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An Asymmetric *B* Factory Based on PEP*

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INTRODUCTION

An Asymmetric B Factory to be installed in the PEP tunnel has been under study at SLAC, LBL and LLNL for several years. A mature design for a 9 GeV x 3.1 GeV electron-positron collider with a design luminosity of 3 x 10^{33} $cm^{-2}s^{-1}$ is presented. Solutions now exist for all the technical problems, including issues related to high currents (e.g. beam instabilities, feedback systems, vacuum chamber design, lifetime degradation and radiation power dissipation in the interaction region) and those related to the different energies of the beams (e.g. beam separation, beam - beam interaction and detector requirements). The status of the design, including prototype development, will be discussed.

PROJECT HISTORY

A design Study was began by a joint SLAC/LBL/Universities group in March 88 culminating in the publication of two reports in Oct. 89, a machine feasibility study [1] and a physics study [2]. In December 89 SLAC's EPAC strongly recommended a B Factory program at SLAC and encouraged machine studies. A new feasibility study was published in February 1990 which had both rings in the PEP tunnel [3]. By November 1990, we had sufficient confidence in the design to organize four in-depth subsystem reviews by outside experts [4]. These reviews were timed so that the results could be incorporated into the Conceptual Design Report published in February 1991 [5]. At the same time, SLAC and LBL, together with LLNL, submitted a formal proposal to the DOE requesting construction and R&D funds in FY93. In March 1991, the DOE organized a detailed technical, cost and schedule review which solidly endorsed the project. We are currently setting up the project organization in order to be ready to start construction in October 1992.

MAIN PARAMETER CHOICES

B Factory Physics Requirements

B Factories are e^+e^- colliders designed to study CP violation in B^0 meson decays and operate at the $\Psi(4s)$ resonance (center-of-mass energy 10.6 GeV). The electrons and positrons should have different energies to enhance the sensitivity of the measurements of CP violation [2]. Since positrons are more stable against ion trapping, the low energy beam is chosen to be positrons. We have adopted energies of 9.0 GeV for the electrons and 3.1 GeV for the positrons. The important detection requirement is to differentiate and separately identify the decay products of the *B*-mesons and the $\bar{B}$-mesons. This means a vertex resolution of about 60 microns, requiring that the inner radius of the vertex chamber be about 2.5 cm. The magnitude of the CP violations is expected to be large in the *B*-Meson system, but the cross-section of the important processes are small, so high luminosity is required. The design luminosity of the B Factory is 3 x 10^{33} $cm^{-2}s^{-1}$.

Machine Design Strategy

The luminosity of an asymmetric collider is given by [1]

$$L = 2.17\times10^{34}\,(1+r)\left\{\frac{I\,E\,\xi_y}{\beta_y^*}\right\}_{+,-}\ \mathrm{cm^{-2}\,sec^{-1}} \qquad (1)$$

where r is the aspect ratio (r = 1 for round beams and r ≈ 0 for flat beams), I is the beam current in Amps, E is the beam energy in GeV, ξ_y is the beam-beam tune shift and β_y^* is the vertical beta function in cm. The expression in brackets can be evaluated for either beam with the simplifying assumptions made here. Most of these parameters are fixed either by the physics requirements or by machine design limits.

The strategy is to choose parameters for single bunch collisions similar to those obtained routinely in existing storage rings. This ensures that the beam - beam interaction is similar, the machine optics problems are tractable and single bunch instabilities are manageable. All the effort is focused on resolving the new problems which are:-

1. Interaction region layout (two rings, backgrounds).
2. Vacuum chamber design (high currents).
3. RF and feedback systems (multi-bunch instabilities).

Design challenges are restricted to high-current and multi-bunch problems which are either engineering problems or, in the case of the multi-bunch feedback system, in an area where there have been enormous improvements in the electronics available on the market. The engineering can be evaluated using standard techniques and leads to solutions that are workable, reliable and conservative. This means that for the most part, no new accelerator physics issues must be addressed which would be less likely to provide definitive solutions.

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TABLE 1 PARAMETER LIST

	Electron	Positron	
Energy	9.0	3.1	GeV
Luminosity	3×10^{33}		$cm^{-2}s^{-1}$
Tune shift ξ	.03		
No. of bunches	1658*		
Bunch spacing	1.26		m
Beta Y*	3.0	1.5	cm
Beta X*	75.0	37.5	cm
Separation	Horizontal		
Beam Current	1.48	2.14	Amp
Bunch Current	0.89	1.29	mA
Vert. IP sigma	7.4		µm
Horiz. IP sigma	186		µm

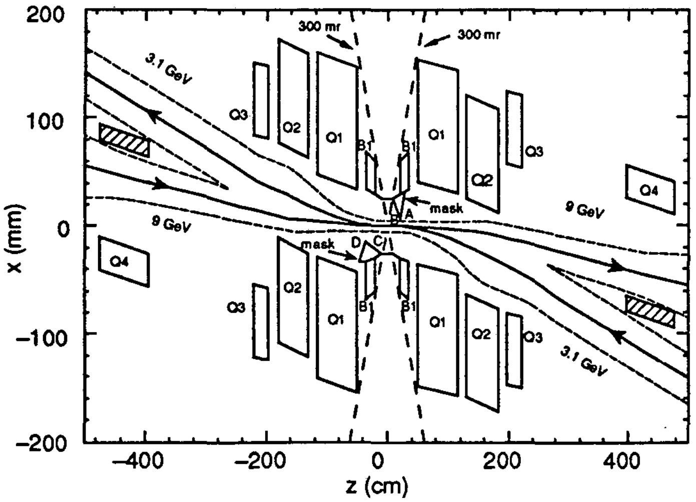
* Assumes 5% gap for ion clearing

INTERACTION REGION

The interaction region has been laid out to be compatible with either a head-on or a crossing angle configuration [6]. Our initial choice is head-on collisions with flat beams separated magnetically. This configuration is the closest to conventional circular colliders so that the luminosity estimates are the most reliable. Since the magnetic separation produces synchrotron radiation from which the detector must be shielded, the detector masking is easier with a crossing angle. This option is maintained for a future upgrade. Permanent magnets will be used for the LER focusing, while a septum quad is needed for the first HER quadrupole 4 m from the IP.

We have demonstrated that background conditions are one to two orders of magnitude better with flat beams than round beams because the quadrupoles are weaker, the beam angular divergence is smaller so that the beam size in the quads is smaller and the separation angle can also be smaller [7].

FIGURE 1 THE INTERACTION REGION LAYOUT



We have obtained completely satisfactory masking solutions for the head-on case using an "S" bend geometry to reduce backgrounds. The synchrotron radiation conditions are acceptable and particle backgrounds from bremsstrahlung and beam - gas interactions have been evaluated and acceptable rates demonstrated.

The vacuum requirements in the straight sections upstream of the detector are 1×10^{-9} torr which is easy to achieve as this part of the straight section is not subject to synchrotron radiation outgassing.

IP Design Criteria

We have developed a rather stringent set of criteria for the IR design based on experience from other machines and the special requirements of the B Factory.

1. The aspect ratio of the beam at the IP should not exceed 25 : 1 (very flat beams can make overlap difficult).
2. The quadrupoles must not be too far away from the IP ($\approx 100\ \beta_y^*$) as chromatic aberrations due to the strong focusing become unmanageable.
3. All apertures in the Interaction Region must be designed for a beam of at least 15 σ (uncoupled in the horizontal plane, fully coupled in the vertical plane).
4. Synchrotron radiation background must be evaluated for beams with tails having larger emittance in both planes (the beam - beam effect can blow up the tails of the distribution).
5. Parasitic beam crossings should have a separation of at least 7 σ (particles in the tails must not see the non - linear field in the core of the other beam).

IP Engineering Status

We have a detailed layout of the IP region including all the magnets, supports, collimators and the innermost detector elements. The permanent magnet bends and quadrupoles for the LER are based on Sm_2Co_{17} (which has the best radiation hardness and temperature stability) and meet all of the aperture and strength requirements. The synchrotron radiation power density on the masks and collimators is reasonable and preliminary engineering designs have been made, including thermal and stress analysis. All of these elements fit inside a 31.2 cm diameter support tube which spans the whole detector and also contains the vertex detector. The elements will be pre-aligned within this tube prior to installation inside the detector.

We are studying two different solutions to the septum quadrupole for the HER. We have a detailed design for a superconducting Panofsky septum quadrupole which would be just outside the detector and is compatible with all of the constraints. We have a conceptual design for a room-temperature Collins type septum quadrupole which we are in the process of engineering.

RING LAYOUT

The B Factory will be based on the existing PEP Ring [8] and takes advantage of the existing components and infrastructure. This leads to significant reductions in the cost and the scheduling uncertainties usually associated with conventional construction. Tunnel constraints have driven the basic layout of the rings in the PEP tunnel and the lattice optics which determine the magnet strengths and positions.

The HER arcs have a completely regular periodic structure containing 12 identical cells [9]. These cells are slightly longer than in PEP (15.125 m instead of 14.35 m) allowing room for flanges in the vacuum system (PEP had only one 14.35 m vacuum chamber per cell). At the ends of each arc, there are two dispersion suppressor cells, each slightly longer than the arc cells (16.013 m). The straight sections consist of 8 FODO cells, each 15.125 m long except in special straights.

The LER layout is based on the HER for standardization. The length of the standard period is exactly the same as the HER (15.125 m) and the quadrupoles are stacked vertically to simplify installation. The bend magnets are short to maximize the radiation damping (1 meter long), and the bend is placed close to the quadrupole so that it can be placed on a common support raft. The bend is always down-beam from the quadrupole, so that the synchrotron radiation strikes the chamber wall downstream of the bend.

The HER Magnets are recuperated from PEP:- 192 5.4 m dipoles, 20 low field dipoles, 192 quadrupoles and 144 sextupoles. All of these magnets will be taken from the PEP tunnel and the coils removed and refurbished. The mechanical shape of every magnet will be measured in an automated measurement facility and some fraction (20%) will also be measured magnetically and the results compared with the original data to confirm the validity of the procedure.

The LER magnets and some HER magnets are new and will be based on the designs used for the PEP magnets.

VACUUM CHAMBER

The vacuum chamber design is dominated by the high currents required. We are designing the chambers for a maximum current of 3 Amps corresponding to $\approx$ 10 kW/meter or $\approx$ 2 kW/cm^2 (PEP was designed for 10 kW/meter). The vacuum chamber will be copper as pioneered in HERA at DESY [10]. The advantages are:- high thermal conductivity, self - shielding (no lead) and the outgassing rate is ten times less than aluminium [11-13]. Detailed engineering studies of the chamber construction are complete. A copper test chamber will be built this year and its synchrotron radiation outgassing properties will be evaluated at BNL.

Vacuum Chamber Engineering

We have completed a detailed examination of the radiation escaping from the chamber as a function of chamber shape and wall thickness. The conclusion is that an octagonal shape beam chamber with 5 mm walls is completely self shielding even under the most extreme assumptions about the long term performance capabilities. We have selected a phosphor bronze alloy with 2% tin for the beam tube and the pumping channel as it has high structural strength even after brazing but is still capable of being drawn . We are developing specifications for the surface finish and fine tuning the profile to optimize the extrusion process. We have used energy deposition data from an EGS4 calculation to evaluate temperature profiles across the chamber and the thermal stresses which has enabled us to dimension the cooling channels. We have evaluated the vacuum loading on the chamber to ensure its mechanical stability. We have developed a detailed longitudinal profile of the synchrotron radiation deposition which serves as the input to the pumping calculations.

In the HER, the required pumping imposes distributed ion pumps in addition to lumped pumps. Distributed ion pumps cannot be used alone, as there is a high gas load in straight sections where there is no magnetic field for the pumps. In the LER, only lumped pumps will be used as there is no magnetic field in the region where the gas load is greatest. A completely satisfactory engineering design for the vacuum system has been obtained, including all the major components.

The result of these studies is a chamber design that is optimized in all respects for our B Factory. It has also been a necessary part of obtaining an accurate cost estimate.

RF SYSTEM

RF Sources

The cavities will be powered from 1 MW commercial klystrons at the B Factory frequency of 476 MHz. Each will be attached to two cavities via a circulator. This will require windows capable of transmitting 500 kW which we are developing. We are also studying the possibility of modifying the present PEP klystron design to produce 500 kW. If this is successful, the klystrons could be built at SLAC.

RF Cavities

Multi - bunch instabilities are caused by fields produced by one bunch which resonate for a sufficiently long time that they can act on the following bunch. The prime candidates are the RF cavities and specifically the resonant modes in the cavities. The fundamental mode is used for acceleration, so all the effort is being devoted to reducing the strength of the higher modes. This problem is similar for either room temperature cavities (copper is preferred) or superconducting cavities. Fewer superconducting cavities are needed which is an advantage, but extracting the higher modes to a room - temperature load is a problem, as is reliability. We are adopting copper RF cavities because we have considerable experience with this technology.

The cavity shape is chosen to minimize the number of trapped modes and these modes are strongly coupled to outside loads using waveguides which are beyond cutoff for the fundamental accelerating mode [14]. We are adopting a cavity with 'noses' similar to the Daresbury and ALS cavities rather than the smooth shape developed at LEP for superconducting cavities. This choice maximizes the cavity shunt impedance and minimizes the RF power required to establish the RF voltage. A computational method of calculating the shunt impedance of the fundamental mode in the presence of the wave guide couplers has been developed and this technique is being used to optimize the cavity. A model (pill-box) cavity has been developed to measure waveguide coupling, cross-check the computations and investigate the practical difficulties involved. The calculations of the higher order mode damping and measurements on the model cavity agree and show that damping the higher modes to a Q of 30 has been achieved.

The mechanical design of the cavity is progressing with calculations of the thermal loading. The other cavity components, such as the tuners and couplers We have funds for the design and construction of a high-power cavity to investigate the manufacturing difficulties.

FEEDBACK

Even assuming that the higher modes in the RF cavities are damped as well as we know how, the rise times of the multi - bunch instabilities are still much too short ($\approx$ 5 ms) and a powerful, wideband feedback system will be needed. Our design is based on a fast (2 ns risetime) bunch-by-bunch system detecting the phase offset of the bunch and feeding back after 90° synchrotron oscillation (about 7 turns later). To demonstrate the feasibility of this concept we have initiated a complete program of simulation and bench testing.

Feedback Program

A tracking program has been developed to follow bunches around the ring incorporating all the longitudinal effects including the feedback system. The feedback algorithm which is applied in the tracking program has also been developed [15]. A front end detection circuit has been built to evaluate signal-to-noise capabilities of a fast detection system [16] and the measured characteristics of this circuit are used in the tracking program. Analytic calculations and simulations have been performed to understand the effect of limiting the power capability of the output kicker amplifier.

The results show that the concept works and that only 2.5 kW is required from the power amplifiers to stabilize the beams. The front end detection circuits have demonstrated the capability to measure phase errors of 0.5 at 476 MHz, with 27 dB rejection between adjacent bunches.

POWER SUPPLIES

The electrical power installed at PEP is adequate for the B Factory. In both B Factory rings, the magnets that are connected in long strings will be powered from the existing power supplies, which will undergo extensive rebuilding. All the heavy bus-bars needed are available from PEP. All other magnets will be powered using DC-to-DC converters placed in the tunnel, providing considerable flexibility (as in CESR). These converters are supplied from an existing DC bus attached to an existing PEP power supply.

A large number of the power supplies are recuperated including all the dipole, quadrupole and sextupole string supplies and the mother supplies for DC-DC converters, all of which come from PEP and all the power supplies for the injection system (except the kickers) which come from the SLC Arcs and Final Focus and are the same vintage and type as all the other supplies in the injection chain.

INSTRUMENTATION

The Instrumentation for the B Factory is based heavily on existing designs, but will be new equipment. The major cost item is the beam position read-out electronics which will be derived from the ALS design. All the engineering, maintenance and trouble-shooting capability exists at SLAC for commissioning and operation. The other instrumentation is mostly standard.

CONTROL SYSTEM

The control system for any large accelerator project requires about two hundred man-years of software. We intend to base the control system for the B Factory on the SLC Control System and capitalize on the manpower investment which has already been made. Additional functionality will be added to treat circulating beams and part of the system will be upgraded to exploit newer technology. In this way we can reduce the software requirements to about one quarter of what would be required if we started from scratch.

SLC AS INJECTOR

SLC will be the injector for the *B* Factory [17] but it will also be used for other programs. The constraints that have been assumed are:-

1. The SLC experimental program will be completed by the time the *B* Factory will be ready.
2. The SLC may be required for a fixed target program or as an injector into a test facility for a new final focus or an NLC accelerating Structure.
3. The SLC damping rings and the positron target are available for use in the *B* Factory injector chain.

The injection system is based on the transfer of single bunches of electrons and positrons on each pulse of the linac into single buckets in each ring. These bunches will contain 20% of the total required charge when filling from scratch, but will only contain 4% when topping up. Bypass lines will be added in the linac so that the low energy beams do not traverse the full length of the accelerating structures, which would lead to energy jitter and emittance degradation. SLAC has the finest injector in the world for a *B* Factory with its demonstrated capability to produce high-intensity bunches of positrons and electrons.

TABLE 2 INJECTION PARAMETERS

Ring Energies		
HER (e^-)	9 GeV	(10 max, 8 min)
LER (e^+)	3.1 GeV	(4 max, 2.8 min)
Ring Currents		
HER	1.48 Amps -	6.9×10^{13} e^-
LER	2.12 Amps -	9.7×10^{13} e^+
Ring Particles/Bunch (with 5% gap)		
HER		$\approx 4 \times 10^{10}$ e^-
LER		$\approx 6 \times 10^{10}$ e^+
Linac Repetition Rate (pps)		60 - 120 pps
Linac Current ($e^\pm$/bunch/pulse)		$0.2 - 1 \times 10^{10}$
	SLC presently operates with	*$2 - 3 \times 10^{10}$*
Time Between Bunches (nsec)		4.20
Ring Kicker Pulse (Start to Finish)		≤ 300 nsec
Topping Off Time from 80 to 100%		3 minutes
Filling Time from zero		6 minutes

IR Protection during Injection

Adjustable collimators will be provided in the Arcs to limit the acceptance to ± 10 σ. Adjustable collimators will also be provided in the straight section upstream of the detector, set to ± 12.5 σ. In the Interaction Region, the physical apertures allow ±15 σ and an additional ± 2 mm for closed orbit errors. We have tracked injected particles with large energy and transverse position errors for 20,000 turns in the ring and never found particles being lost in the Interaction Region.

ADVANTAGES OF THE SLAC SITE

SLAC is available as the injector. The PEP tunnel is available including:- all of the electrical power, most of the electrical power distribution, all of the DC bus bars in the tunnel, most of the water cooling system and all of the water distribution piping. The PEP ring components provide:- 90% of the HER magnets, 30% of the ion pumps and supplies, half of the Instrumentation wiring and half of the power supplies. SLC provides:- 75% of the control system software and 100% of the injector power supplies. This gives us a head start both in money and in construction time.

TABLE 3 BUDGET

E,D& I	$ 32,241,000
M&S and Labor	$101,537,000
Total	$133,778,000
Contingency	≈ 25%
Construction time could be 42 months	

PROJECT STATUS

A Conceptual Design Report has been produced and a Project Data Sheet has been submitted to the DOE by SLAC, LBL and LLNL requesting construction funding in FY93. A DOE cost, schedule & technical review solidly endorsed the project.

The budget has been evaluated in great detail (down to WBS Level 8), and this was validated by the DOE. The construction time will most likely be dominated by the funding profile, nevertheless, detailed project schedules have been prepared which show that, from a technical standpoint, the machine could be built in 42 months.

SUMMARY

We have a conservative design that achieves all of the goals and every technical aspect of the design has successfully undergone an independent technical review. We have a strong and experienced collaboration for executing a construction project (PEP was a joint SLAC/LBL project) and the SLAC, LBL and LLNL laboratory infrastructures are large enough to manage a project of this magnitude. SLAC, with its existing powerful injector and large tunnel, is an ideal site for an asymmetric B Factory. There is no technical impediment to starting in 18 months and we are aggressively seeking funding.

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