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B-FACTORY INTERACTION REGION DESIGN*

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Abstract

High luminosity B-factories are generally high current (1-3 A) e+e- storage ring accelerators that operate at a center-of-mass energy equal to the mass of the Upsilon (4S) resonance (10.58 GeV). The high beam currents are achieved by storing a large number of bunches (several hundred to several thousand) into each beam. Two designs, the ones located at SLAC and KEK, also have asymmetric beam energies. This imparts a boost to the nearly stationary B mesons formed from the decay of the 4S resonance and allows precision vertex tracking detectors to look for a difference between the decay profiles of the matter and anti-matter B mesons, thereby observing a violation of CP. Bringing the stored beams into collision is one of the major challenges of any B-factory design. In order to achieve high luminosity the beams must be tightly focused. This pushes the final focusing elements close enough to the interaction point to be inside the solenoidal field of the physics detector. In addition, beam-related detector backgrounds from synchrotron radiation and scattered beam particles must be kept below an acceptable level. The major B-factory designs at Cornell University, KEK, and SLAC have all addressed these problems in various ways that depend on specific accelerator design decisions. This paper discusses the accelerator parameters and detector constraints that influence an interaction region (IR) design, as well as how the various IR designs address the challenges posed by a high luminosity B-factory.

1 ACCELERATOR PARAMETERS

Several factors must be balanced in the design of any IR. First, detector backgrounds from the incoming beams, always a concern, must be manageable. But there are several accelerator parameter decisions that strongly affect the design of an IR, and some of these parameter selections are not driven by IR concerns but are the result of other constraints of the accelerator design. Some of the parameters that affect any design of an IR are:

- Beam energies
- β_y^*
- Beam coupling or beam aspect ratio
- Head-on or crossing angle collision
- Beam bunch spacing
- Beam currents
- Beam size and beam emittance
- Beam-Stay-Clear

1.1 The beam energies of a B-factory

For B-factories, the beam energy range is somewhat restricted since all designs have a center-of-mass energy of 10.58 GeV. However, the three B-factory designs use different beam energies. The SLAC, LBNL, LLNL PEP-II design[1,2] has the largest energy asymmetry (9 on 3.1 GeV) while the Cornell CESR-III design[3,4] has symmetric beam energies and the KEK design (KEKB)[5,6] has an intermediate energy asymmetry of 8 on 3.5 GeV. How these beam energy selections affect the IR designs will be discussed in more detail shortly.

1.2 β_y^*

The vertical beta function value (β_y^*) at the interaction point (IP) for all three B-factory designs is small: 1–2 cm. In order to achieve these small β_y^* values the final focusing elements of the beams must be very close to the collision point. All three designs have machine elements within 1 meter of the IP, which places these elements inside the detector magnetic field.

1.3 Beam coupling

The beam coupling or beam aspect ratio at the collision point is another important parameter. Generally, the flatter the beams—vertical over horizontal beam size as small as possible—the easier it is to control synchrotron radiation (SR) backgrounds. This is one reason why round-beam designs are difficult. However, extremely flat beams are also difficult to achieve. The accelerator must be very precisely aligned in order to get the beam coupling much below 2%. All three B-factory designs use a beam coupling of 2-3%.

1.4 Collision angle, bunch spacing and beam separation

At what angle the beams collide plays an important role in designing how the beams are separated. Head-on colliding beams are certainly the most difficult to separate. The beam energies, the distance between beam bunches and the collision angle determine the beam orbit geometry near the IP. Each B-factory design has a different approach in dealing with this aspect of the IR design.

1.5 Large beam currents

To obtain a high luminosity, all B-factories have significantly large beam currents; typically 1-2 A per beam.

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These large beam currents pose several difficulties for IR designs. Synchrotron radiation power is a distinct concern throughout the accelerator but this is especially true inside or just outside the detector where space is tight and temperatures must be carefully controlled.

The large beam currents also induce I^2R heating losses and higher-order-mode (HOM) losses. These power losses can be quite large and special care must be taken that beam pipes are smooth and conductive throughout the IR. Unwanted cavities in the beam pipe near the IP—almost unavoidable due to the large beta functions and/or the merging of two beam pipes—have HOM absorber material to limit their Q and lower the amount of local resonant heating.

1.6 Beam size and beam emittance

The beam size in the IR influences many aspects of the design. Masking for SR, magnet apertures and beam separation all depend on the size of the beams. The size is determined by the emittance of the beam and the beta functions in the IR. Although the beam emittance is an important IR parameter, the range of this parameter is generally set by other aspects of the accelerator, usually by the circumference of the ring and the design of the lattice for each beam. In some cases, the emittance is increased through the use of wigglers. The beta functions near the IR are usually lower in high emittance accelerators than they are in accelerators that have low emittance in order to keep the beam sizes reasonable. In general, the larger the beam, the more difficult it is to protect the detector from SR; especially the radiation that is emitted from the particles out at a high number of beam sigmas.

1.7 Beam-stay-clear and beam tails

The collision of the two beams induces a disruption in the colliding bunches, which kicks beam particles out to large transverse distances (many beam sigmas) from the beam center and starts to lower the lifetime of the beams. For this reason, as well as to increase accelerator flexibility, the beam-stay-clear (BSC) aperture is usually made as large as possible especially near the IP. In addition, in order to minimize detector backgrounds from lost beam particles, one prefers a beam aperture that gets larger as the beams approach the IP. However, the desire for large beam apertures must be balanced with the need to install masks near the IP for both SR and lost particle backgrounds and the need to keep magnet apertures reasonably sized. The population of particles in these "beam tails" is a major concern in estimating SR background rates. The particles at large transverse distances from the beam center have the best chance of generating photons that can directly strike the detector beam pipe.

2 DETECTOR CONSTRAINTS

The physics detector of a B-factory needs to be as efficient as possible in collecting the interesting physics events. This is the important definition of integrated luminosity—how many physics events are accumulated. Toward this end, the detector imposes some requirements on the accelerator and also complicates the IR by its presence. Some detector needs and constraints are:

- Low backgrounds
- Maximum solid angle for detecting particles
- Smallest possible radius for the beam pipe
- A beam pipe that is as transparent as possible
- A solenoidal detector field of 1–1.5 T

2.1 Low Backgrounds

The beam-related backgrounds, both SR and lost particles, must be kept below a level that allows the detector to operate with minimal impact on detector efficiency. In addition, the radiation levels must also be kept low enough to ensure that detector components have a reasonable (5–10 yr.) lifetime before being damaged. One of the primary ways of keeping the lost beam particle backgrounds low is to have a very low vacuum in the beam pipe upstream of the detector. All B-factory designs ask for a low vacuum in these regions.

2.2 Maximum solid angle

Maximizing the solid angle of the detector means that the space left for accelerator components that are inside the detector is very precious. The beam pipe, supports and magnetic elements must be as compact as possible.

2.3 The detector beam pipe

The beam pipe around the IP needs to have as small a radius as possible to get a precision vertex tracker as close to the collision point as possible. In addition, the beam pipe needs to be as transparent as possible to the emerging physics events and yet be opaque to the SR from the beams. The choice for all three B-factories is a Be beam pipe that is coated on the inside with a high Z material (e.g. Au) to absorb the SR photons.

2.4 Detector magnetic field

The detector has a solenoidal magnetic field with a value in the range of 1-1.5 T. Any accelerator magnets inside the detector field must be either permanent magnet (PM) or superconducting. The detector magnetic field will also steer the beams because the beams are not traveling down the axis of the detector. Each B-factory design has a different approach toward solving these difficulties.

3 B-FACTORY IR DESIGNS

Some of the accelerator parameters that influence the design of the IR and the choices made by the three accelerator designs are listed in Table 1. Comparing B-factory IR designs, we shall see how these parameter selections have influenced each design.

Table 1. Some Parameters of the B-factories

	PEP-II		KEKB		CESR-III	
	e+	e-	e+	e-	e+	e-
E (GeV)	3.1	9.0	3.5	8.0	5.3	5.3
I (A)	2.1	1.0	2.6	1.1	0.5	0.5
β_y^* (cm)	1.5	2.0	1.0	1.0	1.0	1.0
ε_x (nm-rad)	66	49	18	18	251	25
$\sigma(x,y)$ (mm)	181, 5.4		77, 1.9		388, 11.7	
Coupling (%)	3		2		3	
ξ	0.03		0.05		0.03	
S_b (m)	1.26		0.59		4.2	
# of bunches	1658		5027		45	
θ_c (mrad)	head-on		± 11		± 2.1	
L ($cm^{-2}sec^{-1}$)	3×10^{33}		1×10^{34}		1.8×10^{33}	

3.1 PEP-II

As stated earlier, PEP-II has the largest energy asymmetry (9 on 3.1 GeV) of the three designs. This permits the design to have head-on colliding beams. The fairly small bunch spacing (1.26 M) means that a strong horizontal bend magnet (B1) must start separating the beams as soon as possible after the beams have collided. This tapered magnet starts at about 21 cm from the IP and separates the beams enough so that the tune-shift at the first parasitic crossing (0.63 M) is small. Immediately following B1 is the vertical focusing quadrupole (Q1) for the low energy beam (LEB). This horizontally defocusing magnet continues to separate the beams. Separation is maximized by superimposing a dipole field over the quadrupole field, which shifts the magnetic center of Q1 to where the high energy beam (HEB) is located. These two magnets are in the detector field and are therefore permanent magnets. The next magnet (Q2) is a horizontally focusing septum quadrupole for the LEB—the HEB travels through a field free region. The following two magnets (Q4 and Q5) are also septum magnets and are the final focusing doublet for the HEB. Figure 1 shows a plan view of the IR for PEP-II. It is important that Q2 be a septum magnet. If it were a shared magnet, with both beams going through it, a large amount of the beam separation gained in B1 and Q1 would be lost.

The rapid separation of the beams by B1 and Q1 generates significantly high-power fans of SR. The SR fan from the upstream Q1 magnet must be masked from the detector beam pipe and the power absorbed by the mask must be completely removed to maintain a constant temperature for the PM material of B1 and Q1.

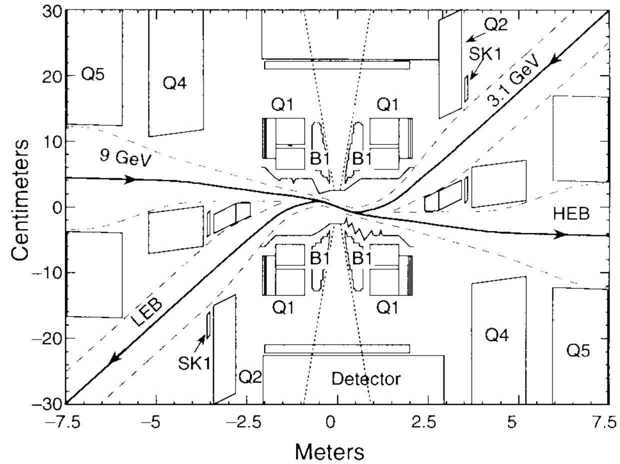

Figure 1. Layout of the interaction region of the PEP-II B-factory. The vertical scale is highly exaggerated. The detector for PEP-II is offset in z by 37 cm in the direction of the HEB.

The SR fans generated by the HEB as it travels through the B1 magnets are very intense. However, the 49 kW of power in these fans do not strike any nearby surfaces and are absorbed in a dump that starts about 12 m away from the IP in the downstream HEB beam pipe. The primary source of SR background is the photons that scatter to the detector beam pipe from the mask tips. Because of this, the PEP-II design is insensitive to SR from the beam tails. Some care must still be taken to ensure that photons generated by particles in the beam tails do not directly strike the detector beam pipe. Once this is achieved, the SR background rates from beam tail particles are much lower than the background rates produced by the photons that scatter from the mask tips.

The design has no room for a compensation solenoid to help cancel the effects the detector field has on the beam orbits. Instead, the location of the IP is allowed to move vertically. This displacement means that the two beams will receive a vertical kick from Q1 which partially compensates the steering effects of the detector field. In addition, the center of the Q2 and Q4 magnets are also vertically displaced by a few mm to further steer the beams before correctors positioned between Q4 and Q5 can be used to continue correcting the beam orbits. A series of skew quads completes the corrections needed to compensate for the effects of the detector field[7].

The two beams go into separate pipes in the Q2 septum magnet so the beam pipe in front of Q2 and behind Q1 is the largest beam pipe in the IR. This local bulge in the beam pipe can trap HOM energy. Some amount of absorber material (e.g. silicon carbide) will be mounted in this chamber to limit the amount of resonant power trapped in this region.

The HEB travels through two bend magnets located between 22 and 27 m from the IP. The magnet closer to the IP is a low field bend magnet, which minimizes the

SR striking the IP region. The magnets sweep out a large fraction of lost beam particles that were produced even farther from the IP. Consequently, the region from these magnets to the IP is the primary source of lost particle backgrounds in the detector for the HEB. The LEB goes through a vertical bend magnet at about 10 m from the IP that is also effective in sweeping out lost beam particles that have been produced further upstream. The PEP-II design calls for a low vacuum in these regions in an effort to minimize lost particle backgrounds. In addition, the PEP-II design includes a graded beam aperture where the aperture gets larger as the beams travel to the IP. This also helps to reduce the background rate from lost particles.

3.2 CESR-III

The accelerator at Cornell is a single storage ring with equal energy beams of 5.3 GeV. The final focus doublet is located close to the IP with the vertical focusing quadrupole made up of two elements. The first is PM material and is positioned very close to the collision point (0.34 m to 0.84 m). The rest of the vertical focusing and all of the horizontal focusing is accomplished by two superconducting quadrupoles (Q01 and Q02). Figure 2 shows a layout of the CESR-III IR.

Cornell has developed a scheme to store many bunches into each beam and still use only one storage ring. Electrostatic plates separate the beams into different orbits around the ring that intersect each other in several places. However, by carefully selecting which rf buckets to fill with charge, they plan to be able to store up to 0.5 A in each beam. In order to get this much current into each beam it is necessary to introduce a small crossing angle of ±2.1 mrads. This allows the beams to be far enough apart at the first parasitic crossing (2.1 m) so that the extra tune-shift is small. The crossing angle introduces some SR due to the bending of the beams in Q01 and Q02, but the power is not high (3 kW) and it is directed nearly forward and should not contribute to detector backgrounds. The small amount of near IR bend radiation means that SR background calculations are dominated by radiation from particles in the beam tails and by upstream bend magnets.

The relatively small circumference of the Cornell ring when compared to the other two B-factories means that it is difficult to get beam emittances that are much below 250 nm-rad for 5.3 GeV beams. This means the maximum β_x value needs to be kept reasonably low in order to keep the x size of the beams manageable. To achieve this, the final focusing elements are close to the IP.

CESR-III has no compensation solenoids. The beams are nearly parallel to and only slightly offset from the detector axis so there is very little beam steering from the detector field. A family of skew quads take out the coupling induced by the solenoidal field.

Since CESR is a symmetric energy accelerator, the masking must be symmetric on either side of the IP. This

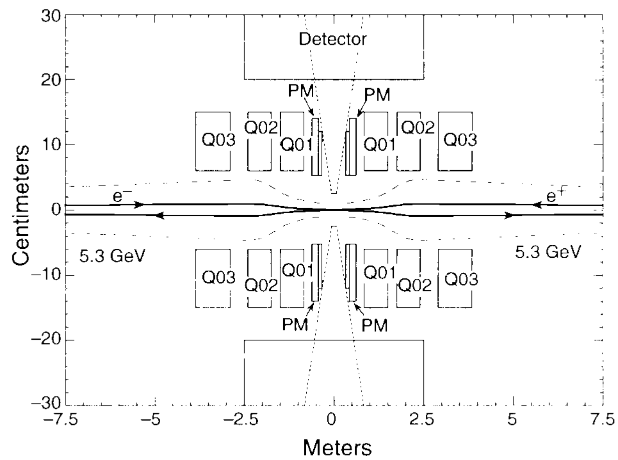

Figure 2. Layout of the CESR-III interaction region. The vertical and horizontal scale are the same as in Fig. 1. The QO3 magnets are not used except for round beam studies.

leads to SR backgrounds that are dominated by photons that strike the inside, or detector beam pipe side, of a downstream mask. These surfaces usually have a fairly large solid angle view of the detector beam pipe so photons that bounce out of these surfaces have a good chance of entering the detector.

The arc magnets begin about 15 m from the IP with the start of a low-field bend magnet. The hard-bend arc magnets are so close to the IP that lost beam particles originating from the start of the arc are swept out into the detector and are a major source of lost particle background. The design asks for a low vacuum pressure in this region.

3.3 KEKB

The B-factory at KEK has beam energies of 8 and 3.5 GeV. This smaller energy asymmetry makes it difficult to collide the beams head-on. This is one reason the KEKB design collides the beams with a crossing angle of ±11 mrads. The large crossing angle helps to separate the beams quickly, which allows the KEKB design to have the smallest bunch spacing (0.6 m) and hence the smallest parasitic crossing (0.3 m). The large crossing angle also helps to separate the beams enough to place the first septum magnets (QC1E) about 3 m of the IP. The design minimizes the bending of the incoming beams, which minimizes the SR that can cause detector backgrounds. This produces an asymmetric lattice design around the collision point (the other two designs have symmetric optics) and concentrates all of the bending of the beams to the downstream side of the IP. The beams are still bent because the first vertically focusing quadrupole (QCS) is shared. QCS is a superconducting quadrupole and the three remaining quadrupole pairs are normal-conducting septum quads. Figure 3 shows the layout of the KEKB design near the IP.

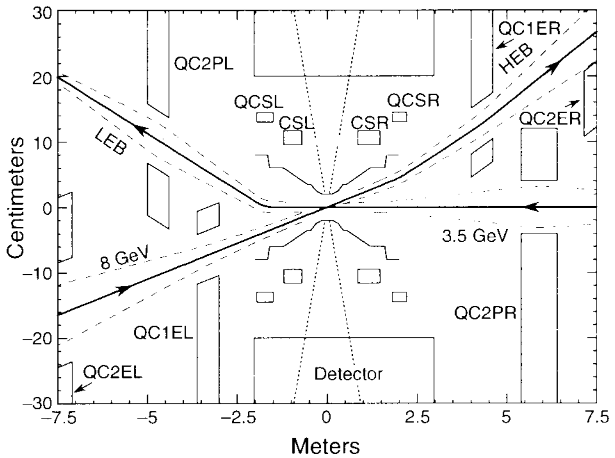

Figure 3. Layout of the KEKB interaction region. The scale matches that found in Figs. 1-2. CSL and CSR are compensating solenoids.

The cyrostats that contain the QCS magnets also contain compensating solenoids that are positioned inboard of the QCS magnets. These two coils together completely cancel the detector integral B•dl seen by the beams by operating at 2-3 times the strength of the detector field.

The KEK design uses the Tristan tunnel to house the storage rings. This tunnel is the largest of the three designs (3016 m in circumference) and this allows the KEKB design to have small beam emittances. These small emittances have made it possible to use larger beta functions near the IP without making the transverse beam size too large, which in turn allows the final focusing elements to be positioned farther from the IP where the beams more separated. The small emittances make it easier to shield the detector from SR, and it also means that the detector backgrounds from SR are almost entirely driven by the particle density in the beam tails, out at high beam sigma.

KEKB also has a single beam pipe near the IP that splits into two pipes, one for each beam, so there is a local cavity that can trap resonant power. Absorber material will be placed in this cavity to limit the resonant power.

Not bending the beams as they approach the IR, significantly lowers the number of SR photons that can cause background in the detector. However, this also tends to lengthen the amount of beam pipe that must have a low vacuum in order to keep the lost particle background at an acceptable level.

4 SUMMARY

Several accelerator parameters influence IR designs of B-factories. The beam energies, β_y^* values, emittances, coupling values, currents, bunch spacing, and collision angles are all important parameters that affect IR designs. The physics detector also has conditions or requirements that must be included in any design. Low backgrounds, maximum solid angle, a small thin beam pipe, and a large solenoidal field are some of the requirements for a B-factory detector.

Of all of these parameters, the selection of the beam energies probably has the largest single impact. The CESR-III design with symmetric-energy beams has the simplest IR. The focusing elements are naturally shared because both beams are in the same ring. A small non-zero crossing angle is utilized to enable the storing of more beam bunches, which increases the current and hence the luminosity. The other two B-factories (KEKB and PEP-II) have asymmetric beam energies (3.5 on 8 and 3.1 on 9 GeV). The different beam energies mean that each beam is in a separate storage ring and that each beam has separate final focusing elements near the IP. Both designs have one shared quadrupole, the vertical focusing quadrupole of the LEB, which helps to further separate the beams horizontally and allows the next final focus element to be a septum magnet. The KEKB design minimizes SR as a source of background by not bending the incoming beams near the IR. This, with the smaller energy asymmetry and small beam emittances leads the design to a crossing angle of ±11 mrads and to different beam optics on either side of the IP. The PEP-II design has a large enough energy asymmetry to be able to collide the beams head-on. However, in order to get the beams far enough apart at the first parasitic crossing, powerful bend magnets are positioned very close to the IP. The final focus optics are kept symmetric, but this means the shared vertical focusing quadrupole generates significant SR on the incoming side that must be masked and absorbed.

Essentially, all three B-factory IR designs have to address the same problems. The design differences primarily occur when initial accelerator parameters are chosen (beam energies, crossing angle, beam emittances, etc.). These parameter decisions lead to IR designs optimized for the particular choices made.

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