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R&D on high momentum particle identification with a pressurized Cherenkov radiator

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ABSTRACT

We report on the R&D results for a Very High Momentum Particle Identification (VHMPID) detector, which was proposed to extend the charged hadron track-by-track identification in the momentum range from 5 to 25 GeV/*c* in the ALICE experiment at CERN. It is a RICH detector with focusing geometry using pressurized perfluorobutane (C_4F_8O) as a Cherenkov radiator. A MWPC with a *CsI* photocathode was investigated as the baseline option for the photon detector. The results of beam tests performed on RICH prototypes using both liquid C_6F_{14} radiator (in proximity focusing geometry for reference measurements) and pressurized C_4F_8O gaseous radiator will be shown in this paper. In addition, we present studies of a *CsI* based gaseous photon detector equipped with a MWPC having an adjustable anode–cathode gap, aiming at the optimization of the chamber layout and performance in the detection of single photoelectrons.

1. Particle identification at high momenta in heavy-ion collisions

The aim of ultra-relativistic heavy-ion experiments is to identify and study the quark–gluon plasma (QGP) [1,2]. Different particle production mechanisms, e.g. bulk production from the QGP as a thermal source or parton fragmentation, can be explored by exploiting various particle identification methods. The separation of pions, kaons and protons at low momenta ($p < 3$–5 GeV/c) in heavy-ion collisions is for example done with the measurement of the specific energy loss in tracking detectors like a Time Projection Chamber (TPC) or a time-of-flight measurement. Hadron specific effects in the fragmentation of partons and the subsequent formation of jets in vacuum and in the QGP medium (hadro-chemistry) [3–6] require the identification of different particle species above 5 GeV/*c* on a track-by-track basis.

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The ALICE detector [7–9] at the Large Hadron Collider (LHC) serves as a representative example of an ultra-relativistic heavy-ion experiment. It was designed to cope with the high charged particle densities expected in central Pb–Pb collisions at LHC energies (up to $dN/d\eta = 8000$ at mid-rapidity) and consists of seventeen detector systems. The experiment provides charged particle tracking from $p_T \simeq 0.15\,\text{GeV}/c$ up to high transverse momenta combined with excellent particle identification capabilities for the mid-rapidity region $|\eta| < 0.9$.

Recently, the ALICE collaboration presented measurements of identified particles exploiting the relativistic rise region of the specific energy loss in the TPC (dE/dx) [10]. In this method the particle identification is done on a statistical basis, and not track-by-track. The dE/dx distribution of unidentified tracks is fit with a global Bethe–Bloch response based algorithm in order to obtain the fraction of different particle species. By determining the yields for protons, kaons and pions in pp and Pb–Pb collisions the nuclear suppression factors (R_{AA}) were measured up to 20 GeV/c.

To significantly enhance the particle identification capabilities in this regime by track-by-track measurements, we have investigated the construction of a new detector, the Very High Momentum Particle Identification Detector (VHMPID). Designing a thin VHMPID with low material budget enables the proposal of a device that would fit in front of the ALICE calorimeter modules and which will allow the measurement of full jets with identified particles in the momentum range from 5 to 25 GeV/c. A detailed description of the project can be found in Ref. [11].

The layout of one detector module is shown in Fig. 1. It is a Ring Imaging Cherenkov (RICH) detector with focusing geometry using pressurized perfluorobutane (C_4F_8O at 3.5 bar) as radiator medium. As a photon detector a Multi Wire Proportional Chamber (MWPC) with the *CsI* photocathode was investigated as the baseline option. The segmentation, size, position and orientation of the mirror and photon detector array were optimized with an optical design program (ZEMAX© [12]) and led to a 3×3 array of $50 \times 50\,\text{cm}^2$ spherical mirrors and the same number of photon detectors of about $18 \times 24\,\text{cm}^2$ active surface. The separation between the radiator gas volume and the detector gas (CH_4) is ensured by a sapphire window of 5 mm thickness with UV anti-reflective coating. The optical wavelength range of the detector is limited by the sensitivity of the *CsI* layer (quantum efficiency > 0 for $\lambda < 205$ nm), the transmissivity of the radiator gas ($> 60\%$ for $\lambda > 150$ nm), the sapphire window ($> 55\%$ for $\lambda > 155$ nm) and the reflectivity of the mirror ($> 77\%$ for $\lambda > 150$ nm). Two additional tracking chambers on the top and bottom of the module will improve the track-matching performance and particle identification capabilities. The total height adds up to 70 cm, whereof 50 cm is used for the radiator gas and yields in very low material budget with a total radiation length of 22% (see Table 1).

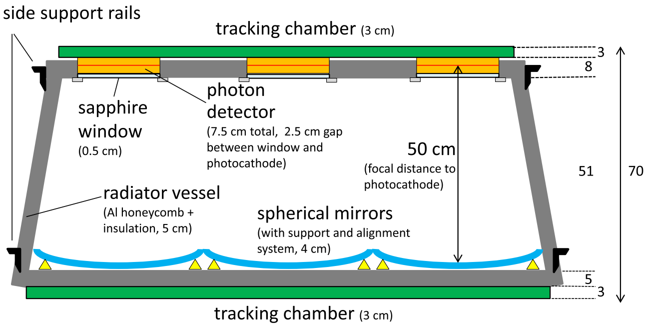

Fig. 1. Longitudinal cross-section of one VHMPID module, showing the depth or thickness of main components (not to scale).

2. Optimization of the photon detector

The choice of a MWPC with a segmented *CsI* photocathode (with $4 \times 8\,\text{mm}^2$ pads) and CH_4 as detector gas was driven by the large photosensitive area to be covered at a reasonable cost and the capability to operate in a magnetic field of 0.5 T. In order to improve the spatial resolution and decrease the spread of the charge induced on the cathode with respect to the existing ALICE-HMPID [13] a study on the distance between the anode wire and the cathode pad plane (anode–cathode gap) was performed in a dedicated test beam time at the CERN-PS accelerator providing a secondary pion beam. A liquid C_6F_{14} radiator in a proximity focusing RICH configuration was used. The proximity gap was set at 31 mm in order to reproduce the expected ring radius of 4.7 cm generated in the C_4F_8O gaseous radiator when using a negative pion beam with a momentum $p = 6\,\text{GeV}/c$, while the radiator thickness was chosen to be quite small (3 mm) to reduce the number of photons and minimize the photon signal overlap.

For each event the Cherenkov angle for each photocathode pad is calculated from the distance to the measured position of the beam particle on the photon detector. Pads are then combined to clusters representing the single photoelectron hits in position and size due to induction spread and induced signal. In Fig. 2 the Cherenkov angle resolution for single pads $\sigma_{\alpha,\text{Pads}}$ is shown as a function of the chamber gas gain A_0 for different anode–cathode gaps (0.8, 1.2, 1.6 and 2.0 mm). The gas gain A_0 is extracted from an exponential fit to the photoelectron pulse height spectrum as in Ref. [14]. The Cherenkov angle resolution for single pads decreases ($\sigma_{\alpha,\text{Pads}}$ increases) with the gas gain and larger anode–cathode gap. At the same gas gain, a smaller anode–cathode gap results in an improved $\sigma_{\alpha,\text{Pads}}$ since the induction spread is reduced significantly.

Table 1
Estimated radiation length of different components of the VHMPID detector.

Detector component	X/X_0 (%)
Bottom and top radiator vessel panel	7
Photon detector and tracking layers	3
Mirror	2
Radiator gas	4
Sapphire window	6
Total	22

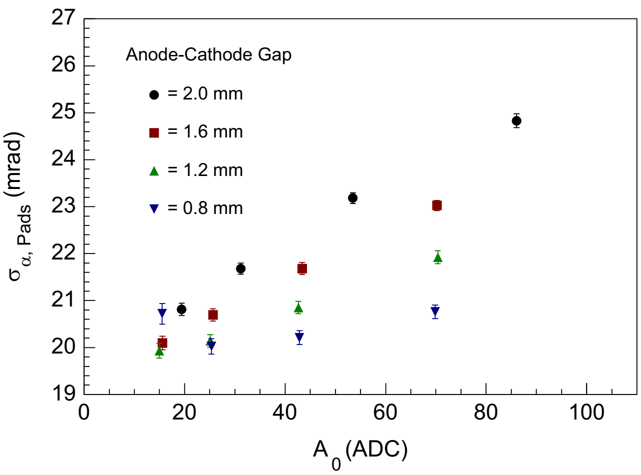

Fig. 2. Cherenkov angle resolution for single pads $\sigma_{\alpha,\text{Pads}}$ as a function of the chamber gas gain A_0 in ADC for different anode–cathode gaps.

Table 2
Variation with C_4F_{10} gas radiator pressure of refractive index and momentum thresholds for Cherenkov emission.

Radiator pressure (bar)	Refr. ind. at 175 nm	π thresh. (GeV/c)	K thresh. (GeV/c)	p thresh. (GeV/c)
1.0	1.00153	2.5	9	17
2.0	1.00306	1.8	6.4	12
3.5	1.00535	1.3	4.8	9.1

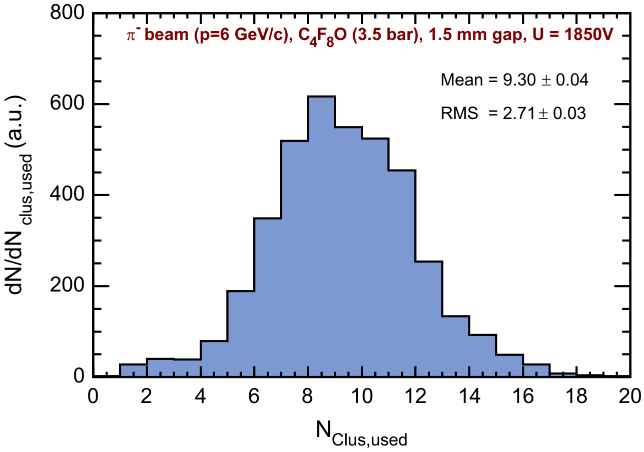

Fig. 3. Number of photon clusters per ring $N_{\text{Clus,used}}$.

More details on the optimization of the photon detector can be found in Ref. [14]. Further developments such as *CsI*-based Thick GEM photon detectors [15,16] and micro-channel plate detectors (Photonis Planacon XP85012Q with bialkali photocathode) were considered as well.

3. Pressurized radiator gas

In order to study separation between kaons and pions above $p > 5$ GeV/c momentum, a pressurized perfluorobutane as a Cherenkov radiator was studied. In Table 2 the momentum threshold for Cherenkov emission for C_4F_{10}, which from simulations is expected to have a similar refractive index to C_4F_8O [17], is shown for different pressures. To prevent condensation of C_4F_8O at a pressure of $P = 3.5$ bar, the radiator gas needs to be heated to a temperature of $T \simeq 40$ °C.

The performance of the pressurized radiator gas was studied with a negative pion beam with a momentum $p = 6$ GeV/c. The same photon detector as in Section 2 was used, but in combination with a heated and pressurized radiator vessel (diameter $D = 16$ cm and length $L = 59$ cm) and a spherical focusing mirror (diameter $D = 16$ cm and radius of curvature $ROC = 100$ cm). The photon detector was operated with an anode–cathode gap of 1.5 mm and an anode voltage of 1850 V, which corresponds to $A_0 \simeq 50$ ADC channels.

In Fig. 3 the number of photoelectron clusters that are associated with a Cherenkov ring $N_{\text{Clus,used}}$ is shown. A mean number of detected photons per pion of $N_{\text{phot}} = 9.3$ is achieved. To filter out the background from electronic noise and improve the signal of identified particles a Hough Transform is applied to all clusters, which finds local maxima in the parameter space of the Cherenkov angle and calculates a Cherenkov angle θ_{Cher} for each beam particle [11].

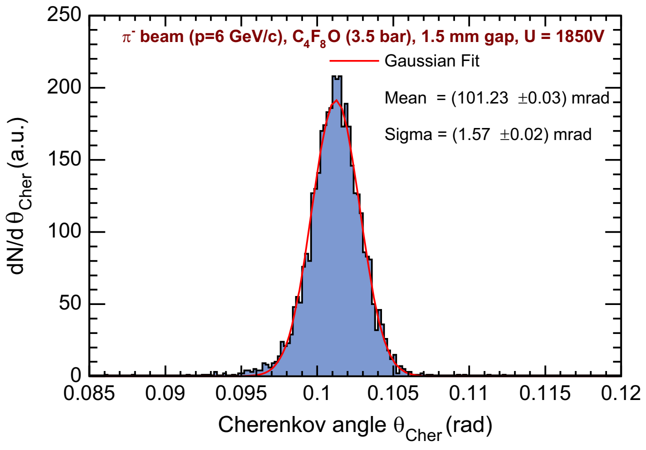

Fig. 4. Cherenkov angle θ_{Cher} for all pions with a momentum $p = 6$ GeV/c.

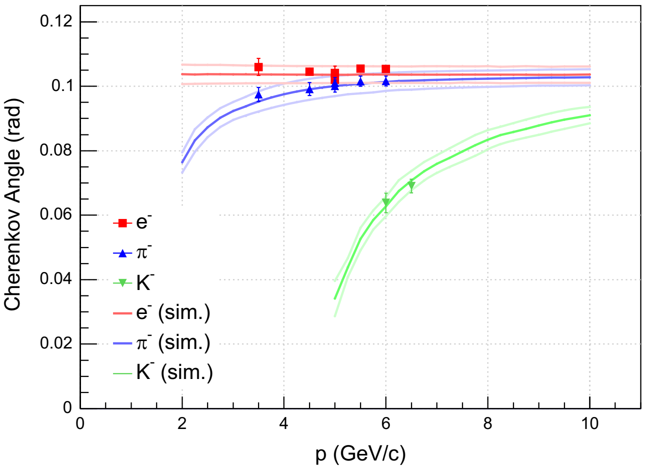

Fig. 5. Cherenkov angle θ_{Cher} and resolution σ_θ (shown in error bars for data and thin lines for simulation) for data (symbols) and simulation (lines) for electrons, pions and kaons as a function of particle momentum p.

The Cherenkov angle distribution for all pions with a momentum $p = 6$ GeV/c is shown in Fig. 4 together with a Gauss fit. A Cherenkov angle resolution of $\sigma_\theta = 1.5$ mrad is achieved. This is slightly higher from what is expected from an ideal calculation (without background) resulting in $\sigma_\theta = \sigma_{\theta,\text{cluster}}/\sqrt{N_{\text{Clus,used}}} = 3.6/\sqrt{9.3} = 1.2$ mrad with $\sigma_{\theta,\text{cluster}}$ being the Cherenkov angle resolution for single clusters [11].

The beam contains a significant contamination from electrons and kaons in the momentum range considered for the VHMPID. Fig. 5 shows the Cherenkov angle and resolution for pions, kaons and electrons at different particle momenta. Pion and electron separation is achievable below a momentum of 4 GeV/c and kaon signals can be observed starting from 5 GeV/c. To reproduce and extrapolate the results observed in the test beam setup, Monte Carlo simulations based on GEANT3 [18] have been used.

4. Summary

The results of beam tests performed on RICH prototypes using a pressurized C_4F_8O gaseous radiator and a MWPC with a *CsI* photocathode and a small anode–cathode gap showed an excellent performance. In average about 10 photons were detected per Cherenkov ring leading to a Cherenkov angle resolution of 1.5 mrad. In conclusion, the layout of the photon detector as well as the radiator gas pressurization and heating concept have been fully validated by demonstrating that the required particle identification performance can be achieved.

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