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THE BEAM-STAY-CLEAR DEFINITION OF THE PEP-II *B* FACTORY*

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1 ABSTRACT

We describe the definition of the beam-stay-clear (BSC) for the PEP-II project[1], a collaboration of SLAC, LBNL, and LLNL. We devote special attention to the region near the collision point where both beams, the low-energy beam (LEB)[2] and the high-energy beam (HEB)[3] have large β function values. The BSC of each beam is defined so as to maximize the flexibility of the accelerator design while at the same time satisfying the mechanical constraints imposed by getting the beams separated after collision and by keeping the beams inside the good field region of the final focusing magnets[4]. The beam separation scheme, which plays an important role in the BSC definition, is also described. The flexibility of the design is explored by studying various parameter values for luminosity, tune shift, β_y^*, and vertical-to-horizontal beam aspect ratio and verifying that the beam envelopes generated by these changes remain inside the defined BSC.

2 INTERACTION REGION

The 9.0 GeV HEB and the 3.1 GeV LEB of the PEP-II *B* factory collide head-on at the interaction point (IP). The beams are brought into collision by two horizontal dipole magnets (B1) located between 21 and 70 cm on either side of the IP. The magnets are tapered in order to maximize the detector angular acceptance. The two beams share one more magnetic element (Q1) which is located just behind each B1 magnet (from 90 to 210 cm from the IP). Q1 is a hybrid magnet in that it contains a dipole field and a quadrupole field. The quadrupole field supplies vertical focusing to both beams. The dipole field shifts the magnetic center of the quadrupole field so that the HEB essentially goes through the magnetic center of Q1. This configuration produces the maximum amount of horizontal beam separation in Q1 by bending the LEB away from the HEB. Both B1 and Q1 are made of permanent magnet material. The fact that these magnets are immersed in the detector solenoidal field plus the need for a compact design led to the choice of a permanent magnet. The separation of the beams by B1 and Q1 is enough to allow the next machine element (Q2) to start 2.8 m from the IP. Q2 is the horizontal focusing magnet of the final doublet for the LEB and is a septum magnet which has a field-free channel for the HEB. The next two machine elements are septum quadrupoles Q4 and Q5 which form the final-focus doublet for the HEB. Figure 1 is a layout of the interaction region (IR) out to ±7.5 m.

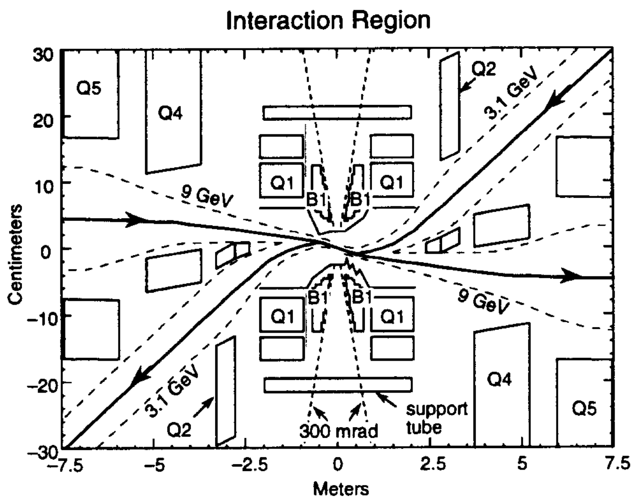

Figure 1. Layout of the interaction region of PEP-II showing the separation of the two beams. The dashed lines marked "300 mrad" define the angular acceptance of the detector. Note the exaggerated vertical scale.

The maximum beam size near the IP is set by the amount of beam separation at Q2 and by the magnet apertures of Q1, Q2, Q4, and Q5. In addition, the PEP-II design incorporates a graded aperture philosophy near the IP. The intent is to make sure that the beam pipe and fixed mask apertures near the IP are larger than the rest of the ring apertures. This keeps detector backgrounds to a minimum by limiting the number of beam particles that get lost near the IP.

The four IR magnets (Q1, Q2, Q4, and Q5) must all have excellent field quality. The β functions are very large in these magnets and a poor magnetic field in any one of these magnets severely shrinks the machine dynamic aperture.

3 BSC DEFINITION

In general, one would like to make magnet apertures and beam pipes as large as possible in order to maximize the flexibility of the accelerator design. However, realis-

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tic constraints on the size of the beam; beam separation, magnetic field quality, graded aperture, and masking for synchrotron radiation backgrounds limit the size of the beams. Table 1 describes a BSC definition for the PEP-II accelerator which satisfies these constraints and at the same time includes an accelerator design that is as flexible as possible.

Table 1. Definition of the PEP-II BSC.

HEB			$\beta^*_y = 1.5$ cm $\beta^*_x = 50$ cm	
z (m) from IP	Emittance (nm-rad) Horiz. ε	Vert. ε	BSCx	BSCy
0-30	50	25	15σ+2 mm	15σ+2 mm
30-60	100	25	12σ+5 mm	12σ+5 mm
60+	75	37.5	12σ+10 mm	12σ+5 mm
LEB			$\beta^*_y = 1.5$ cm $\beta^*_x = 50$ cm	
z (m) from IP	Emittance (nm-rad) Horiz. ε	Vert. ε	BSCx	BSCy
0-14	100	50	15σ+2 mm	15σ+2 mm
14-60	100	50	12σ+5 mm	12σ+5 mm
60+	100	50	10σ+10 mm	10σ+5 mm

The emittances shown in table 1 are uncoupled ($\varepsilon_x+\varepsilon_y$) for x (horiz.) and fully coupled (($\varepsilon_x+\varepsilon_y$)/2) for y (vert.). The calculation of the beam σ also includes dispersion added in quadrature. The extra mms on the BSC definitions allow for closed orbit distortions.

4 MACHINE FLEXIBILITY

The beam size constraints mentioned above essentially set limits on the size of the beam divergence angles at the IP defined as $\sigma'_x = \sqrt{\varepsilon_x/\beta_x}$ and $\sigma'_y = \sqrt{\varepsilon_y/\beta_y}$ where the emittances are the nominal colliding beam values. A machine flexibility study was made in which the accelerator design was altered by changing three basic parameters of each beam: the tune shift, the β^*_y value and the beam aspect ratio. The accelerator model assumes energy transparent scaling relations for the colliding beams[5]. Namely, that both beams have the same transverse dimensions at the IP and that the horizontal and vertical tune shifts are equal for each beam. The beam currents were limited to 3A and the total emittance of each beam was limited to 100 nm-rad. In addition, the natural emittances of 39 nm-rad for the HEB and 24 nm-rad for the LEB were treated as minimums. In a few cases the beam bunch spacing was altered in order to change the emittances of the beams. Table 2 summarizes the machine parameters that were changed and the range of variation for each parameter.

Whenever possible, the luminosity was kept at or above the nominal value of 3×10^{33} cm^{-2} sec^{-1}. A total of 20 machine configurations were studied. The first three configurations are listed in Table 3. The first case in table 3 lists the parameters for the nominal machine design. The second case shows the machine design that is used to define the BSC for the 0-30 m section of the HEB and the third case lists the parameters for the design that defines the BSC for the LEB.

Table 2. Range of the parameters varied in the machine flexibility study.

Machine parameter	Range
HEB tune shift (ξ_{e-})	0.02 – 0.05
LEB tune shift (ξ_{e+})	0.01 – 0.05
HEB β^*_y	1.0 – 3.0 cm
HEB β^*_y	1.0 – 3.0 cm
Beam aspect ratio (v/h)	0.0143 – 0.04
Beam current limit	3 A (both beams)
HEB emittance	39 – 100 nm-rad
LEB emittance	24 – 100 nm-rad

Table 3. The standard machine design and the two machine designs that define the BSCs. The shaded numbers are the maximum values allowed for the IP divergence angles based on the BSC definitions.

Parameter	Machine configuration Nominal	HEB BSC definition	LEB BSC definition
HEB tune shift ξ	0.03	0.03	0.03
LEB tune shift ξ	0.03	0.03	0.03
HEB β^*_y (cm)	2.0	1.5	3.0
LEB β^*_y (cm)	1.5	1.5	1.5
Aspect ratio v/h	0.03	0.03	0.03
HEB $\eta_x = \eta_y$	0.0	0.0	0.0
LEB $\eta_x = \eta_y$	0.0	0.0	0.0
HEB I (A)	1.00	0.75	1.49
LEB I (A)	2.16	2.16	2.16
HEB ε_x nm-rad	49	49	49
LEB ε_x nm-rad	66	49	98
HEB ε_y nm-rad	1.48	1.48	1.48
LEB ε_y nm-rad	1.97	1.48	2.95
HEB $\sigma_x'=\sigma_y'$ μrad	272	314	222
LEB $\sigma_x'=\sigma_y'$ μrad	362	314	444

A particular machine design had to have IP divergence angles that were less than or equal to the shaded numbers above in order to qualify as fitting inside the BSC envelopes. In addition, the divergence angle made by a $15\sigma_y$ fully coupled beam, produced by the two BSC defining designs in table 3, was also considered an upper limit for any machine design. This criteria was not met in all cases. This usually occurred when the total emittance of one of the beams was large. It was felt that all possible machine designs must meet the minimal requirement of a $10\sigma_y$ fully coupled beam fitting inside the BSC in order for vertical injection to be efficient. The low emittance injected beam is launched into the stored beam at $8\sigma_y$ fully coupled. All 20 machine designs investigated met this requirement. In fact, all but one design fit at least a $12\sigma_y$ fully coupled envelope into the defined BSC space.

4.1 *Nominal beam energy configurations*

Of the 20 machine configurations, 17 use the nominal beam energies of 9.0 GeV and 3.1 GeV. Of these 17, seven are cases in which the tune shifts are low (0.02). Machine designs with low tune shifts are the most difficult to contain inside the BSC envelopes and still achieve the design luminosity. This is usually because these designs tend to have larger emittances in order to get a luminosity value that is back up to near the nominal value. In general, adjusting the beam aspect ratio helps in getting the beams to fit inside the BSC envelopes.

One of the most difficult cases has an LEB tune shift of 0.01, an HEB tune shift of 0.02, twice the normal bunch spacing (2.52 m, which increases the beam emittances for the same luminosity) and β^*_y values of 1 cm. This particular design achieves a luminosity of only 1×10^{33} cm^{-2} sec^{-1} with a beam aspect ratio of 0.0143. This design also has the smallest vertical aperture of $10\sigma_y$ fully coupled mentioned above. All seven cases of low tune shifts have luminosity values that are below nominal. They range from 1 to 2.4×10^{33} cm^{-2} sec^{-1}.

Three of the 17 designs investigated machines that achieved higher than nominal luminosity. High tune shifts (0.05) and low β^*_y values (1 cm) allow for a luminosity of 1×10^{34} cm^{-2} sec^{-1}. The low emittance of these high luminosity designs makes them easy to fit inside the BSC envelopes.

4.2 *Designs with 12 on 2.46 GeV beams*

The three remaining cases with beam energies different from the nominal values were designs with beam energies of 12.0 GeV and 2.46 GeV. These energy settings are for running at the Upsilon(5S). At 12 GeV the HEB has a lower limit for the emittance of 55 nm-rad. The three cases differ by the anticipated tune shifts for each beam. The first case assumes equal tune shifts of 0.03. In this case the LEB β^*_y is lowered to keep the LEB current at 3A. Further lowering of the LEB β^*_y (to 1.25 cm) allows the luminosity to increase (to 4×10^{33} cm^{-2} sec^{-1}) while maintaining a beam current of 3A for the LEB and an emittance of 53 nm-rad for the HEB. The second case has tune shifts of 0.04 and 0.025 for the HEB and LEB respectively. In order to increase the HEB emittance up to the minimum of 55 nm-rad, the bunch spacing was increased from the nominal of 1.26 m to 1.89 m. Lowering the LEB β^*_y, as in the previous case, again leads to a luminosity of 4×10^{33} cm^{-2} sec^{-1}. The third case has tune shifts of 0.05 and 0.02 for the HEB and LEB respectively. This time the bunch spacing has to be increased to 2.52 m in order to get the HEB emittance up to 67 nm-rad. Lowering the LEB β^*_y to 1 cm attains a luminosity of 3.3×10^{33} cm^{-2} sec^{-1}.

5 SUMMARY

The BSC definitions of the PEP-II *B* factory, while producing as large a beam envelope as possible in order to maximize the flexibility of the accelerator design, also satisfies the physical constraints imposed on the beam sizes near the interaction region. The separation of the beams and the need for a high quality magnetic field inside the quadrupoles near the interaction point both set limitations on the size of the beam envelope. In addition, PEP-II has adopted a graded aperture design where the BSC near the interaction point is larger than anywhere else in the ring in order to minimize detector backgrounds especially during injection. These constraints essentially set an upper limit on the divergence angle of the beam at the collision point. The flexibility of the machine design was investigated within the defined BSCs by varying beam tune shifts, β^*_y values and the vertical to horizontal beam aspect ratio. Reasonable limits were set for the beam currents (less than 3A) and emittances (less than 100 nm-rad) for both beams in any particular design. Machine configurations with low tune shifts are the most difficult to fit inside the BSC and still produce a luminosity near the nominal value of 3×10^{33} cm^{-2} sec^{-1}. High tune shift (0.05) configurations were found that produce high luminosity (1×10^{34} cm^{-2} sec^{-1}) and easily fit inside the BSC envelopes. Configurations with beam energies of 12 and 2.46 GeV were also investigated which were able to produce at least the nominal luminosity and still fit inside the defined BSC envelopes.

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