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PEP II: SLAC-BASED ASYMMETRIC B FACTORY*

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Abstract

The proposal for upgrading the existing PEP collider at SLAC to enable the copious production of boosted B mesons is the result of several years of collaborative study by groups representing LBL, LLNL and SLAC. The PEP II design has evolved in a considered fashion from its initial conceptualization to a very advanced level of understanding, well-substantiated by R&D results on the key design issues. We describe the proposed upgrade, review the early conceptual decisions, outline the significant remaining questions, and briefly describe current results from the ongoing R&D effort which have shown these questions to be tractable and the initial concepts to be sound.

INTRODUCTION

Three laboratories, LBL, LLNL and SLAC, have jointly proposed[1] PEP II, an upgrade of the existing PEP collider to bring 9.0 GeV electrons and 3.1 GeV positrons into collision at a design luminosity of 3×10^{33} cm^{-2} s^{-1}.

Below we describe PEP II and show how it takes advantage of existing and, in some cases, unique capabilities of SLAC beams, beam lines, tunnels and conventional facilities. Next, we review the early strategic decisions leading to this specific conceptualization. The adopted strategy was based upon the judgment that the remaining unanswered questions could be dealt with through a vigorous R&D program. Following is a description of the subsequent R&D programs ongoing for several years at many laboratories. Positive results are now available affirming the soundness of the initial directions taken.

In addition to the engineering R&D effort other studies are taking place. These include beam injection and interaction region (IR) design paying attention to the detector interface. Some goals for the continuing R&D program are mentioned.

PEP II: WHAT IT IS

The PEP II upgrade to an Asymmetric B Factory will convert the existing single-ring machine to one having two rings with a single interaction region. The differing energies of the two beams (hence asymmetric) will provide a boost to the collision center of mass at 10.6 GeV, the mass of the Υ(4S), that will allow the measurement of decay lengths for detection of CP violation in the decay of B^{o} mesons. Both rings will be contained within the existing PEP tunnel of 2.2 km circumference. The high-energy ring (HER), which circulates electrons, will be constructed using the refurbished dipole, quadrupole and sextupole magnets from the existing PEP ring. The second, low-energy ring (LER) will be constructed of all new components and will be supported above the HER.

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In order to bring the beams into collision the positrons will be lowered to the level of the electron ring by vertical bending magnets and then the beams will be brought into head-on collision by manipulating the trajectories in the horizontal plane with dipole and quadrupole magnets.

The high-intensity low-emittance SLAC electron and positron beams developed for the SLC will be retained and used to the fullest advantage to ensure a robust, reliable injection system. These transversely damped beams will be extracted at the appropriate point along the linac for their respective energies and transported in two parallel-bypass lines in the linac housing to connect to existing PEP injection lines.

PEP II PARAMETERS: WHY IT IS

The primary factor influencing the strategic choice of the PEP II design parameters is the need for a high-circulating current (see below). The parameters chosen were judged to create a context in which the most-significant remaining questions were tractable and could be verified by a vigorous R&D program. This is illustrated here starting with an earlier formulation for luminosity[2]:

$$L = 2.17 \times 10^{34} (1+r)\, \Delta\nu\, (E I / \beta^*_y)^{\pm} \quad (1)$$

where the parameters and their ranges are: Flat beams ⇔ $0 \le r \le 1$ ⇔ round beams; $\Delta\nu$ is the beam-beam tune shift, which is nominally 0.03 (a reasonable choice for a limited-range parameter which is not truly free), E is the beam energy (GeV) and is determined mainly by the physics, 9.0 GeV for e^- and 3.1 GeV for e^+. β^*_y is the vertical beta function (cm) at the IP and is limited to be ≥ 1 cm by bunch length and optics considerations.

I is the beam current (amperes), which is the only remaining free parameter. Thus a luminosity of 3×10^{33} cm^{-2} s^{-1} will require a beam-current value on the order of 1 ampere. The ± indicates that E, I, and β^*_y are evaluated for each ring separately.

Collective Effects and Synchrotron Radiation

The most significant challenges associated with the high current required for a B factory are those associated with *synchrotron radiation* (SR) and the phenomena referred to as *collective effects*. The high level of synchrotron radiation power creates high thermal loads and a large dynamic gas load (see below). The implications of the latter are less widely known so for clarity we add a note here.

In this context collective effects are modifications of beam behavior due to beam-induced forces, such as beam-induced wakefields (RF fields in the vacuum chambers and RF cavities). Forces on circulating currents are naturally characterized by their impedances. In the frequency domain a broadband impedance is used for the *single-bunch collective instabilities.* Whereas, the *multibunch-collective instabilities* are influenced by the narrow-band impedance.

The broadband impedance in a machine is generally due to discontinuities in the vacuum chamber and is distributed around the circumference of the ring. The primary sources of the narrow-band impedance are the unwanted higher-order modes (HOMs) excited in the high-Q RF cavities. These can only be controlled by limiting the number of cavities and clever cavity design.

Simply stated, then, to achieve a high-circulating current a choice is made of whether it is best to have a large charge in a small number of bunches or a smaller charge in a large number of bunches. In one case, the single-bunch instabilities may limit performance and the broadband impedance must be made smaller. In the second case, which is unavoidable for B factories, the narrow-band impedance must be limited to control the multibunch instabilities.

Achieving High Current

For PEP II it was decided that the single bunch parameters should be made similar to those routinely used in existing machines. This means that constructing a machine with a value for the broad-band impedance similar to the existing PEP ring (about 1 Ω) will suffice. The high current is achieved by increasing the number of bunches to 1658 in each ring. Multibunch instabilities will be controlled by reducing the narrow-band impedance and providing a feedback system to give the remaining stabilization. A short list of important PEP II parameters are given in Table 1. The fact that PEP II has two rings for asymmetric energies means that another possible multibunch effect, that of parasitic-bunch crossings (bunches passing at points other than the interaction point) is minimized. Two rings also divide the high power deposition from synchrotron radiation.

Table 1. PEP II, Short List of Parameters

Rings:	e^-		e^+
Energy (GeV)	9.0		3.1
Luminosity (cm^{-2} s^{-1})		3×10^{33}	
Plane of Separation		Horiz.	
Tune shift ξ (or $\Delta\nu$)		0.03	
No. of Bunches per ring		1658[a)]	
Bunch Spacing (m)		1.26	
Bunch Current (mA)	0.89		1.29
Beam Current (A)	1.48		2.14
Beams at the Interaction Region:			
β_y^* (cm)	3.0		1.5
β_x^* (cm)	75.0		37.5
Vert. size, σ_y^*(μm)		7.4	
Horiz. size, σ_x^*(μm)		186	

a) Assumes 5% gap in beam for ion clearing.

R&D PROGRAM

With this decision the technical challenges for the R&D program become:

- Design of RF cavities and a feedback system to control multibunch instabilities.
- Vacuum chamber design for high-power SR.

Damped RF Cavity R&D

The focus of this effort is to design and build a cavity that suppresses the HOMs, thus reducing the narrow-band impedance. A unique new design has now been developed[3] using a broad-band technique for damping these modes. This design incorporates damping waveguides into the cavity that are positioned to couple to the HOMs and propagate these frequencies to a load while only slightly perturbing the fundamental mode (because it is below the waveguide cutoff frequency). The cavities and waveguides are constructed of room-temperature copper.

A prototype cavity has been constructed (see Fig. 1) and is now being tested. In this figure can be seen the three rectangular damping waveguides placed 120° apart azimuthally about the beam axis. Some preliminary test results from this cavity are shown in Fig. 2. For comparison, the magnitudes of the excited modes are plotted versus frequency for the case where the damping waveguides are plugged and again when the plugs are removed. The fundamental mode at 476 MHz is indiscernibly perturbed while the especially-dangerous monopole mode TM011 has been suppressed to a Q=30, well below the acceptable target value of 70.

Work on the cavity design and the low-power tests will continue but we are now planning, along with Chalk River Laboratory (CRL), for the construction of a high-power test cavity to demonstrate satisfactory cavity cooling. A 500 kW, 476 MHz klystron has been fabricated and operated on a test stand at SLAC.

Cavity and RF window tests will commence in about one year.

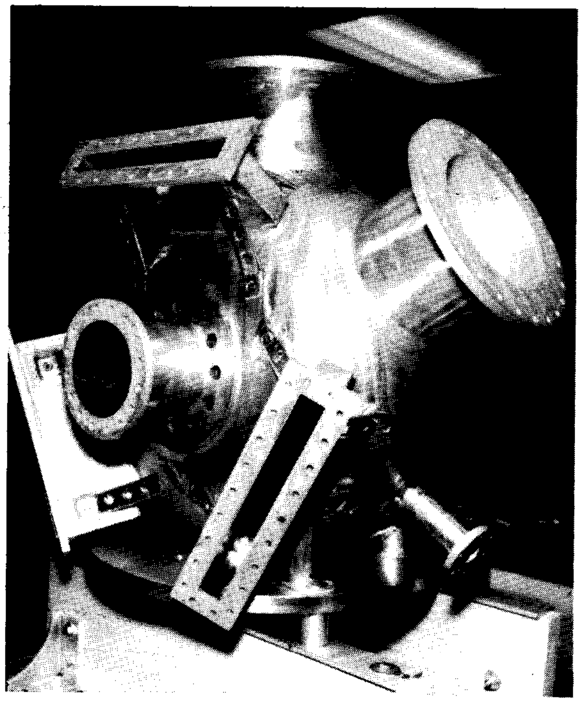


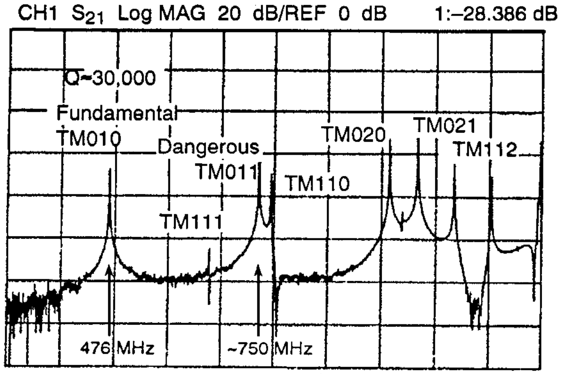
Fig. 1. PEP II low-power cavity prototype.

Longitudinal Feedback System R&D

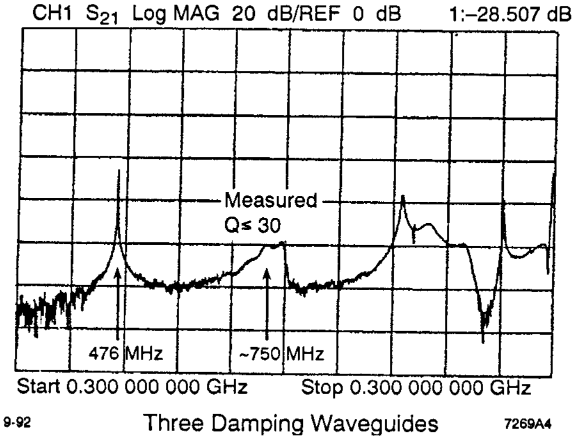
Suppression of the HOMs in the RF cavities, though highly effective, is not complete. There will still remain weak wakefields sufficient to generate multibunch instabilities if left unchecked.

The solution to controlling these oscillations of bunch phase with respect to the RF drive is to measure the phase error for each of the 1658 stored bunches, compute a correction and apply this correction by a kick in energy 90° later in synchrotron phase. A schematic of this feedback system[4] is shown in Fig. 3, where it is seen that the key ingredient is a farm of digital signal processors (DSPs) that operate in parallel to compute the correction signal to be applied to each bunch energy. A signal proportional to the phase offset of each bunch is detected on each turn and, because the synchrotron tune is near 0.05, there are more than 20 samples taken per synchrotron oscillation. This is an overabundance of measurements for the determination of the phase of a single-frequency sine wave and so only every fourth sample need be taken. This technique, called "down sampling," allows a factor of ten reduction in the number of DSPs required when compared to initial estimates.

A prototype system for PEP II has been tested in the laboratory with good success, and the architecture has been adopted by the ALS at LBL and DAΦNE at Frascati. Furthermore, recent tests have been conducted using the prototype hardware and software for this system on the SPEAR storage ring at SSRL. These tests were a successful demonstration that the system hardware and software all work synergistically by suppressing synchrotron oscillations on an actual beam bunch. Soon there will be an opportunity for testing the system on the ALS at a high-bunch repetition rate of 500 MHz, a rate more than double the 238 MHz required for PEP II.



No Damping Waveguides



Three Damping Waveguides

Fig. 2. Measured damping of HOMs.

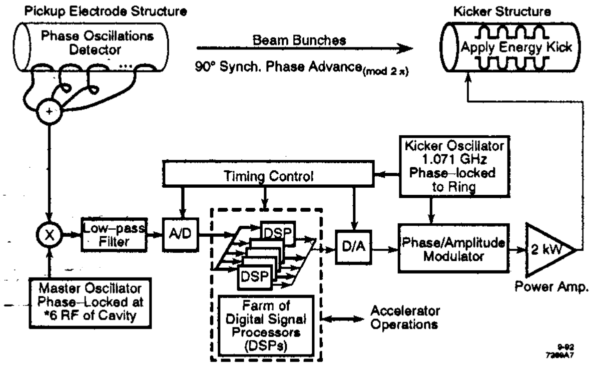


Fig. 3. Longitudinal feedback system schematic.

Vacuum Chamber R&D

The high SR power will give a high-thermal load on the vacuum-chamber walls, along with a large dynamic-gas load due to photodesorption. At the same time, the control of ion trapping and background from beam-gas scattering will demand a very low vacuum approaching 1 nTorr near the IP.

Meeting these constraints with components designed within the broadband impedance budget has required a vigorous and ongoing R&D effort.[5] Photodesorption as the primary contributor to the gas load has been carefully investigated as a property of material, fabrication technique, prior exposure, and photon energy. Copper has been found to be the preferred material because of its low-desorption coefficient, high-thermal conductivity and its good shielding properties for protecting external components from radiation. The higher cost of copper is offset by the simpler shape of the chamber and the reduction in the total amount of pumping needed.

A prototype copper-vacuum chamber has been exposed during beam tests on the VUV ring at NSLS. These results have shown that practical design and fabrication techniques for copper chambers are available. It is expected that operating pressures will be reached after initial-beam scrubbing of about 50 A-hrs. It has been demonstrated that this performance can be improved further using argon-glow discharge techniques.

Preparation for testing the energy dependence of photodesorption is under way using the X-ray beam line at NSLS.

OTHER STUDIES

Injection System

Key to the design of PEP II is a robust, efficient and powerful injector.[6] The availability of high brightness (high phase-space density) beams at the needed energies ensures that frequent short fillings are attainable with a built-in safety factor. The capability of collimating to obtain small beams (compared to the ring acceptance) with intensities sufficient for orbit measurements, is expected to be an important diagnostic tool during commissioning.

The design of the transport optics is well understood and will utilize much of the existing PEP injection lines. In most storage rings much attention is given to chromatic corrections at the interaction point. For PEP II this same attention has been applied to correcting the chromaticity at the injection region with a resulting large increase in the off-momentum acceptance (see Fig. 4).

Injection can be either on-axis (for diagnostic purposes) or the normal accumulation mode. Two fast-pulsed kickers, separated by π-phase advance, will be assisted by DC magnets to generate a closed bump in the vertical plane with its maximum amplitude at a Lambertson septum magnet. A key to achieving the high efficiency required for the system is the careful design of the beam-stay-clear aperture in this region coupled with the advantage given by the availability of high-current pulses with an emittance equal to or less than that used for SLC.

The conclusion of these studies is that a highly efficient, robust-injection system is attainable.

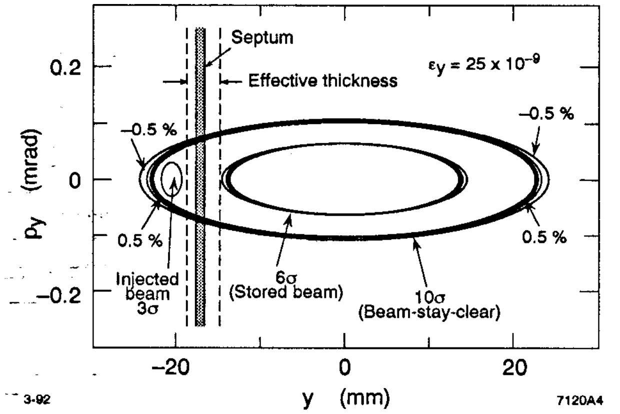


Fig. 4. Phase space acceptance at HER septum after chromatic correction.

Interaction Region

A Machine Detector Interface Study Group has investigated[7,8] many issues influencing the design of the IR optics and beam-separation scheme. These issues include backgrounds, detector protection, masking and power dissipation, vacuum pumping, alignment and support. The IR can be configured for head-on or crossing-angle collisions. Photon masking is also eased by using an S-bend geometry. Rare-earth permanent-magnet dipoles and quadrupoles are used within the detector field. A detailed plan is now available that includes all magnets, supports, collimators, masks, etc., including cooling and vacuum pumping. The SR-power distribution is known and manageable. All beam components within the detector will be prealigned and supported within a single carbon-fiber support tube and placed in the detector as a single unit.

CONCLUSION

Benefiting from the results of R&D and other study efforts, the PEP II upgrade is now a sound and mature design. Results have all been very positive and no technical obstacles have been uncovered. The collaboration is poised and ready to commence final engineering and construction when funding is available.

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