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Construction and test of a RICH prototype for the NA62 experiment

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ABSTRACT

A RICH prototype has been constructed and tested. The detector was cylindrical, 17 m long and 60 cm diameter, filled with neon gas at atmospheric pressure. A spherical mirror with 17 m focal length was used and 96 photomultipliers were placed in the mirror focal plane. The prototype was exposed to a 200 GeV/c momentum negative beam derived from the CERN SPS in the 2007 fall. The performances of the detector in terms of Cherenkov angle resolution, number of photoelectrons and time resolution are presented.

1. Introduction

The NA62 experiment [1] has been proposed at CERN in order to measure the branching ratio of the ultra-rare decay $K^+ \to \pi^+ \nu\bar{\nu}$. The main background is $K^+ \to \mu^+ \nu$ which must be suppressed by a factor 4×10^{-13} in order to have a background to signal ratio smaller than 10%: this goal can be accomplished by a combination of kinematical cuts and by pion–muon separation. According to the MC simulation of the experiment, a kinematical suppression of 8×10^{-6} can be reached. A muon rejection factor of 10^{-5} can be achieved exploiting the different penetration probability through matter of the two particles. A further 5×10^{-3} suppression factor can be provided by a Ring Imaging CHerenkov (RICH) detector.

The momentum range over which pions and muons must be identified by the RICH is between 15 and 35 GeV/c; the best pion–muon separation is achieved when the lowest accepted momentum is close to the Cherenkov threshold. As full efficiency is achieved only at a momentum about 20% higher than the threshold, the latter has to be 12.5 GeV/c for a pion, i.e. the index of refraction n must be such that $(n-1) \approx 60 \times 10^{-6}$. Neon gas at roughly atmospheric pressure fulfills this requirement and also guarantees a small dispersion [2]. On the other hand, the tiny $(n-1)$ implies a small number of emitted Cherenkov photons per unit length and therefore a long radiator is mandatory. A 10 m long neon RICH was built and operated by the SELEX experiment [3] and a longer one was proposed by the CKM collaboration [4]. The available space for the RICH in the NA62 experiment setup is about 18 m: a detector of about this size is foreseen.

In a RICH detector [5] the Cherenkov light, emitted at an angle θ_c by a charged particle of velocity βc larger than the speed of light in the crossed medium (c/n), is imaged by means of a spherical mirror onto a ring on its focal plane. The ring radius r is related to the Cherenkov angle as $\theta_c = r/f$ for small n (as it is the case for gas radiators), where f is the mirror focal length. The relation between Cherenkov angle and momentum p of a charged particle of mass m is given by

$$\theta_c^2 = \theta_{c\,\mathrm{MAX}}^2 - m^2c^2/(m^2c^2 + p^2) \quad (1)$$

where $\theta_{c\,\mathrm{MAX}} = \sqrt{2(n-1)}$ is the Cherenkov angle for $\beta = 1$. The θ_c resolution must be better than 80 μrad in order to achieve the requested pion–muon separation.

Besides pion–muon separation, the NA62 RICH detector must fulfill two other very important tasks: provide the time of pion crossing with 100 ps resolution (in order to suppress accidental

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coincidences with an upstream beam detector) and give the level-zero trigger for a charged particle. These further requirements led to the choice of fast single-anode photomultipliers (PM) with a small size in order to match both the Cherenkov angle and the time resolution constraints.

A fast simulation was developed taking into account the proper generation of Cherenkov photons, the geometry of the mirror and the PM performances.

In order to validate the detector design based on the simulation, a RICH prototype was built and tested.

The paper is organized as follows: the detector design details are given in Section 2, where the RICH vessel (Section 2.1), the spherical mirror (Section 2.2), the photomultipliers (Section 2.3) and the readout system (Section 2.4) are described, while the results obtained from test-beam data are reported in Section 3 and the following subsections.

2. Detector design

2.1. The vessel

The RICH prototype vessel was made by five stainless steel sections, two of them (the longest ones) recuperated from an existing beam line at CERN and three new ones (Fig. 1). Each section was made by a cylindrical tube in axis with the beam with a 610 mm outer and 597 mm inner diameter and a length (along the beam direction) of 2636, 5986, 5986, 2486 and 286 mm, respectively. For the interconnection with the other sections, at both ends of each tube a stainless steel flange was welded, 18 mm thick (5 mm of which extending beyond the tube), with a constant 658 mm outer diameter and a minimum 603 mm inner diameter; a 5 mm thick O-ring at each flange connection guaranteed vacuum tightness. The shortest section was placed at the downstream end of the prototype and contained the mirror support structure. The vessel was closed by two endcaps, both made of stainless steel, 30 mm thick, with the same outer dimensions as the flanges. The downstream endcap had four holes for the vacuum pump, the gas inlet and for two rods for the mirror alignment. In the upstream endcap 96 holes were drilled to accommodate the PM and one central hole for the beam entrance window. This window was made of SCHOTT[7] BK7 radiation resistant glass and had a thickness of 11 mm.

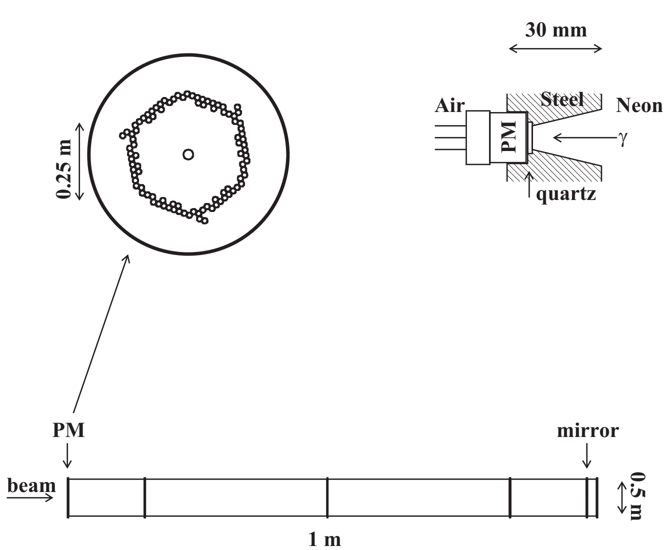

Fig. 1. The RICH prototype setup. At the bottom a side view of the prototype is shown; a front view of the upstream endcap is shown on the top left; a detail of the upstream endcap cut, together with a photomultiplier, is shown on the top right. The scales are different in each picture, as indicated; in the bottom plot the horizontal and vertical scales are also different.

In order to have a good neon purity inside the vessel, the following procedure was adopted: the vessel was first evacuated, then filled with nitrogen, evacuated again and finally filled with neon at 987 mbar pressure. The temperature (23.5 °C on average) was monitored by means of six sensors placed along the vessel, which was covered with an insulating foam.

2.2. The mirror

A 500 mm diameter and 25 mm thick glass mirror, with a 17 010 mm focal length, was manufactured by MARCON.[8] The mirror optical quality was tested by the company and checked independently. The D_0 parameter (the diameter of the smallest spot image of a point source, placed in the mirror curvature center, where 95% of the light is collected) turned out to be smaller than 0.5 mm. The mirror was prepared to have good reflectivity up to the near ultraviolet by means of aluminum deposit on the surface; a MgF_2 film was placed over the aluminum to avoid oxidation. The mirror support structure was the following: a Y-shaped aluminum structure was fixed at the prototype vessel; in the middle of the Y, a spherical joint (uniball) was connected to an aluminum cradle supporting the mirror by means of two Teflon pieces in order to avoid any stress. The mirror cradle was oriented by means of two rods connected at 250 mm from the uniball and producing a rotation around the horizontal and vertical axes, respectively. Each rod was independently moved by a step motor located outside of the RICH vessel. One motor turn corresponded to a 1.75 mm advance of the rod and was subdivided into 4096 steps (nominal 1.7 μrad resolution); the motors were remotely controlled. A laser was aligned with the beam line before the mirror mounting and later used to orient the mirror. The final mirror alignment was done with the beam. The mirror surface was placed at 17 060 mm from the inner surface of the PM endcap.

2.3. The PM

Metal packaged PM of the HAMAMATSU[9] R7400 series, either of the U-03 (UV glass window) or of the U-06 (quartz window) type, were chosen for their compactness, fastness and relative cheapness. The R7400 PM has an insulation cover in polyoxymethylene of roughly cylindrical shape, 15.9 ± 0.4 mm wide and 11.5 ± 0.4 mm long (U-03) or 12.8 ± 0.5 mm long (U-06). The eight PM dynode voltages are provided through a HAMAMATSU E5780 HV divider (2.8 MΩ total resistance), which has a cylindrical shape, 17.0 ± 0.2 mm wide and 15.0 ± 0.5 mm long and has three cables: an RG-174/U cable for signal output and two AWG22 cables for high (negative) voltage supply and for grounding. The photocathode (with 8 mm minimum active diameter) is bialkali made and has a typical radiant sensitivity of 62 mA/W at the 420 nm peak wavelength, corresponding to a 20% quantum efficiency; the PM wavelength sensitivity is between 165 (U-06) or 185 (U-03) and 650 nm and the integral of the quantum efficiency over the photon spectrum was estimated to be about 0.60 eV (U-03) or 0.75 eV (U-06). The typical PM gain is 7×10^5 at 800 V (maximal safe HV is 1000 V). The R7400 typical rise time is

[7] Advanced Optics SCHOTT AG, Hattembergstr. 10, 55122 Mainz, Germany (www.schott.com).

[8] MARCON Costruzioni Ottico Meccaniche, via Isonzo 4 - 30027 San Doná di Piave (VE) Italy (www.marcontelescopes.com).

[9] HAMAMATSU PHOTONICS K.K., 314-5, Shimokanzo, Toyooka-village, Iwata-gun, Shizuoka-ken, 438-0193, Japan (www.hamamatsu.com).

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Table 1
Distance of PM from the center

PM	0	1	2	3	4	5	6	7	8
r (mm)	173.6	187.9	171.7	187.1	187.9	173.6	190.5	194.7	182.7
PM	9	10	11	12	13	14	15	16	
r (mm)	189.6	198.0	216.0	225.5	189.6	200.4	194.7	190.5	

There are six groups, each rotated by 60° with respect to the previous one; PM numbers 11 and 12 are present every two groups.

0.78 ns, the transit time is 5.4 ns and the transit time jitter is 0.28 ns (FWHM); late signals (about 1.2 ns after the average) are interpreted as photoelectrons reflected from the first dynode while early signals are photoelectrons extracted directly from the first dynode.

In the RICH prototype 96 PM were mounted, 72 of the R7400U-03 type and 24 of the U-06 type. Twenty four U-03 PM were bought with a guaranteed 1×10^5 minimum gain at 800 V (standard specifications), 24 with 5×10^5 and 24 with 10^6 minimum gain. The 24 U-06 PM were half with 5×10^5 and half with 10^6 minimum gain. All the PM were tested by the firm and independently checked for what concerned efficiency and time performances.

The PM were placed in the upstream endcap, following a hexagonal lattice (honeycomb) with 18 mm side, in the region where the 200 GeV/c pion Cherenkov ring was expected. The distances of each PM from the geometric center are listed in Table 1. A cylindrical hole, 16.5 mm wide, 6.5 mm deep was drilled through the endcap from the outer side with respect to the vessel, to accommodate each PM; a concentric cylinder 13.5 mm wide, 1.5 mm deep was drilled after the previous one. From the inner part of the endcap a truncated cone was drilled, 18 mm wide at the beginning, 7.5 mm wide at the end and 22 mm high, in order to convey the Cherenkov light to the active area of the PM (Winston cone approach [6]). The cone was later covered with an aluminized mylar foil, 50 μm thick, glued to the steel surface, in order to improve the reflectivity. A 1 mm thick, 12.7 mm wide quartz (fused silica) window, provided by Präzisions Glas & Optik GmbH,[10] was glued between the cone and the cylinder in order to separate the PM from the neon. The quartz transmittance was higher than 0.89 at wavelengths longer than 190 nm (0.93 in the visible range), going to zero at 160 nm.

The PM power supply was powered by a CAEN[11] SY2527 crate equipped with six A1733N boards, each one providing 12 channels with SHV connection. Two PM were fed by one HV channel. The PM were operated mainly at 900 V.

2.4. The readout

The PM output signal had a roughly triangular shape with the same rise time as the PM (0.78 ns on average) and a fall time about twice this. At 900 V PM supply voltage (average gain of 1.5×10^6) the output charge is about 240 fC corresponding to a peak current of 200 μA and to a negative peak voltage of 10 mV over 50 Ω. There was also a large variation in gain performances among the PM. In order to profit the fast PM response, the eight-channel NINO ASIC [7] was chosen as discriminator; this chip has an intrinsic resolution of 50 ps and was developed for the output signal of multigap resistive plate chambers. To match the optimal NINO performance region, the PM output was sent to a current amplifier with differential output: a 24-channel customized printed circuit was prepared for this purpose, sending the output to a board containing three NINO ASIC; four boards were available. The NINO chip was operated in time-over-threshold mode and its LVDS output signal was sent to a 128-channel CAEN VME V1190A TDC module, working in trigger matching mode. The VME module contains four HPTDC chips with 97.7 ps LSB producing 19 bits long words (corresponding to a maximum of 51 μs). The TDC memory buffer was asynchronously read out through the VME bus by a commercial PC. Both the leading and the trailing edges of the LVDS signal were recorded providing information on the original signal width, used for the time slewing correction in the analysis. The TDC was operated in continuous storage mode in a dedicated run, giving the same results as the trigger matching mode.

[10] Präzisions Glas & Optik GmbH, Im Langen Busch 14, D-58640 Iserlohn, Germany (www.pgo-online.com).

[11] CAEN S.p.A., via Vetraia 11, 55049 - Viareggio (LU) Italy (www.caen.it).

3. Test-beam results

The RICH prototype was installed at CERN in the NA62 cavern, along the K12 beam line and tested between October 30 and November 10, 2007. A 200 GeV/c negative beam was produced 910 m upstream, from the SPS primary 400 GeV/c proton beam impinging onto the T4 target: it had a 1.8×10^{-3} momentum spread, 30 μrad divergence and a hadron composition at the production (prototype) position of 94.3% (96.2%) of π^-, 4.9% (3.0%) of K^- and 0.7% (0.8%) of $\bar{p}$; muons were also present. The SPS cycle was usually 16.8 s with a flat top of 4.8 s. Two scintillator slabs were used for triggering and about 150 000 events were collected per spill.

The main purpose of the test was to measure the hit multiplicity per ring and the resolution on Cherenkov angle and time measurements.

3.1. Simulation

A fast Montecarlo simulation has been developed taking into account multiple scattering, neon dispersion, quantum response of the PM and quartz window transmittance, as a function of the photon wavelength; channel by channel variations of the quantum efficiency and gain were included. The mirror reflectivity was assumed to be 0.85, the collection efficiency of the Winston cone was taken as 0.8 (for a photon impinging on the mylar foil), both flat in wavelength. A GEANT4 [8] based Montecarlo, with a full simulation of the optics, was also used.

3.2. The data analysis

The average number of PM hits per event was 17 for a pion and six for an antiproton (due to the smaller number of available PM on the antiproton ring). The probability that a PM had fired, if crossed in the center by a Cherenkov ring, was about 30%. If at least four hits were present within ±5 ns, the Cherenkov ring was fitted using a linearized χ^2 with 3 degrees of freedom (radius and two coordinates for the center) taking iteratively the distance of each fired PM from the fitted center. The PM distance used in the fit was an average over a uniform distribution on the Winston cone base from the fitted ring center. The fit was slightly biased given the limited number of available PM. The ring center position was fitted with a resolution of 1.9 mm (r.m.s.) on each coordinate. The pion Cherenkov angle resolution turned out to be about 50 μrad after a ±3 mm cut was applied on the fitted ring center. The pions and antiproton rings were clearly separated (Fig. 2). Similar results were obtained using a log-likelihood technique to fit the Cherenkov ring, by estimating the fraction of Cherenkov photons impinging on each PM.

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The good agreement between data and Montecarlo predictions is shown in Figs. 2 and 3; the tails in the ring center could be due to the beam halo or to large angle scattered particles but are removed by a ± 3 mm cut in both projections in the other plots.

The PM signals were properly time aligned and corrected for the slewing effect. Tighter cuts were used to calculate the event time with respect to those used for the ring fit: only PM having a time within 2.5 ns from the average were considered. An average single PM time resolution of 310 ps (r.m.s.) was found, see Fig. 4. The root mean square of the average event time was measured to be 65 ps. As a further check, the difference between the average time of one half of PM and that of the other half in each event was measured and had a resolution of 140 ps. The accidental rate was about 100 kHz, i.e. the probability of one accidental hit within ± 2.5 ns from the event time was 0.5×10^{-3}. This accidental rate was mainly due to imperfect environmental light tightness.

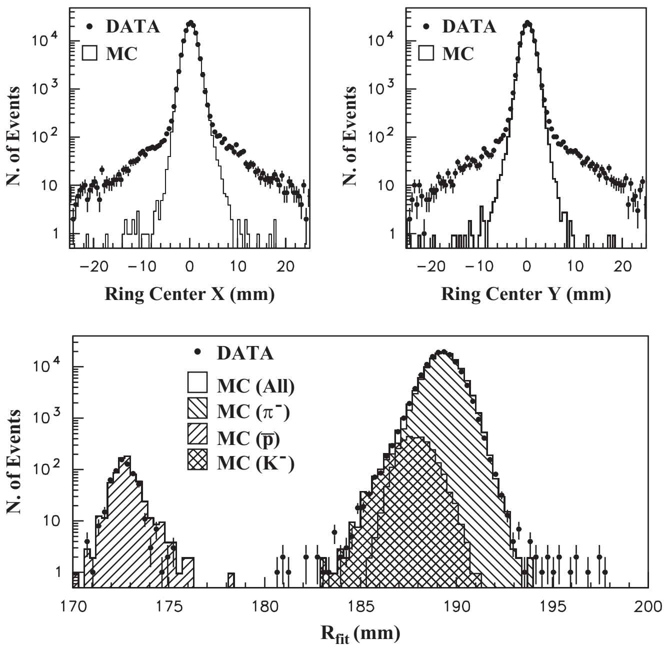

Fig. 2. Top left: fitted ring center (x coordinate); top right: fitted ring center (y coordinate); bottom: fitted ring radius (a 3 mm cut on the ring center, both in x and y, was applied). Data and Montecarlo are shown.

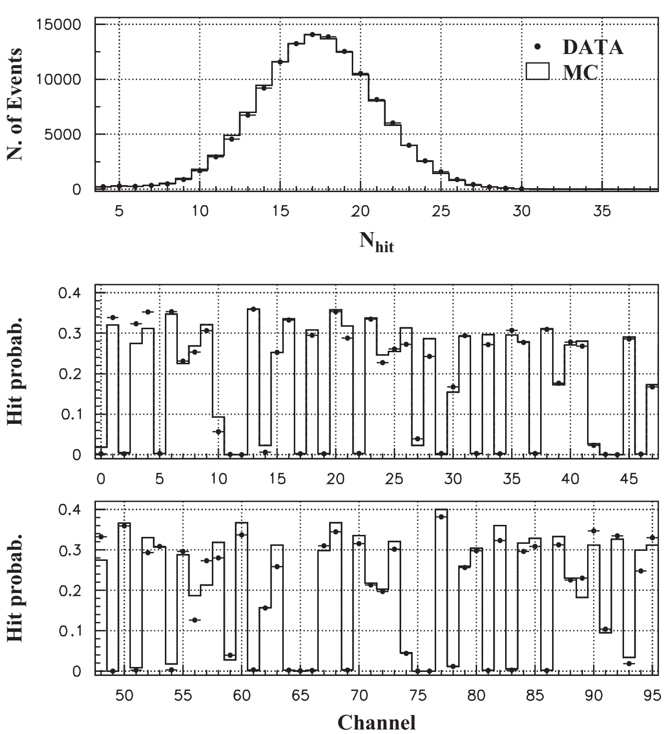

Fig. 3. Top: number of hit PM per event; middle and bottom: probability of each PM to be hit per event. Data and Montecarlo are shown.

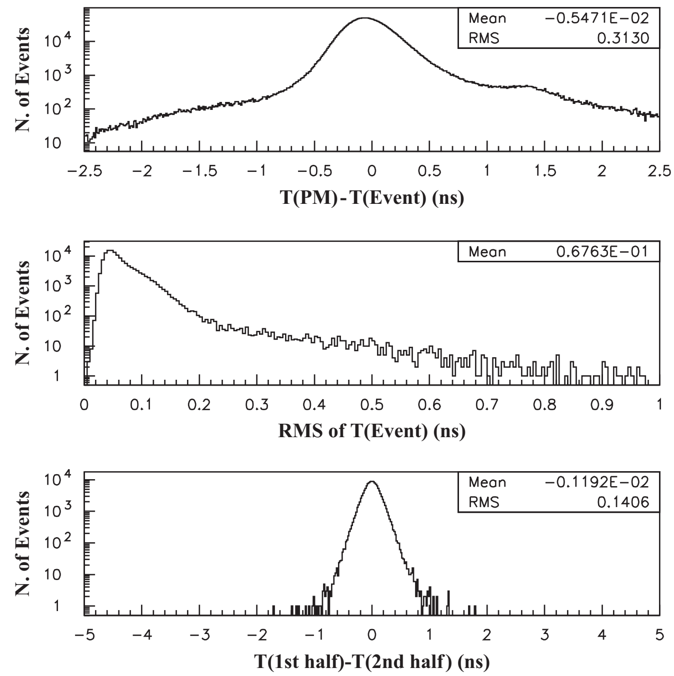

Fig. 4. Top: difference between each PM time and the event time; middle: root mean square of the event time; bottom: difference, event by event, between the average time of one half of PM and that of the other half.

The time delay between the track entering the radiator and the Cherenkov light reaching the PM is about 117 ns; in this time window there is a significant excess of hits with respect to accidentals, accounting for 0.016 detected photons per event. The simulation shows that the time distribution of such hits is due to an isotropic light emission along the particle path in the radiator (such as fluorescence).

The stability of the system was tested in anomalous conditions that could occur during the normal detector operation, i.e. a contamination of the radiator (up to 1% of nitrogen) and a temperature gradient within a couple of meters from the PM endcap. Performances did not change significantly.

The time resolution of R7400U-06 PM turned out to be worse than that of U-03 type by about 30%, without major improvements in light collection efficiency given the presence of a quartz window separating the neon radiator from the PM (see Section 2.3).

4. Conclusions

A RICH prototype with 17 m focal length, filled with neon at atmospheric pressure, has been built and tested. The Cherenkov angle uncertainty turned out to be 50 μrad and the time resolution 65 ps, in good agreement with the expectations of the Montecarlo simulation.

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