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Technological implications for RICH performance

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ABSTRACT

I will review in this talk some examples of RICH detectors operating or being about to, from the point of view of the parameters which determine the Cherenkov angle resolution. The RICH technique is extremely powerful and widely used nowadays in experiments which have to perform particle identification. Depending on the technologies chosen for the detector design, the design resolution can be achieved if important efforts are made, keeping under control the stability of the different components contributing to the Cherenkov angle resolution.

1. Introduction

Ring Imaging Cherenkov is a very powerful technique for particle identification (PID), which is a fundamental requirement for many experiments in high energy physics. RICH detectors, depending on the different technologies adopted, demand however a very careful and stable operation and control of each component (radiator, photon detection, optics when present, etc.).

The level of precision on the Cherenkov angle (θ_C) required by a physics measurement is the key for the choice of technologies needed for the various components, and the level of stability is more mandatory the more the resolution is high. Present applications of RICH detectors include experiments at hadron machines, like LHCb, ALICE, NA62 which have the most harsh environment (very high density of particles in the final state, operation frequency). But the range of applications is very wide: e^+e^- experiments (BELLE, CLEO-III, BaBar), space (AMS, CREAM) and below surface experiments (ANTARES, NEMO, AMANDA, and others). Each has a different request for the level of precision on Cherenkov angle and consequent level of difficulty to keep under control the running stability. I will consider in the following few examples, namely the RICH of ALICE and of LHCb at LHC, NA62 at SPS and AMS and CREAM as examples of space experiments (on satellite and balloon).

2. Cherenkov angle resolution

Once the choice of a radiator has been made, determined by the momentum range of the particles to be identified, the key quantity guiding the technological choices for the construction of a RICH detector is the Cherenkov angle resolution (σ_θ). Depending on the physics measurement planned, an experiment will have to choose the various components considering that the main contributions to the angular resolution are from:

- the choice of the radiator: its index of refraction, thickness and transparency determine the chromaticity and photon multiplicity (N_γ).
- the choice of the photodetectors (PD): their quantum efficiency, pixel size, photon collection efficiency, determine the photoelectron multiplicity (N_{pe}) and their spatial localisation.
- the choice of the geometry (focussed or proximity focussed): it determines the emission point error and the error coming from the path followed by a Cherenkov photon.
- 'external errors': tracking precision, multiple scattering, particle decays or secondary interactions will contribute to the (σ_θ) but depend on the configuration of the experimental layout outside the RICH.

The different contribution combine quadratically so that the total precision per photoelectron will be

$$\sigma(\theta_C) = \sqrt{\sigma(\theta_{rad})^2 + \sigma(\theta_{PD})^2 + \sigma(\theta_{geom})^2 + \sigma(\theta_{ext})^2}.$$

The resolution per ring will be

$$\sigma_{ring}(\theta_C) = \sigma(\theta_C)/\sqrt{N_{pe}}.$$

The resulting separating power for two particles of mass m_1 and m_2 is defined as

$$N_\sigma = (m_1^2 - m_2^2)/(2p^2\sqrt{n^2-1}\sigma(\theta_C)).$$

This means that, given the choice of a radiator with index of refraction n, the range over which particle identification can be achieved with N_σ is more extended the more the $\sigma(\theta)$ is small.

The general rule is therefore to minimize $\sigma(\theta_C)$ and maximize N_{pe}.

One can group the experiments by the range of resolution required for the physics application: in the range of $\sigma(\theta_C) = O(10\text{ mrad})$ there

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are ALICE, SUPER-BELLE, JLAB, CLEO-III, BaBar, HERMES. In the range of $\sigma(\theta_C) = O(1\ \text{mrad})$ there are experiments at hadron machines, like COMPASS, LHCb, NA62.

3. The RICH of ALICE

ALICE is an experiment dedicated to ion collision studies at LHC [1].

The RICH designed for ALICE has as physics aim to identify p, K and π in the range of momentum 1–5 GeV/c. Details of the detector have been given at this conference [2]. It has to handle a particle density of the order 2000 per rapidity unit, but at a relatively small rate (< 10 kHz). The choice of a proximity focus configuration has been dictated by the limited space available.

The technological choices: The radiator chosen is 15 mm liquid C_6F_{14}, providing an $n=1.2989$ at the wavelength of 175 nm, giving a Cherenkov angle = 694 mrad.

The photodetection is performed by a reflective layer of CsI (QE=25% at 175 nm) and MWPC with CH_4 at atmospheric pressure (4 mm sensitive gap) and an analog pad readout. An upgrade is already planned to extend PID up to 30 GeV/c by means of 1 m of C_5F_{12} gas radiator, with a mirror focussed configuration [3]. The ALICE RICH is composed of seven modules $1.5 \times 1.5\ \text{m}^2$ covering 5% of the barrel region. The configuration is shown in Fig. 1.

The main contributions to the resolution are expected to be

1. chromaticity: it amounts to ~10 mrad, determined by the basic dispersion properties of the radiator and it is the dominant contribution.
2. spatial error: the granularity of the photodetectors induce ~5 mrad.
3. geometry: the thickness of the proximity gap give ~4 mrad.
4. track error: the tracking is considered to give a negligible contribution, but it is under investigation with the data.

The total resolution is therefore in the range of 12 mrad. The average number of photoelectrons is about 18. One aspect which requires special care in order to keep the performance as expected is the C_6F_{14} circulation and purification system.

4. The RICH of LHCb

The LHCb experiment is dedicated mainly to the measurement of very rare b decays and of CP asymmetries: separation between π, K and proton over a wide (2–100 GeV/c) range of momenta is therefore mandatory [4].

The particle identification is performed by two RICH detectors.

The technological choices: The upstream detector, RICH 1, covers the low momentum charged particles range ~1−40 GeV/c using 5 cm of aerogel with nominal $n=1.03$ at 400 nm (up to 10 GeV/c) and 95 cm of gas C_4F_{10} ($n=1.0014$ at 400 nm) as radiators, while the downstream detector, RICH 2, covers the high momentum range from ~15 GeV/c up to ~100 GeV/c using 180 cm of CF_4 ($n=1.0005$ at 400 nm) as radiator. The gas radiators are operated slightly above atmospheric pressure and at room temperature. Pressure and temperature are constantly monitored in order to correct the variations of the refractive index. The gas composition is regularly measured with a chromatograph, and the purity is typically above 95%.

In both RICH detectors the focusing of the Cherenkov light is accomplished using a combination of spherical mirrors (four in RICH1 and 52 in RICH2) and flat mirrors (16 in RICH1 and 40 in RICH2) to reflect the image out of the spectrometer acceptance. The spherical mirrors have a radius of curvature of 2700 mm in RICH1 and 8600 mm in RICH2. The mirror alignment is very important in order to keep this contribution to the resolution down to 0.1 mrad [5].

Four hundred and eighty four Hybrid Photon Detectors (HPDs) are used to detect the Cherenkov photons in the wavelength range 200–600 nm. The granularity is 2.5 mm at the photocathode level.

The HPDs operated at −18 kV and are sensitive to the magnetic field: they are surrounded by external iron shields and are placed in MuMetal cylinders to permit operation in magnetic fields of up to 50 mT. This implies that distortion induced by the fringes magnetic field must be monitored and corrected for. Details of the procedure are given in Ref. [7].

A photo of RICH 1 and a schematic of RICH 2 are shown in Fig. 2.

From simulation, the resolution on the Cherenkov angle per photoelectron, expected with this design and the mean number of photoelectrons detected per $\beta \approx 1$ track can be determined. The mean number of photoelectrons is found to be 6.7 for aerogel, 30.3 for C_4F_{10} and 21.9 for CF_4. All the effects contributing to the angular resolution are shown in Table 1, where both the total resolutions and the individual contributions are listed. The resolution has contributions from the uncertainty associated to the chromatic dispersion of the radiators, the finite pixel size and the point spread function (together listed as 'HPD' in Table 1).

For the aerogel it is the chromatic dispersion error which dominates, whereas for the other two radiators the contributions are well matched. To evaluate the contribution which comes from the reconstruction of the track direction, the tracking must be well described by the Monte Carlo (and the alignment of the optics elements rely on it).

The single photoelectron resolution is largest for the aerogel, at 2.6 mrad, and smallest for the CF_4, at 0.7 mrad.

The achieved resolution of the RICH system at present, after about 65 μb^{-1} of data, is respectively 2.2 and 0.9 mrad in C_4F_{10} and CF_4. More details are given in Ref. [5]. The resolution in aerogel is worse than expected by about a factor of between 2 and 3: it is still under investigation [6] because higher statistics is needed to study each of the 16 tiles composing the aerogel wall.

Already at this stage of calibration, the RICH system of LHCb gives excellent results on PID. An example is given in Fig. 3 and more details are given in Ref. [8].

The performance of the RICH obtained with the data rely on many elements: the working conditions and the running stability, monitored by the Detector Control System (DCS) which controls the operating conditions concerning power supply stability (low and high voltage, silicon detector bias); temperature, pressure and humidity, the gas quality, the system to measure the magnetic distortions, the laser alignment monitoring system.

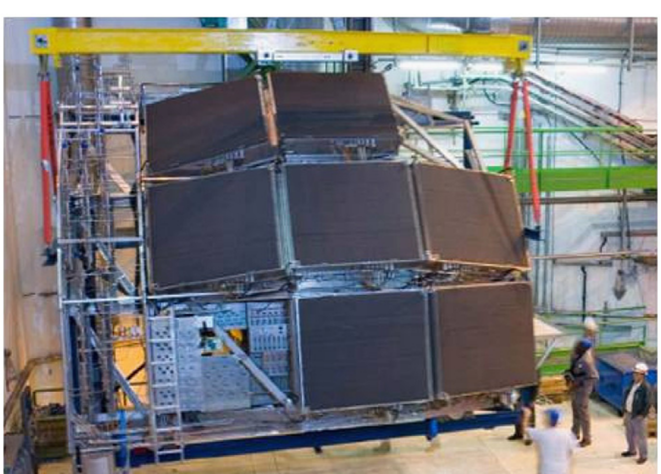

Fig. 1. The integration of the seven RICH modules in the barrel of the ALICE detector (Courtesy of ALICE collaboration).

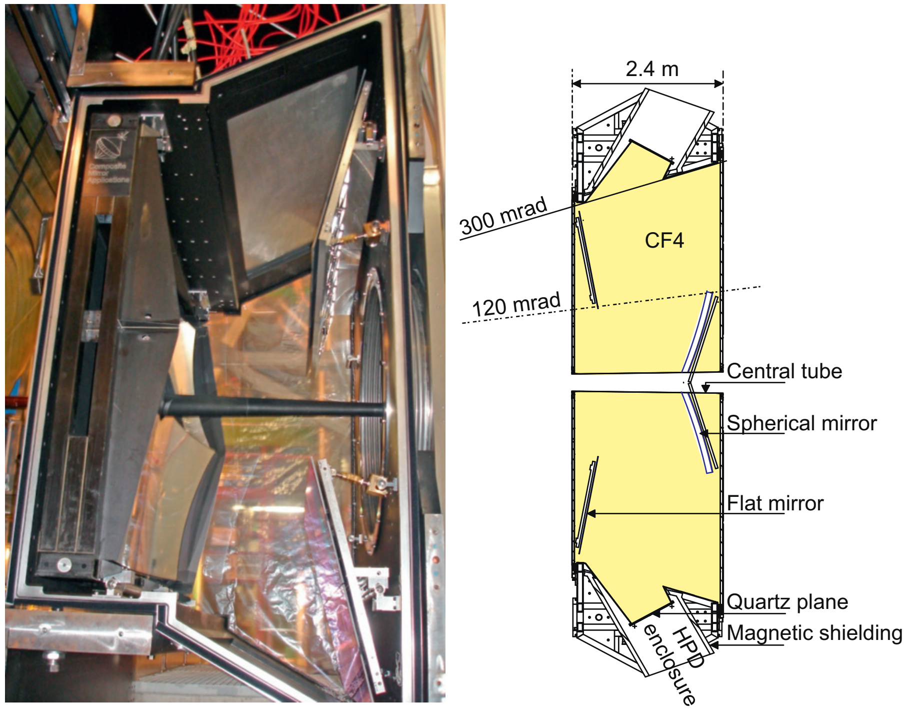

Fig. 2. A picture of the RICH1 open vessel and a sketch of the RICH2 structure.

Table 1
Single photoelectron resolutions for the three RICH radiators. All numbers are in mrad. Individual contributions from each source are given, together with the total.

	Aerogel	C_4F_{10}	CF_4
Emission	0.4	0.8	0.2
Chromatic	2.1	0.9	0.5
HPD	0.5	0.6	0.2
Track	0.4	0.4	0.4
Total	2.6	1.5	0.7

5. The RICH of NA62

The NA62 experiment, which is expected to start in about 1 year time, aims measuring at 10% precision the very rare branching ratio $K^+ \rightarrow \pi^+ \nu\bar{\nu}$ which is predicted by the Standard Model to be $O(10^{-11})$. The dominant background comes from the decay $K^+ \rightarrow \mu^+ \nu$ which has a branching ratio of 63.4% [9].

The planned measurement requires a $\pi-\mu$ separation at least 3σ level in the range of momentum 15–35 GeV/c. The rejection factor to be achieved is 10^{-12}, of which 10^{-5} will come from kinematics and 10^{-5} from the muon veto. To the RICH therefore is requested to reach a rejection factor of 10^{-2} [10].

The experiment will run at the SPS (CERN) with a kaon beam working at 800 MHz. The RICH will have to match the traversing π (10 MHz rate) with the kaon seen by the beam spectrometer (800 MHz rate). This requires to measure the pion crossing time with a precision at 100 ps level.

The design of the NA62 RICH is widely based on the design of the RICH of the SELEX experiment, now closed, which gave an excellent performance [11].

The technological choices: The RICH has a focussed geometry and uses as radiator 17 m of Ne gas at atmospheric pressure. The index of refraction is $n-1 = 62 \times 10^{-6}$ at $\lambda = 300$ nm. The gas is contained in an aluminium cylindrical vessel 17 m long and 4 (3.4) m wide

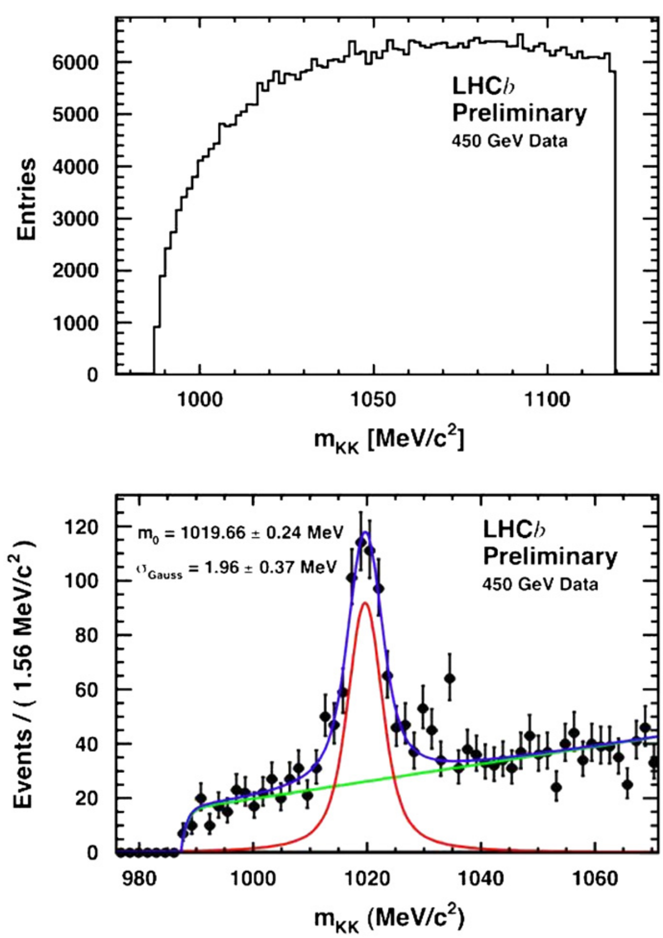

Fig. 3. Invariant mass m_{KK} from the tracking information and assuming K mass on the top, and after having applied PID obtained with the RICH.

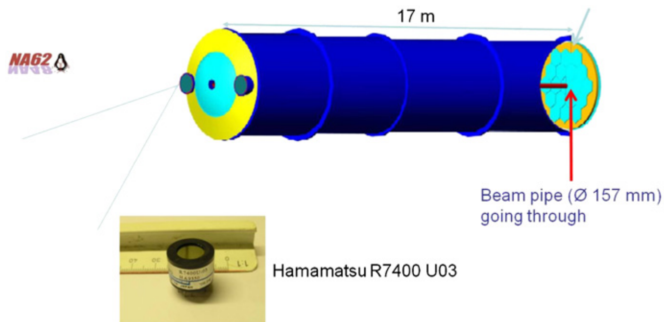

Fig. 4. A sketch of the vessel of NA62 RICH (Courtesy of NA62 collaboration).

upstream (downstream). CO_2 is used to purge the vessel: the gas is then circulated in closed loop, and the Neon is introduced while absorbing the CO_2 in a molecular sieve filter. At the end the vessel is closed by a valve.

The entrance and exit windows are made by thin aluminum plates. The pion threshold is 12 GeV/c and the Cherenkov angle is $\theta_C = 11.3$ for $\beta = 1$ particles.

There are 20 spherical hexagonal mirrors with focal length of 17 m, which focalize the photons onto the photon detector plane located on plates at the entrance window of the gas vessel, as shown in Fig. 4.

The photodetector choice is the PMT Hamamatsu R7400-U03 with a granularity of 18 mm and time resolution better than 100 ps. There are 2000 such PMTs.

The different contributions to the Cherenkov angle resolution for this design are:

1. chromaticity: it amounts to ~ 125 µrad, determined by the basic dispersion properties of the radiator.
2. spatial error: it amounts to ~ 265 µrad, the dominant contribution determined by the granularity of the photodetectors.
3. geometry: the emission point error and the mirrors alignment give ~ 15 µrad.
4. track error: it is expected to be ~ 55 µrad.

To achieve the expected resolution, the RICH of NA62 will have to control: (a) the gas density, in order to follow up the variations in the operating conditions of n ($n = 1 + (n_0 - 1)\ \rho/\rho_0$, where ρ is the gas density at T and P); (b) the leak rate must be kept below 1×10^{-2} Std.cc/s: if this is not achieved, a purifier module will be needed; (c) the stability of the gas purity (contaminants must be $< 1\%$); (d) the mirrors alignment will be important: NA62 expects to achieve with a laser and with the data a level of O(50 µrad) as contribution to the resolution; (e) the photocathode quantum efficiency will be monitored in time.

6. The RICH of AMS

AMS [12] is working in a completely different environment: it is going to be launched on satellite during this year. The aim of the experiment is to measure the cosmic rays spectrum, to search for antimatter and dark matter.

The RICH detector has the task of measuring the particle velocity β and the charge.

In space stability is mandatory, because there can be essentially no maintenance. Solid radiators are therefore more suitable.

The technological choices: The geometry chosen is a proximity focus configuration, to avoid optical elements to align. Two solid radiators are present: 2.5 cm of silica aerogel with index of refraction $n = 1.05$ and a crystal of 0.5 cm sodium fluoride (NaF, $n = 1.334$). There is a conical reflector (reflectivity is $\sim 85\%$) around, in order to increase the acceptance reflecting high inclination photons. An expanded view of the different components is shown in Fig. 5.

The photodetector choice is the PMT Hamamatsu R7600-M16 with plastic guide and with pixel size of $8.5 \times 8.5\ mm^2$. Each individual PMT is shielded from the stray field, which could be up to 300 G. There are 680 PMTs.

The contributions to the resolution $\sigma(\beta)/\beta$ are:

1. the radiators chromaticity: it amounts to ~ 3.2 mrad for aerogel, and 4.8 mrad for NaF.
2. the radiators thickness: it contributes ~ 3.3 mrad for the aerogel, and 0.3 mrad for NaF.
3. spatial error: the pixel size contribution is 4.6 mrad for aerogel and 0.6 mrad for NaF.

The total error is $\sigma(\theta_C) = 6.5(4.8)$ mrad for aerogel (NaF), which means a precision on β of $\sigma(\beta)/\beta = 2 \times 10^{-3}$ and 4×10^{-3} for aerogel and NaF respectively.

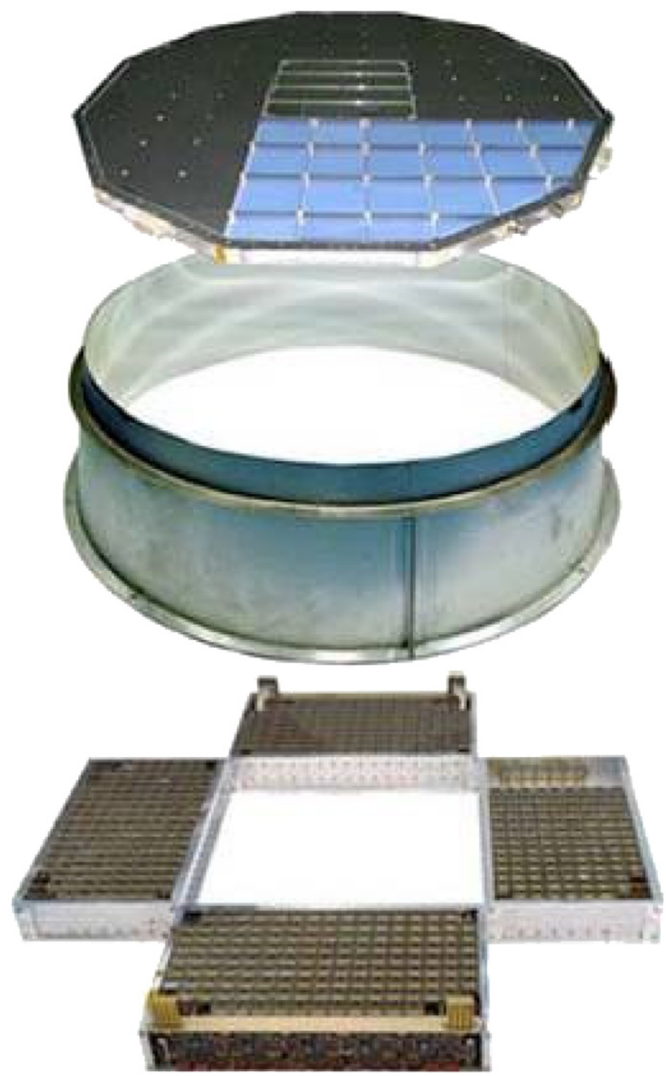

Fig. 5. A sketch of the different components of the RICH of AMS (Courtesy of AMS collaboration).

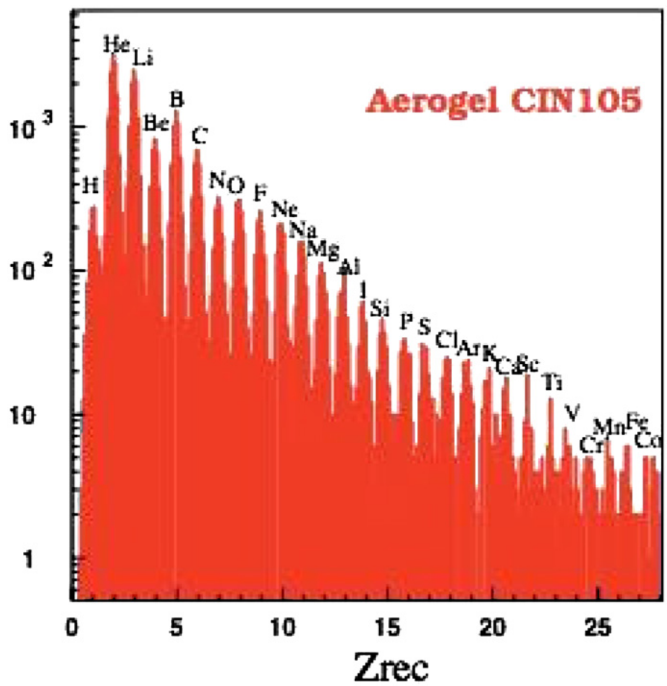

Fig. 6. Separation achieved in a test beam with an aerogel radiator [13]. (Courtesy of AMS Collaboration.).

The RICH of AMS will measure the charge of the particles, task achieved also together with other parts of the detector like the TOF and the silicon tracker. The RICH will measure the charge through the relation:

$$Z^2 \alpha N_{pe}/\varepsilon \times (\sin^2\theta_C)^{-1}$$

where ε is the acceptance and photon detection efficiency.

With a resolution of $\Delta Z = 0.2$ for electric charge, AMS measured in a test beam a very good separation among the different nuclei, as shown in Fig. 6.

The experiment is planned to operate in space for at least 3 years. Clearly effects due to non-uniformity or instability of the radiators or of the photon detection (e.g. drift in the clarity and n of the aerogel, or temperature effects on photon detection, etc…) which introduce possible contributions to the systematic errors must be avoided or at least minimized.

The RICH of CREAM : A similar RICH configuration operated in a balloon experiment, CREAM [14].

The experiment was launched from the US McMurdo base in Antarctica and had five successful flights. The RICH (CHERenkov CAMera, built by a French/Mexican Collaboration in less than 2 years) of CREAM had the aim to measure the electric charge of cosmic ray particles, similarly to AMS.

It consisted of 200 tiles of silica aerogel as radiator.

The optical index dispersion between tiles, and the optical index dispersion in each tile had to be $< 10^{-3}$ and the variation of thickness of aerogel tiles had to be less than 0.2 mm. The photons were readout by 1600 PMT Photonis XP3112 photodetectors.

The systematic requirements were similar as in AMS. The charge distribution measured with the data collected during one of the flights is shown in Fig. 7.

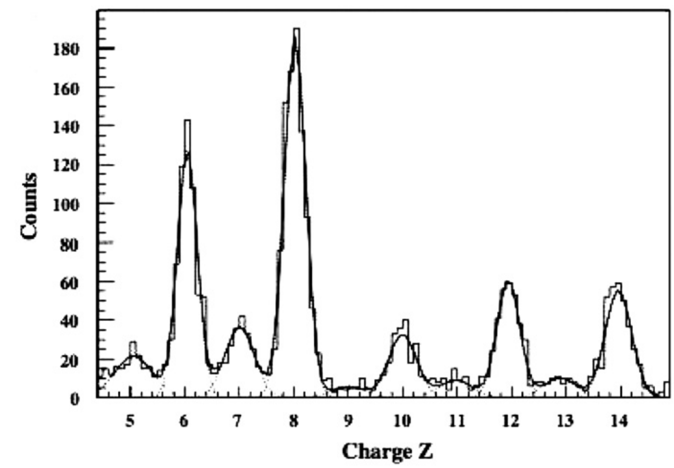

Fig. 7. Charge distribution of the particles measured by the CREAM experiment during one balloon flight (Courtesy of CREAM Collaboration.).

7. Conclusions

The RICH technique is extremely powerful and widely used nowadays in experiments which have to perform particle identification.

The choice of technologies make RICH designs flexible. The stability of the detector operation is often crucial to perform the task in those experiments where high angular resolution is required.

Present technological developments, e.g. in the domain of photodetector time resolution and high quantum efficiency, will allow further improvements.

However RICH detectors are often sophisticated tools which need important efforts both on the hardware side, keeping under control the stability of the different components contributing to the Cherenkov angle resolution, and on the software side in order to translate the detector response in particle identification performance.

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References

[1] The ALICE Collaboration, JINST 3 (2008) S08002.
[2] P. Martinengo, G. De Cataldo, these proceedings.
[3] A. Di Mauro, these proceedings.
[4] The LHCb Collaboration, JINST 3 (2008) S08005.
[5] C. Blanks, these proceedings.
[6] D.L. Perego, these proceedings.
[7] P. Xing, these proceedings.
[8] A. Powell, F. Muheim, these proceedings.
[9] G. Anelli, et al., Proposal to measure the rare decay $K+ \to \pi + \nu\bar{\nu}$ at the CERN SPS, CERN-SPSC-P-326.
[10] M. Lenti, these proceedings; G. Anzivino, et al., Nucl. Instr. and Meth. A 593 (2008) 314.
[11] J. Engelfried, et al., Nucl. Instr. and Meth. A 502 (2003) 285.
[12] AMS Collaboration, Phys. Rep. 366 (2002) 331.
[13] L. Arruda, et al., Nucl. Phys. B (Proc.Suppl.) 172 (2007) 32.
[14] M. Buenerd, in: R. Caballero, J.C. D'Olivo, G. Medina-Tanco, L. Nellen, F.A. Snchez, J.F. Valds-Galicia (Eds.), in: Proceedings of the 30th International Cosmic Ray Conference, Universidad Nacional Autnoma de Mxico, Mexico City, Mexico, 2008, vol. 2 (OG PART1), pp. 453–456.