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Micro-channel plate photon detector studies for the TORCH detector

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ABSTRACT

The Time Of internally Reflected Cherenkov light (TORCH) detector is under development. Charged particle tracks passing through a 1 cm plate of quartz will generate the Cherenkov photons, and their arrival will be timed by an array of micro-channel plate photon detectors. As part of the TORCH R&D studies, commercial and custom-made micro-channel plate detectors are being characterized. The final photon detectors for this application are being produced in a three-phase program in collaboration with industry. Custom-made single-channel devices with extended lifetime have been manufactured and their performance is being systematically investigated in the laboratory. Optical studies for the preparation of beam and laboratory tests of a TORCH prototype are also underway.

1. Introduction

The Time Of internally Reflected Cherenkov light (TORCH) [1,2] is a precision time-of-flight (TOF) detector for particle identification (PID) up to 10 GeV/c momentum. An important motivation of the TORCH development is for the PID upgrade of the LHCb experiment [3,4]. The separation of pions from kaons with a 3σ significance over a 9.5 m flight path at 10 GeV/c requires a TOF precision per charged particle track of $\sim$15 ps. Cherenkov photons are produced when the charged particle passes through 1 cm of quartz radiator plate, and are internally reflected to the photon detectors located up to 2.5 m from the emission point. The photon path reconstruction requires $\sim$1 mrad precision in the measurement of the photon propagation angle θ_z in the longitudinal direction and θ_x in the transverse direction.

Micro-channel plate (MCP) devices are used to time the arrival of single photons. The MCP photon detectors for TORCH need to have an asymmetric finely segmented anode (8×128 channels) corresponding to a pixel dimension of 6.6×0.4 mm^2, a configuration currently not commercially available. A further requirement is that the single photon propagation time must be measured with an overall precision of $\sim$70 ps and, for typically 30 detected photons per track, the precision of 15 ps per track is then achieved. The MCP devices will also need to survive several years in a high occupancy environment with an accumulated annual charge of 1–10 C/cm^2.

An important aspect of the TORCH R&D is the development of customized photon detectors in three phases of development, in collaboration with our industrial partners, Photek UK.[1] During the first phase, five circular-shaped single-channel MCP devices with extended lifetime have been manufactured.[2] The second phase will involve the production of circular-shaped MCP devices with a finely segmented anode. In the final phase, square-shaped tubes incorporating the TORCH lifetime, timing and granularity requirements will be delivered.

The TORCH detector consists of the quartz radiator, a focusing prism and an array of photon detectors. High quality polishing of the optical components, whilst maintaining the parallel surfaces, is essential to preserve the total internal reflection and the angular precision. The focusing element, at the periphery of the quartz plate, uses a cylindrical mirror which maintains the accuracy of the photon propagation angle θ_z, derived from the measured position on the photon detector array.

As an intermediate phase to the full-scale TORCH module, a small-scale prototype is in preparation. A precise mechanical arrangement to interface the optics to the photon detectors is under construction. In the laboratory, light transmission and scattering losses through glass samples are being investigated, as well

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[1] Photek Ltd, St. Leonards-on-Sea, TN38 9NS, United Kingdom.
[2] Model PMT225 from Photek.

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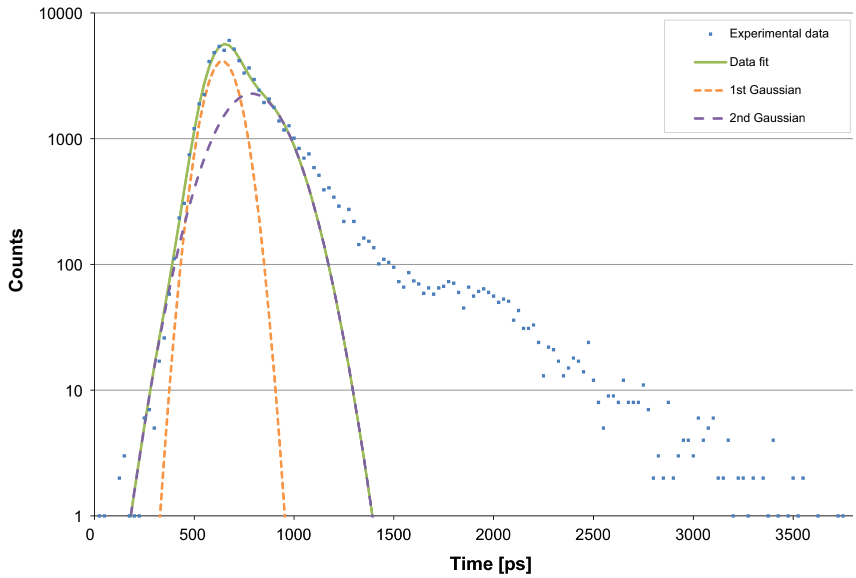

Fig. 1. The single photoelectron timing distribution of a 64-channel Planacon MCP read-out with customized readout electronics (note the vertical logarithmic scale). The distribution shows a prompt signal with a time resolution of ~80 ps, a shoulder on the right of the main peak due to a secondary laser pulse and a tail due to back-scattered photoelectrons.

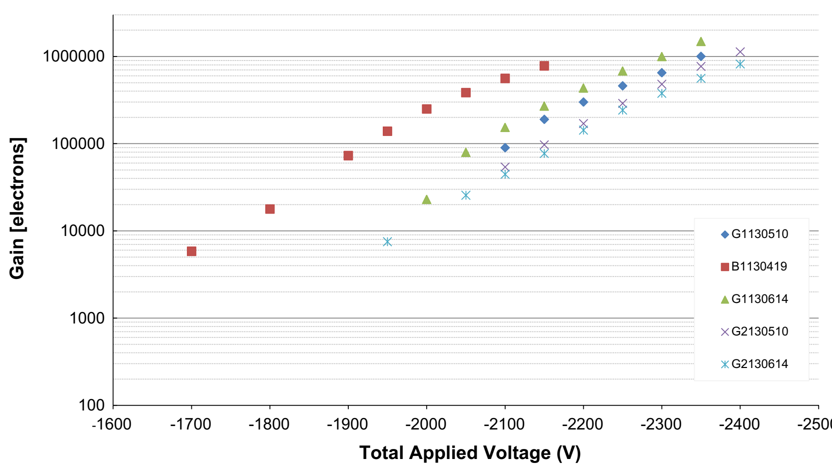

Fig. 2. The gain as function the applied voltage across the MCP for all custom-made PMT225 devices from Photek.

as the properties of the gluing material required between the radiator and the optics. The TORCH prototype together with commercial and custom-made MCP photon detectors and associated multi-channel electronics will be tested in the laboratory and in beam tests at CERN.

2. Photon detector characterization

2.1. Performance of commercial MCP devices

Initially, commercially-available MCP photon detectors with segmented anodes[3] (8 × 8 channels) were characterized with commercial single-channel readout electronics[4] [5]. We have demonstrated that commercial tubes already fulfill the timing requirements for TORCH, with a transit time spread (TTS) of <50 ps. Custom multi-channel electronics [6] based on 8-channel NINO [7] and HPTDC [8] ASICs were used to characterize the same commercial device [9]. The timing performance in the single-photoelectron regime is shown in Fig. 1. The peaked part of the timing distribution is modeled with two Gaussians. The primary Gaussian describes the MCP intrinsic time response and the second Gaussian corresponds to a secondary relaxation pulse of the laser.[5] A TTS of 80 ps is achieved. The secondary laser pulse is seen after ~150 ps which is in agreement with the manufacturer's data sheet. The right-hand tail of the timing distribution is due to back-scattering effects [5]. The long (1.5 ns) range of the tail is explained by the large gap (4.5 mm) between the photo-cathode and the MCP input face.

2.2. Performance of custom MCP devices

The first-phase MCP tubes (PMT225) have been fully characterized by Photek [10] and at CERN [11] using commercial single-channel readout electronics. These tubes are single-channel devices with a 10 μm pore diameter. Tests were performed with single photons (0.3 photoelectrons on average) and at a rather modest MCP gain (3–5 × 10^5 electrons). Fig. 2 shows the MCP gain

[3] Model XP85012-A1 (Planacon) from Burle/Photonis, Lancaster, PA17601-5688, USA.

[4] Model 142, 672, 9327, 566 and 926 from ORTEC, USA.

[5] PiLas, D-12489, Berlin, Germany.

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in electrons as a function of the applied voltage for the five PMT225 devices. The tube B1130419 has been tested at a lower voltage due to its high level of dark counts (230 kHz). The MCP gain for the other tubes follow a similar behavior as the voltage increases.

All five PMT225 tubes show an excellent timing performance of < 30 ps for single photons. Fig. 3 shows the timing distribution of one such device (PMT225/SN G2130510). The PMT225 has a small input gap of 200 μm between photo-cathode and MCP input face. Consequently, almost all back-scattered photoelectrons populate the main peak. The resulting peak asymmetry is modelled by an exponentially-modified Gaussian [12]. The peak shoulder corresponds to the secondary laser pulse and is fitted with a single Gaussian in a way similar to the method explained in Section 2.1.

For the second phase of MCP tubes development, modelling studies are in progress to achieve the required granularity using 8×64 pixels of dimensions 6.6×0.8 mm^2. The resolution of 0.4 mm required for TORCH will be achieved using charge division in the fine pixel direction. This will improve the spatial resolution and the total channel count will be halved. The spatial resolution in the fine direction has been simulated and shows a strong dependence on NINO threshold and MCP gain [13]. These studies result in a requirement of a 10^6 or higher MCP gain, which must be balanced against the requirements on photon detector lifetime.

3. Optical studies

A small-scale TORCH prototype for beam and laboratory tests is in preparation. It consists of a quartz radiator plate ($10 \times 120 \times 350$ mm^3) and a focusing prism coupled to two MCP photon detectors. An adequate gluing material between the radiator and

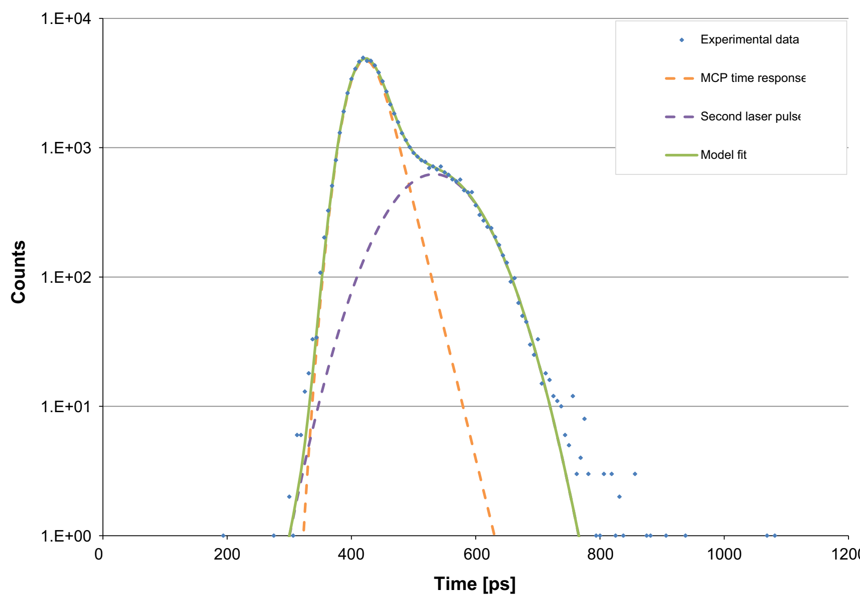

Fig. 3. Single photoelectron timing distribution of the PMT225/SN G2130510 device (note the vertical logarithmic scale). The distribution shows a prompt signal with a time resolution of ~22 ps and a shoulder to the right of the main peak due to the secondary laser pulse. Back-scattered photoelectrons populate the main peak and contribute to its right-hand asymmetry.

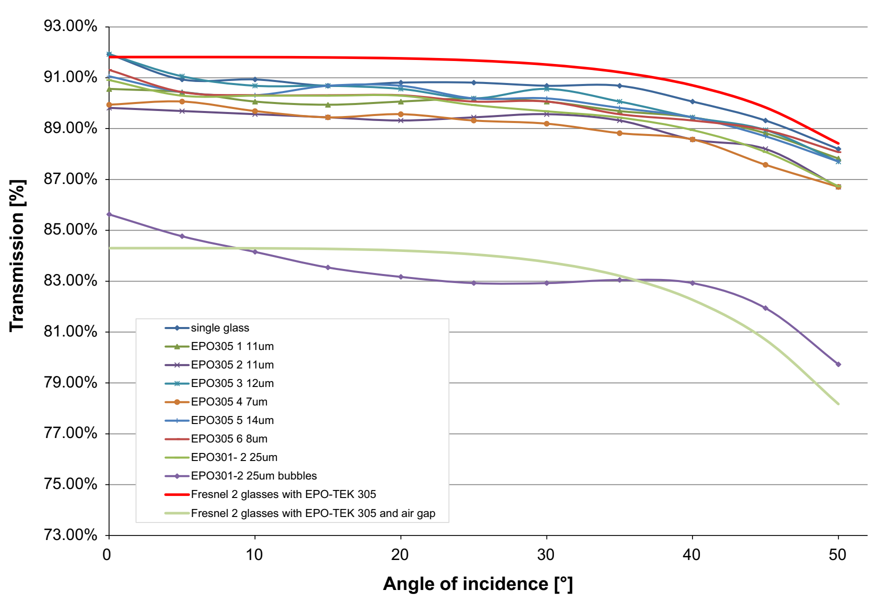

Fig. 4. Transmission curves as function of angle of incidence for a variety of epoxy samples. The red line corresponds to the expectation from the Fresnel equations for a single glass sample and the green line corresponds to two glued glass samples with an air gap due to bubbles. The colored lines with points are the experimental data for different epoxy samples. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

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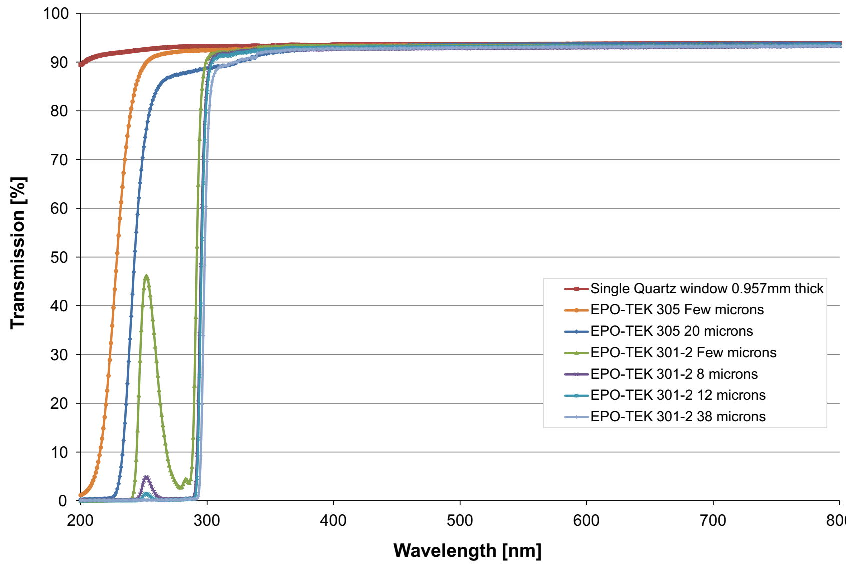

Fig. 5. Transmission curves for a single quartz specimen and for two quartz specimens glued with two epoxies at different thicknesses: EPOTEK 305 and EPOTEK 301-2.

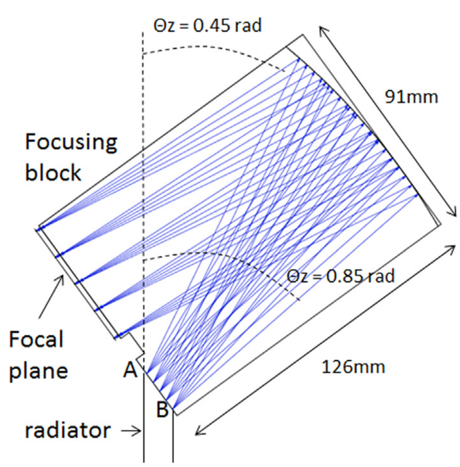

Fig. 6. Side view of the focusing prism simulated in Mathematica. Rays are generated at five emission points from A to B and at five angles in the range 0.45–0.85 rad. The simulation includes refraction effects at the exit of the focusing prism.

the focusing optics is necessary since the optical transmission of the glue and its photon energy cut off will have a significant impact on the number of detected photons.

3.1. Laboratory measurements

An optical setup has been prepared to study the quality of the glue interface between two glass samples. An initial characterization in the laboratory has been carried out using a collimated continuous wave (cw) red laser (640 nm) and a CCD. The light transmission of single glass samples is obtained from the analysis of the laser spot image measured by the CCD. The results are then compared with those where two glass samples are glued with various epoxies of different thicknesses. As expected, no bulk absorption is observed at the 640 nm wavelength. The transmission dependence on the angle of incidence has been investigated and is shown in Fig. 4. The intensity loss at normal incidence for a single glass and glued glass sample is 8–10%. For all samples the transmission is in agreement with that expected from the Fresnel equations. To study the impact of a small air gap in a glued glass sample, bubbles are artificially created in the glue. In this case, the intensity loss at normal incidence is $\sim$15% with a bubble density of $\sim$90%. The intensity loss depends on the bubble-surface ratio. The worst case is a 100% bubble density, equivalent to a continuous and uniform air gap between the two glass samples.

The transmission through quartz and glued samples as a function of photon wavelength in the range 200–800 nm was measured with a spectrophotometer. Fig. 5 shows the transmission for a single quartz specimen and two samples glued with two epoxies. EPO-TEK 305 shows better transmission in the UV region for our application. The aim is to optimize the UV transmission since most of the Cherenkov light emission is in the UV region.

In addition to absorption effects, light can be scattered during the propagation through the glass and the glue, resulting in an increase of the laser spot size. In order to understand quantitatively the relation between this increase and the scattering effect, measurements were made using several holographic diffusers. The difference in spot size before and after the diffuser determines the amount of scattered light. By applying the same procedure, a spot diameter through a single glass sample of 2.39 mm was measured and was identical to that measured through a glued glass sample. Consequently, no measurable scattering effect was identified by using this method.

3.2. Simulation

A Mathematica package dedicated to optics (Optica 3) [14] is used to simulate the optical effects observed in the laboratory. The laser source, glass samples and glue interfaces are modelled. The same package is used to simulate the TORCH prototype being prepared for laboratory and beam tests. Optical aspects such as aberration, distortion, total internal reflection, refraction, etc., are being studied in order to optimize the design parameters. At this stage, an ideal detector is considered.

The focusing quality is studied by considering only the focusing prism and the emission of single rays as shown in Fig. 6. From this simulation the photon position (y_f [mm]) on the photon detector plane can be converted into the photon propagation angle (θ_z [rd]) at the exit of the radiator, described by the equation $\theta_z = -0.008y_f + 0.652$. A small quadratic term of $-3 \times 10^{-6} y_f^2$ can be added to the linear calibration curve in order to include the aberration effect.

The radiator plate is now added to the model and a cone of rays that simulates the trajectories of the Cherenkov photons is generated.

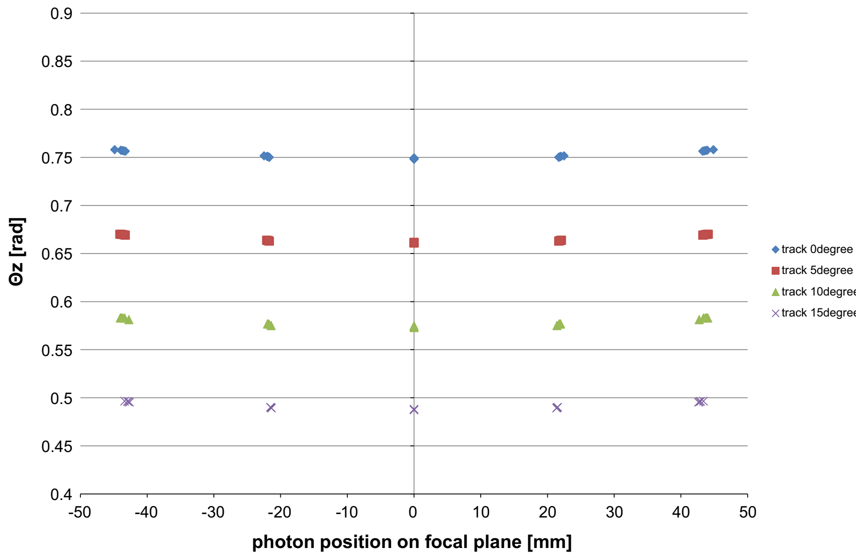

Fig. 7. Photon positions on the photon detector plane for saturated tracks simulated in Mathematica. The track incidence point is at 57.5 mm from the top end of the radiator. Each track generates 100 rays at a wavelength of 420 nm and the Cherenkov angle is 0.82 rad. Photons are emitted at five positions along the path of the track in the 1 cm-thick radiator.

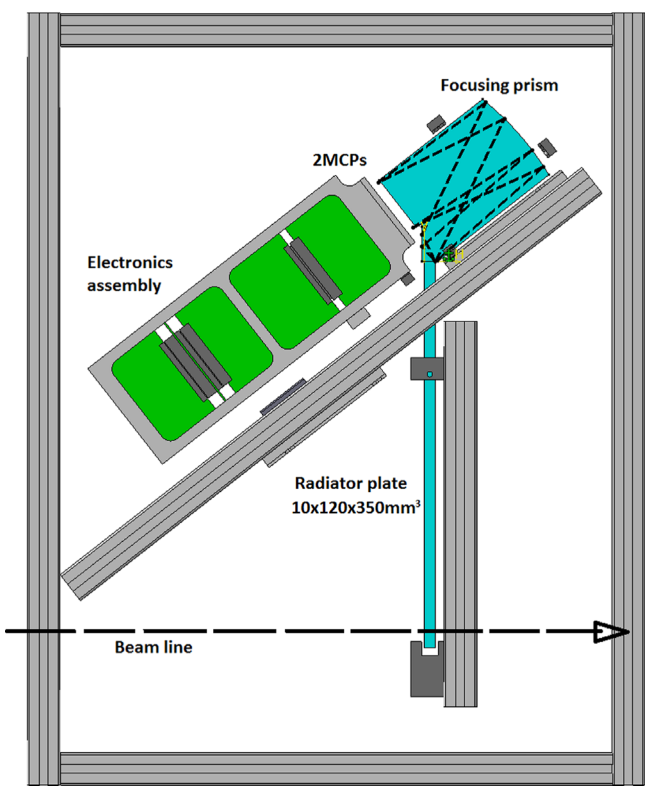

Fig. 8. A schematic view of the TORCH prototype arrangement for use in laboratory and beam tests.

The initial simulation corresponds to saturated tracks; the light cone is emitted at several track positions and angles. Various emission points along the track path through the radiator are also investigated. The angle θ_z through the radiator is calculated and is shown in Fig. 7 as a function of the photon horizontal position on the focal plane.

4. Beam tests

Beam tests will take place between October and December 2014 at the CERN SPS and PS facilities. Optical components of the TORCH prototype are under manufacture. A new generation of custom-made electronics based on the 32-channel NINO and HPTDC ASICs is under development with a channel density improvement and an offline integration of the non-linearity calibration and time walk correction.

The TORCH prototype, mechanically coupled to a commercial 32×32 channel MCP device from Photonis and a Photek phase-two MCP device, will first be characterized in the laboratory. Installation in the beam test area will follow with the associated data acquisition and monitoring. The experimental layout for these tests is shown in Fig. 8. A commercial single-channel MCP tube will be used as time reference signal in a separate and smaller light-tight box.

5. Conclusions and perspectives

The work reported in this paper summarizes the status of the TORCH R&D project. The development of the first-phase customized photon detectors from Photek is complete. The PMT225 tube performance in terms of MCP gain, dark count rate and timing properties for single photons is reported. Second-phase tubes are now in production and are expected to be delivered imminently.

A TORCH prototype is in preparation and has been described. The optical components are in construction, a new generation of electronics is in production, and the mechanical arrangement is under design. Simulation studies of the TORCH prototype in Mathematica have been presented. The photon transmission properties of quartz samples, glues and air gaps have been studied. The focusing quality of the Cherenkov rings at the MCP photon detector focal plane will now be investigated.

Acknowledgments

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References

[1] M.J. Charles, R. Forty, Nuclear Instruments and Methods in Physics Research Section A 639 (2011) 173.
[2] M.W.U van Dijk, N.H. Brook, L. Castillo García, et al., Nuclear Instruments and Methods in Physics Research Section A 766 (2014) 118.

[3] LHCb Collaboration Letter of Intent publication for the LHCb Upgrade, CERN-LHCC-2011-001.
[4] LHCb Collaboration, LHCb Particle Identification Upgrade Technical Design Report 14, CERN/LHCC 2013-022.
[5] L. Castillo García, Nuclear Instruments and Methods in Physics Research Section A 695 (2012) 398.
[6] R. Gao, R. Cardinale, L. Castillo García, et al., Journal of Instrumentation 9 (2014) C02025.
[7] F. Anghinolfi, P. Jarron, A.N. Martemiyanov, et al., Nuclear Instruments and Methods in Physics Research Section A 533 (2004) 183.
[8] M. Mota, J. Christiansen, S. Débieux, et al., IEEE Nuclear Science Symposium Conference Record NS2 (2000) 155.
[9] L. Castillo García, J.M. Fopma, R. Forty, et al., Astroparticle, Particle, Space Physics and Detectors for Physics Applications, 8, 2014633.
[10] T.M. Conneely, et al., Nuclear Instruments and Methods in Physics Research Section A 732 (2013) 388.
[11] T. Gys, L. Castillo García, J. Fopma, et al., Nuclear Instruments and Methods in Physics Research Section A 766 (2014) 171.
[12] I.G. McWilliam, H.C. Bolton, Analytical sChemistry 41 (13) (1969) 1755.
[13] J.S. Milnes, T.M. Conneely, J.S. Lapington, et al., Nuclear Instruments and Methods in Physics Research Section A 766 (2014) 183.
[14] ⟨http://www.opticasoftware.com/⟩.

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