Abstract
The DIRC (Detection of Internally Reflected Cherenkov light) is a new type of Cherenkov ring imaging detector based on total internal reflection that is used for the first time in the BABAR detector at PEP II. The Cherenkov radiators are long rectangular bars made of synthetic fused silica. We describe the R&D on the radiator bars as well as our experience with the DIRC construction. Results of measurements of the bulk transmission, the surface reflectivity, and radiation hardness of the bar material, a study of the influence of bar surface pollutants on the coefficient of total internal reflection, and results of the quality assurance of the finished DIRC radiator bars are presented.

The BABAR Experiment at PEP
BABAR is the detector for the SLAC PEP-II Asymmetric B-Factory.

The PEPII storage rings operate at a center of mass energy that is equal to the mass of the Y(4s) resonance. The two beams of unequal energies, (e-) of 9.0 GeV/c, e+ of 3.1 GeV/c collide head-on. Lorentz boosting the Y(4s) resonance in the direction of the higher energy electron beam (βγ) provided the necessary production rate of B mesons (BR). 1658 bunches (155 μm x 6 μm in transverse dimensions) collide to achieve the design luminosity of 3x10^33 cm^-2 s^-1.

Radiator R&D and Construction Experience

R&D is designed to perform comprehensive studies of beauty and charm mesons and B mesons. BABAR was constructed by an international collaboration of more than 700 scientists from more than 70 institutions. Data taking started in May 1999. The principal goal is to investigate CP violation in B meson decays.

Particle Identification for BABAR

An important issue in studying CP violation is the ability to tag decays of b-quark versus b-antiquark mesons for charged kaons in the momentum range up to 2.5 GeV/c. Particle identification (PID) is also necessary to separate charged pions from charged kaons for momenta up to 4 GeV/c in B decays (e.g. distinguish B -> ππτ from B -> kaonτ). The BABAR driftchamber provides particle identification by measurements of the specific energy loss (dE/dx) for tracks up to 0.7 GeV/c/momentum. A dedicated PID system (DIRC) is required for higher momenta. The DIRC is expected to provide π-K separation well above four standard deviations over most of the acceptance, with a minimum of about 3.7 standard deviations near the most forward direction.

Particle Identification by Comparing the Average Photon Emitting Angle for a Track Measured by the DIRC with the Momentum Measured in the Tracking System (vertex detector, drift chamber).

Principle of the DIRC
- A charged particle with velocity v/c generates Cherenkov photons in the quartz with an angle θγ with respect to its direction.

\[ \cos(\theta_{\gamma}(\lambda)) = \frac{1}{n(\lambda)} \]

- A wavelength of Cherenkov photons.
- Particle identification by comparing the average photon emitting angle for a track measured by the DIRC with the momentum measured in the tracking system (vertex detector, drift chamber).
- Charged pions are detected by total internal reflection inside the bar (surrounded by air n = 1).
- Bar acts as a light guide, due to the flatness and squareness of the bar, the angle of the emitted light is preserved as the photons propagate (up to ambiguities left/right and up/down).
- A ring image is formed on the detector surface. The water magnifies the exit angle by a factor n_w, which is measured for the DIRC quartz bars is 99.8% / m. The bars are square to better than 0.4 mrad and parallel to better than 0.5 mrad. The edges are sharp to 5 μm or better.
- The transverse bar dimensions are small (“hole”) compared to the distance to the PMT plane (“screen”).

Quartz Barbox

The detector is an array of 10752 conventional photomultiplier tubes (PMT) mounted inside a water tank which is filled with 6000 l purified water. The tank is located outside the magnet yoke (standoff box: 308 l) inside a magnetic shield to ensure proper operation of the tubes. The PMTs (ETL 9125B, 29mm diameter, acceptance ~25% at 400 nm, spectral range 300-650nm) measure photon arrival times in 0.5 ns bins with a resolution of 1.8 ns.

Standoff Box

The detector uses long rectangular bars made of synthetic fused silica as both Cherenkov radiators and light guides. Fused silica is a synthetic amorphous silicon dioxide that can be polished to high surface precision and is very radiation hard compared to natural fused quartz.

The bars are arranged in a 12-sided polygonal barrel with a radius of about 84 cm around the beam axis and have transverse dimensions of about 17 mm thick by 57 mm wide, and are 4.9 m long. Not all photons generated by a particle passing through a bar are caught by total internal reflection. Additional photons are lost in the bar due to absorption in the bulk material and on surface imperfections. A typical photon has a pathlength of about 400μm (visible, blue), a pathlength of 6 - 10μm and experiences some 300 bounces before exiting. This puts severe requirements on the surface finish and edge sharpness. The bar surfaces are first ground to the final size, then lapped to reduce substrate damage and finally polished. The typical RMS surface roughness is 0.5μm. The average transmission measured for the DIRC quartz bars is 99.8% / m. The bars are square to better than 0.4 mrad and parallel to better than 0.5 mrad. The edges are sharp to 5μm or better.
**Studies of Raw Quartz Material**

**Radiation Hardness**

The raw quartz material for the DIRC was selected from various available fused quartz and synthetic fused silica candidates. Synthetic fused silica, made from Silicon-bearing compounds (e.g. SiCl₄), are more expensive but chemically more pure and optically more homogenous than natural fused quartz.

**Summary of the tests of the radiation hardness**. Samples of the raw material were exposed to a Co⁶⁰ source (1.17/1.33 MeV photons) in series of increasing doses from a few krad to total doses of about 500krad and the transmission through the sample was measured after each exposure with a HeCd laser at 325nm wavelength.

All types of natural fused quartz showed unacceptable radiation damage and in some cases discoloration. All of the synthetic types were acceptable. Based on these findings synthetic fused silica (Heraeus-Suprasil and TSL-Spectrosil) were chosen as candidate materials for use in the DIRC.

**Optical Properties - “Lobes”**

Studies of the synthetic fused silica showed that both candidate materials showed a diffraction pattern, colloquially called “lobes”, when a laser beam was transmitted at steep angles through polished slices of the material. On the right, a photograph of the image of a HeNe laser beam spot produced by a single pass through a synthetic fused silica ingot is seen. The primary beam spot and two secondary “lobes” are visible as well as some scattered light due to the poor polish of the raw quartz samples.

A measurement of the power in the lobes. A photodiode is scanned across the lobe pattern after a single pass of the HeNe laser through an ingot and the photo-current recorded. For this sample of Heraeus Suprasil quartz, lobe power was approximately 3% of the incident power. The opening angle of the lobes was approximately 10 mrad. Samples of Spectrosil quartz from TSL exhibited similar behavior but with an amplitude smaller by an order of magnitude and only at incident angles outside the DIRC phase space.

The tests of the raw quartz material resulted in the selection of Spectrosil, made by TSL in the UK, as the choice for the DIRC production for bars, wedges and windows. A total of almost 700 quartz bars (dimensions: 17· 35· 1225 mm³) were then produced by Boeing, Albuquerque, NM.

The quartz bars were assembled into barboxes. Each of the 12 DIRC sectors contains one such barbox. Inside, 12 radiator bars, glued together from 4 bar pieces and one quartz wedge, are mounted in an aluminum box and kept in a nitrogen atmosphere. The wedge is a prism which compresses the photon exit angle range. A mirror, glued to the forward end, reflects the photons to the backward end.

The model for the production of the lobes explains them by diffraction off of a periodic inhomogeneity of the index of refraction of the quartz. Appreciable lobe power is observed only when the beam is tangent to the curved inhomogeneity layers as shown in the diagram. Such inhomogeneities could be caused by e.g. temperature variations during the proprietary quartz production process. The model describes the measured wavelength dependence of the power and opening angle of the lobes.

The raw natural fused quartz and synthetic fused silica material (amorphous silicon dioxide, colloquially referred to as “quartz”) is received in the form of large cylindrical ingots, from which typically between 16 and 24 bars may be cut.

The figure shows a quartz ingot in the test setup. A one foot ruler is included for scale. The ingots have a diameter of 19 cm and a length of 125 cm.
DIRC quartz bar during a measurement of optical properties. This motion controlled setup uses a polarized HeCd laser at 442nm in a temperature and humidity controlled cleanroom. After measuring the transmission of the 1.225m long bar, the surface reflectivity is calculated from the intensity loss of the beam after 51 internal reflections.

The result of a survey of about 100 DIRC quartz bars is summarized on the right. The average value of the transmission is (99.9 ± 0.2)%/m and the mean reflection coefficient is (0.9997±0.0002) per bounce, consistent with the expected reflectivity for the nominal surface polish of 0.5nm (rms).

Bar Properties - Quality Assurance

DIRC quartz bar as seen by a digital microscope. A numerical edge-finding algorithm was used to analyze series of images like this to determine the squareness and parallelism of the DIRC bars as well as the imperfections of the bar edges.

The result of a survey of about 570 DIRC quartz bars is summarized on the right. Shown is the result for the non-squareness of the 4 angles that define the cross-section of the bar. That angle is of particular importance for the DIRC since any non-squareness contributes directly to the resolution term. The sigma of the fitted Gaussian is 0.2mrad.

Study the potential degradation of the high initial value of the quartz bar reflectivity due to pollutants during the 10 year expected lifetime of the BABAR experiment. Clean quartz bars were exposed to various surface pollution candidates in a nitrogen atmosphere at room and elevated temperatures. Candidate materials included wet and cured glues, mechanical elements of the barboxes and the components of the DIRC gas supply system.

Plotted is the difference between the reflection coefficient of a bar measured at 25 positions along the width of the bar before and after 42 days of exposure to uncured Hysol glue. No significant reduction of the bar reflectivity was observed due to any of the tested materials.

The DIRC was installed in BABAR in three stages between Nov. 1998 and Oct. 1999. View from backward end of closed SOB. Each of the 12 sectors carries a high voltage crate and readout electronics.

End view of a bar box installed in BABAR. A combination of gaskets and O-rings provides the leak tightness at the quartz-water interface.

View from backward end of opened SOB during barbox installation. Inside the opened right door, the PMT plane is visible.