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Light composite mirrors for RICH detectors: production, characterization and stability tests.

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Abstract

The production of light-weight composite mirror prototypes suitable for application in Ring Imaging Cherenkov (RICH) detectors is described. The goal is the use of such mirrors whenever material budget is a concern. The manufacturing technique is described in detail, together with the achieved results in terms of optical quality. Several ageing tests have been performed on some of the prototypes. The results of these tests are reported.

1 Introduction

Most RICH detectors use spherical mirrors in order to focus onto the photodetectors the Cherenkov photons emitted along the trajectory of a charged particle. A common requirement for the optical quality of the mirror is that the contribution due to the mirror to the uncertainty in the measurement of the Cherenkov angle is negligible.

The characterisation of the mirrors is performed in the optical laboratory. The parameters defining the optical quality of a mirror are the average radius of curvature and the angular precision. The measurement setup, shown in figure 1 and 2 is described in detail in [1].

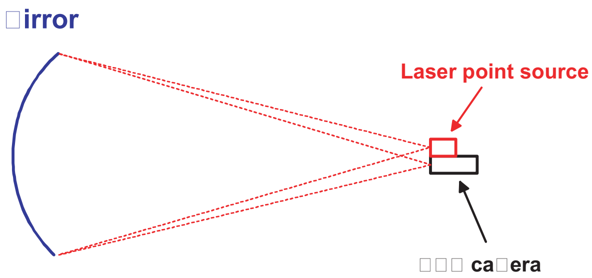

Figure 1: A sketch of the setup used to measure the mirror quality.

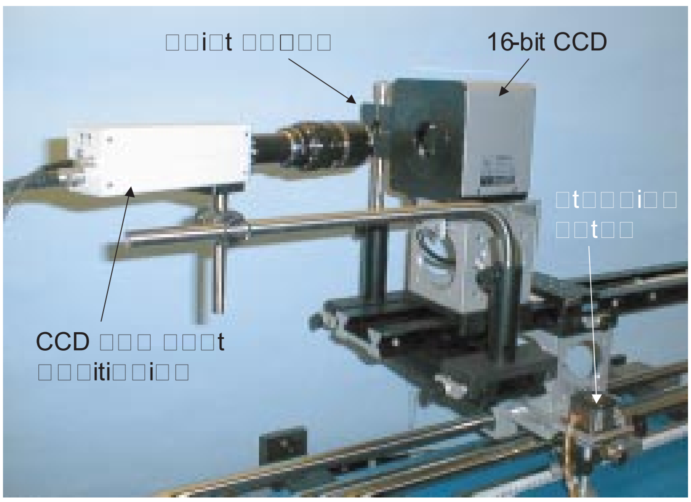

Figure 2: The setup used to measure the mirror quality.

The spherical mirror is placed on a three-point holder mounted on rails. In front of the concave face of the mirror there is a support holding a CCD camera and a point-like light source. The source is an optical fibre connected to a diode laser of wavelength $\lambda = 641$ nm. The point source illuminates the surface of the mirror, and the reflected image is measured by the pixelised silicon sensor of the camera.

The distance between the mirror and the point source is varied until the image of the point source is the smallest. The corresponding distance between the centre of the reflective surface and the CCD sensor is by definition the average radius of curvature of the mirror.

A figure of merit D_0 is defined as the diameter of the smallest circle that can be drawn on the image of the point source which comprises 95% of the total reflected intensity.

If the light distribution of the image had Gaussian shape, D_0 would correspond to four times the rms value σ_s of the distance between the nominal centre of curvature and the impinging point of the photons. The angular precision σ_θ of a mirror with radius of curvature R is related to D_0 according to:

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

where the factor 2 in the denominator accounts for the reflection on the mirror surface.

The LHCb [2] experiment is equipped with two RICH detectors [3]. RICH 1 is close to the interaction region, sandwiched between the silicon vertex detector and the first tracking station. RICH 2 is inserted between the last tracking station and the first layer of the muon chambers. RICH 1 specifications require for the mirrors a D_0 lower than 2 mm together with a maximum deviation of $\pm$ 12 mm from the nominal radius of curvature $R = 1700\,\text{mm}$, which translate into a $\sigma_\theta = 0.15\,\text{mrad}$. The amount of material of the mirrors has to be kept as low as possible in terms of radiation length X_0 and nuclear interaction length λ_I in order to limit high energy photon emission, multiple scattering, pair production and hadronic showers upstream the tracking and calorimetric systems. The aim is to achieve a set of mirrors which, while fulfilling the quality specifications, account for less than 2% of X_0 and less than 1% of λ_I.

Light-weight composite mirrors have been produced and successfully operated in the CO_2 threshold Cherenkov counters of the Hall-A beam line of the TJNAF laboratory [4]. The specifications for the TJNAF mirrors require that 90% of the light collected from a point source placed in the centre of curvature is contained in a circle with a diameter of 8 mm. The radius of curvature of those mirrors is 900 mm, which means that the specifications correspond to a maximum allowed $\sigma_\theta = 2\,\text{mrad}$. With 1 mm thick PMMA plate, the TJNAF mirrors constitute only 0.8% of X_0 and 0.4% of λ_I. Compared to the TJNAF specification, LHCb requirements are about a factor 5 tighter in terms of D_0 and a factor 10 tighter in terms of angular precision. However, material budget consideration made it appealing to attempt to exploit a similar technique to manufacture composite mirror prototypes which meet RICH 1 specifications.

2 Manufacturing technique

The mirrors are composed by a layer of polymethyl-metacrylate (PMMA), reinforced on the back by a sandwich structure made of several carbon fibre layers glued to a Nomex[1] honeycomb slice[2]. The basic layers are sketched in figure 3.

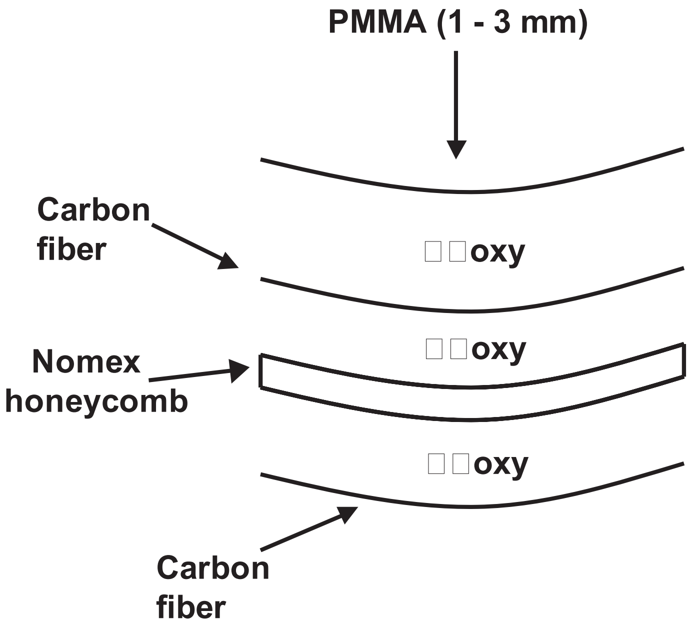

Figure 3: A sketch of a PMMA based composite mirror.

The flat plate is first cleaned by flushing nitrogen or hyper-pure compressed air through a de-ionising gun. This procedure is essential in order to remove dust particles which electrostatically adhere to the PMMA surface and would degrade the quality of the surface of the mirror. The clean PMMA sheet is then inserted in a double 6 mm thick aluminium frame.

The next step is the shaping of the PMMA plate into a spherical surface with the correct radius of curvature. The plate is heated to a temperature higher than the glass transition temperature (150 °C) of PMMA. The hot soft material is

[1]Nomex is the brand name of a family of high temperature resistant fibres produced by DuPont

[2]FlexCore Nomex Honeycomb available from Hexcel Corporation

then bent to spherical shape applying an under-pressure on one face of the plate. A sketch of the PMMA-shaping setup is shown in figure 4.

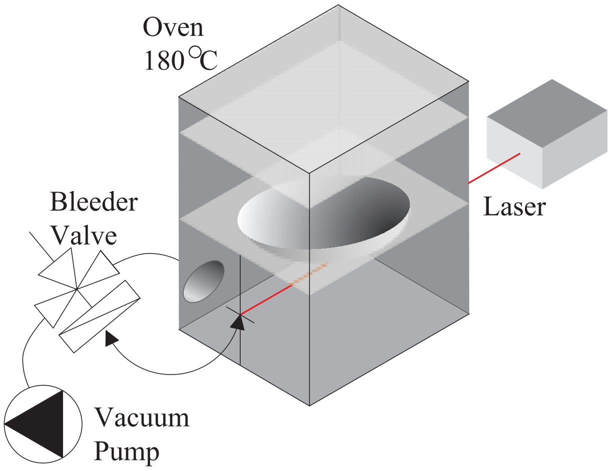

Figure 4: A sketch of the setup for the shaping of the mirrors: an oven is suspended above a vacuum chamber. The lower half of the PMMA-holding frame lies on top of the vacuum chamber.

The first prototypes were made using a square frame, 840×840 mm, with a circular hole. The two planes of the frame were kept together by 16 screws which pass through the PMMA. Between the bottom plane and the PMMA there is a silicone o-ring which guarantees the air tightness of the assembly.

The frame is then placed inside an oven which uniformly heats the PMMA sheet to 180 °C. Underneath the oven, mounted on the same supporting structure, there is a vacuum chamber with a circular aperture. Once the PMMA has reached the desired temperature, it is rapidly taken out of the oven and placed on top of the vacuum chamber covering the circular aperture. Air is extracted from the chamber and the hot PMMA sheet starts bending under the effect of atmospheric pressure, acquiring a spherical shape. A horizontal laser beam crosses the vacuum chamber. The distance between the beam and the upper plane of the chamber can be adjusted and made equal to the sagitta corresponding to the required radius of curvature. The laser spot is displayed on a screen and it starts deforming when the PMMA touches the beam. At this point the analogue valve connecting the pump to the vacuum chamber is closed and air is slowly let inside the volume via a second analogue valve. A fine tuning of the curvature is done via these two valves until the PMMA cools down to room temperature.

The first samples showed a systematic deformation along two axes parallel to the edges of the square frame. The effect, even if reduced, was present also when the plastic layer was cut to circular shape before the insertion in the frame. The deformation was ascribed to the non-uniform distribution of the heat during the cooling down of the PMMA. Small deformations and cracks were also present, in correspondence of the screws.

In an attempt to reduce all sources of asymmetry in the manufacturing procedure a new circular frame with an external diameter of 835 mm has been designed. In the new frame there are no screws. The assembly is kept together by the weight of the top aluminium ring and two metal clamps. A substantial improvement in the average quality of the curved sheets has been obtained with the modified setup.

After the shaping step, a check of the curvature of the PMMA sheet is performed by placing it on a spherical aluminium mould. The mould is polished to a roughness of 100 nm and has a radius of curvature of 1700 mm.
If the fit to the aluminium mould is satisfactory, the PMMA is abraded on the convex surface to increase the adherence of the glue.

The core of the support is a layer of flexible Nomex honeycomb. Three layers of non-directional carbon mat are glued on each side of the honeycomb. All the layers are glued at once by means of two-component epoxy resin[3] onto the back of the PMMA sheet, which is placed on the aluminium mould. Particular care is taken when placing the first carbon layer on the PMMA, to guarantee good adherence and strictly avoid corrugations which would be printed through during the gluing. The assembly is vacuum bagged and a pressure is applied on the assembly to guarantee adherence of the components to each other and to the mould during the polymerisation of the epoxy resin. A high pressure during the process ensures better results in terms of geometrical precision of the mirror. However, at high pressures, a print-through effect of the honeycomb structure onto the mirror surface occurs, due to the softness of the PMMA. A compromise pressure of 6 kPa has been used for the first produced mirrors.

The best results have been obtained for supports manufactured in two steps: first the three layers of carbon mat are glued to the PMMA with a pressure of 30 kPa; then the honeycomb and three more layers of carbon mat are glued with lower pressure. The first carbon mat–epoxy layers protect the mirror surface from the print-through effect.

3 Production quality

Figure 5 shows the D_0 measurement for the mirror with the best angular precision. With $D_0 = 1.5$ mm and a radius of 1623 mm, $\sigma_\theta = 120$ μrad. The spot image in the centre of curvature is shown in figure 6.

Composite mirrors have been manufactured varying several parameters:

- PMMA: 1, 2 and 3 mm thick layers have been tried: the results show that 2 mm thick sheets are the best performing ones. Prototypes with

[3] Araldit LY5082 and Hardener LH5083 from Astorit AG

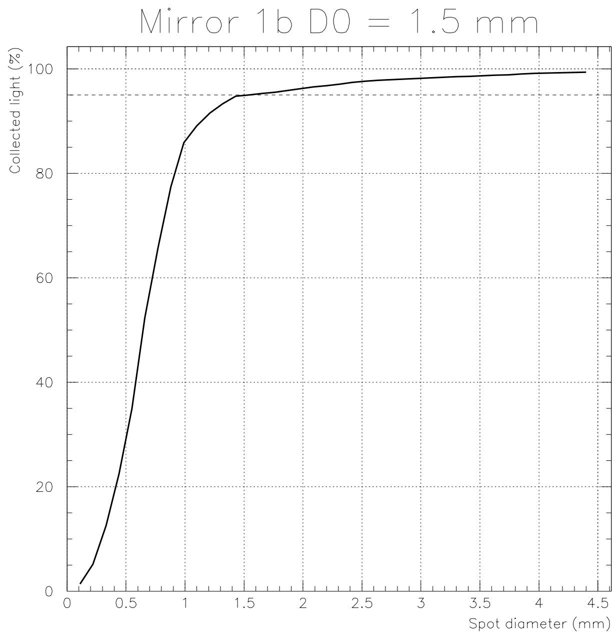

Figure 5: D_0 measurement for one composite mirror prototype.

1 mm thick PMMA sheets proved to be too sensitive to the print-through effect, resulting in a poor optical quality, D_0 being systematically larger than 5 mm. On the other hand residual stresses in 3 mm thick layers cause significant deformation, leading to a split of the focus into two separate spatial points a few mm apart.

- Carbon mat: two different sets of layers have been tested, 3×9 mg/cm^2 or 2×6 mg/cm^2 + 1×15 mg/cm^2. In all cases identical assemblies were formed on each side of the honeycomb. No significant differences in the results have been observed, but it turned out to be easier to eliminate the corrugations from a thinner carbon layer, and the second configuration was adopted as standard.

- Honeycomb: 5 and 10 mm thick honeycomb has been tested for two different cell density. No systematic influence of the core thickness or the cell density on the mirror quality has been noticed. Several prototypes have been manufactured using honeycomb with overextended cells. This kind of core, however, has anisotropic properties, and cannot be bent along the direction of overextension as easily as along the orthogonal direction. As a result the mirrors show a slight cylindricity, and the image of the point source is elongated beyond the allowed tolerance.

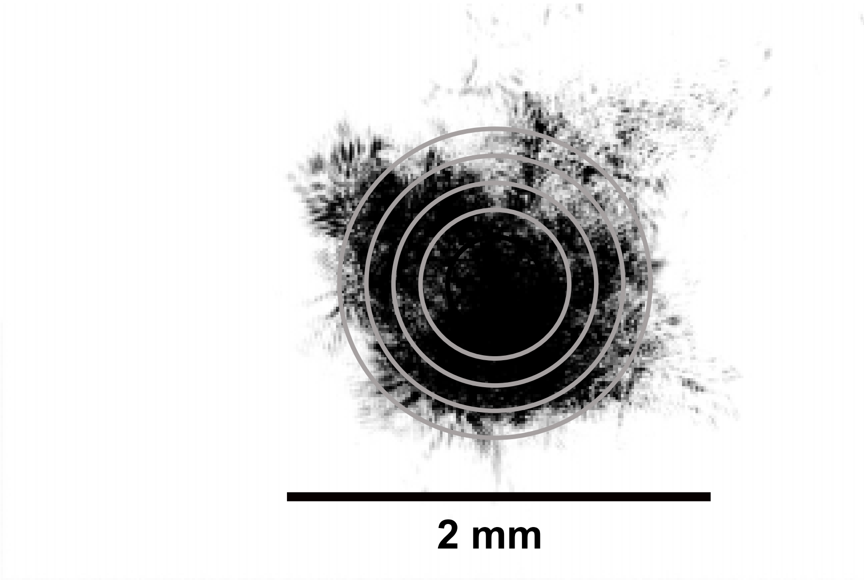

Figure 6: Spot image of the mirror prototype with $D_0 = 1.5$ mm. The circles drawn on the image are to show the method of measurement of D_0 and the pitch between them is enlarged for clarity.

- Gluing conditions: the temperature at which the polymerisation of the epoxy glue is performed influences the process time and the rigidity of the product. The highest stiffness is obtained for temperatures of the order of 80 °C. However, the hardness of the PMMA drops with increasing temperature, and the print-through effect is enhanced. The highest quality prototypes have been obtained with the gluing performed at 35–40 °C inside a convection oven with a temperature uniformity better than 0.5 °C.

Figure 7 summarises the results obtained with the optimised technique.

Mirrors have been produced in two shapes, 46×39 cm rectangular and circular with a diameter of 60 cm. The best results in terms of D_0 have been obtained with the rectangular shape, but for those mirrors the radius of curvature was systematically smaller than the nominal 1700 mm of the mould. This shrinking effect is due to the non homogeneous distribution of the stresses during the polymerisation process, since all the circular mirrors have the radius of curvature within 0.5 cm from the nominal value.

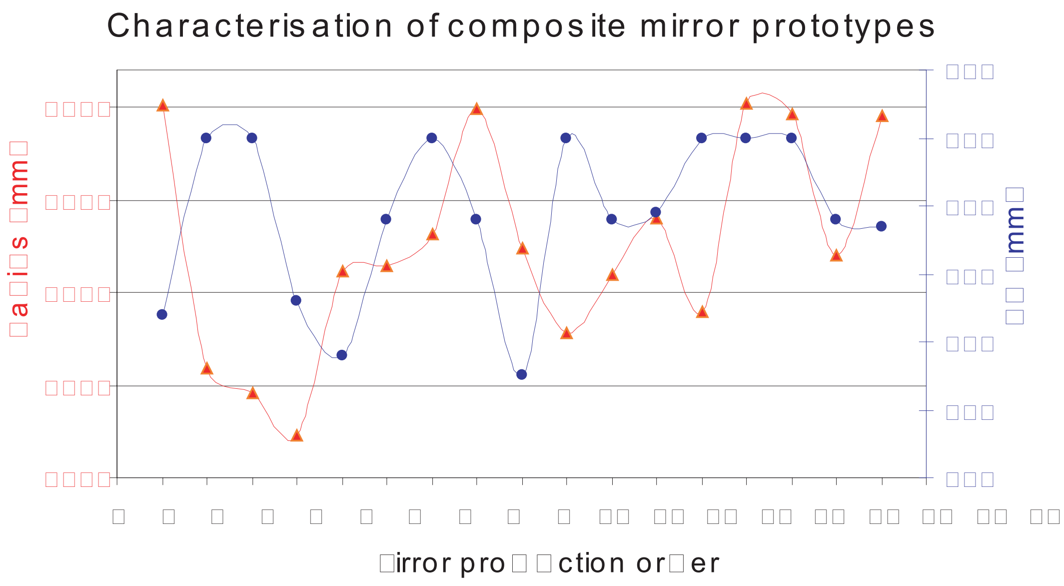

Figure 7: Summary of the achieved results. For each produced mirror the radius of curvature (red triangles) and the D_0 (blue circles) are plotted. A value of $D_0 = 5$ mm has been plotted as a lower limit for mirrors for which the image of the point source is larger than the CCD sensor area.

4 Stability tests

4.1 Thermal cycles

Two mirrors have undergone thermal cycles to test the tolerance to temperature change. It can also be considered as an accelerated ageing test. The results of the test are summarised in table 1.

	Before test	24 hours at 40°	+ 24 hours at 60°
Mirror Therm1			
D_0(mm)	3.5	4.2	
R(mm)	1620	1660	
Mirror Therm2			
D_0(mm)	5.3	4.5	3.3
R(mm)	1700	1740	1740

Table 1: Thermal cycles compatibility test results.

The radius of curvature increases during the first temperature cycle, but it is not affected by subsequent ones. The change is most probably due to a postcuring effect on the epoxy resin, and it motivated the use of the oven during the polymerisation phase. Mirrors manufactured at 35–40° show very little sensitivity to temperature cycles.

4.2 Fluorocarbon compatibility tests

The compatibility of PMMA-based composite mirrors to the fluorocarbons has been tested, since the RICH 1 mirrors will be placed inside the C_4F_{10} gas radiator. Linear fluorocarbons, such as n-C_4F_{10}, have a low chemical activity, but they show a kind of washing property on materials, very similar to the effect of degassing in vacuum, as can be pointed out confronting the deformation data for spacecraft material with the data for materials, specially composite and polymers, exposed to completely fluorinated compounds [5, 6]. The behaviour of the tested materials will in principle not depend on the kind of per-fluorocarbon: C_5F_{12} and C_6F_{14} have been used for the tests. Two rectangular mirrors have been placed in a saturated C_5F_{12} atmosphere inside a gas-tight aluminium box. The results are shown in table 2.

Days in C_5F_{12}	0	20	40	60	100	140
Mirror FC1						
D_0(mm)	1.8		3.6	3.8	4.5	5
R(mm)	1611		1556	1597	1580	1552
Mirror FC2						
D_0(mm)	~ 8	~ 8		~ 8	~ 8	
R(mm)	1620	1555		1542	1520	

Table 2: Fluorocarbon compatibility test results.

After 40 days in C_5F_{12} at room temperature and atmospheric pressure the radius of curvature of mirror FC1 shrank by 55 mm, while D_0 moved from 1.8 mm to 3.6 mm. The shrinking effect does not seem to be systematic, as after 20 more days of exposure the radius increased by 41 mm, to decrease again by 17 mm after 40 more days. A second mirror, labelled FC2, was exposed to C_5F_{12}. Its radius of curvature shrank by 65 mm after the first 20 days and by 13 mm after 40 more days. The test is ongoing to check if mechanical stability is reached at a certain point. At the same time, two samples of PMMA have been exposed to a saturated C_6F_{14} atmosphere at 40° to search for possible variations in the mechanical properties of the material which could cause the deformation of the composite assembly. The temperature is chosen in order to accelerate the ageing process without affecting the mechanical properties of the samples.

The Young modulus of PMMA has been measured to be 2.9 GPa prior to the exposure to fluorocarbon. The measurement is has been performed by means of static deflection induced by weights attached to the free end of 2 mm thick PMMA bars. Regular checks have been performed on the two samples. During the six months of the exposure, no change in the weight and dimensions was detected. The Young modulus has been stable within the experimental resolution of $\sim 1\%$.

5 Conclusions

Several samples of lightweight composite mirrors have been manufactured with very good optical properties.

However, the instability to fluorocarbons is a disadvantage in view of a possible use of this kind of composite mirrors in the RICH 1 detector of the LHCb experiment. The development program is focused on attempts to overcome the difficulty by modifying the manufacturing steps or the structure of the mirrors to increase their stiffness. One possible way is to reinforce the edges by means of ribs which would lie outside the acceptance of LHCb. The excellent results in terms of optical quality and material budget make them a suitable low-mass mirror option for a RICH detector with inert gas radiator.

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