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# DIRC – The Particle Identification System for BaBar

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## I. INTRODUCTION

I have the pleasure of reporting on the status of the DIRC particle identification sub-system[2] of the BaBar Detector[3], running at the asymmetric B Factory at SLAC[4]. The acronym DIRC stands for “Detection of Internally Reflected Cherenkov Light.” This device grows out of our group’s experience with ring-imaging Cherenkov devices founded on a long partnership with Tom Ypsilantis and in particular with the CRID device for the SLD experiment[5]. Blair Ratcliff had the brilliant idea of using the totally internally reflected Cherenkov light created in quartz bars, and transported out to the photon detectors by those same quartz bars, to provide excellent $\pi$, K, p particle identification in the momentum range important for the B Factory[2]. His naming of this new instrument was aptly “CRID” spelled backwards. The detailed design, building and commissioning of the DIRC sub-system was the work of a large international collaboration of French and U.S. groups[1]. The device has proven to be a very robust detector, with the promised performance essentially fully realized, and is being effectively utilized in almost all of the current BaBar physics analysis.

The DIRC information combines with $\frac{dE}{dx}$ information from the Drift Chamber and the silicon tracker to provide the hadronic particle identification information for the BaBar experiment. The Cherenkov angular separation of pions and kaons is shown in Figure 1, where one sees that an effective angular resolution of ~2 mrad is required to provide a three sigma separation for the high momentum region, while at low energies the ($\frac{dE}{dx}$ + DIRC) work very well.

BaBar requires good particle identification for momentum up to about 4.2 GeV/c coming from two quite distinct tasks to be performed, in two quite separate momentum regions. One task is tagging of B’s from the decay products, which typically have momentum below 2GeV/c and the second task is identifying exclusive few-body B decays, where the momenta are typically between 1.7. and 4.2 GeV/$_c$. BaBar also imposes constraints of radiation robustness on the technology of choice (the DIRC region will enjoy of order 10 krads of radiation dose over a ten-year lifetime), and of minimal radiation length in front of the CsI calorimeter (e.g. < 20% of a radiation length) which hopes to measure low energy photons down to energies of ~20 MeV.

## II. THE BABAR DETECTOR AND THE DIRC

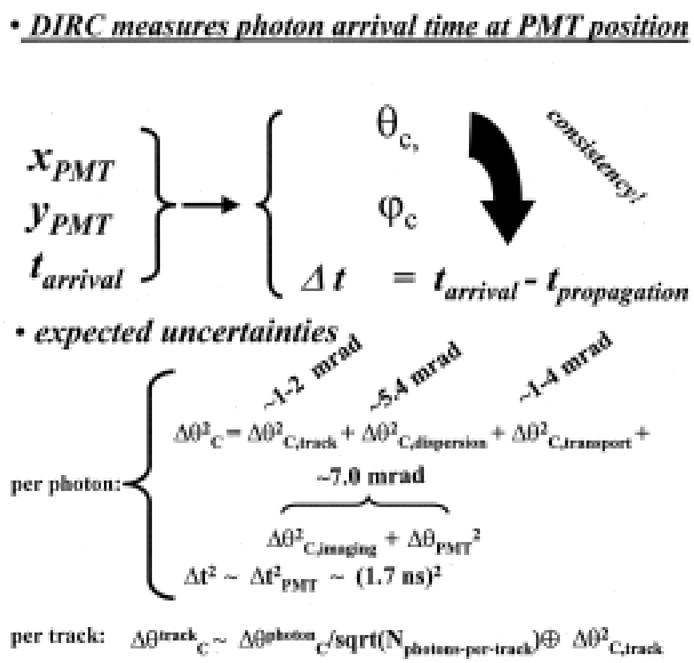
The BaBar detector[3] is shown in Figure 2 and the DIRC system in Figure 3 and 4. The experiment is the usual $4\pi$ collider detector with multilayered sub-systems, each attacking a specific aspect of event measurement. Moving out from the beam pipe, the silicon vertex tracker works with the drift chamber in tracking the charged particles measuring their momentum, while providing precision measurements of secondary decay vertices. The DIRC system taggs the hadronic particle identification while the electro-magnetic calorimeter of CsI crystals measures electron and photon energies, and the

Instrumented Flux Return provides muon identification and some $K_L$ tagging. The experiment is immersed in a 1.5 Tesla magnetic field.

The DIRC system is composed of 12 bar boxes completely surrounding the beam pipe at a radius of 0.80 metres and covering polar angles from 25.5° to 141.4°. Each bar box contains 12 synthetic fused silica bars 490 cm long, 1.7 cm thick and 3.5 cm wide with optical quality surface (polished to <5 Å rms roughness, and square to better than 0.3 mrad). The quartz bars serve both as a radiator and as a light guide for the Cherenkov light, and are optically coupled to ~11,000 PMT on the focal plane surface by 1.2 metres of purified, distilled water of index of refraction n = 1.346, a good match to that of the fused silica with n = 1.473. A charged particle traversing the radiator with velocity greater than the velocity of light in fused silica, emits Cherenkov photons in a cone of half-opening angle $\cos\theta_c = {}^{1}/_{n\beta}$, and some of these photons are always totally internally reflected and transmitted to the end of the bar, and hence through the water to the 11,000 PMT detectors. See Figures 2, 3, and 4. The bars have mirrors attached to one end, and all the Cherenkov light comes out into the water region, to be detected by the ETL 9125 photo-multipliers. A typical photon has wavelength around 400 nm (300-600nm), suffers around 200 bounces down the quartz bar, and flies ~5m of path length with around 30 nsec time delay, (10-60nsec).

The DIRC is intrinsically a three-dimensional device, measuring the x, y coordinates of the photon detected (which together with the tracking information measure the Cherenkov θ and ϕ angles) and the time of arrival of the Cherenkov photon.

The resolution expected from this device is given below, where the four terms contributing to the single photon resolution are from tracking, from chromatic effects, from small effects due to transport of the images and, finally, the optics and geometry.



Of these four terms, the chromatic (~5.4 mrad) and geometry (~7.0 mrad) dominate. The resolution for a given particle profits from $1/\sqrt{Npe}$ due to photon statistics, for all of the terms but the tracking contribution.

Imaging in the DIRC is not a trivial exercise, due to the distortions and ambiguities (initial reflection, up/down, left/right, mirror reflection, wedge reflection) which lead to some sixteen $\theta_c$, $\phi_c$, ambiguities per PMT hit. However, the largest problem comes from photon hits from accelerator backgrounds. This can amount to 200 kHz of noise per phototube. However, the good intrinsic timing of the DIRC saves the day. Figure 5 shows a typical single event display on the left for the full time window, and the same display where $\pm$ 8 nsec time window is selected on the right. The time-selected data shows essentially no background! The event display on the left has ~1000 hits, while the one on the right has one or two hits beyond the DIRC "rings." The 1.7 nsec time resolution, shown in Figure 6, is very important!

The single photon Cherenkov angular resolution is also shown in Figure 6, where the current performance is $\sigma(\theta_c)$ = 9.6 mrad, as compared to the expectation of 9.5 mrad. The resolution is dominated by 7 mrad from geometry/optics, 5.4 mrad from chromatic effects and (2-3) mrad from imperfections on the bar surface and angles. In addition to the clear peak, one notices a background of ~10% coming from combinatorics, track overlap, accelerator backgrounds, knock-on delta rays and reflections at the glued bar junctions.

Figure 7 displays the number of detected Cherenkov photons per track, as a function of the polar angle of the incident particle, where between 20 and 60 photons are observed with a quite strong angular dependence. Since the higher momentum tracks tend to be at small, forward angles, this peaking helps the actual track resolution just where it is needed! The actual Cherenkov angular resolution for a track, also shown in Figure 7, is 2.4 mrad, about 10% worse than expected. We believe this shortfall is primarily due to the lack of detailed understanding of the relative alignment of the DIRC and the tracking systems.

## III. OPERATIONAL EXPERIENCE

So much for the DIRC concept, the design and the basic performance plots. One operational concern has been lifetime – i.e., degradation over time of the system performance. In Figure 8 we plot the change in the photon yield per year for each of the twelve bar boxes, showing (1-2)% loss per year. This result is obtained using LED pulser calibration data and analysis per run of the photon yield in Bhabha and muon pair events for real data. A small loss of detected photons is observed with little expected effect on performance over a 10-year lifetime. There have also been concerns over the observation of a "milky" appearance on some PMT front glass, in late 1999. After a serious study program[6], the milkiness is explained as the result of sodium depletion in the PMT glass envelope, but no substantial loss of PMT's is expected over a 10-year life, and no substantial loss of performance of the PMT is expected. Around 20 PMT's are lost each year due to (probably) high voltage breakdown. After three years' operation of the DIRC system, over 99% of the PMT's are still fully operational!

Accelerator backgrounds represent the most serious challenges for stable operation of the DIRC system. In Figure 9 the inefficiency of the DIRC due to the TDC electronics dead time is shown. The BaBar experiment began in 1999 with luminosities of $8.10^{32}$ $cm^{-2}$ $sec^{-1}$ and with rates in the DIRC PMT scalers up to 300 kHz. If these rates had been allowed to grow linearly with luminosity, the DIRC would have been literally "dead-in-the-water!"

However, you see in Figure 10 the improvement in scaler rates for the PMT as a function of luminosity, as the machine performance steadily improved and shielding was steadily improved, -- from early 2000, through 2001, and the most recent shielding in 2002(7). The TDC electronics will be replaced in the fall of 2002 with new faster chips with deeper buffering which will keep the DIRC dead time less than 5% at 2.5 MHz scaler rate.

## IV. PERFORMANCE

Now to the performance of the DIRC system as a hadron particle identifier. In Figure 11 the pion/kaon separation capability is demonstrated on tagged data, selecting $D^{*-} \rightarrow D^o\pi^-$ and the $D^o$ meson subsequently decaying into a $K^-$ and a $\pi^+$. Here the final pion and kaon are kinematically identified, and plotted on the scatter plots showing the quite separate pion and kaon bands. Clear separation is observed. A separation of $4.3\sigma$ is achieved at 3 $Gev/_c$, and about $3\sigma$ at 4 $Gev/_c$. The K selection efficiency and $\pi$ misidentification rates are shown in Figure 12 for normal selection criteria and average ~88% efficiency for $K^{'s}$, with an average of 2% to $\pi$ misidentification, but rising to 10% at the highest momentum. Figure 13 shows a different hadron particle selection, where efficiency is slightly sacrificed for a much higher rejection power, and the $\pi$ misidentification is kept below (1-2)% at all momenta.

## V. THE FUTURE

Figure 14 displays the laboratory's goals for luminosity at PEP II over the next seven years, with the expectation of logging ½ atobarn by 2005/6. The laboratory has begun consideration of an upgrade of the B Factory to a machine with $10^{36}$ $cm^{-2}$ $sec^{-1}$ luminosity. These aggressive luminosity goals (surely with increased machine backgrounds coming hand-in-hand) represent a serious challenge for the DIRC particle identification system. With improved shielding and the upgrade of the TDC electronics, the current DIRC system should work well up to luminosities close to $10^{34}$ $cn^{-2}$ $sec^{-1}$, but beyond that one looks for new technical upgrades.

To this end, we have embarked on an R&D program to explore possible upgrade scenarios. An essential tool in this program is a cosmic ray test bed. Figure 15 shows the layout of our test set-up. The muon spectrum is hardened by four layers of 13" steel absorber, giving roughly 400 MeV increments up to 2.5 GeV/$_c$. The stack has 1" thick scintillation counters between each layer (60" to 90" each), and provides very wide angular coverage. Two scintillation tracking hodoscopes, together giving ± 1 mrad angular accuracy and ±3.0 mm spatial accuracy, is mounted on movable rails above the test set-up, to allow full exploration of long test counters.

The R&D program is initially focused on evaluating new photo-detectors, then moving to testing their operation as Cherenkov detectors using a spare DIRC bar box and the cosmic ray telescope. Finally, on the basis of finding a suitable photon detector, we need to develop an optimal optical arrangement to collect the light from the bars onto the photo cathode surface. For the new photo-detectors, we are looking for compact devices that can be efficiently stacked, with good quantum efficiency (~20-30%), good spatial resolution (~ few mm), and capable of good time resolution (~150 psec). The current DIRC performance (see section 2 above) is dominated by chromatic effects (5.4 mrad) and geometrical/optical effects (7 mrad). The small pad photo-detectors to be studied promise substantial improvements in the spatial resolution and hence good gains in the geometric contributions, while the good timing performance could allow improvements by a factor of 3 in the chromatic contributions[8]. This provides clear motivation for the R&D program.

The first studies will be focused on three different photo-detectors:

(a) The Hamamatsu flat panel 64-channel PMT [H8500], with specifications:
  - 8x8 array of 6mm x 6mm pads
  - gain of a few $10^6$
  - rise time $\lesssim$1 nsec, and ~ 150 psec transit time spread
  - cross-talk at a few %
  - (49.7 x 49.7) mm active area

(b) The DEP electrostatically focused hybrid photo-diode [DEP HPD PP0380AU] with 61 channels of 2 mm x 2 mm pads

(c) The DEP proximity focused hybrid photo-diode [DEP HPD 0380 AJ] with 73 channels of 2 mm x 2 mm pads.

The first results on the Hamamatsu flat panel PMT are shown in Figure 16, where a schematic of the PMT and the circuitry used for the measurement are shown. An initial time resolution of < 200 psec is indicated for operation with single photo-electrons[9]. This is an encouraging first result! Figures 17 and 18 show the photographs of the two DEP hybrid photo-diodes which will be tested soon. The electrostatic focusing in Figure 18 has a demagnification of about 2.

Serious work is needed to come to a realistic optical design, and this awaits an evaluation of the performance of the three photon detectors on hand. Gedanken solutions are shown in Figures 19 and 20, for the Barrel geometry and End Cap, respectively. One imagines taking advantage of the low magnetic field (~1 gauss) in the existing Stand Off

Box which holds the 6,000 liters of purified, distilled water coupling the light from the quartz bars to the current 11,000 PMT's. A quartz block for each bar box might focus the light on a focal plane for one of the new photo-detectors under test. In the forward direction -- see Figure 20 -- a quartz plate with a reflecting/focusing block on the outer edge, after T. Kamae *et al.*(10), might offer a good solution.

To summarize our nascent R&D activity: a cosmic ray test set-up with good angular acceptance and range-hardened muon tags is now beginning operation. Three types of new single photon detectors, with promising specifications from the manufacturers, are in hand, and the characterization of their performance has begun. The initial results look promising, but we should have interesting, and more substantive, results by the fall conferences.

## VI. CONCLUSION

So, to conclude: Blair Ratcliff's DIRC concept is a brilliant new idea for hadron identification in the B Factory energy regime. It has proven to be a robust device delivering close to the design performance, and is being broadly used in almost all BaBar physics analysis. With continued prudent efforts on improving local shielding and the installation of the new TDC electronics, the DIRC should perform well for PEP II luminosities up to $10^{34}$ cm$^{-2}$ sec$^{-1}$. R&D for improved particle identification performance and to support very high luminosity environments has begun, and the initial results look promising.


## ACKNOWLEDGEMENTS

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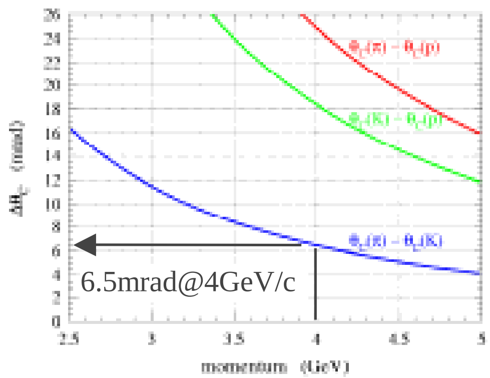
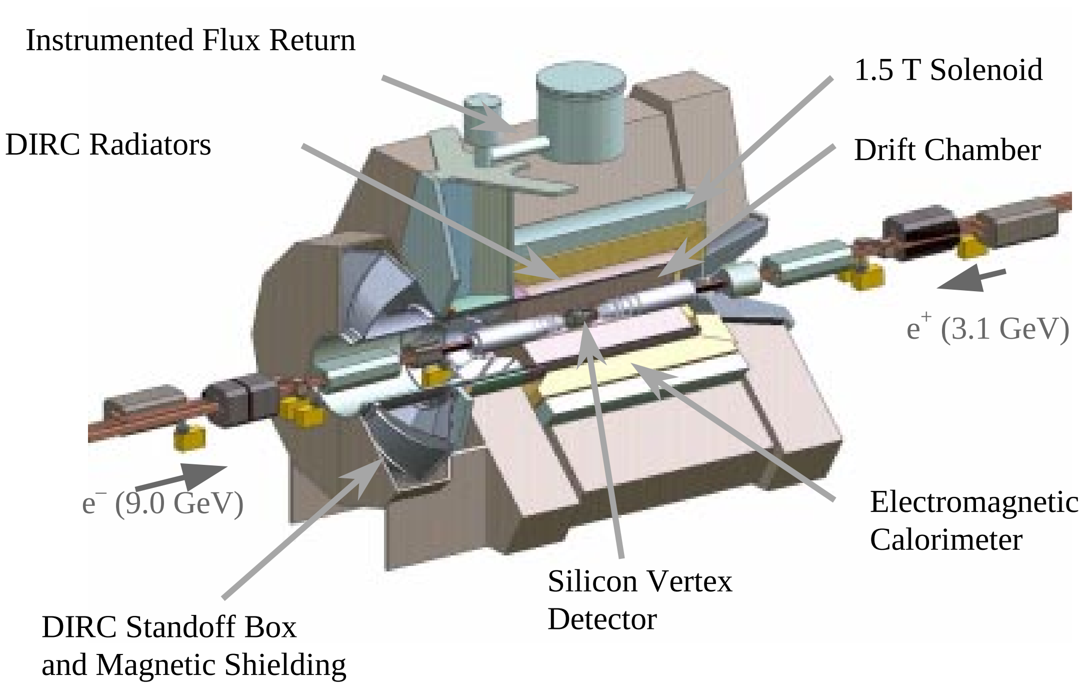



**Figure 1: Cherenkov angle separation as a function of momentum.**

**Figure 2: Schematic of BABAR detector.**



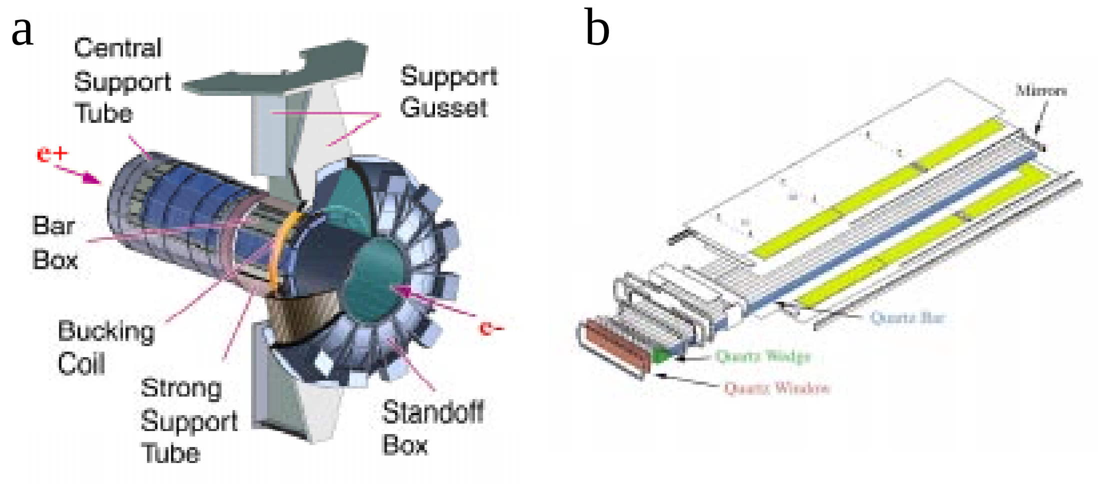



**Figure 3: Exploded view of the DIRC support structure (a) and schematic of DIRC radiator bar**

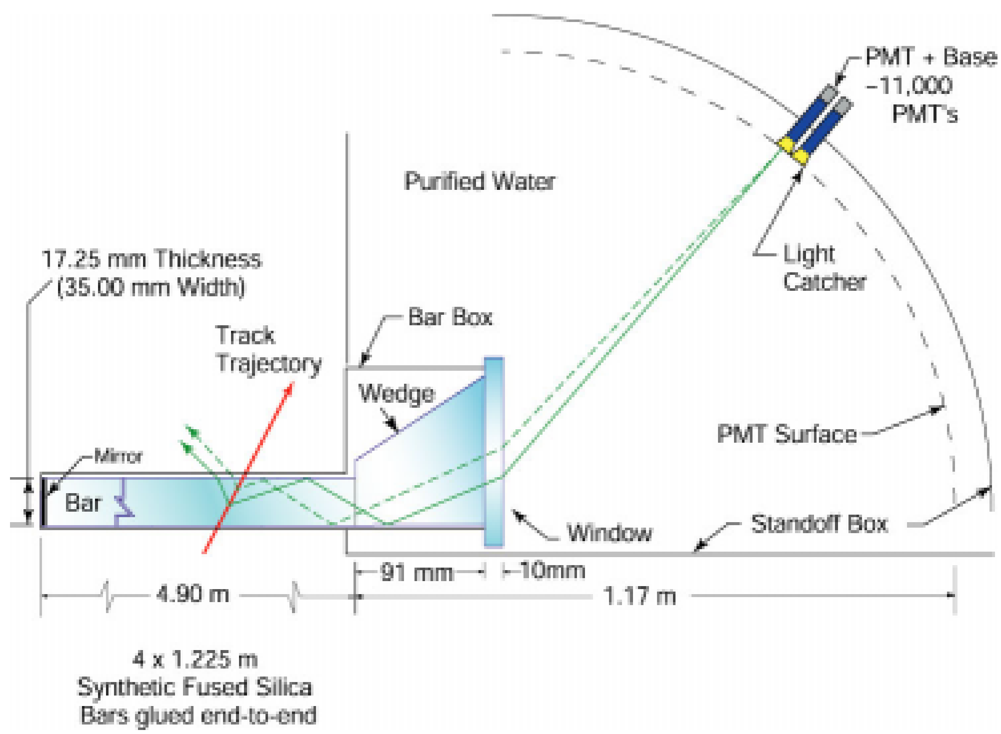



**Figure 4: Schematic of DIRC fused silica radiator bar and imaging region.**

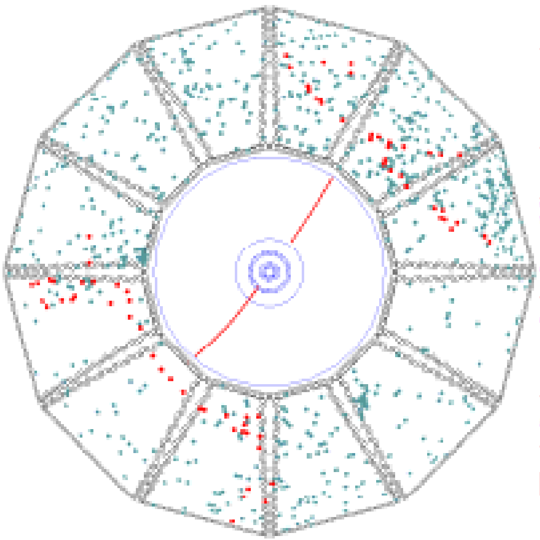


**Figure 5: Display of a di-muon event reconstructed in BABAR.**

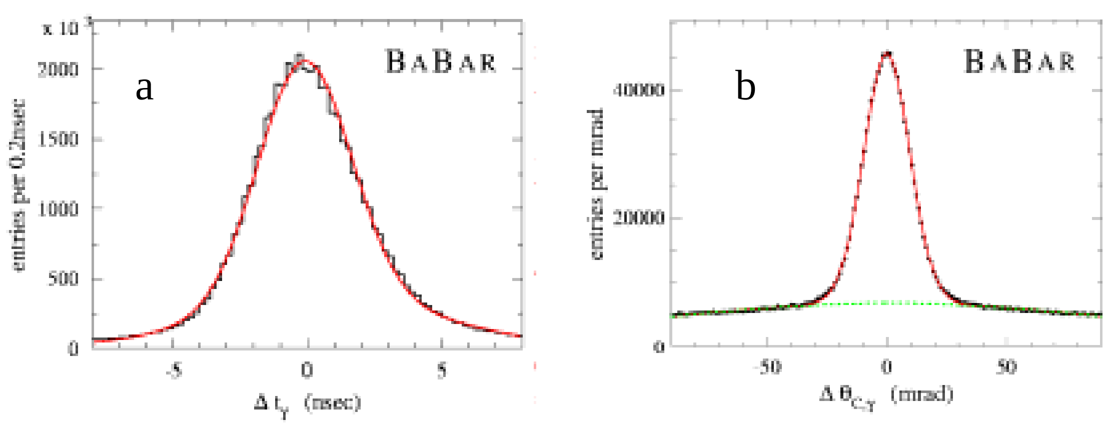



**Figure 6: Single photon time (a) and Cherenkov angle resolution (b).**

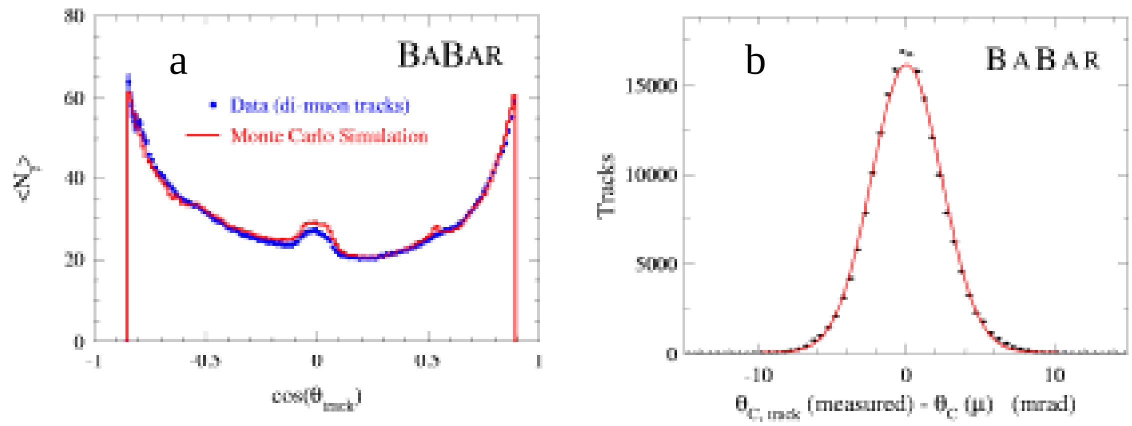



**Figure 7: Number of  detected photons vs. track polar angle (a) and resolution of the reconstructed Cherenkov angle per track (b).**

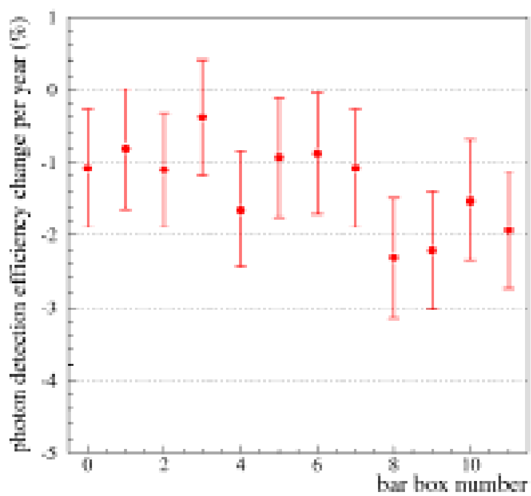



**Figure 8: Change of  photon yield per barbox per year.**

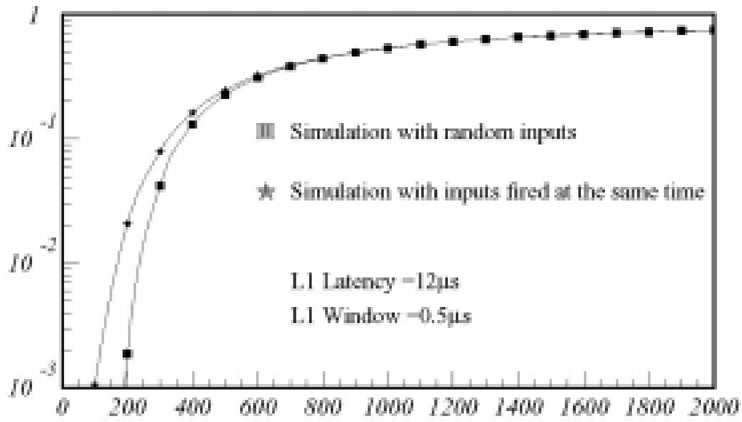



**Figure 9: TDC deadtime vs. PMT input rate.**

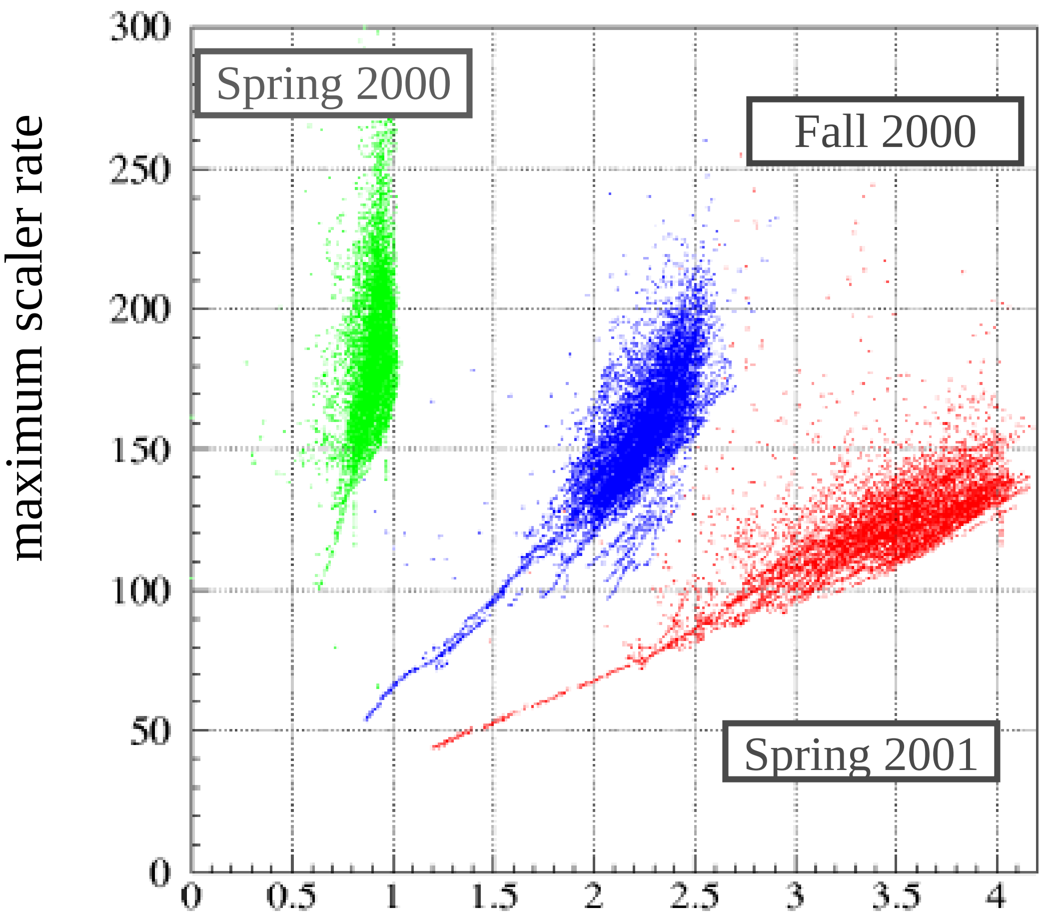



**Figure 10: Maximum scaler rate vs. luminosity for three shielding configurations.**

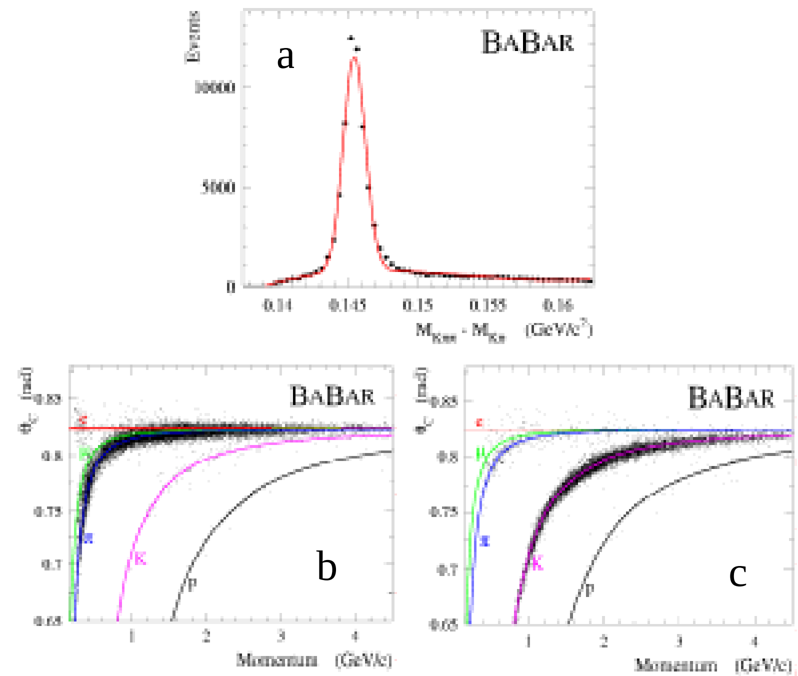



**Figure 11: Pion/Kaon separation capability demonstrated on the kinematically identified $D^* \rightarrow K^- \pi^+ \pi^-$ tracks.**

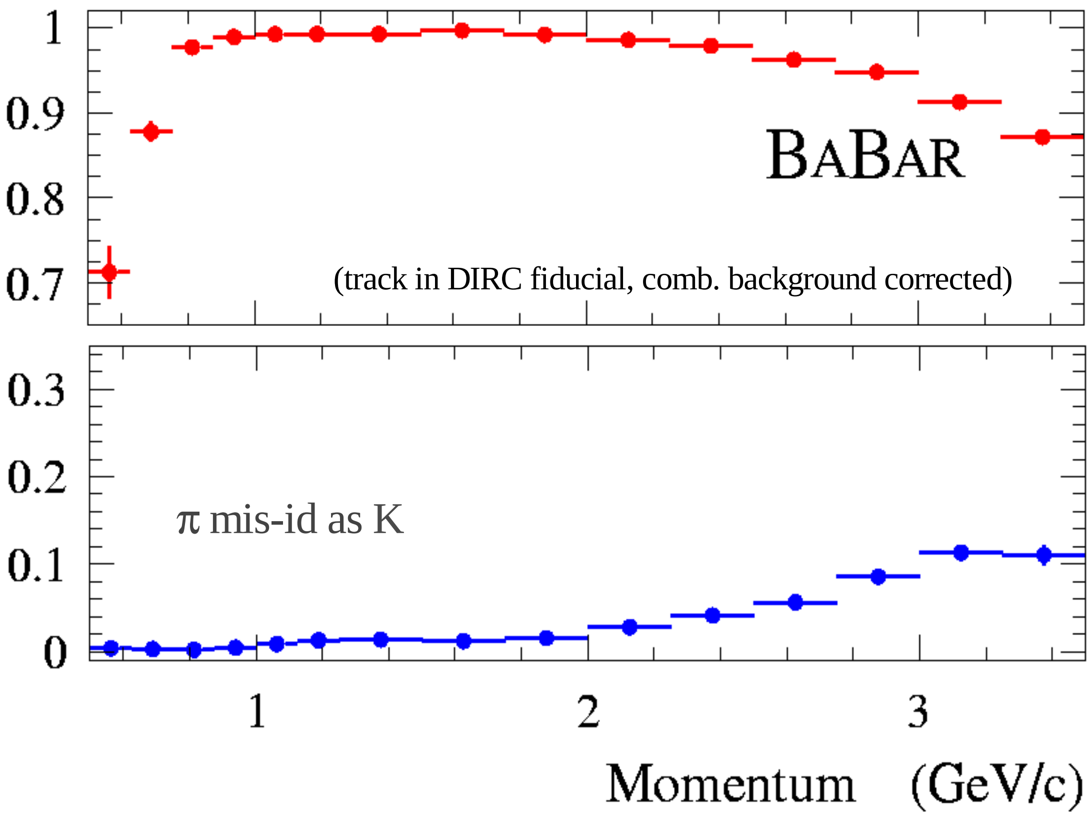



**Figure 12: Kaon selection efficiency and pion mis-identification probability.**

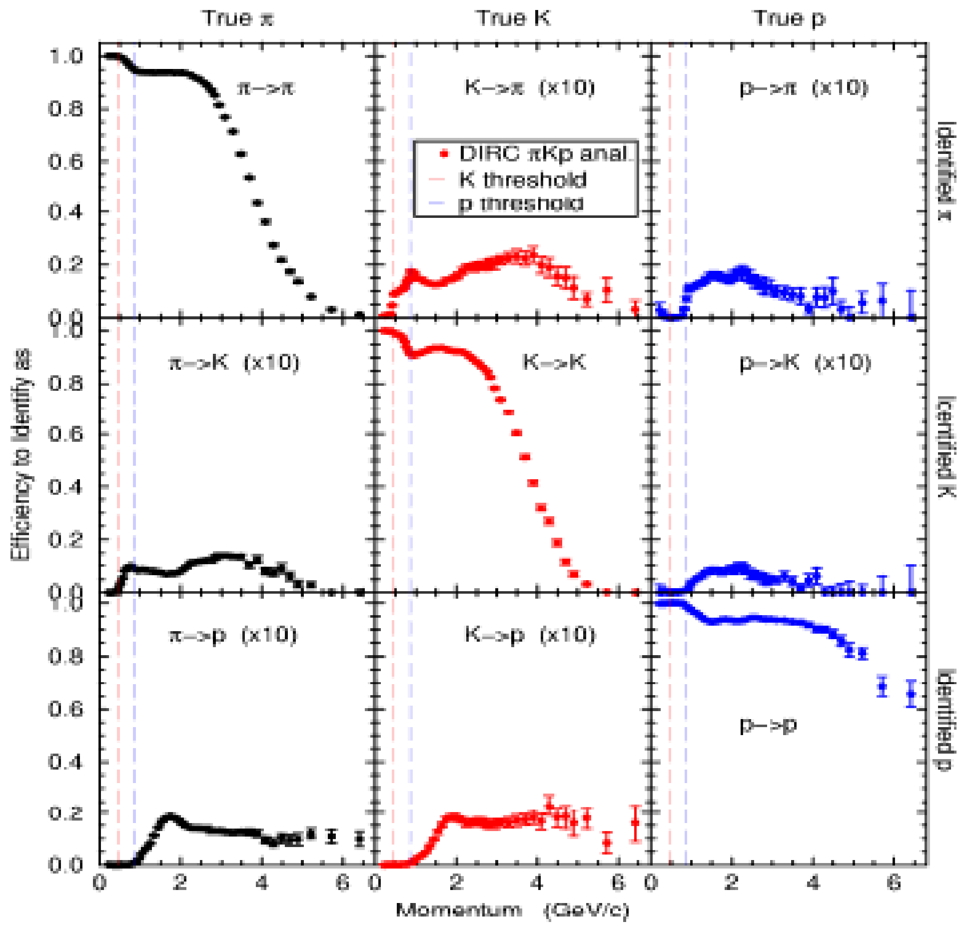
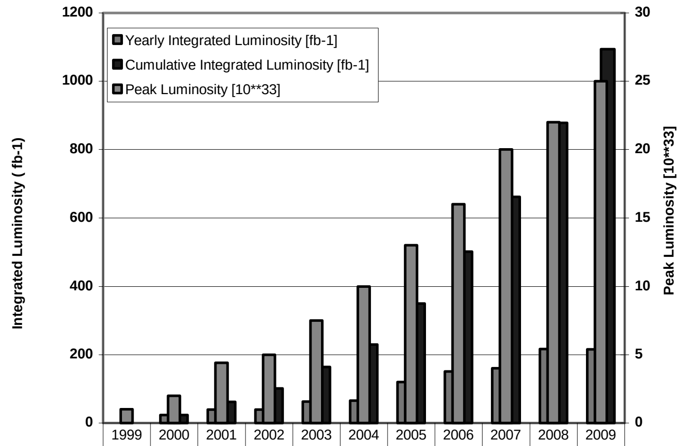



**Figure 13: Particle selection, where high selectivity is desired.**




| | 1999 | 2000 | 2001 | 2002 | 2003 | 2004 | 2005 | 2006 | 2007 | 2008 | 2009 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Yearly Integrated Luminosity [fb-1] | 0.3 | 23 | 39 | 39 | 62.6 | 66.1 | 120.1 | 151 | 160.1 | 217 | 216 |
| Cumulative Integrated Luminosity [fb-1] | 0.3 | 23.3 | 62.3 | 101.3 | 163.9 | 230 | 350.1 | 501.1 | 661.2 | 878.2 | 1094.2 |
| Peak Luminosity [10**33] | 1 | 2 | 4.4 | 5 | 7.5 | 10 | 13 | 16 | 20 | 22 | 25 |

Year

**Figure 14: Luminosity Goal of PEP-II B Factory vs. time**

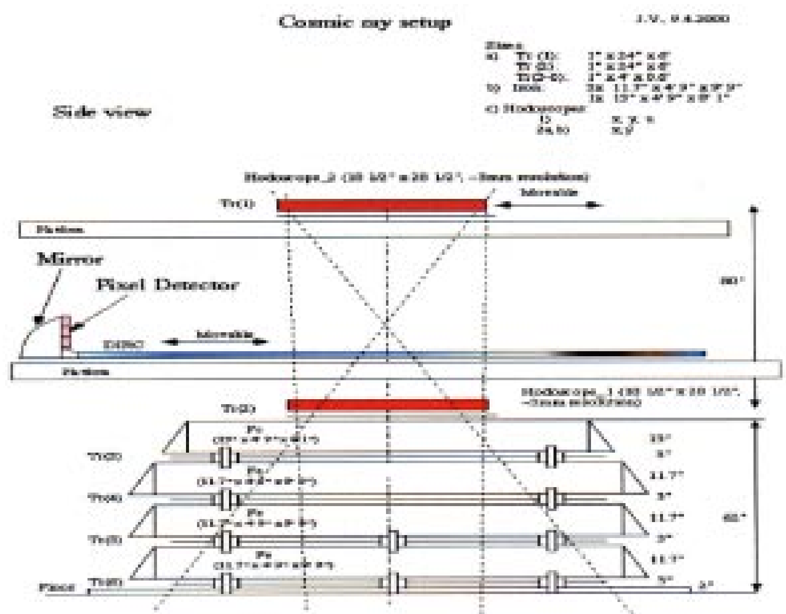



**Figure 15: Sketch of cosmic ray test set-up at SLAC.**

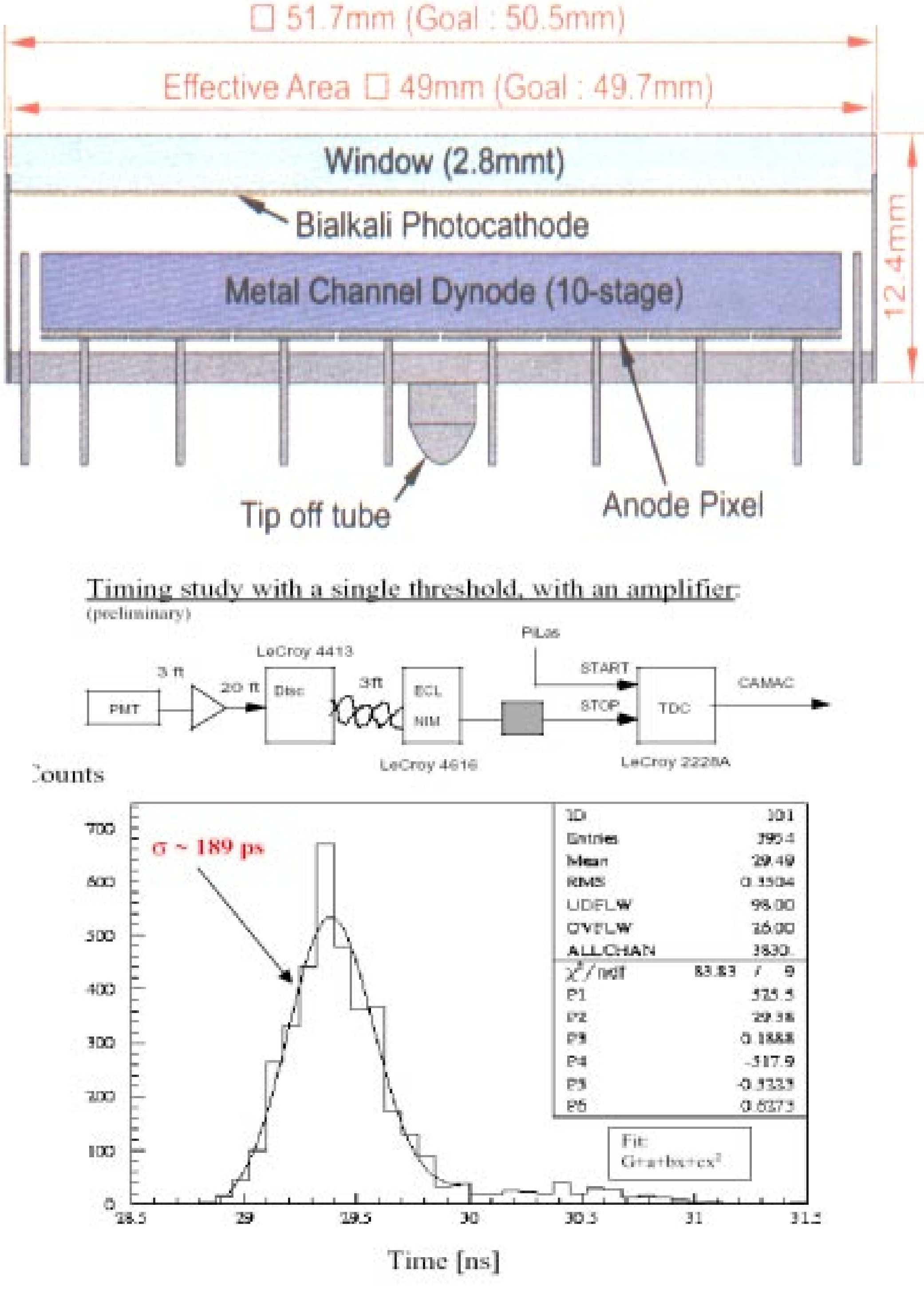



**Figure 16: Sketch of the Hamamatsu PMT, the electronics used for the test and the preliminary time resolution measured for single photoelectrons.**

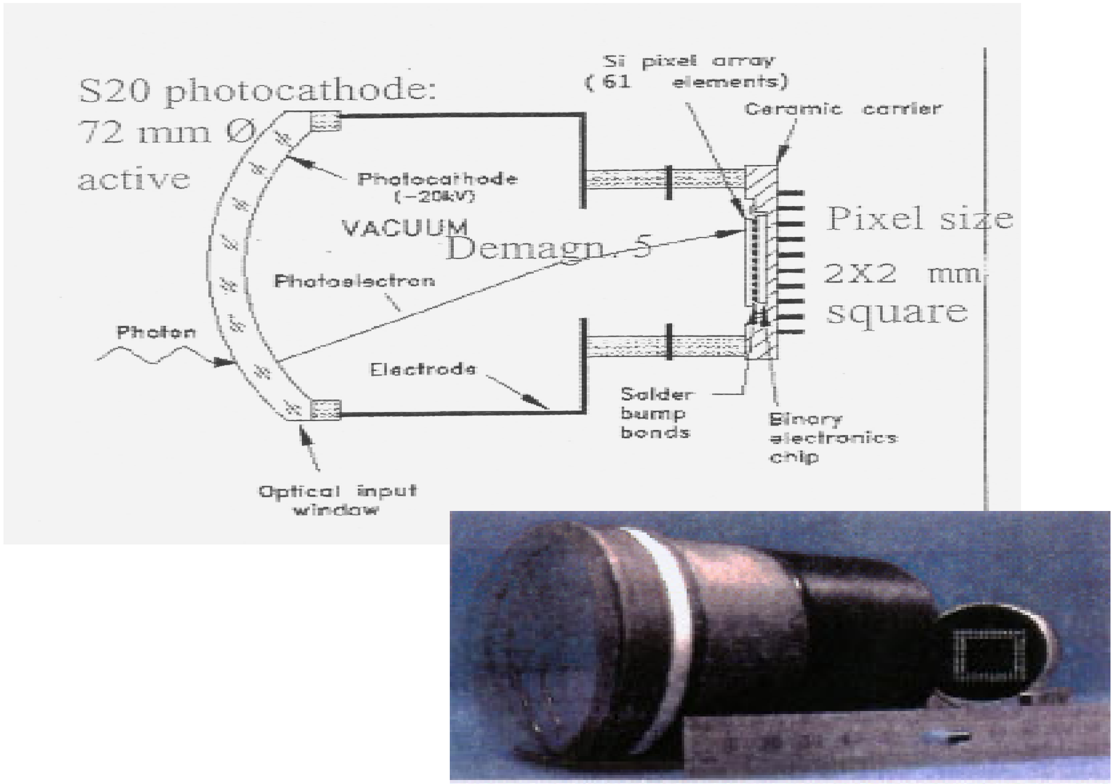



**Figure 17: Photograph of the DEP HPD PPO 380Au, with schematic of the focusing optics.**

DEP 73-channel Proximity Focussing HPD (0380AJ):

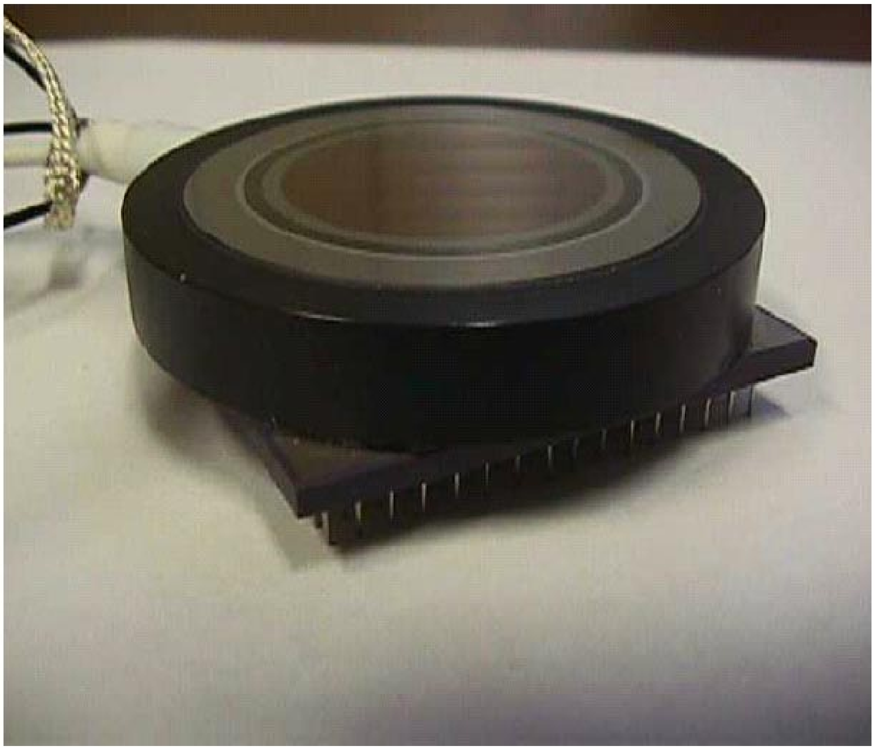


**Figure 18: Photograph of the proximity focusing DEP HPD.**

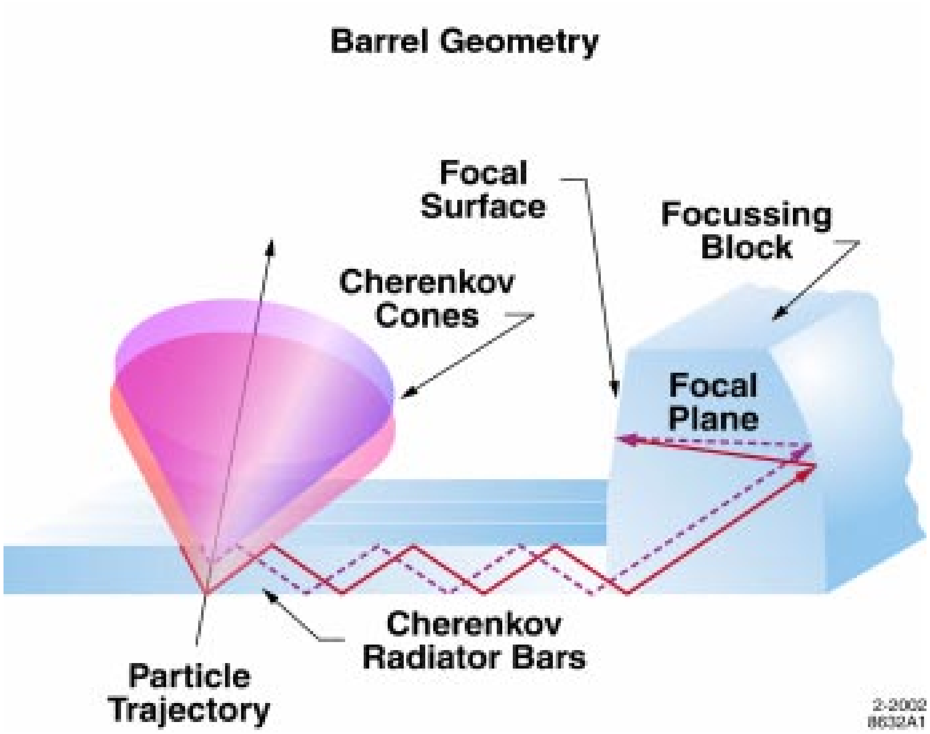



**Figure 19: Possible optical layout for the barrel counters.**

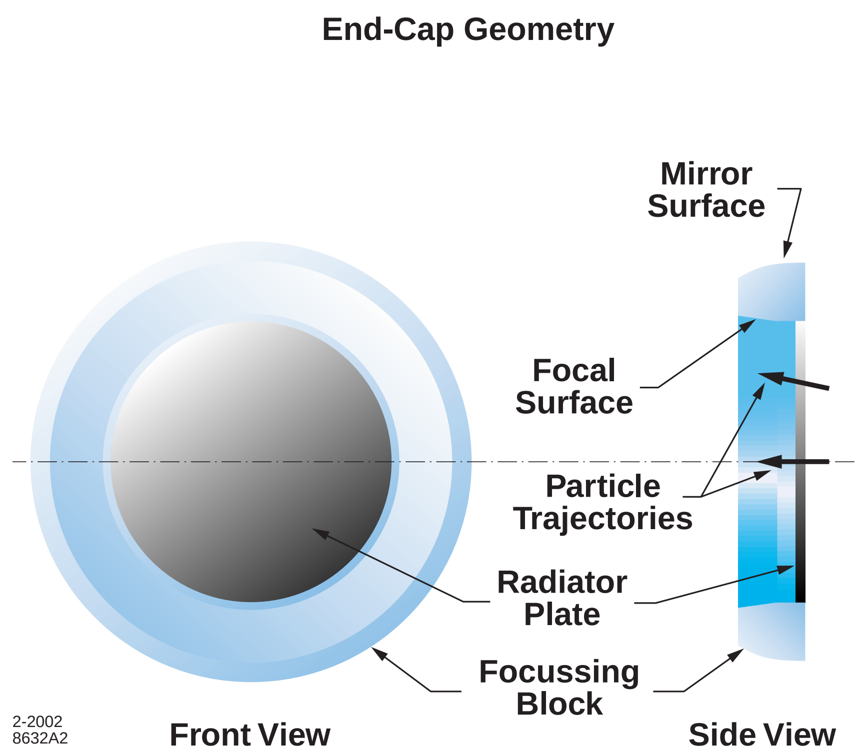



**Figure 20: Possible optical layout for a forward detection.**