

CLAS12 RICH

Technical Design Report

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Abstract

This document describes the technical layout and the expected performances of a Ring Imaging CHerenkov (RICH) detector for the CLAS12 spectrometer. The detector is designed to provide CLAS12 with the capability to identify kaons with momentum between 3 and 8 GeV/c with a rejection power with respect to pions and protons of about 1:500.

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Part I

Physics

Lepton scattering is the basic tool for determining the fundamental structure of matter, in particular of the nucleon, from which the observable physical world around us is formed. Such experiments, using high energy lepton beams, tested successfully the theory of Quantum Chromodynamics (QCD), which describes all strongly interacting matter in terms of quark and gluon degrees of freedom. The successful prediction of the energy dependence of parton distributions, which were introduced to describe the structure of the nucleon, has been one of the great triumphs of perturbative QCD.

In the following sections, we briefly summarize the main physics items that will benefit from the RICH construction. A more detailed discussion can be found in [1].

1 Nucleon structure: towards a three-dimensional image

After four decades of lepton-nucleon scattering experiments, our knowledge on the universal parton distribution functions (PDFs) and fragmentation functions (FFs), which connect the partonic dynamics to the nucleon, has been dramatically improved. On the other hand, the gain in precision has often revealed intriguing aspects of the nucleon structure. Among these surprises are the sizeable breaking of isospin symmetry in the light sea quark sector, suggesting differences between the sea quark and antiquark distributions, the steep rise of the distributions at small momentum fractions, and an interesting pattern of modifications of the distributions in nuclei. Certainly one of the most surprising results is the unexpectedly small fraction, about a quarter, of the proton's spin that is due to the contribution from quarks and antiquarks.

This finding has triggered a vast experimental and theoretical activity aiming at clarifying the role gluons and parton orbital angular momenta play for a complete description of the proton spin structure. New concepts of Transverse Momentum Dependent (TMD) distribution and fragmentation functions, which go beyond the collinear approximation, are a key to unravel the intricacies of the intrinsic motion of partons and the possible connection between their orbital motion, their spin and the spin of the nucleon, which cannot be described with standard (e.g. collinear) parton distributions. Experimental measurements have confirmed the applicability and necessity of including these novel correlations in QCD in order to understand complex structure of nucleons. These TMD distributions together with the so-called Generalized Parton Distributions (GPDs) provide for the first time a framework to obtain information towards a genuine three-dimensional momentum and space resolution of the nucleon structure. This knowledge will have an important impact to other fields of nuclear and high-energy physics. The mapping of GPDs and TMD distributions and the deduction of a three-dimensional image of the nucleon is a major focus of the hadron physics community and constitutes a milestone in the physics program of the Jefferson Laboratory (JLab) 12 GeV upgrade [2].

While GPDs can be probed in hard exclusive processes where the nucleon stays intact and the final state is fully observed, TMD distributions are most successfully measured in semi-inclusive deep-inelastic scattering (SIDIS). In SIDIS experiments, at least one hadron is detected in the final state in addition to the scattered lepton. These experiments are the most

powerful tool for directly obtaining flavour dependent information about the nucleon’s quark structure. In particular, they provide unique access to the elusive strangeness distributions and to the role of the strange quarks in the fragmentation process. Pioneering polarized semi-inclusive DIS experiments have revealed surprising effects in various different kaon production observables, which deviate from the expectations based on u -quark dominance for the scattering off a proton target. Recent experimental (COMPASS, HERMES) and theoretical studies indicate the fragmentation involving strange quarks may have a very different orbital structure, and studies of P_T dependencies of different hadrons in SIDIS will be critical in understanding the dynamics of hadronization process.

These kaon results point to a significant role of sea quarks, and in particular strange quarks. For almost all kaon observables, the deviation from the expected behaviour is most pronounced in the kinematic region around $x_B = 0.1$ (x_B being the Bjorken scaling variable), which is well covered by CLAS12. In order to fully explore the power of SIDIS experiments, pion, kaon and proton separation over the full accessible kinematic range is indispensable.

For exclusive processes, in the handbag approach where the helicity amplitudes depend on hard partonic subprocess and the GPDs, different spin and azimuthal asymmetries of exclusive hadrons can provide a unique possibility to access the elusive chiral-odd GPDs. Identification of kaons will be critical for separation of different exclusive states involving K s and K^* s.

Measurements with kaons in semi-inclusive and hard-exclusive processes will be crucial in understanding the underlying dynamics behind spin-orbit correlations in hard processes and accomplishing the CLAS12 program of studies of the three-dimensional structure of the nucleon.

2 Effects of nuclear matter

Besides the exciting new aspects of nucleon structure, a very interesting pattern of modifications of parton distribution and fragmentation functions in nuclei has been observed in lepton-nucleon scattering, which caused vast experimental and theoretical activities. The understanding of quark propagation in the nuclear medium is essential for the interpretation of high energy proton-nucleus interactions and ultrarelativistic heavy-ion collisions. Lepton production of hadrons has the virtue that the energy and momentum transferred to the hit parton are well determined, as it is “tagged” by the scattered lepton and the nucleus is basically used as a probe at the fermi scale with increasing size or density, thus acting as femtometer-scale detectors of the hadronization process. Theoretical models can therefore be calibrated in nuclear semi-inclusive DIS and then applied, for example, to studies of the Quark-Gluon-Plasma in ultrarelativistic heavy-ion collisions.

The experimental results achieved over the last decade demonstrate the enormous potential of nuclear SIDIS in shedding light on the hadronization mechanisms. For all observables investigated so far, a very distinct pattern of nuclear effects was observed for the various different hadron types. However, the existence and relative importance of the various stages, like the propagation and the interaction of the partons, color-neutralization and formation of the final hadron, are far from being determined unambiguously.

With the unique and well-determined leptonic and hadronic planes of SIDIS the azimuthal

angle between these planes determines the path of the produced hadron. The nuclear modification to the angular modulation of the production rate, as well as transverse momentum broadening of the produced hadrons, provides a sensitive probe to the color and parton density fluctuations inside nucleus, which is very important for understanding the initial condition of relativistic heavy ion collisions.

In this panorama, JLab12 with its high beam intensity and the usage of a large variety of nuclear targets will provide data in a kinematic region that is very suitable for studies of nuclear effects. The potential of performing a fully differential analysis is a key to disentangle the various different stages of hadronization. The capability of identifying pions, kaons and protons over the whole kinematic range of interest will be crucial for gaining more insights into the space-time evolution of the hadronization process.

3 Search for exotic mesons

The phenomenology of hadrons and in particular the study of their spectrum led more than forty years ago to the development of the quark model, where baryons and mesons are described as bound systems of three quarks and of a quark-antiquark pair, respectively. Beyond these experimentally extensively observed states, phenomenological models and lattice QCD calculations suggest also the existence of exotic configurations such as hybrids (qqg), tetraquarks ($qq\bar{q}\bar{q}$) and glueballs. The experimental verification of such exotic states would significantly deepen our knowledge about the dynamics of QCD. A very attractive method to identify exotic mesons is through strangeness-rich final states, where the kaons from the decay of the involved ϕ -meson are usually high energetic. Kaon identification over the whole accessible momentum range would hence provide unique capabilities for the study of strangeonia and the search for exotic mesons.

4 Impact of CLAS12 with a RICH

The exciting physics program for CLAS12, aiming at a detailed investigation of the three-dimensional structure of nucleons, is based on the unique features of the upgraded CEBAF and CLAS12 spectrometer:

- high beam energy and intensity,
- high beam polarization,
- longitudinally and transversely polarized proton and deuterium targets without dilution,
- variety of nuclear targets,
- large acceptance, multipurpose spectrometer.

Measuring the kaon asymmetries is likely to be as important as pions; new preliminary results from the HERMES experiment suggest that the kaon Sivers moments provide strong access

to the orbital angular momentum of the sea quarks. The present capabilities of the present CLAS12 design are weak in this respect and should be strengthened.¹

The addition of a RICH detector would significantly enhance the particle identification capabilities of CLAS12 and make Hall B an ideal place for obtaining flavour separated information about the complex multi-dimensional nucleon structure. The novel TMD distributions and GPDs will be uniquely explored in the valence kinematic region where many new, intriguing aspects of nucleon structure are expected to be most relevant. Furthermore, as pions greatly outnumber the other hadrons at nearly all kinematics, the RICH detector can tremendously reduce the backgrounds for the detection of unstable particles that decay to at least one charged non-pion, hence opening a new window for studying exotic mesons with strangeness contents.

Table 1 lists approved CLAS12 experiments [3] where the RICH detector would provide the potential for new insights into the physics outcome of the planned measurements or is even required for.

The main objectives of the physics program for CLAS12 with a RICH detector are:

- *The role of strangeness:* Exploration of the elusive strange distributions in the nucleon in the valence kinematic region and of signatures for intrinsic strangeness using kaon production in unpolarized and doubly longitudinally polarized deep-inelastic scattering off proton and deuterium targets, as well as exclusive kaon-hyperon and ϕ -meson production.
- *Intricacies of parton intrinsic transverse momentum:* Study of the flavour and kinematic dependence of the intrinsic transverse quark momenta employing fully differential analyses of pion and kaon production in unpolarized deep-inelastic scattering off proton and deuterium targets.
- *Nucleon imaging in transverse momentum space and the role of spin-orbit correlations:* Mapping of the full set of leading and subleading TMD quark distributions via the extraction of spin- and azimuthal asymmetries for pions and kaons from deep-inelastic scattering off unpolarized, transversely and longitudinally polarized proton and deuterium targets.
- *Gluon imaging in coordinate space:* Study of the transverse spatial distribution of 'valence-like' gluons from hard exclusive ϕ -meson production.
- *Effects of nuclear matter:* Investigation of quark propagation through cold nuclear matter via nuclear hadronization and transverse momentum broadening employing pion and kaon production in deep-inelastic scattering off a variety of nuclear targets.
- *Dynamics of QCD and the search for exotic mesons:* Study of exotic meson configurations via the tagging of strangeness-rich final states in quasi-real photoproduction.

¹From PAC30 Report

status	experiment	topic	beam days	rating
A	06-117	Quark propagation and hadron formation	60	A ⁻
A	06-112	Probing the proton's quark dynamics in SIDIS	60	A
A	07-107	Studies of spin-orbit correlations with longitudinally polarized targets	103	A ⁻
A	11-005	Meson spectroscopy with low Q^2 electron scattering	119	A ⁻
C1	11-111	Transverse spin effects in SIDIS with a transversely polarized target	100	A
A	12-007	Exclusive ϕ -meson electroproduction	60	B+
C1	12-009	Measurement of transversity with dihadron production in SIDIS with transversely polarized target	110	A
A	09-007	Studies of partonic distributions using SIDIS production of kaons	110	A ⁻
A	09-008	Studies of the Boer-Mulders asymmetry in kaon electroproduction with H and D targets		A ⁻
A	09-009	Studies of spin-orbit correlations in kaon electroproduction with polarized H and D targets	103	B ⁺

Table 1: Approved CLAS12 experiments [3] which would benefit from the RICH detector (upper part) or even require it (lower part).

Part II

The RICH Detector

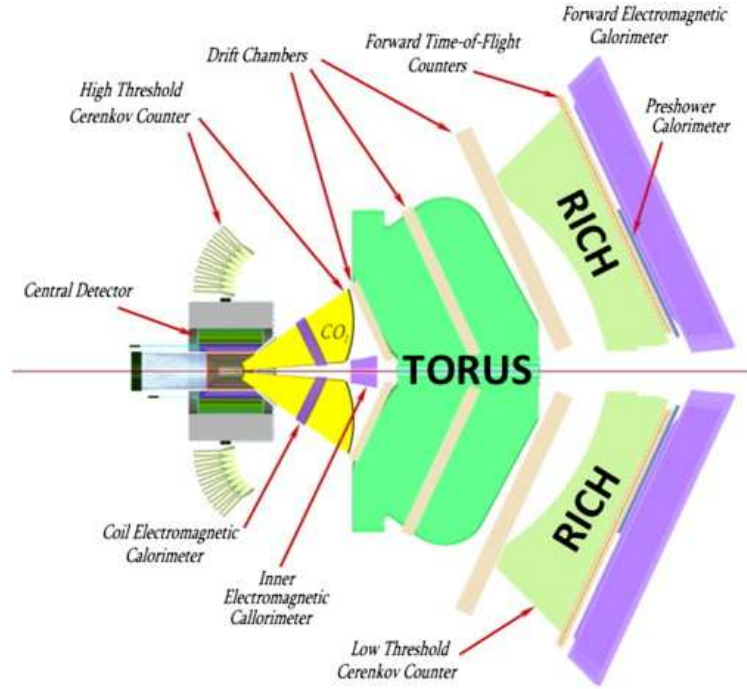


Figure 1: Schematic view of the CLAS12 spectrometer

5 General layout of the RICH detector

5.1 The CLAS12 spectrometer

The CLAS12 spectrometer in Hall B [2] is designed to operate at a luminosity of $10^{35} \text{ cm}^{-2} \text{ s}^{-1}$, an order of magnitude higher than the CLAS at 6 GeV, and with highly polarized beam and nucleon targets. The detector, shown in Fig. 1 consists of two parts, a Forward Detector (FD) and a Central Detector (CD).

The CD, with the high-field (5 T) solenoidal magnet, is used to detect particles at large angles. It has a barrel tracker, a TOF system for charged particle identifications and a neutron detector. The solenoidal field will also be used to shield the FD from the Moller background.

The FD detects charged and neutral particles in the polar angle range between 5° and 40° . It is based on the 2T superconducting toroidal magnet and retains the same six-sector structure of the CLAS spectrometer. It includes a tracking system made of a vertex tracker and three regions of Drift Chambers, the second of which inside the toroidal field, two gas Cherenkov detectors (High-Threshold Cherenkov Counter, HTCC, and Low-Threshold Cherenkov Counter, LTCC) for electron/pion separation, a Time-Of-Flight (FTOF) system for hadron identification and an electromagnetic calorimeter to help in electron identification and to detect neutral particles.

The CLAS12 targets will be located inside the CD. There will be unpolarized as well as longitudinally or transversely polarized targets.

5.2 Particle ID requirements for SIDIS kaons

The production rate of protons, kaons and pions has been studied using a high statistics (see table 2) MC event-lists² with torus field polarity outbending for negative particles. These event-lists, generated with CLASDIS, were subject to the standard DIS cuts ($Q^2 > 1\text{GeV}^2$, $W^2 > 4\text{GeV}^2$, $0.1 < y < 0.85$, and $z > 0.3$) and filtered through the CLAS12 acceptance using the GEMC simulation. The hadron yields within the CLAS12 forward detector acceptance are shown in a 2D binning in momentum and polar angle in Fig. 2.

π^+	$1.7 \cdot 10^9$	π^-	$1.2 \cdot 10^9$
K^+	$106 \cdot 10^6$	K^-	$52 \cdot 10^6$
p	$816 \cdot 10^6$	$\bar{p}$	$6.4 \cdot 10^6$

Table 2: Number of CLASDIS generated tracks (in 4π) for each hadron type.

In most of the kinematic plane, the kaon rate is about one order of magnitude lower than the rate of pions and protons. Thus, a successfully kaon ID requires a rejection factor from pions around 1:500, i.e. a contamination in the kaon sample of few percent. This corresponds to 4σ separation.

The high momentum region (above 6 GeV/c, i.e. $z \rightarrow 1$) is important to study the transition from the hard semi-inclusive to the exclusive regime. The intermediate momentum ($4 < P < 6\text{GeV}/c$) and angle ($15^\circ < \theta < 25^\circ$) region is in turn important to reach the highest values of the hadron transverse momentum. Therefore, CLAS12 must provide the best PID performances in these two regions.

²it has been produced for the proposal C12-11-111 and corresponds to 80 days of continuous CLAS12 running at a nominal luminosity of $5 \cdot 10^{33} \text{cm}^{-2} \text{s}^{-1}$

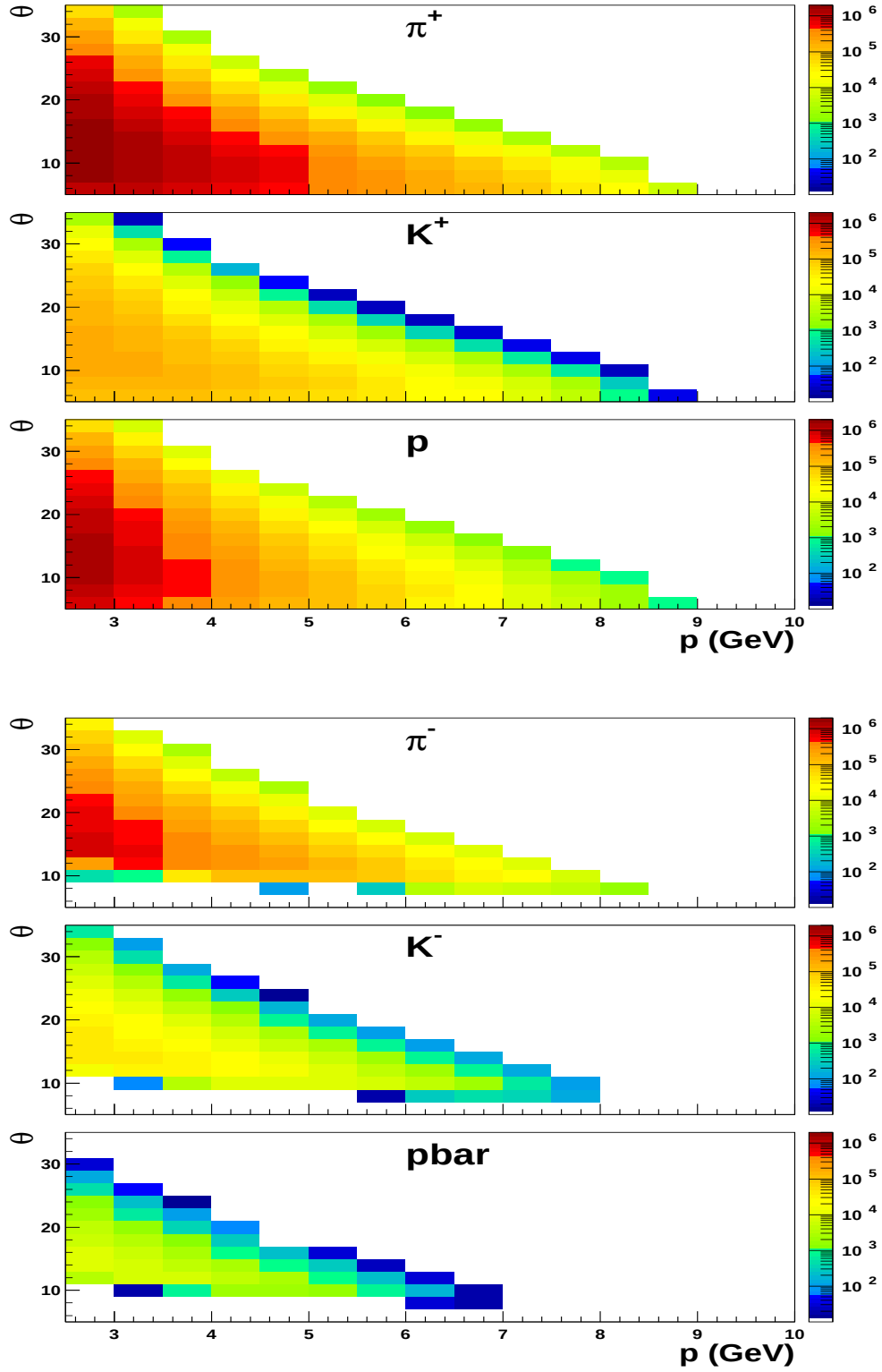


Figure 2: Hadron yields within acceptance in a 2dim binning in p (2.5–10 GeV) and θ (5–35 degrees).

5.3 Particle ID with CLAS12

Particle identification for hadrons in the FD is obtained by combining the information of HTCC, LTCC and FTOF. As will be shown in the next sections, no sufficient separation of kaons from pions can be achieved by using only these detectors in the momentum range relevant for SIDIS reactions. However, they may give relevant contributions in specific kinematic regions and should be included in the general CLAS12 particle ID software. More details on this point will be given in Sect. 13.3.

5.3.1 Time-of-Flight

The FTOF system is composed by two panels of plastic scintillators, the Panel-1a with 15 cm wide bars and the Panel-1b with 6 cm wide bars. Combining the two panels, the time resolution ranges between 45 and 80 ps, depending on the polar angle of the particle. The distance between the target and the FTOF system is about 650 cm and the expected time difference between different particles is shown in Fig. 3. At forward angle ($\theta = 5^\circ$), a 4σ separation between kaons and pions requires a time difference $\Delta T(\pi K) = 180$ ps, which may be reached up to about 3.6 GeV/c momentum. At larger angles ($\theta = 36^\circ$), a 4σ separation corresponds to a $\Delta T(\pi K) = 320$ ps, achievable up to 2.8 GeV/c momentum. We conclude then that the FTOF will provide the required kaon to pion separation up to momenta of about 3 GeV/c.

5.3.2 High Threshold Cherenkov Counter

The HTCC is a detector designed to separate electrons from pions with high efficiency and hermeticity. It is composed by a CO_2 radiator and PMTs with quartz window. The expected number of photoelectrons for electrons is about $n_{pe} = 16.5$, with small dependence on θ and no ϕ dependence. Kaons and protons are always below threshold and cannot be detected. For pions, the number of p.e. goes from 0 at the threshold of about $P = 5$ GeV/c up to 12 at $P = 10$ GeV/c. Pion inefficiency may be estimated by calculating Poisson fluctuations on the number of p.e.. For example, with a minimum number of p.e. $n_{pe} = 3$, a 3σ pion to kaon separation may be obtained only above $P = 7.8$ GeV/c, as shown in Fig.4. A 4σ separation may be obtained only in the extreme region of the kaon momentum distribution.

5.3.3 Low Threshold Cherenkov Counter

The LTCC is basically the same already used in CLAS. It is made by a C_4F_{10} gas radiator with pion threshold at $P = 2.7$ GeV/c and a number of p.e. about a factor of two smaller than the HTCC. Kaons are below threshold for momenta up to about 9 GeV/c. Moreover, it has limited acceptance in ϕ and irregular acceptance, and for this reason in CLAS it has been used for particle ID only after careful determination of fiducial regions. As done for the HTCC, the LTCC pion inefficiency is shown in Fig. 5 as a function of the momentum. A 3σ separation may be achieved above $P = 7.7$ GeV/c only with a minimum cut $n_{pe} = 2$. Such low cut however may lead to incorrect identification due to possible background hits. The required 4σ cannot be obtained over the whole kaon momentum range.

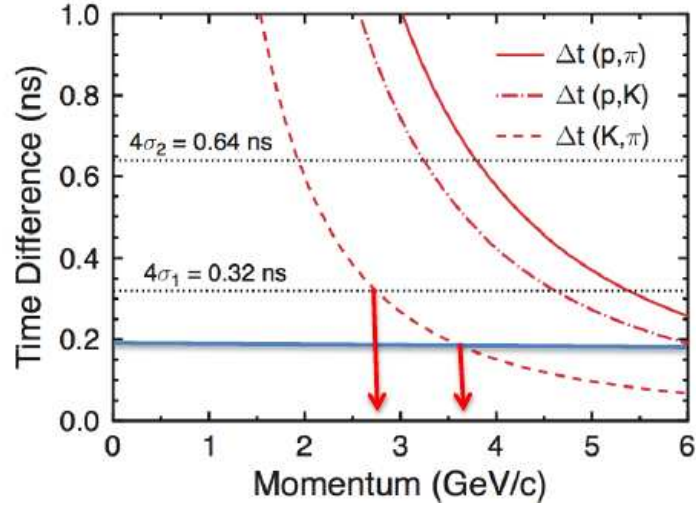


Figure 3: Time difference between various particles as a function of the momentum as measured by the FTOF. The horizontal blue line indicate the required 4σ separation in the forward, while the line marked at 0.32 ns indicates the same cut for the large angle regions.

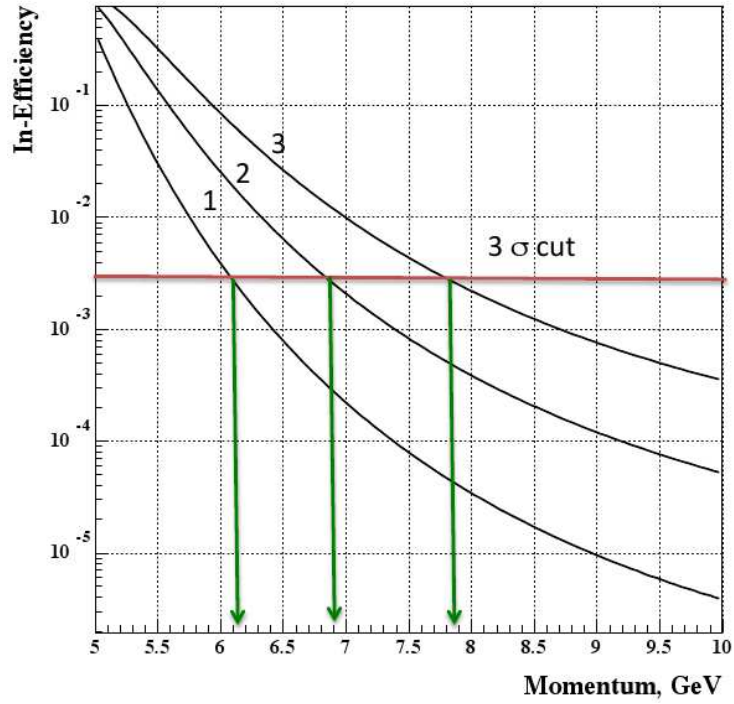


Figure 4: Pion detection inefficiency in the HTCC for minimum $n_{pe} = 1, 2, 3$ as a function of the momentum. The horizontal line indicate the 3σ separation.

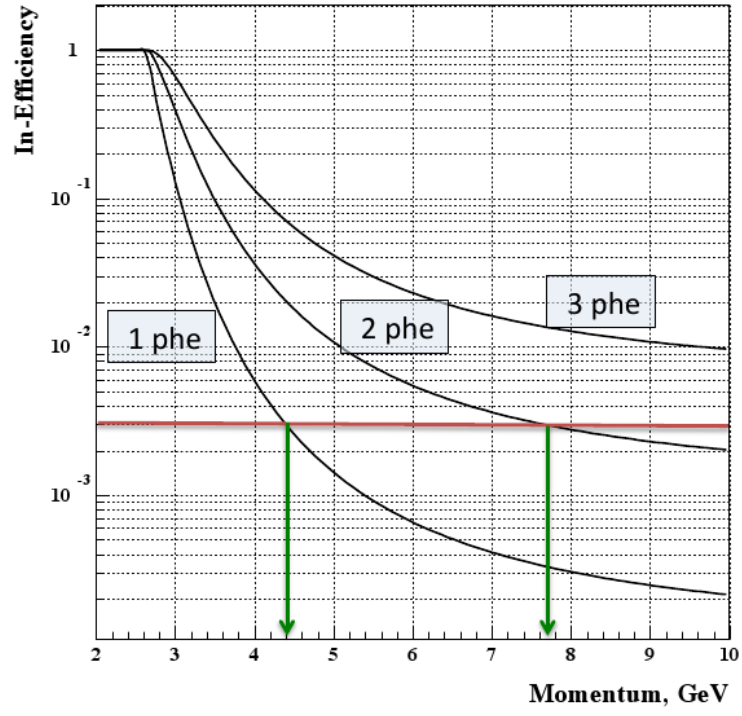


Figure 5: Pion detection inefficiency in the LTCC for minimum $n_{pe} = 1, 2, 3$ as a function of the momentum. The horizontal line indicate the 3σ separation.

5.4 The RICH detector for CLAS12

As discussed in the previous section, CLAS12 can't provide adequate kaon identification in the momentum range between 3 and 8 GeV/c. Improved particle identification and event reconstruction can be achieved in this momentum range by replacing at least one sector of the existing LTCC with a RICH detector. The idea of a RICH detector is schematically shown in Fig. 6. When a fast particle cross a radiator with a velocity β larger than the velocity of the light, it emits Cherenkov photons in a cone with opening angle θ_C given by

$$\cos(\theta_C) = \frac{1}{\beta n(\lambda)} \quad (1)$$

where $n(\lambda)$ is the refractive index of the radiator, which may depend on the wavelength λ . The number of Cherenkov photons emitted per radiator thickness unit L and at a given wavelength is

$$\frac{d^2 N}{dL d\lambda} = \left(\frac{2\pi\alpha Z^2}{\lambda^2} \right) \sin^2(\theta_C) \quad (2)$$

After a gap region where the cone opens up, the photons are detected and the ring can be reconstructed. A precision measurement of the Cherenkov angle provides the velocity of the particle and, together with information from the tracking system, it allows the identification of the particle. Thus, the capability of identify particles with a known momentum and different velocity is governed by the Cherenkov angle resolution σ_θ , as shown in Fig. 7. It can be effectively parametrized by the separation in units of resolution n_σ between the angle distributions for the various particles. Contamination due to misidentification and detection efficiency can be estimated once n_σ and the relative yields are known.

Several RICH detectors have been used in different experiments and in various configurations. For example, the one adopted in Hall-A [4] uses a freon (C5F12 or C6F14) radiator and a CsI-deposited multi-wire proportional chamber as a UV-photon detector. However, it does not achieve the required pion rejection factor at momenta greater than 3 GeV/c. As shown in Fig. 8, any gas or liquid radiator doesn't provide sufficient angular separation in the necessary momentum range. Thus, the CLAS12 momentum range imposes the use of aerogel as the unique available solution. In addition, with respect to the use of freon in the UV region, such a solution offers a lower chromatic error and a higher quantum efficiency in the detection of photons in the visible wavelength spectrum.

Different solutions for the photodetectors have been considered. For example, matrices of SiPM are compact and robust devices and can in principle better cope with the fringe fields of the torus magnet. The developments in their production technique has recently shown, and is expected to continue in the next years, fast progresses in the suppression of background dark-counts (per surface unit) and a cost reduction towards values lower than for standard photomultipliers. Very promising are also the Large-Area Pico-second Photo Detectors (LAPPD), based on the Micro-Channel Plate photomultipliers. Combining integrated advances in material sciences and electronics, this innovative technology aims at the production of large scale photodetectors with high spatial and time resolutions at low costs.

Although promising, these two options don't guarantee at present the adequate performance and reliability, thus the only affordable solution for photodetectors are the Multi-

Anode PhotoMultipliers Tubes (MAPMTs). They have high quantum efficiency in the visible and near UV region, give a fast response and provide the necessary spatial resolution. Among different types of MAPMTs, the Hamamatsu H8500 are the best choice in terms of costs and performances.

There are many constraints imposed by other detectors already in the construction phase. To fit into the CLAS12 geometry, the RICH should have a six-sector projective geometry that occupies the space between the torus cryostats and covers the scattering angles from 5° to 30° . In one sector, the available space for the RICH is basically the same as for one LTCC sector. The external frame has a trapezoidal shape, with a major base of about 4.3 meters, a height of about 3.8 meters and a depth of about 1 meter and it is tilted by 65° with respect to the vertical. A view of one RICH sector within the CLAS12 spectrometer is shown in Fig. 9.

Being placed before the TOF and calorimeter, the RICH is also subject to material budget limitations. The LTCC has a total thickness of $0.032X_0$, while the FTOF scintillator bars have a thickness of $0.12X_0$ and the preshower calorimeter a total thickness of $5X_0$. We will take these numbers as a reference, however one should take in mind that, as will be discussed in the following, most of the RICH material budget will be constituted by the photodetectors, that will be located at small polar angles, where the particles have on average higher momentum.

The detector will be located outside of the torus magnetic field, however residual small field can be present at the RICH position. Extrapolating the existing field map calculations, one obtain the residual field values shown in Fig. 10. The field is basically negligible close to the beam line and increases with the polar angle, reaching a value of about 3 gauss at 13° , the expected maximum angle covered by the RICH photodetectors.

In order to reduce the area to be covered with photon detectors from several squared meters to about 1 m^2 , and thus to decrease the cost, a hybrid solution has been developed [5], as shown in Fig. 11. For forward scattered particles ($\theta < 13^\circ$) with momenta $p = 3 - 8\text{ GeV}/c$ a proximity imaging method will be used, where the Cherenkov cone is imaged directly. For larger incident particle angles of $13^\circ < \theta < 35^\circ$ and intermediate momenta of $p = 3 - 6\text{ GeV}/c$ the Cherenkov light will be focussed by a spherical mirror, followed by two further passes through the radiator material and a reflection from planar mirrors before detection. The Cherenkov light will be produced from a thicker amount of aerogel material than it will be reflected through, to compensate yield losses whilst obtaining a focalised ring. For momenta below $2.8\text{ GeV}/c$ the TOF system will provide the required π/K identification for polar angles up to 40° . At high momentum, the HTCC provides good identification for pions. Rough kinematic coverage of the different detections are shown in Fig. 12.

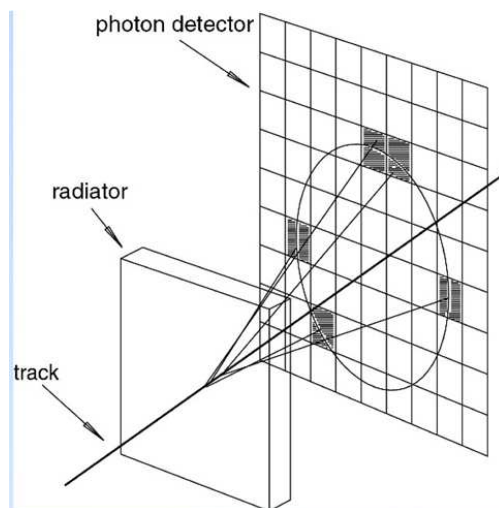


Figure 6: Schematic view of a RICH detector.

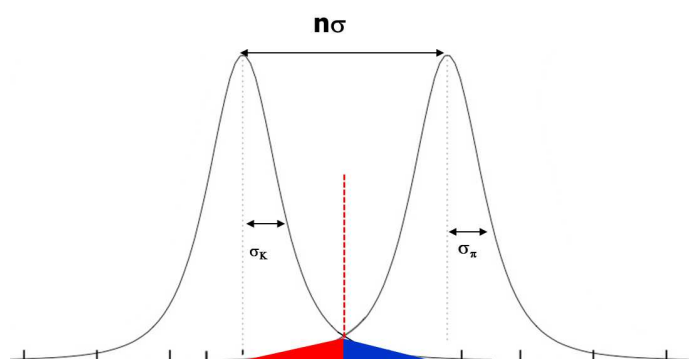


Figure 7: Pion to kaon separation in the RICH: the red triangle indicate the pion contamination while the blue one the kaon loss.

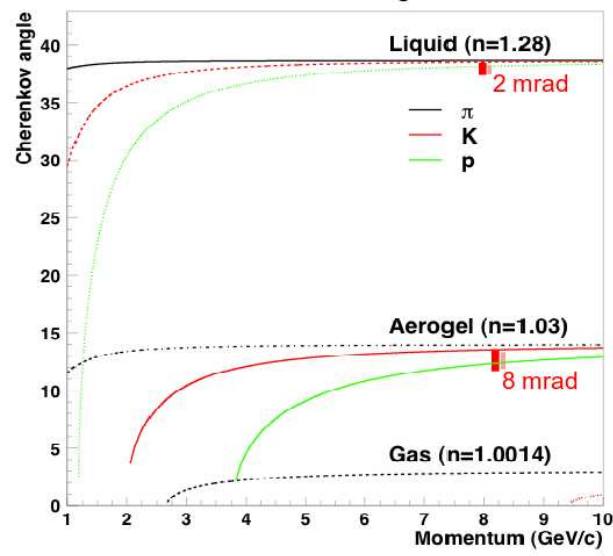


Figure 8: Cherenkov light opening angle as a function of the momentum for different particles using liquid, gas or aerogel radiator. Also indicated are the angular separations between pion and kaon rings at the highest momentum in CLAS12.

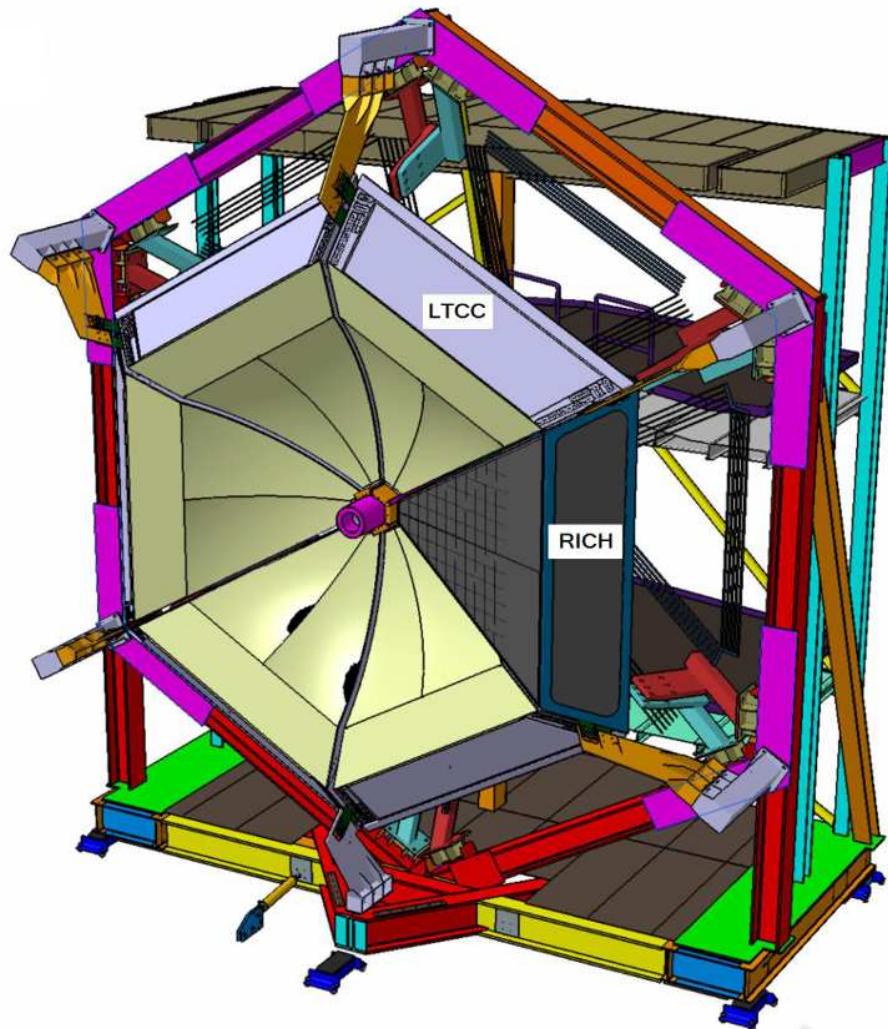


Figure 9: Pictorial view of the CLAS12 setup with one RICH module replacing one of the LTCC modules.

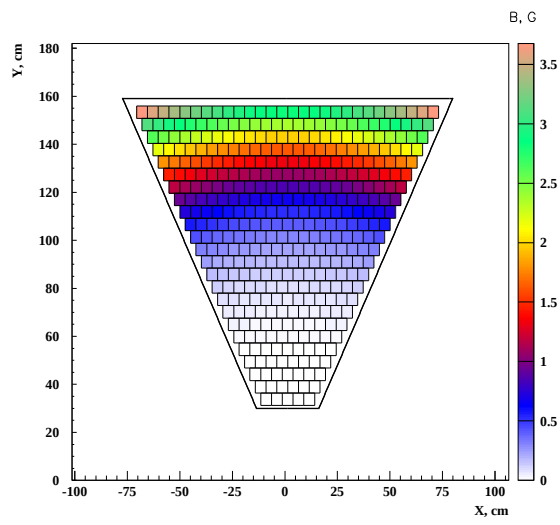


Figure 10: Residual toroidal magnetic field, indicated by the vertical color scale, in the region covered by the RICH photodetectors.

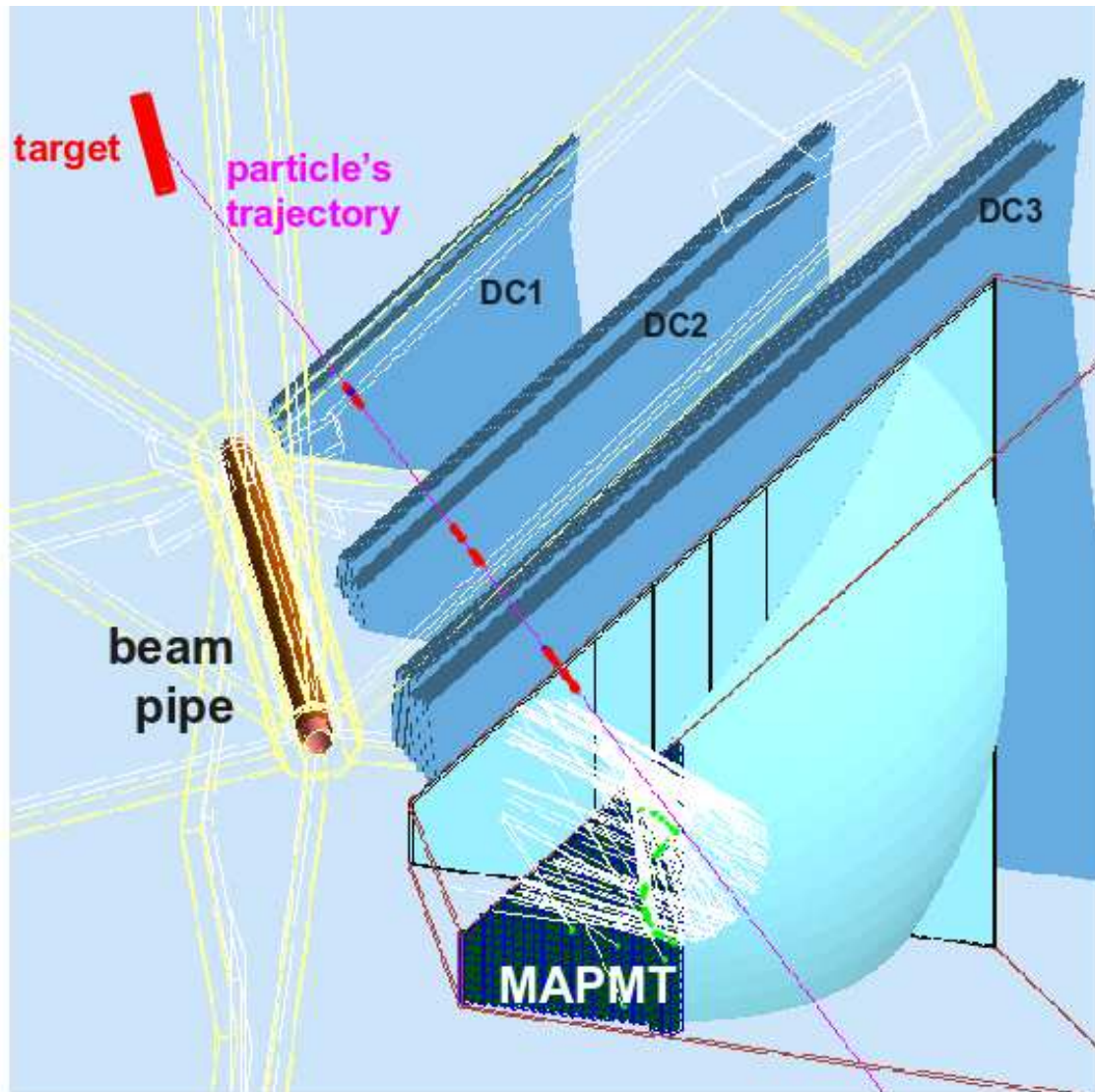


Figure 11: Layout of one sector of the RICH detector, placed just after the third region of Drift Chambers (DC3).

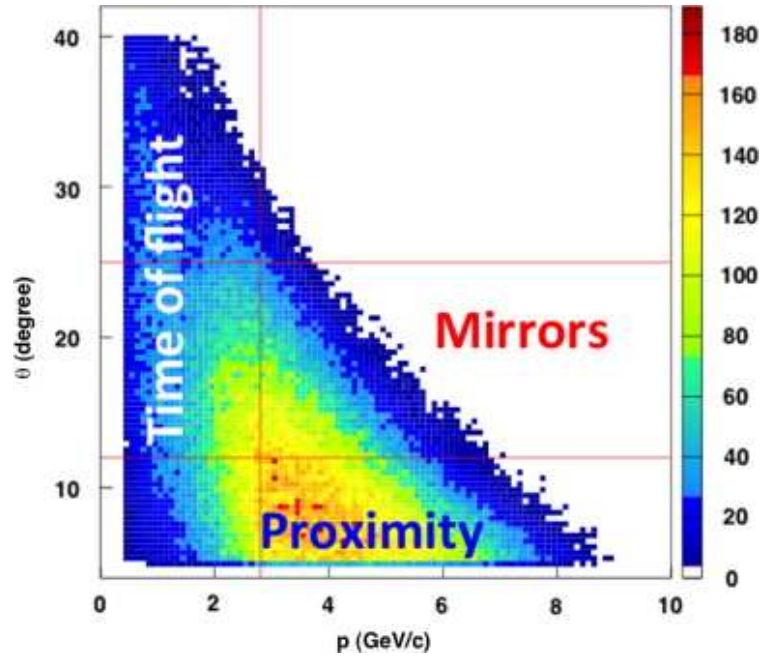


Figure 12: Scattering angle versus momentum of the hadrons in the CLAS12 forward spectrometer. The TOF counters cover the low momentum region, a proximity focusing RICH is suitable for the high-momentum region at forward scattering angles, while at intermediate momenta and large scattering angles a mirror system could be the most effective option. The boundaries in scattering angle are arbitrarily defined by the two horizontal lines just for illustration.

6 The Cherenkov radiator

Silica aerogel is an amorphous solid network of SiO_2 nanocrystals with an extremely low macroscopic density. It is used since decades in threshold Cherenkov counters for high energy physics. More recently, aerogel has been used as radiator material for Ring Imaging Cherenkov (RICH) detectors in several particle physics experiments (HERMES, LHCb, AMS, BELLE, etc). See e.g. [9] and references therein.

The optical properties of aerogel represent a crucial point for the performances of RICH detectors. For instance, any angular dispersion of the emitted photons affects the precision of the Cherenkov angle measurements. In addition, a high transparency (Transmittance) and a proper refractive index are required in order to collect a sufficient number of photons for a reliable ring reconstruction. For these reasons, a systematic characterization of the main optical properties has been carried out in laboratory on a variety of different aerogel samples.

6.1 Optical properties and basic formalism

One of the main properties of aerogel radiators for RICH detectors is the chromatic dispersion, i.e. the dependence of their refractive index on the incident light wavelength. This effect has been estimated to be among the largest contributions to the uncertainty on the Cherenkov angle.

In order to study the chromatic dispersion, one needs precise measurements of the aerogel refractive index. The *prism method* [11, 12], illustrated in Fig. 13, allows to measure the refractive index through the Snell-Descartes formula

$$\delta = \alpha - \beta + \arcsin \left(n \sin \left[\beta - \arcsin \left(\frac{\sin \alpha}{n} \right) \right] \right) , \quad (3)$$

which relates the angular displacement δ of the scattered photons with the refractive index n through the incident angle α and the fixed angle β .

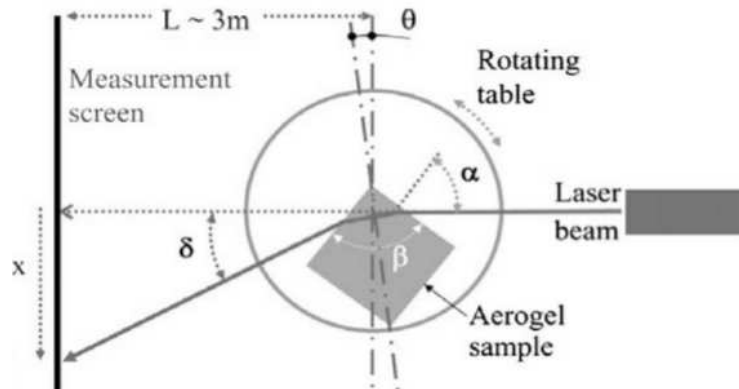


Figure 13: The prism method to measure the refractive index (source [11]).

A complementary approach is provided by the *gradient method* [11]. This method consists in mapping the refractive index transverse gradient over the whole tile by measuring the deviation of a laser beam incident normally to its surface in different positions. The gradient map allows in turn to map the refractive index averaged over the tile thickness.

The dependence of n on the wavelength λ can be studied by using light sources of different wavelength (e.g. lasers) and fitting the data with the *dispersion relation* (see e.g. [12]):

$$n^2(\lambda) - 1 = \frac{P_1 \lambda^2}{\lambda^2 - P_2^2} , \quad (4)$$

where P_1 and P_2 are free parameters (Section 6.3).

The combined effects of scattering, reflection and absorption of photons in a material are usually described in terms of: 1) *transmittance* T , which accounts for the residual light transmitted in the forward direction; 2) *transflectance* T_F , the fraction of light emerging in all directions from the sample; 3) *reflectance* R , the fraction of light emerging in backward direction. For a sample of thickness t (in cm), the transmittance can be expressed as

$$T = e^{-t(\frac{1}{\Lambda_A} + \frac{1}{\Lambda_S})} = T_F e^{-t/\Lambda_S} , \quad (5)$$

where Λ_A is the *absorption length*, Λ_S is the *scattering length* and $T_F = e^{-t/\Lambda_A}$.

The transmission in aerogel is usually parametrized through the Hunt formula (see, e.g., [10])

$$T = A e^{-Ct/\lambda^4} \quad (6)$$

which assumes that the absorption, parametrized by $A = T_F$, is independent from the wavelength λ and that the Rayleigh scattering has a λ^{-4} dependence. The *clarity* coefficient C is proportional to the radiation scattered per unit of sample length, and is usually measured in μ^4/cm . Tiles with a good optical quality have values for A and C close to 1 and 0, respectively. Absorption length and scattering length (in cm) are related to A and C through:

$$\Lambda_{abs} = -t/\ln A \quad \Lambda_{sc} = \lambda^4/C . \quad (7)$$

These quantities can be extracted from transmittance measurements operated with a spectrophotometer (Section 6.4).

6.2 Aerogel samples

At present, aerogel tiles of large size and with optical properties suitable for the CLAS12 RICH are produced only by two Russian groups in Novosibirsk [6]. Samples of different refractive index, thickness and size, produced in different periods, have been characterized by means of a spectrophotometer and tested in dedicated test-beams (CERN, INFN-LNF). For comparison, several aerogel samples produced in Japan by Matsushita-Panasonic [7], with refractive index $n = 1.03$ and $n = 1.05$, were also tested. The one with $n = 1.03$ was successfully used in the Hermes RICH [10]. Recently, several aerogel samples produced by the US Aspen company [8], with refractive index $n = 1.01$ and $n = 1.05$, were also tested. The complete list of the tested samples is reported in Table 3.

Table 3: Aerogel tiles tested

Manufacturer	Production	n	thickness (cm)	area (cm $\times$ cm)	Number of tiles
Matsushita (Japan)	< 2012	1.03	1.0	10 $\times$ 10	3
Matsushita	< 2012	1.05	1.0	10 $\times$ 10	3
Novosibirsk (Russia)	Jun 2012	1.04	2.0	6 $\times$ 6	4
Novosibirsk	Jun 2012	1.05	2.0	6 $\times$ 6	4
Novosibirsk	Jun 2012	1.06	2.0	6 $\times$ 6	4
Novosibirsk	Jun 2012	1.05	3.0	6 $\times$ 6	4
Novosibirsk	Jun 2012	1.06	3.0	6 $\times$ 6	4
Novosibirsk	Jun 2012	1.05	2.0	10 $\times$ 10	8
Novosibirsk	Dec 2012	1.05	2.0	10 $\times$ 10	5
Novosibirsk	Dec 2012	1.05	2.0	6 $\times$ 6	4
Novosibirsk	< 2012	1.05	3.0	10 $\times$ 10	4
Novosibirsk	Feb 2102	1.05	1.0	10 $\times$ 10	1
Novosibirsk	Feb 2012	1.05	2.0	10 $\times$ 10	1
Novosibirsk	Feb 2012	1.05	3.0	10 $\times$ 10	1
Aspen (USA)	Nov 2012	1.05	1.7	9.5 $\times$ 9.5	2
Aspen	Nov 2012	1.05	1.7	6.5 $\times$ 6.5	1
Aspen	Nov 2012	1.01	1.7	6.5 $\times$ 6.5	1

6.3 Refractive index and chromatic dispersion measurements

The refractive index of Novosibirsk tiles has been measured with the prism method (Section 6.1) using the setup sketched in Fig. 13. Originally, the measurement was carried out using three lasers of different wavelength: $\lambda=632.8$ nm (red), $\lambda=532$ nm (green), $\lambda=405$ nm (blue). The use of lasers has the advantage of high-intensity and narrow beams, producing relatively intense and well defined spots on the screen. However, this approach resulted in a poorly constrained dispersion law (based on only three points). More recently, similar measurements were performed using the beam extracted from a spectrophotometer (Fig. 14). The setup (Fig. 15) includes a couple of focusing lenses and a CCD camera.



Figure 14: The Lambda 650 S PerkinElmer spectrophotometer used for the aerogel characterization.

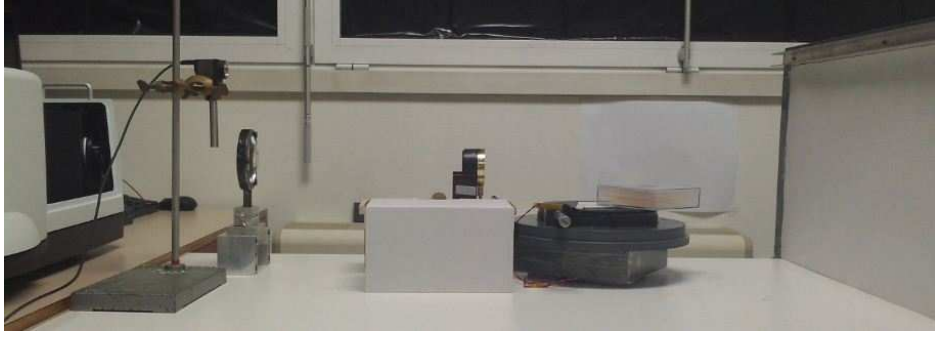


Figure 15: Setup for the prism method using the spectrophotometer beam. From left to right: spectrophotometer, CCD camera, two focusing lenses, aerogel tile on a rotating stage and screen.

With this technique one can in principle measure the refractive index at any wavelength in the range 450 – 650 nm (outside this range the intensity of the spots on the screen is too low), thus constraining the dispersion law with a greater number of points. A test of the method was successfully carried out doing measurements at five different wavelengths: 450nm, 500nm, 550nm, 600nm, 650nm. The measured displacements and the fits based on the Snell-Descartes law are shown in Fig. 16.

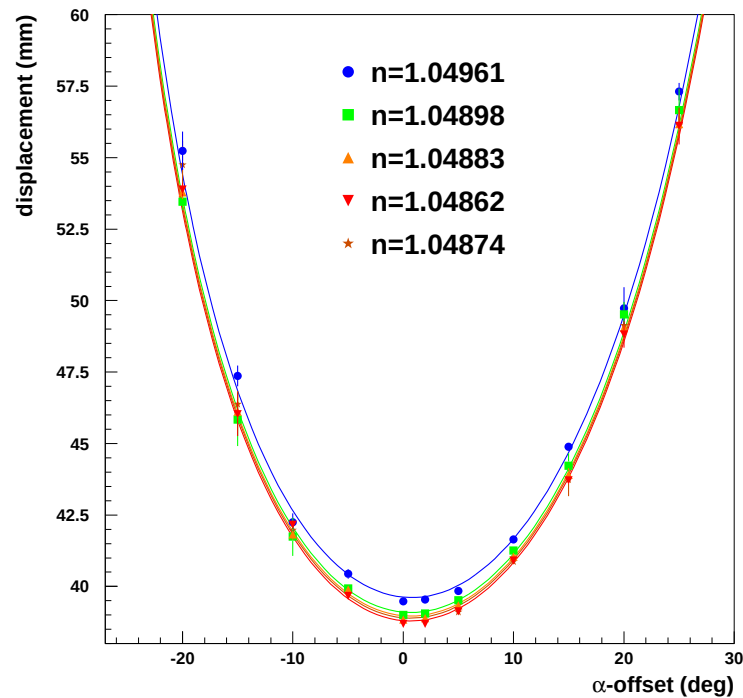


Figure 16: Displacements for the five wavelengths (spectrophotometer beam) as a function of the incident angle α for a Novosibirsk aerogel tile with $n = 1.05$.

The extracted refractive indices are reported in Fig. 17 as a function of the incident wavelength (chromatic dispersion). The points were fitted (black curve) with the dispersion relation (eq. 4). The figure also shows a model for the chromatic dispersion (red curve) based on the formalism described in [13], in which the λ -dependence of n is derived as a combination of those of air ($n_{air}(\lambda)$) and quartz ($n_{SiO_2}(\lambda)$), the main components of aerogel, which are well known in the λ -range investigated here. The model, normalized to the fit curve at 400 nm, is consistent with data within the uncertainties, but exhibits a slightly weaker dispersion.

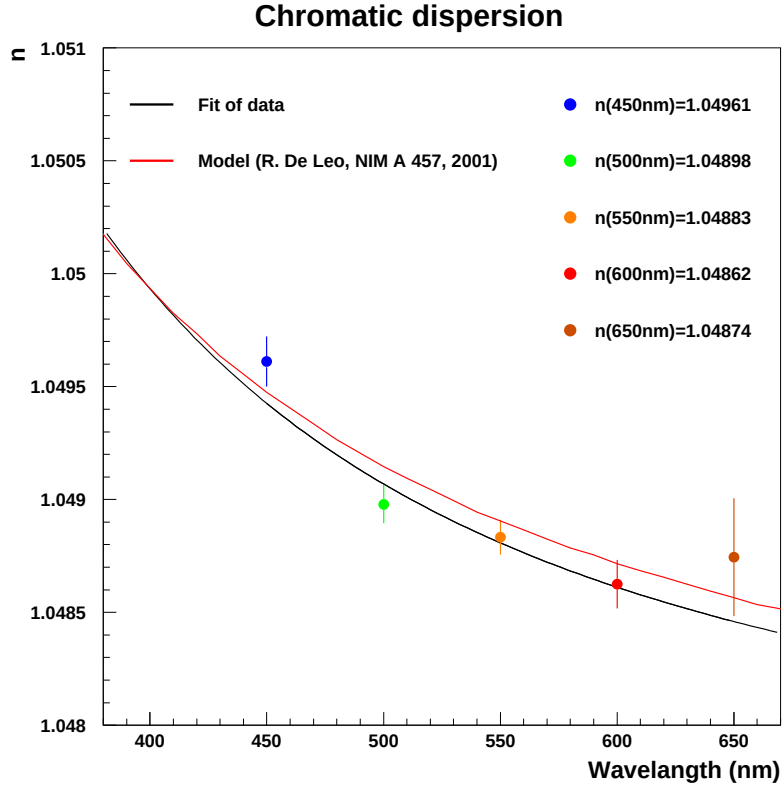


Figure 17: Chromatic dispersion measured for a Novosibirsk aerogel tile with $n = 1.05$ using the beam extracted from the spectrophotometer at five wavelengths. Also shown is a model (red line) based on the formalism described in [13] normalized to the fit curve at 400 nm.

The prism method allows to determine the refractive index only in the proximity of the tile edges. However, due to local inhomogeneities, the refractive index can change significantly (variations up to $\delta n \approx 10^{-3}$) throughout the tile. The gradient method [11] allows virtually to map the refractive index over the whole tile. The method is based on the idea that, in the presence of a local transverse gradient of n , a laser beam impinging normally to the tile surface is deflected by a continuous refraction effect. The deflections of the laser beam observed in different points of the tile can then be related to local transverse gradients of refractive index. Figure 18 (Left) shows an example of gradient map, measured at 8 mm

steps over a wide portion of a large-area Novosibirsk tile. Figure 18 (Right) shows the corresponding refractive index map averaged over the tile thickness. Since, in principle, the thickness of the tile is not uniform (variations of the order of 0.3-0.5 mm are expected), the latter map needs to be corrected for these thicknesses variations.

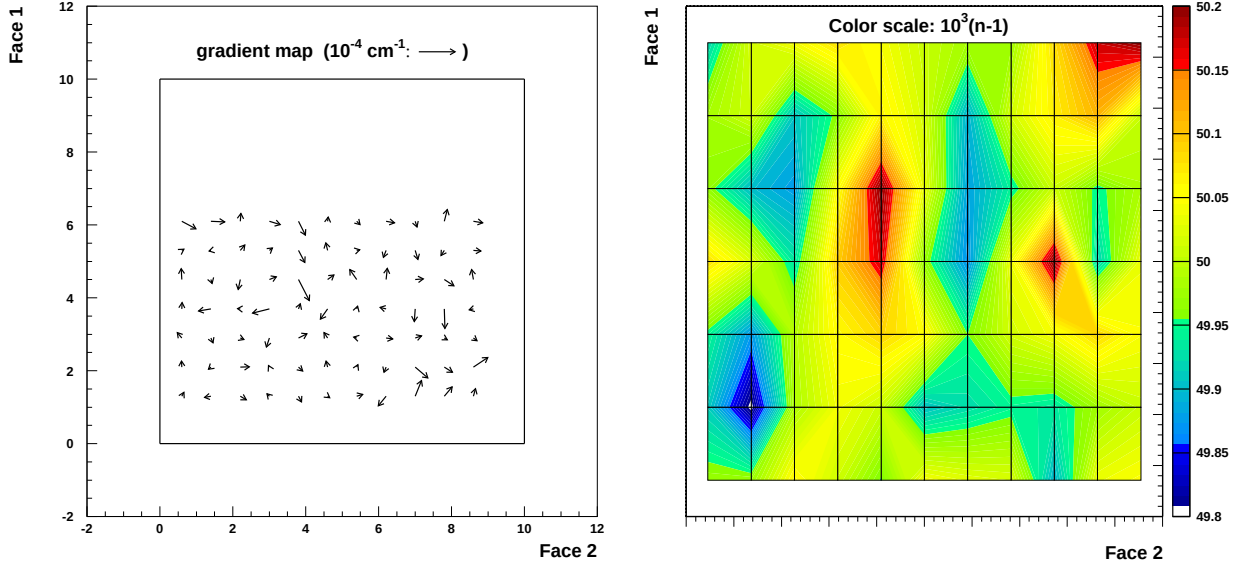


Figure 18: Left: Refractive index gradient map for a large area Novosibirsk tile. Right: Refractive index map corresponding to the measured area (not corrected for thicknesses inhomogeneities).

6.4 Transmittance measurements

Precise measurements of the aerogel transmittance as a function of the light wavelength are being performed using the spectrophotometer (Fig. 14). A systematic characterization of all the aerogel samples listed in Table 3 has been carried out.

In Figure 19 the measured transmittance is reported as a function of the wavelength for one Matsushita (red points) and two Novosibirsk (black and blue points) tiles, all with $n = 1.05$ but with different thicknesses (1cm, 2cm and 3cm, respectively). We see that at $\lambda = 400\text{nm}$, the reference wavelength for the CLAS12 RICH, the 2cm Novosibirsk tile exhibits about the same transmittance of the 1cm Matsushita one. From these measurements we can conclude that the optical quality of the Novosibirsk aerogel is superior to the Matsushita one (used in the Hermes RICH).

Recently, the Aspen Company has also started the production of aerogel tiles for RICH detectors. In Fig. 20, the transmittance and the scattering length measured for one tile with $n = 1.01$ (blue circles) and for three tiles with $n = 1.05$ (green, red and yellow circles) are reported as a function of the wavelength. For comparison the measurements of a Novosibirsk tile (black circles) are also shown.

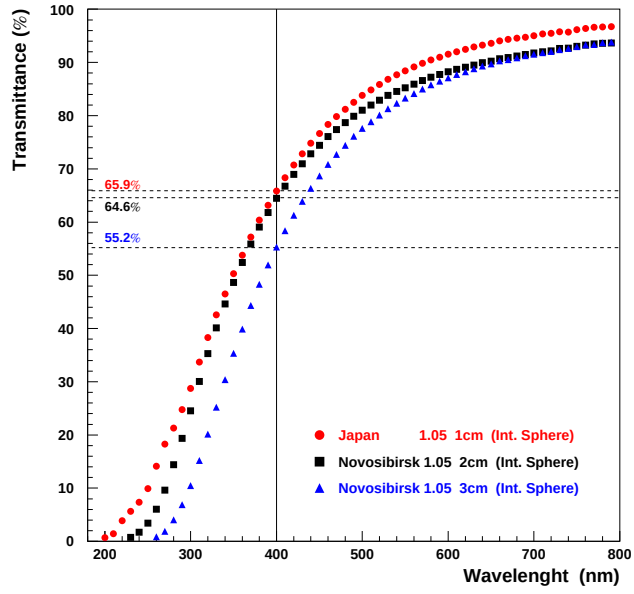


Figure 19: Comparison of the transmittance measured as a function of the wavelength for a 1cm Matsushita tile (red) and a 2cm and 3cm Novosibirsk tiles (black and blue). All tiles have nominal refractive index $n = 1.05$.

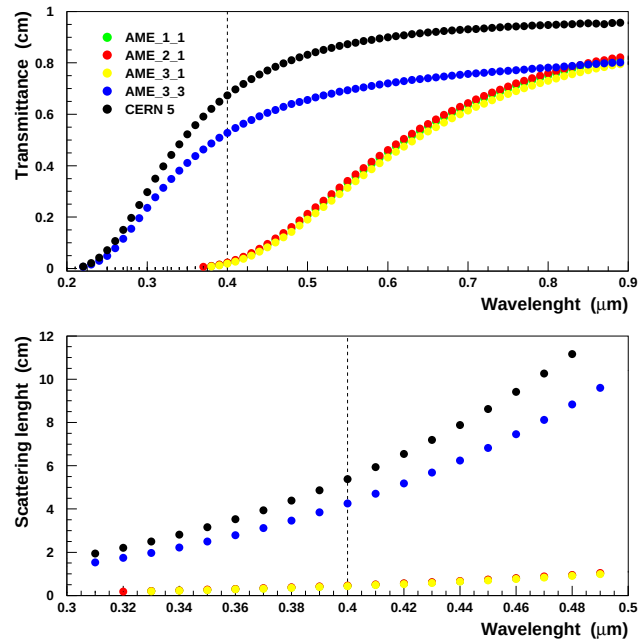


Figure 20: Transmittance and scattering length of the $n = 1.01$ (blue) and $n = 1.05$ (green, red and yellow) Aspen tiles compared with a $n = 1.05$ Novosibirsk tile (black).

The only Aspen tile with reasonable performances is the $n = 1.01$ one, though still considerably below the performances of the Novosibirsk one. Therefore, at the moment, the Novosibirsk aerogel represents the best choice for the CLAS12 RICH.

Fitting the measured transmittance with the Hunt formula (eq. 6) and using eqs. 7 one can extract the transreflectance and the absorption and scattering lengths. In Fig. 21, the measured transmittance (top left) and the extracted transreflectance (top right), absorption length (bottom left) and scattering length (bottom right) are shown as a function of the wavelength for eight $n = 1.05$ Novosibirsk tiles. Basically no differences in the scattering length have been found, while, apart from one tile, the absorption length maximal variations are of the order of 25%.

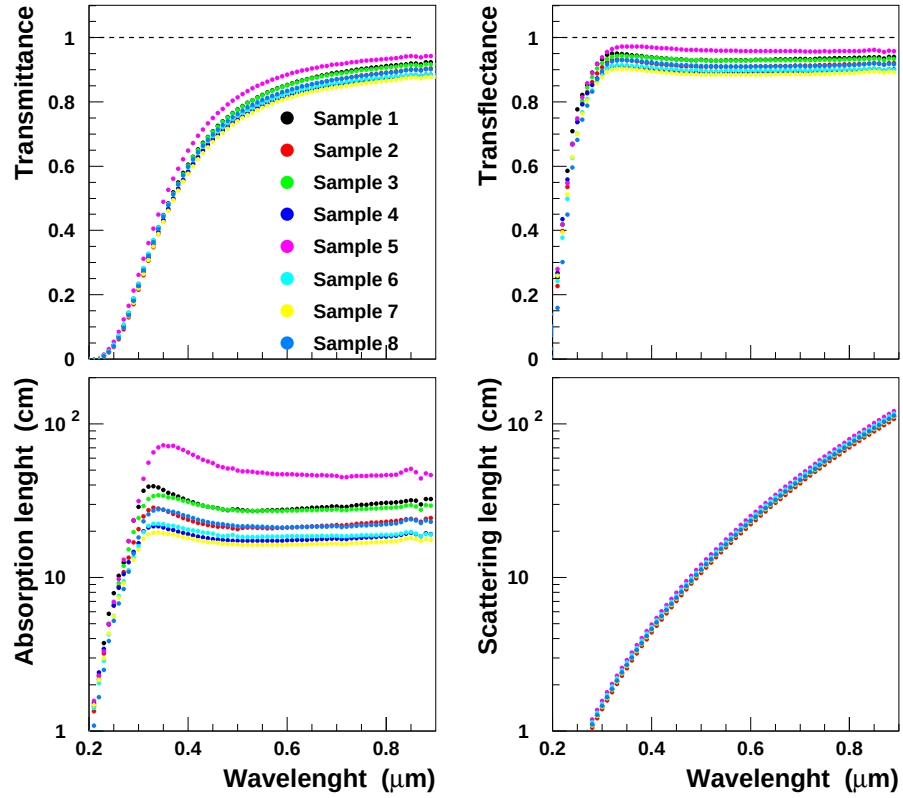


Figure 21: Comparison of the transmittance, transreflectance, absorption and scattering lengths as a function of the wavelength for eight 2cm thick $n = 1.05$ Novosibirsk tiles.

The uniformity of the optical quality has been also checked by performing measurements in different points on the surface of each tile. In Fig. 22 we compare the transmittance and the scattering and absorption lengths measured at $\lambda = 400\text{nm}$ in six different spots indicated by the different symbols. Small deviations are observed.

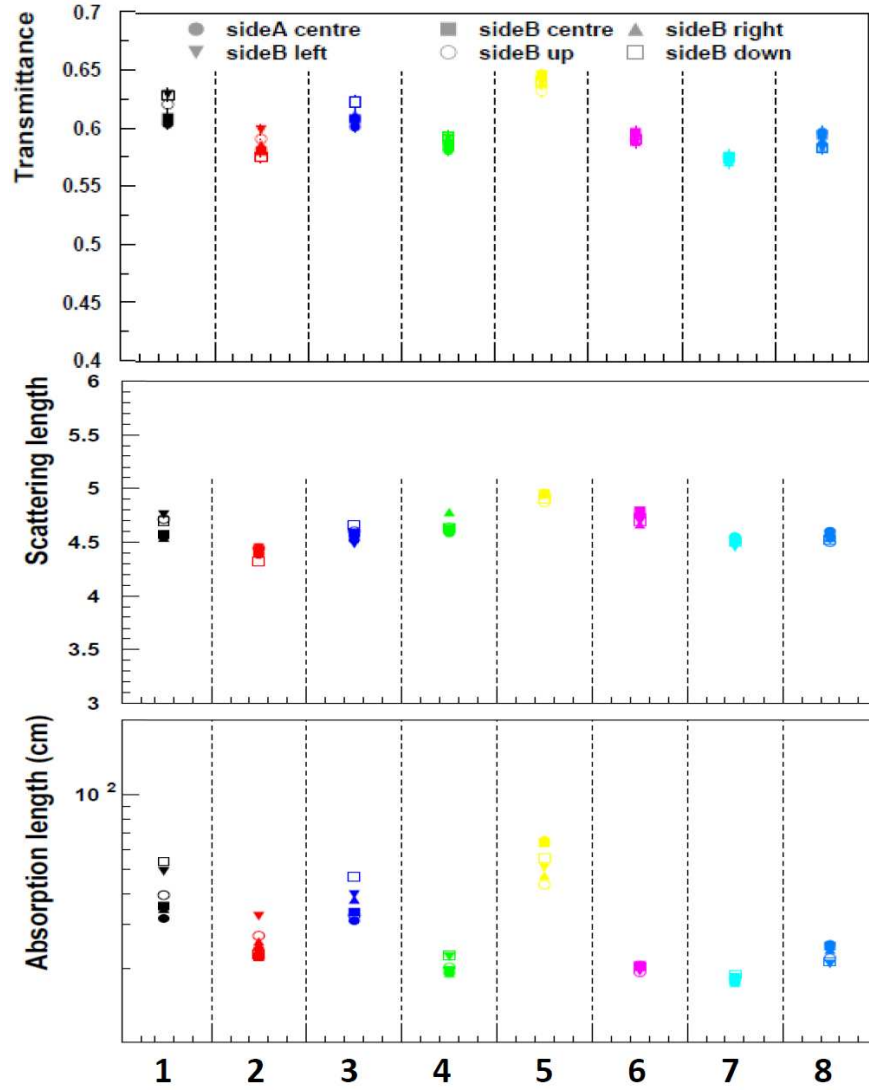


Figure 22: Comparison of transmittance, scattering and absorption lengths measured at $\lambda = 400\text{nm}$ in different spots (different symbols) on the surface of the eight 2cm thick $n = 1.05$ Novosibirsk tiles.

The various Novosibirsk aerogel tiles belong to different productions made in 2012 or earlier. The “AMS prod” tiles are the oldest ones (residuals of the AMS production), the “CLAS prod1” ones have been produced at beginning of 2012, the “CLAS prod2” and “CLAS prod3” ones in June 2012 and the “CLAS prod4” ones in November 2012. The scattering length of the tiles with $n = 1.05$, measured at $\lambda = 400\text{nm}$, is shown as a function of the production time in Fig. 23. There is a clear trend showing that the production technique and the resulting quality of the aerogel is significantly improving in time.

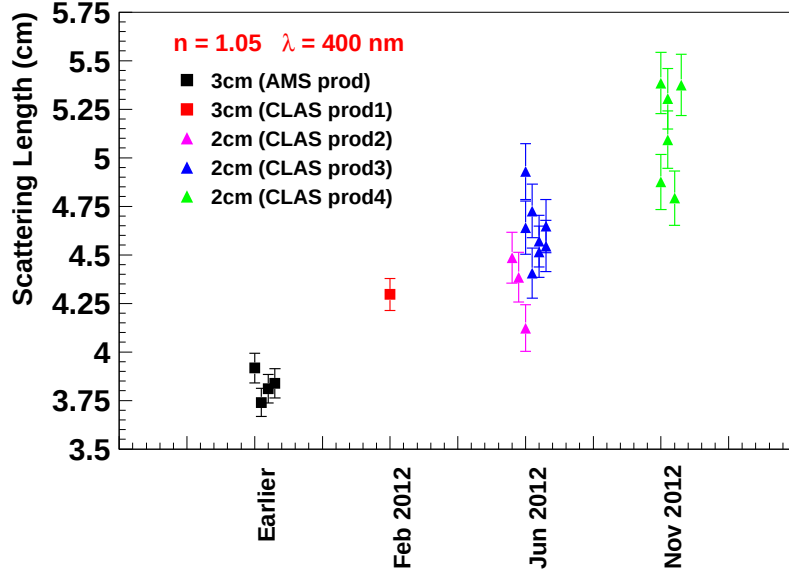


Figure 23: Scattering length at $\lambda = 400\text{nm}$ for $n = 1.05$ Novosibirsk tiles versus the production time.

6.5 Monitoring the transparency at the CERN test-beam

A prototype of the CLAS12 RICH was tested at the T9 facility at CERN using a 6-8 GeV pion/kaon beam extracted from the PS. During the two test-beam (August and December 2012) most of the Novosibirsk aerogel tiles listed in Table 3 were employed.

The Novosibirsk aerogel is hydrophilic, i.e. tends to absorb water molecules from the air, resulting in a degraded transparency. In order to reduce the absorption of humidity from the air and to partially expel the water already absorbed, several approaches were attempted:

- storing the tiles in a dry-atmosphere cabinet (Fig. 24)
- storing the tiles in a box fluxed with nitrogen (August CERN test-beam)
- baking tiles at a few hundreds (Celsius) degrees for a few hours (August CERN test-beam)
- sealing the tiles within small plastic bags after use (December CERN test-beam)



Figure 24: Dry cabinet for aerogel storage.

In order to monitor the status of the aerogel during the two test-beams, the transmittance of the each tile was measured several times, usually before and after being used on beam (i.e. exposed to air). The measurements were performed with a simple setup made by a laser (blue light, 405 nm), a photodiode and a multimeter, as shown in Fig. 25. The aerogel tiles were placed between the laser and the photodiode, and the output signals (in mA) from the latter were recorded by the multimeter. For each measurement, the photodiode signal was recorded with ($I_{aerogel}$) and without (I_0) the aerogel tile in front of the laser. The transmittance was then evaluated as the ratio between the two: $T = I_{aerogel}/I_0$. The final results for the transmittance of each aerogel tile were evaluated as the average of the values obtained in 10 independent measurements. This method has the advantage of being very fast (a few minutes for each set of measurements) but introduces several systematic effects (the spectrophotometer values are systematically smaller). The RMS of each set of measurements was then assigned as an estimate of the global systematic uncertainty ΔT (error bars in Fig. 26).

Figure 26 shows the enhancement of the aerogel transmittance after being stored for more than 100 hours in the box fluxed with nitrogen. Similar trends were observed for other tiles. Storage periods shorter than 60 hours do not result in appreciable improvements. Also shown are measurements performed a few months later using both the laser setup and the spectrophotometer. During these months the aerogel was sealed in small plastic bags. The laser measurements demonstrate that the transmittance is preserved if the aerogel is sealed.

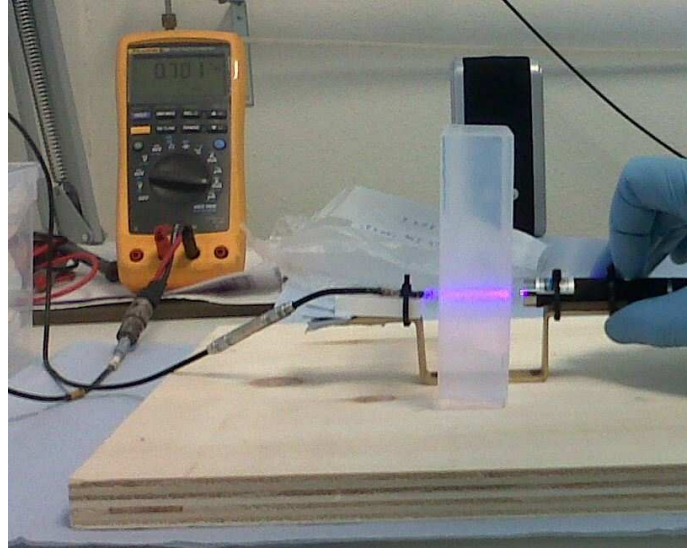


Figure 25: Simple setup used for fast measurements of aerogel transparency at 405 nm.

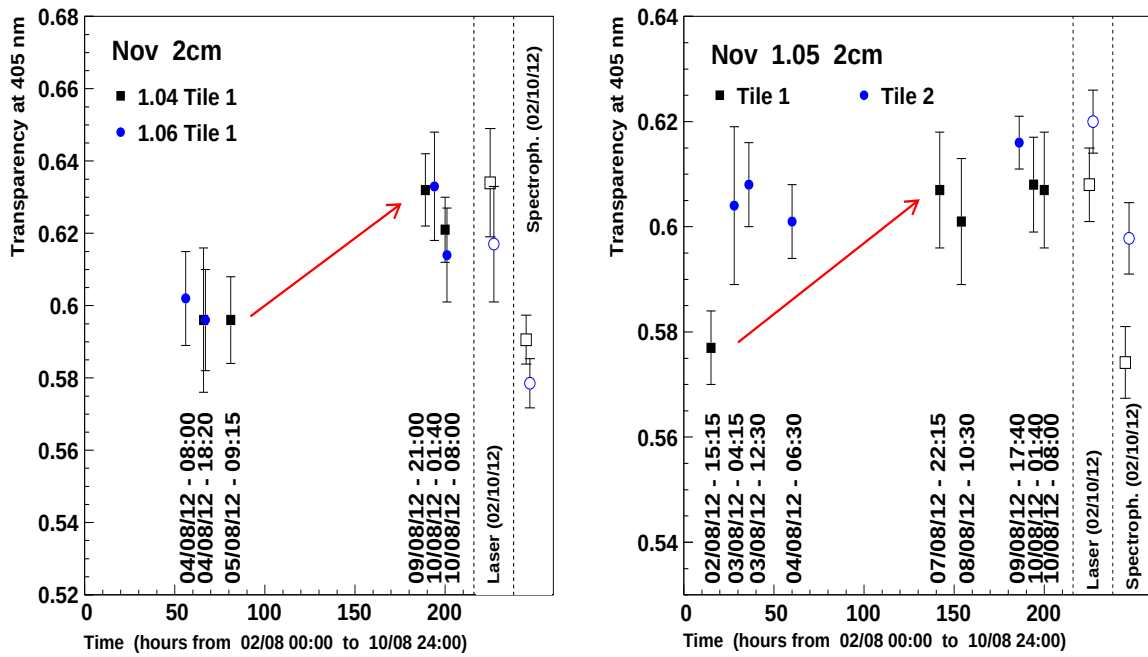


Figure 26: Measurements of aerogel Transmittance with the laser setup before and after long periods (Left: 108 h, Right: 127 h) of storage in box fluxed with nitrogen. More recent measurements, performed (with both the laser and the spectrophotometer) several months later to monitor the long-time stability, are also shown (see text).

7 Photon detectors

There are several requirements limiting the choice of photon detector. For instance, the photon detector must provide a spatial resolution of less than 1 cm. Due to the imaging aspect of the RICH and since multiple photon detectors will be tiled into large arrays, it is crucial that the photon detector provides an active area with minimal deadspace. The photon detector must also efficiently detect single photon level signals and, due to the aerogel radiator material, should be sensitive in visible light wavelengths.

MultiAnode PhotoMultiplier Tubes (MAPMTs) exist as promising candidates for the CLAS12 RICH and the currently selected photon detector is the flat-panel Hamamatsu H8500 [32] MAPMT, which offers an adequate compromise between detector performance and cost. The H8500 MAPMT comprises an 8×8 array of pixels, each with dimensions $5.8 \times 5.8 \text{ mm}^2$, into an active area of $49.0 \times 49.0 \text{ mm}^2$. Furthermore, the device has a very high packing fraction of 89%.

These MAPMTs are not advertised as the optimal choice for single photon detection, while other tubes, specifically designed this regime (as for example the R8900 or the new R11625), are much more expensive in terms of cost per unit area. For this reason, detailed studies to characterize the response of the H8500 have been performed.

The H8500 are produced in two versions, the H8500C with normal glass entrance window and the H8500C-03 with UV-enhanced glass window. The quantum efficiency of these two tubes are shown in Fig. 27. It is maximal in the blue light region, thus matching the emission spectrum of Cherenkov light in the aerogel.

These tubes are also sufficiently insensitive to the residual magnetic field expected in the RICH position. In Fig. 28, we show the variation in the anode gain measured by the Hamamatsu for a corner (left) and a center (right) pixel as a function of the magnetic field. Significant reduction of the gain of maximum 25% are expected only above 20 gauss.

7.1 Single photon response

The response of 28 H8500 phototubes (14 of each of the two version) to a low intensity photon beam was done by using a laser emitting blue light, remotely controlled to scan the MAPMT surface, and standard VME electronics for the readout. The set-up was installed inside a *black box* to isolate the MAPMT from any background light (see [14] for further details).

The intensity of the laser was reduced at a few photons per pulse by adjusting the tune of the laser and by using neutral density filters. With the two motors, the laser was moved across the MAPMT window in order to illuminate one by one all the 64 pixels. At each laser positions, the charge distribution measured by all the 64 pixels of the MAPMT was recorded using a CAEN V792 ADC (with a charge resolution of 0.1pC/channel). Typical spectra measured for two illuminated pixels of one of the MAPMTs are shown in Fig. 29. One can identify a prominent pedestal peak, followed by a broader distribution of one or more photoelectrons.

To extract the parameters of the MAPMT response, these distributions were analyzed following the method described in [15]. The ADC spectrum measured on each pixel has been fitted using the equation

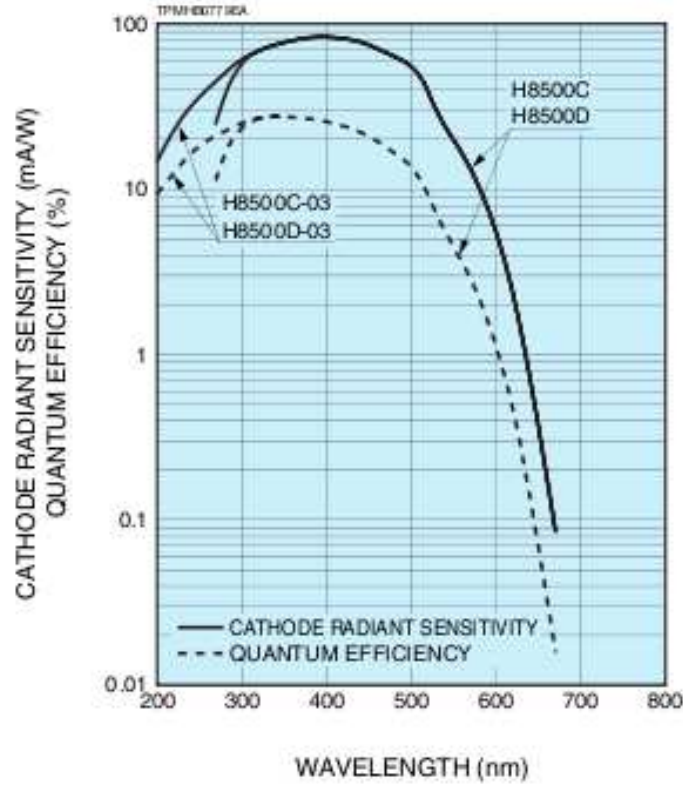


Figure 27: Quantum efficiency (dashed lines) of the H8500C and H8500C-03 MAPMTs (dashed lines) taken from the Hamamatsu datasheets.

$$f(q) = A \left[e^{-\mu} P(q) + \sum_{k=1}^N \frac{\mu^k e^{-\mu}}{k!} G_k(q) \right] \quad (8)$$

where q is the ADC channel readout and $P(q)$ and $G_k(q)$ are functions (normalized to 1) describing the shape of the pedestal and of the k^{th} photoelectron ($p.e.$) peak, respectively. Each term in the sum is weighted by the Poisson probability of having $k = 0, 1, 2, \dots, N$ $p.e.$ when μ is the average number of detected $p.e.$.

For the narrow measured pedestals, the gaussian shape was used, while for the $p.e.$ peaks several different parametrizations have been tried. It was found that the best results (in terms of convergence of the fits and of uniformity of the function parameters) were obtained using gaussian distributions as well, even though other shapes could provide in some cases slightly better values of χ^2 . The free parameters of the fits are:

- the constant A , that, being all the factors in the sum normalized to one, gives the total number of recorded events;
- the gaussian mean (m_0) and width (σ_0) of the pedestal term;
- the gaussian mean (m_1) and width (σ_1) of the first $p.e.$ peak;

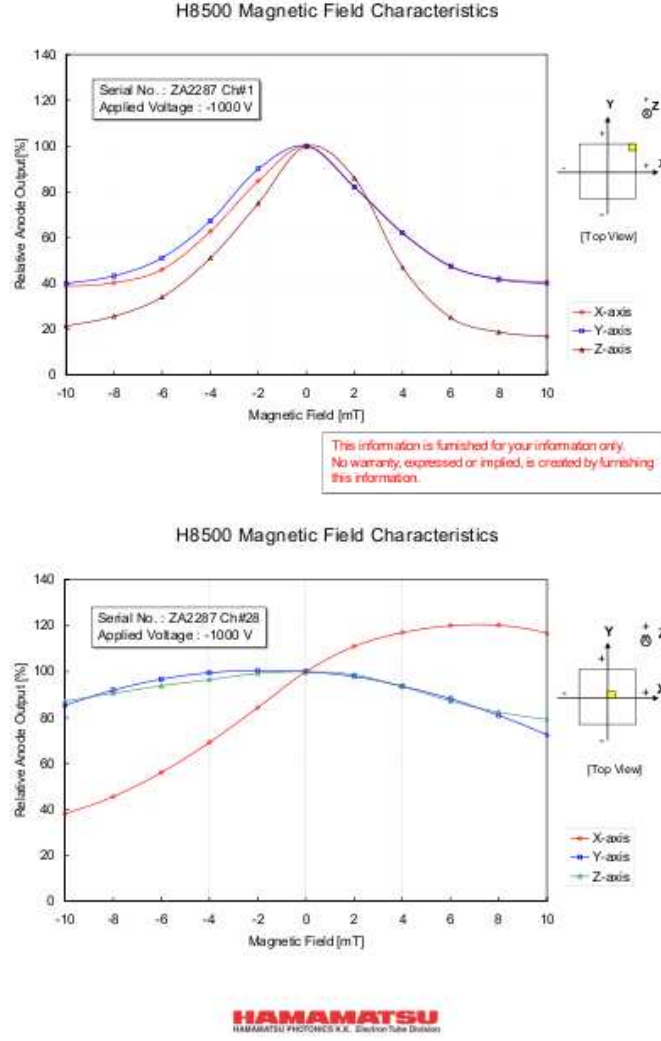


Figure 28: Variation in the response of a corner (top) and center (bottom) H8500 pixel as a function of the applied magnetic field in mT.

- the distance (d) between the first and second *p.e.* peaks;
- the average number (μ) of the detected *p.e.*.

The mean and width of the k^{th} peak, for $k > 1$, are computed as $m_k = m_1 + (k - 1)d$ and $\sigma_k = \sqrt{k}\sigma_1$. Typically, the average number of *p.e.* was less than 1, so that the total number of *p.e.* peaks considered in the fit was chosen to be 5.

At the nominal supply voltage of -1000V, we compared our measured average MAPMT gain (in ADC channels) with the one provided by the Hamamatsu datasheets. Results are shown in Fig. 30, where red circles (blue squares) represent our data for H8500C (H8500C-03) MAPMTs and the histograms represents the Hamamatsu data (arbitrarily rescaled). Error bars on the points show the RMS of the distribution of the 64 pixels of one MAPMT. The agreement is very good, thus making us confident on our analysis technique.

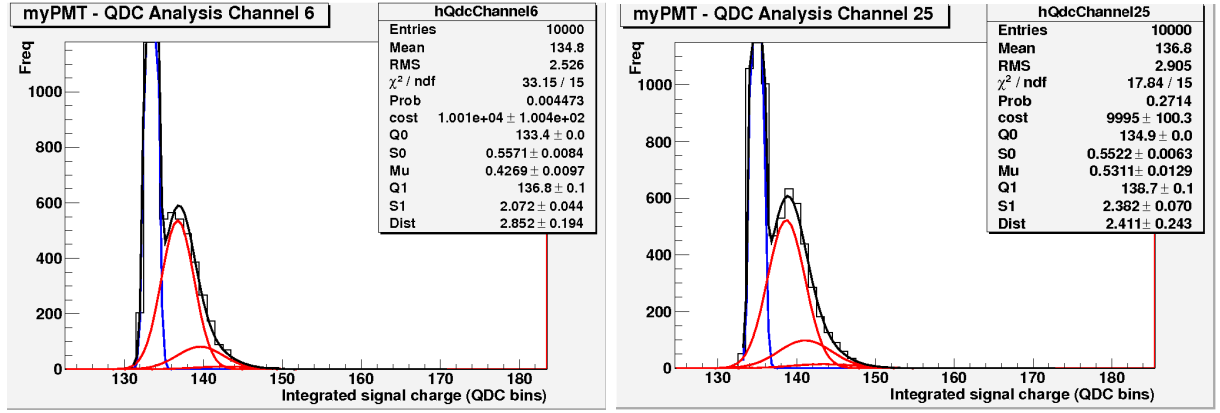


Figure 29: Two representative ADC spectra for pixel 6 (left) and 25 (right) of the CA4658 MAPMT at HV=-1000 V. The curves show the total fit (black), the pedestal (blue) and *p.e.* (red) contributions.

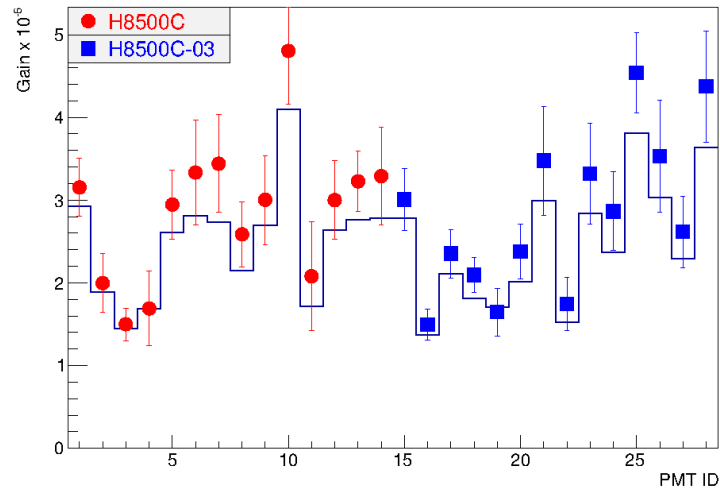


Figure 30: Average measured gain (in ADC channels) at HV = -1000 V for the 14 H8500C (red circles) and the 14 H8500C -03 (blue squares) compared with the arbitrarily normalized data sheet values from Hamamatsu (histogram). The error bars represent the RMS of the distribution on the 64 pixels.

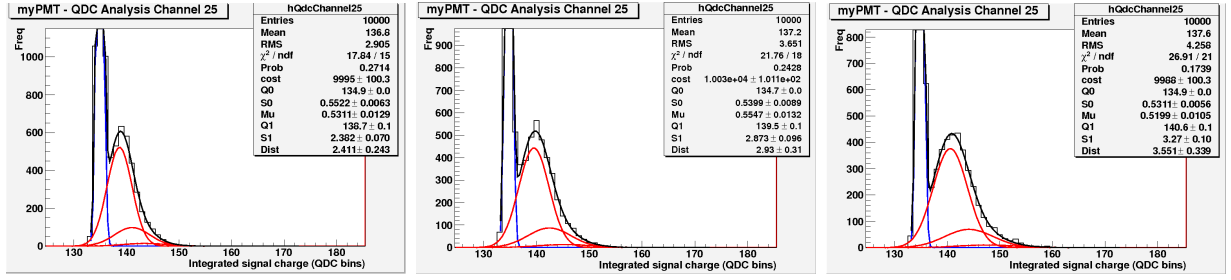


Figure 31: ADC spectra for the pixel 25 of the CA4655 MAPMT for (from left to right) HV=−1000, −1040 and −1075 V. The curves are the results of the fits, as in fig. 29

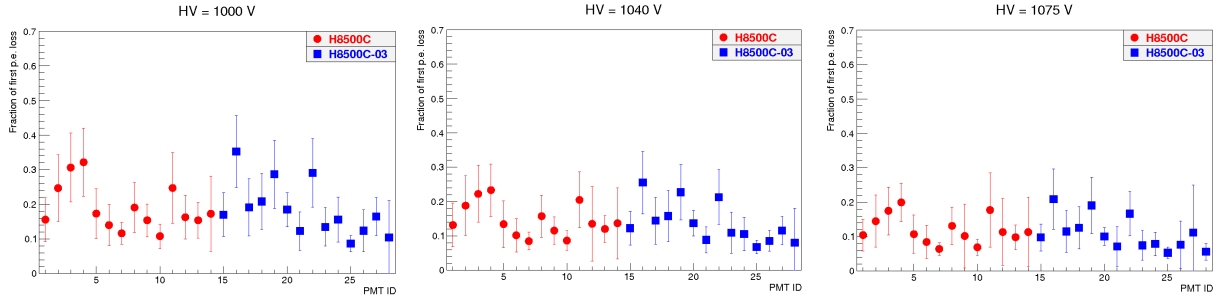


Figure 32: Fraction of the first *p.e.* peak loss, estimated by integrating the gaussian fit above the pedestal cut, at HV=−1000 V, −1040 V and −1075V. Average values on all the 64 pixels for each of the 14 H8500C (red circles) and the 14 H8500-C03 (blue squares). The error bars represent the RMS of the distribution on all the 64 pixels of each MAPMT.

Increasing the supply voltage, the separation between the signal and the pedestal improves significantly, as shown for a pixel of one MAPMT in Fig. 31. This is a crucial point. In fact, in the CLAS12 RICH, the signal amplitude will be no more than one photon per pixel, thus it is important that the fraction of the single *p.e.* spectrum below the pedestal peak would be as small as possible. One can estimate this loss of events by integrating the gaussian curve of the first *p.e.* peak below a suitable cut selected to remove the ADC pedestal. Assuming a cut at 3σ above the pedestal peak, we obtained the results shown in Fig. 32 for the three supply voltages of −1000 V, −1040 V and −1075 V. We see that, at the highest voltage, except for one MAPMT, the average loss doesn't exceed 20% and that, within one RMS, all the MAPMT pixels have loss below 30%.

7.2 Cross talk

Another important parameter to be studied is the cross talk, i.e. the probability that a photon hit the MAPMT in one pixel but it is detected by one of the neighbours. To study this, we compared at the response of one pixel when it is directly illuminated by the laser beam with its response when the laser illuminates one of the four adjacent pixels. An example is shown in Fig. 33. In each histogram, the vertical red line represent the threshold to remove the pedestal (3σ cut).

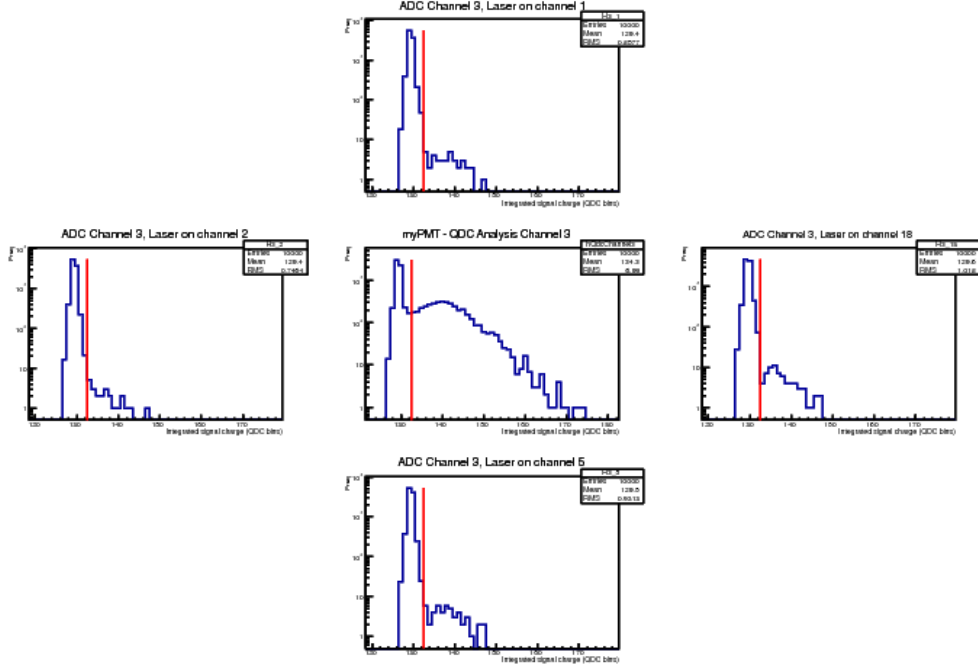


Figure 33: ADC spectrum measured by one pixel at HV=-1075V when it is directly illuminated by the laser (central histogram) and when the laser illuminates one of the four adjacent pixels (other 4 histograms). The red line indicates the threshold cut to remove the pedestal.

The cross talk is then computed as the ratio between the events above threshold when the laser illuminates the neighbour pixel with the number of events above threshold when the pixel is illuminated. In Fig. 34, we show this ratio for the 28 MAPMTs with normal (red circles) and UV enhanced (blue squares) glass window. Each point represent the average of the 64 pixels of one MAPMT and the error bar the RMS of the distribution. We found a cross talk level of few percent, in agreement with the expected performance. No strong differences have been found between the two types of H8500.

7.3 Gain analysis

In fig. 35, we show the fraction of event loss as a function of the MAPMT gain, for different threshold levels: low threshold (full squares), high threshold (empty diamonds, corresponding to a 3σ cut) and ultra-high threshold (crosses), as measured at HV=-1075V. The red full circle represent the average value of all the individual pixel gains measured in our tests. Requiring a maximum loss of $\approx 15\%$, a minimum gain of about 3×10^6 is needed, which means about 1.5×10^6 at HV=-1000V, the reference Hamamatsu high voltage. As shown in Fig. 30, only few of our MAPMT, which represent an average, random sample of the Hamamatsu production, are close to this value and none of them is clearly below.

In. Fig. 36, we show the distribution of the event loss for each of the 64 pixels of our 28 MAPMTs. A possible quality selection may be done by requiring that no more than 5% of the pixels of one MAPMTs don't exceed 30% of event loss. Only two of our MAPMTs

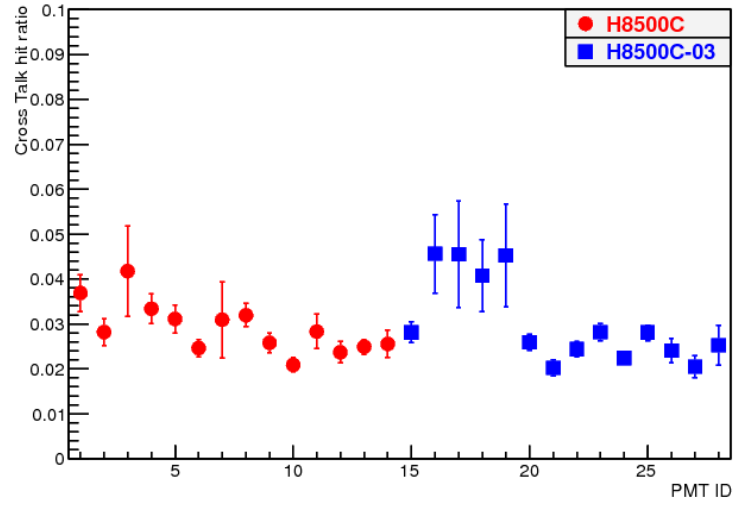


Figure 34: Cross talk fraction for the 28 MAPMTs: the points represent the average of the 64 pixels and the error bars the RMS of the distribution.

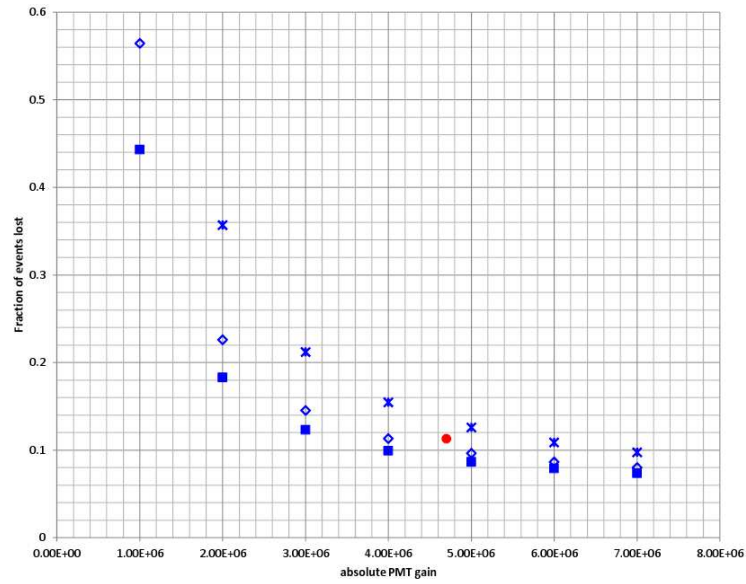


Figure 35: Fraction of event loss as a function of the MAPMT gain for three different threshold levels: low threshold (full squares), high threshold (empty diamonds, corresponding to a 3σ cut) and ultra-high threshold (crosses), as measured at HV=-1075V.

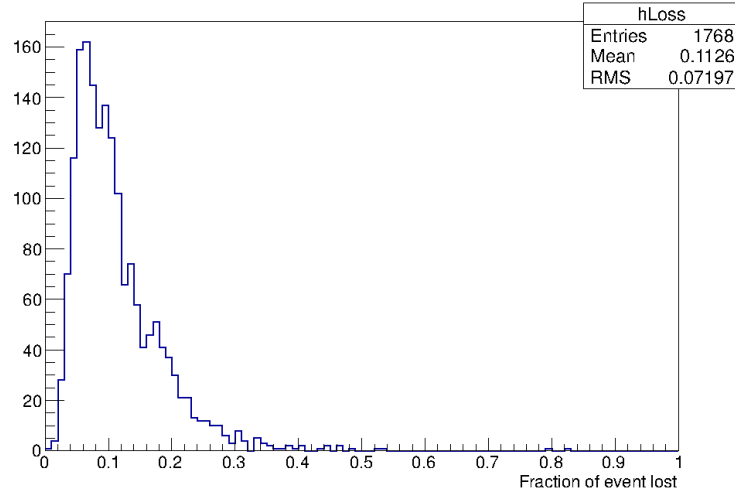


Figure 36: Distribution of the pixel event loss measured at HV=-1075V for all the 28 MAPMTs tested.

would be discarded according to this criterium, corresponding to less than 10% of the tubes tested.

7.4 Dark current analysis

The MAPMT dark current is a source of uncorrelated background and can impact on the detector performance. A dark current measurement is provided by Hamamatsu for each H8500C. The dark current measured by Hamamatsu is for the entire MAPMT, i.e. for a single channel this number needs to be divided by 64. First of all, a correlation of dark current and PMT gain is investigated. However, no clear correlation could be established (see Fig. 37).

The average gain and dark current values of the 28 MAPMTs, see Fig. 38, show no significant difference between standard and UV entrance window types. The average dark count rate R_{dc} can be computed from the dark current, assuming that essentially all dark counts are single photoelectron signals, by

$$R_{dc} = \frac{I_{dc} dt}{G \times e}, \quad (9)$$

with I_{dc} being the dark current, the time interval dt which is set to 1 s to get R_{dc} in counts per second, G is the MAPMT gain, and e is the elementary charge. In this case the average dark count rate is between 500 – 1000 Hz except for MAPMTs with excessive dark current.

The cross talk measurements (see Sect. 7.2) have been also analysed with respect to the dark current. In Fig. 39, we show the cross talk level of the 28 MAPMTs measured with HV=-1075V as a function of the dark current quoted by Hamamatsu. No strong dependences have been found.

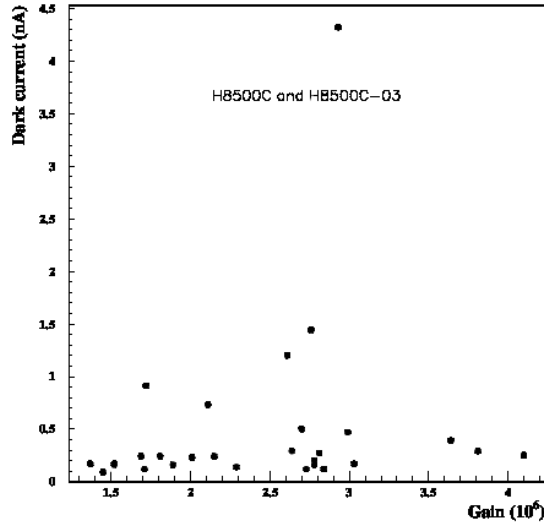


Figure 37: Dark current provided by Hamamatsu as a function of MAPMT gain.

7.5 Alternative MAPMT option

A promising alternative to the H8500 is offered by the new H12700 devices that Hamamatsu is planning to put on the market by the beginning of 2014. While keeping the same package, pixel size and pin structure of the H8500, a new dynode design, with a different voltage divider ratio, allowed to increase the performances in the single photon regime. In particular, a significantly better resolution with the same average gain has been obtained. This should translate in a larger separation between the single photoelectron signal and the noise pedestal, thus allowing higher detection efficiency at lower power supply. Being a new device, even if almost ready to be commercialized, some test needs to be performed in order to fully understand its characteristics, in particular the dark current level. These tests are planned by fall 2013.

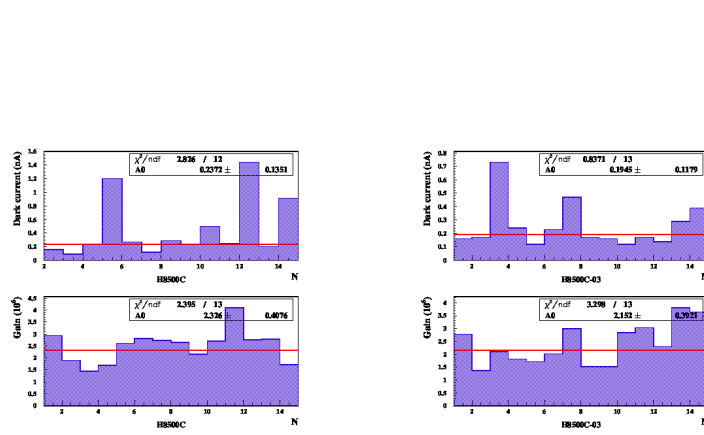


Figure 38: Average gain and dark current for 14 H8500C (left) and 14 H8500C-03 with UV window (right).

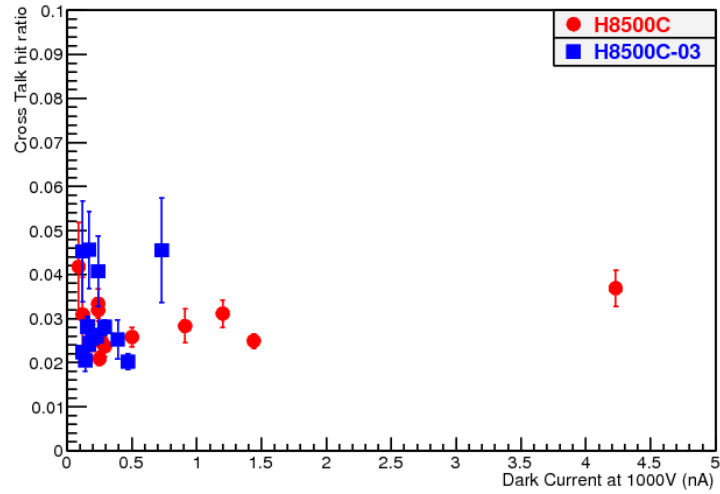


Figure 39: Cross talk fraction for the 28 MAPMTs as a function of the dark current quoted by Hamamatsu: the points represent the average of the 64 pixels and the error bars the RMS of the distribution.

8 Electronics and readout

8.1 Introduction

In current design the Cherenkov radiation is collected on a large array of MAPMT H8500; the total number of independent channels per sector is expected to be 25600, thus requiring highly integrated front-end electronics with modular design. In fact the impact of the electronics material on the detectors downstream the RICH must be minimized, in terms of background and particle straggling at least.

A typical modern architecture of the readout electronics consists of front-end cards with dedicated Application Specific Integrated Circuit (ASIC) configured, controlled and readout by programmable devices such as Field Programmable Gate Array (FPGA) either close to the front-end or onto the acquisition node depending on the ASIC features and the specific needs in term of real-time processing. The choice of the ASIC candidates has to be driven by the fulfillment of the detector requirements, the availability of on-the-shelf components or availability after minor development (no brand new development) and the existing experience within the collaboration.

Performance and status of different chips have been analyzed. Promising and interesting new developments such as VMM1 chip at Fermilab [24] and CLARO chip at INFN Milano [25] have been dropped due to the early development stage. Other more consolidate potential candidates such as the highly compact APV25 [26] have been excluded since cannot satisfy all requirements. The 64 channel DREAM [27] chip, working in analog sampling mode, could be a potentially interesting solution, even though it necessitates some additional developments for the RICH application. More details will be given in Sect. 8.6. At the end, our final choice is based on the 64 channel MAROC [28] (MAROC is an acronym for Multi Anode Read Out Chip), an ASIC manufactured by Omega Group of LAL (Paris, France), currently at version 3 (MAROC3). This solution satisfies all the relevant requirements and therefore it represents our mainstream option, taking also into account our consolidated experience on MAROC electronics design and operation.

In the proposed design we end up with stacked PCB layers behind each MAPMT sensor. The first layer houses the ASIC front end and ancillary components (e.g. external amplifier) and it is directly connected to the anodes array³. A second PCB will host the FPGA in charge of configuring, managing and acquiring one or more ASICs and the low voltage and HV bias distribution. The design foresees the use of the JLab SSP [30] as controller and collector of the front-end data, so that part of the development will have strong synergies with the current JLab upgrade activity. Data are transmitted on high speed serial (optical) lines minimizing the wiring and therefore the material budget.

With that *sandwich* architecture the total photon detection surface will be covered by a fixed number of basic units or tiles made up by two or three sensor each. The total spacing for electronics will not exceed 20 cm in depth (including MAPMT and mechanical support).

In the present analysis, the most relevant issues have been considered, ending up to a conceptual design of the electronics readout. Optimization of all the technical details is in progress.

³Decoupling or attenuation lines between anodes and ASIC inputs are considered part of the front end.

8.2 Requirements

Here are summarized the component main requirements that must be fulfilled by the readout electronics.

- **Trigger rate and dead time** - The expected readout trigger rate is 20 kEvents/s; the electronics shall sustain such rate with a dead time smaller than few %.
- **CLAS12 trigger latency** - The maximum CLAS12 trigger latency is 8 μ s. The electronics must satisfy this latency and keep track of events that occurred up to 8 μ s before the arrival of the trigger in the electronics.
- **SPE sensitivity** - The front end must be sensitive to single photoelectron (SPE). This translates to a minimum detectable charge at the level of few 10^6 electrons (see section 7.1).
- **Number of channels** - One RICH sector will have 25600 independent anodes. The electronics must provide the same amount of readout channels.
- **Anode gain spread compensation** - The electronics shall be able or permit to compensate the gain dispersion among the anodes of the MAPMT that typically is around 1 : 2 but that can be as high as 1 : 4 (see section 7.3).
- **Crosstalk** - Crosstalk between electronics channel should be smaller than the photodetector crosstalk (see section 7.2). A level of 1% is considered acceptable.

The front-end electronics, mounted behind the photon detector, shall cover the photon-detector area at maximum and shall have a total thickness not larger than 10 cm. This relatively small space may impact on heat dissipation and therefore the electronics must have a power consumption as small as possible. Being invested by the same dose rate of the rest of the detector (see section 12.2), the ASIC and all active components (voltage regulators, transceiver, FPGA) must be radiation-hard.

The temporal development of the MAPMT signal allows a time resolution below 1 ns (Transit Time Spread for H8500 is around 0.4 ns [32]). The dark noise rate goes up to 1 kHz per MAPMT with typical level below 500 Hz (see section 7.4), and therefore its contribution to the background rate is negligible for acquisition window at the level of few hundred ns (hit/event on the whole sector $\ll 1$). The main restriction on the time resolution comes from the possibility to disentangle the direct and reflected photons whose time difference (2 m or more difference in traveling distance) is about 6 ns or slightly more. Therefore a time resolution of the order of 1 ns would be very appreciated to help the reconstruction program but is not a stringent requirement.

8.3 MAROC Front End electronics

The MAROC [28], has been originally designed for the ATLAS Luminometer in AMS 0.35 μm CMOS technology and is currently in a well consolidated, production phase. The block diagram of the MAROC internals is reported in Fig. 40 while the main specifications are in Tab. 4.

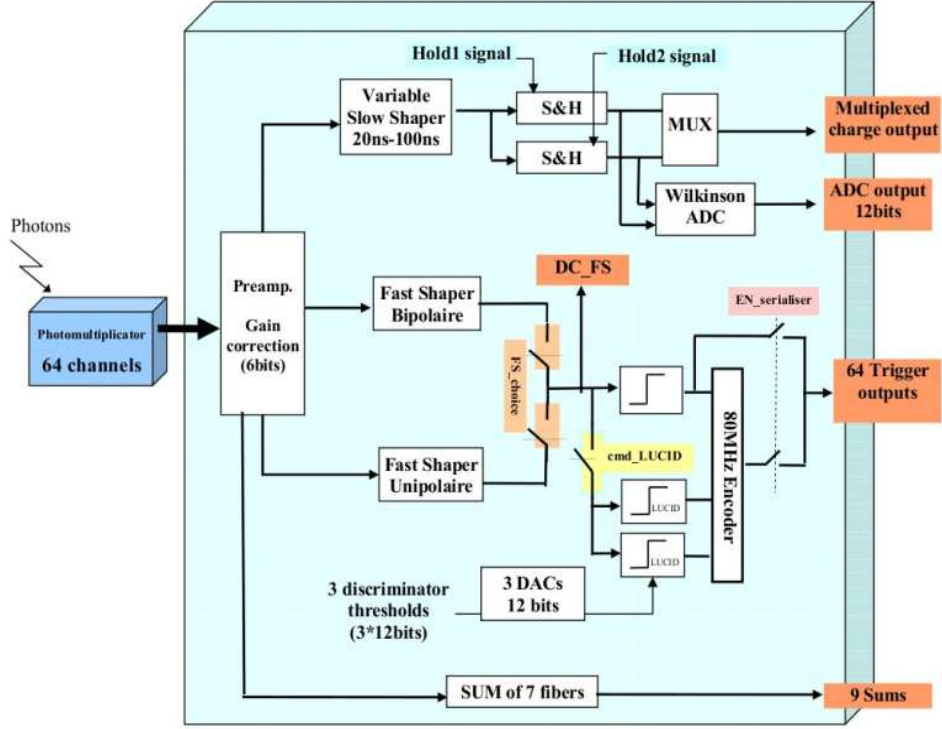


Figure 40: MAROC block diagram.

The chip consists of 64 independent channels and provides both the analog and binary (digital) information of each channel. The single channel has a pre-amplification and configurable 8 bit gain correction stage followed by three independent lines:

- a binary line with a fast shaper (~ 20 ns peaking time) followed by a discriminator with configurable threshold designed to provide 100% efficiency at one third of photoelectron;
- an analog line with a slow shaper ($\sim 30-210$ ns) followed by two track and hold circuits that permit the charge measurement through a serial multiplexing (single analog output of the 64 channels);
- a third line converges on one of the 8 embedded analog sums; each sum collects up to 8 consecutive (and selectable) channels.⁴

⁴The sum signals are expected to have a time resolution similar to the PMT's intrinsic resolution.

Table 4: MAROC3 and DREAM specifications.

Spec	Unit	MAROC3	DREAM
Technology		AMS 0.35 CMOS μm	
Number of channels	ch	64	64
Input polarity		neg.	pos. and neg.
Max Input dynamics	fC	5000 (30 p.e.)	50 - 1000 (4 steps)
Variable preamp. gain	bit	8 (0-4)	2
Analog output		MuX (5 MHz)	MuX Diff. (20 MHz)
Analog Shaping Time	ns	20-100	50 - 1000 (16 steps)
Analog Pipeline Size	cell	1	512
Pipeline Frequency	MHz	none	1 - 50
Binary output		64 parallel	OR only
Digital Shaping Time	ns	10-20	50 - 1000
Threshold range	bit	10	8
100% Trigger efficiency	p.e.	1/3 (50 fC)	-
Noise	fC	2	-
Linearity	%	2	< 2
Cross talk	%	1	-
Power consumption	mW/ch	3.5	10

The binary information of the 64 channels are available as parallel outputs that can be synchronized with an external trigger (EXT mode) or used as self generated trigger (SE mode). Both fast and slow shapers are highly configurable in terms of peaking time and dynamic range.

The MAROC needs 20 I/O lines for its configuration and readout (+ 64 independent lines for the binary information), including both the charge output fed into an external ADC and the internal Wilkinson ADC output. Some of the 18 lines (HOLD signals, ADC RESET, ADC Clock, and 3 additional levels) can be paralleled on more chips, while other can be daisy chained (Multiplexed output control, SLOW Control). Therefore, of the 20 I/O channels, 5 lines need to be connected to each single MAROC independently (+ the 64 binary hit bits), while the others can be shared by multiple MAROCs.

Charge measurement The charge measurement through the analog line requires an external “HOLD” signal within about 200 ns (maximum HOLD latency) from the event, which will freeze the charge on an holding capacitor that can be subsequently readout in a serial multiplexed way (with up to 5 MHz clock) either as an analog value or converted to a digital value by an internal Wilkinson ADC. The relatively small HOLD latency makes impossible during normal acquisition the use of the MAROC analog lines in the CLAS12 RICH. The analog information can be used for calibration purposes, in dedicated runs or in a restricted way during normal acquisition.

Binary information On the other hand the digital line is suitable for the RICH application; the binary information of each channel is promptly available in parallel and can be sampled with a predefined clock on an adequate deep external digital pipeline. The sensitivity of the threshold, its stability and the noise of the digital line have been measured; results are presented in section 8.4.

The digital information of each MAROC consists of 64 bits/events or 8 bytes/event which corresponds to 3200 bytes/events of the whole single sector; this size combined to the 20 kHz event rate can be easily managed by any modern DAQ such as the SSP based. Even in a simplified architecture where all MAROC data words are fully serialized, the total data rate is at the level of 64 Mbytes/s which are easily sustained by many modern serial links.

A precise time measurement can be obtained from the 8 MAROC sum lines fed into a fast amplifier (e.g. NINO [33]) followed by sub-nanosecond TDCs.

For its initial application in ATLAS the MAROC has been designed to be radiation tolerant, using the suitable AMS 0.35 μm CMOS technology[34], and therefore we expect no radiation issues. In any case we intend to test the radiation tolerant capability of the final electronics in a neutron radiation facility.

8.4 MAROC test and characterization

All MAROC tests have been conducted on the existing implementation designed by members of our group for applications in nuclear medicine[35]. Such implementation is optimized for many optical photons detection in self generated trigger mode, and analog readout. However it already includes several features suitable for the CLAS12 RICH: compactness, modularity (front end with ASIC and FPGA linked to a separated controller board), low power consumption, easy coupling with Hamamatsu H8500. Single photoelectron capabilities have been investigated by many tests in laboratory using laser source at single photoelectron level and under charged beams in different readout modes.

The read out system has been successfully used in analog mode and in external trigger in the RICH prototype test at CERN in 2012 (see Sect. 11). After that, an upgrade of the FE cards has been performed and in July 2013 a dedicated test has been conducted at the Frascati BTF to mainly characterize the binary readout in experimental conditions with Cherenkov light.

As shown in the following sections, all those tests and characterization confirmed the excellent single photon capabilities both in analog and binary mode, making it a suitable candidate for the RICH readout.

8.4.1 External mode: Analog response

Figure 41 shows the analog response of a single pixel illuminated by a laser pulse (emitted at $t \sim -20$ ns) at single photoelectron level for different delays of the sampling relative to the trigger. The shaped pulse is bipolar as expected showing two local maxima (in absolute value): the first is positive and ensures the largest precision to the charge measurement but it occurs pretty early (20-30 ns); the second, with opposed polarity, has less dynamic range

but it offers additional 100 ns to the trigger latency⁵.

Actually the earlier maximum cannot be used in typical experimental conditions where the trigger formation takes longer than ~ 50 ns from the occurrence of the physical event, as in the CERN prototype test setup where the acquisition was synchronized with the second maximum. The good results presented in Sect. 11 demonstrate the adequacy of the chosen conditions, although they are not optimal.

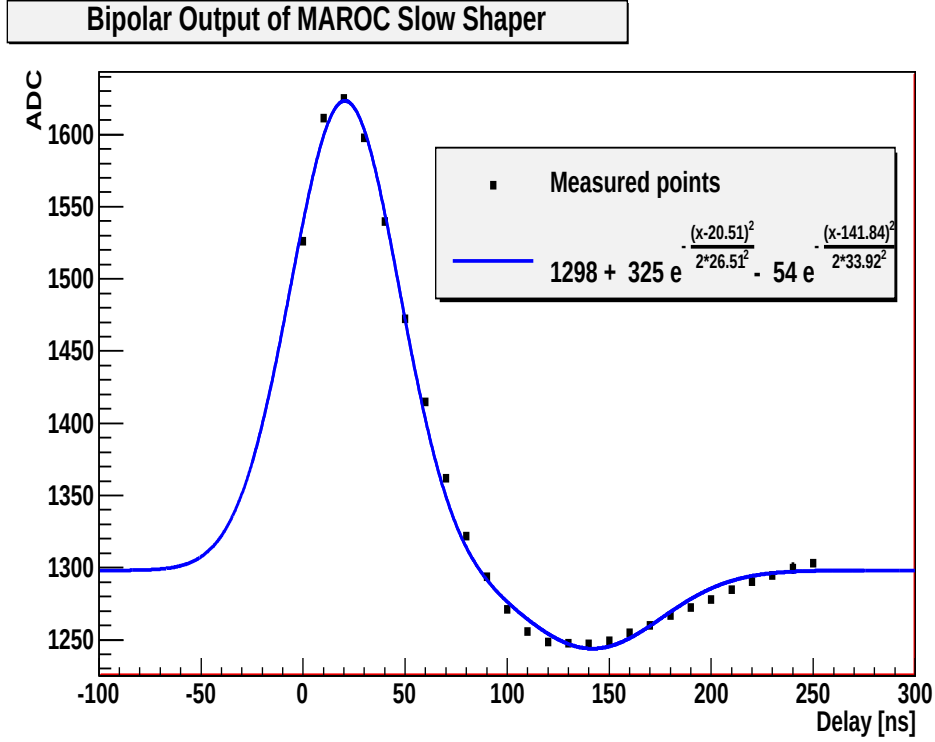


Figure 41: Slow Shaper output waveform reconstructed

8.4.2 External mode: Binary signal

MAROC binary information comes from the discrimination of the output of the fast shaper lines. The characterization of the quality of such information (in terms of single photo-electron detection capability) has been conducted correlating the binary and analog data, varying (and optimizing) essentially the discriminator threshold (common to the 64 MAROC channels), the synchronization time between the analog and binary lines and the pre-amp gain, both in self (calibration) and external (experimental) trigger modes, with and without laser source.

Figure 42 shows the SPE spectra (with pedestal) of a single MAROC channel, illuminated by a laser source at SPE level taken on the first analog maximum. This represents the optimal

⁵In case of saturation the second maximum could shift in time compromising the synchronization with the trigger.

conditions which are possible by the availability of a pulse that trigger the laser source. In red the events recorded on the analog line, which are at the same time above threshold in the binary line (those that provide the binary “1” response).

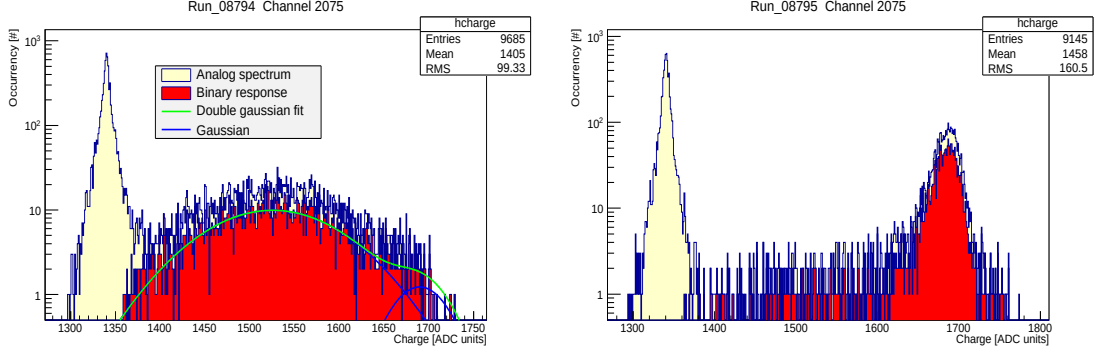


Figure 42: SPE spectra at different gain, over threshold events in red. Left plot unit gain, right plot gain = 4

The separation between signal and pedestal is very clear already with gain $G = 1$ (left plot), as highlighted by the red binary events demonstrating the excellent sensitivity of the binary readout to single photon. At gain $G = 4$ (right plot) the analog is getting saturated but the binary data are still remarkably good. The small mismatch between the two histograms (binary inefficiency relative to analog) in the overlapping region (above pedestal) is due to a non optimal relative synchronization between analog and binary readout, as will be discussed at the end of this section.

Figure 43 reports SPE spectra on the second maximum. Here, the SPE region appears on the left side of the pedestal due to the shaping of the input signals. In red we show the binary signal at three different thresholds. In this case binary and analog lines are properly synchronized. Although the separation of the analog line is slightly worse than in figure 42, as expected (due to the selection of the second maximum) the binary cut is still of impressive quality (middle plot).

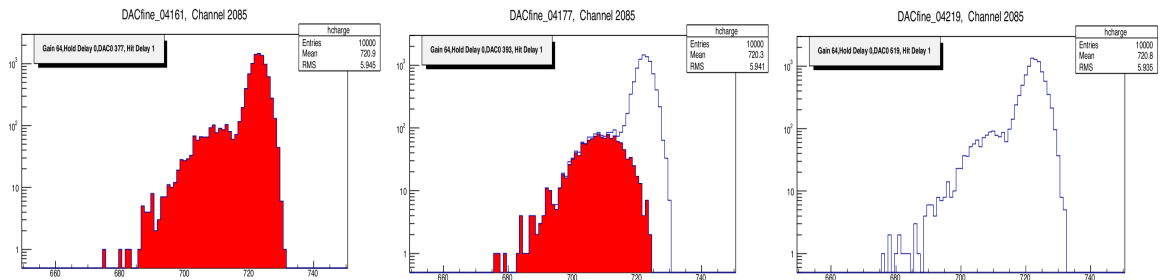


Figure 43: MAROC charge spectrum at single photoelectron level in external trigger mode using three very different digital thresholds (DAC values); threshold increases from left to right. The red histogram represents events with binary signal.

Figure 44 shows the effect of the analog-binary synchronization time on the SPE spectra; when the synch is not optimal the red histogram (binary signal) does not completely overlap the full spectrum above the pedestal because analog and binary are looking at slightly different times. Current MAROC electronics allow a 25 ns step for tuning.

It is worth to point out that in the final operating conditions (binary readout) the analog information will be basically used only for calibration purpose in self trigger mode where the analog-binary synchronization is not an issue or as estimation of the common noise, which does not require synch between the two lines.

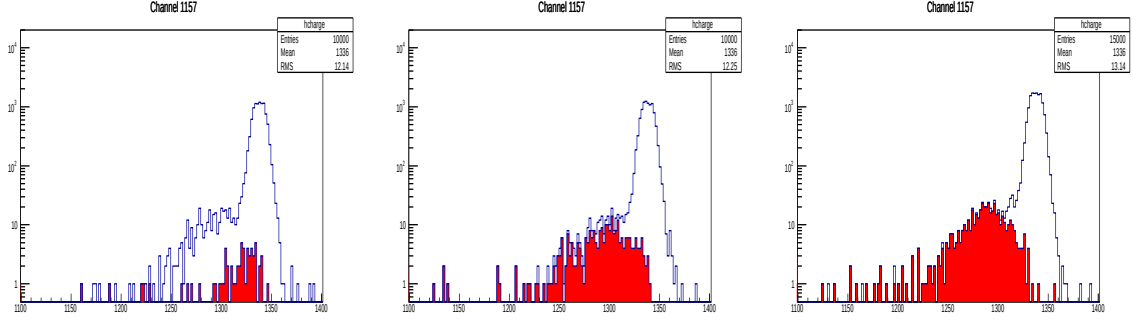


Figure 44: SPE spectra at three different synchronization time (25 ns step) between analog and binary lines.

8.4.3 Dark count and SPE in self trigger mode

The binary readout combined to the self trigger capability offers the possibility to measure rather quickly the dark count of the individual MAPMT channels, get information for the equalization of the channel gain and define the optimal threshold. Figure 45 reports the acquisition rate (not corrected for CPU busy time) versus the binary threshold level in case of laser source off and on, acquired in self trigger mode, only one MAROC channel enabled. The noise region is clearly evident in both source conditions. Dark count rate of the single anode is at the level of $10 \div 20$ Hz as expected from MAPMT specification and it extends roughly as the SPE signal with laser light on. The SPE region is pretty large, showing that the threshold level is not very critical, and count rate decreases rather slowly indicating that the fast shaper is probably working in a sort of saturated regime.

It is worth mention that the measurement of the dark rate spectrum as a function of the binary threshold can be adopted for the calibration of the combined system MAPMT plus electronics. In fact the drop of the noise region can be easily detected and all channels can be equalized (via the gain setting) to the noise drop at the same (or nearly) threshold value thr_n . Once this is done the optimal threshold is chosen as $thr_s = thr_n + k\sigma_{thr}$ where k is a reasonable factor (2 or 3) and σ_{thr} is the width of the noise drop (estimated either on the count rate derivative or the distance between 10% and 90% of the drop).

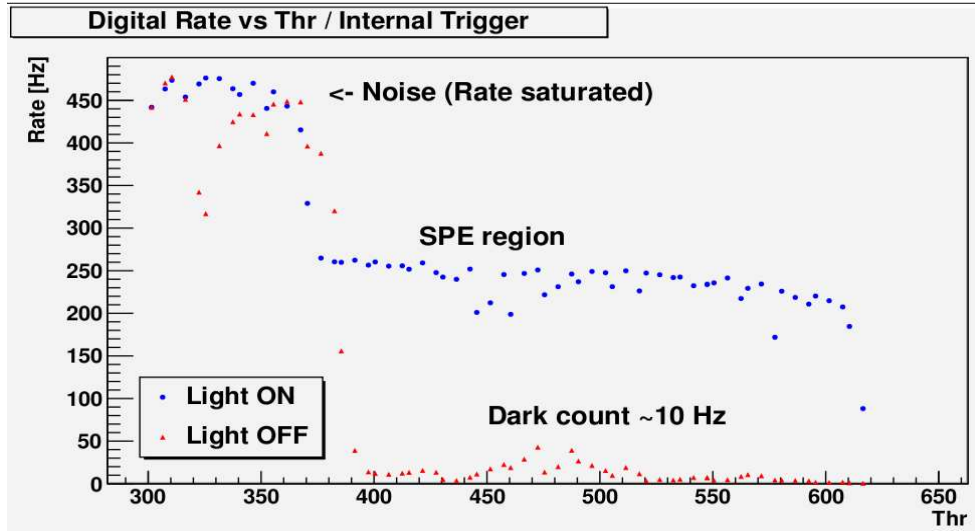


Figure 45: Acquisition rate in self trigger mode with laser trigger on and off.

8.4.4 Gain equalization by thermal noise

The use of the self trigger capability of the MAROC can be further exploited for calibration purpose, measuring the thermal (dark) spectra of each anode. Figure 46 shows dark spectra of two different channels acquired in self trigger mode with timing tuned on the first maximum of the analog pulse. Considering the small dark count rate, a similar measurement in external trigger would require much more time, unless one uses an external light source as in figure 42. This kind of spectra can be analyzed by an automatic procedure to equalize the gain of each channel and again to select the proper discrimination threshold. It represents a tuning gain and threshold procedure in addition to the one discussed in the previous section.

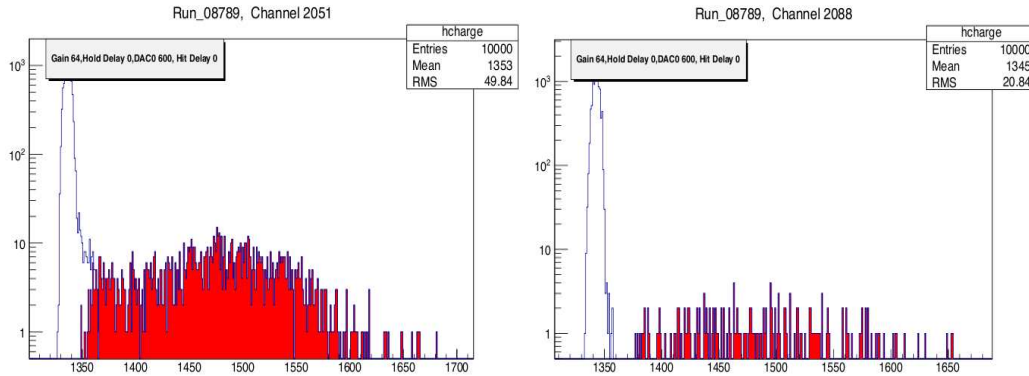


Figure 46: Dark spectra for two different channels. Analog timing calibrated on the first (positive) maximum of the analog waveform.

8.4.5 Effect of cabling on noise level

All RICH prototype tests have been performed connecting the MAPMT to the electronics front-end by flat, high density, shielded SAMTEC cable, 1.5 m long (HQCD series), see for example Fig. 47. This configuration is imposed by the layout of the existing MAROC electronics and the MAPMT on the RICH prototype. In the final RICH, electronics will be directly connected to the MAPMT, avoiding a potential source of relevant noise. In fact figure 47 shows the measured noise level (RMS of pedestal of the analog data) in the laboratory for different cable length and electronics gain. It is clear that without cable the noise is basically absent independently from the experimental conditions. Most of the noise is related to a common effect and can be largely suppressed by offline analysis of the analog data, averaging a consistent number of channels and subtracting to each channel value the mean value. This procedure has been applied in the analysis of the CERN test beam data, however it must be taken in mind that it may reduce the dynamic range of the data and that it cannot be applied to the binary data.

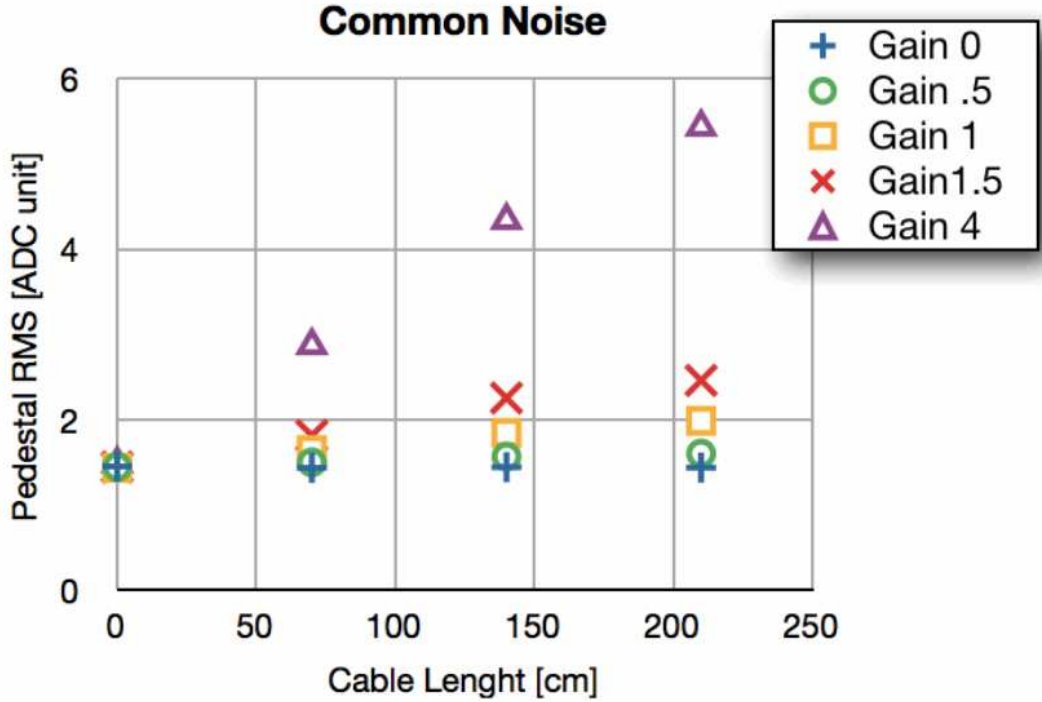


Figure 47: Noise effects of the cable length connecting MAPMT to the front-end electronics. Note that this noise level is significantly dependent on the experimental condition.

8.4.6 Power consumption and heat

MAROC power consumption is small as $3.5 \text{ mW}/ch$ and the current INFN electronics consume a bit less than $0.5W$, so for 400 of them we estimate a total absorption of $200W$. Including all the components, the total power consumption won't exceed $400W$.

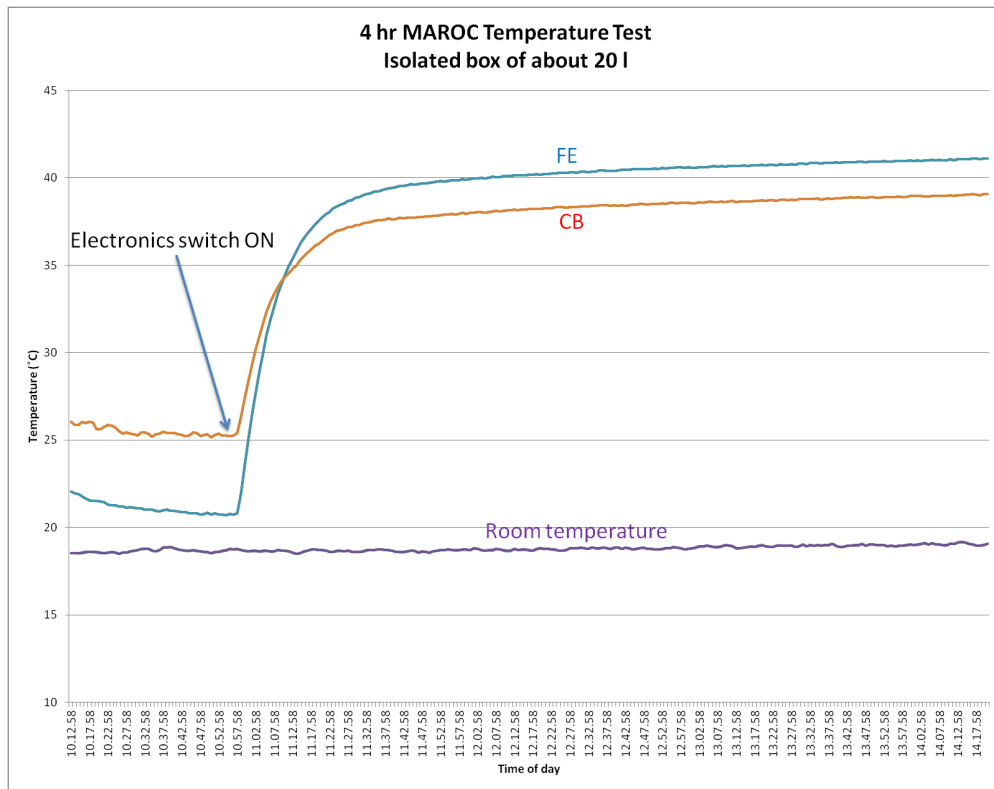


Figure 48: Results of a 4 hours test of the MAROC Electronics regarding heat production and dissipation. Eight Front End (FE) cards have been mounted on two Control Boards (CB). The set up was closed inside a sealed container of about 20 l volume, without any cooling, held inside a room at constant temperature of 18 Celsius.

A first thermal test of heat production and dissipation of a MAROC set up having 8 Front End (FE) cards on two Controller Boards (CB) has been done in July 2013 using a sealed container with a volume of 20 liters, without any cooling, putted inside a constant temperature room held a 18 Celsius. The result was that the temperature close to the FE reached an equilibrium temperature never exceeding 42 Celsius for the FE and 39 Celsius for the CB (see Fig. 48). Note that when the electronics was switched ON the air inside the container was above the room temperature. The temperature probes were directly put in contact to one of the FE cards and in an interstice of the CB in order to measure the temperature in the worst situation. Further test are foreseen in the next months.

If needed, dissipation of this heat will be performed in the RICH by flowing fresh air inside the electronics housing.

8.5 DAQ Electronics: from PMTs to DAQ modules

In the present preliminary design, the DAQ electronics is composed by three logical (and actually physical) layers; the block diagram of the first two layers and connection is shown in figure 49.

1. ASIC Board: it hosts the front end MAROCs, 8 channels fast amplifiers (such as the NINO chip[33]) for the MAROC sum lines, a DAC for the discriminators of the amplified sum lines, the MAROC bias circuitry, a common delay line (for the HOLD signal) and the connectors toward the PMT and the upper layer. One card will serve up to three PMTs. The card is directly connected to the PMTs to minimize possible source of noise as discussed in section 8.4.5. In this scheme, the analog response of the MAROC is used only for calibration and assumed to be converted to digital information by the internal Wilkinson ADC. The ASIC Board needs to connect up to 284 lines with the FPGA level as detailed in table 5; however, the OR lines can be suppressed without any relevant impact, as well as the external ADC. The differential NINO output can be converted to unipolar (LVDS-LVTTL) with marginal temporal degradation; in this optimized scheme, the total lines to be connected are 245.
2. FPGA Board: it hosts a capable FPGA (e.g. Xilinx Artix-7 XC7A100T with 285 I/O and 4 Gigabit Transceivers) which will configure the front-end MAROC, distribute the trigger, read the front-end, provide the proper input registers (64 for each MAROC) with adequate ($8\mu s$ latency) pipeline and TDC functionality (with resolution of at least 1 ns). In addition an electrical-optical transceiver will permit the transmission over a fast optical line toward the DAQ board of the next layer. A single FPGA Board will manage up to 3 MAROCs, thus reducing the optical link and exploiting effectively the FPGA resources. The FPGA Board will also contains the distribution lines of the HV (to the PMTs) and Power (+5 VDC and Ground) to the ASIC Board.
3. DAQ Board: it consists of the standard CLAS12 SSP VXS module in charge of controlling and acquiring data from up to 32 FPGA boards by fast optical links. The FPGA boards will be compliant with the SSP specifications and transfer protocol.

With this scheme in mind, assuming that:

- each binary channel transition has a 13 bits time information associated (with 1 ns resolution, 13 bits provide 8192 ns time range)
- each MAROC sum line has a 14 bits time information (0.5 ns resolution),
- the maximum hit occupancy is 20% (safe value),
- a fast 2.5 Gbps serial link,
- the multiplexing MAROC factor of 3 (up to 3 MAROCs on one optical link),

the expected readout time (from MAROC to SSP transmission time) is:

$$(13 \text{ bits} \times 64 \text{ channels} + 14 \text{ bits} \times 8 \text{ sums}) \times 0.2 \text{ occupancy} \times 3 \frac{\text{MAROCs}}{\text{board}} \times \frac{1}{2.5 \text{ GHz}} \sim 230 \text{ ns} \quad (10)$$

that corresponds to a dead time of $\sim 0.5\%$ at 20 kHz.

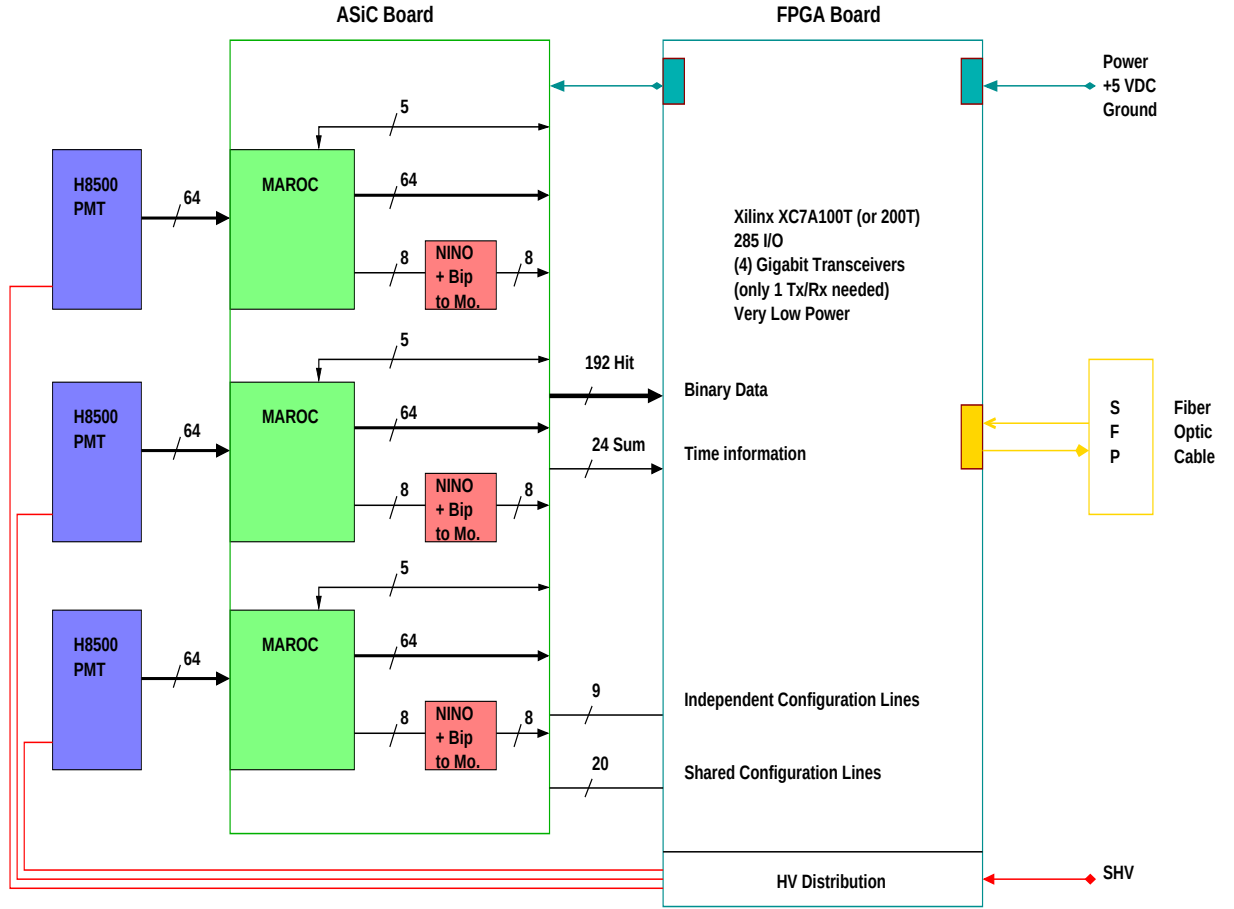


Figure 49: Readout Electronics Block Diagram; optimized connection between ASIC and FPGA Boards.

8.6 Alternative option: DREAM

The excellent MAROC performances measured in the above-reported tests and characterizations (as well as in the RICH prototype test at CERN) are more than satisfactory for the operation of this chip in the CLAS12 RICH and therefore MAROC represents the current mainstream choice as front-end chip in the RICH readout electronics.

However, potential costs and resources optimization can still be obtained adopting the alternative 64 channel DREAM ASIC[27] under development for the CLAS12 Micromegas and therefore well fit into the CLAS12 DAQ without significant additional effort from the RICH collaboration. The chip architecture derives, in part, from previous developments made for the AFTER and AGET chips[31].

The block diagram is shown in fig. 50 and specifications are in table 4.

The DREAM collects, amplifies, filters, discriminates and stores the analog signal of the sensor in an analogue 512 deep memory. The sampled signals, marked by the trigger, are read-out asynchronously without affecting the analogue memory storage; in this way the pipeline guarantee a deadtime-free operation for trigger rates up to 20 kHz. The sampled

Group	I/O lines	Purpose	Connection	Comment
Signal	64×3	MAROC/HitBit	independent	
	16×3	NINO/Output differ.	independent	if unipolar 8×3
	2×3	MAROC/OR	independent	unessential
	2×3	NINO/OR differ.	independent	unessential
Config	3×3	MAROC/ADC Control	independent	
	4	MAROC/Slow Control	daisy chain	
	4	MAROC/MUX Out	daisy chain	
	2	MAROC/HOLD	parallel	
	3	MAROC/ADC RST, CLK	parallel	
	1	MAROC/EN_OTAQ,	parallel	
	1	MAROC/CTEST	parallel	
	1	MAROC/VDD_FSB	parallel	
	2	DAC/I2C	serial/shared	
	3	Ext. ADC/SPI	serial/shared	optional
	2	Delay/Conf	shared	
Total(A)	284	no optimization		
Total(B)	269	no OR, no ext ADC		
Total(C)	245	no OR, no ext ADC, unipolar NINO output		

Table 5: ASIC Board pinout

signals must be digitized by an external ADC.

The main differences between the MAROC3 and DREAM chips are:

- input dynamic range in DREAM is optimized for gaseous detectors and therefore typically smaller than for a PMT output;
- DREAM hosts a long (512 cell) analog pipeline for each channel with sampling clock up to 50 MHz; this permits to have a trigger latency up to $\sim 10\mu s$;
- DREAM gain can be adjusted in 4 steps only (instead of 8 bits excursion in MAROC); the analog output allows monitoring and correcting for the anode dis-uniformity;
- the DREAM binary output is the sum (OR) of the 64 discriminated analog levels (while MAROC offers all 64 channels);
- DREAM analog data can be readout at 20 MHz, allowing to sustain a trigger rate up to 20 kHz (with 4 samples/trigger);
- the ADC that converts the analog DREAM levels must be provided by the readout electronics (MAROC has an internal, rather slow ADC converter).
- the DREAM project is in a consolidated development phase, while MAROC is already at the 3rd version.

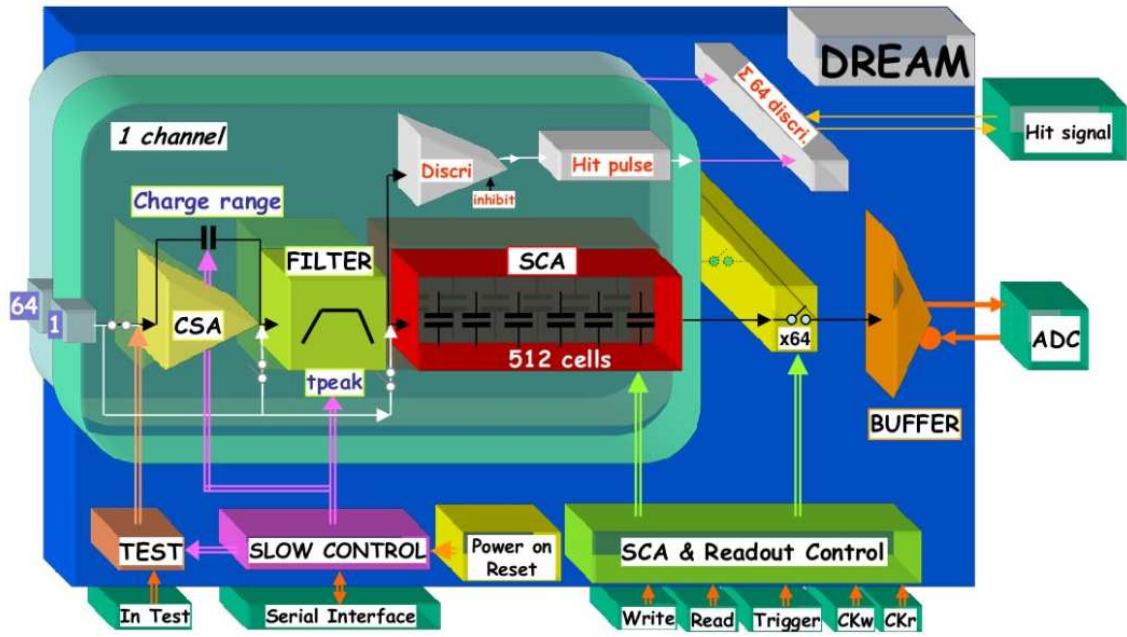


Figure 50: DREAM block diagram.

The DREAM offers a modest time resolution which can be evaluated to about 6 ns (the minimum shaping time divided by $\sqrt{12}$). Similarly to the MAROC chip, the sum of the binary signals can provide an improved time resolution, which must be measured.

In order to match the PMT output to the DREAM input the passive adapter board shown in fig. 51-left has been designed and realized. The board will attenuate the PMT signal (if needed) and reduce the parasitic coupling between the channels. A schematic diagram is shown in Fig. 51-right.

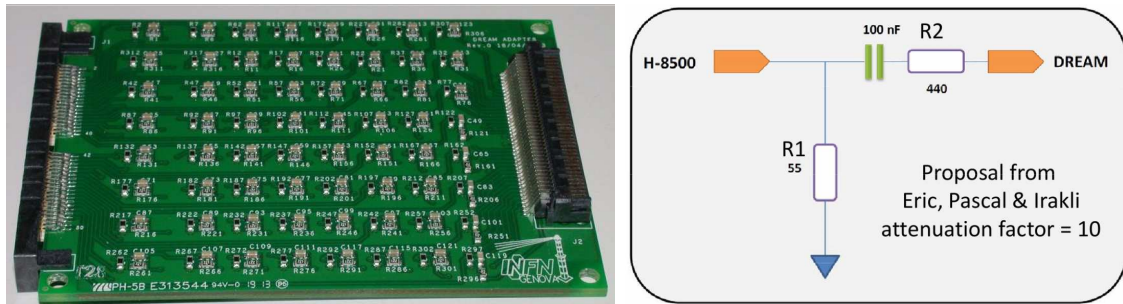


Figure 51: MAPMT-DREAM adapter board.

Test of the DREAM option are planned by the end of the year.

9 Mirrors

The proposed RICH detector exploit an elaborated mirror system to contain the Cherenkov photons within the module and direct them toward the photodetectors.

Photons produced at large angles are reflected and focused to the MAPMT region through two large mirrors (several squared meters), one planar just before the aerogel tiles and a spherical one placed above the MAPMT array. In the design and construction of these mirrors, besides the performances in terms of reflectivity, two main parameters should be considered. The first one is the rigidity: the two mirrors cover an area of several squared meters, thus a high rigidity is mandatory, to ensure that, during several years of operation, deviations from the nominal position do not spoil the RICH performances. The second one is the material budget, that should be kept as low as possible in order to preserve the performances of the detectors placed just behind the RICH.

In addition to the two main mirrors, the inner walls on the sides of the module structure will also be covered by mirrors, in order to keep all the produced Cherenkov photons within the RICH module. Being these mirrors in the torus coil shadow, their requirements in terms of material budget are less stringent.

9.1 Mirror quality requirements

Since in the CLAS12 RICH the reflected photons undergoes at least two reflections to reach the photodetector region, a high reflectivity, larger than 90%, is needed in the visible and near UV wavelength region that matches the typical Cherenkov wavelength distribution and the quantum efficiency of the photon detector. Moreover, in order to preserve the photon emission direction, the surface roughness of all the mirrors should be of the order of $100nm$ and, for the spherical mirror, a curvature precision $\Delta R/R < 1\%$ is required. These are rather standard requirements for RICH applications.

9.2 Geometry of the mirrors

The curved mirror has a spherical shape, with curvature radius of $4000mm$, covers a surface of about 3.5 m^2 and is tilted by 65° with respect to the beam axis. The flat mirror is placed on the entrance side of the module and before the aerogel tiles and has a surface of approximately 3.5 m^2 .

A mandatory requirement for any material to be used in the RICH for CLAS12 is to be as transparent as possible respect to the particle crossing. Also the total weight should be minimized, considering the size of the involved surfaces, to reduce the possible deformations due to the gravity. All such specifications should not, however, impact on the stiffness and durability of the structure nor on the required reflecting characteristics. A well assessed method to fit all the above characteristics is to realize a structure made of carbon-fiber reinforced polymer (CFRP), one surface of which is made reflecting. This technique has been successfully employed in several mirrors used in satellites for optical research in space (see for example [16]) and also for the RICH1 of the LHCb experiment [17]. Many companies, in Europe or USA, are able to manufacture such kind of mirrors [18, 19, 20, 21].

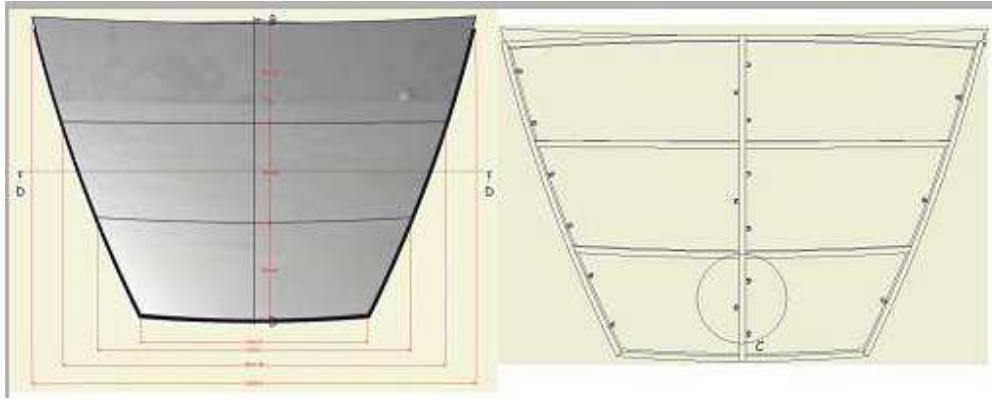


Figure 52: Spherical mirror geometry and back of the CFRP mount frame. On the left plot, the three jacks for the submirror alignment are highlighted.

The challenging aspect of these mirrors is their size, because such large areas cannot be coated with the reflecting material in one single manufacturing. This imposes the choice of dividing the mirrors in smaller submirrors of surface of the order of 1m^2 .

The spherical mirror surface will be segmented into six rectangular quadrants with three different footprint types as shown in figure 52. Each submirror is a self-supporting sandwich structure made of two skins of CFRP with the staking sequence 0/-45/45/90 and a core of rohacell foam thick 19 mm. The total thickness of the sandwich is 20.6 mm. The mirror face of the sandwich support must have a preliminary roughness of about $0.8\text{ }\mu\text{m}$ achievable by reducing the mold surface roughness to better than $0.8\text{ }\mu\text{m}$. An extra epoxy resin layer will be deposited so that it can be polished by means of abrasive paste and get a surface roughness of about $0.1\text{ }\mu\text{m}$ ready for the reflective film deposition. The coating is made by aluminum layer of 80nm thickness and SiO_2 or MgF_2 protective layer of 160nm thickness. The six mirrors are mounted on a common frame made of CFRP and can be individually adjusted in angle and position by means of three different jacks, see Fig. 52 right. The mount frame, made of CFRP, will be derived from a curved plate with a thickness of about 50 mm and inner curvature radius of about 4040 mm

The structure of the planar mirror will be different, though it will also be segmented in six smaller submirrors as shown in Fig. 53. The six submirrors will be made by thin (0.8 mm) glass skins [23] mounted on CFRP support that will also constitute the entrance window of the RICH module. This layout will ensure the required optical properties, the necessary rigidity and will match the limits in the amount of material, in particular for the upper part of the detector (in the lower part, the total amount of material is largely dominated by the MAPMTs and the electronics). As for the spherical mirror, each planar submirror will be installed on the support by means of three jacks that allow to adjust the relative alignments. The whole system will also be used to support the aerogel tiles.

The lateral mirrors are less demanding, being placed out of the active region of the CLAS12 spectrometer. Thus, we foresees the less expensive and less demanding option of thin glass or aluminum mirrors of 2mm thickness, applied on the inner side of the RICH external frame. The total area of these mirrors will be about 4 squared meters.

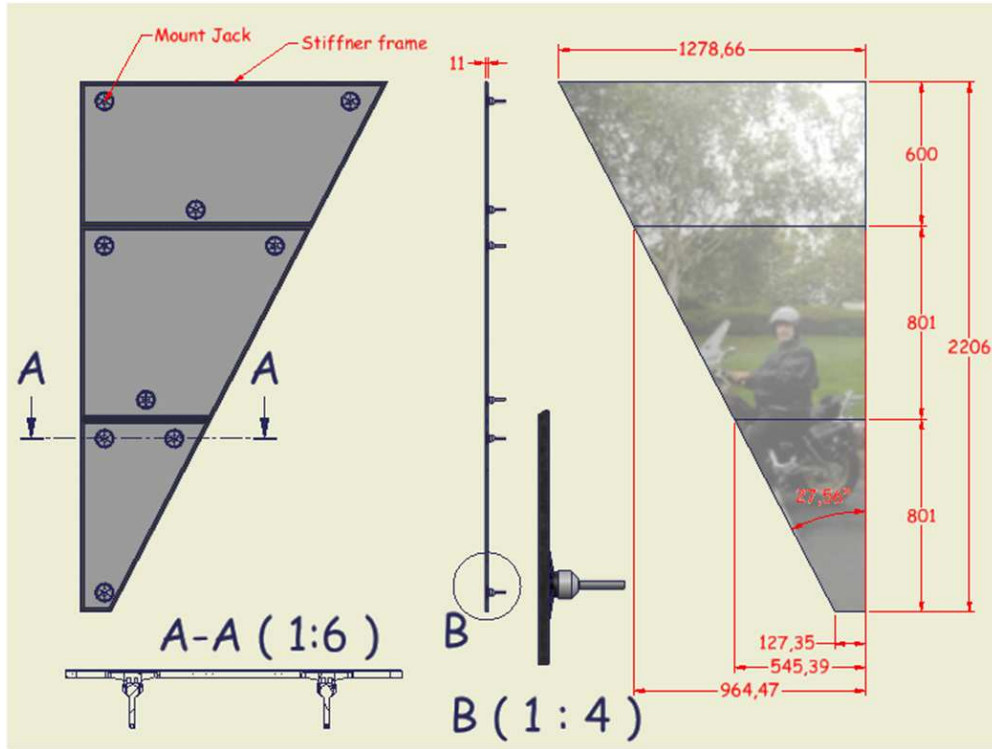


Figure 53: Geometry of one half of the planar mirror.

9.3 Alternative technology

A possible alternative solution for the large spherical mirror is provided by the so-called *precured tiles* technology developed by the Alenia [19] company for the construction of large antennas for satellites. The mirror is divided in smaller sub-mirrors (tiles), with geometry and size to be optimized. These precured tiles are constituted by a CFRP substrate on which the reflecting surface is deposited, and are then assembled in autoclave on the support panel. While cheaper in terms of costs (smaller mold, easier coating), this option needs some *R&D* activity to guarantee the necessary optical properties after the assembly procedure.

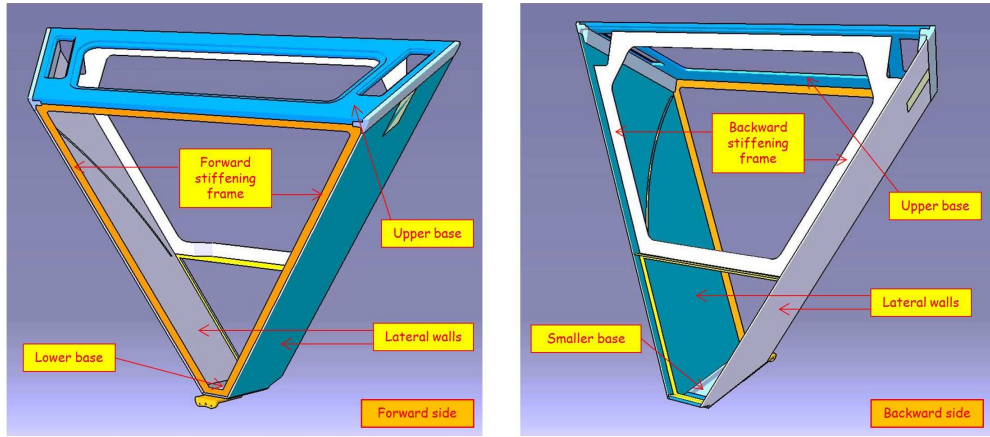


Figure 54: External frame of the RICH module.

10 Design and construction of the detector

One RICH module will have the same dimension of one LTCC module and the total weight of about 1300 Kg is also similar. Thus, it is expected to fit perfectly inside the CLAS12 structure and no problem in the installation phase are expected (see Fig. 9). The same tools and procedures foreseen for the installation of the LTCC will also be user for the RICH. The module is tilted by 25° respect to the normal to the e^- beam axis and has a roughly isosceles trapezoidal shape, with the major basis 3766 mm long. The average distance of the module respect to the middle of the target is 5646 mm with a distance of 1875 mm respect to the e^- beam axis. The angular range 5° - 13° roughly indicates the region covered by the MAPMTs, the angular range 5° - 25° the region subtended by the aerogel tiles.

The material budget of the RICH is about $0.07X_0$ in the upper (large angles) part and about $0.28X_0$ in the lower part (small angles), the latter mainly due to the MAPMTs and electronics. The impact of the RICH on the performance of the downstream detectors (FTOF and calorimeter) at small angles will be discussed in Sect. 12.3. No effect is expected at larger angles.

10.1 External frame design

Part of the components of the module structure has the role of structural support and will be built as a one-piece element, while the remaining components may be disassembled. The lateral walls of the module consist of two plates in aluminum alloy (AL6082 T6), connected one to each other on the lower smaller base, by a single monolithic plate, and on the upper greater base by a frame, both made in aluminum alloy, as shown in Fig. 54.

The forward side of the module is reinforced along its periphery by means of a stiffening frame, which has the function to minimize the deflection of the side walls. Similarly, the backward side of the module is reinforced in its upper area by a stiffening frame with the same function. Both stiffening frames will be made of aluminum alloy. All structural connections of the described components are made by screws, avoiding welding, that may generate undesired

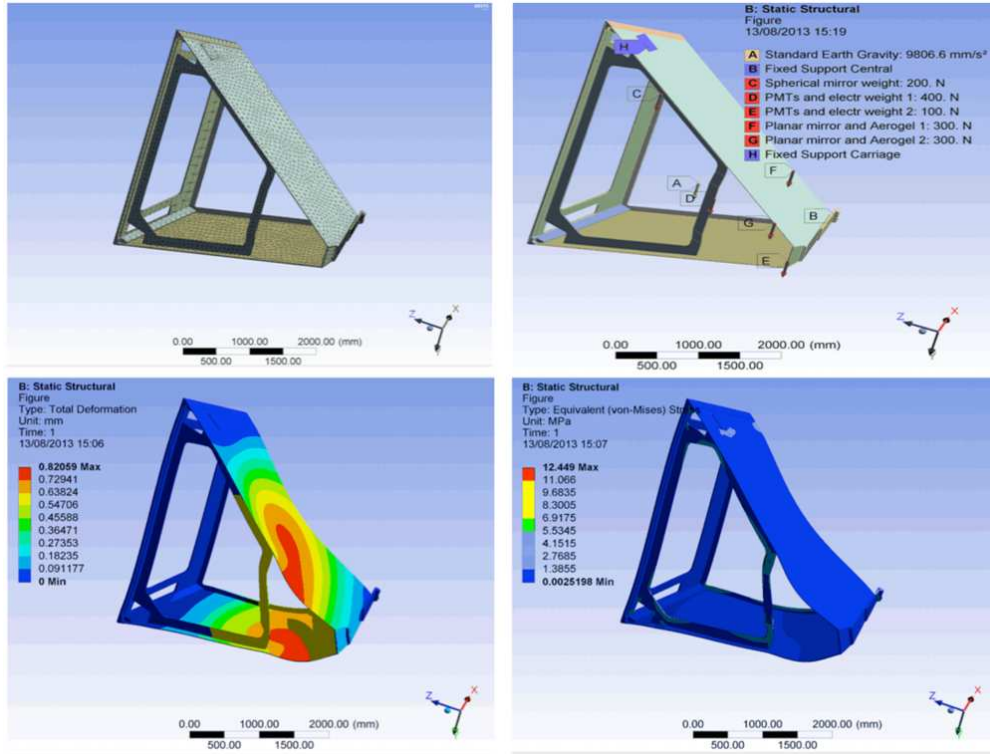


Figure 55: Load deformation analysis of the RICH extrnal frame.

deformations. On the inner face, each one of the lateral elements will be made reflecting with a thin layer (about 2mm) of glass or aluminum, as discussed in Sect. 9.

A preliminary FEM calculation of the structure was performed by simulating the loadconditions both during installation and in the final CLAS12 operation. The described geometry, with the stiffening ribs, allows to maintain the maximum total deformation under the millimeter, as shown in Fig. 55.

Orthogonally to the incoming particles direction, the front face of the module is constituted by a removable self supporting frontpanel, made in CFRP, with an internal layer of rohacell and two external skins of carbon fiber. In the inner face, the panel is integrated by a reflective layer, which constitutes the planar mirror of the RICH. In contact with the reflective surface are housed the aerogel tiles. The described elements are shown in Fig. 56.

The backward side of the module, shown in Fig. 57, is constituted by two different components: the lower one hosts the panel with MAPMT and electronics, while the upper one is made by a removable, self-supporting CFRP (rohacell core plus carbon fiber skins) panel. The central area of the frame that constitutes the upper greater base of the module is closed by a removable self supporting panel, made in CFRP (rohacell core plus carbon fiber skins). Two slots made along the shorter sides will lodge the supporting panels for the connectors of HV, LV electronic cables and for the gas pipe system.

The mechanical components and the stiffening elements will be produced through milling machines to guarantee the geometric positions of the various components within 0.5mm accuracy. All the removable components are designed with an adequate system of sealing,

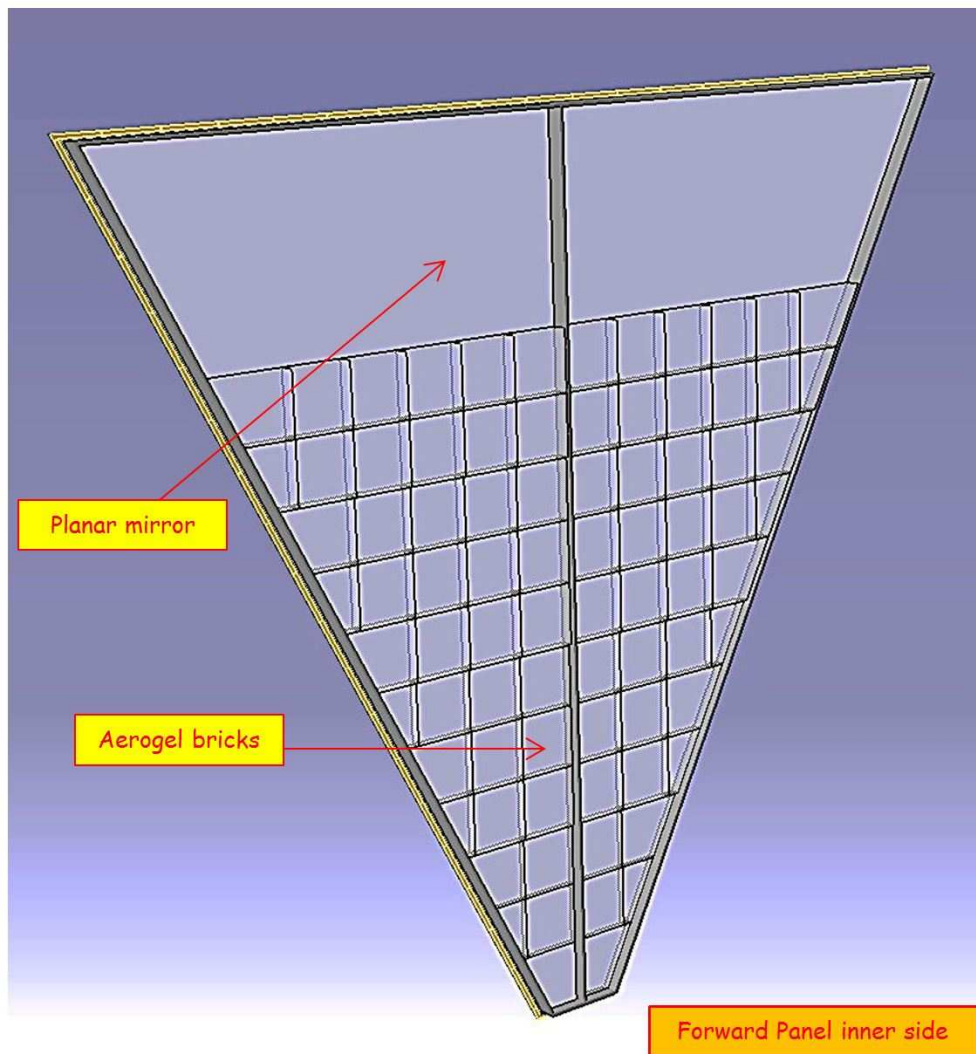


Figure 56: Inner side of the RICH Module forward plane.

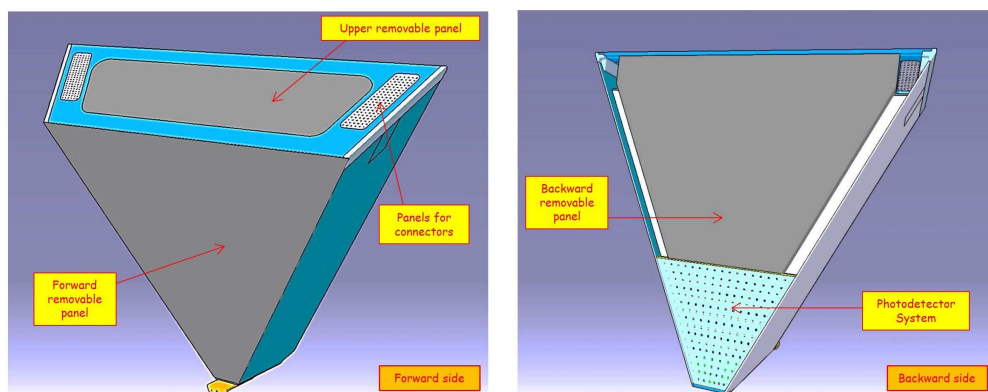


Figure 57: The RICH Module backward plane. Left: front view; Right: back view.

Layer	Material	Thickness (mm)	Angle (rad)
(+Z)			
9	Epoxy_Carbon_UD_395GPa_Pregreg	0.2	0
8	Epoxy_Carbon_UD_395GPa_Pregreg	0.2	-45
7	Epoxy_Carbon_UD_395GPa_Pregreg	0.2	45
6	Epoxy_Carbon_UD_395GPa_Pregreg	0.2	90
5	SAN_Foam_81kgm3	8	0
4	Epoxy_Carbon_UD_395GPa_Pregreg	0.2	90
3	Epoxy_Carbon_UD_395GPa_Pregreg	0.2	45
2	Epoxy_Carbon_UD_395GPa_Pregreg	0.2	-45
1	Epoxy_Carbon_UD_395GPa_Pregreg	0.2	0
(-Z)			

Figure 58: The sandwich CFRP lamination sequence and orientation.

in order to ensure the dark and the low-humidity conditions inside the module necessary for the operation of the RICH. Machining to be performed on CFRP components, of reference elements designed for the realization of coupling between different components, will be performed on metal inserts (passivated aluminum alloys or titanium alloy), in order to obtain even for this type of material the best precision for mechanical coupling.

10.2 The front panel

The front panel is envisaged to be at the same time the entrance window of the RICH detector and will support the planar mirror and the aerogel tiles. Due to the fact that it will shield all the foreword detectors, it must have as low mass as possible according to the mechanical mirror deformation and stiffness allowable. In order to fulfill the latter assumptions the planar mirror support will be manufactured in sandwich CFRP material. A preliminary Finite Element Analysis (FEA) of the entire assembly including the mirror and the aerogel tiles has been performed. The sandwich CFRP lamination sequence and orientation are shown in Fig.58.

The total thickness of the sandwich is about 9.6 mm with a foam core thickness of 8 mm and two CFRP skins of 0.8 mm thickness each. The density of the core foam is $8.1 \times 10^{-2} \text{ gcm}^{-3}$, while the epoxy carbon unidirectional pre-preg is 1.54 gcm^{-3} . The total weight of the mirror is about 17.14 kg, while the aerogel tiles have a total weight of about 36 kg. Two load cases have been studied in order to minimize the mechanical strain and the mass budget of the mirror support. In the first case, the gravity load was applied along the x axis (see Fig.59), in order to simulate deformations in the data taking position, while in the second case the gravity load was applied along the z axis to simulate the mechanical deformation during handling or aerogel tiles installation. All around the mirror and in the middle plane a reinforcing rib is foreseen, with a thickness of 9.6 mm and a height in the z direction of 50 mm. In the simulation, the mirror assembly is simply supported along the short edge and the two adjacent sides, while the side parallel to the short one is assumed free to move, even though in the real case also that side will be simply supported. The maximum displacement component along the z axis obtained from the FEA is about $0.6 \mu\text{m}$ for the first case study and 1.9 mm for the second one. The maximum rotation around the y axis in the data taking position is $7.71 \times 10^{-4} \text{ mrad}$, Fig.59, while in the second case study it is 2.2 mrad at maximum, Fig.60.

The finite element modal analysis was performed also to take into account mechanical

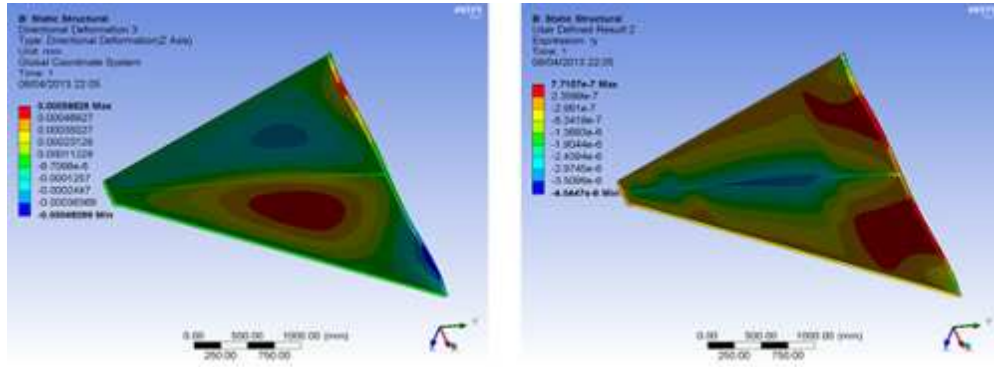


Figure 59: Load deformation analysis of the front panel with gravity applied the x axis.

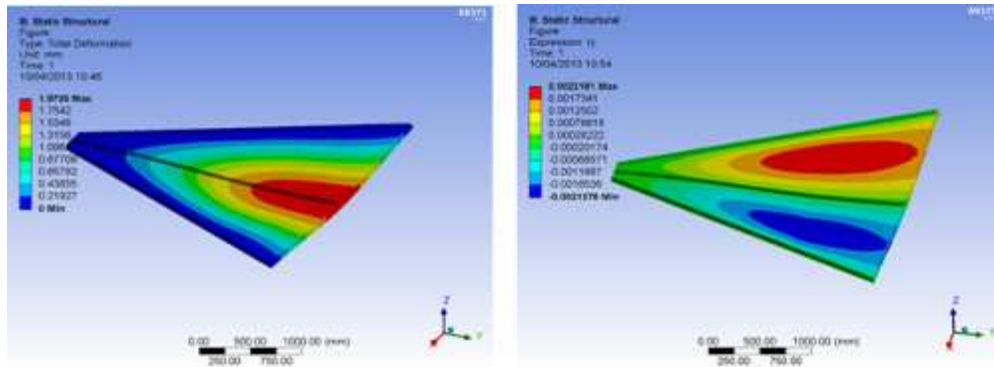


Figure 60: Load deformation analysis of the front panel with gravity applied the z axis.

vibrations or potentially dangerous mechanical resonances that could arise coupling with ground motion or plant vibrations. The first ten vibrating modes were computed and the correlated resonant frequency are listed in the Tab. 6. More detailed analyses are planned, like random vibration analysis, in order to find out the sensitivity of each component to vibration loads that are random in nature. An example will be the study of aerogel support response during handling, installation or transportation.

The sandwich CFRP support that will hold the six sections of the planar mirror and the aerogel tiles will be manufactured by means of lay-up technology, as shown in Fig.61. A metal mold will be used to stack the CFRP skins and the foam core all together with a vacuum bag for autoclaving and curing.

The aerogel tiles will be hold in place by a web of nylon wires attached to the lateral reinforcing ribs of the mirror, similarly to what has been done in the Hermes RICH detector.

10.3 Spherical mirror

A preliminary Finite Element Analysis of the entire assembly including the spherical sub-mirror and the mount frame has been performed. The sandwich CFRP lamination sequence and orientation are shown in Fig. 62 for both mirror and mount frame, with total thickness

Mode	Mode Resonant Frequency (Hz)
1	15.145
2	26.443
3	34.464
4	44.786
5	52.536
6	65.629
7	67.908
8	85.207
9	87.360
10	94.449

Table 6: The frequencies of the first ten resonant modes.

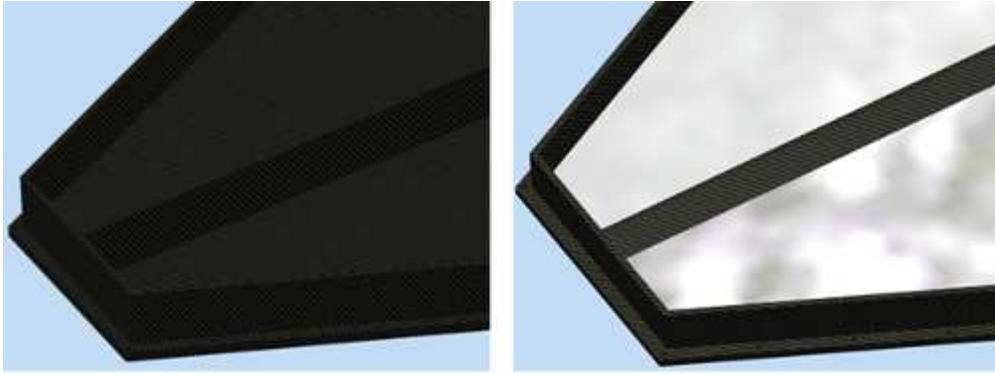


Figure 61: aerogel support and planar Mirror.

of 19 and 49 mm, respectively. The mount frame static analysis was carried out considering as loads the self-weight of the frame and the sub mirror weight (15 kg total).

The standard earth gravity was applied to the FEM model either along the z axis and either along the y axis in order to find out the static response at the two opposite and possible installation position inside the CLAS12 forward carriage frame. Results of the static analysis are shown in Fig. 63. The total maximum displacement of the mount frame, in the worst case, is $194\mu m$ and is well below the tolerances. Each sub mirror will be aligned by means of a laser tracker in order to reconstruct the ideal sphere with radius equal to 4000 mm within $20\mu m$. The finite element modal analysis was performed also to take into account mechanical vibrations or potentially dangerous mechanical resonances that could arise coupling with ground motion or plant vibrations. The first six vibrating modes were computed and the correlated resonant frequency are listed in the Fig. 64. More detailed analyses are planned, like random vibration analysis, in order to find out the sensitivity of each component to vibration loads.

Laminate : laminato_01

Plies

- a Cycom 381 IM7 UD nominal
- b 31 A;FC-/32

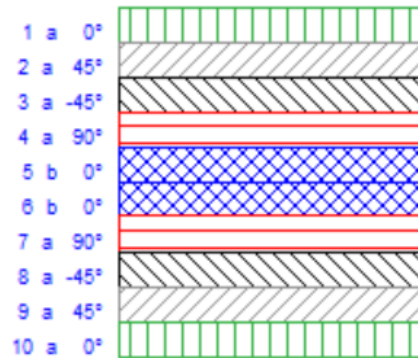


Figure 62: CFRP mount frame lamination.

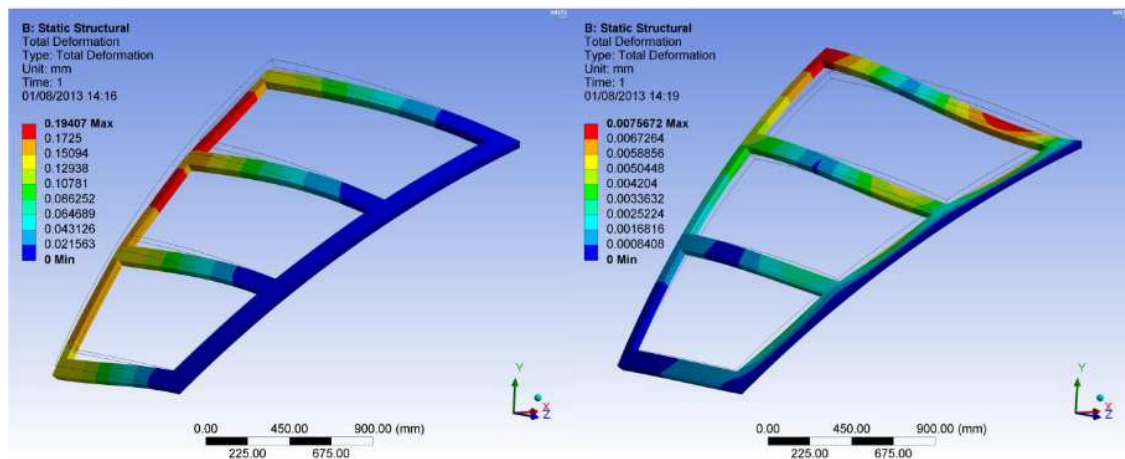


Figure 63: Total deformation of the mirror mounting with gravity load along y (left plot) or z (right plot).

Mode	Frequency [Hz]
1.	32.39
2.	37.78
3.	44.70
4.	56.92
5.	133.85
6.	157.83

Figure 64: Frequency of the first six resonant modes of the spherical mirror support structure.

10.4 Electronics housing

All the about 400 PMTs are housed in a self-supporting panel together with the front end electronics. The panel is installed on the RICH outer metal frame and is light and gas tight. It also acts as gas and light shield, as shown in Fig. 65. The PMT side is in contact with the inner volume of the RICH which is fluxed with nitrogen in order to control the internal humidity. The electronic side is open, even if a very light screen is foreseen in order to get a thermal separation with respect to the downstream FTOF detector. A dry air flux inside the rear volume is planned to dissipate about 400 W of thermal power. A preliminary calculation was performed, showing that the minimal air flux to be fluxed in the volume to keep the inner temperature stable is about 13 l/s with a speed of roughly 0.4 m/s.

The central panel will be manufactured using a very light but rigid material, as for example *Duroston-EPM-203*, that consists of resin reinforced with glass fiber, or CFRP. It will have special connectors for the plugging to the MAPMT pins. An outer stiffening frame is fixed on the perimeter of this panel, while the external frame will be made in aluminum alloy. When fully assembled, this panel will constitutes a complete self-supporting system that can be simply inserted in the RICH module, as shown in Fig. 66.

The MAPMTs are grouped in motherboards hosting pairs or triplets in order to minimize the construction complexity keeping at the same time the capability to efficiently cover the panel, as schematically shown in Fig. 67. Each motherboard will have one ASIC chip per MAPMTs, one FPGA for I/O, low and high voltage connections. Optical fibers and electronic cables will run on the sides of the module, in the torus coil shadows toward the power supply and SSP crates, as shown in Fig. 68.

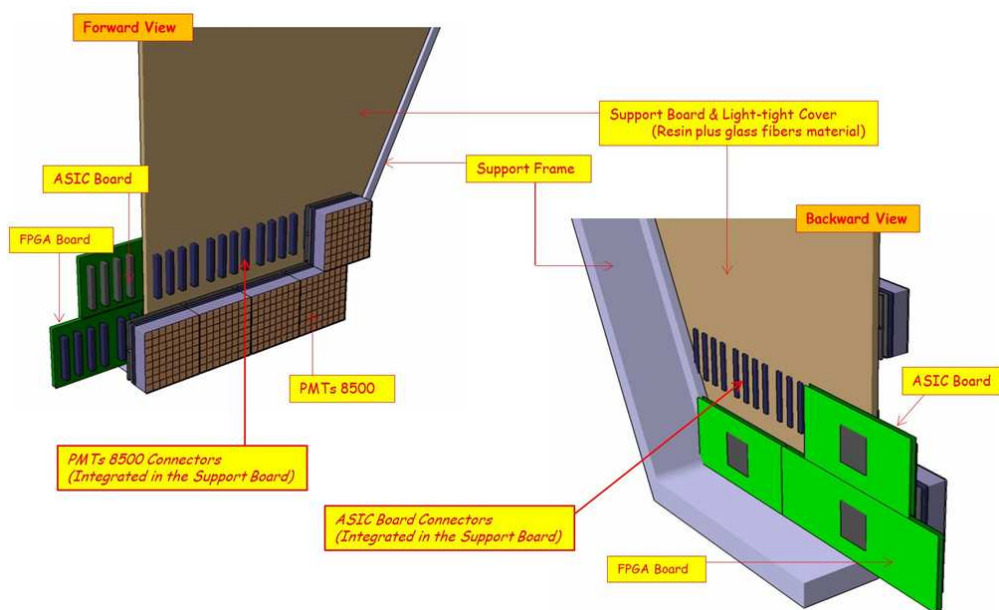


Figure 65: Frontal (left) and rear (right) views of the panel supporting the MAPMTs and the electronics.

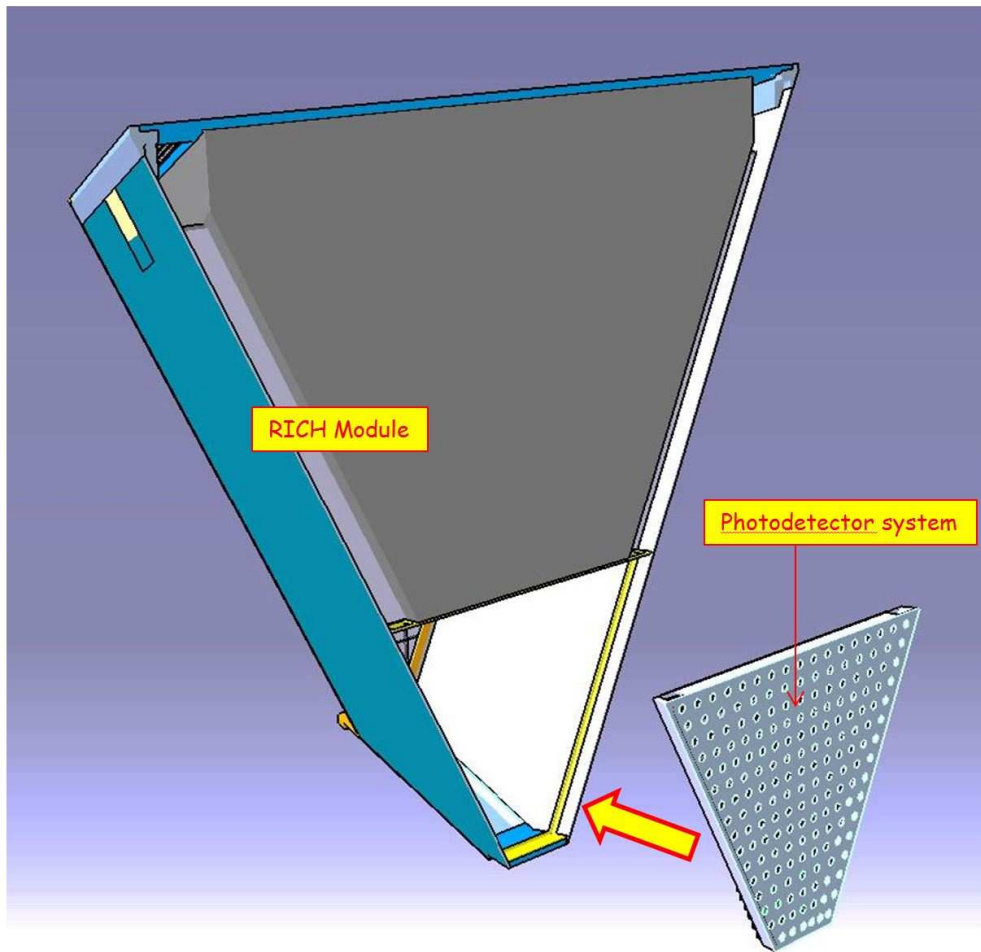


Figure 66: Assembly of the electronics panel in the RICH module.

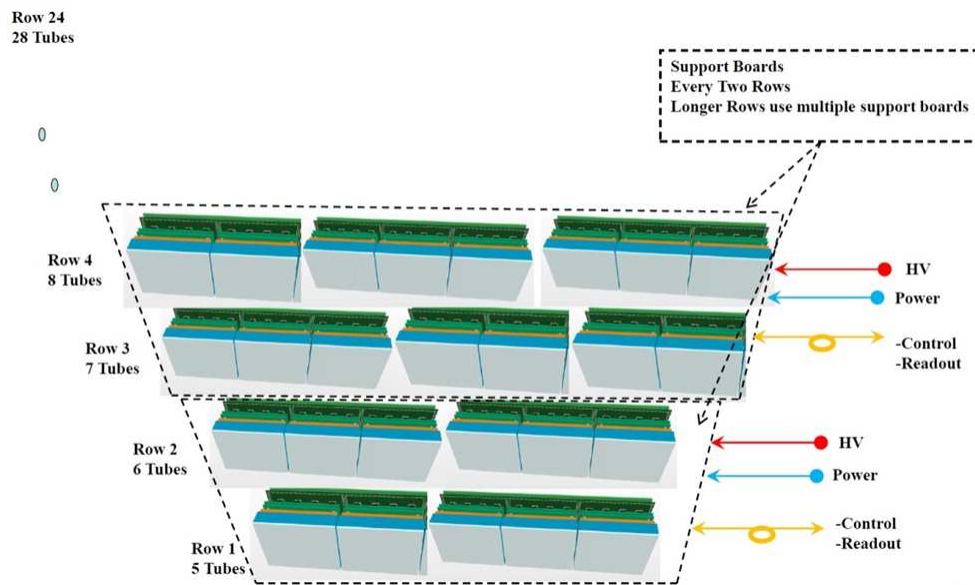


Figure 67: Schematic view of the mosaic assembly of the MAPMT motherboards in the electronic panel, with indication of the necessary cable connections.

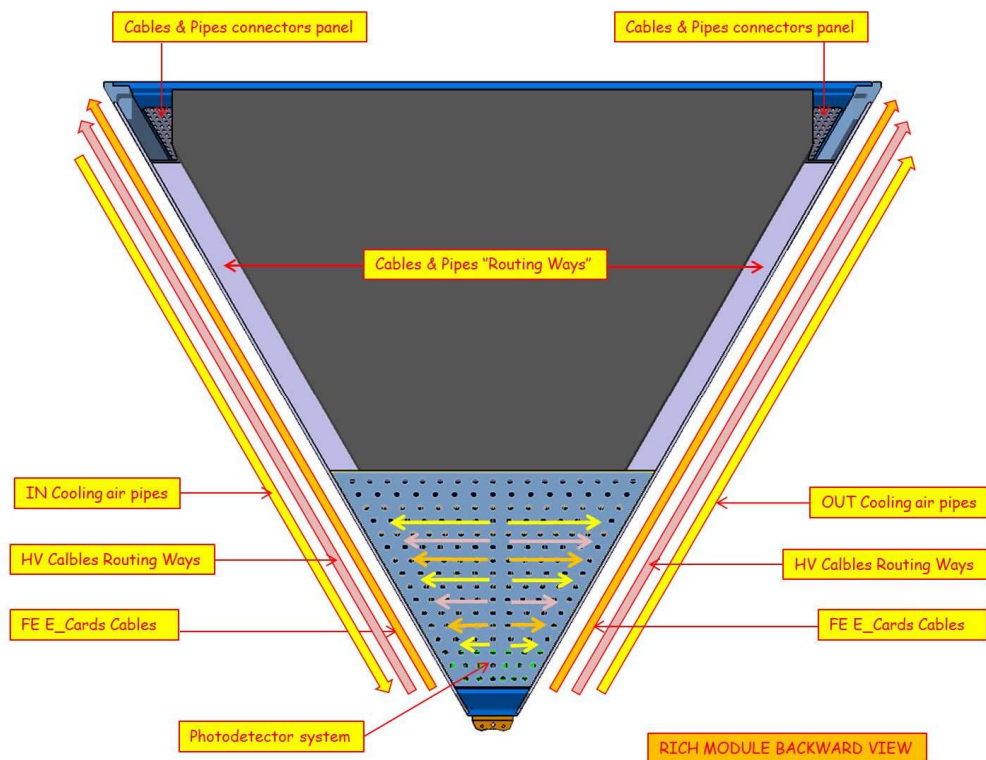


Figure 68: Routing of the cables from the electronic panel toward the racks.

11 Test of a RICH prototype

The RICH configuration presented in Sect. 5 is challenging in two major points: (i) the pion rejection factor necessary to correctly identify kaons, and (ii) the number of photoelectrons surviving the multiple pass through the aerogel. Some aspects of these questions have been addressed in laboratory tests, as for example measurements of the optical properties of the aerogel or the single photon response of the MAPMTs. However, a necessary step of this project is the validation of the proposed RICH geometry in conditions as close as possible to the real measurements. For this, a campaign of test beam has been undertaken in 2011 and 2012, using hadron as well as electron beams and prototypes of increasing complexity.

A first, preliminary, test has been performed in July 2011 at the T9 beam line of CERN using a simplified prototype, made by an aerogel radiator of variable thickness and refractive index, about 30 cm of gap and eight MAPMTs H8500. This first test showed that the chosen MAPMTs were actually capable to detect single photons also in the real experimental conditions and that the photon yield was sufficiently high to encourage further studies.

In 2012, a test has been performed at the Frascati Beam Test Facility (BTF) in order to setup the necessary acquisition system.

Finally, two new test beams have been performed using a large scale prototype specifically designed to provide the proof-of-principle of the detector. These tests have been done at the T9 test beam of CERN. Results of these tests will be extensively discussed in the next sections.

11.1 Prototype construction

In the real detector, the photons are revealed basically in two different conditions:

- at small angles (roughly below 13°) they are directly detected by the MAPMTs;
- at large angle particles, they are detected after two reflections and a double pass through the aerogel radiator.

As will be discussed in the Sect. 13.2, basically a typical RICH event may include photons detected in both conditions. To keep as simple as possible the construction, but at the same time to allow all the necessary measurements, the prototype has been designed in order to work in the two conditions: (i) direct light; (ii) reflected light.

The RICH prototype has been build at LNF inside a large (approximately $1.6 \times 1.8 \times 1.6$ m³) light-tight box, with internal modular supports holding the various components, that may be inserted or removed.

The Fig. 69 shows the schematic view, the project design and the realization of the prototype for the direct light measurements. The Cherenkov light is produced on the aerogel radiator, propagate for 1m inside the box and is then detected by an array of 28 MAPMTs, alternated of the type H8500C with normal glass and H8500C-03 with UV glass. The aerogel support can host tiles of approximately 58×58 mm² and of different thickness. The MAPMTs are mounted on a circular support and can be radially moved so to intercept the Cherenkov ring produced with different opening angles depending on the refractive index. The ring coverage varies between about 90% for a minimum MAPMT radial position of 280mm and 60% for the maximum radial position of 400mm. The main goals of these measurements are:

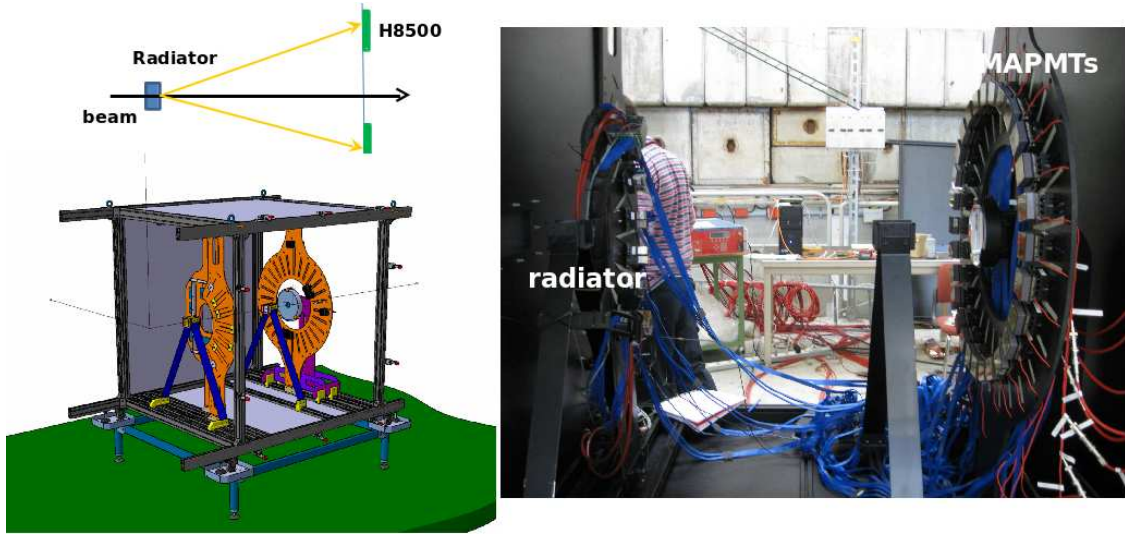


Figure 69: Top left: concept of the direct light measurements. Bottom left: drawing of the prototype. Right: picture of the prototype.

- study in details the Cherenkov angle resolution;
- measure the π/K separation up to 8 GeV/c;
- estimate the pion detection efficiency.

In Fig. 70, we show the setup for the reflected light measurements. In this case, the aerogel support is placed closer to the MAPMTs plane, then we have a spherical mirror which reflects the Cherenkov photons back toward a system of eight squared planar mirrors (dimensions $11.5 \times 11.5 \text{ cm}^2$) which send the light to the MAPMTs. The MAPMTs are mounted on a support similar to the one used for the direct light, but optimized to better match the coverage of the planar mirrors and the bigger Cherenkov ring radius due to the larger photon path. The ring coverage runs from about 75% (minimal radial position of 350 mm) to 50% (maximal radial position of 540 mm). The planar mirrors may be moved longitudinally to optimize the total gap length with respect to the focal length of the spherical mirror (thus maximizing the focussing effect), even though the geometrical constraints of the prototype didn't allow to put the MAPMTs on the mirror focal plane. The supports of the planar mirrors are designed to allow the insertion of tiles of aerogel, in order to study the photon yield absorption within the aerogel.

For these measurements, the main goal is the study of the depletion in the photon yield due to the multiple passes of the Cherenkov photons in the aerogel, namely:

- compare runs without or with aerogel absorber in front of the planar mirrors;
- optimize the aerogel thicknesses;
- compare the optical quality of different mirrors.

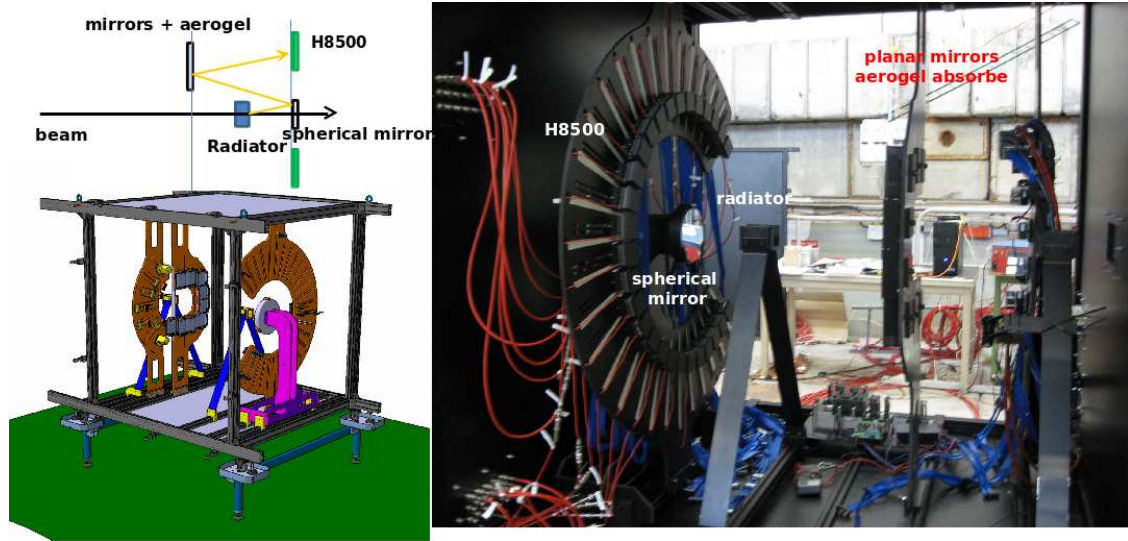


Figure 70: Top left: concept of the reflected light measurements. Bottom left: drawing of the prototype. Right: picture of the prototype.

Additionally, one could also study the π/K separation and the detection efficiencies. However, we must stress that the geometry of the prototype is different from that of the CLAS12 (smaller gap, photodetectors not on the focal plane of the mirrors), thus the results we have obtained will not be indicative of the final RICH performances. On the other hand, they will be used to tune the Monte Carlo simulations, that ultimately will provide us the expected performances of the detector.

The setup is completed by two planar Gas Electron Multiplier (GEM) chambers, installed outside of the RICH box, for tracking of the incoming particles, and by a gaseous threshold Cherenkov detector (part of the T9 equipment), used to make offline selection of pure pion or heavier hadron beam. Finally, two small plastic scintillators were placed at the end of the beam line, just after the second GEM chamber, to define the trigger signal of the DAQ system.

11.2 The T9 beam line at CERN

The main tests of the RICH prototype have been performed at the T9 beam line located in the East Area of the PS/SPS complex at CERN. The primary proton beam is sent to a target to produce a secondary beam. Different targets, magnets and collimators allow to select the composition of the secondary beam (electrons, muons or hadrons), the charge and the momentum (from 3 to 8 GeV/c). In our test, we run with the hadron target with negative charge (see the hadron intensities in Fig. 71) and momentum between close to the maximum range covered by CLAS12 in the two configurations: 8 GeV/c for the direct light and 6 GeV/c for the reflected light.

The time structure of the beam was determined by the extraction of one or more spills from the primary PS proton beam. Each spill had a duration of 400ms and the period of the PS operation was 40 s, so that overall the duty cycle was of the order of few percent.

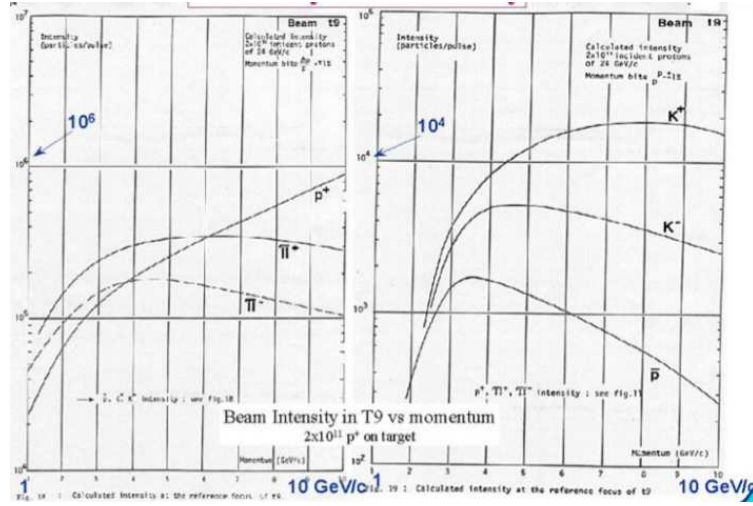


Figure 71: Hadron intensities as a function of the momentum in the T9 configuration of our tests.

From Fig. 71, we estimated in our beam a relative population of $\pi^- : K^- : \bar{p}$ of 160 : 4.5 : 1, approximately independent from the momentum in the range between 6 and 8 GeV/c.

The T9 standard equipment included a gas Cherenkov counter that has been used to separate pions from heavier hadrons by adjusting the gas pressure so that only pions were above threshold. A sample ADC spectrum is shown in Fig. 72, where we see a broad distribution due to the pions and a narrow pedestal peak of below-threshold hadrons. Cut at 150 channel (5σ above the pedestal peak) is set to separate pions from other hadrons.

11.3 Electronics and DAQ

The prototype was made by 28 MAPMTs for a total of 1792 channels. They were readout through the MAROC3 chip described in Sect. 8.4. Each MAROC3 chip was mounted on a front-end (FE) card connected to the MAPMT through a flat cable. The 28 FE cards were installed on a number of back-plane (BP, each of them may host up to 16 cards), connected to two control boards (CB). The total available channels are 4096 in a very compact system. The various components and the assembled set-up are shown in Fig. 73.

The GEM were readout using APV25 cards, which allow the analysis of the pulse shape of each strip by sampling the signals at fixed time intervals. Each card has 128 channels, thus one GEM was read by 2 APV card per side. The system was completed with a CAEN V785N ADC for the threshold Cherenkov readout. The DAQ software managed the acquisition of the different systems through a CAEN VME bridge V2718, connected to the computer via optical link.

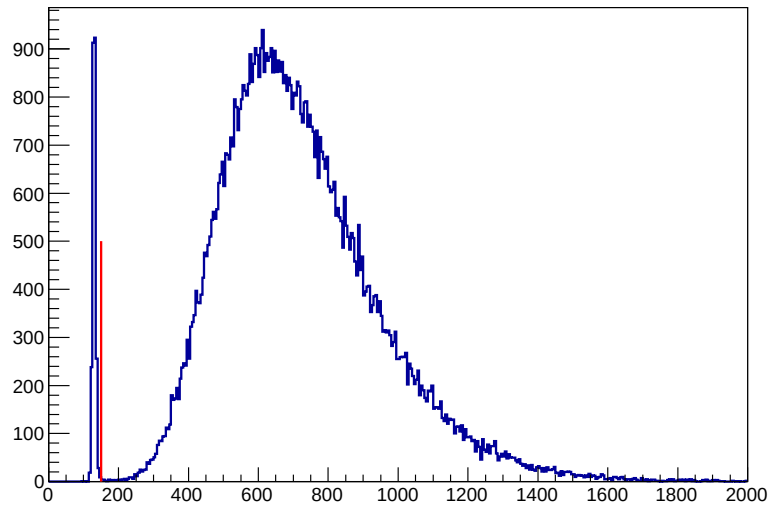


Figure 72: Typical ADC spectrum of the threshold Cherenkov counter. The red line indicates the threshold to separate pions from heavier hadrons.

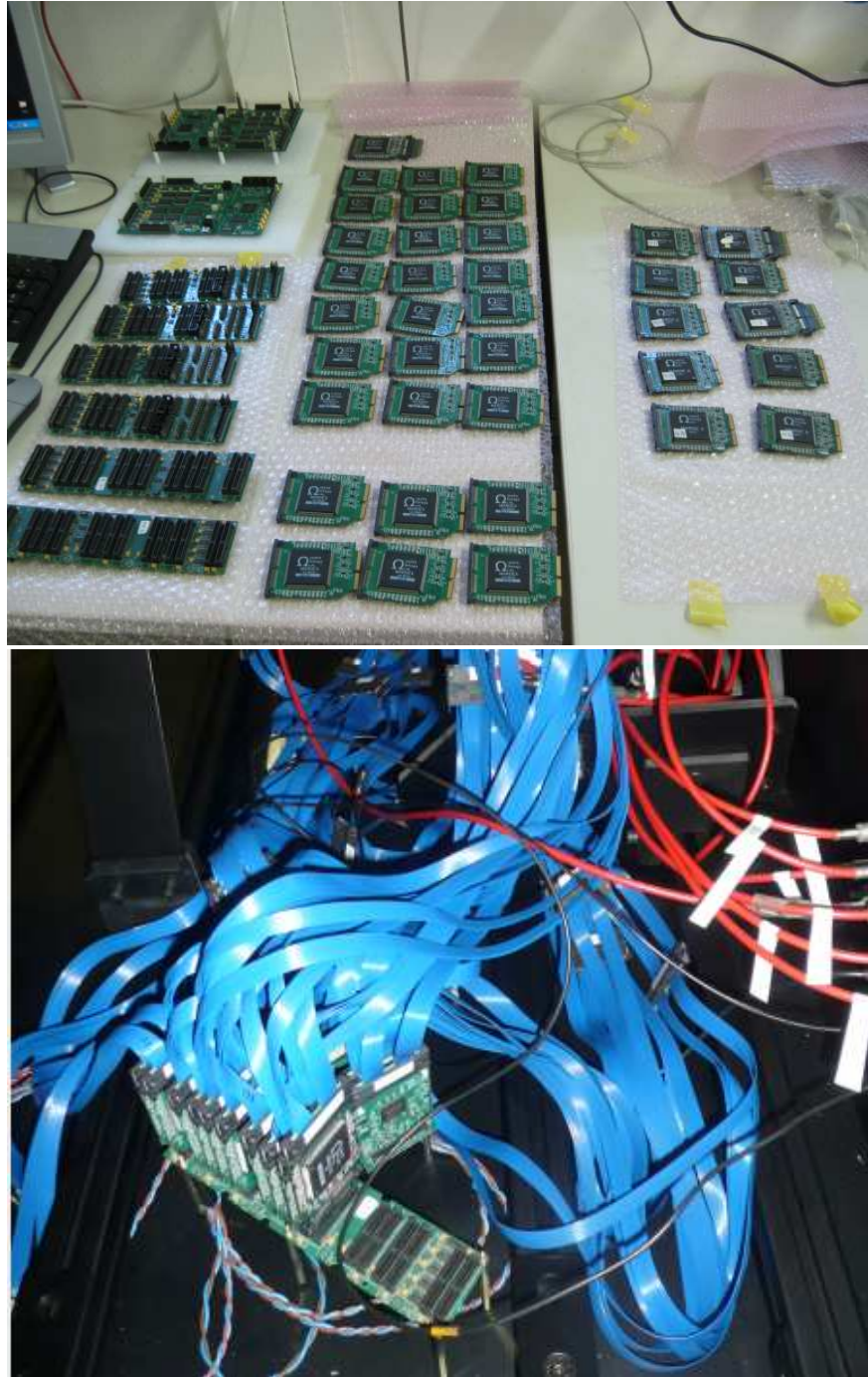


Figure 73: Left plot: the various components of the MAROC3 electronics. Right plot: the assembled setup installed in the RICH prototype box.

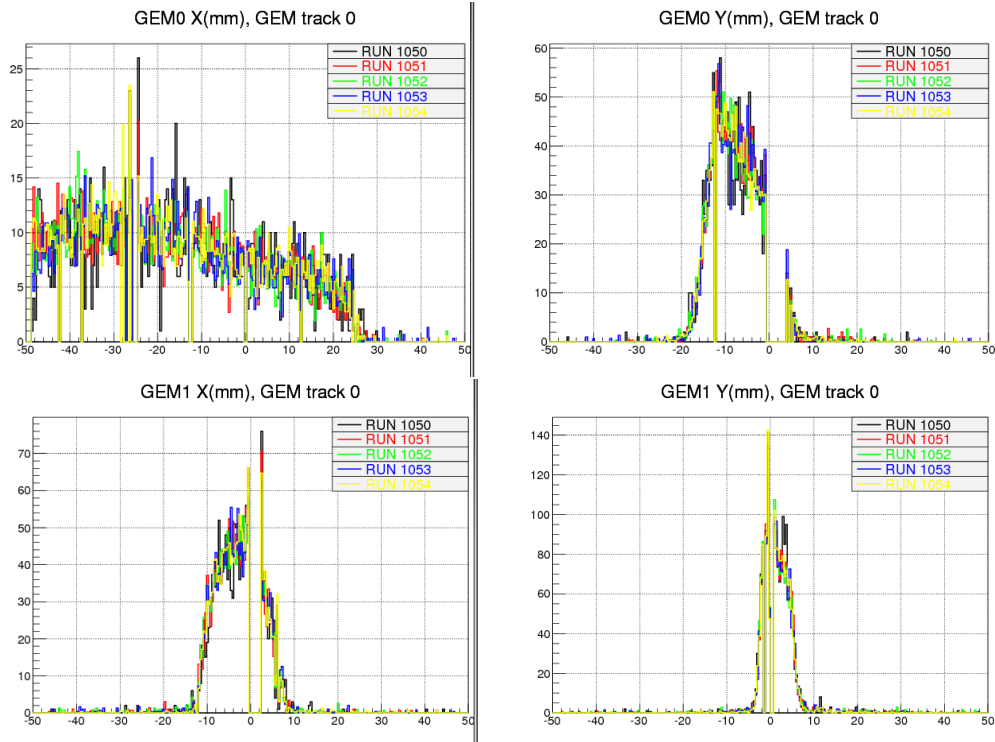


Figure 74: Horizontal and vertical beam profiles measured on GEM0 (upstream to the RICH, top plots) and GEM1 (downstream to the RICH, bottom plots).

11.4 Track reconstruction

Particle's trajectories are measured through two GEM chambers, placed about 4 meters far each other, with the downstream one about 80 cm after the MAPMT plane. Each chamber has a $10 \times 10 \text{ cm}^2$ area and is readout in 256 strips for both x and y . In each event, the strip signals are sampled three times at 20ns intervals, thus good signal are searched for by looking at peaks in the strip ADC distributions of all the 3 samples. In addition, one may require correlation between the amplitudes of the signals measured in the two planes of one GEM. A good GEM hit is obtained by any pair of signals measured on the two planes of one chamber. A good GEM track is reconstructed by matching one hit on the first GEM with one hit on the second GEM.

The beam profiles measured in the two GEM chambers are shown in Fig. 74 for several different runs over the data taking period. The holes in the distributions are due to noisy strips that have been removed in the off-line analysis. The measured profiles don't show any significant modification across the test period, thus ensuring the stability of the beam conditions and of the tracking system. The profile is wider on GEM0 (upstream GEM) because of the focussing of the beam. Part of the beam on the horizontal plane was missing the tracking system, resulting in a decreased tracking efficiency. There is also a different beam collimation in X and Y , so that the horizontal width is about twice the vertical one.

A typical distribution of the number of tracks per event is shown in Fig. 75. Most of the events have no good tracks, because of the tight cuts used for the reconstruction and also

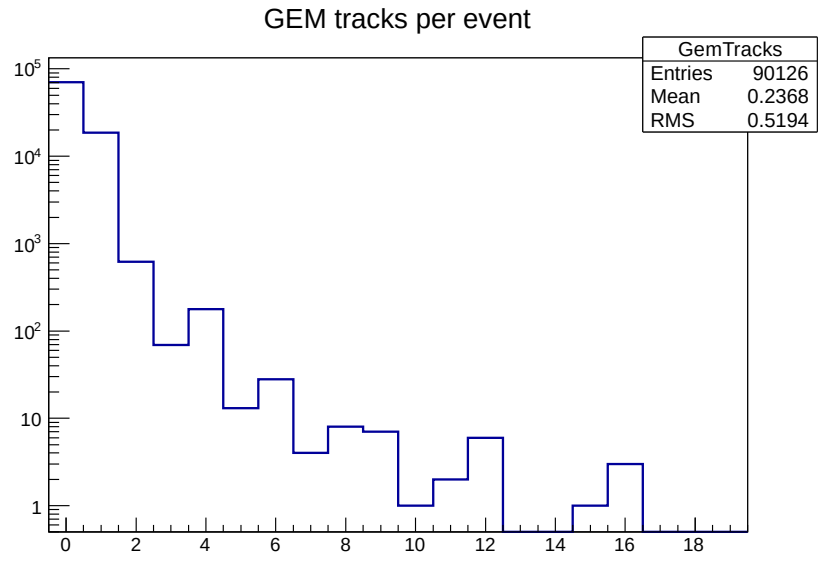


Figure 75: Number of GEM tracks per event.

because of the partial beam coverage of the first GEM. When more than one track in the event is found, only the one obtained from the biggest strip signals is retained. The average GEM efficiency was of the order of 30%. Loosening the cuts, efficiencies larger than 50% are obtained (limited by the partial coverage of the beam), without affecting the results.

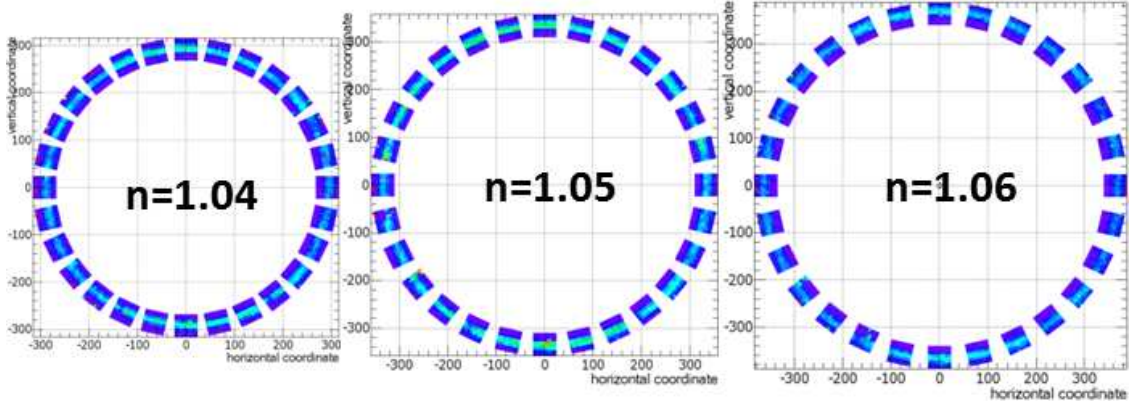


Figure 76: Cherenkov photon hit pattern measured with aerogel of different refractive index.

11.5 Ring reconstruction

In the prototype configurations, for the direct as well as for the reflected light measurements, the expected Cherenkov photon patterns are rings centered on the projection of the particle's track onto the MAPMTs array plane. MAPMT hits are identified by applying a 5σ cut above the pedestal peak. Examples of the measured hit distributions for different aerogel refractive index is shown in Fig. 76.

The Cherenkov rings are reconstructed by minimizing the quantity

$$S(R, X_C, Y_C) = \sum_{i=1}^{N_{pe}} [(x_i - X_C)^2 + (y_i - Y_C)^2 - R^2]^2 \quad (11)$$

where (x_i, y_i) are the coordinates of the i_{th} photon hit, (X_C, Y_C) are the coordinate of the ring center and R its radius. The minimization can be performed either analitically or using MINUIT.

In the analysis, one can make the ring reconstruction using only the MAPMTs array, fitting at the same time the center coordinates and the radius (a *3par* fit), or using the center information from the GEM track and fitting only the radius (a *1par* fit). In the latter case, a better resolution is expected, because of the reduced number of free parameters. Comparison between the two fits have been used as a validation of the GEM track reconstruction.

In principle, in the *3par* fit 3 hits are sufficient to reconstruct the ring, while in the *1par* fit just one would be enough. However, with such small number of hits the background may lead to uncorrect particle identification, thus a minimum number of 4 hits is always required.

The Fig. 77, shows for example the hit distribution of one event measured with $n = 1.05$ and $t = 2$ cm aerogel, together with the fitted ring. We can identify in this event 12 good hits laying on the ring, plus one hit (in the bottom center MAPMT) far enough from the ring that can be considered as background. Thus, an iterative procedure has been implemented in order to suppress background hits. A hit is considered as background if its distance from the fitted ring is bigger than some cut. In this case, the hit is removed and a new fit is performed taking into account only the remaining good Cherenkov hits. The cut value has been optimized to the data. In fact, a too loose cut will include too many background

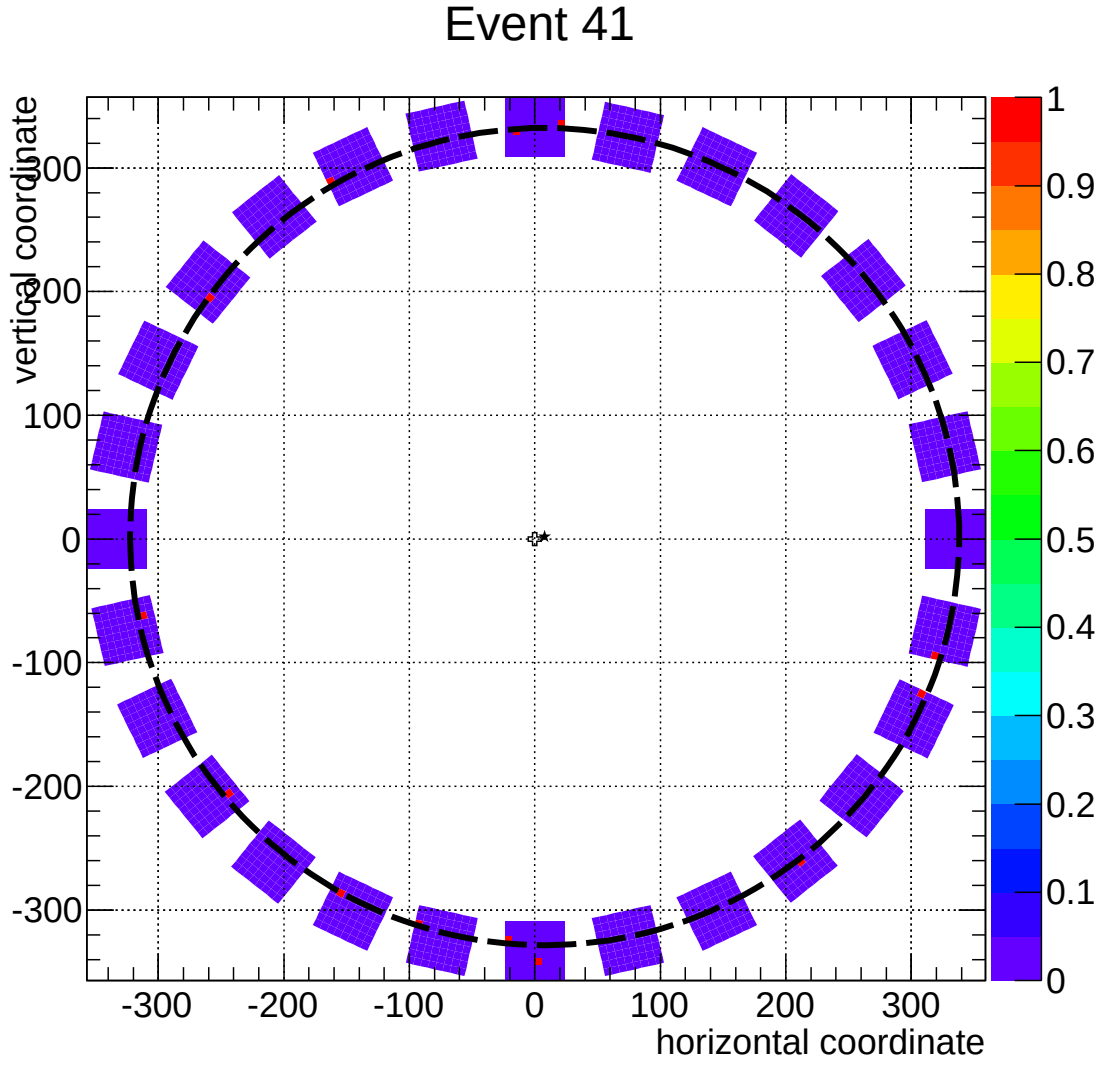


Figure 77: Hit distribution of one event measured with $n = 1.05$ and $t = 2$ cm aerogel. The circle show the Cherenkov ring fitted to the hits.

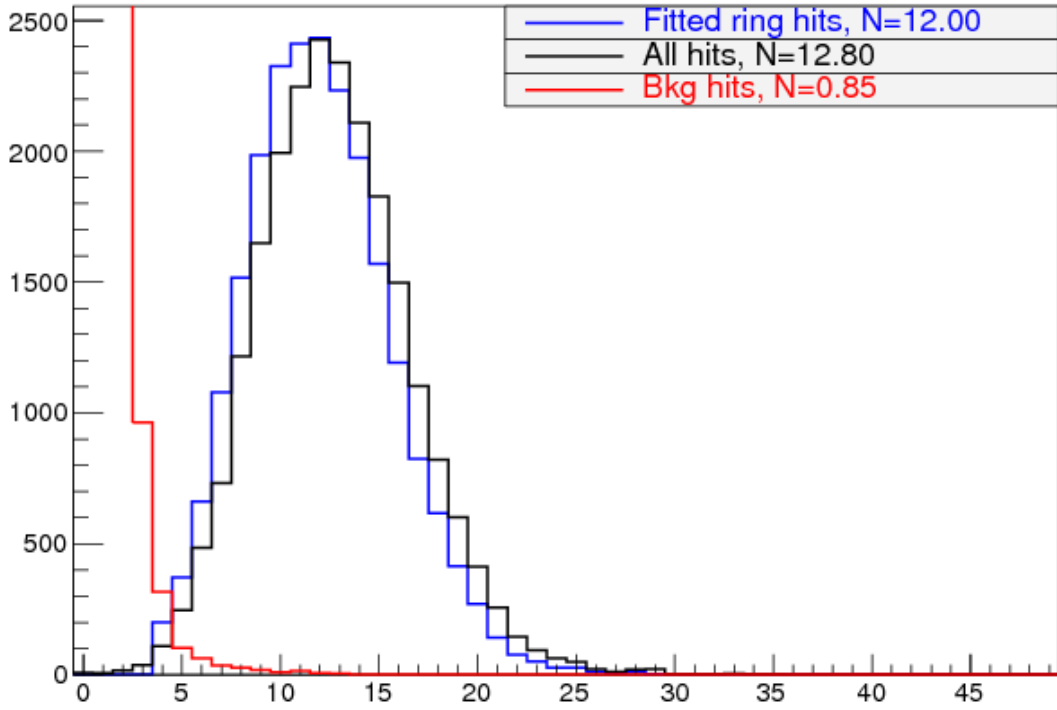


Figure 78: Number of MAPMT hit per event: all hit above threshold (black histogram), background hits (red histogram) and Cherenkov hit (blue histogram). Mean values of the distributions are reported in the legend.

hits, thus worsening the resolution, while a too tight cut will remove good photons, again worsening the resolution. An optimal value of 12mm has been found. In Fig. 78, the total number of hits (black histogram), background hits (red histogram) and Cherenkov hits (blue histogram) are shown. On average, with respect to about 12 Cherenkov hits, we have less than 1 background hits per event. Taking into account the total number of channels in the ring region, it corresponds to a background occupancy of about 10^{-4} .

Having the radius of the Cherenkov ring, the Cherenkov angle θ_C can be computed knowing the path length of the photons and taking into account the refraction on the surface between the aerogel and the external air, as shown in Fig. 79. The measured radius can be expressed as

$$R = \frac{A}{2} \tan(\theta_C) + \left(G - \frac{A}{2}\right) \tan(\theta_g) \quad (12)$$

where θ_g is the photon angle after the refraction, G is the gap length and A is the aerogel thickness. Here, we assumed that the emission of the photons takes place on average in the middle point of the aerogel tile. Applying the Snell's refraction law and eq. (1) relating the Cherenkov angle and the refraction index, one can solve numerically eq. (12) and obtain the Cherenkov angle or, equivalently, the refraction index.

The Eq. (12) can be easily generalized to take into account multiple passage through

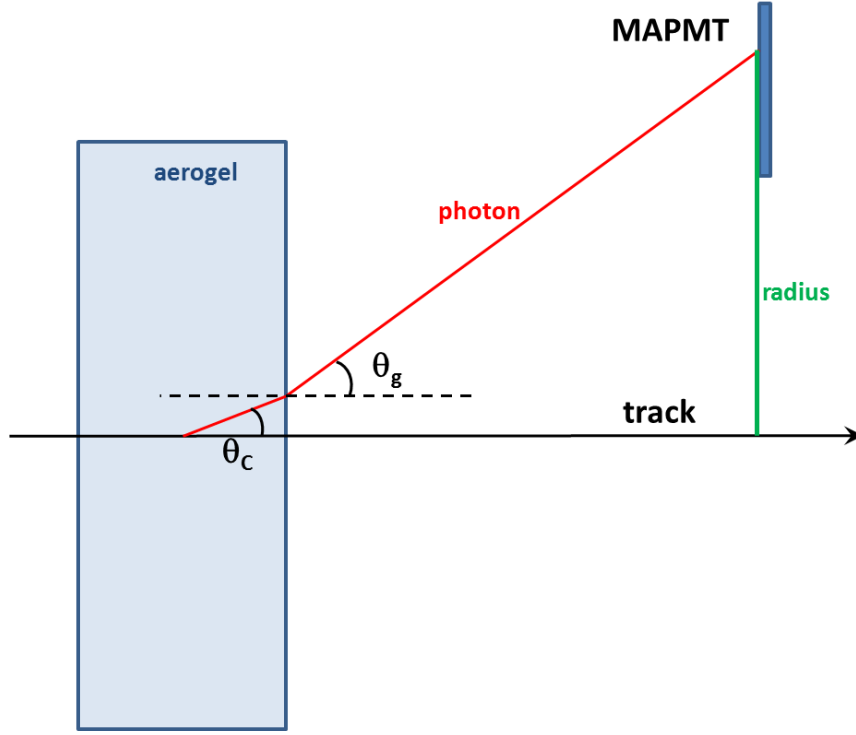


Figure 79: Illustration for the Cherenkov angle reconstruction.

different media, as will be discussed in the section 11.8.2 on the measurements with different optical filters.

11.6 GEM alignment

Rough alignment of the GEM chambers was done during the installation of the setup. A finer alignment has been obtained off-line by fitting the GEM tracks to the ring reconstruction.

A set of alignment $X_{GEM0}, Y_{GEM0}, X_{GEM1}, Y_{GEM1}$ constants has been introduced to take into account possible displacements of the GEM on the transverse plane with respect to the beam line. These displacements have been determined by minimizing the quantity:

$$Q(X_{GEM0}, Y_{GEM0}, X_{GEM1}, Y_{GEM1}) = RMS(R) + Mean^2(\Delta X) + Mean^2(\Delta Y) \quad (13)$$

where $RMS(R)$ is the RMS of the distribution of the Cherenkov ring radius in the *1par* fit and $Mean(\Delta X)$ and $Mean(\Delta Y)$ are the mean values of the distributions of the difference between the GEM track (projected on the MAPMT plane) and the ring center coordinates obtained in the *3par* fit. In Fig. 80, we show the Cherenkov angle distribution from the *3par* fit (left, $\sigma = 1.6$ mrad), from the *1par* fit before (center, $\sigma = 2.5$ mrad) and after (right, $\sigma = 1.4$ mrad) the offline alignment. An improvement of more than 10% in the ring resolution has been obtained from the *3par* to the *1par* fit. The stability of the procedure has been checked by calculating the alignment constants from several runs with different beam energies, as shown in Fig. 81. The six runs at $P = 8$ GeV/c have been taken at

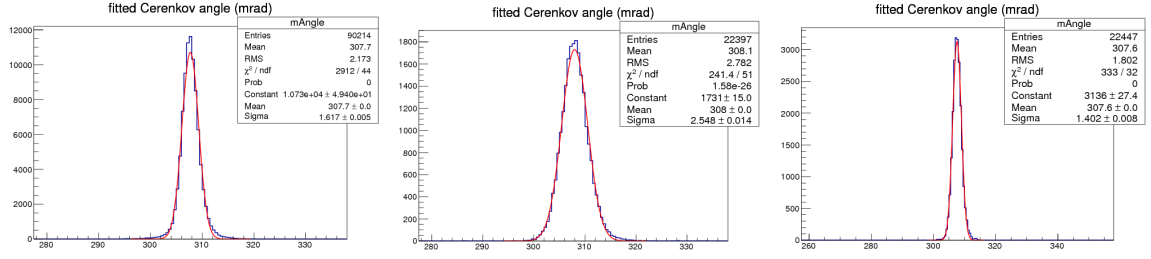


Figure 80: Cherenkov ring radius from the $3par$ fit (left), from the $1par$ fit before (center) and after (right) the GEM alignment procedure.

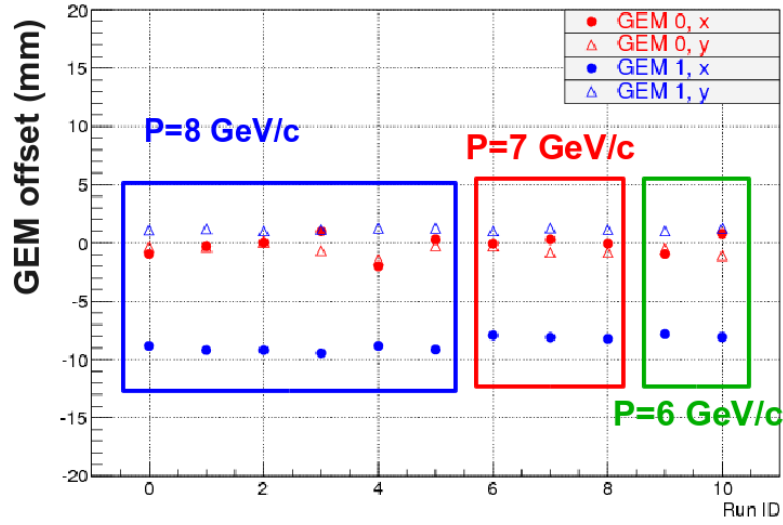


Figure 81: GEM alignment constants for various runs at different beam energies.

the beginning and the runs at $P = 6, 7$ GeV/c at the end of the data taking, but no major differences have been found. The final alignment constants are reported in Tab. 7.

11.7 Direct light measurements: pions and kaons

We report here the main results of the measurements with the direct light configuration, discussing the pion and kaon reconstruction and separation. Our reference run conditions have aerogel with nominal refractive index $n = 1.05$ and $t = 2$ cm thickness (December 2012 production in Tab. 3) and beam with $P = 8$ GeV/c, the highest reachable in the CLAS12 RICH. Our Cherenkov ring reconstruction is performed with a $1par$ fit using the GEM alignment constants in Tab. 7. We select events with at least 4 MAPMT Cherenkov hits (after background subtraction).

GEM	X_{GEM} (mm)	Y_{GEM} (mm)
0	-0.32 ± 0.12	0.00 ± 0.13
1	-9.14 ± 0.03	1.04 ± 0.02

Table 7: GEM alignment constants.

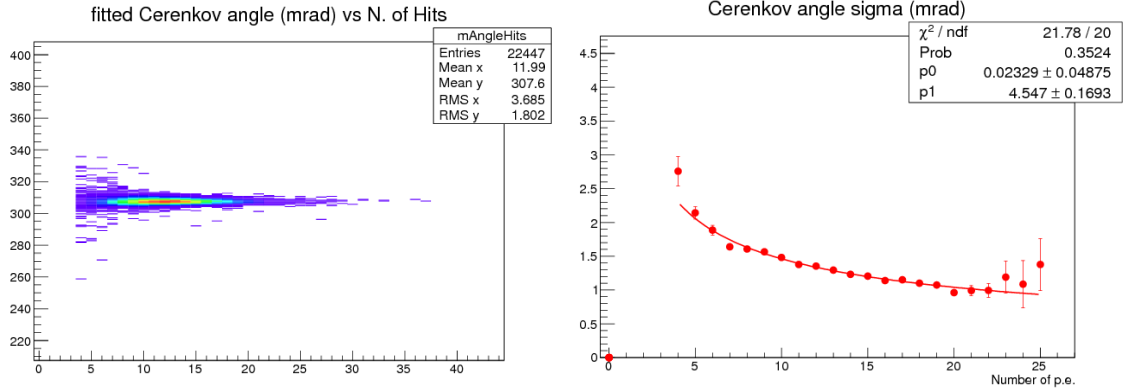


Figure 82: Data with $n = 1.05$ and $t = 2$ cm. Left plot: Cherenkov angle versus the number N_{pe} of photoelectrons. Right plot: gaussian width of the Cherenkov angle distribution as a function of N_{pe} .

11.7.1 Pion Reconstruction

Pion events are selected by requiring a gas Cherenkov counter signal above threshold, see Fig. 72.

In the left panel of Fig. 82, we show a scatter plot of the Cherenkov angle versus the number N_{pe} of photoelectrons. It is clear that the distributions get narrower as N_{pe} increases. For a fixed number of N_{pe} , the angle distribution has been fitted with a gaussian to extract mean and width. The mean values don't show any appreciable deviation from the one obtained in the integrated fit (see Fig. 80 right). The gaussian widths are expected to follow the statistical law:

$$\sigma_{\theta} = \frac{\sigma_{1pe}}{\sqrt{N_{pe}}} \quad (14)$$

where σ_{1pe} is the single photon detection resolution. To take into account possible spurious contributions, in particular from the tracking system, the results in the right plot of Fig. 82 has been fitted with the function

$$\sigma_{\theta} = \sigma_0 + \frac{\sigma_{1pe}}{\sqrt{N_{pe}}} \quad (15)$$

The fit gives a constant term compatible with zero and a single photon resolution $\sigma_{1pe} = 4.55 \pm 0.17$ mrad.

We now assume as identified pions those events with an angle within $\pm 3\sigma$ around the mean value, with the σ given by the fit in the right plot of Fig. 82. We then calculate the pion detection efficiency as the ratio between the number of identified pions and the number

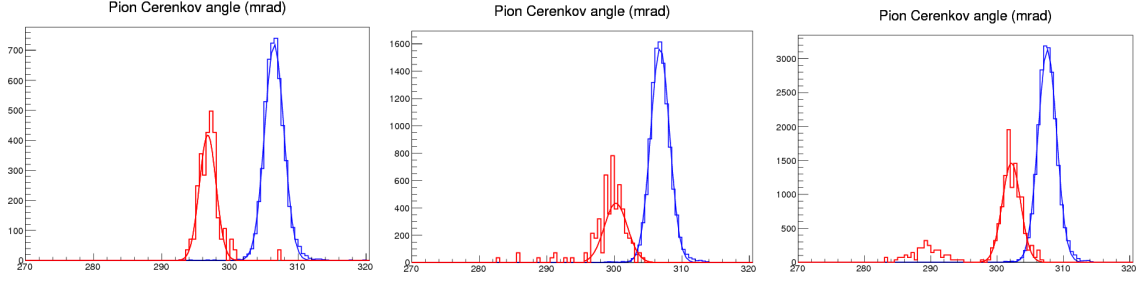


Figure 83: Pion Cherenkov angle distributions (in mrad, blue histograms) compared with those from events with gas Cherenkov signal below threshold (red histograms), for $P = 6, 7, 8$ GeV/c beam (from left to right).

P (GeV/c)	$\theta_C(\pi)$ (mrad)	$\sigma_\theta(\pi)$ (mrad)	$\theta_C(K)$ (mrad)	$\sigma_\theta(K)$ (mrad)	n_σ	R
6	306.52 ± 0.02	1.41 ± 0.02	296.76 ± 0.15	1.23 ± 0.15	6.9	726
7	306.78 ± 0.02	1.40 ± 0.01	299.97 ± 0.19	1.64 ± 0.21	4.7	520
8	307.58 ± 0.01	1.40 ± 0.01	302.16 ± 0.08	1.40 ± 0.07	3.9	475

Table 8: Gaussian mean and width of pion and kaon Cherenkov angles, number of σ separation and rejection factor, the latter computed assuming $\sigma_\theta(K) = \sigma_\theta(\pi)$.

of events with gas Cherenkov counter signal above threshold. We obtain $\epsilon(\pi) = 98.4 \pm 0.1\%$. No beam energy dependence has been found.

11.7.2 Kaon Reconstruction

Events below the gas Cherenkov counter threshold includes both kaons and antiprotons. In Fig. 83, we compare the Cherenkov angle distributions measured for these events (red histograms) with the distributions for pions (blue histograms) at the three beam energies $P = 6, 7, 8$ GeV/c, from left to right. The red histograms are rescaled by the relative beam intensities (see Sect. 11.2). We see the prominent kaon peak separated from the pion one and, at the highest energy, some tail of the $\bar{p}$ peak, which disappears as the energy decreases because it goes out of the MAPMTs radial coverage. In Tab. 8, we report the mean and width of the gaussian fits of the pion and kaon angles and, in the last two columns, the number of σ separation n_σ between kaon and pion and the kaon to pion rejection factor R . For the last two numbers, to avoid the large fluctuations in the value of $\sigma_\theta(K)$ due to the small kaon statistics, we assumed $\sigma_\theta(K) = \sigma_\theta(\pi)$. We define n_σ as:

$$n_\sigma = \frac{\theta_C(\pi) - \theta_C(K)}{[\sigma_\theta(\pi) + \sigma_\theta(K)]/2} \quad (16)$$

The rejection factor is computed from the fraction of pions out of a 3σ cut falling below the kaon peak. As we see, we match the requirement $R \geq 500$ basically in the whole momentum region.

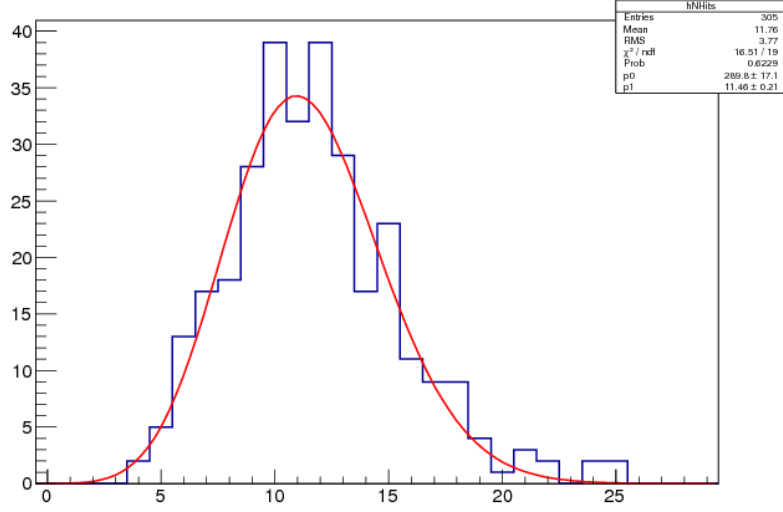


Figure 84: Number of Cherenkov hits per event for kaons with $P = 8$ GeV/c.

P (GeV/c)	$\epsilon(\pi)$ (%)	$\epsilon(K)$ (%)
6	98.4 ± 0.2	99 ± 2
7	98.3 ± 0.1	95 ± 2
8	98.8 ± 0.1	67 ± 3

Table 9: Pion and kaon detection efficiencies measured at three momenta. The errors are statistical only.

To calculate the kaon efficiency, we need to know the number of incoming kaons in the beam. From Fig. 71, the K/π flux ratio may be estimated only approximatively, thus we used a statistical analysis of the measured photon yield. We consider for example the highest beam energy, $P = 8$ GeV/c, and we apply a cut $\theta_C > \theta_C^{min}(K) = 296$ mad to separate kaons from $\bar{p}$. In Fig. 84, we show the number of Cherenkov photon hits per event measured for the kaons. The histogram is fitted with a Poisson curve in order to estimate the fraction of events with less than four hits, the minimum required for the ring reconstruction. We found this fraction basically negligible for kaons for all the momenta.

The pion and kaon peaks partially overlap, especially at the highest beam energy. Thus, to suppress the pion contamination, we consider as identified kaons those events with

$$\theta_C^{min}(K) < \theta_C < \theta_C^{min}(\pi) \quad (17)$$

where $\theta_C^{min}(\pi) = \theta_C(\pi) - 3\sigma_\theta(\pi)$ and the pion ring width $\sigma_\theta(\pi)$ is the N_{pe} -dependent one of the fit in Fig. 82. The efficiencies, for both pions and kaons, are reported in Tab. 9.

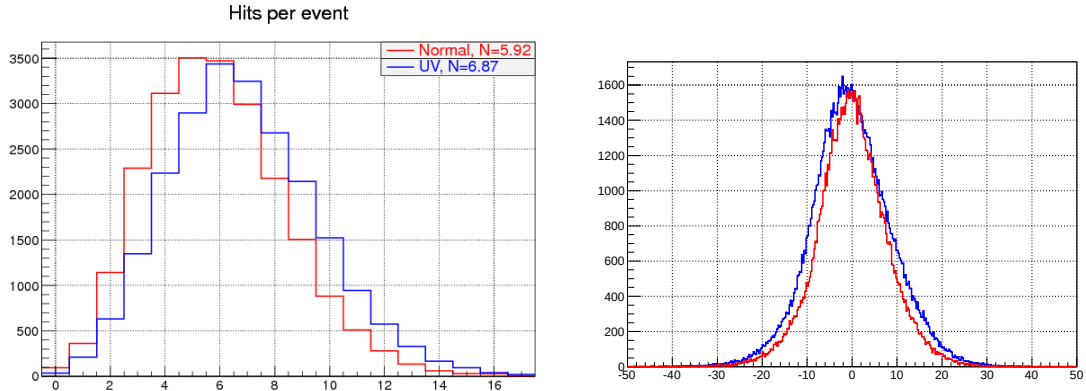


Figure 85: Left plot: number of hits per event with normal glass (red histogram) and UV-enhanced glass (blue histogram) MAPMTs. Right plot: same comparison for the residuals.

11.8 Direct light measurements: systematic studies

In this section, we discuss several systematic measurements performed varying the aerogel radiator as well as the MAPMT configuration. On one side, they will be used to tune the Monte Carlo simulation of the CLAS12 RICH, on the other side they will give us information on the improvements that can be obtained in the final detector.

11.8.1 UV photons

The array of MAPMTs include 14 with normal glass window H8500C and 14 with UV-enhanced glass window H8500C-03, alternated along the ring. The effect of the UV photons can be estimated by comparing the photon yield and Cherenkov angle resolution using only the MAPMTs of the same type. In Fig. 85, we show the distributions of the number of MAPMT hits (left plot) and of the residuals, i.e. the distance between the hit and the ring (right plot). The red histograms refer to normal glass MAPMTs and the blue ones to the UV-enhanced glass. The latter have on average one hit more, but the residual distribution is significant broader and slightly off from zero. This is due to the bigger scattering of the UV photons before reaching the MAPMTs. The result is that, though having one Cherenkov hit less, the resolution is better using the normal glass, as shown by Fig. 86, where the gaussian width of the Cherenkov angle as a function of N_{pe} for the two types of MAPMT is compared with the one obtained using all the 28 MAPMTs. In Tab. 10, we report the extracted values of the single photon resolution. Overall, we observe that H8500C-03 have a resolution about 30% worse than the H8500C.

11.8.2 Chromatic effect studies

The Cherenkov ring resolution has been studied as a function of the photon wavelength by applying optical filters just after the aerogel radiator. Data have been acquired by selecting pion events and the set of available filters allowed to span the entire range of relevant wavelengths, from UV to the red. At each wavelength, the refraction index is obtained from the

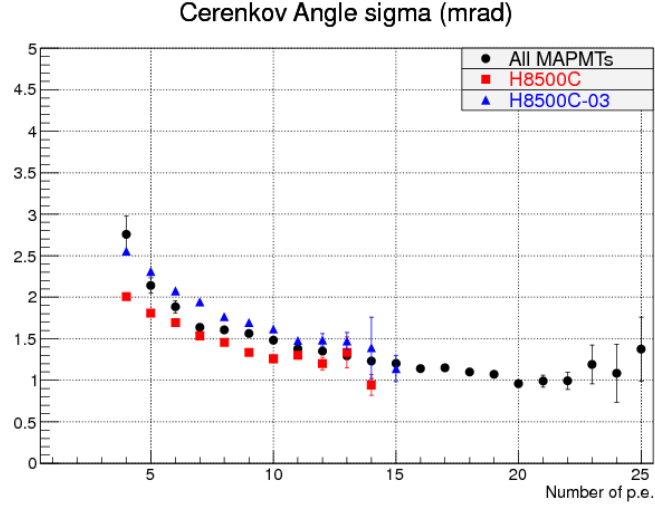


Figure 86: Gaussian width of Cherenkov ring radius as a function of N_{pe} measured with 14 UV-enhanced glass MAPMTs (blue triangles), with 14 normal glass MAPMTs (red squares) or with all the 28 MAPMTs (black circles).

	σ_{1pe} (mrad)
14 H8500C	3.96 ± 0.16
14 H8500C-03	5.09 ± 0.03
All 28	4.55 ± 0.17

Table 10: Single photon resolutions of the Cherenkov angle for the various type of MAPMTs.

Cherenkov angle through the eq. (1).

In the left plot of Fig. 87 we show the results for the case of aerogel with nominal refraction index $n = 1.05$ and $t = 2$ cm. The blue line is a fit of the data using the dispersion relation, eq. (4), with the gray band showing the uncertainty due to fitted parameter errors. The black line represent the dispersion relation used in the Monte Carlo simulations, which is in good agreement with the measurements. At our reference wavelength $\lambda = 400\text{nm}$, where the MAPMTs have the highest quantum efficiency, we obtain a refraction index $n = 1.0492 \pm 0.0004$. According to the quotation provided by the Novosibirsk factory, the refractive index at $\lambda = 400$ nm can be obtained by using the equation

$$n^2(400\text{nm}) = 1 + 0.438\rho \quad (18)$$

The measured aerogel density is $\rho = 0.230\text{g/cm}^3$ and the value $n_{quoted} = 1.0492$, in perfect agreement with our measurements.

Similar studies have been performed with a 2cm tile with nominal refraction index $n = 1.06$ and the results are shown in the right plot of Fig. 87. The collected statistics is lower here, especially at the extreme wavelengths, nevertheless we found a good description of

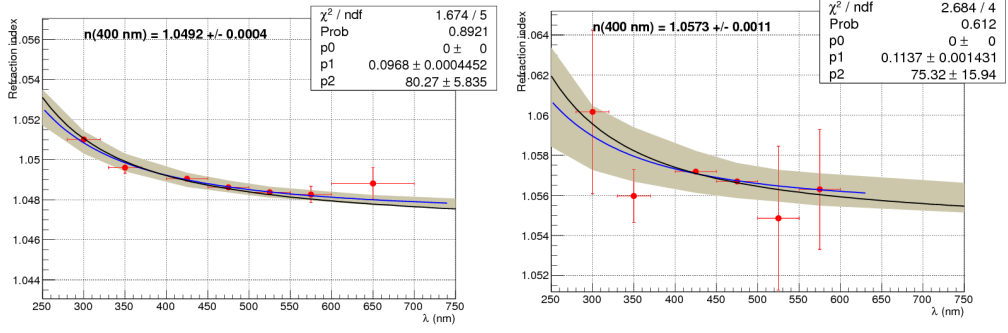


Figure 87: Measured refractive index as a function of the wavelength for an aerogel tile with $n = 1.05$ (left) and $n = 1.06$ (right) nominal refractive index and $t = 2$ cm aerogel. The blue curve is a fit of the data using the the dispersion law (with error indicated by the gray band) and the black curve is the dispersion curve used in the Monte Carlo simulations.

the data using the dispersion law of eq. (4), which gives at the wavelength $\lambda = 400\text{nm}$ a refractive index $n = 1.0574 \pm 0.0010$, slightly lower than the nominal one.

11.9 Reflected light measurements

For these measurements we ran with two different curved mirrors, a glass spherical one and a composite elliptical one, produced at JLab as a prototype for the HTCC detector. The setup (see Fig. 70) was completed by the aerogel radiator placed about 20 cm before the curved mirror and a set of eight planar mirrors, in front of which tiles of aerogel could be placed.

Though similar in the concept, this configuration is not the same as for the CLAS12 RICH. In fact, the total gap length is much smaller (about 1.3m vs 3m) and it was not possible to put the MAPMTs on the focal plane of the mirrors. In addition, the relative alignment of the mirror system with the prototype box was checked only at a few mm level and a relative off-line alignment of the various elements was performed using the Monte Carlo simulations. Thus, we expect to obtain from the prototype measurements a worse ring reconstruction resolution than in the CLAS12 RICH. However, the results will be used to tune the Monte Carlo simulations from which we will estimate the RICH resolution.

We run with beam momentum of 6 GeV/c, the maximum momentum reached at large angles in the CLAS12 RICH. In the nominal configuration we had aerogel radiator with refractive index $n = 1.05$ and thickness $t = 6$ cm. Data were recorded with and without aerogel absorbers in front of the planar mirrors. Here we used tiles with $n = 1.05$ and $t = 2$ cm, five from the latest production (Dec. 2012, see Tab. 3) and three from a previous production (June 2012, see Tab. 3).

11.9.1 Results with the spherical mirror

The spherical mirror, produced by the Marcon company [22] was made of glass, had a diameter of 25cm and a focal length of 90 cm. In Fig. 88, we show the number of hits per event with and without the absorbers for incoming pions. We have 13.1 p.e. without absorber and 5.3 with absorber, with a yield loss of about 60%.

The ring radius reconstruction for the two measurements is compared in Fig. 89 and all the relevant numbers are reported in Tab. 11. In the left plot of Fig. 89, we compare the radius distribution measured without absorber with the results with the absorber. We see a worsening of the resolution, from $\sigma_R = 2.67 \pm 0.01$ mm without absorbers to $\sigma_R = 3.79 \pm 0.02$ mm with the absorbers. This is largely due to the decrease in the number of p.e. The resolutions as a function of the number of p.e. is shown in the right plot of Fig. 89. While without absorber there are events up to $N_{pe} = 20$, with the absorbers the maximum value with significant statistics is $N_{pe} = 11$.

The data in the left plot of the Fig. 89 have been fitted with eq. (15). As we see from Tab. 11, we observed a slight worsening of the single photon resolution, of the order of few percent. We also observed a non-negligible, though small, constant term σ_0 . This term arises from effects not strictly associated to the Cherenkov ring reconstruction (it doesn't scale with N_{pe} but from other effects like misalignment in the setup. We know from the direct light data (see Fig. 82) that GEM tracking misalignments are negligible, thus we may conclude that this term is most likely due to misalignment in the mirror system of the prototype. A much better control of the relative alignments will be obtained in the CLAS12 RICH final detector. Thus, we can safely subtract this constant term from the radius resolution, yielding

Marcon Mirror, 6 cm 1.05

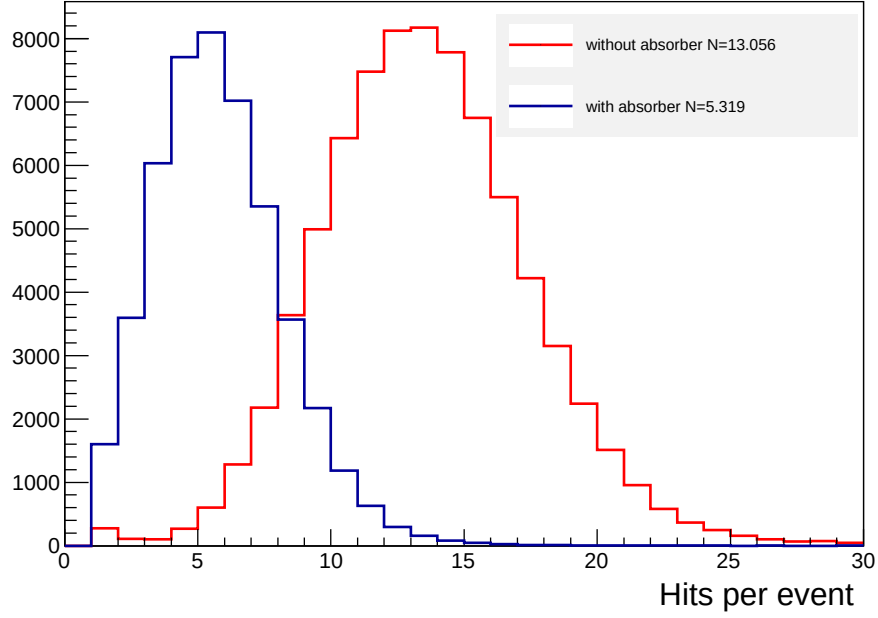


Figure 88: Number of hits per event for data without the aerogel absorber (red histogram) and with the 2cm aerogel absorbers placed in front of the planar mirrors (blue histogram).

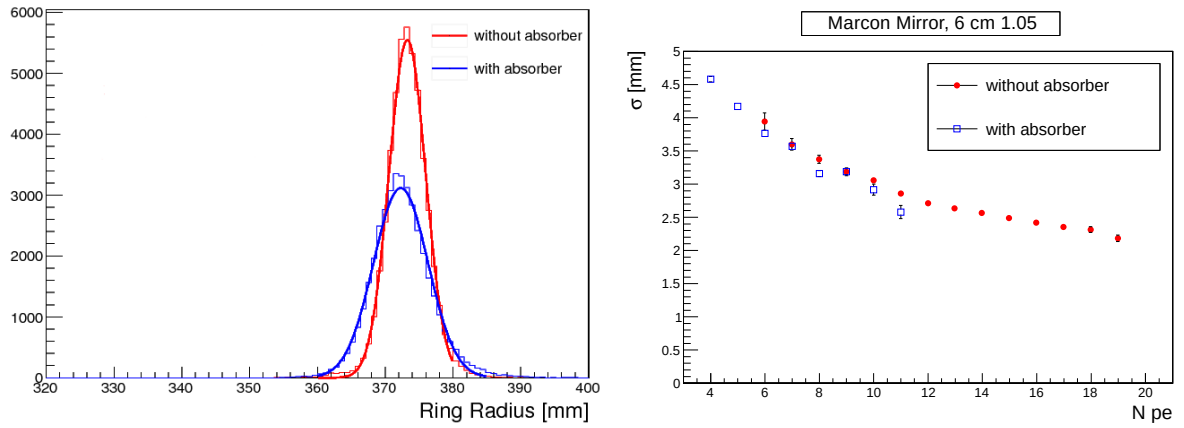


Figure 89: Left plot: ring radius distributions without (red histogram) and with (blue histogram) the aerogel absorber. Right plot: gaussian width of the ring radius as a function of the number of $p.e.$ for runs without (blue empty squares) and with (red filled circles) the aerogel absorbers.

Absorbers	R (mm)	σ_R (mm)	σ_{1pe} (mm)	σ_0 (mm)	σ_R^{corr} (mm)	σ_θ^{corr} (mrad)
NO	373.31 ± 0.01	2.67 ± 0.01	8.81 ± 0.25	0.22 ± 0.07	2.45 ± 0.07	1.71 ± 0.05
YES	372.19 ± 0.01	3.79 ± 0.02	9.10 ± 0.21	0.35 ± 0.09	3.44 ± 0.09	2.41 ± 0.06

Table 11: Resolutions for pion rings without and with aerogel absorbers: radius gaussian mean (R) and width (σ_R), single photon resolution (σ_{1pe}) and constant term (σ_0), radius resolution after correction for the constant term (σ_R^{corr}); last column reports the corrected resolution on the Cherenkov angle (σ_θ^{corr}).

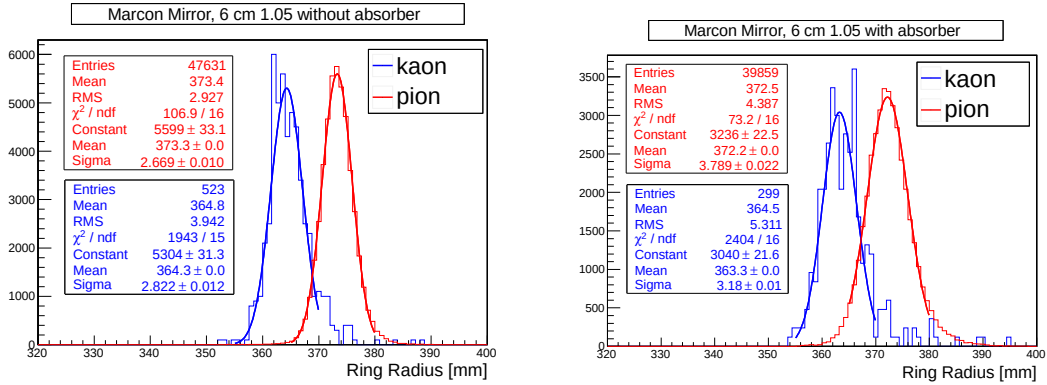


Figure 90: Pion (red histograms) and kaon (blue histograms) ring radius distributions without (left plot) and with (right plot) aerogel absorber in the reflected light data with aerogel radiator with $n = 1.05$ and $t = 6$ cm.

the final pion ring radius resolutions reported in the last two columns of Tab. 11 in terms of radius (σ_R^{corr}) and Cherenkov angle (σ_θ^{corr}).

The kaon/pion separation power is shown in Fig. 90 without (left plot) and with (right plot) the aerogel absorbers. By correcting also the kaon resolution for the constant term, we obtain the pion/kaon separations of $n_\sigma = 3.6$ (no absorbers) and $n_\sigma = 2.8$ (with absorbers).

11.9.2 Comparison with the JLab mirror

We made measurements also using an elliptical mirror produced at JLab placed instead of the spherical one. This mirror had semi-axes $a_x = 1848$ mm and $a_y = 1613$ mm, cut in a rectangular shape of approximately 533×361 mm². Comparison between the results with the two different mirrors have been done in order to have a first rough estimate of the performance dependence on the mirror technology and shape. Due to the complications in checking the alignment of this mirror with respect to the beam line and to the asymmetry produced in the Cherenkov ring, this comparison will be performed by doing a $3par$ fit, i.e. without using the GEM tracking information. When fitting the ring, a rescaling of the horizontal and vertical coordinates of +4% and -4% has been applied, in order to take into account the elliptical shape of the mirror surface.

The number of p.e. with two mirrors are compared in Fig. 91 without (left plot) and with (right plot) aerogel absorbers. No significant differences have been found. The single

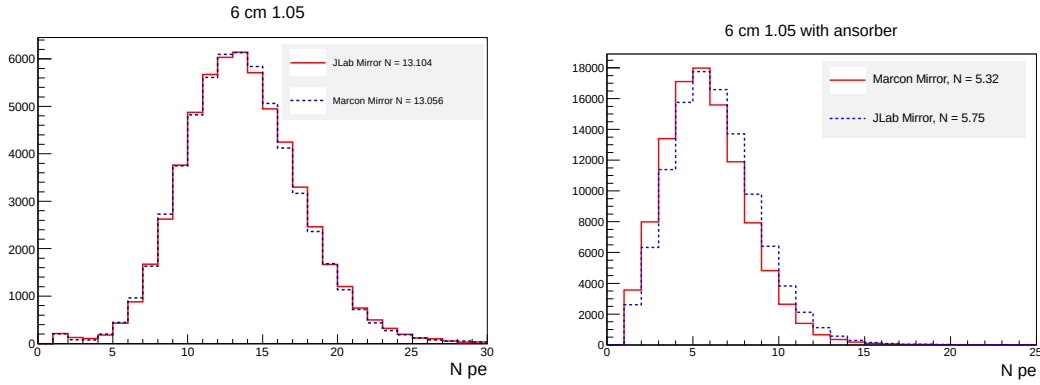


Figure 91: Number of p.e. per event using JLab composite (red full histograms) and Marcon glass (blue dashed histograms) mirrors: results without (left plot) and with (right plot) aerogel absorbers.

Absorbers	Marcon	JLab
NO	13.38 ± 0.04 mm	14.64 ± 0.06 mm
YES	16.24 ± 0.07 mm	17.29 ± 0.07 mm

Table 12: Single photon resolution σ_{1pe}^R of the Cherenkov ring radius extracted from reflected light data with and without aerogel absorbers for Marcon (spherical) and JLab (elliptical) mirrors.

photon resolutions σ_{1pe}^R are compared in Tab. 12. The numbers are very close, with the composite JLab mirror having a slightly (about 1 mm) worse resolution.

11.10 Monte Carlo comparison

The setup used in the CERN test beam has been implemented in a Monte Carlo using the same **GEANT4** package used in the simulation of CLAS12. Several parameters of the simulations required a fine tuning and have been validated by comparing with the test beam results. After this process, a satisfactory agreement between the simulation and the test beam data has been obtained, thus allowing to apply the Monte Carlo code to simulate the response of the CLAS12 RICH with confidence that the results will be a reasonable estimate of the detector performances.

The test beam simulation includes:

- the exact geometry of the setup, with the same MAPMT configuration files used to reconstruct the experimental data;
- detailed description of the aerogel characteristics, based on laboratory characterization;
- full digitalization of the MAPMTs response;
- hadron tracks taken from the experimental data;

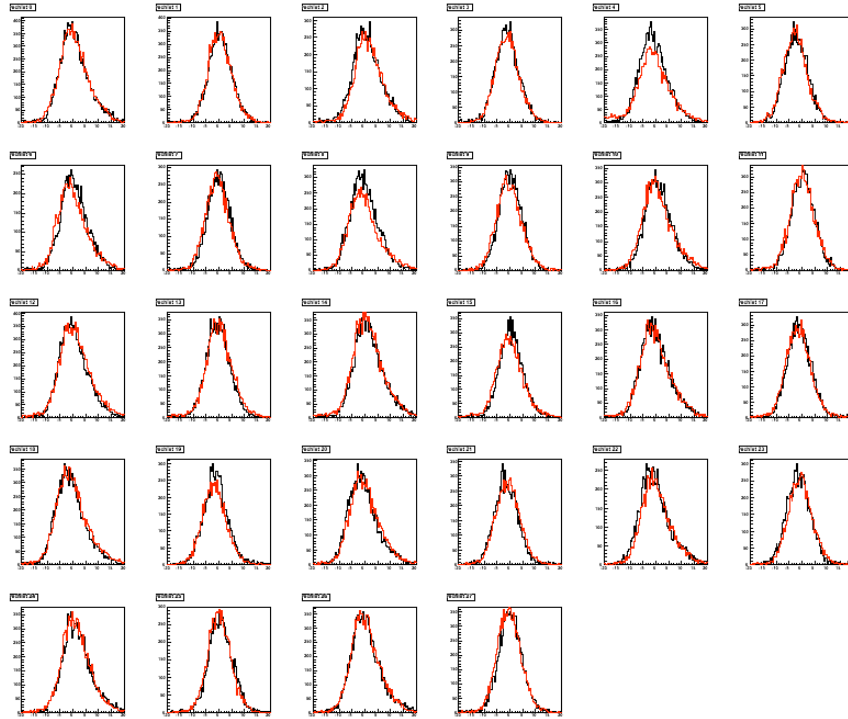


Figure 92: Residuals from experimental data (red histograms) and Monte Carlo simulation (black histogram) compared for each of the 28 MAPMTs in the direct light configuration with aerogel with $n = 1.05$ and $t = 2$ cm.

The optical properties of the aerogel are defined through a number of empirical parameters describing not only the propagation of the light inside the medium (as for example the scattering length or the dispersion), but also the surface effects. Validation of the model is provided by the dispersion law shown in the Fig 87, where the curve used in the simulation is in good agreement with the experimental data.

The digitalization of the MAPMT response has been done by implementing the pixel structure of the H8500 tubes, including the dead spaces between the pixels and the global efficiency measured in the laser tests. Based on these tests, for each MAPMT hit, a 3% cross talk probability has been applied. Finally, at each event random dark counts with a probability of 10^{-4} , as measured in the test beam, has been added to the list of real hits.

We take as benchmark for the comparison with simulation the data taken with $n = 1.05$ and $t = 2$ cm (direct light) and $t = 6$ cm (reflected light). The quality of the agreement between data and simulation is shown in Fig. 92, where, for each of the 28 MAPMTs, the residual distributions from data (red histograms) and Monte Carlo (black histograms) are compared.

In Fig. 93, we show comparison of the photon yield and ring radius resolution between data and Monte Carlo. The agreement between data and simulation is good in all the cases.

The Monte Carlo simulation allows the study of the individual contribution to the overall resolution measured in the prototype test beam. The results of this analysis are shown in Fig. 94 for the direct light data (empty green triangles), the reflected data without (empty blue

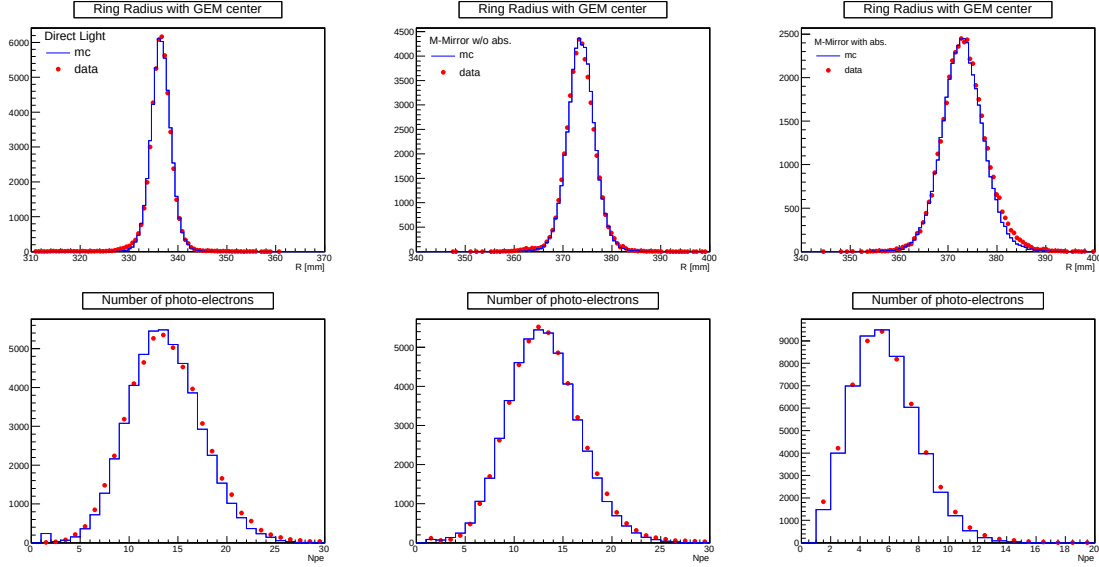


Figure 93: Photon yield (first row) and ring radius resolution (second row) for direct light (left), reflected light without (center) and with (right) aerogel absorbers: comparison between experimental (red points) and Monte Carlo (blue line) data.

circles) and with (filled red circles) the absorbers. Here, we show the separated contribution to the single photon resolution on the Cherenkov angle σ_θ . The various contributions are:

- MAPMT response and digitalization (DIGI in Fig. 94): it includes pixel size, cross talk and random background effects;
- misalignments in the mirror setup (MISAL);
- aerogel associated effects, namely surface effects (SURF), Rayleigh scattering (RAYL), dispersion (DISP) and emission point uncertainty (EMIS).

For the direct light data, we see that the main contribution comes from the dispersion. It is also the main contribution for the reflected light without absorbers, while it is smaller with absorbers because the double pass through the aerogel provide a suppression of the UV photons. The surface effect increases from direct to reflected light without and with absorbers because of the increasing number of surfaces crossed by the Cherenkov photons. The emission point uncertainty increases from direct to reflected light because of the thicker aerogel (2 vs 6 cm), only marginally compensated by the focusing of the spherical mirror because the MAPMTs were not positioned on the mirror focal plane. The Rayleigh contribution is negligible for the direct light data. It becomes relevant for the reflected light data and increases with the absorbers because of the larger amount of aerogel crossed by the photons. Finally, the MAPMT contribution increases from direct to reflected light data mainly because of the increasing weight of the random background hits with respect to the decreasing number of Cherenkov photons and the ring fraction coverage.

The last significant contribution in Fig. 94) is related to misalignments in the mirror system. However, it won't play any role in the CLAS12 RICH, where the alignment of the

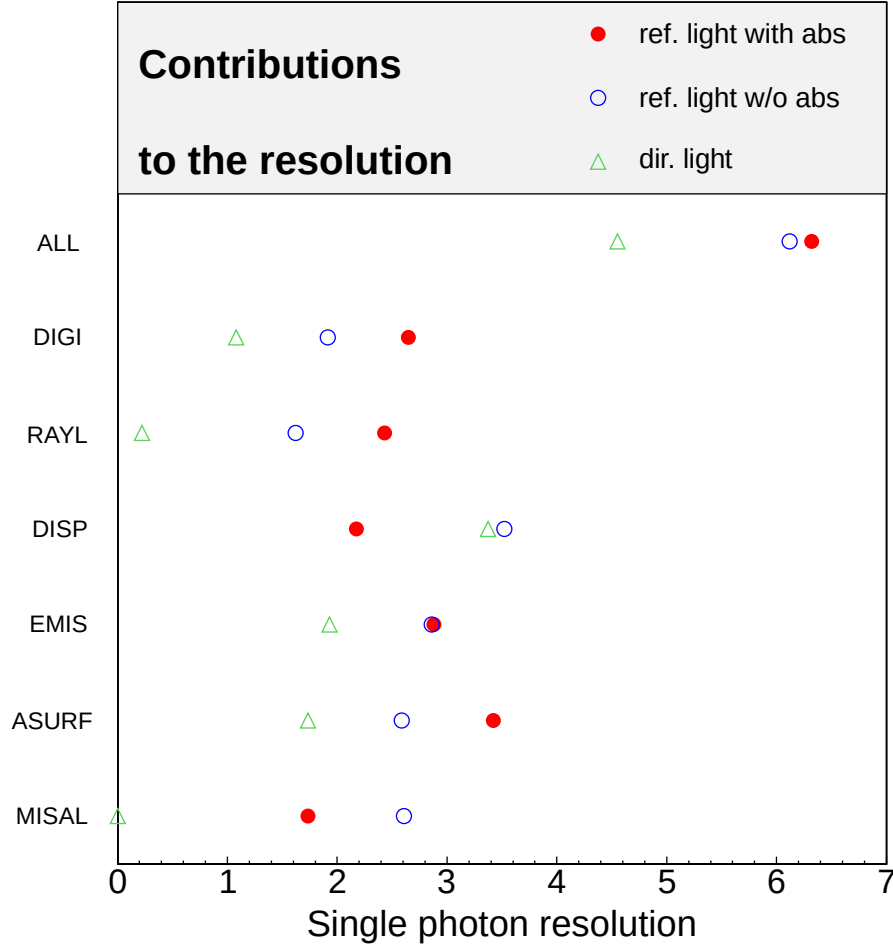


Figure 94: Contributions to the single photon resolution for the direct light data (empty green triangles), the reflected data without (empty blue circles) and with (filled red circles) the absorbers. See the text for the details.

mirror system will be carefully checked in the assembly phase and monitored during the data taking (see Sect. 12.4).

11.11 Summary from the test and possible improvements

In the previous sections, the Tabs. 8 and 11 report the final results of the testbeam with the RICH prototype. The Monte Carlo simulation has been tuned in order reproduce at best these results and the expected RICH performances (presented in the next section) have been computed using the same simulation. In the previous section, we discussed the various contributions to the measured resolutions. The misalignment contribution may be neglected, because in CLAS12 we will carefully check the alignment of the various components of the RICH. For some of the others, in particular, those connected to the aerogel characteristics, several improvements may be foreseen, based on the prototype results.

In the prototype, we used 14 H8500 with normal glass and 14 with UV-enhanced glass.

The latter ones provide on average one photoelectron more, but they also provide a worse resolution, see Tab. 10. The single photon resolution measured with normal glass MAPMTs is in fact about 30% better than for UV-enhanced MAPMTs and about 15% better than the one measured with all the 28 MAPMTs. Thus we expect a corresponding improvement in the pion/kaon separation using only those normal glass MAPMTs.

Another improvement is the better ring coverage (close to the limit given by the H8500 packing fraction of 89%) that we will have in the final RICH. In the prototype, for example in the direct light measurements, the coverage was worse by an additional factor of 15 – 25% and, if we apply a cut $N_{pe} > 7$, we gain about 7% in resolution with a loss of pions of only 10%. Therefore, in the CLAS12 RICH we may reject the events with smaller number of Cherenkov hits, improving the resolution by about 10% but without decreasing too much the efficiency.

The biggest contributions to the Cherenkov ring resolution come from the aerogel. Clear improvement has been shown by comparing two aerogel samples with the same nominal characteristics but coming from different productions. By looking at the time evolution of the aerogel production shown in Fig. 23, further improvements may also be foreseen.

In the reflected light measurements, we found that a significant fraction of the Cherenkov photons survive after the double pass through the aerogel, with small degradation in terms of optical characteristics. The real RICH will benefit of a longer path length than in the prototype (that will make easier the separation of the hit patterns of different particles) and a longer mirror focal length (that will reduce the dependence on the photon emission point). On the aerogel side, any improvement, in particular for the surface effects, would not only increase the number of produced photons, but also would reduce the yield depletion due to the double passage.

12 Operating the RICH

12.1 Installation in CLAS12

The module will be assembled in dry and clean environment to preserve as much as possible the optical quality of the aerogel tiles. The aerogel is in fact hydrophilic and humidity absorption may lead to reduction of the transparency. However, test measurements (see Sect. 6.5) have shown that, once fluxed with nitrogen or even dry air, the optical performances are recovered without any major loss.

The external frame will be mounted first and the lateral mirror skins will be applied. The front panel with the planar mirror and the aerogel tiles, the spherical mirror and the electronics panel will be assembled in parallel and then mounted on the external frame. Finally, the upper and back panel will be applied and the module will be ready for installation in CLAS12. Once installed, cabling and connection to the gas system will be completed.

External dimensions and overall weight of the RICH module are very similar to those of the LTCC. This means that installation tools (see for example Fig. 95) and procedures of the LTCC will also be used for the RICH.

12.2 Backgrounds

Two main issues associated to the backgrounds may be identified: the Cherenkov light produced by charged background particles and the radiation damage of the MAPMTs.

12.2.1 Optical photons

Optical photons may be produced by background charged particles crossing the aerogel tiles or the glass window of the MAPMTs. The main source of charged background comes from Moller electrons, with a rate of hundreths of MHz . However, these electrons are contained by the solenoidal magnetic field of the central detector and/or by the target field within a cone of small aperture and directed toward the beam pipe. The Fig. 96 shows expected photon rates from simulations performed ⁶ at a luminosity $L = 10^{34} cm^{-2} s^{-1}$ and assuming a trigger gate window of 20 ns. Extrapolating at nominal luminosity $L = 10^{35} cm^{-2} s^{-1}$, the results indicate an expected photon rate is of the order of 10^{-4} , corresponding to 1 – 2 background hits per event. This background rate can be easily managed by the likelihood algorithm used in the RICH particle ID described in Sect. 13.1. For comparison, in the prototype data reconstruction a background rate of about one p.e. per event (including all the contributions) was not a problem even using a much more simplified event reconstruction.

Optical photons are also produced by the SIDIS tracks crossing the MAPMTs. Being associated to physics tracks, they may be included in the reconstruction algorithm and used to improve the separation power.

⁶These simulations have been performed for the proposal C12-11-111 with transversely polarized target, wich runs at one order of magnitude smaller luminosity



Figure 95: Example of the tools for the installation of one LTCC module that may be used also for the RICH.

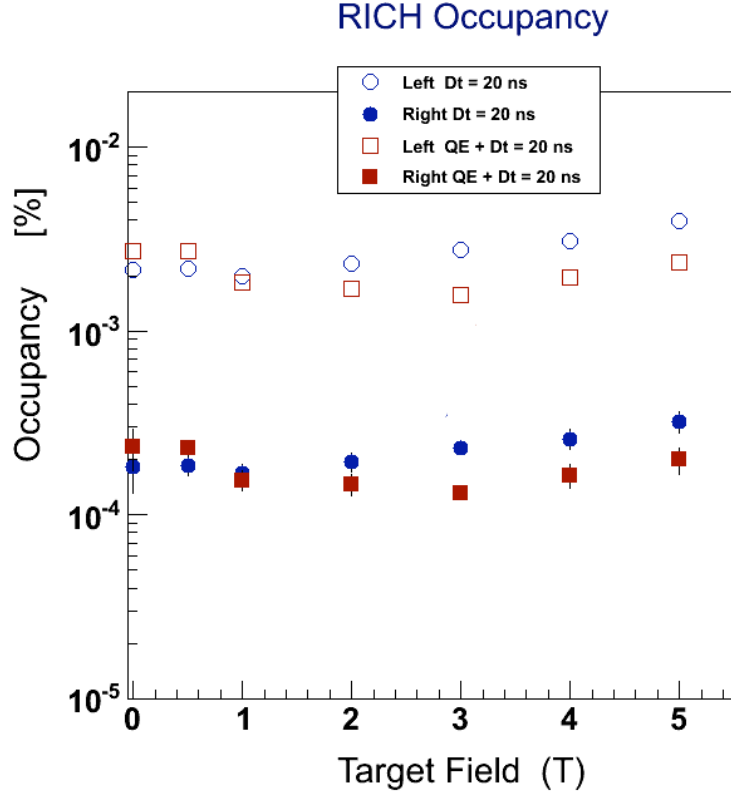


Figure 96: Optical photon background occupancy (in percent) for different transverse target field at a luminosity $L = 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$. Empty symbols: total photons. Full symbols: detected photons, applying MAPMT quantum efficiency.

12.2.2 Radiation damage

The main source of radiation comes from secondary neutrons produced within the CLAS12 spectrometer that may cause damages to the most sensitive components of the MAPMTs (like the glass window or the socket) and to the front end electronics. Since the MAROC chip was designed for the ATLAS luminometer, we don't foresee any issue for the electronic readout. On the other hand, simulations have been performed to estimate this neutron flux on the MAPMT plane and results are shown in Fig. 97 as a function of the distance from the beam line measured on the RICH MAPMT plane. Different GEMC physics data cards describing the interaction of secondaries in CLAS12 may produce lower flux by a factor of two. In addition, the flux strongly depends on the beampipe structure, which is still under development. Thus, these results may be considered as an upper limit on the expected flux. Assuming a duty cycle of 60%, the total neutron flux can be estimated of the order of $5 \times 10^9 \text{ n/year} \times \text{cm}^{-2}$, about two order of magnitude below the limit after which loss in performances may occur [37]. It is also approximately the same order of magnitude of the Belle experiment during its whole data taking and two order of magnitude less than the expected fluence in Belle-II and LHCb-2 [36].

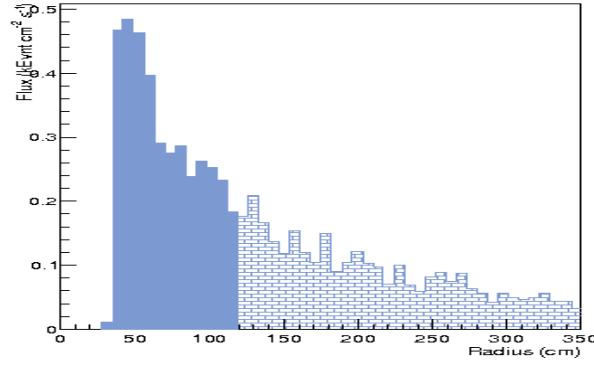


Figure 97: Neutron flux as a function of the radius on the RICH MAPMT plane. The MAPMT coverage is shown by the full blue filling of the histogram.

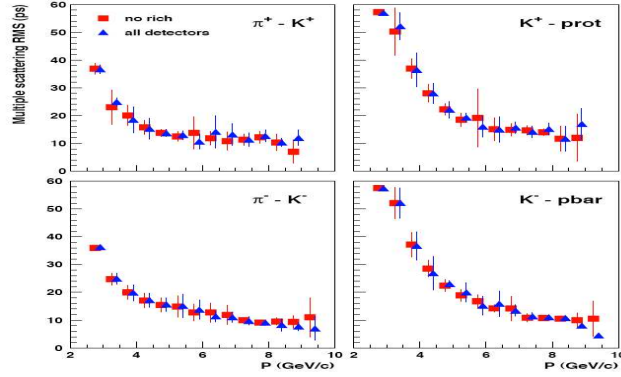


Figure 98: Time difference for various pair of particles due to multiple scattering without (red squares) and with (blue triangles) the RICH as a function of the momentum.

12.3 Impact on the other CLAS12 detectors

The CLAS12 detectors located after the RICH are the Time-of-Flight FTOF, the preshower and the electromagnetic calorimeter (PCAL and EC).

12.3.1 Impact on the FTOF

Multiple scattering of particles crossing the RICH may reduce the time resolution of the FTOF detector. GEMC simulation have been performed to study this effect. In Fig. 98, we show, as a function of the momentum, the RMS of the time difference for various pairs of particles due to multiple scattering, without (red squares) and with (blue triangles) the RICH. As we see, no significant contributions are added by the RICH. These values are also much smaller than the best time resolution foreseen for the FTOF, $\sigma(T) = 40ps$, except for the very low momenta, where the time resolution requirement are less stringent.

12.3.2 Impact on the calorimeter

Energy loss and showering in the RICH materials may affect the energy resolution of the calorimeters, in particular for electrons. The material budget of the FTOF and of the preshower calorimeter PCAL, placed right after the RICH and before the forward calorimeter EC, are $0.12X_0$ and $5X_0$, respectively. Both PCAL and EC are sampling calorimeters with energy resolution of the order of $10\%/\sqrt{E}$.

The total thickness of the RICH is $0.07X_0$ in the upper part ($\theta > 13^\circ$) where in principle low energy particles might be more affected. Thus, the effect of the RICH is negligible. In the lower part, the total thickness of the RICH is about $0.28X_0$, mainly due to the MAPMTs and to the front-end electronics, more or less a factor of two worse than the FTOF. The expected impact of the RICH is then limited.

12.4 Commissioning and calibration

Each component of the RICH will be tested in laboratory before installation. Aerogel optical quality and MAPMT gain maps will be produced. Mechanical relative alignment of the mirrors and with respect to the MAPMT will be made by means of laser tools in the assembly phase. Stright (zero-field) tracks will also be used to monitor the alignments during the data taking. A number of procedures has been established for commisioning the detecor and to monitor the RICH response after its installation in CLAS12,

Runs with internal trigger will be periodically performed and analog readout single photoelectron levels due to thermal noise will be analysed as described in Sect. 8.4.4. This will allow to perform the initial gain equalization of all the MAPMT pixels and, later on, to monitor the stability of the electronic readout.

Electron tracks will be selected in CLAS12 to tune the pattern recognition and reconstruction algorithms. The RICH particle identification performances will be validated and monitored in time using known narrow resonances, as for example K_S for pions, ϕ for kaons and Λ for protons. Finally, physics events without tracks in the RICH sector will be used to estimate the background levels.

13 RICH performances

13.1 Reconstruction algorithm

Because of the complicated geometry of the CLAS12 RICH, the expected Cherenkov photon hit pattern will hardly be a full ring, even for the most forward particles. In general, it will be mixing between photons detected directly and photons detected after reflections. Thus, the event reconstruction and the particle identification require a sophisticated algorithm taking into account all the possible hit distributions.

The reconstruction algorithm is based on the simulation of the expected photon hits and a likelihood fit. For a given track t and a particle hypothesis h (with $h = \pi, K, p$), a direct ray tracing for a large number of generated photons is used to calculate the hit probability for each MAPMT pixel. Then, the measured hit pattern is compared to the hit probability densities for the different hypotheses through a likelihood function

$$\mathcal{L}^{t,h} = \sum_i \log \left[P_i^{t,h} C_i + \bar{P}_i^{t,h} (1 - C_i) \right] \quad (19)$$

where the sum on i runs over the measured hits and the C_i represent the hit pattern from data with

$$C_i = \begin{cases} = 1 & \text{if the } i\text{th pixel is hit} \\ = 0 & \text{if the } i\text{th pixel is NOT hit} \end{cases} \quad (20)$$

The probability of a given hit for the track t under the hypothesis h is given by

$$P_i^{t,h} = 1 - \exp \left(- \frac{N_i^{t,h}}{\sum_i N_i^{t,h}} n^{t,h} - B_i \right) \quad (21)$$

being $N_i^{t,h}$ and $n^{t,h}$ the measured and expected number of hits in the pixel i , the probability of no hit is $\bar{P}_i^{t,h} = 1 - P_i^{t,h}$ and the term B_i accounts for the expected background photon hits. The hypothesis that maximizes the likelihood function (19) is assumed to be true.

Quantitatively, one may define a quality parameter

$$R_{QP} = 1 - \frac{\mathcal{L}^{t,h}(2^{nd})}{\mathcal{L}^{t,h}(1^{st})} \quad (22)$$

using the likelihood for the first and second best hypotheses. A value $R_{QP} \rightarrow 0$ means poor identification (the two hypotheses have similar likelihood), while a value $R_{QP} \rightarrow 1$ means good identification (the best hypothesis has much bigger likelihood than all the others).

13.2 Event reconstruction

An example of one simulated event for a positive track with $P = 6.3$ GeV/c and $\theta = 6^\circ$ is shown in the left plot of Fig. 99. The red stars show the measured hits (including a couple of background hits), while the blue, green and cyan points show the expected photon patterns for pions, kaons and protons. Even if the pion and kaon expected hit distributions are close each other, the large number of photoelectrons (eight in this example) allows a clear identification of the track as a pion, with a quality parameter $R_{QP} = 0.59$.

For a large angle, low momentum, track the situation is illustrated in the right plot of Fig. 99. In this case, the number of photoelectrons is smaller and they are more scattered around the photodetector plane, however the expected patterns for the different hypothesis are better separated, thus the correct identification of the track can be successfully obtained (a pion in this case with $R_{QP} = 0.98$)

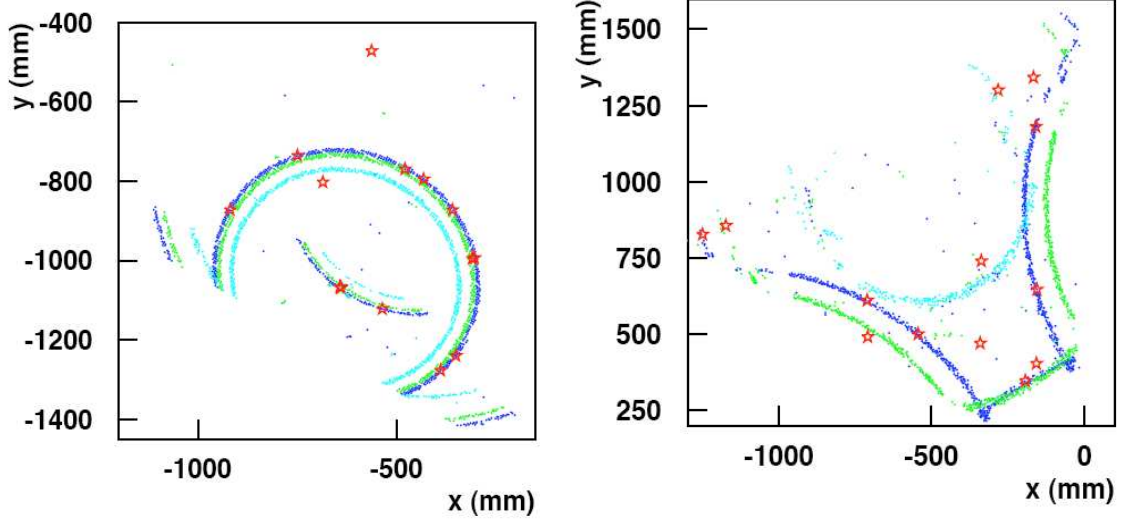


Figure 99: Photon patterns for one track with $P = 6.3$ GeV/c and $\theta = 6^\circ$ (left plot) and $P = 3.7$ GeV/c and $\theta = 22^\circ$ (right plot): red stars show actual hits, while the blue, green and cyan points show the expected hit distribution for pions, kaons and protons.

Simulated distributions of R_{QP} comparing the different hypothesis are shown in Fig. 100 for momenta between 6 and 8 GeV/c and inbending particles. Each row corresponds to a different type of generated particle (pion, kaon or proton), while each column to a different type of identified particle. Last column show cases where the number of photoelectrons is too low and the identification cannot be performed. Plots along the diagonal refer to correct identifications, while off-diagonal plots refer to contaminations. The plot in the second row and second column shows the distribution for kaons correctly identified as kaons, from which an average efficiency $\epsilon(K) = 94.1 \pm 1.3\%$. Also for pions and protons the efficiency is well above 90%. The plot in the second column, first row shows generated pions but reconstructed as kaons, yielding the pion contamination well below 1% reported in the legend of the plot. We see that the R_{QP} values are distributed around 0.5, due to the closeness of the expected patterns. Nevertheless, the large number of photoelectrons allows a clear identification with negligible contaminations.

The quality parameter distributions for low momentum ($P = 3 - 5$ GeV/c) particles are shown in Fig. 101, for inbending (left panel) and outbending (right panel) particles. Here, the distributions are peaked toward one because of the better separation of the photon patterns which leads to easier identification. The number of photoelectrons is smaller for outbending particles in general and for (anti)protons in particular, leading to somehow lower detection efficiencies. Nevertheless, Kaon efficiency is close to 90% for inbending and to 70%

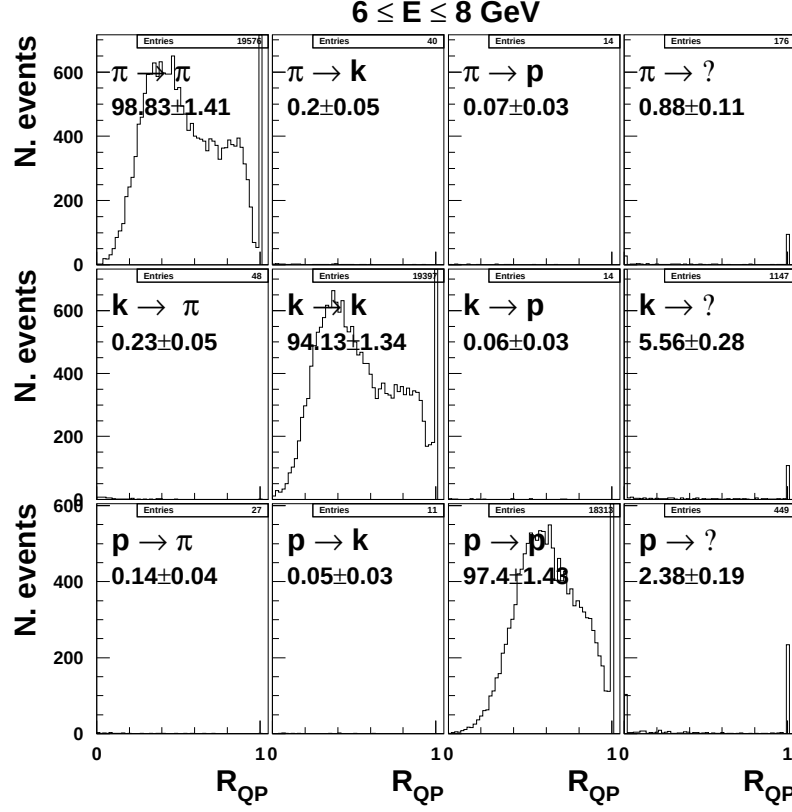


Figure 100: Quality parameter distribution for simulated inbending tracks with momentum between 6 and 8 GeV/c. Each row corresponds to a different type of generated particle, while each column to a different type of identified particle. Last column shows cases where the number of photoelectrons is too low. Plots along the diagonal refer to correct identifications, while off-diagonal plots refer to contaminations.

for outbending particles, with contaminations below 1%.

We point out that these numbers have been obtained without any optimization of the reconstruction algorithm. Fine tuning of the quality estimator definition and of the likelihood calculation will improve the performances of the reconstruction, in particular for lower momentum particles. We also remind that other CLAS12 detectors may help in specific kinematic regions in the particle ID, as will be discussed in the next section.

13.3 Particle Identification in CLAS12 with the RICH

In order to identify the kinematic regions where the RICH performances have to be optimized for the discrimination of kaons from pions and protons, and to quantify the benefits from the RICH PID, a quantitative study in a 2D space spanned by the hadrons momenta and polar angles was carried out. The study takes into account, in each bin, estimates of pion and proton contaminations (misidentification as kaons) provided by the FTOF, the HTCC and

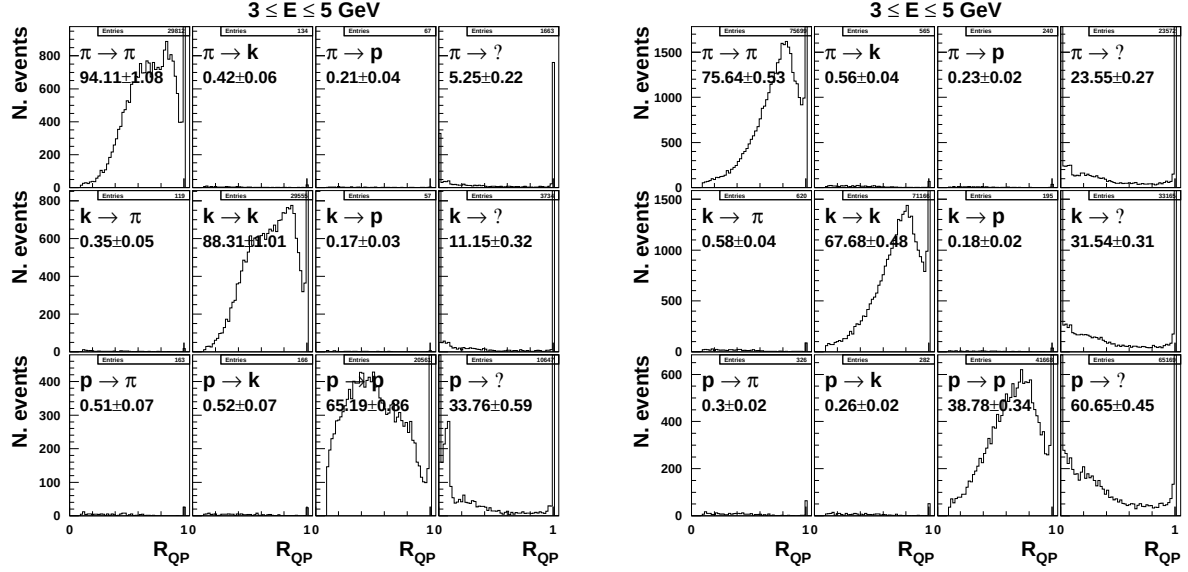


Figure 101: Quality parameter distribution for simulated inbending (left panel) and outbending (right panel) tracks with momentum between 3 and 5 GeV/c. Each row corresponds to a different type of generated particle, while each column to a different type of identified particle. Last column show cases where the number of photoelectrons is too low. Plots along the diagonal refer to correct identifications, while off-diagonal plots refer to contaminations.

the RICH detectors as well as the RICH efficiency for kaon identification (evaluated with the likelihood method).

For this study, the MC event-lists described in Sect. 5.2 were processed through the GEMC simulation, taking into account the FTOF resolution (σ_{TOF}) as a function of the scintillator length, the pion-to-kaon, kaon-to-proton and pion-to-proton contaminations from the FTOF calculated (numerical integration) in each bin assuming a 90% efficiency (see e.g. Fig. 102 for the pion-kaon case).

The pion-to-kaon contaminations from the HTCC were calculated only for pions with momenta larger than 5 GeV (pions with $p < 5$ GeV as well as all kaons and protons at CLAS12 kinematics are under threshold in the HTCC, i.e. correspond to a 100% contamination). For this estimate, the average number of photo-electrons per each momentum bin was extracted from the expected curve (see figure 4). The contamination was evaluated in each momentum bin using the Poisson distribution $P_\mu(\nu)$ with $\mu = \langle N_{phe} \rangle$ and $\nu = N_{phe}$, and considering all cases in which the number of photo-electrons is smaller than 4 (i.e. from 0 to 3). At least 4 photo-electrons were required for a pion reconstruction in the HTCC with 100% efficiency.

The RICH pion and proton contaminations and kaon efficiencies were calculated using the likelihood approach and processing, for each bin, a fixed number of hadron tracks through the GEMC simulation. To be conservative, the RICH contaminations were forced to be always at least $1 \cdot 10^{-3}$, and the final flux ratios (corrected for the contaminations from FTOF, HTCC and RICH and the kaon efficiencies) were forced to be at least $1 \cdot 10^{-2}$. Furthermore,

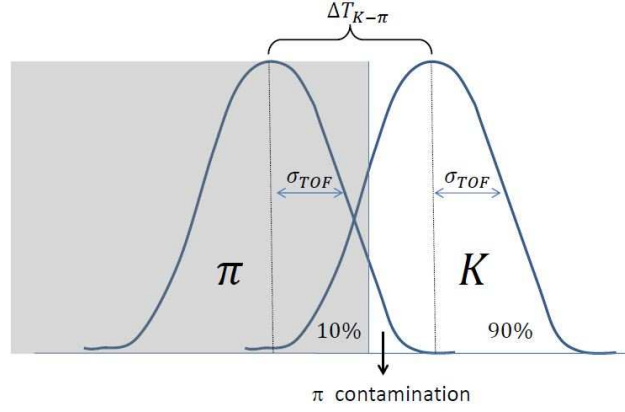


Figure 102: Pion contamination (percentage of pions misidentified as kaons) assuming a 90% efficiency.

the RICH PID was applied only for kaon efficiencies larger than 30%.

To quantify the benefits of the FTOF, HTCC and RICH PID in the pion/kaon and proton/kaon separations, the following three ratios were defined:

$$r_1 = \frac{\pi_{yields}}{K_{yields}} , \quad (23)$$

$$r_2 = \frac{\pi_{yields} \cdot [\pi_{contam}(FTOF) \cdot \pi_{contam}(HTCC)]}{K_{yields} \cdot K_{eff}(90\%)} = r_1 \cdot \frac{\pi_{contam}(FTOF) \cdot \pi_{contam}(HTCC)}{K_{eff}(90\%)} , \quad (24)$$

$$r_3 = \frac{\pi_{yields} \cdot [\pi_{contam}(FTOF) \cdot \pi_{contam}(HTCC) \cdot \pi_{contam}(RICH)]}{K_{yields} \cdot K_{eff}(90\%) \cdot K_{efficiency}(RICH)} = r_2 \cdot \frac{\pi_{contam}(RICH)}{K_{efficiency}(RICH)} , \quad (25)$$

and similarly for the proton/kaon case (though without the HTCC terms). These ratios represent: (i) r_1 is the total production yield ratio, computed within the CLAS12 acceptance; (ii) r_2 is the inverse of the pion (proton) to kaon rejection factor, using the FTOF, the HTCC and the LTCC; (iii) r_3 is the inverse of the pion (proton) to kaon rejection factor, using also the RICH.

In Figs 103-105 the three ratios above are shown (in the upper, middle and lower panels, respectively) for the three hadron combinations π^+/K^+ , p/K^+ and π^-/K^- . The FTOF provides a good particle identification at low momenta ($p < 2.8 GeV/c$) and HTCC provides a reasonable PID up to $P = 3.5 GeV/c$ and at high momenta ($P > 7.0 GeV$). With the current geometry, the RICH provides required the PID capabilities in the full range, and especially in the intermediate momentum range ($3.5 GeV/c < P < 7 GeV/c$), where the FTOF and HTCC fail to discriminate the kaons from pions and protons.

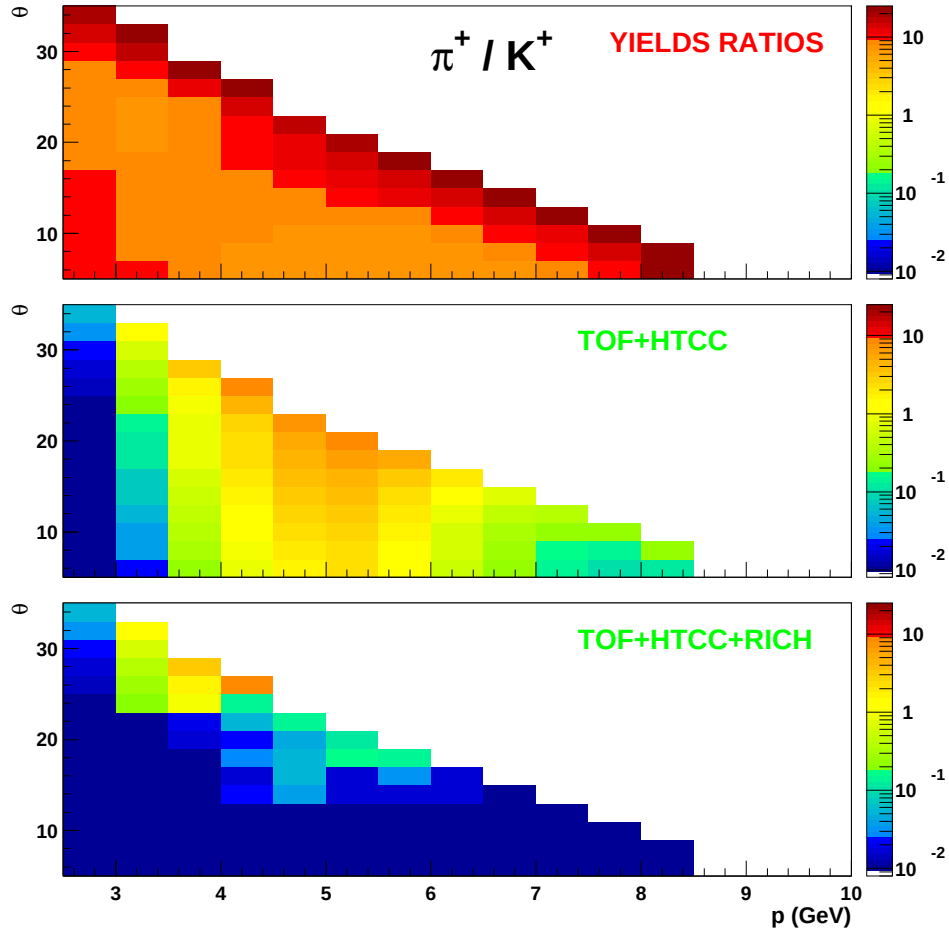


Figure 103: Top plot: π^+ to K^+ production yield ratio within CLAS12 acceptance in a 2D binning in p (2.5 – 10 GeV) and θ (5 – 35 degrees). Middle plot: 2D π^+ to K^+ contaminations using FTOF, HTCC and LTCC detectors. Bottom plot: 2D π^+ to K^+ contaminations using also the RICH detector.

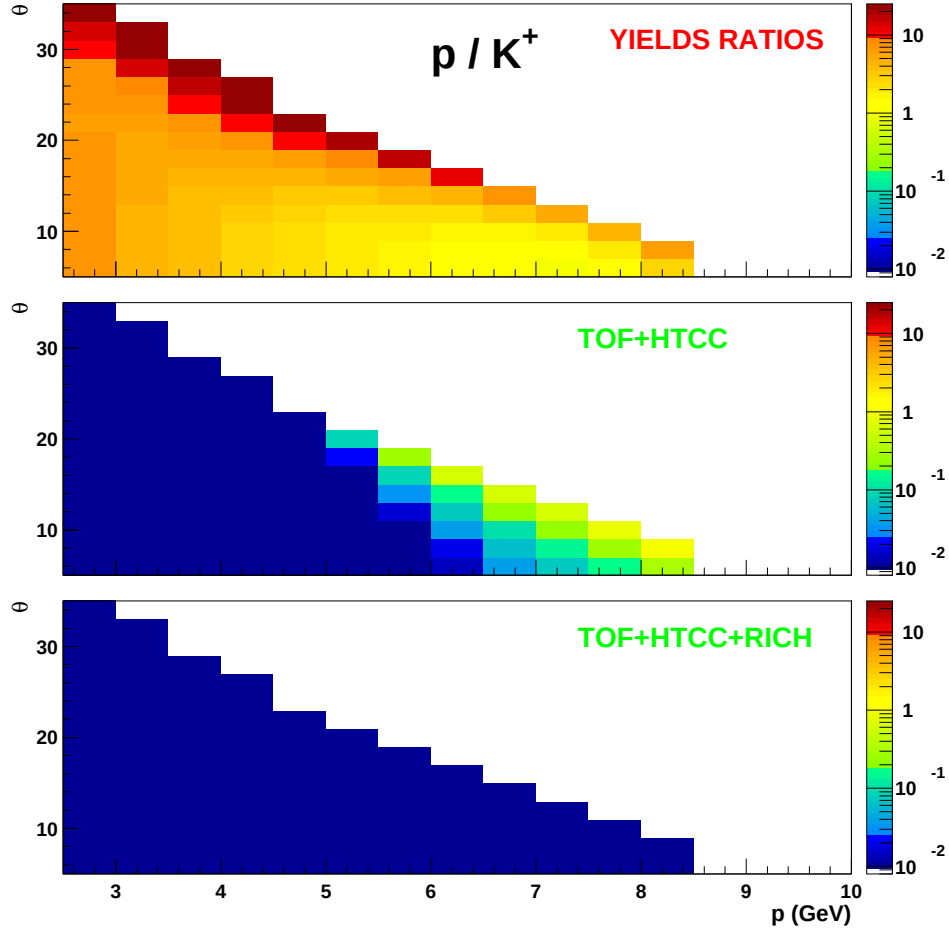


Figure 104: Top plot: proton to K^+ production yield ratio within CLAS12 acceptance in a 2D binning in p (2.5 – 10 GeV) and θ (5 – 35 degrees). Middle plot: 2D proton to K^+ contaminations using FTOF, HTCC and LTCC detectors. Bottom plot: 2D proton to K^+ contaminations using also the RICH detector.

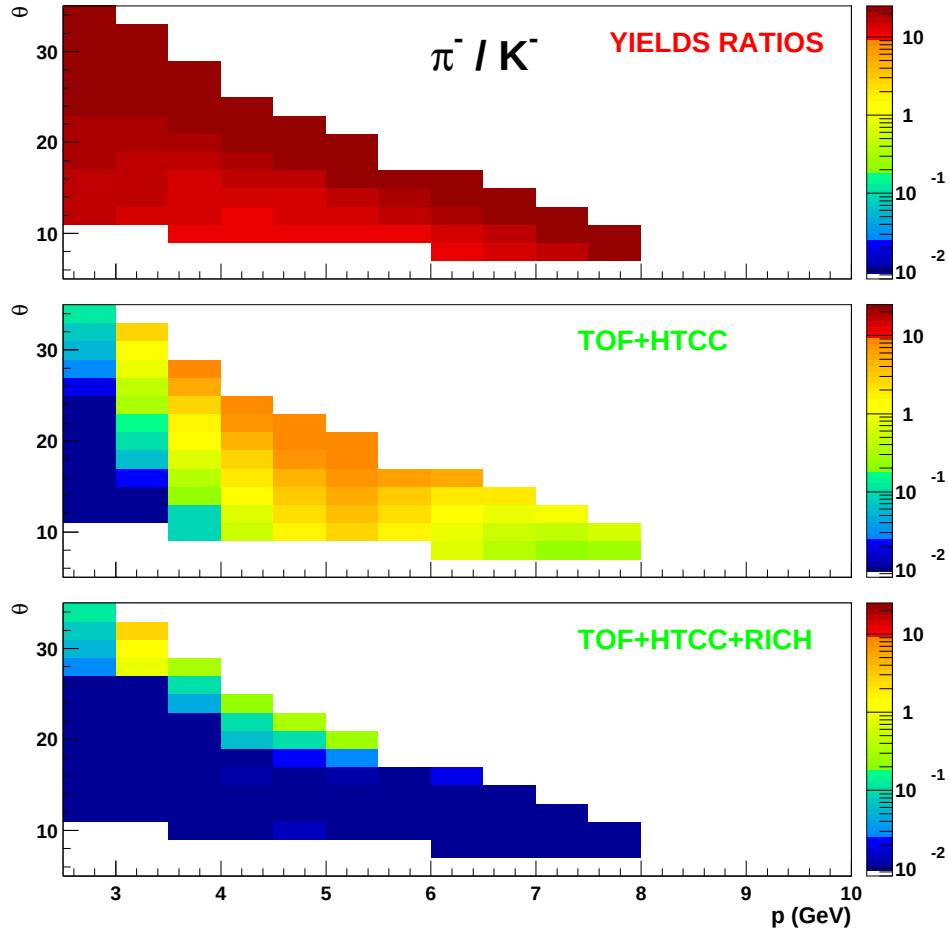


Figure 105: Top plot: π^- to K^- production yield ratio within CLAS12 acceptance in a 2D binning in p (2.5 – 10 GeV) and θ (5 – 35 degrees). Middle plot: 2D π^- to K^- contaminations using FTOF, HTCC and LTCC detectors. Bottom plot: 2D π^- to K^- contaminations using also the RICH detector.

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