The BaBar Experiment:

A study of CP violation in B meson decays

Abstract

The main aim of the BaBar collaboration is to measure CP violation in the B meson system. The B mesons are Lorentz boosted allowing their decay times to be measured. This required an asymmetric detector design. The BaBar detector was fully completed and commenced data taking in May 1999.

Introduction

Three discrete transformations which are potential symmetries of nature are:

Parity	P	Reverses the handedness of space
Time reversal	T	Interchanges the forward and backward light cones
Charge conjugation	C	Interchanges particles and antiparticles

The combined operation CP replaces a particle by its antiparticle and reverses momentum and helicity. Electromagnetic and strong interactions are symmetric with respect to C, P and T. Weak interactions violate C and P separately, but preserve CP and T to good approximation. However, certain rare processes all involving neutral K mesons, exhibit CP violation. All observations to date are consistent with an exact CPT symmetry which requires T violation when CP is violated.

Everything in the Universe appears to be made from matter and essentially no antimatter. In 1967, Andrei Sakharov stated that the existence of CP violation is one of three necessary conditions for this asymmetry to have evolved from an early matter-antimatter symmetric Universe.

Within the Standard Model of particle physics, CP symmetry can be broken. However, the amount of CP violation that the model predicts is too small to explain the matter excess in the universe. This indicates that the investigation of CP violation could reveal some new physics.

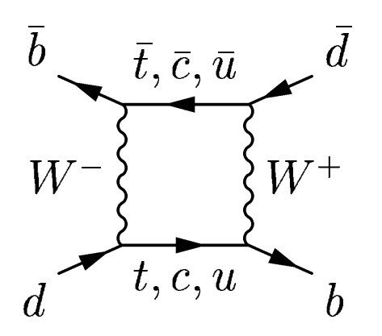
The Standard Model predicts that CP violation should be large in specific decay modes of the B meson. The aim of the *BaBar* experiment is to investigate this CP violation and search for new physics. The quark content and masses of the B mesons are shown below:

$$\left.\begin{array}{l}\mathrm{B}^+ = \mathrm{u}\bar{\mathrm{b}} \\ \mathrm{B}^- = \bar{u}\mathrm{b}\end{array}\right\} 5278.9\ \mathrm{MeV} \qquad \left.\begin{array}{l}\mathrm{B}^0 = \mathrm{d}\bar{\mathrm{b}} \\ \bar{\mathrm{B}}^0 = \bar{\mathrm{d}}\mathrm{b}\end{array}\right\} 5279.2\ \mathrm{MeV} \qquad \left.\begin{array}{l}\mathrm{B}_s^0 = \mathrm{s}\bar{\mathrm{b}} \\ \bar{\mathrm{B}}_s^0 = \bar{\mathrm{s}}\mathrm{b}\end{array}\right\} 5369.3\ \mathrm{MeV}$$

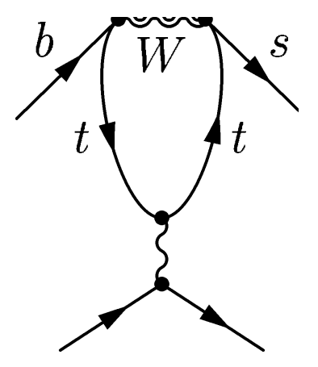
The manifestations of CP violation can be classified in three categories:

1. B decays where the amplitude for the decay and its CP conjugate process have different magnitudes. This gives time independent signals in both charged & neutral B decays.
2. CP violation in the B^0–$\bar{\mathrm{B}}^0$ mixing process. This signal is dependent on the time difference between the B^0 & $\bar{\mathrm{B}}^0$ decays.
3. CP violation in the interference between decays with and without mixing when the final states are common to B^0 and $\bar{\mathrm{B}}^0$. This is also time dependent.

Shown below are diagrams for the B mixing process and the interesting penguin decay amplitude:



The mixing (box) diagram



The Penguin Diagram

The Experiment

The *BaBar* experiment is being constructed at the Stanford Linear Accelerator Center (SLAC) in California. *BaBar* is an e^+e^- experiment tuned to the $\Upsilon(4S)$ resonance. $\mathrm{B}\bar{\mathrm{B}}$ pairs are produced by the decay process:

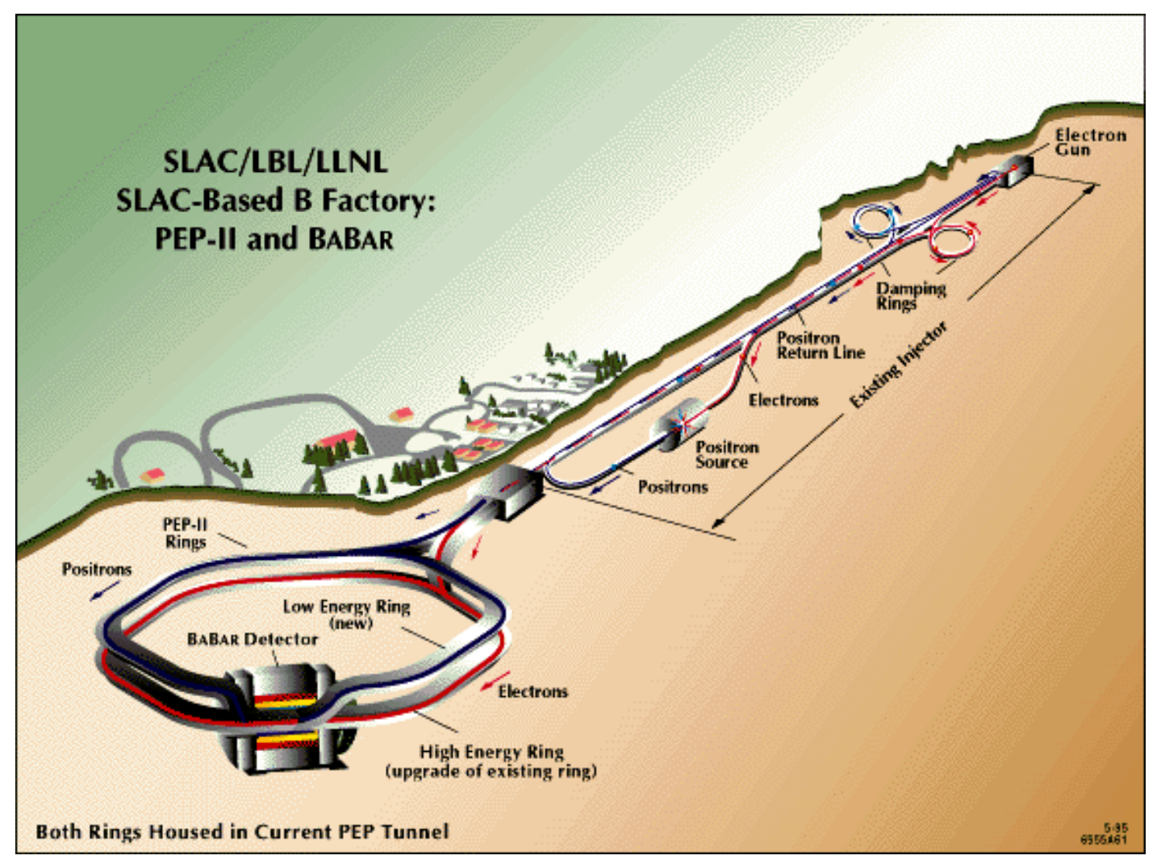
$$e^+e^- \rightarrow \Upsilon(4S) \rightarrow \mathrm{B}\bar{\mathrm{B}}$$

The small mass difference between the Υ(4S) resonance and the two B mesons means that in the Υ(4S) rest frame the B mesons are almost at rest and travel only a short distance before decaying; this makes their lifetimes hard to measure. To overcome this an asymmetric machine was proposed. This means using colliding beams of unequal energy (9 GeV electrons on 3.1 GeV positrons) thus Lorentz boosting the Υ(4S) in the direction of the beam axis. This results in the B mesons having appreciable velocities and hence measurable decay lengths.

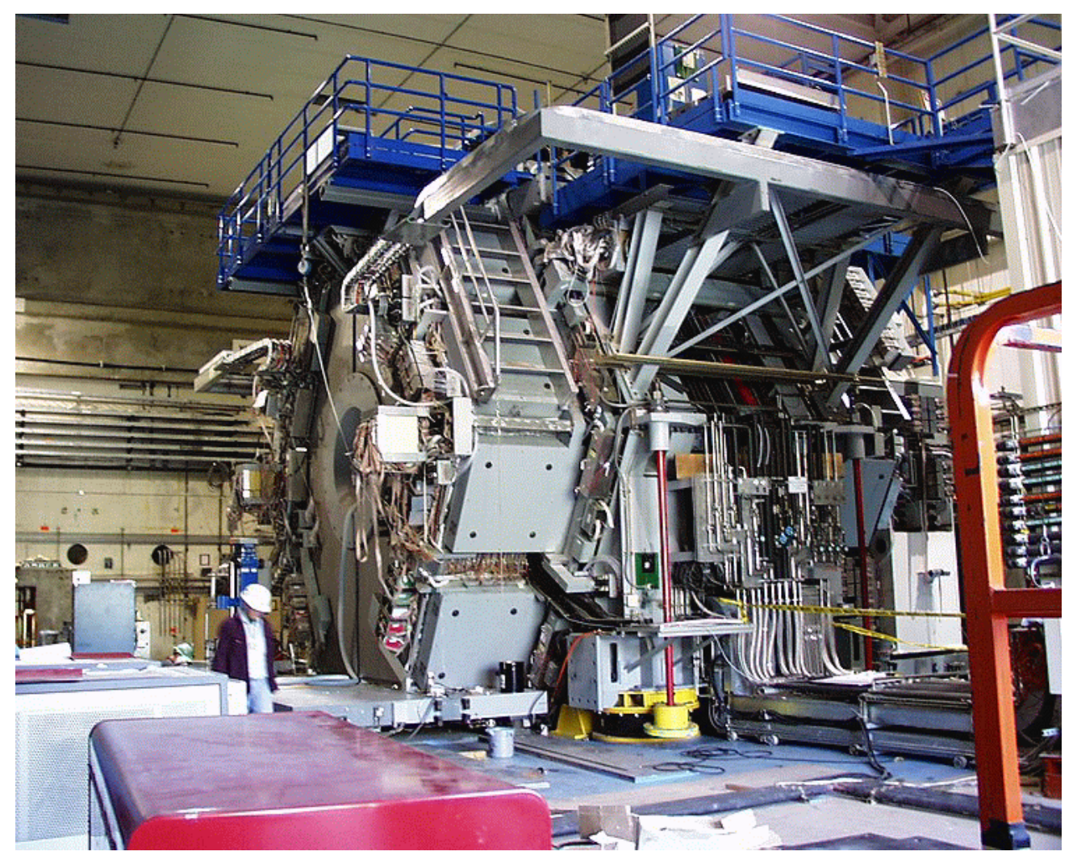
To produce asymmetric collisions two separate storage rings are required because of the two different beam energies. Furthermore complex magnetic fields are required to bring together and separate the beams at the interaction point (IP). In addition, to provide enough B mesons the machine must have high luminosity ($3.0\mathrm{x}10^{33}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$). The PEP-II B-factory was designed and built with just these characteristics.

Stanford Linear Accelerator Center (SLAC) in California, USA.

The BaBar Detector



The PEP–II bfactory



The BaBar Detector

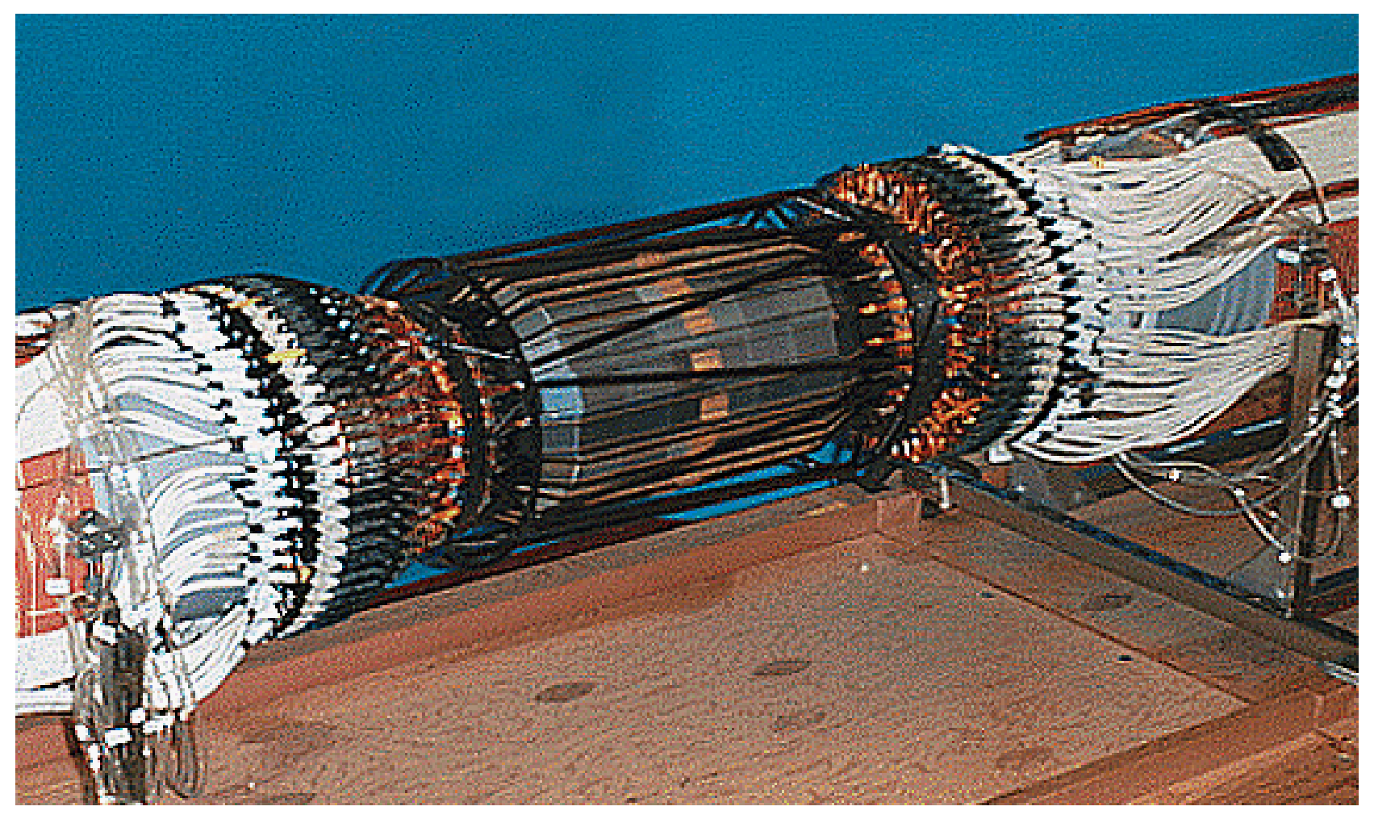
The *BaBar* detector consists of a silicon vertex detector, a drift chamber, a particle identification system, a Caesium Iodide (CsI) electromagnetic calorimeter, and a superconducting solenoidal magnet (1.5 T) with flux return instrumented for muon identification.

To function optimally and to achieve the physics aims the detector requires:

1. Maximum possible acceptance in the centre-of-mass system. This requires an asymmetric detector design.
2. Excellent vertex resolution. The B mesons travel almost parallel to the beam axis. To measure their decay time difference accurately, stresses the z-component of vertex resolution.
3. Accurate particle tracking over the range 60 MeV $< p_t <$ 4 GeV.
4. Identification of e, μ, π, K and p particles over a wide kinematical range. In particular π-K discrimination at high momenta (2-4 GeV).
5. Detection of photons and π^0's over a wide energy range, 20 MeV $< E <$ 4 GeV.

The Silicon Vertex Tracker

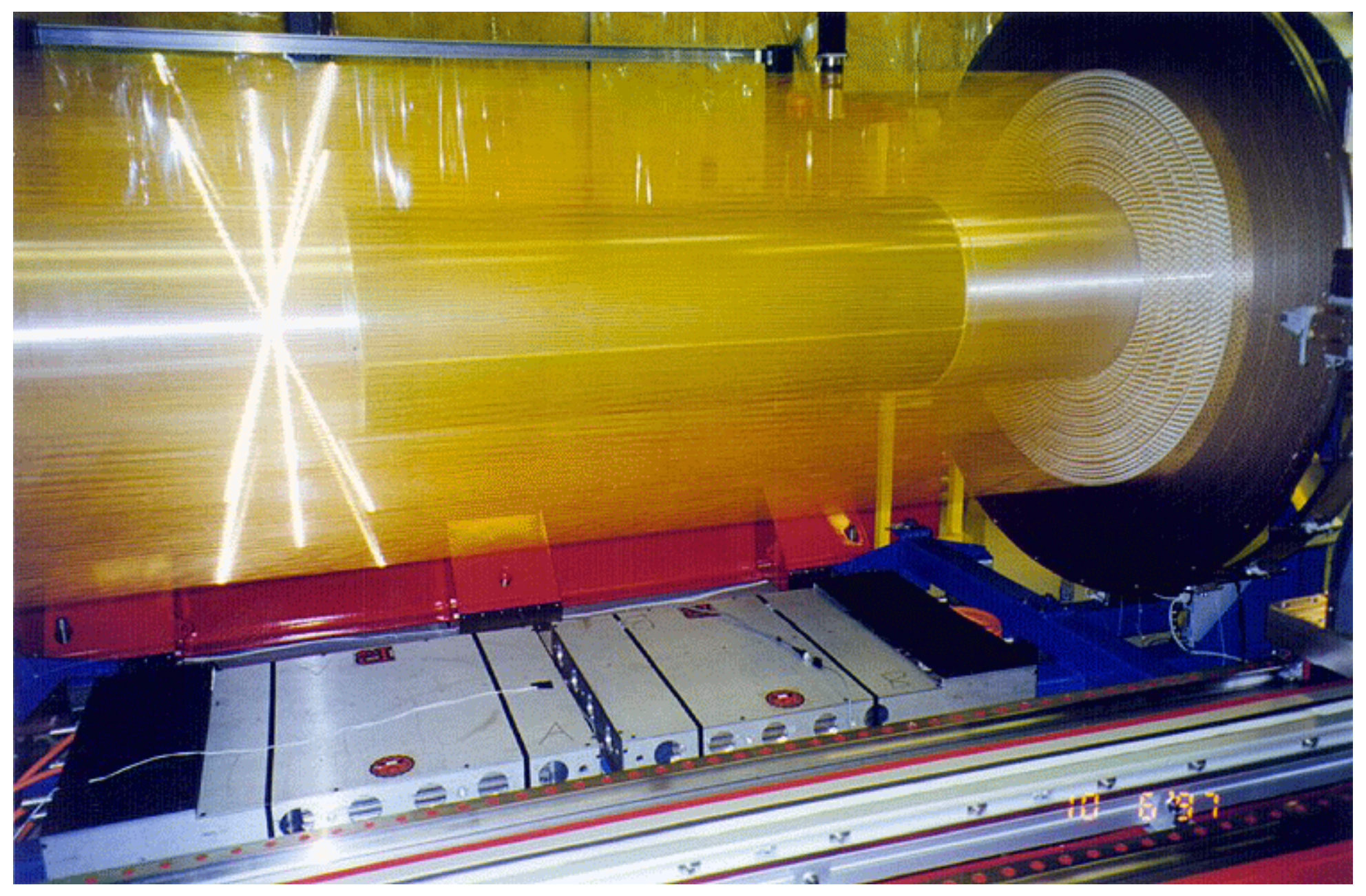
The SVT is constructed from 340 silicon microstrip detectors which cover an area of about 1 m^2 with a total of $\sim$ 150,000 readout channels. These are arranged in five concentric cylindrical layers with each layer azimuthally subdivided. The silicon is 300±30μm thick and has high resistivity. The silicon is AC coupled with polysilicon bias resistors. The main aim of the SVT is to reconstruct the decay vertices of the two primary B mesons in order to measure the time difference between the two decays. The is achieved by measuring precisely where particles pass through the silicon layers and by using this information the decay vertex can be reconstructed. The resolution, σ_z, is 12 μm for the inner layers and 25μm for the outer layers.



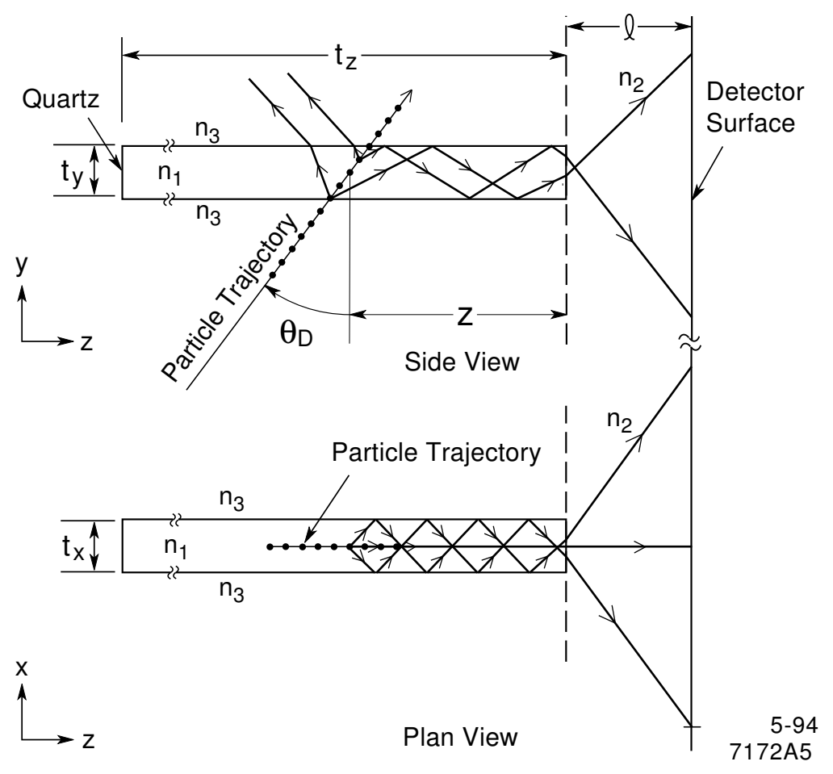
The Silicon Vertex Tracker

The Drift Chamber

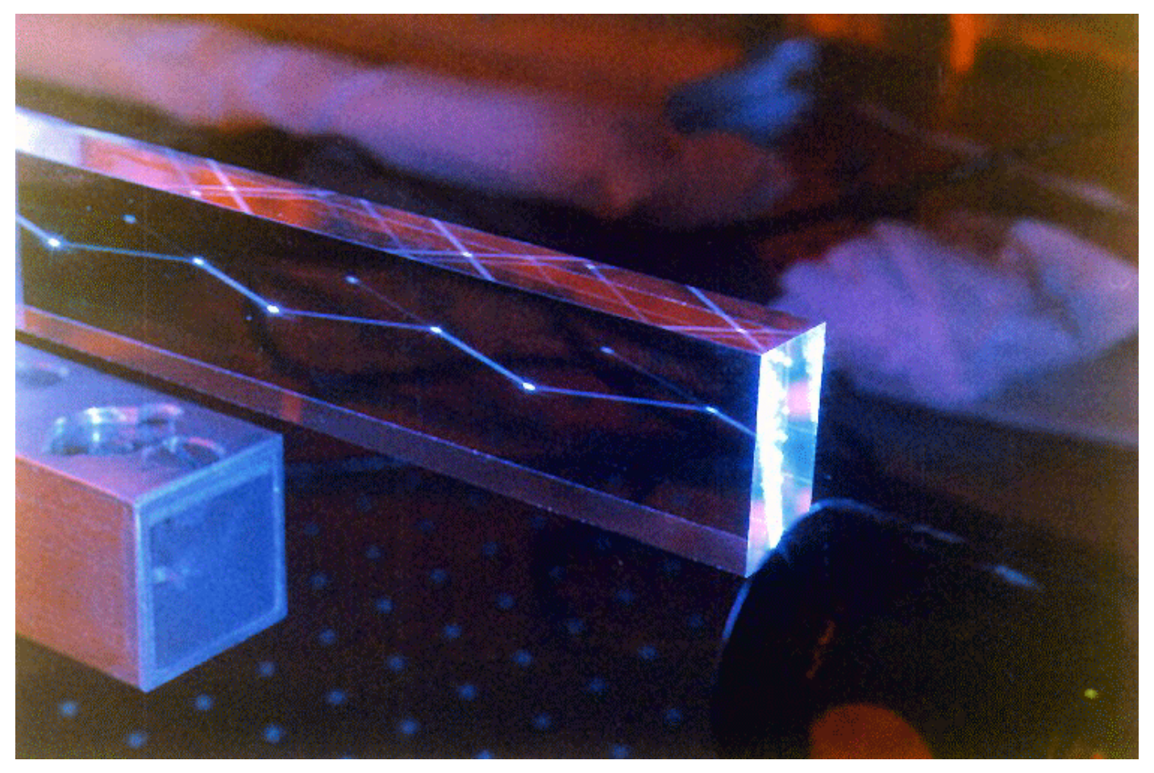
The drift chamber is the main tracking device of the *BaBar* detector. It is a 2.8m long cylinder with flat aluminium endplates. Between the two endplates are strung gold-plated tungsten-rhenium sense wires and gold-plated aluminium field shaping wires. The chamber is filled with a helium-isobutane gas mixture (low density to minimize multiple scattering). High voltage is applied between the wires and when a charged particle passes through the gas is ionized. The electrons produced from ionization then drift to the sense wires and are read out. There are about 28,000 wires in total. This provides approximately 40 spatial coordinates per track. The curvature of the track (produced by the 1.5 T magnetic field) can now be measured which provides an accurate transverse momentum (p_t) measurement. For tracks with momentum above 1 GeV the p_t resolution is $\sim$0.3%.



The Drift Chamber



Principle of the DIRC



A DIRC Quartz Bar

The DIRC

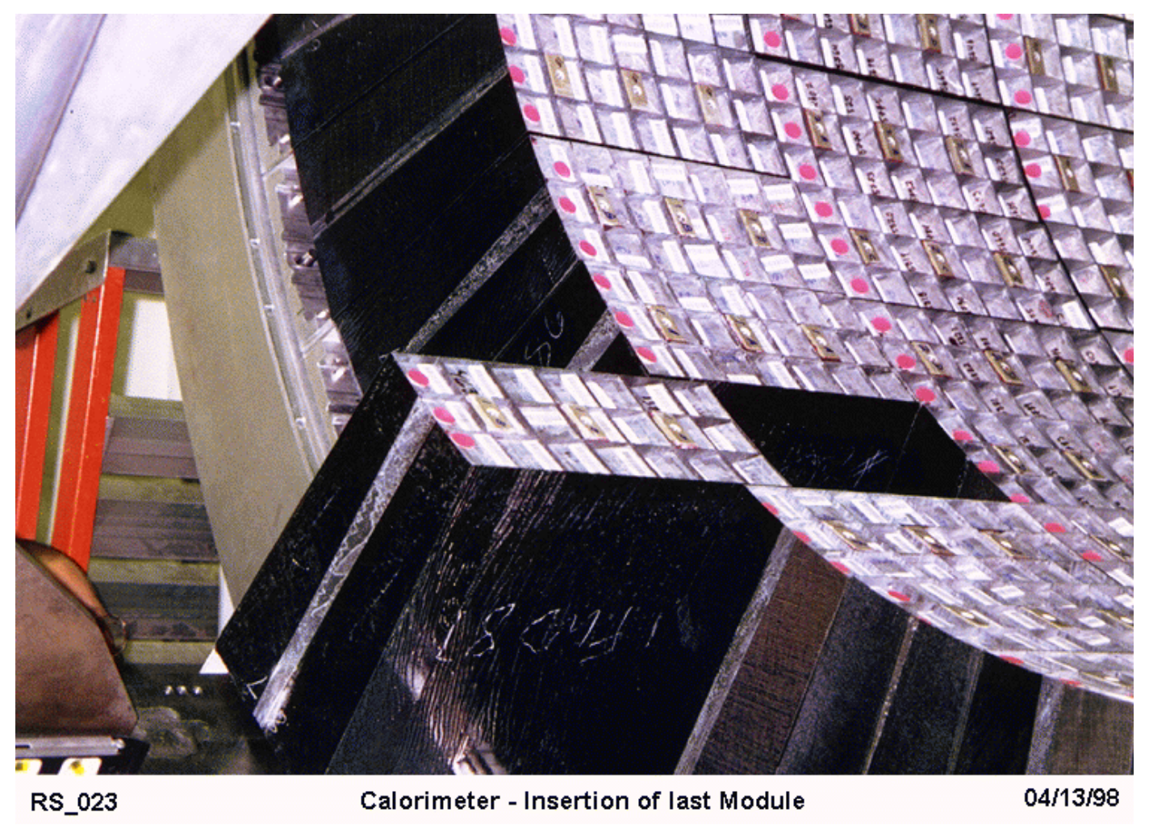
The DIRC, an acronym for Detection of Internally Reflected Čerenkov (light), is a new type of Čerenkov based detector for particle identification (PID). The DIRC radiator consists of 144 long, straight bars of synthetic quartz with rectangular section, arranged in a 12-sided polygon barrel placed just outside the drift chamber. When a charged particle passes through the quartz faster than the speed of light (in quartz) Čerenkov light is emitted in a cone, the opening angle of which is determined by the velocity. The angle at which the photons are produced is preserved as the light propagates down the bar via successive total internal reflections. At the end the Čerenkov image is allowed to expand in a medium of purified water. This is then measured by a close packed array of $\sim$11,000 photomultiplier tubes. Using this information the particle's velocity can be measured. From this and its momentum measurement (from the drift chamber) the particle can be identified.

The Electromagnetic Calorimeter

The electromagnetic calorimeter is the most expensive part of *BaBar*. It is made from 6600 CsI crystals which are held in place by a carbon fibre matrix. When particles enter the crystal they produce electromagnetic showers. This is in turn produces scintillation light in the crystal which is readout out using photodiodes. Using this information the energy of the electromagnetic shower can be summed to give the energy of the incident particle. The energy resolution for photons at a polar angle of 90° is:

$$\frac{\sigma_E}{E} = \frac{1\%}{\sqrt[4]{E}} \oplus 1.2\%$$

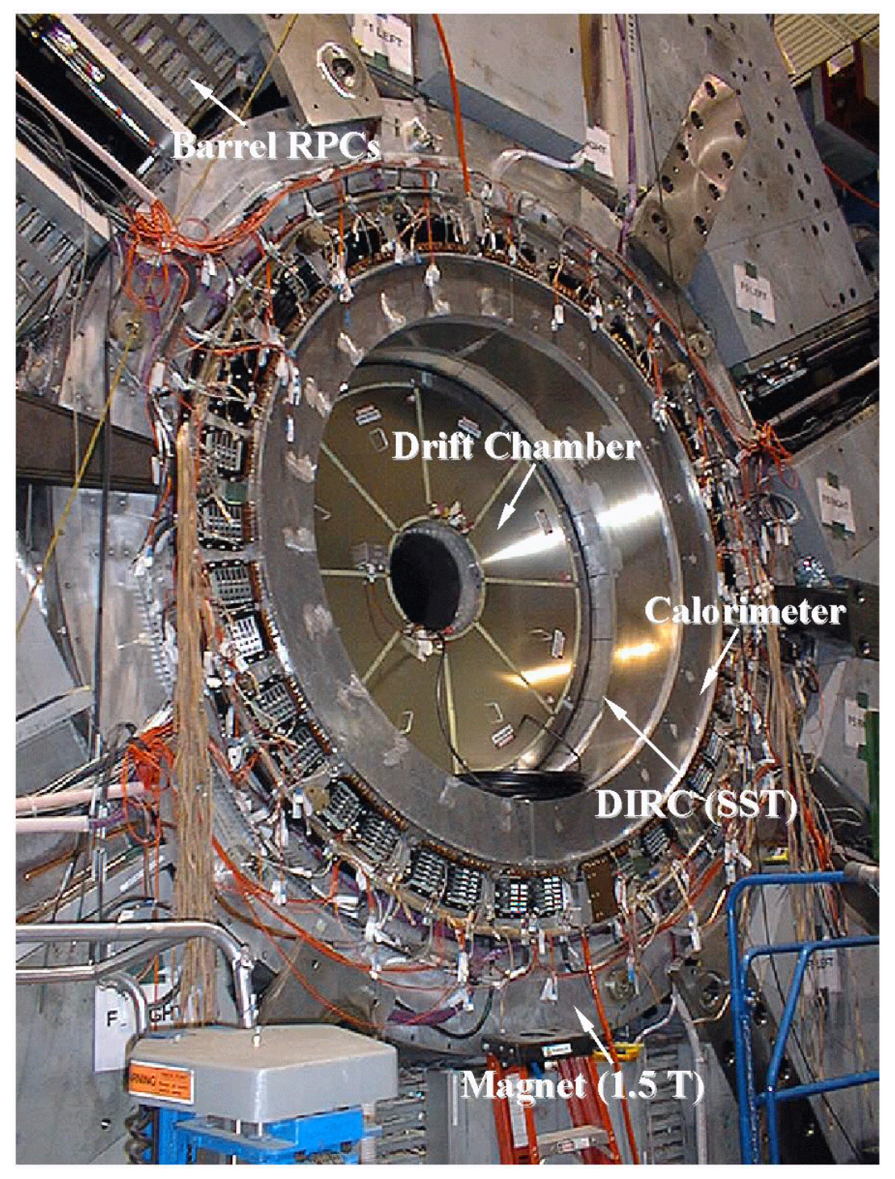
The constant term is due to front and rear leakages, intercalibration errors and light collection nonuniformity. To achieve the best performance of the calorimeter requires a precise energy scale calibration and careful monitoring of the short and long term variations of response. One device which has been built to achieve this goal is a fibre-optic light pulser calibration system. This injects light into the CsI crystals using fibre optics to simulate the CsI scintillation light. This enables monitoring of short term changes in the readout of the calorimeter.



The Electromagnetic CsI Calorimeter

The IFR

The IFR (Instrumented Flux Return) is the large magnetic yoke used to contain the magnetic field. It is instrumented with layers of RPC's (Resistive Plate Chambers) in order to detect muons. A novel feature of *BaBar* is the graded segmentation of the iron (2-10 cm) which increases with the radial distance from the interaction region. This improves the K_L^0 and low momentum muon identification, without introducing too many new layers. The solid angle coverage is maintained down to 300 mrad in the forward direction and 400 mrad in the backward direction.



Endview of Detector

Conclusion

The *BaBar* detector in conjunction with the PEP-II accelerator started taking data in May 1999. We have produced several million B meson pairs and intensive studies are underway investigating possible asymmetries. The first results will be shown at summer conferences and published later this year.

References

[1] The *BaBar* collaboration, "*BaBar* Technical Design Report", SLAC-R-95-457.
[2] The *BaBar* collaboration, "The *BaBar* Physics Book", SLAC-R-504.

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