 1.03×10^{34} cm^{-2} s^{-1} [1] and 6.1×10^{33} cm^{-2} s^{-1} [2], respectively. Integrated luminosity of 1 fb^{-1} is obtained within only two or three days of operation. The accumulated physics data in KEKB and PEP-II had produced the discovery of CP violation in B and anti-B meson system.

Common features of the B-factories to realize the high luminosity include high beam current of about 2 A in LER and 1 A in HER, small β_y^* at the interaction point (IP) and a short bunch length. Major differences between them include crossing scheme at the IP and the type of RF cavities. KEKB has adopted a finite-angle crossing scheme at an angle of ± 11 mrad, whereas PEP-II adopted head-on collision using separation dipole magnets. The RF cavities will be discussed in detail later.

Recently, there is increasing physics motivation for upgrading the B-factories to increase the luminosity by one or two orders of magnitude to reach 10^{35} or even 10^{36} cm^{-2} s^{-1}. Design works for Super-KEKB and Super PEP-II are going on. The major upgrading to Super-KEKB is considered in 2006 to 2007 so as not to lose its competitiveness to LHC-B and BTeV. In order to realize such an extremely high luminosity, the beam current should be increased to about 10 A or even 20 A with a very short bunch length of 3 mm. In addition, according to recent beam-beam simulations, the crab crossing is expected to drastically increase the beam-beam tune shift limit, that results in a further increase of the luminosity.

In this paper, we discuss issues related to the extremely high beam current in the Super B-factories. In particular, requirements and possible solutions for the hardware components such as RF system and beam-line vacuum components are described. Some of the operating experiences of the present B-factories are also given. In addition, a possible crab crossing scheme is proposed.

HIGH CURRENT BEAM

Table 1 shows major beam parameters currently operating in KEKB and the design values of Super-KEKB for the luminosity of 10^{35} cm^{-2}s^{-1}. It is expected that the luminosity further increases by several times with the same beam current if the crab crossing scheme is adopted. A much higher luminosity of 10^{36} cm^{-2}s^{-1} is also considered with a beam current of about 20 A in LER and 8 A in HER together with the crab crossing.

Table 1: Major beam parameters currently operating in KEKB and the design values of Super-KEKB for 10^{35} cm^{-2}s^{-1}

	KEKB		**Super-KEKB**	
	LER	**HER**	**LER**	**HER**
Particles	e^+	e^-	e^-	e^+
Beam energy (GeV)	3.5	8.0	3.5	8.0
Beam current (A)	1.41	1.06	9.4	4.1
Circumference (m)	3016		3016	
No. of bunches	1284		5120	
Bunch spacing (m)	2.4		0.6	
Crossing angle (mrad)	±11		±15	
RF voltage (MV)	8.0	13.0	14.0	23.0
β_x at IP (cm)	59	58	30	30
β_y at IP (cm)	0.58	0.7	0.3	0.3
Bunch length (mm)	6∼7	6∼7	3	3
Beam power (MW)	2.5	3.7	18.3	16.0
(radiation loss)			(11.3)	(14.3)
(parasitic loss)			$(7.0)^\dagger$	$(1.7)^{\dagger\dagger}$
Luminosity (/cm^{2}s)	1.03×10^{34}		1×10^{35}	

Total loss factor is assumed $40^\dagger$ and $50^{\dagger\dagger}$ V/pC.

The high beam current immediately results in following considerations. Although they were also important in the B-factories, much more attentions and measures are needed for the Super B-factories.

- Coupled-bunch instabilities: The growth rate is proportional to the beam current. Any higher-order mode (HOM) impedance in cavities or other beam-line components should be sufficiently reduced. Instabilities caused by other sources such as the resistive wall, fast-ion and photo-electron cloud also need to be suppressed. A powerful bunch-by-bunch feedback system is inevitable.
- Heating and other problems: Beam-line components are exposed to strong HOM, synchrotron radiation, and even the intense beam itself. They can be damaged by heating, discharge or even direct hit of the beams. They must be robust and low-impedance.
- Impedance budget: The total loss factor and the imaginary part of the impedance in the ring should be kept as low as possible, especially for the short bunch length.
- Large RF power and heavy beam-loading: A large amount of power lost by the beam should be compensated by the RF system. On the other hand, required RF voltage is relatively low, regardless of the high beam current. As a consequence, a large amount of power should be provided by each cavity. High-power RF components should be stably operated at about one MW. The heavy beam-loading also needs careful design of the control system for the accelerating mode.

RF SYSTEM

Two types of cavities are used in KEKB: Accelerator Resonantly coupled with Energy Storage (ARES) [3] and single-cell superconducting cavities (SCC) [4]. The ARES alone is used in LER and a combination of ARES and SCC is adopted in HER. The RF system has been operating stably. It is expected that it can be used with a beam current of up to about 10 A in LER and 4 A in HER of Super-KEKB, if following improvements and changes are made. This strategy helps greatly reduce the construction cost for the upgrading.

- The impedance at driving frequencies associated with the accelerating mode of cavities should be much more reduced by a strong feedback system, even with the ARES and SCC.
- The HOM dampers should be improved to absorb a large amount of HOM power of up to 100 kW/cavity generated in the cavity.
- The number of RF stations and the beam power provided by each cavity should be increased to meet the large amount of total beam power, four times as high as that of KEKB.
- Other small changes are reducing the loaded-Q values of the accelerating mode, eliminating tapers outside the cavity to reduce the loss factor, and so on.

The RF-related parameters are shown in Table 2. More details are discussed below.

Table 2: RF parameters for Super-KEKB

	Super-KEKB	
	LER	**HER**
Beam current (A)	9.4	4.1
Beam power (MW)	18.3	16.0
RF voltage (MV)	14.0	23.0
RF frequency (MHz)	508.887	
Revolution freq. (kHz)	99.4	
Type of cavities	ARES	ARES+SCC
No. of cavities	28	16+12
Voltage/cav. (MV)	0.5	0.5/1.3
Detuning (kHz)	71	31/74
No. of cav./klystron	1	1/1
No. of klystrons	28	16+12
Klystron power (kW)	850	850/480
AC power (MW)	40	23+10

Instability Driven by the Accelerating Mode

Growth rate and cures In storage rings, the resonant frequency of the cavities should be detuned toward the lower side in order to compensate for the reactive component of the beam loading. The detuning frequency (Δf) is given by

$$\Delta f = \frac{I \sin\phi_s}{2V_c} \times \left(\frac{R}{Q}\right) f = \frac{P_b \tan\phi_s}{4\pi U}, \qquad (1)$$

where f is the RF frequency, I the beam current, ϕ_s the synchronous phase, V_c the cavity voltage, P_b the power to the beam, and U the stored energy in the cavity. For the B-factories, Δf can be comparable to, or even exceed the revolution frequency, due to the large beam current and small revolution frequency (large circumference ring). The coupling impedance at the driving frequencies, the upper synchrotron sideband of revolution harmonic frequencies, becomes significantly high due to the high impedance of the accelerating mode. A key issue for the RF system of the B- and Super B-factories is how to avoid the longitudinal coupled-bunch instability caused by the large detuning of the cavities.

KEKB and PEP-II have taken different strategies to solve the problem. As seen in Eq. 1, Δf is reduced by increasing the stored energy U or the accelerating voltage V_c. The ARES used in KEKB is a normal-conducting three-cavity system where an energy-storage cavity operating in a high-Q mode is coupled with an accelerating cavity via a coupling cavity in between. And the SCC is operated at a high accelerating voltage. The stored energy in the ARES and SCC is about ten times as high as that in conventional normal-conducting cavities. Thus the detuning frequency is reduced by a factor of ten.

In PEP II, conventional normal-conducting cavities are used and the detuning frequency exceeds the revolution frequency. PEP-II relies on a combination of feedback loops to reduce the impedance at the driving frequencies: a direct loop, a comb filter loop, and a bunch-by-bunch feedback system.

Operation in B-factories There is a sufficient margin for the stability threshold in HER of KEKB: no instability has been observed up to the design beam current of 1.1 A. In LER of KEKB, on the other hand, even with the ARES cavities, suppression of the instability is marginal at the design beam current of 2.6 A. The threshold current is even reduced due to the lower operating RF voltage than the design value to avoid excessive HOM heating at several vacuum components. Consequently, the -1 mode damper is needed to store a beam of more than 1 A, although the required reduction of the impedance is about 15 dB and it is sufficient to apply it to only one RF station among ten stations.

In PEP-II, it was observed that the growth rate is higher than expected and the margin for stable operation with various errors is relatively small with high beam current. One reason is deterioration of the feedback property due to saturation of klystron output power. The operating beam current is sometimes limited by RF trips caused by the unstable feedback loops [5].

Super B-factory case In the case of Super-KEKB, even with the ARES and/or SCC, the detuning frequency becomes close to the revolution frequency. The growth rate of the -1 mode will be much higher than the case of KEKB and much more impedance reduction is required. A powerful feedback system with comb filters is inevitable, although the number of modes that need to be cured is much less than the case of conventional cavities.

Bunch-Gap Transient

A part of the ring is reserved as an abort gap where no bunch is filled to allow for a rise time of the beam abort kicker. The abort gap also works as an ion-clearing or photo-electron clearing gap in the electron or positron ring, respectively. The gap length of KEKB is about 0.5 μsec, that is 5% of the ring circumference. The bunch gap, however, modulates the longitudinal position of the bunches, since the beam-loading effect is different between the bunch train and the gap. A large phase modulation can affect the RF system such as modulating the RF power and phase and deteriorating the performance of the feedback loops. In addition, the luminosity can be reduced by different phase modulation between the two rings.

In order to avoid the harmful effects, it is desired that the phase modulation is kept less than several degrees. The high stored energy of the ARES and SCC is also beneficial to reduce the phase modulation, since it is inversely proportional to the stored energy. Even so, the gap length should be reduced to less than 0.2 μsec. Otherwise, the phase modulation will be unacceptable. A faster rise time of the abort kicker is required.

HOM Damping

The accelerating cavity of the ARES in KEKB and the PEP-II cavity have waveguides to extract and damp the HOM's generated in the cavities. The SCC in KEKB adopted a beam-pipe damping scheme, where ferrite absorbers are attached inside the beam pipe on both sides of the cavity.

To use the ARES and SCC in Super-KEKB, followings should be taken into account. First, the HOM power per cavity is estimated to be about 100 kW and 50 kW in LER and HER, respectively, which is beyond the capacity of the present HOM absorbers. The HOM dampers must be improved to meet the requirement. Second, the growth rate of the instability is increased due to the higher beam current. A longitudinal bunch-by-bunch feedback is required, which is not necessary in KEKB. The growth time of transverse instability is about 3 ms and it can be cured by the present bunch-by-bunch feedback system.

BEAM-LINE COMPONENTS

In the operation of KEKB and PEP-II, several beam-line components have suffered from various kinds of troubles caused by the high current beam. A lot of efforts have been made to solve the problems: the improvements allow us now to store a beam of 1$\sim$2 A stably. This kind of efforts, however, would continue whenever the beam current is pushed to higher values. It provides us with useful information also for the Super B-factories to review the troubles and cures taken in the B-factories. Some of the experiences in KEKB are presented below.

Movable Masks

Movable masks are used to block particles out of normal orbit in order to reduce background noise on the physics detector and to avoid any damage on the detector and other hardware components caused by the abnormal beam.

Early versions of the movable masks in KEKB have mask-heads protruded inside the chamber. They had various kinds of troubles: vacuum leaks occurred several times due to heating or discharge. In addition, coupled-bunch instability was excited at several hundred mA. Most of them are caused by trapped HOM in the masks. Although they were improved to some extent by attaching HOM absorbers that reduces the Q-value of the trapped HOM, it is hardly expected to be able to be used with much higher beam current.

They have been replaced with a moving-chamber type of the masks similar as those used in PEP-II. The amount of HOM power is reduced and is not trapped. The masks of this type have been operating well. One problem encountered is heating of the bellows on both sides of the masks caused by TE-like HOM generated at the bending region around the mask-head. Two measures have been taken: one is to reduce the bending angle to have more smooth transition, and the other is to install HOM dampers that selectively damp the TE mode propagating along the chamber. The improved mask is expected to withstand a beam of several amperes. More details are presented elsewhere [6].

Bellows and Other Components

Bellows had serious troubles several times. In most cases, finger contacts for RF shielding are damaged due to discharge caused by HOM or synchrotron radiation. In particular, the TE-like HOM generated near the masks or other non-symmetric structures is harmful, since the slits between the fingers are located longitudinally. It would be the best solution if a bellowsless system is possible, where all adjacent vacuum chambers are welded to each other. Alternatively, a new type of bellows is being considered. It has a comb structure connection for the RF shield, instead of the RF shield fingers [6]. It is expected to reduce the loss factor and to avoid multipactoring.

Some other problems related to the high current beam encountered in KEKB are listed below.

- Heating of chambers and radiation masks near the interaction region caused by radiation and/or HOM.
- Abnormal heating of Beryllium beam pipe of the Belle detector due to a resonant build-up of HOM trapped between two radiation masks.
- Troubles on strip line electrodes of feedback kickers caused by discharge and/or thermal stress.

Damage by Unstable Beam

In KEKB, an unstable beam sometimes caused a large effect on the beam-line hardware components. The most serious problem was damage of the head of movable masks. Grooves or protrusions were generated on the surface of the mask head, which prevented the beam injection and storage. Another problem was a large amount of radiation hitting the Silicon Vertex Detector of the Belle detector. The worst case was 5 kRad at one time. Since its performance can be degraded with an accumulated dose of about 500 kRad, this is also a serious problem for a long-term operation.

It was found that they were caused by an unstable beam due to RF trips. The longitudinal phase and energy of the beam drastically changes, that gives rise to a large deviation from normal orbit and optics. Although interlock signals in the RF system are connected to the beam abort system, it did not help all cases: the abnormal RF field sometimes resulted in unstable beam before any interlock is detected to trigger the abort system.

In order to solve the problem, the protection system was reinforced as follows. The beam abort is triggered when the longitudinal phase of the beam deviates from a nominal value by one degree. The beam abort is also triggered by an abnormal cavity voltage caused by discharge or quench in the SCC. After these protections were completed, the RF trips never caused any damage on the masks or other components [7]. In addition, beam-loss monitors using PIN diodes were implemented along the ring [8]. These fast abort systems work to protect the beam-line components against abnormal beam conditions.

CRAB CROSSING

Luminosity Boost

The finite-angle crossing scheme adopted in KEKB does not require any separation dipole magnets and makes the interaction region much simpler than in the head-on collision scheme. Another advantage is that bunches are separated quickly after the collision so that parasitic collision is not a concern, even when every bucket is filled by bunches. Geometrical luminosity reduction was estimated to be 10 — 20 %, depending on the bunch length. The crab crossing scheme [9] was considered to be a fall-back option in case some unexpected problems are encountered with the finite-angle crossing scheme. The success of KEKB encourages us to employ the finite-angle crossing also in Super-KEKB, even with a larger crossing angle of ± 15 mrad. It is considered that the luminosity of 10^{35} cm^{-2} s^{-1} can be reached with this scheme.

A recent beam-beam simulation showed, however, that the head-on collision can drastically increase the beam-beam tune shift limit that results in a significant luminosity increase by several times [10]. The effect is much more than what had been thought before. Consequently, the crab crossing scheme is attracting much more attention for Super-KEKB. Parameters for the crab crossing is shown in Table 3.

Table 3: Parameters for the crab crossing in Super-KEKB

	LER	**HER**
Beam energy (GeV)	3.5	8.0
Beam current (A)	9.4	4.1
RF frequency (MHz)	508.887	
Crossing angle (mrad)	± 15	
β_x^* (m)	0.3	0.3
$\beta_{x,crab}$ (m)	100∼200	200∼400
Required kick (MV)	0.90∼0.64	1.45∼1.03

Crab Cavities

In order to generate a transverse kick needed for the crab crossing, crab cavities will be used. It must be a HOM-damped structure as the accelerating cavities. Since the crab cavity is operating in a dipole mode such as the TM110 mode, there is a lower frequency parasitic mode. It is the TM010 mode which corresponds to the accelerating mode in the accelerating cavities and has high longitudinal coupling impedance. It is difficult to damp this mode with the conventional damping scheme using waveguide dampers or beam pipe dampers.

Type-I cavity A superconducting crab cavity for the B-factories was proposed in 1992 [11]. It employs a coaxial beam pipe damper together with a notch filter attached to an extremely polarized cell (“squashed” cell). All monopole and dipole parasitic modes are damped, including the lowest frequency TM010 mode and the unwanted polarization of the TM110 mode, while the crabbing mode is kept high Q-value. The R&D efforts are being continued at KEK, aiming at fabricating full-scale niobium cavities [12].

This cavity was designed for a beam of 1∼2 A and is expected to have sufficient properties for the B-factories. However, if it is used in Super-KEKB LER with a beam current of 10 A, following problems can arise. First, the HOM power of more than 200 kW should be absorbed by the HOM dampers. However, similar types of dampers used in the SCC of KEKB have been operated up to only about 10 kW. Second, much more reduction of the HOM impedance is required for the 10 A beam. It should be noted that the growth rate of transverse instability driven by one crab cavity can be comparable to that of about ten accelerating cavities, even if the HOM impedance is about the same. The reason is that a large beta-function at the crab cavity, $\beta_{x,crab}$, is chosen to reduce the required kick voltage, whereas the growth rate is proportional to $\beta_{x,crab}$.

Type-II cavity for 10 A Recently, a new design of crab cavity was proposed for much higher beam current [13]. It is equipped with several waveguide HOM dampers. Optimization of the cell and dampers has been carried out. All parasitic modes except the TM010 mode are sufficiently damped for a beam of 10 A. The highest HOM impedance is reduced by a factor of ten compared with the type-I cavity. In addition, the loss factor is reduced by half since relatively widely opened beam pipes are used compared with the coaxial beam pipe of the type-I cavity.

In order to avoid the instability driven by the TM010 mode, following measures are studied. The frequency of this mode is controlled at the middle of adjacent revolution harmonic frequencies. It can be done by implementing frequency monitoring system and two independent tuners. The coupling impedance at the driving frequencies is further reduced by a feedback system using parallel comb filters, which is similar as the -1 mode damper for the accelerating cavities. The required feedback gain is less than 20 dB, which is comparable to the existing -1 mode damper of KEKB.

OTHER ISSUES

Positron Blow-up by Photo-Electron Cloud

Blow-up of the positron beam caused by photo-electron cloud [14] was one of the most serious problems in KEKB. In order to cure it, solenoid coils were wound on the chambers of LER. As the covered length by the solenoid coils is increased, the threshold current has been increased. Most of the drift space is now covered by the solenoids and the serious blow-up disappeared up to the present operating beam current [15]. For the Super-KEKB it seems inevitable to adopt the ante-chambers similar as those used in PEP-II. In addition, to suppress further the electron cloud density, the charge of stored beams will be switched: the positron beam is stored in HER and the electron beam in LER.

Continuous Injection

Continuous injection is being tested at KEKB and PEP-II. In this scheme the lost particles of the stored beam are continuously compensated by injection while the detector is taking physics data. This scheme must be adopted in the Super B-factories to maximize the integrated luminosity because of a short beam life time. It also allows for pushing the beam-beam tune shift limit significantly higher that shortens the beam-beam interaction lifetime significantly.

FUTURE STUDIES

For realizing the Super B-factories, many studies and developments must be done. Key issues for the RF system are improvement of the HOM dampers and a powerful feedback for the accelerating mode-related instabilities. Beamline components must be robust and low-impedance. In particular, R&D of the ante-chambers, movable masks, and bellows (or bellowsless system) are crucial. It is planned that crab cavities will be installed in KEKB in 2005 to examine the effect of the crab crossing. Finally, we believe that continuous efforts to push the beam current of the present B-factories higher will give us important directions toward the Super B-factories.

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