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A RICH with aerogel for a hadron collider

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on behalf of the LHCb RICH groups

Abstract

Operating a RICH detector with an aerogel radiator is a significant challenge at a hadron collider such as the LHC due to the high event rate and multiplicity of the produced charged tracks. Large-size tiles of silica aerogel with excellent optical quality have recently been produced for the LHCb RICH detector. The photon yield and Cherenkov angle resolution from these tiles have been maximized. Results of laboratory measurements and beam tests are reported. The uniformity of the index of refraction within a tile has also been studied.

Keywords: RICH; Silica aerogel; Optical properties; Detector ageing; Photoelectrons; Cherenkov angle

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1. Introduction

Aerogel is one of the three radiators in the RICH system of the LHCb detector [1], an experiment which will study B decays and CP violation at the LHC. The LHCb RICH system, described in more detail in Ref. [2], is designed to provide a powerful particle identification tool [1,3]. The silica aerogel will cover the momentum range 2–10 GeV/c for π/K separation. In this range, it will provide an identification efficiency of K's of about 80%, with a π misidentification at the level of 1% [1,3].

The harsh environment presented by the LHC makes the use of aerogel extremely challenging. Low numbers of photoelectrons are typically produced (~6–7 per saturated track from a 5 cm tile) which must be identified as Cherenkov rings in high multiplicity and, as yet unknown, background conditions. Radiation hardness and high angular resolution are mandatory. An example of the complexity of a $b\bar{b}$ event pattern recognition is demonstrated in Fig. 1, showing simulated rings in the LHCb RICH1 detector.

Hygroscopic aerogel produced at the Boreskov Institute of Catalysis (Novosibirsk) has been chosen for the LHCb RICH1 detector. A significant R&D activity has been undertaken over the last few years in order to obtain large-size

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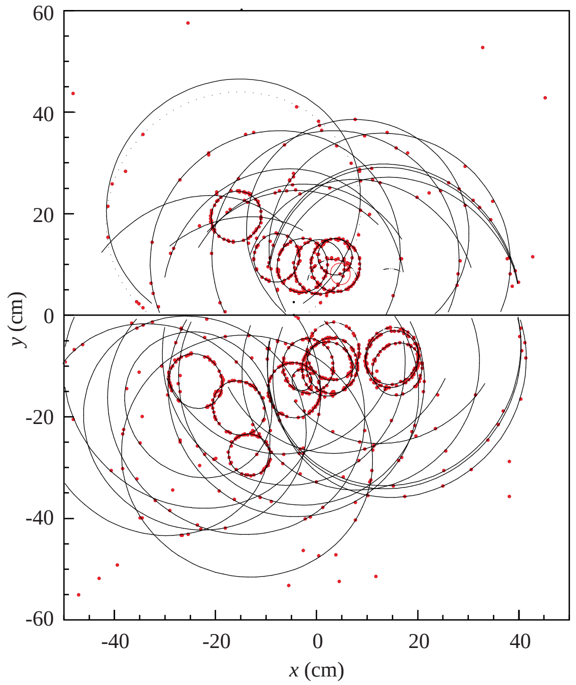

Fig. 1. Simulated rings in the LHCb RICH1 detector. The large rings are from the aerogel.

blocks with high transparency and low clarity factor. Large size (dimension $200 \times 200 \times 50\,\mathrm{mm}^3$) silica aerogel tiles with unprecedented optical quality are now available. In this paper, tests on tiles with dimensions $100 \times 100 \times 40\,\mathrm{mm}^3$ are presented.

2. Characterization of aerogel

Silica aerogel consists of solid quartz-like structure (SiO_2). The density used in LHCb is around $0.145\,\mathrm{g/cm}^3$, corresponding to an index of refraction of ~1.030. The transmittance T of light of wavelength λ in the aerogel can be described by the formula [4]

$$T(\lambda) = A\mathrm{e}^{-C \cdot t/\lambda^4} \tag{1}$$

where A is the surface scattering coefficient, t is the thickness of the aerogel block and C is the clarity factor. A and C are used to specify the optical quality of the sample.

The diffusion is usually the limiting factor for the performance of aerogel when used as a Cherenkov radiator. The length scale of the microscopic structure of the material is such that the dominant contribution to the total diffusion comes from the Rayleigh scattering, which scales as λ^{-4}. The absorption cross section is, within a wide range, wavelength independent and can be neglected for our application.

We have measured the transmittance by means of a double beam spectrophotometer. A scan in the wavelength range between 200 and 800 nm is performed in steps of 1 nm. The resulting curve is then fitted to formula (1) to extract A and C. Typical values for the Novosibirsk tiles are $C \simeq 0.0050\,\mu\mathrm{m}^4/\mathrm{cm}$ and $A \simeq 0.95$.

The aerogel tiles in LHCb must achieve a particle identification in the range 2 to $10\,\mathrm{GeV}/c$ and therefore a refractive index of $n \simeq 1.03$ is chosen. The refractive index of the aerogel is measured at wavelengths $\lambda = 543.5$ and 632.8 nm with a He–Ne laser source. Measurements are performed using mainly the prism method. Fig. 2 shows a schematic view of the setup. An aerogel block is positioned on a turntable downstream of a laser beam. The spot on the screen is measured by a CCD camera. The sample is rotated until the deflection angle θ_{out} reaches its minimum. The resolution achieved with this method is $\sigma_n \simeq 3 \times 10^{-4}$.

A programme of R&D was performed at the Novosibirsk Institute of Catalysis to make possible the use of aerogel at the LHC. In order to minimize the loss of photons, the aim was to

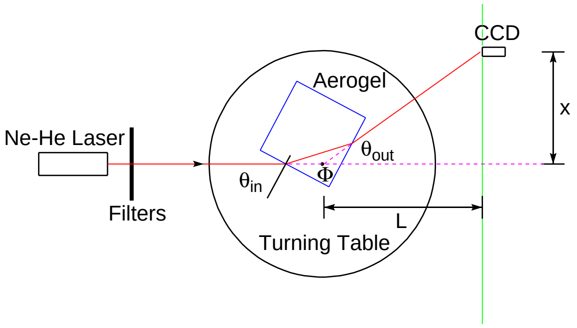

Fig. 2. The experimental setup used for the measurement of aerogel refractive index.

achieve the best possible optical quality for aerogel tiles of large dimension. This resulted in the production of aerogel tiles in 2002 of dimension $\sim 10 \times 10 \times 4\,\text{cm}^3$, with T around 35% at $\lambda = 400\,\text{nm}$ and C between 0.0045 and $0.0065\,\mu\text{m}^4/\text{cm}$. The measurements reported here are performed on these tiles.

In 2003 a large tile of dimension $11.6 \times 11.6 \times 5.5\,\text{cm}^3$ was produced, shown in Fig. 3. The full thickness chosen for LHCb is 5 cm, and therefore the aerogel wall could be made with only one layer, rather that stacking several layers. The characteristics of this tile were $C = 0.0057\,\mu\text{m}^4/\text{cm}$, and $T = 30\%$ at 400 nm. The final step in producing large and thick tiles was successfully completed in 2004, with the production of 3 tiles of dimensions $20 \times 20 \times 5\,\text{cm}^3$ all being produced with a C better than $0.0062\,\mu\text{m}^4/\text{cm}$, shown in Fig. 4. Optical measurements of these tiles, are in progress; Fig. 5 shows the transmission of the tile of Fig. 4.

3. Ageing effects in aerogel

Inside the LHCb RICH1 detector, the aerogel radiator wall will be positioned at a radial distance of about 10 cm [1,3] from the beam and about 1 m downstream of the interaction point. It will be exposed to a significant particle flux, up to $3.5 \times 10^{12}\,\text{particles}/\text{cm}^2/\text{year}$. We have therefore tested and measured possible ageing of aerogel due to intense irradiation.

The ageing of aerogel has been investigated [5] by exposing aerogel tiles to very intense γ radiation from a ^{60}Co source, and by exposure to proton and neutron high intensity beams. The transmit-

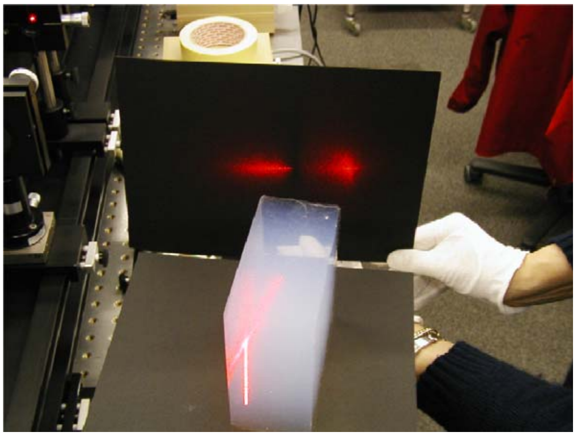

Fig. 3. The aerogel tile of dimension $10 \times 10 \times 5.5\,\text{cm}^3$ being tested with a laser beam. Its index of refraction was 1.0260.

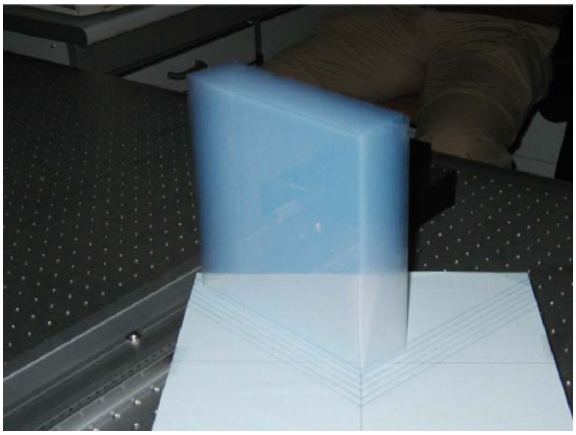

Fig. 4. A tile of dimension $20 \times 20 \times 5\,\text{cm}^3$. Its index of refraction is 1.0308.

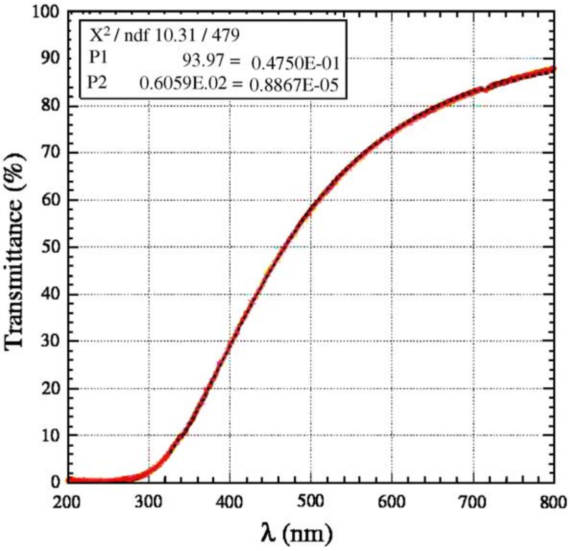

Fig. 5. T measured for a tile of dimension $20 \times 20 \times 5\,\text{cm}^3$. The clarity from the fit is $C = 0.0060\,\mu\text{m}^4/\text{cm}$.

tance and clarity have been monitored as a function of increasing irradiation dose. The refractive index n has also been measured before and after irradiation. No detectable degradation of the optical parameters has been observed for doses equivalent to a few times the LHCb lifetime in the case of γ and proton irradiation. A slight worsening of the clarity due to neutron irradiation was observed however, for a fluence corresponding to the LHCb lifetime, C increased by only about 5%. This is not a significant concern for the performance of LHCb particle identification.

Because this aerogel is hygroscopic, tests have been carried out to determine the degradation in T and changes in n induced by humidity absorption in air. The test revealed that an exposure to humid air changes the optical properties of the aerogel, but the original properties are completely restored by baking the exposed sample to a temperature of about 500 °C. In LHCb, it will be ensured that the aerogel will never be exposed to humidity during running.

4. Performance of aerogel in a testbeam

A crucial parameter for any RICH detector is the Cherenkov angle resolution. The main contributions are:

- from the pixel size of the photodetector ($\sim d/4R$, where d is the linear pixel size and R the focal distance),
- from the chromatic dispersion of the radiator, due to the fact that n is a function of λ. This contribution is $\sim 1/2[\sigma_n/(n-1)]$, where σ_n is the variation of refractive index over the detected wavelength range, but relies on the form of functional behaviour assumed for n.
- from the photon emission point: this contribution can be expressed as $\sim t \sin\theta_C \cos\theta_C/L\sqrt{12}$, where t is the radiator thickness and L the distance to the photodetectors.
- from the precision with which n of the radiator is known ($\sim 1/2\ [\delta(n-1)/(n-1)]$).
- from the imperfect knowledge of the incoming particle direction, measured by the tracking system.

For the case of the aerogel in RICH1, all these contributions combine to 2.6 mrad, calculated by a Monte Carlo simulation of the detector.

Several beam tests were performed at the CERN PS to check if the measured resolution and photoelectron yield were well predicted by the simulation. Hybrid Photon Detectors (HPDs) were used as photodetectors [6,7]. In all these tests, the particle identification potential of an aerogel-based RICH detector was studied using both pure π^- and mixed π^+/p beams of momenta ranging from 6 to 10 GeV/c.

The Cherenkov emission angle θ_C was extracted from the photoelectron hit coordinates and a complete knowledge of the geometry of the setup using the retracking algorithm described in Ref. [8]. Data taken with four pad-HPDs [9] indicate a resolution, per detected photoelectron, of $\sigma(\theta_C) = (5.0 \pm 0.3)$ mrad [7]. Contributions to the resolution arising from the factors described above are expected, from the simulation, to be 3.1 mrad [7].

Recently, tests with the pixel HPD [10,11], which is the chosen photodetector for the LHCb RICH system, have been carried out. The data are still being analysed. Preliminary results indicate that $\sigma(\theta_C) \sim 2.8$ mrad, while the expected value from simulation of the test configuration is 2.4 mrad.

5. Study of Δn across a tile

A possible contribution to the Cherenkov angle resolution could come from a sizeable variation of refractive index within a tile. The refractive index of the aerogel is tuned during the production phase [12]. The refractive index n and the density ρ are related by the expression

$$n(\lambda) = 1 + k(\lambda)\rho. \tag{2}$$

Typically, if the density is expressed in g/cm^3, $k = 0.21$.

Local inhomogeneities of the density lead to point-to-point variations of the refractive index

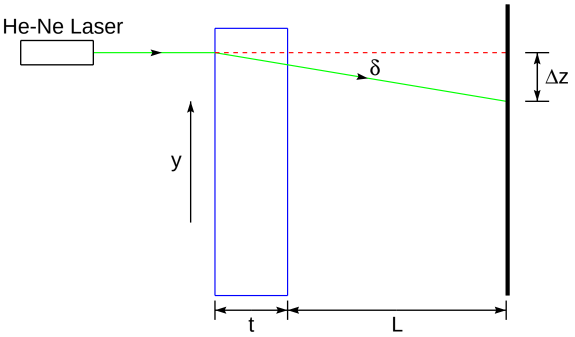

Fig. 6. Setup using a laser beam to study the refractive index uniformity.

within the tile. These variations contribute to the Cherenkov angle measurement inaccuracy. In order for this contribution to have a negligible effect on the total θ_C resolution, the maximum allowed refractive index variation $\sigma(n-1)/(n-1)$ should be significantly less than 1%, corresponding to an uncertainty $\sigma(\theta_C)$ less than 1.17 mrad for $n = 1.03$.

A method already applied in the past [13] to study possible refractive index variations is shown in Fig. 6. It makes use of a laser beam directed perpendicular to the aerogel surface. The deviation angle δ is proportional to the refractive index gradients, $\mathrm{d}n/\mathrm{d}y = n \cdot \delta/t$, where t is the thickness of the block. The variation of n along the y direction can be easily calculated from the measurements of $\delta(y)$ scanning over the aerogel surface

$$\Delta n(y) = \frac{n}{t} \cdot \int_{y_0}^{y} \delta(y)\,\mathrm{d}y. \qquad (3)$$

Results from one tile are plotted in Fig. 7. The measurement has been made with a red laser ($\lambda = 633\,\mathrm{nm}$).

We performed an alternative study, which makes use of an electron beam. This method is based on the Cherenkov effect itself, and it is therefore appropriate to check directly the changes of refractive index variations convoluted with the emission spectrum of the Cherenkov photons transmitted by the aerogel. The experiment has been called "APACHE" for *Aerogel Photographic Analysis by CHerenkov Emission*. The setup used is shown in Fig. 8.

A light-tight box was installed in the 500 MeV electron beam of the DAΦNE Beam Test Facility in Frascati [14,15]. The electron beam impinged upon different entrance points of the aerogel block surface. A tilted spherical mirror focused the

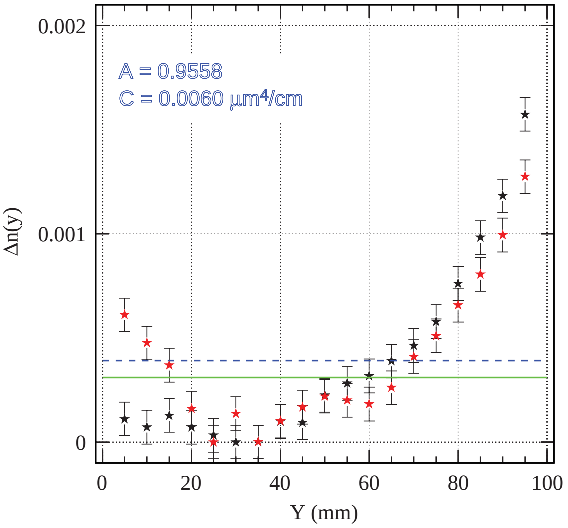

Fig. 7. Variations of the refractive index from a scan of one tile. The solid line shows the maximum spread Δn allowed, the dotted line shows the mean value of Δn measured. The two set of points refer to the two orthogonal scans performed on the same $100 \times 100 \times 41\,\mathrm{mm}^3$ tile.

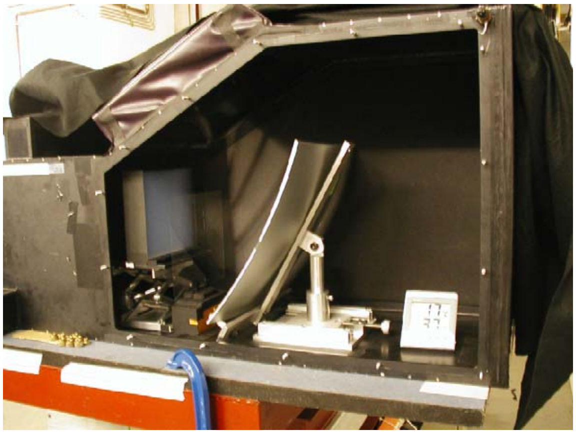

Fig. 8. The APACHE experimental setup.

Cherenkov photons onto 8″ × 10″ black & white photographic films,[1] acting as photodetector. The dark box volume was flushed with nitrogen to avoid as much as possible variations of the optical properties of the aerogel due to the absorption of humidity in air [5]. A black paper screen was used to absorb photons produced in the nitrogen upstream of the aerogel. After each run of data taking, the exposed films were processed by a professional photographic laboratory.

Since the mirror is spherical and tilted with respect to the beam direction, spherical aberrations distort the focusing properties in a non trivial way. As a consequence, the Cherenkov rings on the detector plane are no longer perfectly circular, but they are distorted into elliptical shapes. The exposed tile was the same for which results with the laser method have been shown in Fig. 7. Fig. 9 shows a comparison between a full GEANT4 simulation [16] and the data. The Cherenkov photons produced in aerogel and nitrogen are clearly visible.

By using the hit-by-hit retracking algorithm [8], the distribution of the reconstructed Cherenkov angle was formed, as shown in Fig. 10. The peak position is well determined and is used as estimator of the Cherenkov angle measured at that entrance position. A comparison of these values for each beam entrance points gives the variation of the mean angle θ_C. In a given position, data were taken with and without a UV filter at the exit surface of the aerogel. It has been verified by means of simulation that the resolution in the peak position is 0.3 mrad. The angular distributions are significantly wider for runs without the filter, since the UV photons have a much higher probability of being scattered by Rayleigh mechanism, as described in Eq. (1).

To check the stability of the run conditions, a good indicator is the Cherenkov angle distribution of photons produced in the nitrogen volume between the aerogel and the mirror. The value of the angle corresponding to the nitrogen is expected to be constant from run to run, apart for refractive index variations due to temperature and pressure changes, which are very small. Any significant displacement of the nitrogen Cherenkov peak can thus to be ascribed to uncontrolled variations of the beam direction.

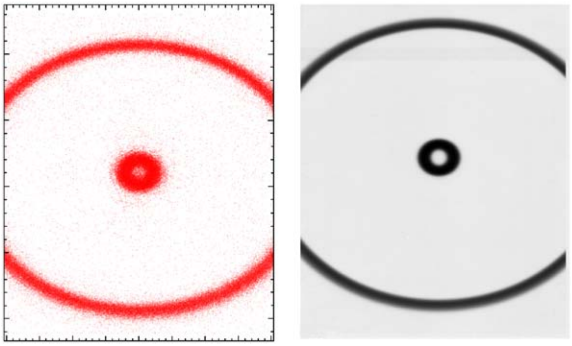

Fig. 9. A GEANT4 simulation (left) and data (right) of the photons collected on the detection plane of the APACHE experiment.

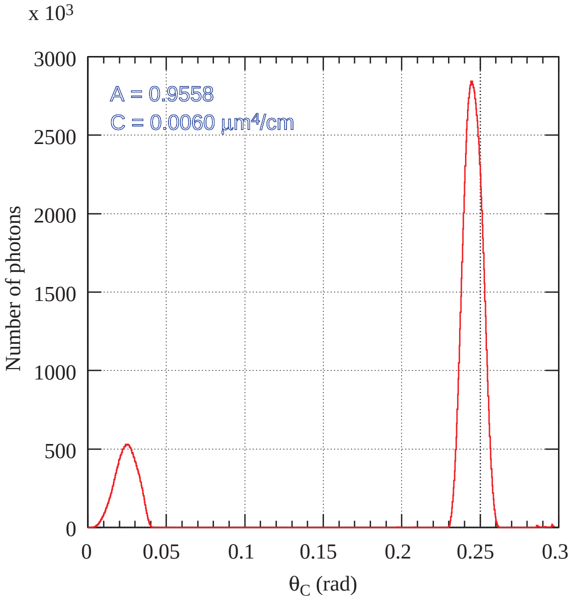

Fig. 10. The distribution of the reconstructed angle θ_C in a typical APACHE run.

The results of the scan over the aerogel surface are shown in Figs. 11 and 12. The nitrogen data show a constant behaviour except for three points. For these runs a movement of the beam must be considered in the reconstruction. The same points therefore were not considered in the distribution of Fig. 12 to evaluate the spread in n.

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[1] Kodak® Professional TRI-X 400 Film/400TX.

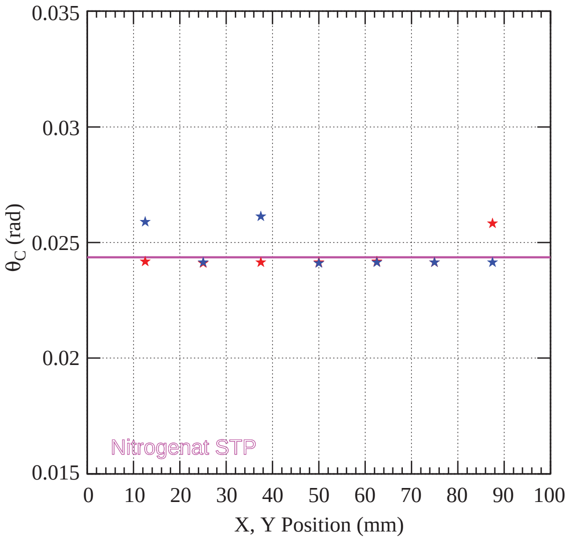

Fig. 11. The reconstructed Cherenkov angle θ_C for nitrogen, for the runs scanning the aerogel surface. The continuous line defines the angle expected for $\lambda = 633$ nm at STP.

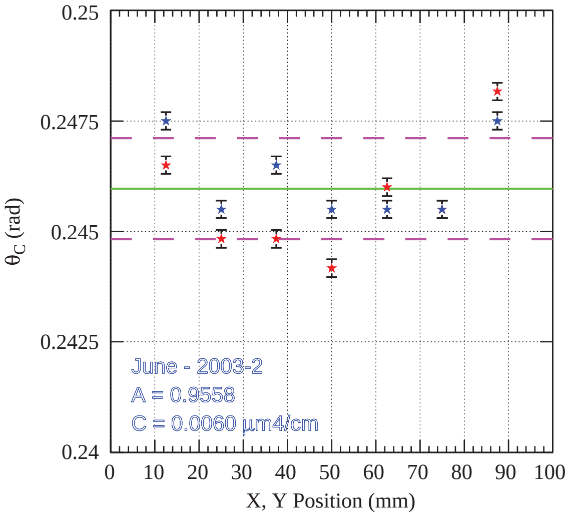

Fig. 12. The reconstructed Cherenkov angle θ_C as a function of the beam entrance position on the tile surface. The two sets of points correspond to the two scans performed, one horizontal (along *X*) and one vertical (along *Y*).The blue dashed lines define the 1σ region around the average value for θ_C.

To study the uncertainties associated with this method, small changes in the setup geometry or beam conditions were simulated. The beam direction has been varied both as parallel displacement and as a tilt with respect to the nominal beam axis. The film position in space has been varied in order to check the effect of systematic shifts in the reconstruction parameters in the analysis. It has been found that small misalignments do not contribute substantially to the accuracy for measuring the relative variations of *n*.

The measurements with the electron beam agree well with the results using the laser beam, indicating that the spread in *n* across a tile is contained within 1%, contributing negligibly to the total angular resolution of the aerogel.

6. Conclusions

A RICH detector using an aerogel radiator is an ambitious project for a hadron machine like LHC. The LHCb experiment is planning to use large size blocks which have been tested for ageing under intense particle fluences, and in testbeams. The very promising results justify with confidence that the performance expected by the LHCb simulation will be achieved in the real detector. Possible background conditions related to the machine could however make the task even more difficult. It must be stressed that exploiting the measurements of a RICH detector implies very detailed and sophisticated software tools.

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