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A HIGH RESOLUTION LIQUID RADIATOR DIFFERENTIAL ČERENKOV COUNTER

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ABSTRACT

A liquid-differential Čerenkov counter built to separate protons from kaons between 2 GeV/c and 9.5 GeV/c or kaons from pions up to 5 GeV/c is described. This counter has a 20 cm diameter useful cross-area. It can accept a $\pm 7\%$ momentum bite around its nominal setting. A resolution $\Delta\beta/\beta$ better than 3% is achieved in the vicinity of $\beta = 1$.

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1. INTRODUCTION

Identification of long-lived charged particles can be made through a simultaneous measurement of momentum and velocity. In the velocity range $0.95 \leq \beta = v/c \leq 0.995$, gas-differential Čerenkov counters may have the required resolution power, but they need large gas pressures, even when a gas with high refractivity such as freon is used. When the necessary thickness for the pressure vessel windows is included, they finally bring more matter along the particle trajectory than would liquid radiators.

On the other hand, there are difficulties to achieve enough resolution with liquid counters^{1,2)}. The smallest refractive index of a transparent liquid at room temperature is ~ 1.24 (FC88 fluorochemical compound), giving a Čerenkov angle θ of about 35° . The velocity resolution being $\Delta\beta/\beta = \operatorname{tg} \theta \cdot \Delta\theta \approx 0.7 \Delta\theta$, a very tight angular definition $\Delta\theta$ has to be achieved. $\Delta\theta$ includes the variation of the angle between the direction of the particle and the counter axis, the chromatic dispersion of the Čerenkov light, and the aberrations of the optical system. The first contribution is directly related to the acceptance of the counter and should be kept as high as possible. The last two contributions must be minimized by optical means. A catadioptric system has been successfully studied to satisfy these needs. It focuses the Čerenkov light, emitted in a 20 cm useful diameter light radiator, on an annular slit. The resolution of the counters which have been built and which have been used in an actual experiment³⁾ is $\Delta\beta/\beta \approx 3 \times 10^{-3}$, good enough to distinguish protons from kaons up to 9.5 GeV/c and kaons from pions up to 5 GeV/c in a beam with a divergence of 3 mrad.

The optics and the mechanical mounting are described in Sections 2 to 4. Calibration and performance are explained in Sections 5 and 6.

2. CALIBRATION SYSTEM

The mean angle of the Čerenkov light emitted in the fluorochemical compound FC88 by a particle with a velocity of 0.995 is 46.5° after refraction outside the radiator cell.

The negative lateral chromatic dispersion outside the cell is about 12 mrad over the wavelength spectrum between 3500 Å and 4800 Å, which is the useful range for the use of ordinary optical materials coupled to a photomultiplier with a D cathode.

In order to achieve a resolution $\Delta\beta/\beta \approx 3 \times 10^{-3}$, for a particle beam having a 3 mrad divergence, the optics must have geometric aberrations giving rise to less than 1 mrad angular error and it must correct the chromatic dispersion by more than a factor of 10.

Several systems have been studied. Aspherical ones have been rejected *a priori*, because of the difficulty and the price of machining aspherical surfaces. The simplest convenient solution is a single meniscus whose back surface is metallized and acts as a mirror. Figure 1 shows a sketch of the optical system with the main parameters which are adjusted in order to optimize the counter. Their meaning is as follows:

R_2 : radius of curvature of the mirror face of the meniscus;

R_1 : radius of curvature of the correcting diopter;

$CD = t$: thickness of the meniscus as measured on the axis;

$BD = \ell$: position of the cell exit face. The cell contains the liquid which radiates the Čerenkov light.

The radius R_1 and the thickness t of the lens are the two adjustable parameters which suffice for making the necessary corrections. The mirror radius R_2 determines in first approximation the dispersion of the foci for different Čerenkov angles. It is chosen in order to satisfy both requirements of large enough dispersion and of reasonable limits to the counter dimensions. With such optics, the position and diameter of the foci move along a cone to a good approximation. Thus, the use of a conical mirror [(2) on Fig. 1] allows all foci to be brought onto the surface of a cylinder which is coaxial to the whole system. In this way, two movable coaxial cylinders may be used as a variable-opening, displaceable slit for the selection of a given light angle and acceptance. The need for a costly annular diaphragm is thus also avoided.

The opening angle α of mirror (2) is 57° . Its apex position is chosen such that the diameter of the cylinder of focus is 256 mm.

The reflecting mirror (3) is toroidal in order to focus the light which goes through the diaphragm on the photomultiplier. Contrary to both other mirrors, the shape of the latter one has been determined graphically.

All optical components are made of polymethyl methacrylate. The photomultipliers used are the Philips XP1230. FC88^{*)} is used as radiator in the velocity range from $\beta = 0.95$ to 1, and FC75^{*)} is used from $\beta = 0.90$ to 0.95.

3. EVALUATION OF THE MIRROR LENS

The parameters of the optics have been optimized with an interactive computer program, which was developed for that purpose. Trajectories of principal rays may be visualized throughout the system on a display screen. The intersection of skew rays with any plane perpendicular to the optical axis or, after reflection by mirror (2), with any plane parallel to the principal axis can also be visualized. The scale of the display is chosen at will.

The procedure is iterative. Starting values are given for the geometrical parameters including limiting physical apertures. Refractive indices of the Čerenkov radiator and of the optical parts are given for three wavelengths 3500 Å, 4150 Å, and 4800 Å in Table 1. The angle of the Čerenkov light emitted by a particle of a given velocity β is calculated for each of these wavelengths, after refraction through the radiator window. Parallel rays which originate from a series of 41 points distributed over the useful area of the window (Fig. 2) are traced through the system for each wavelength.

Principal rays for two neighbouring velocities are sketched in the zone of the focus in Fig. 3. The velocity resolution of the counter is given by the ratio $(\varepsilon_1 + \varepsilon_2)/2d$, where ε_1 and ε_2 are the widths and d is the distance of the focal

*) FC88 and FC75 are trade marks of the Minnesota Mining Co.

areas in order for the two velocities β_1 and β_2 to be separated. Its minimization through the adjustment of the geometrical parameters is limited by the dimensions of the optics. These determine the possible values of the mirror curvature R_2 . R_1 and t are varied in steps. R_2 is then readjusted in order to keep the foci on a desirable mean radius. The cell is also moved along the axis to ensure full light acceptance. A few iterations are sufficient to obtain the best values of the parameters for the given physical constraints. In the neighbourhood of the solution the actual resolution is determined by the skew-ray patterns.

The optimization is done for the highest velocity which needs the highest resolution. The whole calculation is then made for the lowest velocity in order to check that the resolution is not too much impaired.

The parameters adopted for the construction of a counter with a uniform efficiency over a 20 cm diameter sensitive area are given in Table 2.

Figure 4 shows the tracing of the principal rays in the focusing zone for the three wavelengths of achromatization for $\beta = 0.95$ and $\beta = 1$. The point diagrams of three times 41 rays on a plane tangent to the focusing cylinder are given in Fig. 5 for the velocity range 0.95 to 1 (FC88 radiator) and in Fig. 6 for the velocity range 0.90 to 0.95 (FC75 radiator). Figure 7 shows point diagrams for $\beta = 0.995$ and $\beta = 1$ on a ten times magnified scale.

With the parameters of Table 2, the velocity dispersion along the diaphragm is about $1.2 \times 10^{-3} \text{ mm}^{-1}$ and the computed resolution $\Delta\beta/\beta$ is about 6×10^{-4} .

4. CONSTRUCTION

The mirror lens is made of polymethyl methacrylate with good transmission in the near UV region (Fig. 8). Polishing and optical controls have been done in our laboratory. All mirrors have been coated with aluminium^{*)}.

Positioning of the optical elements is performed using as a reference a plane surface machined on the main frame, which is a stabilized light alloy casting. The

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main frame is mounted on a horizontal axis around which it may be rotated. This horizontal axis is borne on a horse-shoe pedestal which can in turn be vertically rotated. Both movements are remotely controlled by motors.

Two movable coaxial cylinders with thin edges form the diaphragm. The actual position and the width of this diaphragm are also remotely changed and controlled.

The cells containing the liquid radiator are maintained at a constant temperature by a thermostatically-controlled water supply circulating in a surrounding jacket.

Two thin metal cylindric covers, which are fitted to the main frame, close the counter and make it light-tight. In Fig. 9 open views taken during assembly show the main frame and mirrors (1) and (2).

Mirror (3) reflects the light towards a ring of 24 Philips XP1230 photomultipliers (PMs). Most of the time the PMs in the ring are electronically combined into six groups of four PMs each. Combinations of eight times three PMs and four times six PMs are also available, depending on the rejection and efficiency required. A block diagram of the electronics is given in Fig. 10. The pulses fed into the logic come from the PMs through a linear fan-in, which delivers the linear pulse from a four-PM group to a low-level threshold (10 mV) pulse-shaping circuit which drives the logic itself.

5. SETTING UP AND CALIBRATION

5.1 Setting up

To set up the counter, the light path is traced back through the optics. A mercury spectral lamp is placed right behind the diaphragm, which is only slightly opened -- a few tenths of a millimetre. The light, simulating refracted Čerenkov radiation, is observed backward at the radiator cell position with a telescope focused at infinity. A total reflection prism with an angle $\pi/3$ is placed in front of the telescope (Fig. 11). Rays making a large angle with respect to the telescope axis may be observed through the telescope by suitably rotating the prism.

After having aligned the telescope axis with the mechanical axis of the counter, the axis of the mirror lens is aligned in the same direction by requiring that images of the diaphragm slit corresponding to positions of the light source at right angles to each other coincide in the focal plane of the telescope.

The degree of geometrical correction of the optics for each wavelength is measured by the variation of incident angle of the light entering the telescope, i.e. by measuring the position of the diaphragm image in its focal plane when the telescope is moved parallel to itself over the entire aperture of the radiator cell. Owing to residual aberrations, an S-shaped pattern is obtained. The flatter the S, the better is the correction. Figure 12 shows the best shape obtained after measurements for a few longitudinal positions of the mirror lens. The total widths of angular aberration is less than 0.5 mrad.

The chromatic dispersion has been measured between the 4350 Å and 4050 Å lines of the spectral lamp. The corresponding Čerenkov angles differ by 2 mrad at the exit of the radiator cell. The measured difference for test rays after traversal of the counter optics is (2.2 ± 0.05) mrad. Hence the optics compensates the Čerenkov dispersion to about 10%.

5.2 Absolute calibration

The absolute calibration, i.e. the determination of the selected velocity β as a function of the position of the diaphragm is done by means of an optical method. The angle of simulated refracted Čerenkov rays is measured with the help of the prism in front of the telescope. The rotation of the prism is measured by Poggendorf's method (see Fig. 11). The zero is obtained by adjusting the prism base perpendicular to the telescope axis. Since the angle of the prism is precisely known, the angle of the light-ray can easily be determined for any wavelength from the prism rotation necessary to obtain a centred image in the telescope. After calibration, the position of the diaphragm corresponding to an angle of 45° of the light-rays with the axis is controlled with the help of a pentagonal prism (Fig. 13). The coincidence of the image of a small portion of slit illuminated by the spectral lamp with its diametrically opposite counterpart was verified.

5.3 Calibration with particle beams

In order to check the optical calibration in real conditions, a momentum-analysed beam of particles has been used. The trigger was defined by two scintillators, 12 m apart. The area of the first one was $23 \times 23 \text{ cm}^2$. The other being only $1 \times 1 \text{ cm}^2$, was placed right in the beam focus, ensuring a momentum bin $\Delta p/p$ of 1.2% at the most. In these conditions, after having oriented the counter along the main axis of the beam, the position of the diaphragm was scanned around the theoretical value given by the absolute calibration.

Figure 14 shows the comparison of the results of both methods. The horizontal scale is the distance (up to a constant) between the centre of the diaphragm and the reference plane used for setting up the optics. A check has been made with 4 GeV/c protons, the diaphragm having a width of 3 mm. The difference between the calibrated and measured values of β are in agreement within the intrinsic resolution of the counter.

6. EFFICIENCY RESOLUTION AND REJECTION

The counter efficiency depends on the Čerenkov light intensity, i.e. on the radiator thickness and on various other factors, such as the over-all reflectivity of the different mirrors, the opening of the diaphragm, the spread-out of the Čerenkov image due to the divergence of the beam and the multiple scattering in the cell. Furthermore, it also depends strongly on the electronic combination used for defining an event. The results quoted below are obtained with the six-fold coincidence electronics with a radiator thickness of 4 cm.

Figure 15 shows the counter efficiency versus the opening of the diaphragm for a pion beam of 3.2 GeV/c with a divergence limited to $\pm 2.5 \text{ mrad}$ including the multiple scattering in the cell. The steep slope of the curve at low aperture depends on the size of the image at the diaphragm. In the present case, the flat top is reached for twice the computed value for a zero-divergence beam (see also Fig. 7). The flat top efficiency is 85% and corresponds to about 1 photoelectron per PM.

Figure 16 shows the response curve of the counter for two values of the diaphragm aperture. The measurements were made with a beam defined by two scintillation counters and an identical differential counter, set on the protons, with a diaphragm opening of only 1 mm, giving a 3.2 GeV/c proton beam of less than 2.6 mrad divergence and with a $\Delta p/p$ of 1.4%. These curves allow efficiency corrections to be made for the various settings used with this counter.

6.1 Angular acceptance

With the same set-up, but using a 5 GeV/c beam with a $\Delta p/p = \pm 3.5\%$, the counting rate of the tested counter is recorded versus its orientation with the axis of the beam in order to determine the angular acceptance of the counter for different openings of the diaphragm (Fig. 17).

6.2 Comparison with experiment

Velocity scans for 5 mm and 3 mm opening of the diaphragm are shown in Figs. 18 and 19.

The beam had an average momentum of 5 GeV/c with a spread out of 1.2×10^{-2} . Its angular divergence was ± 2.6 mrad, including the multiple scattering due to the matter along the beam line. The difference in velocity of 5 GeV/c kaons and pions is 4.5×10^{-3} .

On Fig. 18 the pion line FWHM is 3.9×10^{-3} , in good agreement with the value computed from the beam characteristics and the intrinsic counter resolution for particles parallel to the counter axis.

Reducing the diaphragm aperture improves the separation between kaon and pion lines (Fig. 19), but it simultaneously cuts the angular acceptance of the counter (Fig. 17). As expected, with the beam used for the tests, the efficiency with a 3 mm diaphragm width is lowered by a factor of about two.

The rejection of the counter has also been measured at 5 GeV/c, the limit for useful K- π separation, by putting two counters of the same type in coincidence. One counter is kept fixed on the kaon peak, while the other is used to scan the

mass spectrum going from pions to kaons, both counters having a constant diaphragm opening of 5 mm. The beam used during this measurement had a larger momentum bandwidth: $\pm 10^{-1}$. The rejection is still about 1.8×10^{-3} in this limiting case.

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REFERENCES

- 1) R. Meunier, J.P. Stroot, B.A. Leontic and A. Lundby, Nuclear Instrum. Methods 17, 149 (1962).
- 2) B.A. Leontic, Nuclear Instrum. Methods 56, 32-44 (1967).
- 3) F. Binon et al., High $p_{\perp}$ two-body correlation and single-particle inclusive hadrons spectra in 24 GeV p-nucleus collisions (to be published).

Table 1

Refractive indices

Wavelength (Å)	Polymethyl methacrylate	FC88	FC75
λ_{mean} : 4150	1.5030	1.2440	1.2804
λ_{min} : 3500	1.5136	1.2475	1.2831
λ_{max} : 4800	1.4979	1.2425	1.2784

Table 2

Counter construction parameters

$R_1 = 3600 \text{ mm}, R_2 = 1190 \text{ mm}$
$t = 100 \text{ mm}, \ell = 490 \text{ mm}$
$\alpha = 57^\circ$
Apex of mirror (2): $AD = 655 \text{ mm}$

Figure captions

- Fig. 1 : Sketch of the optical system.
- Fig. 2 : Pattern of the test rays at the exit window of the radiator cell.
- Fig. 3 : Schematic representation of focalized rays in the plane of principal rays for two velocities β_1 and β_2 ; ϵ_1 and ϵ_2 are the minimum spread out of the focalization zone for all rays and wavelengths.
- Fig. 4 : Display of the focal zone in the plane of principal rays for $\beta = 0.95$ and 1 for the three chosen wavelengths with the FC88 radiator: the square is $20 \text{ cm} \times 20 \text{ cm}$.
- Fig. 5 : Display of point diagrams on the plane tangent to the cylindrical diaphragm for the three chosen wavelengths over the β range from 1 to 0.95. From top to bottom are displayed the velocity ranges 1 to 0.995 (in steps of 5×10^{-3}), 0.995 to 0.977 (2×10^{-3}) and 0.977 to 0.950 (3×10^{-3}). The square is $10 \text{ cm} \times 10 \text{ cm}$.
- Fig. 6 : View analogous to that in Fig. 5 but with the FC75 radiator for various β values in the range 0.95 to 0.9 with steps varying from 2×10^{-3} to 5×10^{-3} .
- Fig. 7 : Enlarged display of the point diagram for $\beta = 0.995$ and 1 in a $1 \text{ cm} \times 1 \text{ cm}$ square, using the changing scale option provided by the program.
- Fig. 8 : Transmission curve of the polymethyl methacrylate.
- Fig. 9 : Open views of the counter seen from the back and sideways. The tuning telescope is replacing the radiator cell.
- Fig. 10 : Diagram of the electronics and schematic repartition of the PMs.
- Fig. 11 : Sketch of the telescope with moving total reflecting prism.

- Fig. 12 : Residual angular aberration along a diameter of the radiator cell.
- Fig. 13 : The absolute calibration check with a pentagonal prism.
- Fig. 14 : Comparison of the optical calibration with a measurement using 4 GeV/c protons.
- Fig. 15 : Counter efficiency, in six-fold coincidence mode, versus the diaphragm opening.
- Fig. 16 : Efficiency versus the diaphragm position for two widths of the diaphragm, namely 5 mm (open circle) and 7 mm (black dot).
- Fig. 17 : Counter efficiency versus vertical (left side) and horizontal (right side) angular orientation of the counter for two diaphragm openings.
- Fig. 18 : Velocity scan at 5 GeV/c with a 5 mm diaphragm width.
- Fig. 19 : Velocity scan for K and π of 5 GeV/c with a 3 mm diaphragm width.

Fig. 1

Fig. 2

Fig. 3

Fig. 4

Fig. 5

Fig. 6

Fig. 7

Fig. 8

Fig. 9

Fig. 10

Fig. 11

Fig. 12

Fig. 13

Fig. 14

Fig. 15

Fig. 16

Vertical

Horizontal

Fig. 17

Fig. 18

Fig. 19