SLAC-PUB-95-6714

STATUS OF THE PEP-II ASYMMETRIC B-FACTORY

THOMAS S. MATTISON*
Stanford Linear Accelerator Center, Stanford University, Stanford CA 94309

for the SLAC/LBL/LLNL B-Factory Accelerator Group

ABSTRACT

The PEP–II project is an e^+e^- storage ring complex with unequal energy beams to study CP violation in the B meson system. High luminosity requires a large number of bunches and a low value of beta at the collision point. The high beam current requires advances in vacuum chambers, damped RF cavities, and feedback systems. Machine elements inside the detector are required to achieve low beta values and magnetic separation.

1. Overview

The PEP–II project[1] is an e^+e^- colliding beam storage ring complex with a design luminosity of 3×10^{33} cm^{-2}s^{-1}. This is sufficient to produce about 30 million $B\overline{B}$ meson pairs a year on the $\Upsilon(4s)$ resonance. The two beams have unequal energies so the resulting B mesons are boosted in the laboratory frame, and their decays can be resolved by a precision vertex detector. The large event sample with resolved decays will allow measurements of CP violation in B decays. Several different decay modes will be accessible, allowing precise consistency checks of the Cabibbo-Kobayashi-Maskawa (CKM) model of CP violation.

PEP-II is being built on the SLAC site by a collaboration of Lawrence Berkeley Lab (LBL), Lawrence Livermore National Lab (LLNL), SLAC, and other international collaborators. The two rings are being built in the PEP tunnel. No civil construction is required. Project approval was granted in October, 1993, with completion planned for late 1998. Total project cost for the accelerator is estimated to be \$177 million (then-year). A Letter of Intent[2] has been written by a broadly international collaboration for a new detector, BABAR, for the single interaction point (IP). The detector cost is estimated as \$75-80 million, with a substantial fraction from non-US sources. Completion of the detector is estimated for early 1999.

2. Luminosity and Asymmetry

The PEP-II design luminosity is 50 times the luminosity achieved by PEP-I, and 10 times that achieved by CESR. The non-linear focussing effect of one beam on the other (quantified by the beam-beam tune-shift ξ) limits the achievable current density

*Work supported by U.S. Department of Energy contracts DE-AC03-76FS00098, DE-AC03-76SF00515, DE-AC03-81-ER40050, DE-AS03-76ER70285, and W-7405-Eng-48

Work supported by Department of Energy contract DE–AC03–76SF00515.

Parameter	HER	LER	Units
Peak Luminosity	3.0×10^{33}		$\mathrm{cm}^{-2}\mathrm{s}^{-1}$
Circumference	2219		m
Number of bunches	1658	1658	
Particles per bunch	2.73×10^{10}	5.91×10^{10}	
Beam current	0.986	2.140	Amps
Beam energy	9.000	3.109	GeV
Bunch length	1.0	1.0	cm
Horizontal emittance	48.2	64.3	nm-rad
Horizontal IP beta	50.0	37.5	cm
Horizontal IP spot size	155	155	μm
Horizontal tune-shift	0.03	0.03	
Vertical emittance	1.93	2.57	nm-rad
Vertical IP beta	2.00	1.50	cm
Vertical IP spot size	6.2	6.2	μm
Vertical tune-shift	0.03	0.03	

Table 1. PEP-II Parameters

in the colliding bunches. It is prudent to design an asymmetric energy machine so its beam-beam behavior can be made as similar to a symmetric machine as possible. To achieve this, it is necessary that $(EI/\beta_y^*)^+ = (EI/\beta_y^*)^-$, where E is the beam energy, and I is the beam current. In this case, the luminosity can be written $\mathcal{L} = (2.17 \times 10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}) \times (1+r)\,\xi_y(EI/\beta_y^*)^{\pm}$ where $r = \sigma_y/\sigma_x$, E is in GeV, I is in amperes, and β_y^* is in cm. The PEP-II design assumes a conservative $r \approx 0$ and $\xi = 0.03$ (PEP-I achieved $\xi \approx 0.05$ in multiple interaction regions). High luminosity is achieved by low β_y^* and a large number of bunches. The parameters of PEP-II are given in Table 1.

High currents require more RF power, and thus more synchrotron radiation (SR) power on the beam pipe. Synchrotron radiation and its heating desorb gas from the beam pipe, which tends to reduce beam lifetime and increase backgrounds. High currents also increase the likelihood of beam instabilities, requiring special design of the RF system, and feedback systems to stabilize the beam. The close bunch spacing allows "parasitic collisions" (not at the low-β point) which add disproportionately to the tune-shift. The beams must therefore be brought together and separated again as close to the IP as possible. Lowering β increases the sensitivity of the machine optics to the energy spread of the beam, unless the focussing magnets are brought closer to the IP, which obstructs the detector solid angle. The bunch length must also be shortened as β is reduced, which requires more RF voltage.

3. Injector

The injector for PEP-II is the SLAC linac, plus the SLC damping rings and positron system.[3] The e^- and e^+ are extracted from the linac at their ring injection energies, and transported in the linac tunnel in separate bypass lines. This avoids the decelerations and miles of linac wakefields that characterized both PEP-I and PEP-SLC injection in the past. Both e^- and e^+ are damped, and injected with emittances lower than the equilibrium in the collider rings. With 10% of the SLC intensity and half the SLC rate, simultaneous topoff of both rings from 80% to 100% full takes only 3 minutes (topoff will be required every 30-60 minutes). Filling from 0 to 80% takes 3 minutes at higher linac intensity.

Magnets for the bypass lines have been ordered. Installation of the linac e^- extraction point and both bypass lines will occur in Summer 1995. The existing PEP injection line magnets and tunnels will be re-used, with new vacuum and instrumentation systems. This work can be done while SLC is running.

4. Magnets and Vacuum Systems

The PEP-I dipoles and sextupoles will be used for the High Energy Ring of PEP-II after refurbishment. The longer PEP-I quads will be cut and/or restacked to match the shorter PEP-I quads before being refurbished for the HER. About 100 new quad coils will be required, perhaps made in collaboration with Novosibirsk. All magnets have now been removed from the PEP straight sections, and 4 of the 6 arcs. About 30% of the dipoles have been refurbished, and 3-5% of the quads and sextupoles. Mounting plates will be installed in the tunnel floor starting August 1994. The first dipoles will be installed in January 1995, and the first quad-sextupole units in July 1995.

The Low Energy Ring is mounted above the HER, with the same number and length of arc cells. The bend magnets are strong and short to increase the emittance and damping rate One straight section is devoted to wigglers, to further increase the emittance and damping. Total wiggler SR power is comparable to the bend SR power. All LER magnets will be new, with LBL responsible for construction, probably in collaboration with IHEP/Bejing. Production is scheduled to begin in Fall 1995, with completion in mid-1997. Start of LER installation will be in Spring 1996, and will overlap HER installation.

There will be 3.5 MW of SR power on the walls of the HER, compared to 5.4 MW for PEP-I. The HER arc vacuum sustem is made of copper, for 10 times less gas desorption than aluminum, and better SR shielding.[4] The dipole chambers are 5 m long copper extrusions with steel flanges, electron-beam welded to water-cooled copper bars, with distributed ion pumps (non-evaporable getter pumps may also be included). The quad chambers are also copper, with pump ports, beam-position-monitors, and bellows protected by RF-shielding fingers and SR masks. The electron-beam welder contract has been awarded, with delivery in June 1995. The copper extrusion bids have been received, and the contract will be awarded in August 1994.

Since the LER bends are short, the SR power hits the beam pipe between magnets, and distributed ion pumps in the bends cannot be used. Instead, grazing-incidence copper photon stops with local pumping will be located on extruded aluminum beam pipe between magnets in the LER. This is similar to modern synchrotron light sources like ALS at LBL[5] and APS at Argonne National Lab. The LER extrusions will be ordered by the end of 1994, with first units scheduled to be done by the end of 1995.

5. RF and Feedback Systems

The PEP-II RF system[6] must supply megawatts of power to overcome SR losses, and supply a large overvoltage to shorten the bunches to 1 cm, with a low enough impedance in the fundamental and higher order modes (HOMs) that the beam remains stable. This is accomplished by minimizing the number of cavities (24 in the HER, 10 in the LER), having only a single cavity per RF feed waveguide, and shaping the cavities to minimize the number of trapped HOMs. The HOMs are also damped via extra waveguides that propagate HOMs to loads but are cut off for the fundamental mode. The cavities are copper rather than superconducting, because most of the power goes to the beam rather the cavity walls anyway, and coupling the high fundamental mode power and damping the HOM power is more complicated for superconducting cavities. There are 5 klystrons for the LER, and 6 for the HER, using the PEP-I surface halls and waveguide penetrations.

Since the beam current can induce a larger cavity voltage than the klystron, a fast feedback system is necessary to stabilize the cavity phase. This in turn requires a high bandwidth klystron, which is being developed in under an agreement between SLAC and Varian, to be tested by the end of 1994. To maximize the feedback bandwidth, fast waveguide is used between the klystrons and cavities, and the cavity phase error is also corrected again after a 1-turn delay.

Since some of the 1658 multibunch modes (times 3 for x, y, and E) are still expected to be unstable, PEP-II will also have bunch-by-bunch fast feedback systems. The longitudinal system measures the arrival time of each bunch at pickup electrodes, fits a synchrotron oscillation to the data over multiple turns, calculates the energy error, amplifies the error signal (2 kW at 1 GHz), and corrects the energy with a fast longitudinal kicker. The implementation uses digital signal processors, each handling several bunches. The transverse system measures the position of each bunch using 4 pickup electrodes at two places about $\pi/2$ apart in betatron phase, mixes the signals to produce position and slope errors, digitizes the error signals and delays them for one turn, amplifies the error signal (250 W at 120 MHz), and corrects the slope with a fast transverse kicker. The implementation is a mix of analog and digital components. Longitudinal system prototypes have been successfully tested at SPEAR and at ALS.[7] A high-gain longitudinal kicker is now installed at ALS, and will soon be operated at high-current in closed-loop mode. The next PEP-II longitudinal prototype will *be* the ALS feedback. A prototype transverse system has also been tested at ALS successfully.

6. Interaction Region

The PEP-II interaction region (IR) must separate the high energy beam (HEB) from the low energy beam (LEB) by a few millimeters before the first parasitic collision at 62 cm from the IP, focus both beams despite a 3-fold energy difference, and not produce large SR or lost-particle backgrounds. The energy difference requires that the beams be in separate focussing quadrupoles as close to the IP as possible. The PEP-II design (see Fig. 1) uses head-on collisions with magnetic separation, avoiding synchro-betatron coupling. The bend direction reverses across the IP, which simplifies the SR masking problem, and also facilitates upgrades to a crab-crossing topology

The B1 bend starts only 20 cm from the IP, and separates the beams before the first parasitic collision. The Q1 quad starts 80 cm from the IP, and gives final vertical focussing to both beams. The HEB is centered in Q1 to minimize hard synchrotron radiation, while the LEB is off-axis, so Q1 contributes to beam separation. The LEB is focussed horizontally by Q2, while the HEB travels through a field-free hole in the Q2 iron. Q4 and Q5 focus only the HEB, with field-free holes for the LEB.

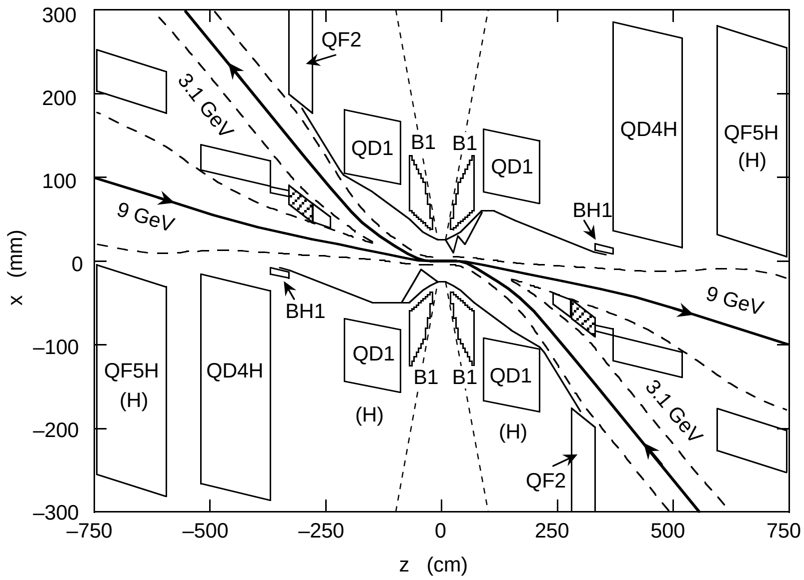

Fig. 1. PEP-II Interaction Region Layout

Both B1 and Q1 are inside the 15 kG detector solenoid field. They are SmCo segmented permanent magnets, similar to the final CESR quads inside CLEO. B1 is tapered to clear the 300 mrad detector acceptance. A superconducting version of Q1 is also under consideration. The IP beam pipe is beryllium with a 25 mm radius, 0.5% of a radiation length thick, and cooled by gas flow (or perhaps water). The IP beam pipe, the silicon vertex detector, the B1 and Q1 magnets, and the synchrotron radiation masks are built into a rigid support tube through the detector. The central piece of the tube is made of 0.5% radiation length thick carbon fiber.

7. Backgrounds

Synchrotron radiation backgrounds have been calculated from all IR bends and quads, for the beam core plus pessimistic tails. Masks prevent SR from hitting the IP beam pipe directly, and are sloped so fluorescence cannot reach the IP beam pipe either. The EGS program was used to model scattering of SR photons through the tips of the masks, and penetration through the IP beam pipe and silicon. Backscatter backgrounds have been estimated (by hand) to be much smaller than tip scattering. The result is 7 photons/μsec in the first silicon layer, compared to limits of 500/μsec from occupancy, or 1650/μsec from radiation damage. Drift chamber backgrounds are negligible. The SR backgrounds are tolerable despite the large currents and bends close to the IP because B1 is too close for its SR to hit the IP directly, the S-bend scheme minimizes backscatter from downstream masks, and LEB photons are soft and easily absorbed in the beam pipe. The silicon vertex detector has such a high channel density that it has a high background tolerance, and it also shields the more sensitive drift chamber outside it.

Backgrounds from lost beam particles have also been calculated using the Decay TURTLE program. Beam-gas Coulomb scattering and Bremsstrahlung was simulated in the IR (0.2 nTorr) and the last half-arc upstream (10 nTorr). A graded aperture of 10, 15, and 20σ enforced by collimators in the IR was assumed. Beam particles and radiated photons that hit within 2 meters of the IP were input into an EGS model of the beamline, detector, and detector response. The results are shown in Table 2. The backgrounds are dominated by upstream Bremsstrahlung that is over-bent by the Q1 and B1 magnets. The backgrounds are below the tolerances by a substantial margin.

	First Si layer	Second Si layer	Third Si layer	Drift Chamber	CsI Calorimeter
Hits per μsec	20	14	7	0.4/layer	0.8
Dose (krad/yr)	10	3.3	0.8	0.001 C/cm/yr	0.009
Detector Limits					
Hits per μsec	140	260	360	7-30/layer	80
Dose (krad/yr)	200	200	200	0.1 C/cm/yr	20

Table 2. Average Occupancy and Radiation Dosage from Lost Particle Backgrounds.

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