Optical telescopes for COMPASS RICH-1 up-grade

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The central photon detection area of the Ring Imaging Cherenkov detector at COMPASS, a particle physics experiment at CERN SPS dedicated to hadron physics, has been upgraded from the previous system formed by wire chambers with CsI layers to a very fast UV extended multi anode photo multiplier tube array (MAPMT), including 576 tubes. The active area covered by the MAPMTs is 7.3 times smaller than the one previously equipped with CsI photocathodes, so 576 optical concentrators transforming the image from the old system focal plane to the new photocathode plane were needed. The telescope system formed by two fused silica lenses was designed, produced and assembled. The first prismatic plano-convex field lens is placed in the focal plane of the RICH mirrors. The second condenser lens is off centered and tilted and has one aspherical surface. All lenses have antireflection coating.

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1 Introduction

COmmon Muon Proton Apparatus for Symmetry and Spin (COMPASS) setup is presently the largest fixed target particle physics experiment at CERN. It was designed to measure the gluon contribution to the nucleon spin [1] and the transverse spin dependent structure function of the nucleon, as well as to perform charm spectroscopy. Ring Imaging CHerenkov detector (RICH1) is one of most important components of the spectrometer and it is used for the identification of scattered hadron particles [14]. During the years 2005/2006 the Ring Imaging Cherenkov Detector underwent a major upgrade targeted mainly to increase the range of photon sensitivity, to provide a much faster response and to suppress the dead time. It has been decided to replace, in the central region, the wire-chambers with CsI photoconverter layer used in the past as photon detectors, with four arrays of 16 channel multi-anode photomultiplier tubes (MAPMT) Hamamatsu R7600-03-M16. The active area of the MAPMTs is smaller than the one to be covered. This type of MAPMT has an $18 \times 18\,\mathrm{mm}^2$ bialkali photocathode segmented into 16 pixels of $4 \times 4\,\mathrm{mm}^2$ array and with gaps between adjacent pixels of 0.5 mm. The area which must be covered by one photomultiplier in the mirror focal plane is $48 \times 48\,\mathrm{mm}^2$ the use of a concentrator optical system to minimize the dead areas is needed. There are some specific requirements for the optical system. The system should have maximized acceptance for the incoming Cherenkov photons with respect to their angular distributions (including an average tilt in the vertical plane). The Cherenkov photon spectrum is rapidly increasing with the light frequency, so the concentrators should have the best performance in the near UV region, also in agreement with the quantum efficiency of the MAPMTs. The used MAPMTs have special borosilicate windows with UV transparency extended down to 200 nm: thus, the system must be efficient from 200 nm to 600 nm with best performance at 300 nm. The limited available space for the optics and the electronics requires an angle between the optical system axis at the entrance (field lens) and at the exit (concentrator). Four couple of frames designed to match the optical and mechanical requirements are used for fixing the MAPMTs, the optical telescopes and the components of the read-out electronic system. Each of them mounts together 144 (12×12) MAPMTs and optical telescopes.

2 The optics for RICH-1 up-grade

2.1 Requirements to optics

The Design of the optics must comply with some requirements. The first one is the system magnification. It is defined simply dividing the entrance window size by the photomultiplier active area ($18/48 = 0.375$). The mechanical design doesnt allow a square window, which result slightly rectangular; the magnification is matched to the longer side (48 mm). The second one is the angular acceptance of the optical system, which must allow us detecting incoming Cherenkov photons in the range of angles that is illustrated in Fig. 1. The full angular acceptance of the final design is 8.3 ° (the 50 % acceptance is obtained for angle as large as 9.5 °). The system must detect as much photons as possible, so it must be able to transmit light in the wavelength range from 200 nm to 600 nm. It is useful to suppress the reflection loses on the optical element surfaces. Also, the crosstalk between pixels must be minimal. It means that the image must exhibit a minimal distortion caused by the lenses imaging system. There was only limited space for the RICH up-grade optics and electronic, so the length should not exceed 150 mm. Appropriate cost for the production of 576 telescopes is an important criteria too.

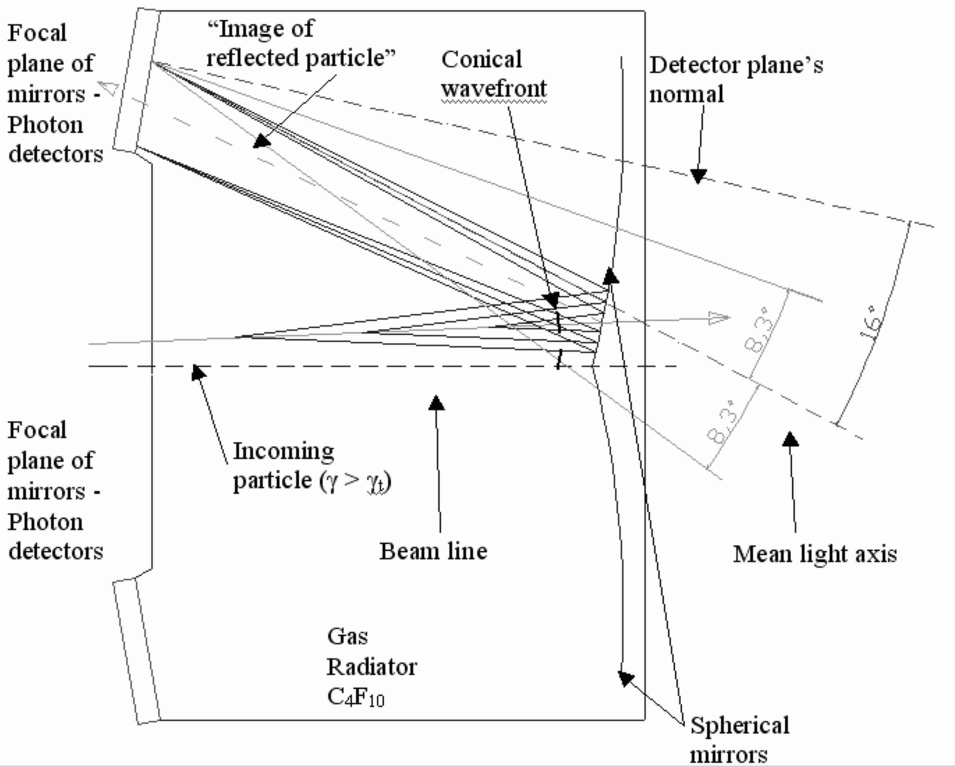

Fig. 1. Schematic cross section of the COMPASS RICH1 detector with the Cherenkov light cone focused into a ring image on the photo-detector plane, which is centered around the virtually reflected particle trajectory.

2.2 Various types of designs

Different possible designs were discussed and tested during the development of the RICH1 up-grade project. Prototypes of thick lenses were produced and used for MAPMT tests [5]. The concept of a thick lens was rejected because of its low collecting efficiency in the COMPASS RICH detector. The required important decrease of the image size (almost 2.7 times in linear dimension) employing only one lens results in significantly worsened optical quality. The resulting radius of curvature is so small, that the lens cannot fill the whole aperture. Moreover, at the edges of the lens, the incident angle is close to 90 ° due to the high surface curvature, so the reflectivity is approaching 100 %. The resulting losses due purely to the limited geometrical coverage are roughly about 30 %. The tapered light pipes, made both as hollow lightguides and as fused silica waveguides seemed also a promising solution. The main problem here is the requirement of the high image demagnification factor on a relative short path of the order of 115 mm. Monte Carlo simulations showed that this system can work only with small angles of acceptance, not in the full required range. The system reflects the light backwards for higher angle of incidence.

2.3 Two lenses telescope

This concept consists of a field lens placed in the focal plane of the mirrors (where the rings are formed) and a condenser lens between the field lens and the MAPMT. The front filed lens is used to bend the rays not passing through the center of the lens towards the condenser lens thus increasing the field of view of the system. The condenser lens projects the field lens image to the plane of the PMT photocathode. In first approximation, the condenser lens defines the magnification of the telescope. A similar system has been used for the HERA B RICH, even if with much smaller demagnification [5]. It was formed by injection molded aspheric acrylic lenses with extended transmission in the near UV (cutting edge at 300 nm) [6]. The choice of material for lenses production depends on the sensitivity of the MAPMT. As we have PMT with special entrance window, the effective photocathode radiant sensitivity is in the range from 200 nm to 700 nm. So we require UV transmittance starting at 200 nm, material isotropy (due to the light polarization), not very high material and production costs and the possibility to produce lenses with aspherical surface. The relative number of detectable photons depends on the wavelength of the edge of the material absorption, see Fig. 2. In the plot, the number n of detectable photons (effective quantum efficiency $QE(\lambda)$ of the PMT multiplied by the spectrum of the Cherenkov radiation $S(\lambda)$) is presented in arbitrary units for different cases of detection with absorption edge at definite wavelengths. The transmission starting at 200 nm is arbitrary fixed as 100 %,, as shown by Eq. 1.

$$n(\lambda) = \frac{\int_{\lambda}^{800} QE(\lambda) \cdot S(\lambda) \cdot d(\lambda)}{\int_{200}^{800} QE(\lambda) \cdot S(\lambda) \cdot d(\lambda)} \tag{1}$$

The polymer lenses are cheap and techniques exist for aspherical lenses production. The transmission is not so good and this type of lenses can be used with PMT sensitive only in the near UV range. The borosilicate glass enables to produce aspherical lenses by a standard glass molding techniques but the edge of absorption in around 290 nm. The fused silica HPFS Standard Grade, Corning code 7980, grade of inclusions and homogeneity 5D has been chosen as a material with appropriative price and suitable quality. It has excellent light transmittance, but an important disadvantage of the fused silica is the impossibility to use the molding procedure for the aspherical lenses production. It was decided to produce the lenses by grinding and polishing procedure, which is relatively cheep for spherical but expensive for aspherical surfaces, where special numerical control machines must be used.

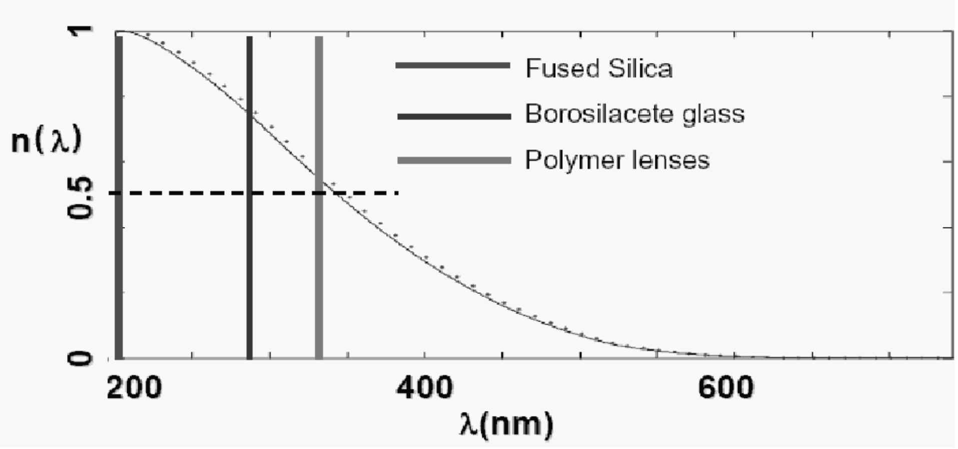

Fig. 2. Relative number of detected photons for absorption edge at different wavelengths

There were special requirement for the two lenses optical system design. First - The mechanical constrains, i.e the maximal allowed length and the limited lateral space have imposed to design a non axial system with tilted components. Second The price of machining aspherical optical surfaces on fused silica lenses is very high so only aspherical surface can be used. Several possible concentrator system concepts were investigated and the non-axial two lens aspherical telescope design with a field and condenser lens was chosen for its proven functionality and thus a shorter development time. A function of merit including mechanical constraints and imaging performance targets was composed in the optical design code Zemax. The design was at first optimized for best performance (for minimal spot size), then its imaging quality was decreased in steps to match the given mechanical and production cost constrains. The effort resulted in a non-axial system with a vertical tilt, where the plano-convex field lens is prismatic on its flat side and the biconvex lens with one aspherical surface. The final design is described by the system parameters that can be found in Fig. 3.

The first lens is plano-convex with spherical surface of radius $R1 = 54.94\,\text{mm}$. The wedge of this prismatic lens is $5.00\,^\circ$. The second lens has an aspherical surface of radius $R3 = 20.70\,\text{mm}$ and aspherical coefficient of 4th order 4^{th} order $\alpha2 = 6.1388 \cdot 10^{-5}$ as you can see in Eq. 2.

$$z = \frac{\frac{r^2}{R}}{1 + \sqrt{1 - \frac{r^2}{R^2}}} + \alpha_2\, r^4\,, \tag{2}$$

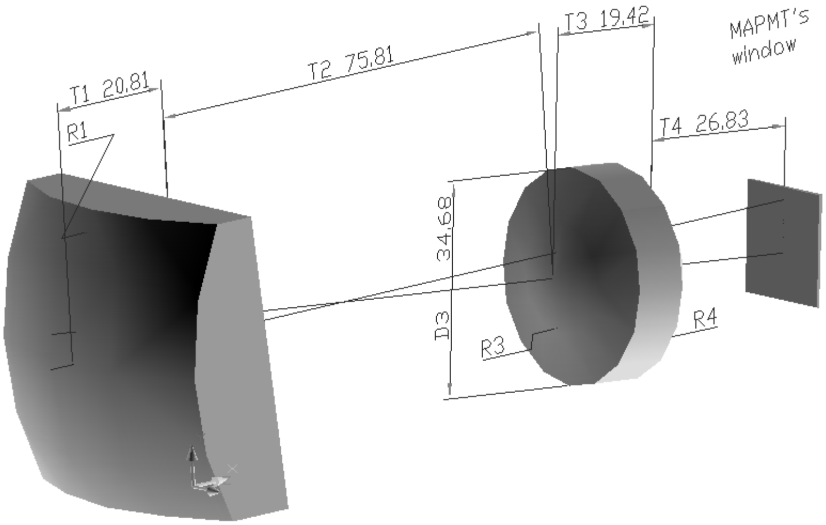

Fig. 3. Final design of the optical system.

where R is the nominal surface radius, r is distance from the axis and z the surface coordinate (parallel to the lens axis). The radius R4 of the spherical surface is 24.96 mm. The final shape of the field lens is not squared but rectangular of size $48.0 \times 44.8\,\mathrm{mm}^2$. The contraction in the vertical direction is caused by the need to tilt the lenses with relatively thick rectangular edges. The surface covered remained the same and one gets even slightly better imaging performances, due to the fact that the rays will not travel through the extreme parts of the field lens, but will be concentrated by the neighboring telescope. The drawback of the rectangular field lens is the unfilled part of the extreme pixels of the MAPMT, but they should be anyway occupied as the remaining ones because of the imaging aberrations. Monte Carlo simulations were performed with Zemax software to compare the imaging performances of different telescope designs by using a set of rays simulating an average photon distribution inside the RICH detector. Results were used as a feedback to the optical design. The problem specific Figure Of Merit (FOM) [7] was built to compare the results of the simulations

$$FOM = \frac{\sqrt{f}}{\sqrt{13 - 12 f_p}} \tag{3}$$

where f is the fraction of the generated energy collected by the detector and f_p the fraction of the collected energy concentrated on the correct pixel. All designs were compared with axial the two aspherical surface design [7]. The final design has a qualities of optical imaging only slightly degraded: FOM is 0.595 (to be compared with 0.622) for the final (two aspherical surfaces design), f_p is 0.89 (to be compared with 0.91). The tolerances analysis for all parameters has been performed. The spot radia and the image shifts have been calculated. From the producer point of view, these are requirements for standard tolerances which can be reached by normal techniques. Only the required tolerance for the decenter of the aspherical surface has serious influence on the parameters to be obtained: it must not exceed 50 μm. The mechanism for precise centre alignment of the lenses into their holder has been used too. All lenses housed in their holders have been checked to confirm their quality and their alignment in the telescope. The only other parameter with stringent tolerance is the maximum tilt of planar surface of the field lenses, which must be smaller than 0.1 °.

2.4 Antireflective coatings

The total Fresnel reflection losses have been calculated to be over 14.4 % for the two lenses system. To suppress these losses we decided to use antireflective coating on both lenses. The spectrum of losses of reflected detectable photons has a maximum at 302 nm. So a single MgF_2 layer was used for reflection suppression in the region between 200–500 nm with reflection minimum at 300 nm. In this way, we obtain an increase in the photon detection efficiency of 8.4 % in comparison with the uncoated ones. We estimate that this coatings increase the number of detected photons of about 5 photons per Cherenkov ring. The spectra of product of Cherenkov photons $S(\lambda)$, of the fused silica internal transmission $\mathrm{T}(\lambda)$ and the PMT quantum efficiency $QE(\lambda)$ are presented at Fig. 4 for:
a) ideal case without Fresnel reflections,
b) lenses with antireflection coatings and
c) without AR coatings.

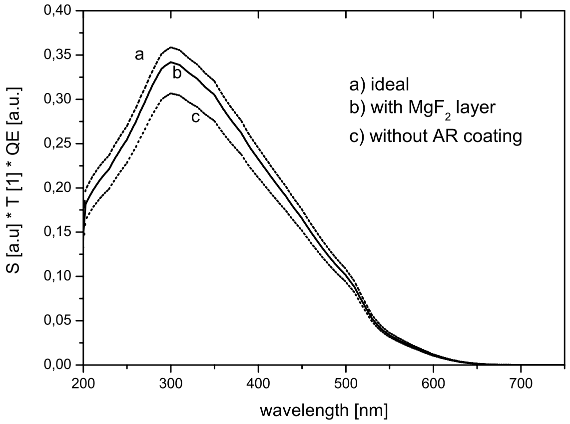

Fig. 4. The spectra of detected photons in the ideal case, namely without refection losses, with and without antireflection coatings.

3 Conclusions

The two lenses optical telescope has been designed for photon detection in the Ring Imaging Detector RICH1 in the COMPASS experiment. The system is formed by a plano-convex and a biconvex lens. The plano-convex field lenses have a 5 ° wedge due spatial limitations for all the telescopes; biconvex lenses have one aspherical surface. Monte Carlo simulations were performed to compare qualities of different designs. The lenses were coated with antireflective coatings. More than 2×600 lenses were tested both standing alone and after assembling in the telescope system [8]. Now 576 telescopes with MAPMTs are mounted on the RICH detector. The COMPASS run in year 2006 has confirmed that this system with MAPMT can give above 60 photons per Cherenkov ring at saturation [9]. It helps to increase the angular resolution of the measured Cherenkov angle and together with a better time resolution enables π/K separation up to momenta of 50 GeV/c.

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