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OPERATION OF A FAST-RICH PROTOTYPE WITH VLSI READOUT ELECTRONICS

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Abstract

We discuss the first test results, obtained with cosmic rays, of a full-scale Fast-RICH Prototype with proximity-focused 10 mm thick LiF (CaF₂) solid radiators, TEA as photosensor in CH₄, and readout of 12×10^3 cathode pads (5.334×6.604 mm²) using dedicated VLSI electronics we have developed. The number of detected photoelectrons is 7.7 (6.9) for the CaF₂ (LiF) radiator, very near to the expected values 6.4 (7.5) from Monte Carlo simulations. The single-photon Cherenkov angle resolution $\sigma_\theta = 19.1$ (15.2) mrad for the CaF₂ (LiF) radiator, to be compared with 19.3 (13.2) mrad predicted by the Monte Carlo calculations. These first results have shown that the Fast-RICH Prototype works well and that the technique is well-suited for the next generation of high luminosity e^+e^- or hadron colliders.

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1 INTRODUCTION

In this paper, we report the first results obtained with cosmic ray muons of a Fast-RICH detector prototype with cathode-pad read out using dedicated VLSI electronics that we have developed.

Our prototype of about 12×10^3 channels was originally designed as a study of the RICH detector component of a “universal detector” proposed in 1988 for an e^+e^- collider *B*-Factory project at the Paul Scherrer Institute (P.S.I.) [1]. The RICH detector, of about 4×10^5 channels, was conceived to ensure—over 4π sterad—a 3σ K/π separation up to 4.0 (3.5) GeV/ c using proximity-focused solid LiF (CaF₂) crystal radiators and TEA in CH₄ as the gaseous photosensor for a fast detector response.

However, the readout electronics, essential component of the detector, was designed so it could be used at LHC. This VLSI electronics is fast, allowing data acceptance within a minimum strobe width of 20 nsec, after a digital delay of 1.32 μ sec for decision-taking, and a data acquisition rate, with zero-suppression, of greater than 100 KHz. The readout electronics, being multiplexed and fully integrated over the back of the photodetector, the number of connections with the counting room is minimized, saving space and strongly reducing the amount of material in the detector volume. The VLSI electronics is discussed in detail in [2, 3, 4], and more briefly in these proceedings by E. Chesi [5].

The conception of the Fast-RICH detector, the response of the photodetector, and the expected performance are commented on in detail in [2, 6], and also briefly recalled in the survey of Séguinot and Ypsilantis in these proceedings [7]. Therefore for completeness, we describe only briefly the prototype structure, the experimental setup, and the data acquisition system. We will mostly discuss the experimental cosmic ray results obtained and their comparison to the expected performance. However, by the time of the availability of these proceedings, more complete tests will have been performed in a test beam at the CERN PS.

2 THE FAST-RICH PROTOTYPE

The mechanical structure of the full-scale barrel Fast-RICH Prototype we built is shown in Figure 1(a). It comprises three sectors, each of 12° in azimuth and between inner and outer radii of 65 and 85 cm respectively, so as to encompass at least 95% of the detectable Cherenkov ring images. The Prototype length of 90 cm corresponds to the half-length of the proposed P.S.I. detector.

The LiF or CaF₂ crystal radiators are visible in Figure 1(b). They are each 10 mm thick, and are fixed on the honeycomb back structure of the detector at distance of 13 cm from the windows. However, only the central sector was equipped with radiators for the cosmic ray tests.

The drawings show the CaF₂ windows (170×162 mm² each, 3.5 mm thick) glued on a rigid aluminum frame, of 95% optical transparency at normal incidence. The parallelepipedic hollow structures, visible above the windows of each sector receive the photodetectors described in [2, 6] and shown in Figures 2 and 3, such that the cathode pads form with the windows a conversion gap of 3.5 ± 0.1 mm. The grooves distributed along the sides of the structure provide a transverse distribution of the CH₄+TEA (17° C) gas mixture, allowing an homogeneous and uniform gas filling. The inner surfaces of the windows are printed (transversely to the detector axis) every 1.5 mm with 100 μ m vacuum-deposited silver traces [8]. The negative potential U_w applied to these strips, along with the positive potential U_a of the anode wires (15 μ m $\varnothing$, 1.27 mm pitch) 0.5 mm above the grounded cathode pads, define the electrostatic configuration of the multiwire photodetector.

Each sector comprises, as described in [2], 30 columns of 128 pads (5.334×6.604 mm²), hence 3840 electronic readout channels.

To assure an accurate Cherenkov angle reconstruction, the parallelism between the radiators and the windows was kept within 0.2 mm over the full length, and the accuracy on the relative angle of two adjacent sectors within 2 mrad.

In operation, the lever-arm volume between radiators and windows is flushed with clean

Argon gas passed through an oxisorb cartridge.

Because of the use of the photosensor TEA in CH_4 , the UV transparency of the lever-arm volume was quite sensitive to the ever-present outgassing of the construction materials; this is especially true of the epoxy resin used to glue the components (despite great care taken to insure a complete polymerization), and also of the moisture from the parts of the structure made of stesalite (glass fiber and epoxy resin). To minimize this outgassing, the inner surface of the radiator support is covered with a $50\text{ }\mu\text{m}$ thick aluminum foil acting additionally as electrostatic shielding for the low-noise front-end amplifiers. Even so, to get a UV transparency in the TEA energy acceptance region ($7.5 < E_{\text{ph}} < 9.3\text{ eV}$) above 95% for 20 cm path length (as monitored at the detector output with a monochromator) took several weeks of rinsing at normal temperature, and during data-taking the Argon flow had to be kept at about $50\text{ }\ell/\text{hour}$ —hence a renewal of the volume every hour. Because of the large TEA photoabsorption cross section, this transparency problem is *a priori* less critical for the photodetector gas itself, although the outgassing rate is comparatively much higher.

3 THE COSMIC RAY TEST SETUP

The cosmic ray test setup (*q.v.* Figures 4 and 5) was conceived to accurately reconstruct the trajectory of incident cosmic ray muons above $500\text{ MeV}/c$ in order to determine the Cherenkov angle of the detected photons.

The detection of a muon (*i.e.*, trigger of the electronic readout) was obtained by a telescope of four scintillation counters S_1 to S_4 in coincidence and a lead filter 30 cm thick. The counters S_1 to S_3 , each of 10 cm $\varnothing$, defined a gaussian angular acceptance region in the polar angle θ relative to the vertical axis with standard deviation $\Delta\theta \approx 31\text{ mrad}$; the trigger rate was about 15 events/hour of which two are high density showers.

The reconstruction of the muon trajectories was obtained by three MWPCs, two of which were mounted above the Prototype (not three as indicated in Figure 4) with 452 mm between MWPC1 and MWPC2 and 648 mm between MWPC2 and MWPC3. Each chamber has two orthogonal planes of 96 wires with 1.27 mm pitch and 4.8 mm gap between the cathode planes (which were $20\text{ }\mu\text{m}$ thick aluminized mylar foils). The MWPCs are flushed with a $\text{CH}_4 + \text{iC}_4\text{H}_{10}$ (90%+10%) gas mixture and read out with the same VLSI electronics used for the Prototype, but using the negative input polarity analog chip.¹⁾

A muon was identified and reconstructed when one and only one hit (cluster) was detected in each of the six wire planes. Hence an “event” is single track.

The chamber alignment was performed with a laser beam, using three survey sights per chamber (so labelled in Figure 4) as a reference for the wire positions. A sight is a cross-hair of two orthogonal lines printed on glass and sealed in a tube such that the cross is centered. The sights are plugged into metallic eccentrics which rotate in the holes visible on the cross-bar in Figure 4. The sights at both extremities of the bar are aligned with respect to the MWPC wires of the same direction, at a known distance from the center of the chamber; whereas, the central sight is aligned on the center of the orthogonal wire plane. The position of the wires is itself given by printed reference points on both the extremities of the mother board of the wire planes. The adjustment of the sights relative to the wires was made by rotation of the eccentrics on a digital table with an accuracy better than $30\text{ }\mu\text{m}$.

The relative alignment between chambers was first performed with a laser successively plugged in each eccentric of the upper chamber. The laser beam is thus at a known position and normal to the wire planes. Then, the two chambers below are physically moved in order to get coincidence between the laser beam spot and the corresponding sights. Finally the position of the chambers are slightly corrected by software such that the distribution of the deviations between the measured (surveyed) coordinates and the corresponding position calculated from a

¹⁾ The use of this VLSI electronics for both the Prototype and the MWPCs shows the versatility of these particular analog chips, RAL110 and RAL110N.

least squares fit to the wire hits is centered at zero. The rms deviations after such optimization are of the order $250\text{ }\mu\text{m}$.

A reconstructed muon trajectory was finally kept as “a good event” if the probability of the χ^2 hypothesis was greater than 1%, in order to select on track “straightness” and, reducing the contribution of multiple Coulomb scattering in the Prototype, increase the mean momentum of detected muons to about $2\text{ GeV}/c$. Therefore, taking into account all of these considerations, the total track reconstruction efficiency relative to the trigger rate was about 40%.

The Prototype was tilted at a 20° angle, as indicated in Figure 5, in such a way that all the UV Cherenkov light escaping from the CaF_2 radiator would hit Sector 2. This angle was determined with an accuracy of 1.7 mrad by measuring the deviation of the laser beam reflected from a mirror fixed to the back side of the Prototype. The position of the Prototype relative to the telescope was ultimately determined by measuring the barycenter of the muon trajectory (in Sector 1) in test runs without TEA.

As illustration of the expected images, Figure 6 shows a Monte Carlo simulation of 100 events produced with a 10 mm thick CaF_2 radiator—in Figure 6(a), for muons impinging at a single point on the radiator, while, in Figure 6(b), for full acceptance of the scintillation telescope taken into account ($\sigma_x = \sigma_y \approx 2\text{ cm}$, $\Delta\theta \approx 31\text{ mrad}$). In Sector 1, the hits correspond to photoelectrons from Cherenkov light generated in the CaF_2 window (ionization from the charged particle was not simulated). Also in Figure 6(a), one can observe the screening effect of the window frames.

4 THE DATA ACQUISITION SYSTEM

The layout of the data acquisition system is shown in Figure 7. The three sectors of the Prototype and the three MWPCs being read out in parallel, a CAMAC interface and VME memory are needed per readout channel (*i.e.*, sector or MWPC) although, for clarity, only one is represented in the diagram. The present system works in single-event mode, but should be improved in the future to run in multi-event mode.

The real-time data acquisition system uses the SPIDER program provided by the CERN ECP/DS group, running under the OS-9 environment [9]. The DAQ control program drives the VLSI readout electronics via the CAMAC interfaces. Each CAMAC interface receives, from the 12-bit data bus of the associated sector (or MWPC), an encoded word per hit pad (or hit wire) containing the row address of the digital chip (5 bits) and the channel address (4 bits) in the chip. A specific combination of 2 of the last 3 bits is recognized by the interface as the readout-end flag of a column. Counting these flags (in 4 bits) defines the column address appended to the aforementioned row and channel addresses. The word address thus formed is transmitted to the VME dual port memory synchronously with the readout clock of the VLSI electronics. A clock readout is generated in each CAMAC interface during the data readout time interval only. The last bit of the data bus provides a BUSY flag during the readout.

A LAM (wired OR of all BUSY lines) is generated when the most populated sector is read out, which is the flag that starts the readout of the VME memories by the microprocessor. At this stage, the sector address and the event number are appended to form an unambiguous 32-bit word address of a hit pad.

A partial on-line analysis is performed during data-taking for monitoring purposes. At the end of a run, the data are automatically transferred via ethernet to the laboratory VAX, and stored on disk for off-line analysis.

Besides the DAQ control program, other user-written programs have been developed to drive the digital chips via the CAMAC interface and the 8-bit control lines by addressing each chip (15×16 per prototype sector, 2×8 per MWPC). The purpose being:

- (i) to set the 16-channel discriminator threshold of the two associated analog chips; and
- (ii) to perform diagnostics on the readout chain.

In the former case, the application is straightforward. In the latter case, random patterns are generated and stored in the register of the digital chips, a readout process is then started, and

a comparison is made between the generated patterns and readout data. A diagnostic of the possible errors is also given by these test programs. The readout process is either slow (~ 200 Hz), using only the CAMAC readout step-by-step, or fast (≤ 15 MHz) by directly reading the VME memories.

It should be noted that during three months of data-taking operation with cosmic rays, we have not registered a single readout error.

5 PROTOTYPE OPERATION AND MONTE CARLO SIMULATION

The Prototype was operated in the cosmic ray test setup between December 1992 and March 1993, for about half of this period. During the data-taking, the lever-arm volume was flushed (*cf.* § 2) with 50 ℓ /hour pure Argon gas, and the photodetectors with 10 ℓ /hour of pure CH_4 , bubbled through TEA kept at 17°C . Otherwise, Argon flowed continuously through all volumes.

Because of the difficulties presented by a low trigger rate for the adjustment of the strobe delay in coincidence with data at the output of the 50 MHz shift registers, the strobe width was set at 100 nsec—although it could be safely reduced to 30 nsec. The adjustment of the voltages U_W and U_a during operation, as well as the DAC values for the optimization of the signal-to-noise ratio, is discussed in § 6 below.

The Monte Carlo program used has been developed over the course of several years, and has been tuned and tested against analytic calculation, such that we feel confident in its general reliability. The simulations discussed in the following paragraphs use the photodetector response previously measured and described in [6]. The quantum efficiency of the CH_4 +TEA gas mixture has been determined from the TEA response in He given in [6], weighted by the relative photoabsorption in TEA vapor with respect to the methane gas. The weighting was done using the measurements we have made with a monochromator of the photoabsorption cross sections for pure CH_4 at the exhaust of the photodetector and for TEA in a separate cell. The dependence with photon energy of the CaF_2 and LiF refractive indices have been taken from [10] and [11]. The transmission of a LiF radiator was measured at CERN, and that of the CaF_2 windows was measured at Karlsruhe [8]. The MC calculations were run for 2 GeV/c muons.

6 EXPERIMENTAL RESULTS WITH A 10 mm CaF_2 CRYSTAL RADIATOR

6.1 Off-line Analysis of the Prototype Raw Data

Figure 8 shows a scatter-plot of the hit pads for a typical cosmic ray run with a 10 mm CaF_2 crystal radiator of 100 good events at the nominal detector voltages ($U_W = -1.680$ KV, $U_a = 1.425$ KV) and threshold DAC value of 6. For these runs, voltage was not applied to the anode wires in Sector 0 (opposite to the photon acceptance region) in order to get an unbiased monitoring of the electronic noise. The mean number of hits per event²⁾ for the clearly visible “hot” channels in Sector 0 (there are three or four of them) is only 0.68 (*i.e.*, $\bar{n} < 2 \times 10^{-4}$ noise hits per event per channel). These hot channels could be masked, if needed. Elsewhere, the noise is negligible or even null.

In Sector 1, the large main spot of 10 cm diameter is formed by the ionizing track of the muons themselves at the impact point in the photodetector, and by the photoelectrons from UV Cherenkov photons produced in the CaF_2 window. The size of the image corresponds to the acceptance of the telescope geometry. The sprinkling of hits around the track spot is believed to be created by scintillation light in the crystal radiator, and by the Cherenkov light produced by δ -rays in the radiator.

Sector 2 is populated by the Cherenkov photons emitted in the radiator. Thus, the partial ring image is clearly evident. Losses due to the screening of the CaF_2 window frame can also be seen. The mean number of hit pads in Sectors 1 and 2 is 5.1 ± 0.2 and 12.8 ± 0.3 , respectively.

²⁾ Some terminology is needed. A raw hit on the cathode-pad plane is “hit pad” or just a “hit”. The digital barycenter of a “cluster” of hit pads is a reconstructed hit, or equivalently, a detected photoelectron (pe). A collection of such detected photoelectrons is an image of the Cherenkov ring. A single ring image corresponds to a single track, and by the trigger requirements thus to a single “event”.

The scatter-plot in Figure 9 shows the reconstructed impact points of the UV photons from the same run, defined by the digital barycenter formed when adjacent hit pads are clustered. The solid line represents the geometric limits for 99% acceptance of the UV photons. The mean number of reconstructed hits per event is 2.20 ± 0.1 and 8.9 ± 0.2 pe/image for Sectors 1 and 2 respectively, and hence a clustering multiplicity of 2.4 ± 0.1 and 1.44 ± 0.02 hit/pe as expected from simulations (including the muon track).

Typical events are shown in Figure 10; they exhibit a good signal-to-noise ratio.

For comparison, Figure 11 shows the scatter-plot of the hit pads for 115 events taken under condition similar to the previous run, except that the gas in the photodetector was pure CH_4 . Here, an “old” track is visible in Sector 2. The mean number of clusters per event is 1.6 ± 0.1 and 0.9 ± 0.1 in Sectors 1 and 2, while in a random test the respective values are 0.05 and 0.16, mainly due to the electronic noise. Hence the residual number of detected photoelectrons in Sector 2 is 0.7 ± 0.1 pe/event. The distribution of these hits is not similar to that of Cherenkov photons; they are correlated with the particle but their origin is not yet well understood.

6.2 Single-Photon Cherenkov Angle Resolution

The image in Figure 12 is a superposition of a sample of 350 events which clearly shows the dead spaces resulting from the window frame screening and from the ceramic spacers every 105.7 mm (16×6.604 mm) which support the anode wires [3, 4]. The total transmission of the Cherenkov radiation due to the design is $T = T_f \cdot T_{tr} \cdot T_{sp} = 79.3\%$, according to this display (the transmission of the window frame $T_f = 0.907$, the transmission through the traces on the CaF_2 windows is $T_{tr} = 0.933$, and the geometric efficiency of the photodetectors because of the spacers is $T_{sp} = 0.937$). These values are in agreement with the loss calculated by Monte Carlo simulation.

A total of 233 muon trajectories, from 579 events, have been reconstructed and kept according to the criteria discussed in § 3. Figure 13(a) shows, for this sample, the reconstructed single-photon Cherenkov angle distribution. The Cherenkov photon peak emerges above a very low background, estimated to be 0.63 ± 0.05 detected photoelectrons per image within the fiducial limits.

By a fit to the data, the actual photoelectron yield (*i.e.*, the number of detected photoelectrons in the peak above the noise per image) is found to be $N_{pe} = 7.7 \pm 0.2$ pe/image. Hence, the signal-to-noise ratio is $\text{SNR} = 12 : 1$.

The angular resolution per photon $\sigma_\theta = 19.1 \pm 0.4$ mrad from the direct measurement of the full-width at half-maximum of the peak. The same value is obtained by a gaussian fit to the data (with a poor χ^2) for the Cherenkov angle with a polynomial background for the noise. The MC simulation, given in Figure 13(b), shows that the angular distribution is asymmetric, explaining its poor description with a gaussian. The rms deviation of the MC distribution is 19.3 mrad, in very good agreement with the measured value. The calculated yield is 6.4 photoelectrons per image as opposed to the detected value of 7.7 given above.

The mean reconstructed Cherenkov angle is $\bar{\theta} = 887.3 \pm 0.5$ mrad, in fairly good agreement with the expected value of 885.2 given by MC.

6.3 Photoelectron Detection Efficiency vs. Detector Gain

In Figure 14(a) we show the variation of the number of detected photoelectrons per image in the Cherenkov photon peak—hence the background subtracted number—as a function of the anode wire voltage, for a fixed value of U_W and $\text{DAC}=6$. This result clearly proves that a rather good detection efficiency is achieved. The narrow plateau is a consequence of the design philosophy, *viz.*, to make the detector fast, since at maximum only $\sim 20\%$ of the avalanche charge is collected. Above the last point (for $U_a > 1.5$ KV) the detector becomes unstable, especially when a shower is detected. For safety then, we run at 1.425 KV.

The Figure 14(b) shows the variation of the cluster multiplicity. This parameter is strobe-width dependent. The variation shown is in good agreement with the preliminary tests discussed in reference [6].

7 EXPERIMENTAL RESULTS WITH A 10 mm LiF CRYSTAL RADIATOR

7.1 Off-line Analysis of the Prototype Raw Data

Figure 15 shows a scatter-plot of the reconstructed photoelectrons (digital barycenter of the clustered hit pads) for a typical cosmic ray run with a 10 mm LiF crystal radiator of 131 good events at the nominal detector settings ($U_W = -1.680$ KV, $U_a = 1.425$ KV, DAC=6). The Cherenkov angle is smaller for a LiF radiator than for CaF_2 , so the ring images overlap Sectors 1 and 2 for the same incident muon angle, as indicated by the fiducial limits calculated for 99% photon acceptance.

7.2 Single-Photon Cherenkov Angle Resolution

The single-photon Cherenkov angle distribution for 121 images is given in Figure 16(a). The photoelectron yield is $N_{pe} = 6.9 \pm 0.2$ pe/image, with an estimated background of only 0.4 ± 0.1 pe/image, and hence again a good signal-to-noise ratio $\text{SNR} = 17 : 1$ is obtained.

The angular resolution σ_θ per photon as calculated from the full-width at half-maximum of the peak is 15.9 ± 0.5 mrad, whilst the gaussian fit shown gives 15.2 ± 0.5 mrad (though with a poor χ^2). In comparison, the rms deviation of the MC distribution is 13.2 mrad, as shown in Figure 16(b), hence slightly lower than the resolution measured. However, in this case the distribution is rather symmetric and a gaussian fit gives an angular resolution of 12.7 mrad with a correct χ^2 .

The measured mean Cherenkov angle is $\bar{\theta} = 845.3 \pm 0.6$ mrad, while the expected MC value is 836.4 mrad; hence a discrepancy of approximately 1%. The estimated yield is 7.5 pe/image, *vis-à-vis* the 6.9 detected.

7.3 Photoelectron Detection Efficiency vs. Electronic Threshold

Figure 17 shows the number of reconstructed photoelectrons per image in the Cherenkov photon peak (background subtracted) and the multiplicity of hit pads per cluster as a function of the DAC threshold value, for $U_a = 1.425$ KV. Each increment of one unit of the DAC corresponds to an increase of about 20 nA on the input current threshold. The absence of a plateau with regard to the setting voltage U_a is normal. The slow variation of the detection efficiency proves the current distribution of the induced pulses on the pads is rather well-peaked.

8 DISCUSSION OF THE EXPERIMENTAL RESULTS

Table 1 summarizes the various contributions to the Cherenkov angular resolution for both radiators; the calculated values were obtained with the Monte Carlo program by changing each variable in turn (except for the chromatic error) by one standard deviation. The dominant source of error is clearly given by the chromatic aberrations. The total errors for CaF_2 and LiF are those previously quoted in §§ 6.2 and 7.2.

Figure 18 shows an analytical calculation [12] of the variations of the main components to the resolution as a function of the azimuthal angle ϕ (with respect to the incident particle direction) and of the photon acceptance. The mean number of expected photoelectrons as well as the single-photon Cherenkov angular resolution from these analytical calculations are in good agreement with the MC calculations.

Table 2 summarizes the comparison between experimental results and MC predictions. The difference in the mean Cherenkov angle for LiF can easily be explained by an uncertainty in the refractive index of $< 1\%$. For the LiF radiator, there is a difference of less than 10% in the photoelectron yield, which is not significant with regard to the uncertainties in the transmissions and in the analytical calculations (see Table 2). However, for the CaF_2 radiator, an excess of 20% is observed over the expected value which is not explained.

Multiple scattering in the radiator is not taken into account in the MC simulation; neither is the momentum dispersion of the incident cosmic ray muons above 500 MeV/c. An estimate of the rms Cherenkov angle error resulting from multiple scattering is less than 1.9 and 1.3

mrads for $p_\mu > 2$ GeV/c, for the CaF₂ and LiF radiator respectively. The contribution of the momentum dispersion of the muons is small. However, because of the constraints applied on the track reconstruction (*e.g.*, $P(\chi^2) > 1\%$), it is not clear that the multiple scattering correction should be applied. Even so, the single-photon Cherenkov angle resolution is in good agreement with the calculations for CaF₂, and only slightly higher for LiF.

9 CONCLUSIONS

The first tests of the Fast-RICH Prototype with cosmic rays have been completed and have shown that the technique works well and as expected; although more detailed investigations and precise measurements in a test beam environment will still be very useful and necessary.

The VLSI readout electronics operation was very reliable over the three months of testing and data-taking. The single-channel noise count probability is of the order 10^{-4} for a 100 nsec strobe-width. The single-photoelectron detection efficiency achieved is estimated to be above 93%, in agreement with previous tests [6].

The number of detected photoelectrons for the CaF₂ and LiF radiators are very near the values predicted by Monte Carlo simulation. The single-photon Cherenkov angular resolutions obtained are slightly higher than calculated by about 10%; the origin of this discrepancy will be investigated.

These results already show that the Fast-RICH technique—Cherenkov ring imaging using a gaseous photoconverter, cathode-pad photon detector with fast VLSI readout electronics—has a performance well-suited for an e^+e^- collider *B*-Factory as well as the next generation of high luminosity hadron colliders.

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Table 1. Summary of the Various Contributions to the Single-Photon Cherenkov Angle Resolution.

Contribution	CaF ₂ [mrad]	LiF [mrad]
chromatic error	18.8	11.4
emission point error	3.0	4.4
total measurement error	2.3	3.3
x -measurement error	2.2	3.1
y -measurement error	0.8	0.9
z -measurement error	0.2	0.3
beam position error (0.4 mm in x and y)	0.5	0.7
beam direction error (0.1° in θ_p and ϕ_p)	1.9	1.9
total θ error	19.3	13.2

Table 2. Comparison Between Experimental Results, Monte Carlo Predictions, and Analytical Calculations.

	CaF ₂ Radiator			LiF Radiator		
	$\bar{\theta}$ [mrad]	σ_{θ} [mrad]	N_{pe} [pe/image]	$\bar{\theta}$ [mrad]	σ_{θ} [mrad]	N_{pe} [pe/image]
Experimental Results	887.3 ± 0.5	19.1 ± 0.4	7.7 ± 0.2	845.3 ± 0.6	15.2 ± 0.5	6.9 ± 0.2
Monte Carlo	885.2	19.3	6.4	836.4	13.2	7.5
Analytical Calculation	886.8	19.7	6.2	836.0	12.2	7.3

FIGURE CAPTIONS

Figure 1. The mechanical structure of the full-scale barrel Fast-RICH Prototype. (a) The three sectors and the hollow structures above the CaF_2 windows which receive the photodetectors. (b) The radiators, shown in a transversal cut of the Prototype, and the principle of the mounting of the electronic readout.

Figure 2. Photographs of a photodetector, showing the cathode pads and ceramic spacers.

Figure 3. Photographs of a photodetector, showing the pin connectors and VLSI readout electronics.

Figure 4. The cosmic ray test setup, showing the mechanical design of the mountings, support structure, scintillation telescope S_1 – S_4 , wire chambers MWPC1–MWPC3, and the Prototype.

Figure 5. The cosmic ray test setup, giving a general schematic diagram of the geometrical arrangement. The Prototype was tilted at a 20° angle. All units are mm. The thickness of the lead is 300 mm.

Figure 6. Monte Carlo simulation of 100 events with a 10 mm thick CaF_2 crystal radiator, for (a) muons impinging at a single point on the radiator; and (b) for full acceptance of the scintillation telescope. The scale is given in cm.

Figure 7. Schematic of the data acquisition system.

Figure 8. Scatter-plot of the hit pads for a typical cosmic ray run with a 10 mm thick CaF_2 crystal radiator ($U_W = -1.680$ KV, $U_a = 1.425$ KV, DAC=6). The scale is in units of pad column and pad line number.

Figure 9. Scatter-plot of the reconstructed impact point of the UV photons from the same CaF_2 run. The solid line represents the geometric limits for 99% acceptance. The scale is cm. The spatial orientation is bus at the top of the plot.

Figure 10. Typical events from the same CaF_2 run. Note the number of pads per cluster and the small amount of background.

Figure 11. Scatter-plot of the hit pads for 115 events taken with pure CH_4 .

Figure 12. Superposition of 335 events showing the dead spaces resulting from the window frame screening and from the ceramic spacers. The scale is in units of pad column and pad line number.

Figure 13. Reconstructed single-photon Cherenkov angle distribution, for a 10 mm thick CaF_2 crystal radiator, (a) as experimentally measured from 233 reconstructed muons (with a gaussian fit and polynomial background); and (b) as expected from Monte Carlo simulation.

Figure 14. Variation with the anode wire voltage, for a fixed value of U_W and DAC, of (a) the number of detected photoelectrons per image in the Cherenkov photon peak (background subtracted); and (b) the cluster multiplicity.

Figure 15. Scatter-plot of the reconstructed photoelectrons for a typical cosmic ray run of 131 events with a 10 mm thick LiF crystal radiator ($U_W = -1.680$ KV, $U_a = 1.425$ KV, DAC=6).

Figure 16. Reconstructed single-photon Cherenkov angle distribution, for a 10 mm thick LiF crystal radiator, (a) as experimentally measured from 121 reconstructed muons (with a gaussian fit and polynomial background); and (b) as expected from Monte Carlo simulation.

Figure 17. Variation, as a function of the DAC threshold value, for $U_a = 1.425$ KV, of (a) the number of reconstructed photoelectrons per image in the Cherenkov photon peak (background subtracted); and (b) the cluster multiplicity.

Figure 18. Analytical calculation of the variation of the main source of errors in the single-photon Cherenkov angle resolution as a function of the azimuthal angle ϕ and the photon geometric acceptance, for (a) CaF_2 radiator, and (b) LiF radiator.

Fig. 1

Fig. 2

Fig. 3

Fig. 4

Fig. 5

sector #

a)

b)

Fig. 6

Fig. 7

Fig. 8

Fig. 9

Fig. 10

Fig. 11

Fig. 12

Fig. 13

Fig. 14

Fig. 15

Fig. 16

Fig. 17