Interaction Region Issues Overview*

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ABSTRACT

This lecture note presents issues associated with the design of an interaction region at an asymmetric B-factory and outlines how those issues are addressed at KEKB.

1. INTRODUCTION

The interaction region (IR) of a storage ring refers to an accelerator portion which surrounds the designated interaction point (IP), where the beam collision occurs and the experimental detector facility is located. The exact definition of IR varies, depending on the context of discussions. Sometimes it means very few magnets and associated beam line components immediately near the IP; sometimes it means the beam line that happens to be in the experimental hall; or sometimes it means the entire beam line between the IP and regular Arc sections.

The goal of an IR design for an electron-positron B-factory is to deliver the highest-possible stable luminosity to the experimental facility, with minimum background noises, and with a minimum tuning time. This goal, by itself, is no different from any other IR design goals at any colliding beam machines. However, several distinct features of B-factories should be noted, namely,

1. Collision of electrons and positrons with asymmetric energies with two separate rings at the Υ''' resonance, $E_{CM} = 10.6$ GeV.
2. A high-current, multi-bunch operation with frequent beam fills.
3. Small beam spot size ($O(100) \times O(2)$ μm^2 or less) to maintain at the interaction point (IP).
4. The experimental facility demands a small radius, thin beam pipe at the IP, and requires to cover a large solid angle in the forward direction.

Many design parameters have to be carefully selected in an IR design. Design decisions are affected by various physical, technical or economical constraints, and by the design group's experience, preference and judgment.

The purpose of this lecture is to walk through IR issues that we come across in the design of B-factories, and outline how the accelerator designers for KEKB[1] are addressing them. Table 1 summarizes some important parameters at KEKB for discussions of the IR design.

Table 1. IR-related parameters at B factories

	Value
Luminosity goal (10^{33} cm^{-2} s^{-1})	10 (2)
Beam energy (GeV)	3.5 / 8
Bunch spacing (m)	0.6 (3.0)
βx* (cm) βy* (cm)	33 1
Emittance x (m.rad) Emittance y (m.rad)	1.8×10^{-8} 3.6×10^{-10}
Bunch Size x (μm) y (μm) z (mm)	 77 1.9 4

A substantial amount of work has been done for the design of KEKB IR. Many results are in internal memos and work group reports which are not publicly distributed. The most recent coherent collection of status reports on the KEKB design is "Proceedings of the Mini-Workshop on TRISTAN II B-Factory (Accelerator)", Dec. 15 - 17, 1993, KEK [2]. However, much progress has been done since then, and the author is freely quoting their results. To the colleagues whose works may not be adequately given explicit credits in this lecture note, the author expresses his apologies in advance.

Convenient references on world-wide efforts towards B-factories are recent proceedings on the "International Workshop on B-Factories". The proceedings of the Workshop in November 1992 has been published by KEK as KEK Proceedings 93-7[3], while reports in the

Workshop of April 1992 has been published by SLAC as SLAC-400[4].

2. ACCELERATOR PHYSICS ISSUES

2.1 Final Focusing

2.1.1 Luminosity Formula and Basic Parameters

The luminosity at a storage ring is given by

$$L = \frac{f_{rev} N_B N^- N^+}{4\pi\sigma_x\sigma_y} \tag{1}$$

The f_{rev} represents the revolution frequency of particles in the ring. At KEKB, since the ring circumference is about 3km, $f_{rev} = 10^5\ s^{-1}$.

N_B gives the total number of bunches per ring. If the bunch spacing of 0.6 m (3 m) is used, N_B will be maximum 5000 (1000) at KEKB.

σ_x and σ_y are spot sizes at the IP. To the first order, the expected spot size at the IP is determined by the quantity β^* and the beam emittance ε:

$$\sigma_x = \sqrt{\beta_x^* \varepsilon_x}, \qquad \sigma_y = \sqrt{\beta_y^* \varepsilon_y}. \tag{2}$$

Q: Using the values of β^* and ε in Table 1, confirm the expected spot sizes at the IP.

N^- and N^+ are the number of particles in a single electron or positron bunch. At a symmetric storage ring where the two beams have equal energies, it is usually set as $N^- = N^+$. At an asymmetric B factory, the bunch intensity is chosen so that

$$N^- E^- = N^+ E^+ \tag{3}$$

holds. This is so that the opposing bunches see the same magnitude of beam-beam effects, taking into account the energy asymmetry.

Q: Determine the values of N^- and N^+, required to achieve the design luminosity goal with parameters given in Table 1 and the constraint of equation (3).

It should be noted that the equation (2) to use with (1) is a first-order approximation formula. Many possible errors in real-life are ignored there. Sources of luminosity reduction include: effects of a beam crossing angle, a finite bunch length, possible beam blow-up due to beam-beam interactions, dispersion errors, orbit mismatch errors and others.

2.1.2 Beam Spot Sizes Near the IP

Knowing that the beam spot is minimized at the IP for the maximum luminosity, what is the behavior of the spot size in the neighborhood of the IP? It can be shown that the beam size σ near the IP as function of z (the distance from the IP) can be written as

$$\sigma_{x,y}^2(z) = \varepsilon_{x,y}\beta^*_{x,y} + \frac{\varepsilon_{x,y}}{\beta^*_{x,y}} z^2 \tag{4}$$

Notice that the quantity $\varepsilon_{x,y}\beta^*_{x,y}$ is the square of minimum spot size, as given in equation (2). The second term in (4) gives the z dependence of the spot size. The factor ε / β^* determines the growth rate of the spot size as function of z. The term "angular divergence" of the beam at the IP is defined as

$$\theta_x = \sqrt{\varepsilon_x / \beta_x^*}, \qquad \theta_y = \sqrt{\varepsilon_y / \beta_y^*}. \tag{5}$$

With KEKB design parameters in Table 1, the angular divergence at the IP is, $\theta_x^* = 234$ µrad and $\theta_y^* = 190$ µrad. Smaller the β^*, larger the angular divergence. Larger the angular divergence, larger the growth rate of the spot size.

The beam spot size grows roughly linearly as function of z, as the beam leaves the IP. Naturally we cannot afford an arbitrarily large spot size throughout the ring, because it would call for very large vacuum chambers and magnets. To control the beam spot size outside the IP to a reasonable range (say, << 1 cm), a whole series of quadrupole magnets need to be used. However, it can be easily seen that within the first few magnets near the IP, the beam spot size tends to be very large (a few cm).

Q: What would be the beam spot size at the point which is 1.5 m away from the IP?

2.2 Remember the Injection Condition

When the desired spot size at the IP and the beam emittance are known, the behavior of the spot size near the IP can be calculated using equation (4). By adding an assumption on the strength of final focusing quadrupole magnets (quads), one can calculate the spot size behaviors further away from the IP. This allows to determine the aperture (~ inner radius size) of vacuum chambers in this area. Then that, in turn, determines the physical sizes of magnets to be used.

An important modification to the scenario above is that we need to take into account behaviors of beams during the injection time.

The bunches that are injected into the ring from the linac have much larger emittance than in the equilibrium condition, where the beam emittance has converged because of the radiation damping. At KEKB the injection beam emittance is expected to be 3.2×10^{-8} m.rad for electrons and 4.4×10^{-8} m.rad for positrons. After injection the emittance and the orbit of the injected beam will converge to those of the stored beam at a time constant called radiation damping time. The damping time at KEKB is expected to be ~ 80 ms.

Another fact to take into account is that injected bunches have significant orbit distortions. In the injection beam line a septum magnet is used to give an extra kick to the injection beam, and to let it approach the stored beam. However, because of the finite septum thickness and the need to separate the stored beam from the outer surface of the septum, injected and stored beams need to be somewhat separated. See Figure 1 and 2 for their graphical explanations.

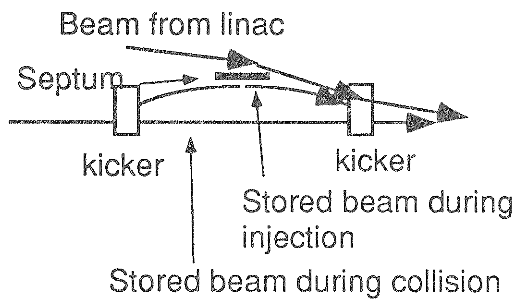

Figure 1. A schematic diagram of the part of the ring near the injection point, and how the orbit is perturbed when the kickers are triggered.

The vacuum chamber aperture has to take into account this large orbit distortions during injection. Its exact magnitude will depend on the construction of the septum and the allowance that the designer allocates as the distance between the stored beam and the septum wall. At KEKB the envelope of the stored beam during injection will spread to occupy a phase space of 1.2×10^{-5} m.rad in x and 1.2×10^{-6} m.rad in y [5].

The beam line aperture near the IP must comfortably accommodate this beam-orbit envelope during the injection time. Otherwise, the beams will be lost near the IP whenever a beam injection takes place It will create severe background noises and radiation dose to the instruments, which is unacceptable.

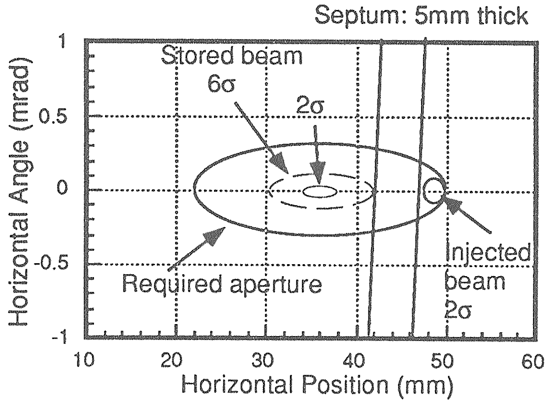

Figure 2. A diagram which shows the beam phase space in the injection condition and how the required aperture is calculated.

Q: Calculate the required vacuum chamber aperture at 1.5 m from the IP, which is required for the beam-orbit envelope during injection at KEKB. Assume $\beta_x{}^* = 33$ cm and $\beta_y{}^* = 1$ cm. Out of x or y, which direction would require a bigger aperture?

2.3 Need for the Two-beam Separation

2.3.1. Why is it important?

Since an asymmetric B factory collides two beams with different energies, the accelerator consists of two separate rings: high energy ring (HER) and low energy ring (LER). The IP is where those two rings intersect. Immediately before and after the IP, the two beams have to be separated into the designated two rings. The separation must be quick. There are two reasons for this.

First, there is a need to introduce extra focusing to the higher energy beam (usually it is the electrons, and KEKB is no exception).

The innermost (the closest to the IP) pair of quadrupole magnets surrounding the IP is common to both electrons and positrons. Since the two beams are of different energies, if one optimizes the focusing for the low energy beam, the focusing for the higher energy beam becomes insufficient. Therefore, one more quadrupole magnet of the same sign should be placed close to the final quads. Yet that additional quad should "talk" only to the higher energy beam. Therefore, the beam separation at that location has to be made sufficiently large to accommodate such a quad magnet.

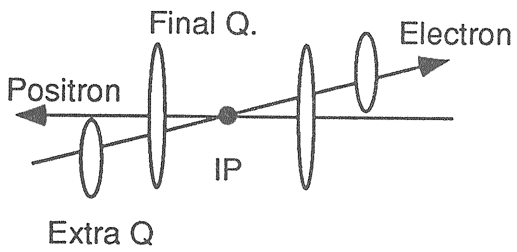

Figure 3. The higher energy beam (electrons) requires an extra focusing.

We note here that this second quad for HER had better be closer to the final quad. This is so as to minimize the chromaticity coming from those quadrupole magnets. The chromaticity ξ is a quantity that characterizes the momentum dependence of betatron oscillation frequencies. In storage rings, it is typically defined as

$$\xi_{x,y} = \frac{\Delta \nu_{x,y}}{\Delta p / p} \tag{6}$$

where $\Delta \nu_{x,y}$ represents the (horizontal and vertical) betatron tunes. The chromaticity is a quantity that one should try to reduce with best efforts. Each quadrupole magnet in the ring will contribute a chromaticity of

$$\xi_{x,y} = -\frac{\beta_{x,y_Q}}{f_Q} \tag{7}$$

where inevitably forces some separation between the β_Q is the beta at the quad (it is <u>not</u> the beta at the IP, β^*), and f_Q is the focal length of the quad.

Equation (4) has shown that the β continually increases as function of z until the beam is adequately focused back with the final quad. The issue is that when we consider HER, the focusing with the final quad is not yet sufficient. Therefore, beyond the final quad, the HER β will still continue to grow. What it means is that if the second extra quad is placed far away from the final quad, it will contribute a large chromaticity, because the β at that point will be large. In conclusion, the second quad had better be placed close to the final quad. Therefore, a sufficient beam separation must be created near the outer end of the final quad.

The second reason for a rapid beam separation is that there is a need to suppress emergence of extra beam-beam interactions, called "parasitic crossing". A parasitic crossing is a beam-beam crossing at space locations other than the designated interaction point.

To obtain a high luminosity, a B factory is usually designed to operate with many bunches in each ring. The bunch spacing may become as short as 60 cm at KEKB. This means that, in a full bunch operation, parasitic beam-beam crossing can take place every 30 cm along the beam line, unless they are well separated quickly enough.

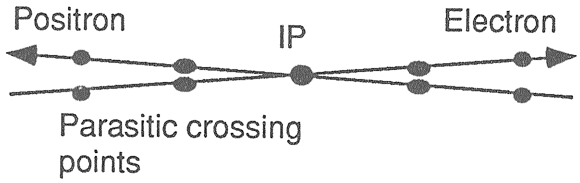

Figure 4. Schematic view of the parasitic crossing phenomenon.

A parasitic crossing does not contribute to the luminosity of experimental interest, but it does contribute to the net beam-beam interactions in the ring, leading to an extra beam blow-up. Also, a parasitic crossing of two beams which are not well separated in transverse directions can cause Coulombic bunch-bunch scattering of two beams. It perturbs their orbits near the IP, and it will lead to a luminosity reduction.

2.3.2 Beam Separation Techniques

At an asymmetric storage ring, there are at least two ways to bring counter-rotating beams into separate rings: one way is to use a set of dipole magnets, the other is to introduce a crossing angle at the IP.

The magnetic separation exploits the fact that the two beams have different energies.

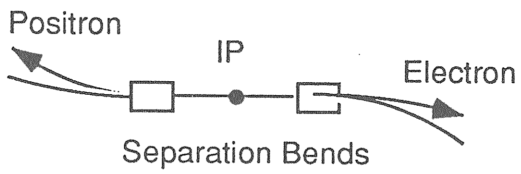

Figure 5. Beam separation with a pair of dipole magnets.

Naturally this scheme would not work if the two beams had the same energy. However, it can be conveniently used at an asymmetric B factory, because the HER and LER beams are bent with different radii within a single bend magnet.

Q. Suppose the two beams had energies of 8 GeV and 3.5 GeV, assume that they are at head-on collisions at the IP. Suppose we place dipole magnets at z= 0.8 m ~ z = 1.2 m. What is the required dipole field strength, if we wish to have a two beam separation of 9 cm at z = 3m ? Use the formula that the beam momentum p (GeV/c), bending radius ρ (m) and the dipole field strength B (T) are related as,

$$3.3356p = B\rho \qquad (8)$$

Q. What if the two beams had energies of 9 GeV and 3.1 GeV?

The required separation bend strength increases if the required beam separation is increased or if the distance between the IP and the bend magnet is increased. Therefore, the separation bend should be placed as close as possible to the IP.

As a totally different method, it is easily seen that the two beams can be also separated, if they are made to cross each other at the IP at a finite crossing angle.

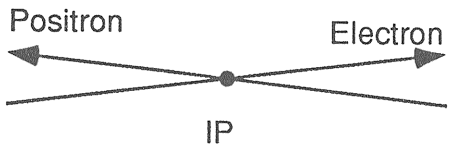

Figure 6. Beam separation based on a finite crossing angle.

Q. What is the required crossing angle if we wish to separate two beams by 8 cm at $z = 3$ m? (A very trivial question, if we ignore the presence of final focusing quad magnets, which will be at $z < 3$ m).

One immediate consequence of the use of a finite crossing angle is a reduction in the luminosity. For a given design spot size, the effective luminosity reduction due to geometrical effects is approximately given by

$$\frac{L}{L_0} = \left(1 + \frac{\sigma_z^2}{\sigma_x^2}\theta_c^2\right)^{-1/2} \qquad (9)$$

In the equation (7), a horizontal beam crossing is considered. The σ_x and σ_z are design beam sizes in x and y, and θ_c is the half crossing angle.

Q. With the beam parameters given in Table 1, what is the luminosity reduction factor, if a half crossing angle of 10 mrad is introduced? What if the bunch length is made longer to, say, 10 mm?

Actually equation (9) ignores the fact that the transverse spot size of a finite length bunch varies along z, during a collision according to equation (4). It also uses an approximation that $\sigma_z\theta_C/\sigma_x$ is smaller than 1. A more exact formula is given by

$$\frac{L}{L_0} = \sqrt{\frac{2}{\pi}}ae^bK_0(b) \qquad (10)$$

where, K_0 is a modified Bessel function and a and b stand for,

$$a = \frac{\sigma_y \cos\theta_c}{\sqrt{2}\sigma_z\theta_y} \qquad (11)$$

and

$$b = a^2\left[1 + \left(\frac{\sigma_z}{\sigma_x}\tan\theta_C\right)^2\right] \qquad (12)$$

Q: Under what conditions the equation (9) is a valid approximation of (10) ?

2.3.3 How Fast Separation is Fast Enough?

The z position (the position along the beam line) of the second quad in HER will determine how rapidly the beam separation off the IP has to start. The z position of the second quad depends on the position of the final quad magnets, which, in turn, is determined based on the required total focusing (β^* at the IP) and possible interference with the experimental facility.

In addition, a number of issues need to be taken into account. The items to consider include: the required field strength of the second quad, the thickness of its coil, the vacuum chamber aperture required for the injection condition, and the thickness of the vacuum chamber.

At KEKB, a beam separation of 9 - 10 cm is considered to be required at the entrance of the second HER quad which is situated at $z = 3$m [5].

In terms of avoiding effects due to parasitic crossing, how much transverse beam separation is necessary depends on beam parameters and characteristics of the ring.

If it were done by using a finite crossing angle at the IP, it is estimated that more than $+/-5$ mrad crossing angle is needed to stay away from harmful parasitic crossing effects, if the bunch spacing of 60 cm is to be handled with KEKB parameters [6].

At an early stage of KEKB operation, the bunch spacing may be much larger, > 3 m. In that case, the crossing angle can be smaller (i.e. < 3 mrad). Actually an IR design based on this small-angle crossing scheme has been pursued for KEKB for a while in the past [2]. However, it is considered necessary to increase the crossing angle for full-bunch operations. Changing the crossing angle usually requires a rebuilding of (at least part of) the beam line, although rebuilding the cryostat for the final superconducting quad is probably not necessary.

2.4 Crossing Angle and Beam-Beam Interactions

2.4.1. Basics

One consequence of using a finite crossing angle is the reduction of the luminosity due to geometrical effects. This has been already mentioned in 2.3.2.

Another important effect of a finite angle beam crossing is the excitation of synchro-betatron resonances.

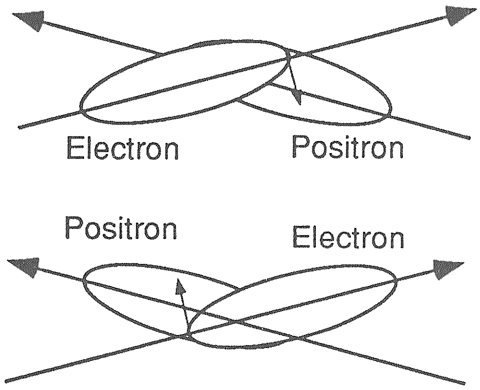

Figure 7. Beam-beam kicks during a beam collision with a finite crossing angle.

Figure 5 shows a schematic view of electron and positron bunches at a finite crossing angle. Because of the flip of the relative offset between the two beams immediately before and after the maximum overlap, the head and tail of a bunch is shown to receive transverse kicks of opposite signs.

A particle that has received a transverse kick will execute an oscillation in the transverse phase space, called a betatron oscillation. Also, within a bunch, individual particles are executing synchrotron oscillations whereby the particles are going back and forth longitudinally, while they gain and loose a fractional energy. Now notice that a bunch will see head-tail kicks from an opposing bunch whenever it passes through the IP, i.e. periodically.

The net effect of these is that if a finite crossing angle is used, and if the betatron and synchrotron tunes are in certain numerical conditions, synchro-betatron resonances can be excited. Some of such resonances will cause a beam-blow up, leading to a further luminosity loss.

Early work by Oide and Koiso has shown [7] that resonance conditions which would contribute to a blow-up of the horizontal beam size are

$$\nu_x = n \pm \nu_s, \qquad 3\nu_x = n \pm \nu_s. \tag{13}$$

A vertical beam blow-up is caused by resonances of

$$\nu_x - 2\nu_y = n, \qquad \nu_x - 2\nu_y = n \pm \nu_s \tag{14}$$

In both (10) and (11) the n denotes an arbitrary integer (including 0). Those resonances would <u>not</u> cause a beam blow-up if the crossing angle were zero.

2.4.2 Simulations

A detailed simulation algorithm has been developed by Hirata to examine beam blow-up behaviors in finite crossing angle conditions [8]. It is based on a strong-weak model where the higher energy beam (electrons) bunches are assumed not to change the profile despite beam-beam interactions, but the lower energy beam (positrons) bunches may have their profile changed.

The formalism by Hirata is constructed in a exact Lorenz-covariant form, and all known effects are taken into account, such as the variation of β as function of z, the finite bunch length, and the variation of the kicks that particles will receive as function of their longitudinal position within a bunch.

An ideal simulation is to combine this beam-beam interaction code with another program which tracks the beam through the design ring lattice which may include possible construction errors, chromaticity and other optical aberrations. This effort has been on-going, but at the writing of this lecture note its results are not ready to be documented.

A simplified form of the calculation is to combine the beam-beam interaction code with an idealized ring lattice which is simply characterized in a 4×4 matrix form. In this case, although the effects due to ring errors cannot be evaluated in details, the behaviors of beam blow-ups as function of ring tunes can be still examined.

The simulation has been repeated with varying machine / beam parameters in a simplified form above, with a beam crossing angle in the range from zero up to 2 × 40 mrad. The results are summarized as follows.

1. The beam blow-up pattern roughly follows equations (13) and (14), but additional resonance lines are seen to cause a beam blow-up.

2. It is essential to keep the synchrotron tune ν_s as small as possible. Otherwise, a large area in the ν_x - ν_y operational plane is carved out as unusable for too small a luminosity.

3. If the synchrotron tune ν_s is kept below 0.02, with nominal beam parameters in Table 1, it leaves relatively large areas in the ν_x - ν_y operational plane, which delivers a reasonably large luminosity (80 ~ 90 % of the no-beam-blowup case) with 2 × 10 mrad crossing. Such areas in the ν_x - ν_y plane appears to be compatible with the desired ν_x - ν_y combinations in the light of considerations on dynamic apertures.

4. The desired synchrotron tune ν_s (< 0.02) is compatible with the ring lattice design of KEKB [9]. This is a good news. The need to maintain a sufficient dynamic aperture in the ring also calls for a smaller synchrotron tune so that severe synchro-betatron resonances are avoided.

In short, there are reasons to believe that a crossing angle of 2 × 10 mrad under KEKB conditions of Table 1 is acceptable in the light of beam-beam interactions. The statement is pending results from more detailed simulations which include finite machine errors in the ring lattice. However, it is conjectured for now that if the machine could not deliver the full design luminosity, it will be more likely because of unfortunate combinations of other machine errors, rather than singly because of the finite-angle crossing at the IP.

Notice that in a finite crossing angle case, if a Crab crossing scheme is successfully implemented [10], the luminosity reduction according to equations (9) or (10) may be restored.

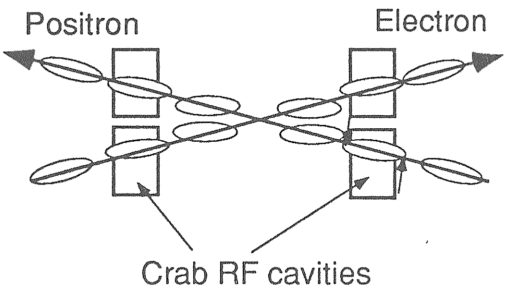

Figure 8. A schematic diagram of a Crab crossing scheme. Notice the change of the orientation of the bunch before and after passing through Crab cavities.

Crab crossing (see Figure 8) is a technique whereby the head-to-tail orientations of opposing bunches are "re-aligned" by using time-dependent transverse kicks from a special RF cavity (Crab cavity) or by other measures. While the beam crossing still occurs at an angle, the transverse forces that individual particles in the bunch feel during a collision no longer have a longitudinal position dependence as depicted in Figure 7.

With Crab crossing, the beam-beam effects are considered equivalent to that in a zero-crossing angle head-on collisions. There will be no geometrical reduction of the luminosity as in equation (9).

Results from the simulations of crossing-angle beam-beam interactions so far indicate that with KEKB parameters, and with a 2 × 10 mrad crossing at the IP, the luminosity performance of KEKB is not compromised by a disastrous magnitude. This allows the designers of KEKB to hold the Crab crossing development as one of the important future upgrade items at KEKB, but not as an essential one for the initial start up and early runs of KEKB.

2.5 Relative Merits of Magnetic Beam Separation and Crossing Angle Beam Separation

The choice of the beam separation scheme with bend magnets vs. crossing angle depends on considerations on the hardware design and the beam dynamics.

The hardware design is affected by the design of the experimental facility (because of the machine - detector interference) and technologies that are available for construction of the accelerator. Chapter 4 will discuss on more of their details.

The nature of beam dynamics issues are determined by the choice of beam parameters, geometry of bunch collisions, and the overall lattice design of the ring. Some of their aspects have been discussed in the early part of this chapter.

Figure 9 summarizes the issues as function of the choice of the beam crossing angle at the IP.

It is seen that with a zero-crossing angle scheme, effects of spurious synchro-betatron resonances which would be feared in finite-angle crossing cases are absent by definition. However, it would require strong separation bend magnets near the IP. Studies have shown that a use of permanent magnets very close to the IP is the only feasible choice for B factories currently under considerations. In fact, PEP-II design has adopted this scheme [11]. The inner end of their separation bend is at z = 30 cm.

Although the main target energy for running a B factory is E_{CM} = 10.6 GeV, there will be needs to run at different energies. Their purposes are for detector calibrations, evaluating the amount of background events, and for studying other Υ resonances. The use of permanent magnets compromises the flexibility in coping with such energy changes. Relatively strong trim windings will be required for this.

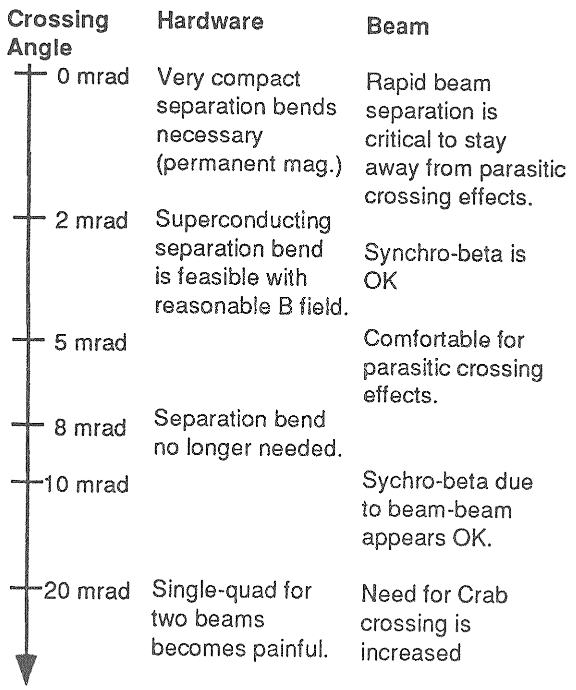

Figure 9. Relationship of hardware and beam-dynamics issues for varying choice of the beam crossing angle at the IP.

By introducing a small crossing angle, the strength and position requirements for separation bends may be relaxed. With a 2 × 2.5 mrad crossing angle, the beam separation with superconducting magnets becomes feasible with realistic magnet designs. If the final quads are built with superconducting magnets, the separation bends may be built in a same cryostat enclosure. Therefore, it offers a design with excellent flexibility for running at with varying center of mass energy. Indeed, until early this year the IR design at KEKB has been mainly pursuing this possibility [2].

When the IP crossing angle is increased, the strength requirement for separation bends continues to decrease. In terms of background noises and radiation to the experimental facility, a weaker separation bend is desirable. This is because the flux and the critical energy of synchrotron radiation from a bend magnet is reduced for a weaker magnetic field.

If the crossing angle exceeds ~ 2 × 8 mrad, the separation bends are no longer necessary under KEKB conditions. At this point, the apace that has been occupied by separation bends becomes available for other uses. For instance, the space may be used for compensations of the detector solenoid field, so that the x - y coupling effects and orbit rotation near the IP is reduced.

It should be also noted that to avoid effects of parasitic crossing, a beam crossing angle of > 2 × 5 mrad is preferred [6]. That is, if a short bunch spacing of 60 cm should be accommodated. By choosing a crossing angle of this magnitude or more, the design gains a much flexibility in the sense that a wide range of bunch spacing vs. bunch intensity combinations are allowed to deliver a same luminosity, depending on the machine performance in the acceptable minimum β^*, single and multi-bunch instabilities, beam lifetime and others.

A larger crossing angle (> 2 × 20 mrad) starts giving an uncomfortable condition against having two opposing beams in the same final quad. This is because the two beam separation in the final quad becomes large. If one beam is centered on axis of the final quad, the other beam inevitably becomes significantly off-centered, leading to a strong emission of synchrotron radiations. Beam dynamics effects from the magnet fringe fields will be a worry, too.

It appears that if ~ 2 × 10 mrad crossing is acceptable from the beam dynamics view point, then it is a rather nice design choice in terms of hardware construction and operational flexibility. As it has been shown in 2.4.1, this much crossing angle is indeed acceptable, as long as the synchrotron tune ν_s can be kept low. The lattice design of KEKB storing rings is compatible with this. The present hardware designs efforts on the KEKB IR is centered on the assumption that we adopt a 2 × 10 mrad crossing at the IP.

3. IR DESIGN FOR KEKB

Figure 10 shows a schematic diagram of the innermost part of the current IR design for KEKB. It is based on a crossing angle collision of 2 × 10 mrad. No separation bend magnets are used. The field strength of the detector solenoid is assumed to be 1.5 T, and it is filling the volume shown in Figure 10. A superconducting compensation solenoid magnet and a superconducting final quad magnet are built in a single cryostat enclosure for each side of the IP.

For the best field compensation against the detector solenoid, attempts are being made to accommodate a longest possible compensation solenoid SOL1 with a field strength > 3 T.

The field gradient of the final quad QC1 is 16 T/m. It is a horizontally defocusing (i.e. vertically focusing) magnet. The coil of QC1 physically starts at z = 1.42 m. However, because of the finite aperture of the magnet, the inner end of the effective field of the quad

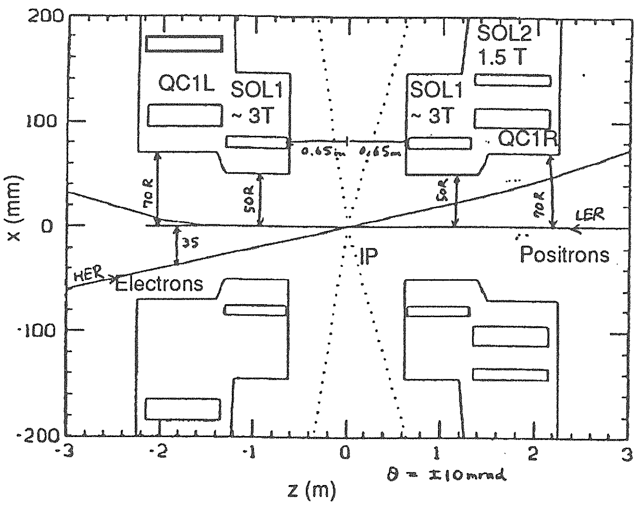

Figure 10. A schematic diagram of the innermost part of the KEKB IR design. The final quad QC1 and compensation solenoid magnets SL1 and SL2 in a pair of cryostat enclosures are shown. The design tranjectories of electrons and positrons are indicated.

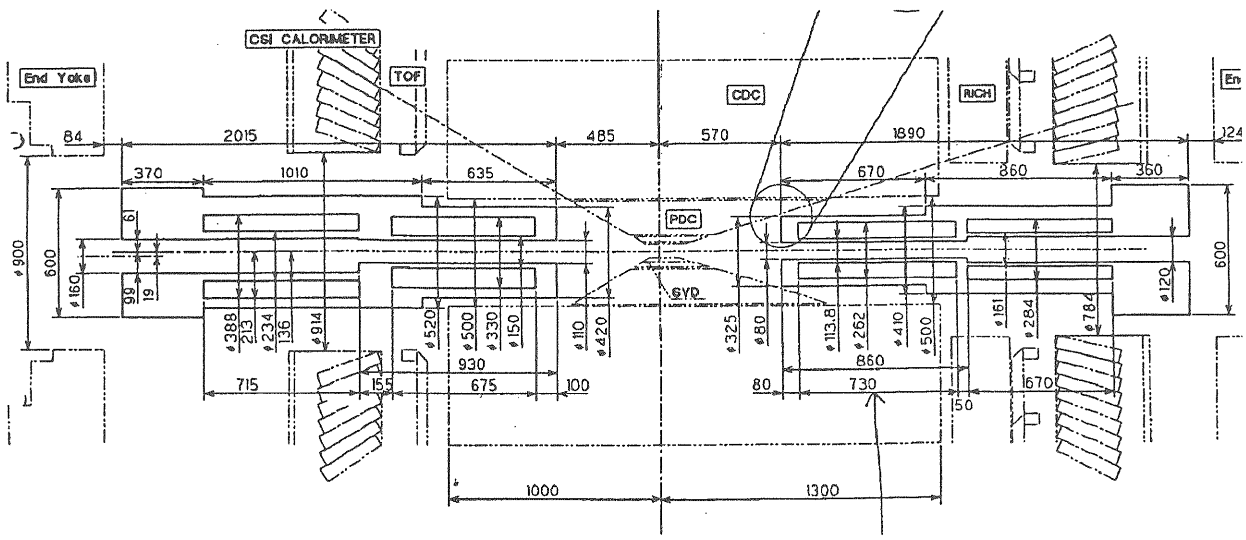

Figure 11. An engineering drawing of the innermost part of the KEKB IR design. It shows roughly the same area as Figure 10. Units are in mm.Outlines of some components of the detector facility are also shown. Detailed dimensions are likely to change before the final design is frozen. This figure is just to show the tighness of the construction of both the experimental detector facility and the accelerator at the IP.

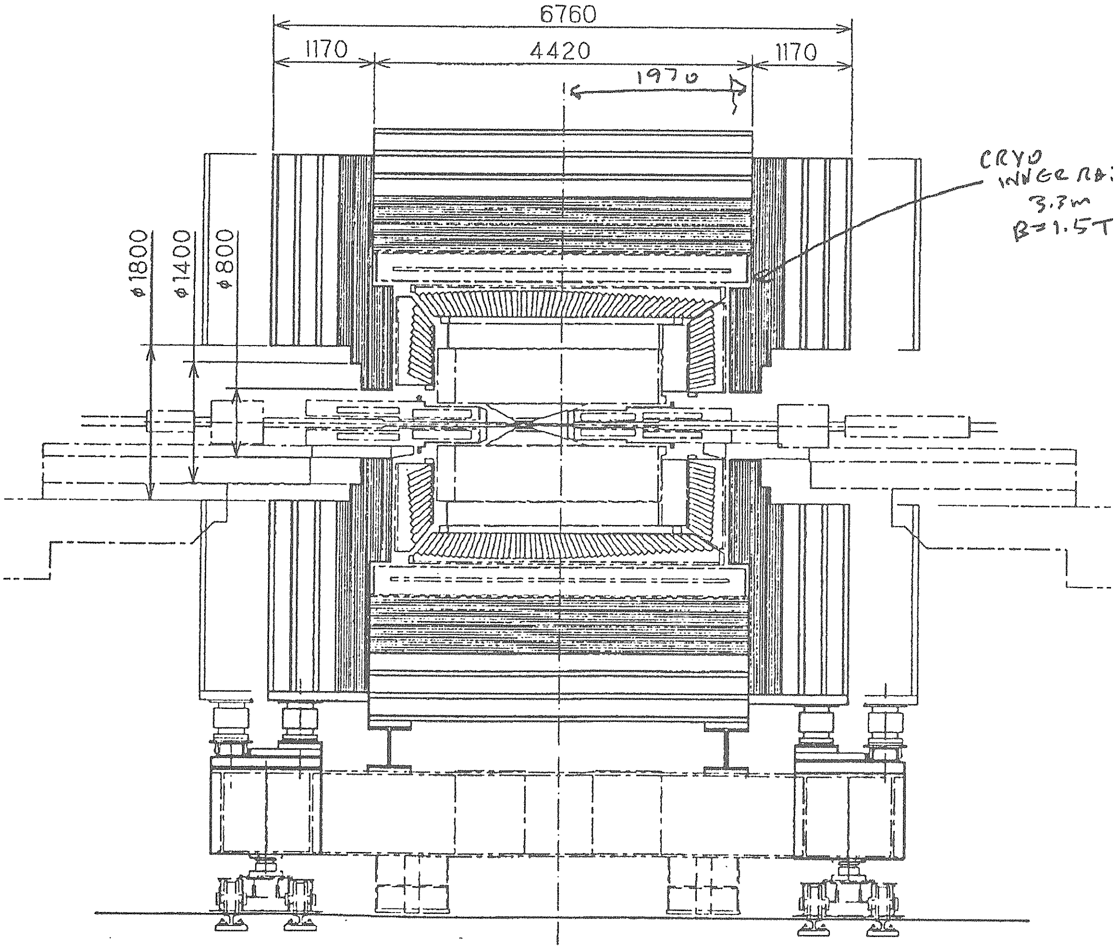

Figure 12. A side view of the entire experimental detector facility at KEKB with some accelerator components near the IP. It is seen that final quadrupole magnets QC1 are buried inside the detector and are immersed in the detector solenoid field.

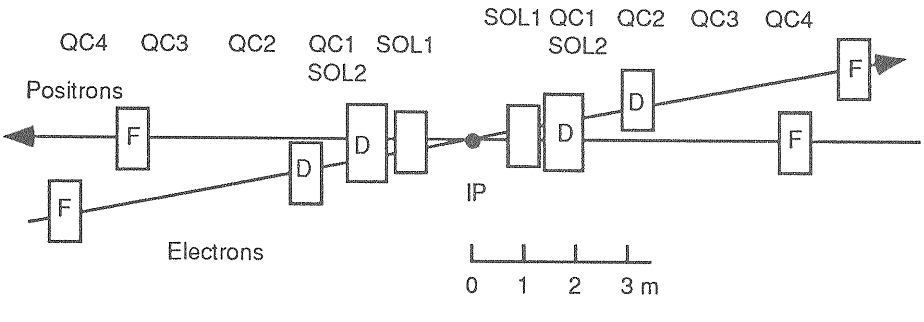

Figure 13. A schematic diagram of the beamline near the IP. SOL1 / 2 and QC1 (final quad) are inside the detector facility. Other QC magnets are outside. A rough scale in z is shown. The horizontally focusing quads are marked F, while defocusing quad (vertically focusing) are marked D.

corresponds to $z = 1.5$ m. Its effective field length is 50 cm. The QC1 is radially surrounded by another compensation solenoid SOL2.

The electron comes from the left side of Figure 10, the positrons in an opposite direction. The incoming positron is centered through the axis of QC1R (right). this is so as to minimize emission of synchrotron radiation into the detector volume. Likewise, the incoming electron is let through QC1L (left) on axis. For this purpose, the axis of QC1L is shifted side-way (in x) by 35 mm, while the axis of SOL2-left is centered on the axis of the detector solenoid.

Figure 11 shows the same area as Figure 10 in a more engineering-like form. Outlines of some detector components are shown. The exact dimensions are likely to change before the final design is frozen. However, tightness of the space allocation between detector components and accelerator elements can be seen. Notice that the interference between the inner corner of the cryostat and end plates of the precision drift chamber (PDC) is the basic factor which determines how close the compensation solenoid can approach the IP.

Figure 12 shows a side view of the detector facility [12] along with cryostats for SOL1 - QC1, another quad QC2 and some support structures. (QC2 is the magnet that gives an extra vertical focusing on electrons which have higher energy.) The detailed design of the accelerator support structures into the detector is not finalized yet. However, one could see that some key accelerator components are deeply stuck inside the detector.

Figure 13 shows a schematic diagram of the IR beam line. Besides the magnets very near the IP (the ones shown in Figures 10 and 11), some outer beam line components are shown. QC3 and QC4 are magnets which give horizontal focusing for positrons and electrons, respectively.

4. DETECTOR - ACCELERATOR BOUNDARIES

Physical sizes and geometrical positions of magnets and vacuum components cannot be arbitrarily chosen in an IR design. This is because of various boundary conditions relative to the construction and operation of the experimental facility.

4.1 Mechanical - Solid Angle Coverage

When the detector-accelerator boundary conditions are considered, the mechanical constraints are the first to come to mind.

Most experimental facilities at a B factory wishes to cover the polar angle down to 17 degrees or so in the forward direction. It is indeed the case at KEKB. Then the experimental group requests to be able to cover down to 30 degrees in the backward direction, also. The inner radius of their central drift chamber has been chosen to be 25 cm, as shown in Figures 11 and 12. The accelerator components have to fit within the left-over space.

Of course, spaces for detector signal read-out electronics and cabling needs to be allocated besides the solid angle coverage of the detector fiducial volume.

4.2 Magnetic - Leak Fields

The issue of magnetic interferences between the accelerator and the experimental facility is bi-directional.

If the separation bend is made of permanent magnets their leak field into the detector volume is very small. Then special magnetic insulation is not necessary. On the other hand, if super conducting magnets are used as separation bends, the magnetic field distortion in the detector fiducial volume becomes large enough to demand a special tracking code, unless an effective field insulation is realized. In an earlier design at KEK-B where the super conducting bend magnets were considered, the magnet design included compensation bend windings to solve this problem [13].

The leak fields due to the final quadrupole magnets are small, because of i) the higher pole nature of the field, and ii) the tracking volume of concern is radially more distant from the magnet, than the case of separation bends. Therefore, a double-layered quadrupole winding is not necessary.

The next to consider is effects of the solenoid field of the experimental facility on the accelerator components. At KEKB the detector solenoid field strength will be max. 1.5 T. Its effects introduce : i) an x-y coupling in the beam, ii) a three-dimensional twist of the design beam trajectory, and iii) magnetic forces on the beam-line magnets.

To some extent it is possible to remove the x-y coupling effects of solenoid fields with skew quadrupole magnets outside the IP region. However, depending on where such magnets can be placed, they can cost for spurious dispersion and operational complications. It has been shown also that skew quads cannot offer complete compensations to solenoid field effects for off-momentum particles, and it can cause a growth in the vertical beam emittance [14].

It is more desirable to compensate the solenoid fields on the spot. It has been discussed that in a free drift region (i.e. a part of beam line with no quad / bend magnets), it is sufficient to bring the total path integral of Bz to zero. However, for quadrupole magnets within a solenoid magnet, the solenoid field in that part should be brought to zero for best results [15].

Figure 13 shows the required solenoid field compensation for the accelerator near the IP, and how it may be achieved in the KEKB design. Active design efforts are on-going to reach a viable engineering solution.

It should be noted that the fields of compensation solenoids, when leaked into the detector tracking volume, can degrade the momentum resolution of the detector facility unless a careful field mapping is done beforehand. The design of compensation solenoids must minimize the leak field strength. During construction of the detector facility, the field mapping data should be collected with the detector solenoid and accelerator components installed together, before the rest of detector elements are inserted.

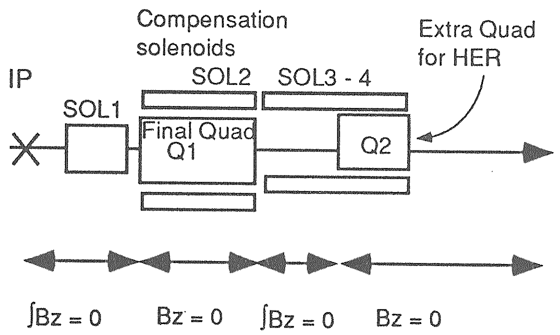

Figure 13. The most desirable solenoid field compensation at KEKB.

Because of the "tight coupling" between the detector solenoid magnet and the accelerator magnetic field strengths, the strengths of IP magnets (separation bends and the final quadrupoles) cannot be casually changed during normal operation of the B factory.

4.3 Radiation - Detector Background

Accelerator-related backgrounds can cause adverse effects on the performance of the detector facility in various areas. They are : i) a higher detector trigger rate and ii) degradation of tracking capacities of the detector, and iii) damage to detector components and insulating materials due to accumulation of radiation dose.

The challenge is to maintain the background levels comparable to the existing e^+e^- colliding beam facilities while the beam intensity at B factories will be larger by at least an order of magnitude.

Two main physical processes to consider are synchrotron radiation (SR) emitted by beam particles when they go through magnets in the IP neighborhood, and beamstrahlung due to residual gas. With IR designs with separation bends, the emissions of SR and tracking of beam-gas interaction products are dominated by the effects of the bend fields, rather than by quadrupole magnets. Hence the experiences with the past single-ring colliders in some cases may not be directly applicable, and very careful simulation efforts are called for.

Other issues include radiative Bhabha processes, secondary particles and photons off masks, disposal of radiation fan near and after the "crotch" area where the electrons and positrons depart, and the vacuum system. A review by H. DeStaebler et al at the '92 SLAC B factory Workshop gives an extensive coverage of those issues [16].

Radiation effects during the injection stage are a worry too, because of the large beam orbit envelope during injection. Although the beam emittance will damp quickly within O(10) msec, using a "coarse" damping ring before the main B factory ring helps reduce this injection radiation problem, if it is at all possible. Unfortunately this is not available for KEKB. An adequate collimation, if it can be implemented, is expected to help.

4.4 Heat

Of concern is the heat created by the accelerator onto the IP beam pipe where the vertex detector is closely located. It is desirable to keep the temperature rise of the beam pipe within 5 degrees C in the presence of the beam.

Three major heat sources are i) beam image current, which is expected to be small O(10) W, ii) synchrotron radiation, and iii) beam-induced higher order mode (HOM) heating, which may reach up to a few hundred watts or more.

It is quite possible to consider some beam tests to evaluate practical aspects of HOM heating with an existing ring. Unfortunately the interpretation of the results may not be straightforward if the beam parameters of machines available for testing are significantly different from those of the real-life B factories.

At least two forms of IP beam pipe cooling have been considered, one using a dry low-temperature gas flow, and the other using cooling water channels. While the latter will result in more materials inside the detector volume, it is clearly the preferred choice due to a much superior cooling efficiency [17, 18]. The fail-safe interlock and the protection against possible corrosion of water channel materials will be the focus of development efforts.

5. MECHANICAL ISSUES

5.1 Mechanical Support

The final quadrupole magnets and compensation solenoids (and separation bend magnets, if there are any) have to be placed deep inside the detector volume as shown in Figure 12. From this arises a problem of the support structure, and magnetic forces exerted on the accelerator magnets due to the detector solenoid field.

In the past, the final quadrupole magnets and associated hardware have been supported mainly by a structure that is situated outside the experimental facility. Some innermost parts of accelerator components have been hooked up to the inner area of the detector mechanically either loosely or tightly.

The KEK-B IR design roughly follows this tradition except that the support of the cryostat enclosure will be provided by a part of the endcap flux return yoke and an extension from it. The mechanical system design has to pay close attentions to the construction order such that sufficient provisions are made for easy detector maintenance and a rapid recovery from such work [19].

The PEP-II design at SLAC has adopted an approach based on a support barrel that will contain the IP vacuum chamber, vertex detector, separation bend magnets and the masks [11]. This allows a good mechanical alignment of components before installation. Once a pre-installation alignment is completed, there will be no big worries on how to maintain it during the installation work, because the key components are by then safely confined within a single structure. Taking apart the structure for maintenance work could become a major undertaking, although so are the cases with other designs. The material of carbon fiber support tube that amounts to 0.5 % of a radiation length is considered acceptable by the group.

5.2 Alignment Strategies

Typical alignment accuracy involving a meter-size magnets is about O(100) μm. This accuracy is probably feasible at KEKB. Special attentions must be paid at a B factory, since the beams in many cases are supposed to go through magnets off axis and magnet alignment can be affected by the presence / absence of the detector solenoid field.

With 100 μs size alignment accuracy the two beams still will not collide in the as-built configuration, because the electrons and positrons will emerge from completely separate rings. Thus, some active alignment correction methods, based on observations of beam behaviors, need to be implemented. The control device can be magnet movers or steering correction coils. Because of the space constraints and magnetic forces, it may be more desirable to simply rely on correction magnets. Steering correction coils (whether separate magnets or superimposed coil winding) will be necessary, anyway, for orbit feedback purposes. However, their adverse effects such as spurious dispersions need to be evaluated.

When a maintenance work is done on the detector facility, it has to be assumed that the IP magnet alignment information will be lost. An algorithm needs to be developed to rapidly search for and restore an optimum collision condition on recovery from such maintenance activities.

5.3 Vacuum System, Masks and Cooling

The vacuum level in the IP neighborhood needs to be of the order of 1×10^{-9} Torr or better. This is based on estimates of experimental backgrounds due to bremsstrahlung products from beam-gas interactions. This vacuum level, of course, has to be achieved in the presence of the beam and, therefore, synchrotron radiation (SR) in the beam line.

Due to the space constraints, the vacuum pumps closest to the IP would be immediately outside the final quadrupole magnets. Hence, a reduction of outgassing rates of the IP vacuum chamber is important ($\leq 10^{-12}$ Torr l / s cm^2). Recent study results suggest that copper should be the preferred material for the vacuum chamber from outgassing aspects [20]. However, for radiation masks and for the parts that see the SR light need a thin layer of heavy metal coating for effective absorption of SR. The inner shape of the vacuum chamber should avoid steep slopes or large steps to reduce HOM heating, although in some cases an irregular chamber inner shape helps block transmision of SR into the detector volume.

To provide a sufficient pumping power the vacuum pumps need to be installed along the IR beam line as much as the space allows, if not at the IP. Of particular importance is the so-called crotch area where the electrons and positrons depart and where a heavy SR flux is expected. When super conducting magnets are used, the space interference with the cryogenic hardware and the vacuum system also needs to be carefully examined.

6. OPERATIONAL ISSUES

6.1 Radiation Protection

Whenever an abnormally high radiation and beam loss are detected or whenever significant magnet excitation errors are found, the beams should be dumped to a well-defined disposal and the experimental detector should be rapidly de-sensitized. This is to protect both the detector hardware and accelerator components. When super conducting magnets are used, the magnet quenches and cryogenic failures also have to be part of the logic.

Since the consequences of failures are serious the protection should not depend solely on operator's watchful eyes. An automated protection logic will be necessary. Of course, poorly designed interlock systems are serious annoyance rather than an operational protection.

6.2 IR Orbit Corrections, Feedback

There is no a priori reason for the two beams from the two rings to collide head-on automatically, without some orbit adjustment. The situation is quite different from a single-ring colliding beam facility. It is essential to develop a system which finds an optimum collision condition and actively maintains it [21]. The beam-beam deflection phenomenon gives an adequate signature of beam collisions with directional information on the relative beam transverse positions. It is considered the most promising for collision search and collision feedback purposes.

Some orbit distortion signals must be used to analyze the beam-beam deflections. It may be based on high resolution beam position monitors (BPMs) in the IP neighborhood; or it may use BPMs distributed over a much bigger region of the ring (for example, the entire ring).

To measure deflection angles and to search for good collision conditions, one may use air-core steering bend magnets to sweep one beam across the other. This resembles the technique that has been used at the SLC. An alternative method which has been proposed recently is to fill the RF buckets in such a way that there will be some bunches in one beam that will not see any counter-acting bunches to meet at the IP. The deflection signal can be detected by analyzing the difference between the orbits of colliding bunches and non-colliding bunches. If the BPM electronics allows separate read-out for those bunches, this scheme should work rather elegantly.

Once a good collision condition is found, it will be still necessary to actively keep the two beams in that condition, i.e. an orbit feedback system. The frequencies of the orbit shifts depend on the mechanical stability of the tunnel or magnet support, and the electrical stability of magnet power-supplies. The effective action frequency of O(10) Hz may be sufficient for the feedback system, since the amplitude of high-frequency mechanical shifts of beam-line components is expected to be small compared to the relevant beam size O(10) μm.

The question on where the orbit correction devices should be installed has to be analyzed carefully. If the sources of IP orbit fluctuations can be safely confined within the IP region itself, it is relatively trivial to develop a system which uses closed orbit bumps in a suitable combination. However, if this cannot be assumed, then a whole-ring orbit correction will have to be eventually considered. This will require a very good understanding of the ring-wide first-order optics (at least), a very high throughput of the BPM data transmission and a fast CPU. A good compromise may be to use a combination of i) a near-IP fast feedback based on closed bumps around the IP, and ii) a slower orbit feedback that works outside the IP with a boundary condition that it shall not affect the orbit in the area for i).

It should be repeated that the beam-beam deflection signal is not sensitive to relative angular mismatch of the two beams. An angular mismatch causes degradation in the luminosity and can lead to spurious sensitivities to synchro-betatron resonances. Thus it is desirable to introduce instruments that allow a reasonably fast (i.e. faster than the time scale of beam lifetime) luminosity measurement, besides the beam-beam deflection technique [22].

6.3 Collision Tune-Up Procedures

Collision tune-up procedures are needed to go beyond a simple search for two beam collisions and to achieve the highest possible luminosity by optimizing the IP dispersion, focal depth, x-y coupling (skew) and others.

If a set of optics tuning knobs are provided, it is in principle possible to eventually reach a good collision condition by repeating beam-beam deflection scans (or by measuring the luminosity) as function of the strengths of those knobs. This simple-minded approach assumes a reasonable orthogonality between the tuning knobs.

In practice such a method may face difficulties, because in a ring environment perturbations created by changing the strength of a magnet or making an orbit bump tend to have multiple effects on the beam, and orthogonalization of such knobs may not be trivial.

If some beam parameters can be specifically measured at the IP, such as the dispersion or x-y coupling, it is possible to deterministically calculate the corrections to apply, rather than going through many knob scans. Similar to a ring-wide orbit feedback, this requires, again, an understanding of the ring optics to a very high degree of accuracy (i.e. what exactly a magnet will do if its strength is changed). The specific beam parameters, of course, will have to be made measurable, too. The beam-beam deflection curve has some finite sensitivities to the relative beam skew (x-y coupling) [23]. The situation is much less clear on the feasibility of sensible dispersion measurements at the IP, except possibly using scans on deflection signals vs. dispersion knobs.

6.4 Beam Instrumentation

The beam position monitors immediately outside the final quadrupole magnets are important for detecting the beam-beam deflection signals, whether they will be the only BPMs to use in such analyses or not. Minimums of three BPMs (preferably four) are needed to deduce the beam-beam deflection angle in a self-contained way, although with certain assumptions the job can be done with two BPMs only. Requirements on the measurement resolution and signal bandwidth have been evaluated [21, 23]. It is also considered desirable to be able to measure the beam profile, or the beam emittance near or at the IP. A possible technique is to use Compton scattering by using laser light. If a reliable measurement is done, the information will be very valuable [24]. The space allocation for light guide for the laser light and photon detectors, however, could be a difficult problem.

Other beam line instrumentations to implement include vacuum sensors, temperature monitors and radiation monitors. They all participate in the space war in the IP region when the installations and cable routing work are considered.

7. CONCLUSIONS

We have outlined the considerations that are involved in the IR design at a B-factory. Many issues are inter-related and some accelerator physics problems are not completely resolved due to a lack of decisive experimental information. Nonetheless, it is seen that efforts are made to come up with an optimized design by following a logical thinking.

ACKNOWLEDGMENT

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REFERENCES:

* Lecture given at OHO-94 Accelerator Summer School, September 1994, KEK.

[1] "Accelerator Design of the KEK B-Factory", ed. by S. Kurokawa et al, KEK Report 90-24 (1991). This is an old report on a B-Factory design at KEK. Many parts are obsolete, but it still gives useful information on a basic thinking on a B-Factory design.

[2] "Proceedings of the Mini-Workshop on TRISTAN II B-Factory (Accelerator)", Dec. 15 - 17, 1993, KEK.

[3] "The proceedings of the International Workshop on B-Factories", KEK, November 1992, KEK Proceedings 93-7.

[4] "The proceedings of the International Workshop on B-factories", SLAC, April, 1992, SLAC-400.

[5] K. Satoh, report in [2].

[6] K. Hirata, report in [3].

[7] K. Oide and H. Koiso, private communications.

[8] K. Hirata, KEK Preprint 93-160 and references therein.

[9] H. Koiso, report in [2].

[10] K. Akai, report in [1] and [2].

[11] "PEP-II, An Asymmetric B Factory", June 1993, SLAC-418 (also LBL-PUB-5379).

[12] K. Abe, private communications.

[13] K. Tsuchiya, report in [2].

[14] K. Oide and H. Koiso, and Phys. Rev. **E49** (1994), 4474.

[15] K. Oide and H. Koiso, private communications.

[16] H. DeStaebler, et al in [4].

[17] Hitoshi Yamamoto, report in [3].

[18] T. Matsuda, private communications.

[19] R. Sugawara, report in [2].

[20] K. Kanazawa, report in [2].

[21] W. Kozanecki, report in [4]. Y. Funakoshi, report in [4].

[22] M. Yamauchi, private communications.

[23] V. Ziemann, report in [4].

[24] K. Nakajima, private communications.