EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

CERN-EP/89-107
August 24th, 1989

DEVELOPMENT OF A RICH DETECTOR FOR ULTRA- RELATIVISTIC HEAVY ION COLLISIONS

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Abstract

A single module of an intended RICH detector for ultrarelativistic heavy ion collisions (NA35 experiment at CERN) has been tested with 1.5 - 3 GeV/c positive hadrons. The Cerenkov photons from a liquid freon (C₆ F₁₄) radiator have been focused by a spherical mirror into a multistep avalanche chamber equipped with an optical readout. The analysis of the events and the results of the reconstruction of the Cerenkov angle are presented. A good agreement between experiment and simulation was observed.

Presented at the 4th Pisa meeting on advanced detectors, May 21-26, 1989.

To be published in NIM.

* Supported in part by contract CII-0250 YU(A) of the Commission of European Communities.

I. Introduction

The analysis of Streamer Chamber data from the collisions of 200 GeV/nucleon ^{16}O and ^{32}S nuclei with different targets has yielded novel and interesting results [1]. However further investigation would greatly benefit from hadron identification in the detection of the emitted particles in addition to the momentum measurement. To this aim we plan to construct two $1 \times 1 \text{ m}^2$ Ring Imaging Čerenkov (RICH) detectors designed to identify particles (pions, kaons, protons) close to midrapidity (2.5 ± 0.6 corresponding to the momentum range 1.2 - 4.0 GeV/c) in heavy ion collisions of the type $^{32}\text{S} + \text{Au}$ [2]. The detector will be positioned on both sides of the vertex magnet allowing identification of positive and negative particles. The momenta are measured from Streamer Chamber data.

Following the design proposed and tested by Giomataris and Charpak [3] our RICH counter utilizes a liquid freon radiator where the Čerenkov radiation is focused by a spherical mirror. For particles of normal incidence spherical mirrors focus the Čerenkov-light into rings in the focal plane centered on the optical axis of the mirror regardless of the impact point. In order to avoid overlapping rings, multiple hits on a mirror should be kept to a minimum. This condition determines the granularity of the detector.

The RICH counter has been designed as an array of hexagonally shaped spherical mirrors closely packed on a planar support, so that all mirrors define a common focal plane at the position of the conversion layer of the photon detector. A section view of part of the detector is shown in fig. 1. The expected hit pattern with resulting rings obtained from a Fritiof simulation of a $^{32}\text{S} + \text{Au}$ collision is shown in fig. 2.

In order to measure the experimental resolution of the intended detector a one module prototype was tested with positive hadrons in the range 1.5 - 3.0 GeV/c at the CERN-PS. We report on the first results of the analysis.

II. RICH detector

The one module prototype RICH detector (fig. 3a) consists of a radiator vessel coupled through a UV-transparent quartz window to a MultiStep Avalanche Chamber (MSAC), filled with a gas mixture containing TMAE (photosensitive compound) allowing UV-photon detection with a gaseous proportional counter [3].

The vessel contains a spherical mirror with a radius of curvature of 13 cm and a diameter of 11 cm. It is filled with freon FC-72 (manufacturer 3M). The quartz window is transparent for UV-light up to 7.75 eV. (fig.4)

The gas mixture inside the chamber consists of 95% helium and 5% ethane, with a small admixture of TMAE vapour at 45 °C [4]. The MSAC is made of stesalit frames ($20 \times 20 \text{ cm}^2$), a quartz entrance and a pyrex exit window, six wire mesh planes and a multi-wire gating plane. The meshes are made out of stainless steel wire, 50 μm diameter with a pitch of 500 μm , interwoven in orthogonal directions. The wire plane used for gating is made out of 100 μm thick wires with a spacing of 1 mm. The operating voltages of the different planes and the distances between them are listed in table 1.

The UV-photons produced in the freon by an incoming particle are focused by the mirror in the 7 mm wide, low-field, conversion region of the detector. The photoelectrons produced in the conversion layer drift to the 4 mm wide preamplification gap. In this high field region a Townsend avalanche is produced and a gain of 10^3 to 10^4 can easily be achieved. A part of this avalanche, 10% to 20% depending on the field ratio between transfer and preamplification region, is transferred through a 50 mm transfer region to the second amplification gap. The transfer gap separates the two amplifying stages, thus reducing the photon feedback which is a serious problem in single photoelectron detection for a gaseous proportional counter. The delay (2.3 μs) introduced by the drift velocity of the electrons in this region, caused by the low electric field, allows the second amplifying stage to be gated. This is achieved by applying a short pulse (800 ns) of opposite polarity to the adjacent wires of the gating electrode, which is placed above the second amplification gap.

Normally the gate is closed which means that the voltage difference between

adjacent wires is about 300 volts (fig 3.b) thus no charge is transferred [5]. The trigger opens the gate bringing all the wires to the same potential for 800 ns (fig.3.c) allowing the whole charge to be transferred. The transferred electrons now reach the second amplification gap, in which a further amplification of about 10^3 is achieved. The anode of this last stage is pulsed with a delayed ($2.5 \mu\text{s}$) 800 ns long pulse of 450 V in addition to the anode voltage of 2.5 kV, to increase the field and to avoid breakdown of the last gap between two triggers.

The total gain of this kind of detector is $10^5 - 5 \times 10^6$. The light production, resulting from an avalanche process, is peaked around 480 nm for gas mixtures containing TMAE [6]. The detector was stabilized at 50°C and operated at outside atmospheric pressure. This is not an optimal solution as the gain of a multistep detector varies with the pressure.

The emitted light is reflected by a planar mirror placed at 45° relative to the pyrex window enabling us to move the camera out of the beam. The image is read out by a Thomson 7852 208x144 pixel CCD camera, equipped with a two-stage image intensifier [3]. The signals from the CCD were fed to a video digitizer board, compatible to the IBM PC/AT bus, which we have designed. A fast ADC (20 MHz) of 8 bit resolution digitizes the video signal. The data acquisition is triggered by external pulses and the ADC is synchronised with the internal clock of the CCD camera. This synchronization allows a better spatial resolution and a very precise luminosity measurement.

The luminosity of each pixel is compared with a software defined threshold and all valid pixels (i.e. having a luminosity greater than the threshold) are stored along with their coordinates in an on-board FIFO buffer. At the end of each frame the contents of the fifos are transferred to the PC hard disk. At the time of the test the board was equipped with 2 kilobytes x 9 bits fifo to store the image, but an improved version is now available with 32 Kb x 9 bits fifo. Because of the limited size of the buffer, an image could contain a maximum of 2048 exposed pixels. An acquisition speed of 12 full images per second was achieved.

III. Analysis

For the analysis we used the 1.5 GeV/c and 2.5 GeV/c data. From 1159 events recorded for the 1.5 GeV/c data, 8% (91 events) were sparks, while for the 2.5 GeV/c data the percentage was 9.2%. This means that 1068 and 1493 events have been used in the analysis at the two energies respectively.

GENERAL

The pattern consists of signals having approximately a two dimensional gaussian shape, truncated due to the digitizer threshold, superimposed upon a random background of narrow, isolated peaks arising from reflections of light from the steel meshes of the chamber, from the mirror, and from CCD noise.

Because of the 2 KB limitation of the card's buffers, a frame could consist maximally of 2048 exposed pixels. Accordingly, we adjusted the threshold at 38 (out of 256) to be able to record complete pictures. If a very intensive picture exceeds this limit (i.e. it has more then 2048 pixels with an intensity above 38), the frame is only partially read-out and such a frame is discarded from the analysis. This was not a serious limitation because such high intensity pictures showed mostly sparks or multiple beam particle hits in the mirror resulting in an abnormal large (> 40) number of photo-electron peaks. We also discarded frames where the total number of exposed pixels was below 200. These pictures were usually empty triggers. The total percentage of these high and low intensity frames does not exceed 10%.

Because of the large number of pixels occupied by a single photoelectron avalanche (50 - 100) there is also a high probability for two or more avalanches to merge into a single cluster in the CCD image, which further complicates the analysis. Several typical rings are shown in fig. 5.

IMAGE TREATMENT

The first task in the analysis of the pictures was to isolate and accurately determine the position coordinates of single photo-electrons. To do this we used two different algorithms :

Algorithm A:

a) Identification of clusters

The first step was to isolate cluster candidates from the background noise. The highest intensity pixel was found and the connected cluster of pixels surrounding it was removed from the picture. This process is repeated on the remaining pixels until the highest intensity pixel falls below some value, usually 50 - 60. The number of clusters found in most cases is less than 30. The analysis then concentrated on each cluster finding all the local maxima in a 3×3 surrounding area. This limits the minimal peak separation to 3 pixels. Peaks for which more than one of the eight surrounding neighbours are below threshold are discarded.

The next step was to decide which of the peaks resulted from a primary photon and which resulted from other sources (reflections, secondary avalanches etc.). To this aim we discarded the peaks with intensity below some threshold value. This value depends strongly on the operating conditions of the chamber and the CCD camera. Typical values range from 70 - 90. After this procedure we were left with about 18 - 22 peaks on the average.

b) Determination of the peak coordinates

For clusters with a single peak we determined their centroid, which defines thus their position. In a multiple peak cluster, we determined the centroid from an $N \times N$ area surrounding the peaks where N is half the distance to the nearest neighbour.

c) Identification of Čerenkov photons

After noise reduction the image consists ideally of Čerenkov photons distributed in a ring-like pattern and the beam spot created by the electrons produced by the ionization of the incident particle in the conversion layer. To separate these two contributions and the remaining noise we used a generalized Hough transform [7] to extract the circular shape with all the three circle parameters free. If our circle finder was successful i.e. if the peak in the Hough transformed space was well defined we kept only the points within a ring of $R \pm 0.2 * R$ determined by the Hough transform. In this way we eliminated spurious points outside the ring. Concurrently, we determined the beam spot as the highest intensity peak inside

the inner $0.8 * R$ radius disk. Although in most cases this determination is successful, in about 10 - 15% of the events we were not able to find the beam spot or we had more than one peak with comparable (high) intensity. The later situation could be a source of error in our final determination of the Čerenkov angle but at the level of this detector it cannot be avoided. The distribution of accepted peak intensities is shown in Fig. 6. together with the distribution of the beam spot peak intensity and the non accepted peaks lying outside the ring.

Algorithm B:

A peakfinder routine was used to mark all the local maxima on the whole image. For each of these maxima the average luminosity of the 8 surrounding pixels was calculated. If this value was less than 40, the peak was discarded. In this way most of the spots which correspond to low luminosity background were eliminated. For the remaining peaks we extracted the cluster boundaries defining primary photons on the CCD image. Starting from one of the peaks we searched for the edge of the cluster defined as the pixel which has more than 5 surrounding pixels below the threshold of the card. In this way we could separate clusters that merged together on the CCD image. The centroid of such a cluster defines the most probable position of the primary photon. From all these photons only those that sit inside the fiducial boundaries of the ring acceptance, which was defined from a Monte-Carlo calculation [8], were taken into account for the rest of the analysis. The beam spot was defined as mentioned in algorithm A. To illustrate this procedure the images from three different stages of the analysis are shown in fig. 7.

ČERENKOV ANGLE RECONSTRUCTION

An iterative method was used to calculate the Čerenkov angle for each of the identified photons. To be able to reconstruct the Čerenkov angle a number of parameters are to be defined:

1. Particle parameters

a) the point of incidence of the particle on the radiator, extracted from the beam cluster.

b) the angle of incidence of the particle, which was assumed to be normal to the radiator plane.

c) the momentum of the particle, given by the beam control magnets.

2. Geometrical parameters

The position in space of the mirror surface with respect to the radiator plane and the CCD camera. In the present test it is determined from the x_0, y_0 coordinates extracted from the Hough transform.

3. Detector parameters

a) index of refraction for freon : 1.27 at 6 eV photon energy.

b) index of refraction for quartz : 1.54 at the same energy as above.

c) absorption length in TMAE : 0.6 cm for a temperature of 45 °C [4].

4. UV-photon parameters

The Čerenkov photons are emitted in a continuum of energies with equal probability along the radiator. The actual path from the emission point to the conversion gap will depend on the photon energy due to the variation of the index of refraction with the photon energy for the freon radiator and quartz window. For a given photon detected in the MSAC there is no information on energy or the emission and photo- conversion depths and therefore a value for these parameters has to be assume. This leads to chromatic and parallax errors in the determination of the Čerenkov angle.

a) photon energy

The Čerenkov light has a continuous spectrum. However, due to the strong absorption of high energy photons by freon and the low quantum efficiency of TMAE at low energies, the energy range of the detected photons is limited to a region between 5.6 and 7.2 eV with a peak at 6 eV. This value is used in the present analysis as the mean photon energy. (fig. 4).

b) emission point

The emission point of the UV-photon along the path of the particle was taken

to be at $1/2$ of the distance between the point of incidence in the radiator and the mirror surface.

c) conversion point

This is given by the mean depth of conversion of the photon in the detector gas. It depends on the mesh distances in the conversion layer of the detector, on the TMAE absorption length and on the photon angle with respect to the quartz plane. For our running conditions the conversion point was 4 mm from the quartz plane.

5) Initial parameters for the reconstruction routine

The reconstruction routine has to be entered with a first set of values for the emission angles (polar and azimuthal) of the photon. In our case the polar angle was the maximum Čerenkov angle using $\beta = 1$. The azimuthal angle was defined as the angle between the plane containing the particle trajectory and the photon spot and an arbitrarily chosen plane.

With the above parameters a photon is tracked from the assumed point of origin (as defined above) with the initial conditions through the different media up to the conversion "plane" , 4 mm behind the quartz window where we have assumed conversion to occur in all cases. Varying the values of polar and azimuthal angles the impact point of the tracked photons on the conversion plane is matched to the detected position. Usually after 4-5 iterations convergence is achieved. For a given particle the Čerenkov angle was then calculated as the mean over all the photoelectrons of this event.

IV. Results

The results obtained for the two different momenta are shown in fig. 8. The figure shows the distributions of reconstructed Čerenkov angles for photons produced by positive beam particles at the CERN PS. The prominent peak at higher angle corresponds to pions, while the smaller peak corresponds to protons. The ratio of the number of protons to pions is in good agreement with the known PS beam content.

The results of the reconstruction procedure applied to Monte Carlo simulated events using the same parameters as for the experimental data and a similar particle content are superimposed on the plot for comparison. A 300 μm position resolution was assumed. The width of the distributions is due to several factors, the largest being the fixed values for the emission and conversion points used in the reconstruction. These two sources contribute 30% and 50% respectively to the width of the distribution. All other sources contribute 20%.

On fig. 9 the reconstructed number of photons is shown for the two different methods of image treatment together with the simulated values. The small expected value $N_{ph} = 19.5$ mainly comes from the fact that the Čerenkov photons have to travel a long distance inside the radiator (~ 8 cm) resulting in a big absorption in freon (fig. 4). The experimental values are 14.8 and 15.5 for the two methods of analysis. The results of the simulated events are in fair agreement with the experimental values given the fact that both the quartz transmission and the mirror reflectivity have not been measured. The corresponding figure of merit expressed by N_0 in the formula for the number of photons:

$$N_{ph} = N_0 \cdot L \cdot \sin^2 \theta$$

where L is the length of the radiator medium in cm, and θ is the mean Čerenkov angle, is 10.8 cm^{-1} .

V. Conclusion

The present test has proven the viability of some features of a focusing RICH detector with the honeycomb structure and optical readout that has been proposed for particle identification in ultrarelativistic heavy-ion experiments. Such a detector fulfils the following requirements for the measurement of high multiplicity events in nucleus-nucleus collisions:

- 1) a sufficient number of detected photons for satisfactory extraction of the mean Čerenkov angle per particle ($\langle N_{ph} \rangle = 15$).
- 2) a satisfactory distribution of the rings - i.e. the circular patterns belonging to different particles are well separated, thus rendering the pattern recognition in a high multiplicity event possible.
- 3) a clearly identifiable beam spot - allowing for an easier tracking of the particle path back to the momentum measuring device (Streamer Chamber, or tracking TPC).

The relatively low figure of merit ($N_0 = 10.8 \text{ cm}^{-1}$) has two sources:

- 1) The long path length of the photons in the liquid freon (required for optical reasons) means that most of the high energy photons are absorbed before reaching the UV-detector, leaving preferentially photons of low energy in the range where the quantum efficiency of TMAE is low.
- 2) The conversion layer in the chamber, is rather thin to allow a good spatial resolution, and it is not possible to compensate for this by increasing the temperature of the bubbler bath, and hence vapour pressure of the TMAE, because of the low boiling point of freon (56 °C).

VI. Acknowledgements

We are specially grateful to G.Charpak, Y. Giomataris and F. Sauli for discussions and suggestions. A. Braem, C.Nichols, E.Barbarito, F.P. Ceglie and M.Perchiazzi, have greatly contributed in solving technical problems connected with the present test.

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FIGURE CAPTIONS :

1. Side-view cross-section of the proposed RICH detector for heavy ion experiments. It will consist of a honeycomb of spherical mirrors which focus the Čerenkov light from a liquid radiator into a Multistep Avalanche Chamber.
2. Monte Carlo simulation of an ^{32}S -Au event detected in a $1\times 1\text{ m}^2$ RICH detector. The hexagons represent the location of the mirrors. The asterisks denote the impact coordinates of the emitted particles while the dots correspond to converted and detected photons.
3. a) Schematic drawing of the MSAC chamber, gate operation in closed (b) and open (c) mode.
4. Transmission curves for the 0.4 cm quartz window, for the 8 cm of freon and TMAE quantum efficiency vs photon energy. The curve labelled total represents the product of all the other curves.
5. Typical scatter plots for single events with normal particle incidence obtained with a 2.5 GeV/c hadron beam. The beam spot is clearly visible for each event.
6. Probability distribution of pixel intensity for peaks that belongs to a) the beam spot, b) the clusters on the ring and c) to clusters which are not located on the ring.
7. Processed image using algorithm B : (a) raw data (b) after cluster identification (c) after centroid calculation.
8. Distribution of mean Čerenkov angle per event: solid line for experimental data, dashed line for simulated events; for (a) 1.5 GeV/c (b) 2.5 GeV/c.
9. Probability distribution of the number of photons per event for the simulation a) and for the experimental data using algorithm B (b) and algorithm A (c).

TABLE 1

Distance to the first grid and operating voltage of the different planes for the Multistep Avalanche Chamber. The plane Nr. 4 is the gating plane. The last plane is pulsed with 450 V.

MSAC OPERATING CONDITIONS		
Plane number	Distance (mm)	Voltage (V)
1	0	-6000
2	7	-5200
3	11	-3500
4	61	(-220,-520) -370
5	67	0
6	73	(+2500) +2950

Figure 1

Figure 2

B

C

Figure 3

Figure 4

Figure 5

Figure 6

Figure 7

Figure 8 A

Figure 8 B

Figure 9