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Technical note

Glass-coated beryllium mirrors for the LHCb RICH1 detector

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Abstract

The design, manufacture and testing of lightweight glass-coated beryllium spherical converging mirrors for the RICH1 detector of the LHCb experiment are described. The mirrors need to be lightweight to minimize the material budget and fluorocarbon-compatible to avoid degradation in the RICH1 C_4F_{10} gas radiator. Results of the optical measurements for small-sized prototypes and for a full-sized prototype mirror are reported.

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Keywords: Beryllium mirror; RICH; LHCb

1. Introduction

The LHCb experiment [1] is designed to study B decays and CP violation at the CERN Large Hadron Collider, LHC. The experiment has a Ring Imaging Cherenkov (RICH) detector system [2,3], that will provide a powerful particle identification tool. The RICH system uses two detectors, RICH1 and RICH2, to cover the momentum range 1–100 GeV/c. In RICH1, the focusing of Cherenkov light onto the photon detectors is achieved using a combination of spherical converging mirrors which lie within the detector acceptance and secondary planar mirrors positioned outside the detector acceptance. The spherical mirrors must be lightweight to minimize the amount of material within the detector acceptance and must be stable in the RICH1 C_4F_{10} fluorocarbon gas radiator environment.

Over recent years, the need to manufacture lightweight large-sized mirror optics for space telescopes led to research with other optical materials to replace glass. Beryllium ($Z = 4$) looked very promising as an alternative material because of its unique properties, ideal for lightweight applications requiring high rigidity. Several beryllium mirrors [4–6] have been fabricated successfully for space applications. Over the past years starting from 1998 [7], two technologies were tested in parallel for the spherical mirrors of RICH1: composite[1] and glass-coated beryllium.

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[1]Two types of composite mirrors were tested. The first type (polymethyl-metacrylate based) was manufactured in house [8], while the second (carbon-fibre resin) was manufactured commercially.

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Table 1
Properties of typical materials used to construct lightweight mirrors

Material	X_0 (g/cm^2)	λ_I (g/cm^2)	E (GPa)	α ($10^{-6}/^\circ$C)	ρ (g/cm^3)
Pyrex (borosilicate glass)	28.1	≈ 97	64	3.2	2.23
Beryllium	65.19	75.2	255	11.5	1.848
Aluminum	24.01	106.4	69	23.9	2.70
Plexiglass (PMMA)	40.49	83.0	3.3	70	1.19

It is the beryllium mirror technology that is described in this paper.

For this application, the attractive properties of beryllium [9,10,12] are a long radiation length, good rigidity, lightweight, non-magnetic, fluorocarbon compatibility, high melting point (1285 °C), low coefficient of thermal expansion, and oxidation resistance in air. The principal disadvantages of beryllium are its high toxicity which requires special safety measures during manufacturing and particular care when handling the mirror, and the higher manufacturing cost when compared to other mirror technologies. Polished beryllium surfaces have a high reflectivity, >95%, in the infrared, while in the visible and ultraviolet the reflectivity is only ~50%. The typical average surface roughness of polished beryllium is ~20−30 nm rms and beryllium surface finishes of ~1−3 nm rms, which can then be evaporatively coated with reflective metals (e.g. aluminum or silver) and a protective coating (e.g. magnesium fluoride) giving reasonable reflectivity in the visible and ultraviolet, is costly and difficult to achieve [11]. Instead a thin glass layer fused onto a beryllium substrate provides a glass surface which can be polished by standard optical methods and then coated with an aluminum reflective film, increasing the mirror reflectivity to better than 90%. The beryllium substrate serves to support the thin glass layer, being rigid enough to maintain the desired reflective spherical surface. The thermal expansion of the glass is tuned to match that of the beryllium.

A comparison between the basic properties of materials [12,13] which can be used to manufacture lightweight mirrors is given in Table 1. The compared properties are radiation length X_0, interaction length λ_I, Young's Modulus E, coefficient of thermal expansion α and density ρ.

2. Mirror characterization

The two main parameters defining the optical quality of a mirror are the radius of curvature R and the average geometrical quality D_0. The parameter D_0 is defined as the diameter of the circle at the mirror centre of curvature (CoC) which contains 95% of the reflected light intensity from a point source placed at the CoC. The setup for the measurement of spherical converging mirrors [14,15] is described in appendix. The precision of the D_0 and R measurements are $\sigma_{D_0} = 0.06$ mm and $\sigma_R = 1$ mm, respectively.

The quantity σ_s, defined as $\sigma_s := D_0/4$, would represent the rms value of the spot light distribution if it had a Gaussian shape. The angular precision of the mirror, σ_θ, is defined as the rms angular deviation of the normal to the mirror surface at a given point from the radius of curvature at that point and is related to D_0

$$\sigma_\theta = \frac{\sigma_s}{2R} = \frac{D_0}{8R} \tag{1}$$

where the factor 2 in the denominator takes account of the reflection at the mirror surface. D_0 is independent of the spot shape and distribution; while σ_θ, where a radial symmetry for the spot is supposed, can be considered an approximation of the rms of the spot distribution.

3. Small-sized prototype beryllium mirrors

Three small-sized glass-coated beryllium mirror prototypes were manufactured in Russia[2] and were tested at CERN [14], during the years 1998 to 2001. Photographs of the prototypes are shown in Fig. 1(a)–(c). The first prototype is simply a circular flat mirror, while the other two prototypes are spherical converging mirrors.

The flat mirror has a diameter of 95 mm and consists of a 10 mm thick beryllium substrate coated with a 1 mm glass layer, resulting in 3.6% X_0 and a D_0 measured[3] to be less than 0.1 mm. The second prototype is also circular, with a diameter of 280 mm, consisting of a 5 mm thick beryllium substrate with a 1 mm glass layer coating and reinforced by a 20 mm thick rib-like structure. The average thickness is 3.3% X_0, with 7.9% X_0 at the ribs and 2.2% X_0 between the ribs. The measured mirror precision is very high, $\sigma_\theta = 0.013$ mrad ($D_0 = 0.85$ mm), and the measured radius of curvature $R = 7926$ mm is close to the design value of $R = 8000$ mm. The rib-like structure ensures high mirror rigidity. After the successful testing of the first two prototypes, a third prototype was manufactured according the LHCb RICH1 specifications of the time [2], $R = 1700$ mm and $D_0 < 2$ mm. The third prototype is rectangular shaped, 375 mm × 300 mm. It consists of a 6 mm thick beryllium substrate without any rib reinforcement with a 0.3 mm glass coating, giving 1.9% X_0. It also has a good precision, $\sigma_\theta = 0.03$ mrad ($D_0 = 0.41$ mm) and $R = 1696$ mm is very close to the design value of 1700 mm.

The measured parameters for the three mirrors are summarized in Table 2 and Fig. 2(a),(b) demonstrates the measurement of D_0. As a result of the success of these small-sized prototypes which proved the technology, a full-sized prototype mirror was designed and manufactured.

[2]Developed and manufactured by Kompozit Joint Stock Company, Moscow; http://www.korolev.ru/english/e_kompozit.html.

[3]The setup to measure the D_0 of flat mirrors needs to be modified to include a high quality spherical reference mirror with a very small D_0 (~0.2 mm) to focus the light, small enough to allow measurement of the D_0 of the flat mirror.

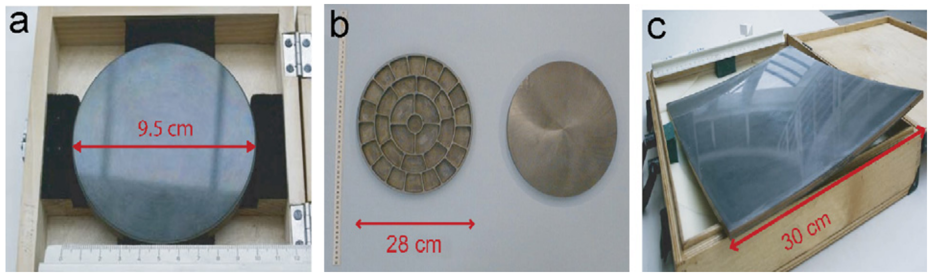

Fig. 1. Photographs of the small-sized prototype glass-coated beryllium mirrors: (a) a front view of prototype 1 (flat mirror); (b) the back side with the reinforcing rib structure and the front side (right) view of prototype 2; (c) a front view of prototype 3.

Table 2
Measured parameters for the three small-sized prototype beryllium mirrors

Mirror	Dimensions (mm)	Thickness (mm)	R (mm)	D_0 (mm)	σ_θ (mrad)	weight (kg)	X_0 (%)
Prototype 1	Ø95	11	∞	<0.1	–	0.15	3.6
Prototype 2	Ø280	6 to 26	7926	0.85	0.013	0.95	3.3
Prototype 3	375 × 300	6.3	1696	0.41	0.030	1.3	1.9

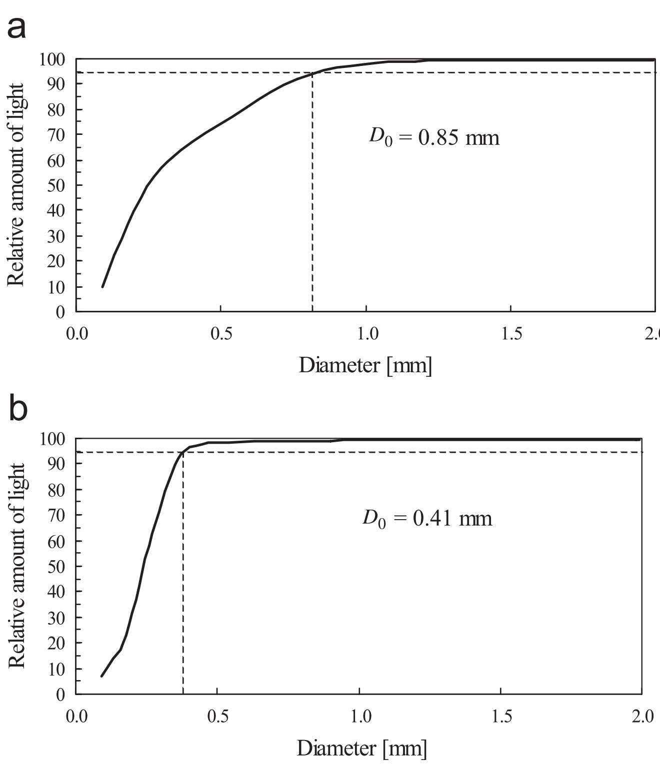

Fig. 2. (a),(b) The measured D_0 for the second (a) and third (b) prototypes. The plots show the relative amount of the reflected light intensity (%) contained inside circles of varying diameters.

4. Design of a full-sized prototype mirror

The full-sized prototype mirror was designed to be as thin as possible, minimizing the $X_0\%$, but at the same time rigid enough not to deform under its own weight. It was designed according to the RICH1 specifications, so that if successful, it could be installed as a final RICH1 mirror. The mirror dimensions were constrained by limitations in the manufacturing size of the beryllium blanks. The largest beryllium blank from which a mirror could be manufactured was disc shaped, 800 mm in diameter. The design consists of a 3 mm thick spherically shaped beryllium substrate ($R = 2700$ mm) coated with a thin glass layer (0.3–0.5 mm), having a 20 mm thick beryllium rim at one edge to support the mirror (see Fig. 3). The shape of the mirror is rectangular in projection. The rim serves to bolt the mirror to the mirror support structure which lies outside the LHCb experimental acceptance. The mirror specifications are listed in Table 3.

The dimensions refer to the drawings in Fig. 6(a,b). The thickness of the beryllium substrate (3 mm) and of the glass coating (0.3–0.5 mm) is to satisfy the material budget within the LHCb acceptance, i.e. $X_0 < 2\%$ and $\lambda_I < 1\%$. The radius of curvature precision σ_R should be better than

$$\sigma_R \simeq \frac{\sigma_d}{r_c} R \simeq 1.6\% \cdot R \tag{2}$$

where σ_d ($\simeq 0.72$ mm) is the photodetector precision (2.5 mm × 2.5 mm pixel size) and r_c is the maximum Cherenkov cone base radius on the mirror ($\simeq 45$ mm for C_4F_{10} in RICH1). A radius of curvature of $R \pm 1\%$ ensures proper focusing of the Cherenkov photons onto the RICH1 photondetectors. The D_0 value is chosen to be smaller than the photodetector pixel size (<2.5 mm) to ensure a good mirror angular resolution ($\sigma_\theta < 0.12$ mrad) which will contribute negligibly to the total RICH1 single photon Cherenkov angle resolution ($\simeq 1.6$ mrad in C_4F_{10} gas). In order to minimize scattering of the reflected light, the smoothness of the polished glass surface is required to be $\sim\lambda/100$, which corresponds to a surface roughness <5 nm rms for the wavelength region of interest, $\lambda \sim 200-600$ nm.

A finite element analysis (FEA) [16] was performed using ANSYS[4] to investigate the support scheme for the mirror

[4] General-purpose FEA computer aided engineering software tools developed by ANSYS, Inc.

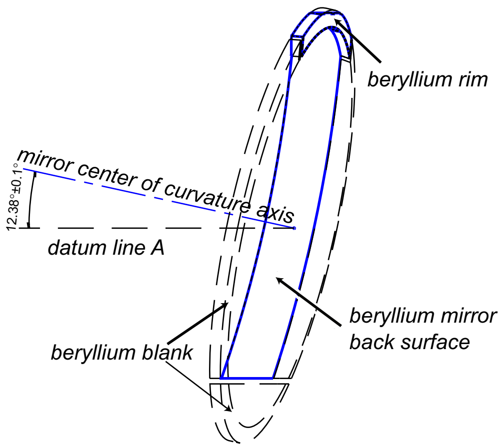

Fig. 3. A drawing showing the outline of the mirror (continuous line) within the disc-shaped blank (dashed line) from which the mirror is machined. Datum line A is the horizontal axis.

Table 3
RICH1 design specifications for the full-sized prototype beryllium mirror

Dimensions (mm)	Average thickness (mm)	R (mm)	D_0 (mm)	X_0 (%)	λ_I (%)	Roughness (nm)
383.5×660	3(Be) and 0.3–0.5(glass)	$2700 \pm 1\%$	<2.5	<2	<1	<5

in the RICH1 setup, the mirror distortion due to gravity for different support schemes, the stresses and displacements induced by thermal expansion, and bolt preload and misalignment of the mating surfaces (see Fig. 4(a),(b)).

For the FEA studies, only the beryllium substrate is considered supported from the rim. The results show that the compression of the rim due to the bolt preload is unlikely to cause any significant mirror deformation. A central single point support system was chosen because it is the simplest scheme and avoids the complications associated with the distortions due to differential thermal expansion between the mirror rim and the support structure and the possible misalignment of the mating surfaces of a multiple point support system. Various combinations of pin diameters and lengths were studied. The mirror was held tilted by 12° vertically (Fig. 4b) supported by the rim from the top, which corresponds to one of the two possible tilts of the mirror in RICH1. A single point support consisting of a 10 mm diameter pin with no protrusion beyond the mirror rim gives the least deflection. The maximum deflection of the mirror surface is 164 μm, compared to a 83 μm maximum deflection for the best case possible where the mirror is supported continuously along the rim. For the analogous case where the mirror is supported by its rim from the bottom, and held tilted vertically by 12° (mirror CoC is pointing downwards), the resulting magnitude of the deflection is the same but the direction is reversed. In addition, the five lowest vibration modes were calculated: 21.4, 59.4, 72.7, 121.3, and 199.4 Hz for both mirror orientations. These modes avoid the typical 50 Hz mechanical vibration of electric equipment which might be present in the LHCb experimental area.

The FEA surface displacements of the mirror due to gravity were used to calculate the variation in the radius of curvature for elemental areas on the mirror surface by a fitting procedure, to obtain the approximate effect on the mirror D_0. The fitting procedure involves looping over each FEA point on the mirror surface to find the four nearest neighbours and then fitting them to a sphere. Each FEA point is weighted by the local surface density of FEA points. The results are shown in Fig. 5. In the y-direction (vertical) the mean shift is ~700 μm with an rms of ~250 μm, while in the x-direction (horizontal, parallel to the rim) and in the z-direction the mean shift of the CoC and rms are similar, i.e., ~20 μm and rms of ~120 μm. This corresponds to a slight increase of the mirror radius of curvature and widening of the spot at the CoC. This is still within the RICH1 tolerances and proves the feasibility of the mirror design.

Drawings of the mirror are shown in Fig. 6(a),(b). The mirror rim has three holes into which titanium inserts are glued; this is in accordance with the beryllium safety rules which prohibit any direct fixing of bolts to the beryllium bulk. The central hole supports the mirror from the top (bottom) and is bolted to the support structure through the titanium insert. Two pins fixed to the support bar are inserted into the side holes as a safety mechanism to prevent rotation of the mirror about the central hole axis in case of accidental shocks. The outer part of the rim is cut to form an angled flat surface, so that when the mirror is bolted to its support bar, it is held at the required angle in RICH1.

5. Manufacture of a full-sized prototype mirror

A year long extensive R&D phase was necessary to manufacture a full-sized prototype mirror. The mirror was manufactured by Kompozit in collaboration with the Vavilov State Optical Institute[5] under the supervision and coordination of IHEP-Protvino. The beryllium was procured from Ulba[6] in Kazakhstan. The full-sized prototype mirror was delivered in July 2005. An overview of the manufacturing process follows.

The so-called "vacuum-hot-pressing" technology is used to produce the beryllium blank at Ulba. Powder metallurgy is used to manufacture beryllium parts. Beryllium powder is placed into a die where the powder is vibrated to obtain a

[5]Vavilov State Optical Institute, St. Petersburg (http://soi.srv.pu.ru).

[6]Ulba Metallurgical Plant, Ust-Kamenogorsk, Kazakhstan (www.ulba.kz).

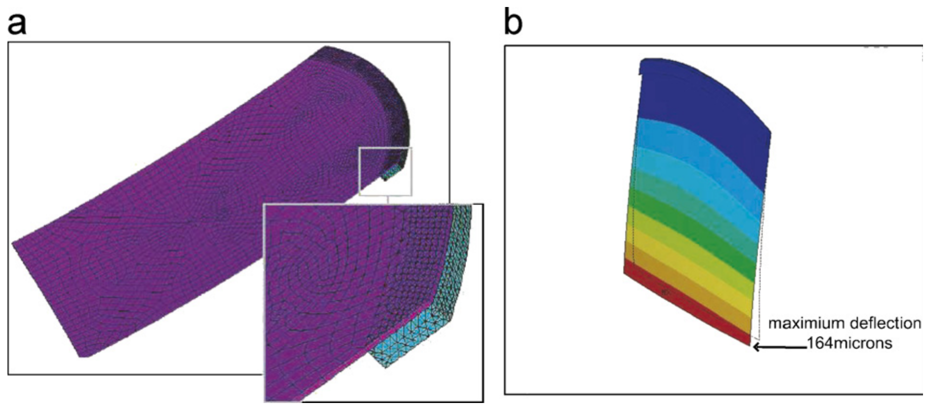

Fig. 4. (a) The mesh model of the mirror beryllium substrate used for the FEA; (b) the deflection contour plot for the mirror supported from the top by a single pin (10 mm diameter and no protrusion) with a vertical tilt of 12° (mirror CoC axis pointing upwards). The maximum deflection of 164 μm occurs at the bottom of the mirror.

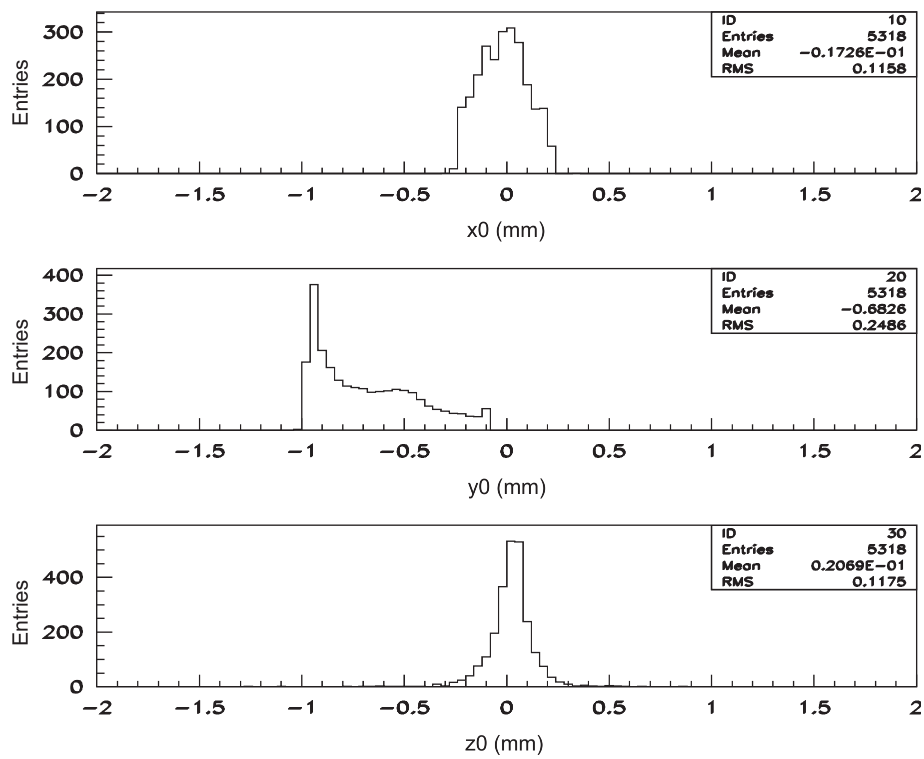

Fig. 5. The distribution of coordinates (mm) of the centre of curvature of elemental areas of the mirror surface. The coordinates $x_0 = 0$, $y_0 = 0$, $z_0 = 0$ correspond to the position of the centre of curvature for the undeformed mirror (no gravity applied).

homogeneous distribution, while heat and pressure are applied to compress and consolidate the powder into a solid metallic object. At the same time a vacuum is applied to outgas and prevent the formation of air bubbles in the blank. The fabricated beryllium blank is rectangular shaped (800 mm × 800 mm) with a thickness of 40 mm. It is then machined down to a 20 mm thick spherical blank Ø800 mm with a radius of curvature approximately equal to the desired value for the mirror. The blank is then sent to Kompozit where it is machined down to the final shape and thickness of the mirror and repeatedly annealed for stress relief. The resultant beryllium substrate is ~4 mm thick and spherically shaped with a radius of curvature very close to its final value. The substrate was not machined down to its design value of 3 mm thickness because of the considerable risk in breaking it during machining. A radiation hard glue with low outgassing[7] is used to glue the titanium inserts into the holes of the beryllium substrate rim.

[7]Propriety information, special glue used also for space applications.

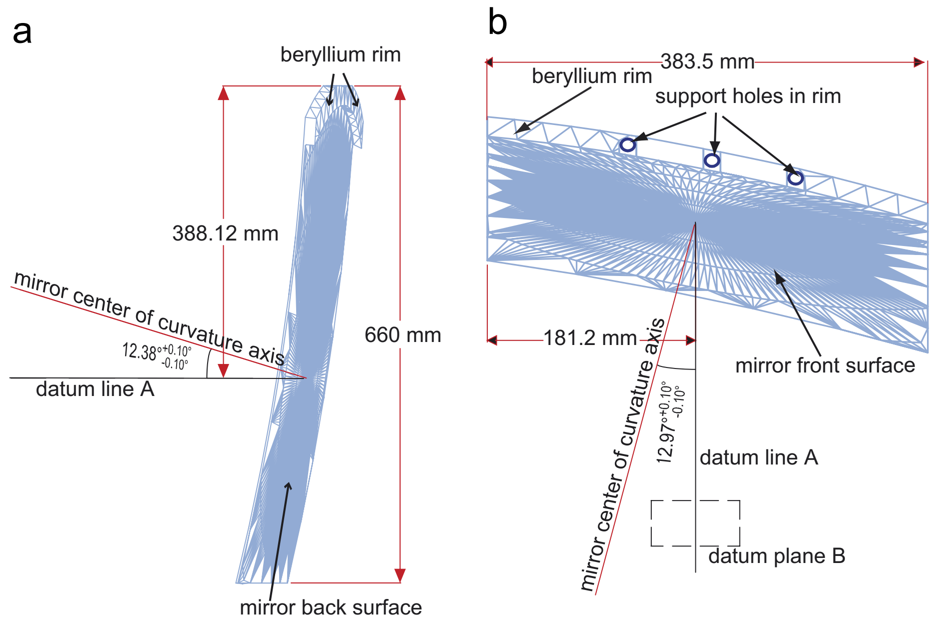

Fig. 6. Two drawings of the mirror, side view (a) and top view (b). The mirror overall dimensions and the angular orientation are shown. The mirror vertical tilt is 12.38° i.e. the angle between the mirror centre of curvature axis (projection onto plane of this page) and the horizontal (datum line A). The mirror horizontal tilt is 12.97° i.e. the angle between the mirror centre of curvature axis (projection onto datum plane B) and the horizontal (datum line A). The web-like line structures in the drawings are to guide the eye.

The glass coating is performed at Vavilov. The glass[8] type is selected to have a coefficient of thermal expansion which matches that of beryllium, $\alpha_{glass} \cong \alpha_{Be}$. Several small glass sheets are placed on the beryllium substrate front face, covering it completely and then the mirror is placed into an oven and heated up to a temperature of $\sim$600 °C to melt the glass. A single glass layer forms and fuses onto the beryllium substrate. The mirror is then left to cool down slowly. The glass layer is then polished using standard optical methods. The fine tuning of the mirror radius of curvature is achieved by the glass polishing, i.e., by varying the thickness of the glass layer across the mirror, typically 0.3–0.5 mm.

The mirror is returned to Kompozit for final qualification, certification and cleaning to remove any residual beryllium dust, before being delivered to CERN for testing. The uncoated beryllium surface (rim and back side) is passivated by the natural formation of a beryllium oxide surface film resulting from its exposure to air.

The last step would be the application of a reflective coating at CERN after the successful testing and consequent acceptance of the mirror. The reflective coating [17] increases the reflectivity to $\gtrsim$85% for wavelengths 250–500 nm and $\gtrsim$70% for wavelengths 200–250 nm. The coating consists of a thin chromium adherence layer followed by an aluminum layer protected by a SiO_2–HfO_2 reflective enhancement layer. This type of coating has already been successfully applied onto the surface of the LHCb-RICH2 glass mirrors.

6. Characterization of the full-sized prototype mirror

The mirror was visually inspected and characterized on its arrival at CERN. On visual inspection, several holes and air bubbles were seen in the glass. These are due to a defect in the glass coating process. There are approximately 60 bubbles varying $\sim$0.5−1 mm in size, concentrated mainly in one sector of the mirror. In addition, the mirror has a large chamfer, up to $\sim$5 mm from the mirror edge, with thicker glass along the bottom edges (opposite to the rim side). Nevertheless, the resulting optical dead area is very small, with the bubbles and chamfer contributing $\sim$0.1% and $\sim$0.5%, respectively. The mirror radius of curvature is corrected (shortened) by the glass layer, which necessitates a thicker glass layer at the edges. The defects in the glass can be eliminated in future mirrors by refining the glass layering technique and also the glass thickness at the edges can be reduced by manufacturing the beryllium substrate with a more accurate radius of curvature. The present glass layer could be removed and re-applied to remove the defects.

The mirror shown in Fig. 8(a),(b) was characterized optically, held vertically by a three-point support as shown in Fig. 9 in appendix. The measured values are $D_0 =$ 3.33 mm and $R = 2675$ mm, shown in the plots of Fig. 7(a)–(c). The mirror was also mounted with the rim at the bottom and vertically tilted by $\sim 13^\circ$ (approximate tilt in RICH1). Within errors, the same values for D_0

[8] The glass properties and composition is propriety information. Its approximate composition is SiO_2 $\sim$60%, CdO $\sim$20%, Nb_2O $\sim$15%, PbO $\sim$5%, B_2O_3 $\sim$2%, BaO $\sim$1%.

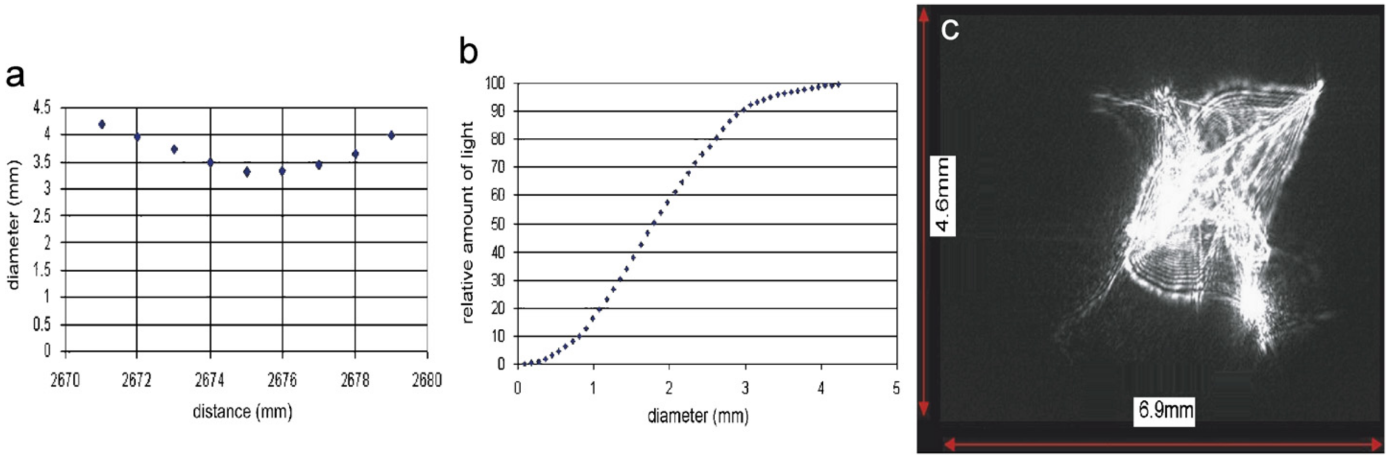

Fig. 7. (a) The spot size versus the distance of the mirror from the CCD camera, the minimum is for $R = 2675$ mm; (b) the relative amount of light (%) as function of the circle diameter for the smallest spot; 95% is contained by a Ø3.33 mm circle, i.e. $D_0 = 3.33$ mm; (c) photograph of the smallest spot i.e. at the mirror centre of curvature.

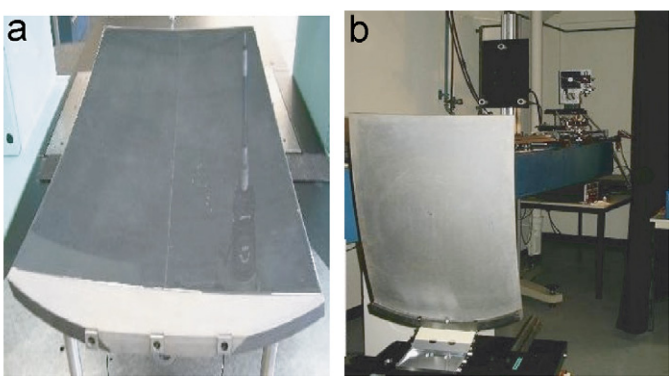

Fig. 8. Two photos of the full-sized prototype mirror; (a) a view from above showing the glass coating (dark area) and the rim; (b) a back view of the mirror supported at the bottom (~13° tilt) showing the grey beryllium substrate and the measurement setup.

and R were measured, proving that the stress and deformations induced in the mirror due to gravity are minimal (Fig. 8).

The CERN metrology service measured the overall dimensions and thickness of the mirror and it was found to be generally within the specifications. The beryllium substrate with the glass is ~4–5 mm thick. On average the mirror consists of a ~3.8 mm thick beryllium substrate with a ~0.4 mm thick glass layer. The glass layer is thinnest at the centre (~0.3 mm) gradually increasing in thickness towards the edges up to ~1 mm. The spatial coordinates of a large number of points (~400) were measured on the mirror surface and then fitted to a sphere to extract the mirror radius of curvature and tilt. The metrology extracted value of $R = 2677$ mm is close to the optical measurement. Also the extracted angular mirror tilts are within the tolerances of the design specifications given in Fig. 6(a),(b).

A summary of the mirror parameters is given in Table 4. The dimensions refer to the drawings of Fig. 6(a),(b). The values for X_0 and λ_I can only be estimated because the exact composition of the glass is not known (propriety information). The surface roughness of the optical surface was not measured at CERN but certified by Kompozit[9] to be $R_z < 5$ nm. The mirror is within the RICH1 specifications, except for the D_0 which should be < 2.5 mm; however the measured value of 3.3 mm is tolerable. The specification of the beryllium substrate thickness was relaxed from 3 to ~4 mm because of the high risk of breaking the beryllium blank during machining.

Table 4
Parameters of the full-sized prototype beryllium mirror

Dimensions (mm)	Substrate thickness (mm)	R (mm)	D_0 (mm)	X_0 (%)	λ_I (%)	Weight (kg)	Roughness R_z (nm)
383 × 660	3.8(Be) + 0.4(glass)	2675	3.33	~1.6	~1	2.7	<5

7. Summary and conclusions

Three small sized beryllium-glass prototype mirrors were manufactured and found to be of good optical quality. As a result, a full-sized spherical beryllium mirror was designed and manufactured according to the LHCb-RICH1 specifications. It is the first beryllium-glass mirror ever fabricated with large geometrical dimensions (~400 mm × 660 mm) but at the same time with a very thin beryllium substrate (~3.8 mm). Overall the optical quality of the full-sized prototype is good, proving that the technological challenges have been overcome. The full-sized prototype satisfies the RICH1 requirements and could be used as a final RICH1 mirror. A general improvement in the parameters and quality would be expected for future beryllium-glass mirrors by refining the manufacturing technique.

[9] R_z is the total roughness i.e. the vertical distance from the deepest valley to the highest peak within the sampling length.

Acknowledgements

We acknowledge that the original idea of using beryllium type mirrors was proposed by Tom Ypsilantis. We thank W. Witzeling (CERN) for the support and advice in running the beryllium mirrors project with the Russian partners and companies. We are also grateful to A. Cherif and D. Pugnat of the CERN metrology team.

Appendix A

The mirror characterization was performed in an optical laboratory at CERN, in a darkroom environment with air circulation and dust filters. The setup for the measurement of spherical converging mirrors is shown in Fig. 9. The mirror to be characterized is held by a three-point support which is mounted on rails. A point-like source is obtained from a diode laser ($\lambda = 641$ nm) connected to an optical fibre. The laser and a CCD camera[10] are fixed to a sliding table and move together along the line of the mirror axis. The CCD camera is 16 bit, with a pixel size of $9\,\mu m \times 9\,\mu m$ and $6.9\,mm \times 4.6\,mm$ sensor size. The sliding table is positioned at a distance d from the mirror, corresponding to the approximate expected radius of curvature of the mirror. The point-like source illuminates uniformly the whole mirror surface and the reflected image (spot) is measured by the CCD camera. The measurement is automated. A LabVIEW[11] program controls both the CCD triggering and the movement of the sliding table using a stepping motor which has a range of 40 mm. The sliding table is moved in steps of 1 mm along its range, varying the distance d between the mirror and the laser light source. At each 1 mm step, the CCD takes a photograph of the spot image. At the end of the scan, the LabVIEW program analyzes all the photographs and finds the smallest spot image using a centre of gravity method, from which the mirror D_0 and R are obtained. The radius of curvature R of the mirror is defined as the distance between the mirror reflective surface centre and the CCD sensor for the smallest spot size.

[10] DTA model HR400E with a KODAK sensor KAF-400E CCD.

[11] LabVIEW (Laboratory Virtual Instrumentation Engineering Workbench) is a platform and development environment for a visual programming language from National Instruments.

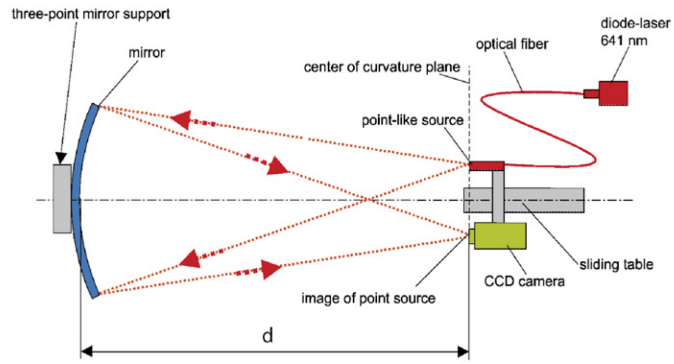

Fig. 9. Schematic setup for the radius of curvature R and the D_0 measurements of a spherical converging mirror.

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