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THE B FACTORY DETECTOR FOR PEP-II: A STATUS REPORT

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Abstract

The performance required of a physics detector at an asymmetric e^+e^- B factory is briefly discussed. The status of the PEP-II detector and associated R&D is then described.

A BRIEF HISTORY

The general features of the physics at e^+e^- asymmetric B factories and the detector requirements imposed by this physics at these machines have been widely discussed at a number of conferences and workshops around the world.[1,2] The existing e^+e^- detectors at DESY, CESR, SLAC, KEK, and LEP provide a clear starting point, but none of them would be capable of meeting many of the specific requirements. There is rather broad agreement on the features needed in a B factory detector, but there is no fully realized design which meets all of the performance goals.[3] Several ongoing workshops centered around PEP-II have addressed the specific detector challenges posed by the high luminosity, asymmetric PEP-II machine.[4] The focus of this effort has been to understand these challenges in detail and then to perform appropriate device R&D to resolve the outstanding issues before the final design. This talk presents a very brief status report on this effort. Time and space constraints prohibit more than a brief outline of any specific topic here, and, unfortunately, many items will not be discussed at all. The interested reader is encouraged to consult the references for more details. In particular, many of these issues have recently been reviewed in detail at the Conference on B Factories: The State of the Art in Accelerators, Detectors and Physics, Stanford CA, April 1992.[2]

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THE ASYMMETRIC B FACTORY PHYSICS ENVIRONMENT

Most tracks produced at an asymmetric B Factory are soft. For an asymmetry of 9 on 3.1 GeV/c, the average pion momentum is about 0.56 GeV/c. The kaon distribution is a bit harder with an average momentum of 0.85 GeV/c. The angular distribution is strongly peaked forward to the high momentum side, and the average momentum is correlated with lab angle. On the other hand, a significant number of important processes produce tracks with much higher momenta. In particular, the rare, but important, two body processes produce tracks in the 1.5 to nearly 5 GeV/c momentum range, and these momenta are also strongly correlated with lab angle. Table I gives a very brief summary of some of the physics issues at the B factory and how they translate into requirements on the detector. The thrust of the present PEP-II based effort is to consider this list of detector requirements in the light of presently understood detec-

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tor technology, and to perform R&D on those detector elements which are the least well understood. The PEP-II detector will contain the following elements: (1) vertex detector, (2) tracking chambers, (3) particle identification, (4) calorimetry, and (5) triggering, data acquisition and computing systems. In the next few sections, I will give a few examples of R&D associated with PEP-II in each of these areas.

Table 1: Synopsis of Detector Requirements

	Physics Needs:	Detector Requirements:
1.	Reconstruct B decays with high efficiency in large number of redundant channels.	• Good charged particle tracking, particularly in multiple scattering limit. • Excellent low energy calorimetry for efficient π^0 reconstruction. • Particle identification to ~4 GeV/c which should not affect calorimeter.
2.	Tag recoil B with high efficiency.	• Good lepton identification. • Good kaon identification.
3.	Measure longitudinal vertex separation of tag and B decay.	• Good vertex detector at small radius.
4.	Record large numbers of B decays.	• Trigger/data acquisition and analysis systems must cope with high event rates. • Detector elements must cope with high backgrounds.

VERTEX DETECTOR

Existing silicon-strip detectors (e.g., at LEP and SLC) have adequate signal/noise performance, and the resolution (~ 10-12 μm) appears to be adequate for the study of CP violation at an asymmetric B Factory. Projects are now underway at several places around the world to improve these devices in a number of ways, including making double sided strips, and improvements in readout.[5] Pixel devices have now been developed with substantially better resolution (3-4 μm).[6] This extra resolution may not be required, at least initially, at the B factory, but pixel devices are substantially more tolerant of extra hits for pattern recognition, and they may also be more radiation hard. It is still unclear if they are more expensive. This is an active area of research around the world and R&D on these devices, some in association with the PEP-II project, continues. In particular, 10x64 hybrid arrays with time correlated pulse height and addressing are now undergoing tests, and there is an active project underway to design and test a B factory compatible readout of the hybrid device.

DRIFT CHAMBER

Design studies for the PEP-II detector have emphasized the importance of obtaining a low mass tracking chamber system, both to improve the track resolution on low momentum tracks, and to decrease the probability for conversion of synchrotron radiation in the chamber that will cause confusion in track finding and fitting. The PEP-II drift chamber design attains this low mass using composite materials, aluminum field wires, low Z gas mixtures, and, most probably, a small cell design.[7] Measurements of resolution in He based gases have demonstrated that momentum resolutions about twice as good as those of argon based gases can be expected in the multiple-scattering dominated low momentum region between 0.1 and 0.5 GeV/c with such a chamber. Construction of a B factory prototype with small cells is under way. This project will test construction features such as feedthrough design in a full length chamber; will measure cell resolution; and will also serve as a prototype test bed for the trigger and data acquisition systems as discussed in following sections.

PARTICLE IDENTIFICATION

Particle identification at a B factory is difficult and highly constrained by the machine environment and the need for good energy measurement of soft photons in the calorimeter which surrounds it. The particle ID detector must be robust and relatively fast. Good π/K separation is required over a wide momentum range between about 0.25 and 4 GeV/c. The amount of material in the device should be small (preferably less than 10%L_{RAD}) and should be distributed as close as possible to the calorimeter in order to avoid degradation in the resolution performance of the calorimeter, and the loss of low energy conversion electrons in the magnetic field. In addition, the cost of the high quality calorimeter scales roughly like the radius squared and there will be substantial cost savings if the particle identification device can be made thin.[8]

There is, as yet, no demonstrated solution. There are, however, a number of interesting ideas and a substantial amount of R&D being carried out around the world.[9] Research associated with PEP-II is underway on the Fast RICH,[10] aerogel threshold Cherenkov counters,[11] the fast CRID,[12] and the DIRC.[13]

The fast RICH is a very interesting device which, in its most promising configuration, utilizes a solid CsI photocathode with an absorbed TMAE layer and pad readout wire chambers.[14] There is a very active world wide program to characterize these devices and to develop prototypes. There are still many pressing issues that need to be addressed for this device, including the factors contributing to the quantum efficiency of the photocathode and its longevity. The fast RICH program associated with PEP-II has started rather recently, and is aimed at first exploring the technical issues associated with the photocathodes, and then moving on to other design issues.

Low density aerogels provide an attractive possibility for simple, low mass particle identification at the B factory, provided that stable material with the right index can be produced, and that the Cherenkov photons can be efficiently extracted. The PEP-II based R&D effort is centered on these two issues. A development program, in conjunction with L. Hrubesh at Lawrence Livermore Laboratory, is underway to study a variety of aerogels, including production techniques and wavelength shifting dopants. The second prong of this effort is to use these aerogels in a prototype program to study photon extraction and readout techniques.

The fast CRID is an attempt to devise a fast device which builds somewhat more directly upon the present day experience with long drift RICH/CRID detectors than other approaches. It is based on a gaseous TMAE photocathode running at elevated temperatures, in a fast drift gas of 80% CF_4 plus 20% C_4H_{10}. The chambers are arranged in a modular array so that the maximum drift time is less than that of the drift chamber (about 1 μs), and the number of wires, and readout channels is very small. Since the photocathode is gaseous, it is continuously refreshed and should not suffer from plating, or slow deterioration.

Detector aging is a major concern for all gas detectors at a B factory. The gas mixture proposed for the fast CRID has shown excellent resistance to aging effects in conventional chambers. A test by the PEP-II based fast CRID group is presently underway to test the performance of this gas mixture (including aging) with TMAE in the gas. A sealed C_6F_{14} radiator is also proposed for this device. R&D is underway to construct prototype trays and verify that the ultraviolet transmission properties of the radiator do not deteriorate with time.

The internal reflection imaging Cherenkov counter (DIRC) is a completely new kind of imaging Cherenkov counter devised to deal with the particle identification design challenges at PEP-II. An active R&D program is now underway to better understand the design issues and prototype the device. Because this is a new kind of counter, which has not been widely discussed outside the PEP-II group, I will give a brief description of the operational principles of the device before discussing the R&D program.

The geometry of a single radiator of the DIRC is shown schematically in Fig. 1. Each radiator is a long, thin, flat "bar" with rectangular cross section. There is a photo-detection surface positioned some distance (l) away from the end of the bar. A track with velocity β passing through the radiator with refractive index n_1 emits the usual Cherenkov radiation in a cone around the particle trajectory with cone half angle θ_C given by the Cherenkov relation.

$$\cos\theta_c = 1/n_1\beta \qquad (1)$$

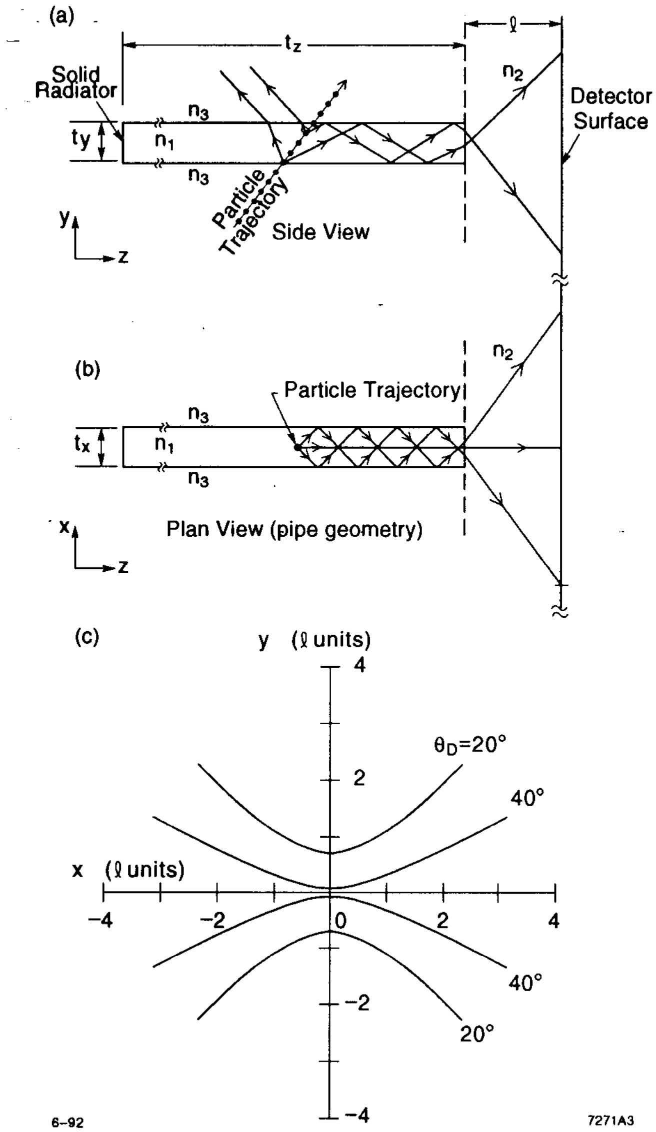

Figure 1. A schematic of Cherenkov light production and image formation in a radiator bar of the DIRC counter; (a) side view; (b) plan view; (c) images on a planar detector placed at distance l from the end of the radiator. These images assume n_1=1.474 and n_2=1.00. In a real detector, n_2 is equal to n_1.

The angles, position, and momentum of the track are provided by a tracking device located in front of the radiator. If the index of refraction of the radiating material (n_1) substantially exceeds $\sqrt{2}$, then, for a particle close to β=1, some portion of the light will always be transported down the "bar" to the end. Since the cross-section is rectangular, angles are maintained in reflections at the surfaces of the bar (up to an additional up-down/left-right ambiguity). In a perfect bar, the portion of the Cherenkov cone that lies inside the total internal reflection angle is transported undistorted down the bar to the end. When it emerges and is allowed to open up by traveling some distance until it hits a two dimensional detection surface, it will form an image as shown in Fig. 1(c). The image is essentially a conic section (suitably modified by refraction at the end) which has been "doubled" because of the up-down reflection ambiguity. In the case shown, the track enters the radiator in the y-z plane so that there is no left/right ambiguity. Since the locus of the image depends on the polar and azimuthal Cherenkov angles (θ_C, ϕ_C), particle identification using Cherenkov angular information can proceed using essentially the same techniques employed by other imaging Cherenkov devices.

A view of the forward quadrant of a possible B Factory detector employing a DIRC is shown in Fig. 2. This particular geometry has no end caps, although a version with end caps is also possible. In this version, it is assumed that the radiator consists of 1.23x4.0x320 cm (t_x, t_y, t_z) quartz bars. The radiator is 10% L_{RAD} thick, and takes about 2.5 cm of radial space including supports. The detector is a closely packed array of photomultiplier (PMT) tubes. The detector box is filled with a fluid whose refractive index matches that of quartz, so there are no reflections at the radiator ends or phototube windows. The device works in the near ultraviolet and the visible, and uses conventional glass-windowed phototubes. It is thin, robust, very fast (a good TOF counter), self triggering, with very compact mass. The performance of this device for fast tracks is typical of that expected for imaging Cherenkovs, as shown in Fig. 3. Moreover, since the number of photons collected has a natural increase as the dip angle of the track increases, the device tends to provide the best separation in the forward angles where it is most critical at an asymmetric B factory. Consequently, the separation shown is greater than 5σ for all momenta expected at PEP-II.

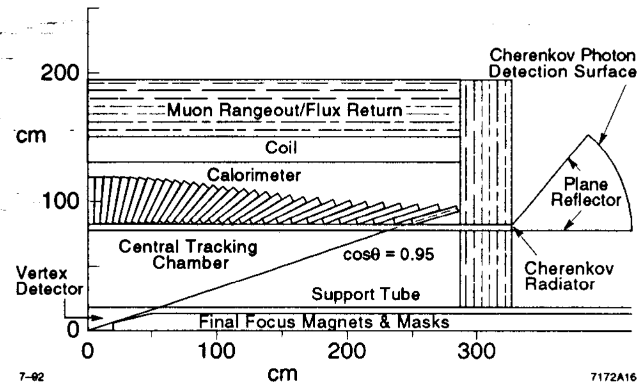

Figure 2. Schematic view of one quadrant of a B factory detector incorporating a DIRC.

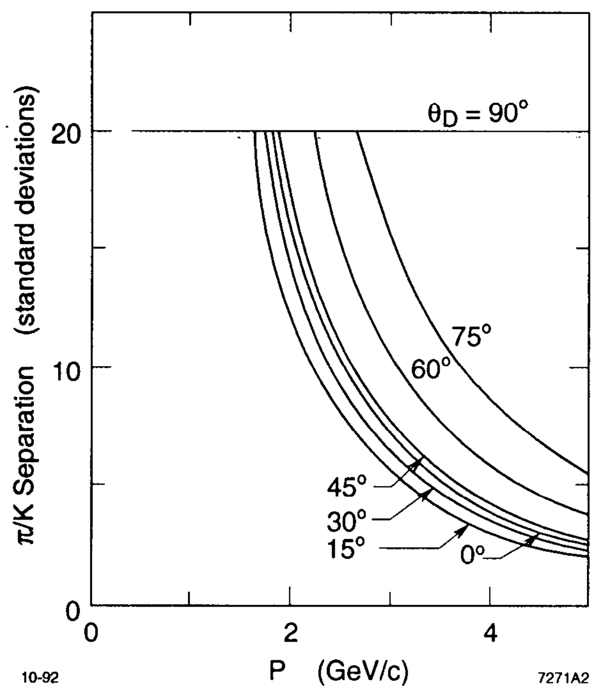

Figure 3. The predicted π/K separation as a function of momentum in a DIRC counter with a detector resolution of 6.8 mr. The lines show the dependance for a variety of track dip angles θ_D.

Of course, there are potential problems that need to be addressed for the DIRC, and since it is a new device, a full scientific prototype is highly desirable. The Cherenkov light must penetrate the magnet end plates to get out of the field and, even some distance from the magnet, shielding the tube array from the field may be troublesome. The number of tubes required is quite large (typically of order 10,000), so the cost will be rather large. The most uncertain elements are the radiator pieces themselves. Though the specifications are not particularly severe by optical standards, the pieces are very large and it will be a major challenge to produce them in the sizes required and still keep costs under control. R&D is now centered on radiator production and evaluation, photodetector evaluation and construction, and software studies, leading to the construction and testing of a physics prototype.

CALORIMETER

High quality calorimetry is important to physics at the B factory, and it is essential that the calorimeter performance not be degraded by material in front of it. A CsI crystal scintillator device is the clear consensus choice. It has excellent resolution and the lowest cost of the crystal calorimeters (for a radius of one meter). Even though the performance of existing CsI systems (e.g., at CLEO-II) is known to be excellent,[15] there are a number of issues which require further work.[16] R&D at PEP-II is centered around three issues; radiation sensitivity; structures and supports; and readout techniques. The literature on radiation damage in CsI is somewhat confusing, and it is not clear whether variations in damage rates are due to dopants or material purity. Research at PEP-II is continuing to better understand radiation sensitivity and to attempt to develop non-destructive acceptance tests for the 10,00 crystals which would be required at a B factory detector.[17] Work is also underway to further define the geometry and support system. Finally, since the radiation sensitivity of the CLEO-II calorimeter is limited at present by electronics noise, research is underway on readout systems which could improve signal to noise. One very promising device under study is the large area silicon avalanche photodiode produced by Advanced Photonics.[18] These devices can probably been made as large as 75 mm in diameter; have high quantum efficiency which, in principle, can be well matched to the CsI output spectrum; have gains of 100 to 1000; and are radiation hard.

COMPUTING

The computing requirements for a B factory are driven by the high event rates, and the large data sets produced. These requirements, when considered in the context of rapid commercial developments in high performance workstations, lead to a proposed Unix model for both on-line and off-line computing at PEP-II.[19] This is a major change from past practice in high energy physics for the entire computing environment, and substantial R&D needs to be performed to demonstrate that such an approach is feasible and desirable. There is a very active program in place and only a few examples can be given here.

First of all, there is a general need to expand the knowledge base in the B factory research community on Unix issues. The thrust of this effort is to get many collaborators using Unix, and then to evaluate the problems encountered and invent solutions. The starting assumption is that there will be a number of different vendors and different Unix standards used by different participating groups, so that part of this evaluation process will be to understand the true machine independence of a given approach.

Secondly, the community needs to learn more about the capability of general-purpose Unix equipment to support real-time needs. Historically, the Unix operating system did not support real-time requirements, and only recently have Unix vendors began to show interest in such issues. Such a completely new tool requires a thorough investigation complete with prototype results before it can be relied upon. The first stage of the prototyping involves IBM RISC System/6000 workstations running IBM Unix to study real-time extensions to an operating system. This work will include developing prototype user code, and then using this system for data acquisition, initially with the drift chamber prototype. This project will also allow experience to be gained with new bus architectures, and development of the requisite experience for making the appropriate final choices when required. At the same time, a general test bench facility for detector research is under development which will allow experimentation with Graphical User Interface (GUI) tools as the high level interface to the data acquisition system

Thirdly, since the distributed computing environment represents a major departure in off-line computing practice for high energy physics, there is a major need to understand more about the environment, to utilize the tools that are becoming available, and to put together appropriate tools if they are not now available. It is clear, for example, that a flexible batch system which can utilize the "free cycles" of a farm system is a must, but at present such a system does not exist. One will need to be developed, hopefully building off of a commercial product, working in concert with other HEP labs. Active R&D must also be done on "modern" programming languages including object oriented techniques, in order to understand how well they cope with the problems we pose, and conversely, how well the physics community can cope with the challenges presented by these new techniques. There has already been substantial progress by many people in developing complete simulation and analysis packages with very powerful graphical user interfaces for use in the Unix environment, much of it related, at least in part, to PEP-II B factory R&D. It is not possible here to discuss any of these projects in any detail, but among these developments are an interactive data display and plotting package (Hippo),[20] an interactive analysis package (REASON),[21] and a full scale detector simulation project (Gizmo).[22] Initial releases of these tools are already available, and the projects continue in rapid development.

TRIGGER & DATA ACQUISITION

The trigger and data acquisition requirements at the B factory are in a qualitatively different regime than present day experiments due to the very rapid beam crossing rates (4.2 ns); possibly significant (but unknown) machine backgrounds; and large target physics rate (~ 100 Hz). Some of the SSC electronics developments seem well suited to the requirements of the B factory and are being actively explored. In general, it is planned to incorporate commercial developments whenever feasible, and to drive the boundary between dedicated hardware and the Unix environment as close to the front end as possible.[23] The complete system is quite complex and many features need a significant prototyping effort in order to understand the performance. For example, the background may be higher than expected and it is extremely important that the performance degradation be graceful. Some of the prototyping efforts for the drift chamber prototype project were briefly mentioned in the previous section. In addition, a project is underway to simulate the full data acquisition and triggering system performance in a behavioral model, to better understand the design issues.

CONCLUSION

There is rather general agreement in the physics community about the desirable features to be incorporated in a detector at an asymmetric B factory. Although much of the detector could be built with existing technology, substantial performance enhancements are needed to utilize the full potential of the machine, and some completely new detector technology must be developed. The R&D program for the PEP-II detector is aimed at resolving the outstanding issues with specific emphasis on the following:

- Continue development of precision vertex detectors, including pixel devices.
- Continue studies of tracking devices. Investigate need for intermediate tracking between the precision vertex detector and the drift chamber. Study gas, cell design, and dE/dx performance in a prototype drift chamber.
- Develop and prototype a low mass, thin, particle identification system.
- Study radiation damage in CsI and develop an improved, low noise, CsI readout. Define requirements for a calorimeterized flux return.
- Prototype data acquisition and analysis systems.

The goal is to finish these studies sufficiently early that a detector design can be in place shortly after the PEP-II machine project begins. This will allow detector construction to be completed by the time PEP-II delivers beam.

ACKNOWLEDGMENTS

I would like to thank my colleagues in the PEP-II detector community upon whose work this talk is based.

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