A RING IMAGING CHERENKOV DETECTOR FOR THE CERN OMEGA SPECTROMETER – THE DESIGN AND RECENT PERFORMANCE

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A large acceptance Ring Imaging Cherenkov detector has been constructed for use at the CERN Omega Spectrometer. The design of the detector is discussed, with attention paid to its principal components, and preliminary results are given which show that the detector is capable of identifying pions, kaons and protons at 80 GeV/c.

1. Introduction

The CERN Omega Spectrometer supports an active and important series of fixed target, high-energy physics

experiments. Crucial to this program of high precision measurements is the development and introduction of a series of new and advanced particle detectors including a large acceptance Ring Imaging Cherenkov detector

Fig 1. General layout of the WA99 experiment at Omega.

(RICH). This detector has been designed to provide enhanced secondary particle identification over a large momentum range and with a spatial resolution sufficient to resolve particles with an angular separation as small as 1 mrad. This single detector will be capable of identifying pions from 5 to 80 GeV/ c , and of providing kaon-proton discrimination up to 160 GeV/ c . Fig. 1 shows the position of the detector in the WA69 high-energy photoproduction experiment which will begin data taking in July 1984.

2. General description

High-energy particles entering the detector produce ultraviolet Cherenkov radiation in a 5 m atmospheric pressure nitrogen radiator. The radiator gas contains less than 10 ppm of oxygen and water vapour to ensure good transmission down to wavelengths of 160 nm. The Cherenkov radiation is focused into ring images by an array of 80 5 m focal length spherical mirrors. An array of 16 Time Projection Chamber (TPC) modules is arranged on the focal surface of this mirror. The radiator gas volume is separated from the TPC gas by 16 quartz windows each constructed from two sheets of quartz. A general view of the detector is shown in fig. 2.

Each mirror has a good reflectivity [3], down to 170 nm (fig. 3), and mirror distortion has been measured to contribute less than 1 mm to the error in reconstructing the Cherenkov ring image. The mirrors have been aligned to have a common centre of curvature ($< \pm 1$ mm) and produce an essentially continuous mirror surface 7 m by 4 m in extent. Fig. 4 shows some reflected images in the

Fig. 3. Reflectivity of the 80 mirrors used in the RICH vs λ (nm). There were 800 measurements at each wavelength.

mirror system and fig. 5 shows the mounting arrangement.

Thirty-two sheets of quartz, each 800 mm $\times$ 200 mm $\times$ 3 mm, are used to construct the window which is 3.2 m by 1.6 m in extent. The measured transmission of the windows is shown in fig. 6, which includes any losses produced by the electric field shaping wires placed on both sides of the quartz sheets.

A single TPC module is shown in plan and elevation in fig. 7, and a photograph of a TPC is shown in fig. 8. Each TPC has a 20 cm long drift volume on either side of a proportional wire plane in the centre of the detector. This plane contains 200 cells each 8 mm $\times$ 4 mm $\times$ 100 mm, each of which contain a 20 μ m sense wire at its centre. The gas used in the TPC is methane (CH_4) with 20% isobutane (C_4H_{10}) and the organic photo-ionizing vapour Tetrakis(dimethylamino)ethylene

Fig. 2. General view of the RICH detector

Fig. 4. Reflected images in the RICH mirror system.

Fig. 5. The RICH mirror mounting system.

Fig. 6. Transmission of 32 quartz sheets used in RICH vs. λ (nm).

(TMAE) at 10°C which gives an absorption length for ultraviolet photons of 50 mm. Electrons produced from Cherenkov photons entering the TPC through the quartz window drift up to 20 cm onto the proportional wire plane. One coordinate of the photon conversion point is given by the wire number while the other coordinate is given by the drift time to the wire plane.

Each sense wire is connected directly to a sensitive preamplifier, which in turn is connected to a second stage amplifier, discriminator, and time-slice encoder,

Fig. 7. Time projection chamber – plan and elevation.

by 2.5 m of ribbon cable. After an event trigger, data from 192 wires in each TPC are strobed into a memory at time intervals which correspond to a drift of 1.6 mm. When all the data has been collected for an event, the contents of the memory are encoded into wire number and time slice and read into CAMAC.

3. Design considerations

The detector was designed with the aim of providing secondary particle identification over a large momentum range. Fig. 9 shows the variation of Cherenkov ring radius as a function of particle momentum for electrons, muons, pions, kaons and protons, with a 5 m atmospheric pressure nitrogen radiator.

It can be seen that at high momenta of the order of 80 GeV/c, the π and K rings differ in radius by only a few mm. In fitting a circle to a photoelectron ring however, the error on the fitted radius is reduced by the square root of the number of constraints in the fit. Hence having a large number of photoelectrons on a ring improves the determination of the radius, important at high energies, and helps reject background.

The overall detection efficiency for Cherenkov photons is the product of the mirror UV reflectivity $R(E)$, the quartz window UV transmission $T_w(E)$, the TMAE quantum efficiency $Q(E)$ and the radiator gas transmission $T_g(E)$. Fig. 10 shows the various efficiencies plotted as a function of photon energy (E) and wavelength. The transmission of the nitrogen radiator gas is corrected for 10 ppm measured oxygen and water vapour contamination.

The number of photoelectrons seen in the detector from a Cherenkov cone angle θ developed in a radiator length L (c.m.s.) is given by

$$N_e = 370 L \sin^2 \theta \int Q(E) R(E) T_w(E) T_g(E) dE$$

$$= N_0 L \sin^2 \theta.$$

We have in our design [1,2] assumed a conservative value of $N_0 = 90$. The numbers of photoelectrons detected for pions, kaons and protons are then as plotted against momentum in fig. 9.

The dominant contribution to the error in reconstructing the position of a photoelectron on a ring image in the TPC is the chromatic dispersion in the radiator gas which is ~ 1.8 mm for nitrogen. Five additional effects each contribute ~ 1 mm to this error, these being, the mirror distortion, diffusion in the TPC drift process, the reconstruction error due to the 4 mm wire spacing, the time slice resolution, and the effects due to the photon conversion depth in the TPC. Adding these errors in quadrature gives an overall reconstruction accuracy of ± 2.7 mm.

Fig. 8. Time projection chamber – photograph.

Fig. 9. Variation of Cherenkov ring radius and number of photoelectrons as a function of particle momentum for nitrogen.

Fig. 10. $Q \cdot T \cdot R$ for RICH (with effects of 10 ppm H_2O and O_2).

4. Preliminary results from ring image analysis

A proton beam of ~ 100 GeV/c (with some π^+ contamination) has been used to investigate the Omega RICH performance. The protons ($\sim 10^3$ s $^{-1}$) passed through the Omega spectrometer, and through the RICH (fig. 1) to produce corresponding ring images. The momentum vector of each track was reconstructed from the Omega spectrometer data using the program TRI-DENT [4]. This vector was then used to predict the coordinates (YCEN, ZCEN) of the ring image centre in the RICH TPCs, and the expected radius (r_p) assuming the particle was a proton. The resolution of Omega is such that the errors on these predicted quantities can be neglected compared to the resolution of the RICH.

As a first step, the distance of each point (r_i) from the above predicted centre (YCEN, ZCEN), for all points (i) in the RICH TPCs has been computed. These points were then assumed to be due to Cherenkov light from the track, with Cherenkov angle:

$$\theta_i = 2r_i/R \quad (R = \text{mirror radius of curvature} = 10 \text{ m}).$$

β for the track was then calculated, using the TRI-DENT fitted momentum, and the proton assumption. This gives a value of the refractive index (n_i) for every point in the RICH TPCs:

$$n_i = \frac{1}{\beta \cos \theta_i}.$$

A histogram of $\epsilon = (n_i - 1) \times 10^6$, for points from one TPC is shown in fig. 11. This shows a clear peak at $\epsilon \sim 310$ due to the protons, on a background of a few percent. There is also a shoulder at $\epsilon \sim 350$ due to π^+ contamination.

Defining a window ("peak") by $380 > \epsilon \geq 240$, and reference bands ("wings") by $450 > \epsilon \geq 380$ and $170 \leq \epsilon < 240$, we estimate the level of background in the "peak" by counting the number of entries in the "wings".

Fig. 11. $(n-1) \times 10^6$ for a single TPC.

Fig. 12 shows the "peak" region with this background assumed flat, and subtracted. The (single point) separation of π and p is clear. The width of the primary peak ($\sigma \sim 12$) corresponds to a single point (σ_r) resolution on r_i of ~ 2.5 mm. We conclude that a search band in radius of $r_p \pm 2\sigma_r$ ($= r_p \pm 5$ mm) should

Fig. 12. Background subtracted $(n-1) \times 10^6$ for single TPC.

contain most of the Cherenkov signal associated with the protons.

The data was then reanalysed, track by track, and the points lying within this band were fitted to determine a radius, y and z coordinates of the centre of the corresponding circle. Note that the data included in these fits came from two TPCs, and corresponded to reflection from two adjacent mirrors, so that good results could only be obtained if the relative alignments of TPCs/mirrors is better than the intrinsic RICH resolution.

As input to this fit, the errors on the wire (z) coordinates, and the drift distance (y) coordinates, were parametrized as:

$$\sigma_z^2 = \sigma_0^2 + \left(\frac{\Delta W}{\sqrt{12}} \right)^2$$

$$\sigma_y^2 = \sigma_0^2 + \left(\frac{\Delta T}{\sqrt{12}} \right)^2,$$

where

$\Delta W = 4 \text{ mm} = \text{wire spacing}$

$\Delta T = 1.6 \text{ mm} = \text{TPC time slice width } (0.04 \mu\text{s} \times 4.0 \text{ cm}/\mu\text{s})$

$\sigma_0 = 2.2 \text{ mm}.$

The constant σ_0 is intended to represent the sum total of all other contributions to the RICH resolution (chromatic dispersion, diffusion, mirror imperfections, etc.). The resulting χ^2 probability distribution (for ≥ 4 points in the fit) is shown in fig. 13. This distribu-

Fig. 13. The χ^2 probability plot (≥ 4 points in fit).

tion should be flat if the input errors are correct and the points are consistent with a circle.

Requiring $p(\chi^2) > 0.05$, to exclude the small number of fits which are poor (probably due to background in the radial search band) we show in figs. 14a and 14b the difference between the predicted (YCEN, ZCEN) and fitted (YFIT, ZFIT) ring centres. Any angular

Fig. 14. a) The Y ring centre from TRIDENT - Y ring centre from ring fit. b) The Z ring centre from TRIDENT - Z ring centre from ring fit.

Fig. 15 a) Normalized error distribution for fig. 14 (a). b) Normalized error distribution for fig. 14 (b).

misalignment of RICH with respect to Omega would show here as a shift from zero. Dividing these distributions (track by track) by the fitted errors on YFIT and ZFIT, we obtain the pull distributions shown in fig. 15. These are to be compared with the normal distribution of unit variance (smooth curves) expected if the input errors are correct. In fig. 16a we show the pull on the

fitted value of r_f

$$\text{pull} = (r_f - r_p) / \sigma_f,$$

which again shows that our assumptions on the input errors are reasonable, and that the fitted and predicted radii are consistent.

Fig. 16. a) Normalized error distribution for the predicted radius – the fitted radius excluding the ring centre. b) The χ^2 probability plot for the predicted radius – the fitted radius excluding the ring centre.

Fig. 17. The distribution of single point residuals to the predicted ring radius.

This last statement can be expressed as a probability, which will provide the basis for particle identification, by squaring the pull to obtain a χ^2 :

$$\chi^2_{i=p} = (r_i - r_p)^2 / \sigma_i^2$$

and computing the probability $p(\chi^2_{i=p})$ of this χ^2 with

Fig. 18. The distribution of fitted ring radii from a 100 GeV/c beam containing both protons and pions.

one degree of freedom. This distribution is shown in fig. 16b, and should be flat if the hypothesis (i.e. that the particle was a proton) is correct.

As a more direct way of showing that the assumed resolution is correct, fig. 17 gives the distribution δr_i of points about the *predicted* radius for fits with $p(\chi^2) >$

Fig. 19. a) An example of a proton ring image in two TPCs. b) An example of a pion ring image in two TPCs.

0.05. The rms. of this distribution is 2.6 mm (note the cutoff at $\pm 2\sigma_r$ has been extended to $\pm 3\sigma_r$ in order to show the tails of the distribution).

Finally, in fig. 18 we show the distribution of fitted radii [with cuts on the number of points and $p(\chi^2)$] with clear p/π separation, and in figs. 19a and 19b ring images from each of the peaks in fig. 18.

The number of photoelectrons observed in the ring images has varied throughout the commissioning of the detector for detailed technical reasons. In the data used to measure the resolution of the detector, the number of photoelectrons observed corresponded to an $N_0 = 40$, although $N_0 = 60$ has been observed. However in this data the wire cluster gain was not optimized, and future values of N_0 should be higher.

5. Conclusions

The ring image Cherenkov detector is now complete and in place in the Omega spectrometer at CERN. The observed resolution realizes the design specification. Problems associated with the relative alignment of TPCs and mirrors have been solved. A meaningful probability for particle identification can be obtained track by track, by comparing predicted and fitted radii. The number of photoelectrons presently observed is less than that specified in the design, but many improvements have been made to increase this number.

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