Lightweight CFRP Spherical Mirrors for the LHCb RICH-1 Detector

Robert N. Martin[*a], Robert C. Romeo[a], Geoff Barber[b], Andre Braem[c], Nick Brook[d], Bill Cameron[b], Carmelo D'Ambrosio[c], Neville Harnew[e], Kenneth Lessnoff[d], Fabio Metlica[d], Dave Websdale[b]

[a]Composite Mirror Applications, Inc., 638 S. Research Loop, Tucson, AZ 85710
[b]Imperial College London, Blackett Laboratory, Prince Consort Road, London SW7 2BW, UK;
[c]CERN, 1217, Geneva 23, Switzerland;
[d]University of Bristol, H H Wills Physics Laboratory, Tyndall Avenue, Bristol BS8 1TL, UK;
[e]University of Oxford Denys Wilkinson Building, Keble Road, Oxford, OX1 3RH, UK

ABSTRACT

The design, manufacture and testing of lightweight Carbon Fiber Reinforced Polymer (CFRP) converging spherical mirrors for the RICH-1 Cherenkov detector of LHCb are described. The mirrors have low areal density to minimize the amount of material in the path of traversing particles and need to be fluorocarbon compatible to avoid degradation in the C_4F_{10} radiator gas. The total area is about $2m^2$ and high reflectivity (typically 90%) over the wavelength range 200-600nm is required.

Keywords: RICH Detector, Cherenkov detector, CFRP, Optical mirrors, lightweight optics, RICH mirrors

1. INTRODUCTION

LHCb is a dedicated second generation B physics precision experiment at the LHC (Large Hadron Collider at CERN, Geneva, Switzerland) to study CP violation by precise determination of the CKM matrix parameters and to search for rare B decays which could be originated by new physics. The LHCb detector schematic is shown in Figure 1.

The LHCb experiment has a Ring Imaging Cherenkov (RICH) detector system to provide a powerful elementary particle identification tool: i.e. pion-kaon separation. The RICH system consists of two detectors, RICH1 and RICH2, to cover the particle 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 are in the path of traversing charged particles therefore it is essential to minimize the amount of material within the detector acceptance. Furthermore these mirrors must be stable in the RICH1 C_4F_{10} fluorocarbon gas radiator and radiation environment.

CFRP lightweight mirror technology ~ 5-6 kg/m^2 appeared to be the most promising for RICH1. An R&D program of CMA in collaboration with CERN was undertaken to test the CMA CFRP technology for light weight mirrors, leading to the production of four large CFRP spherical mirrors for RICH1, each of dimension ~835 mm x 640 mm. The schematic of the RICH1 detector is in Figure 2.

[*] robertmartin@compositemirrors.com; phone 1 520 733-9302; fax 1 520 733-9306

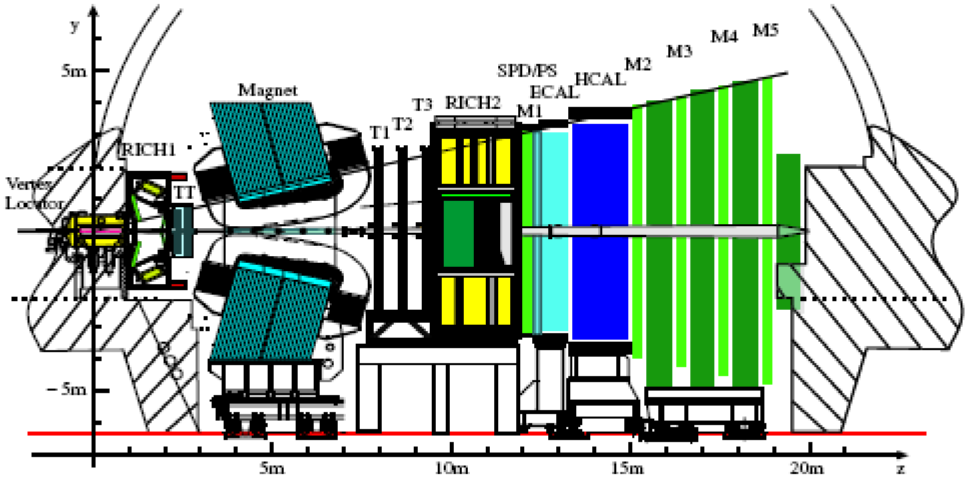


Figure 1. The LHCb detector schematic. The subdetectors are: the VELO (Vertex Locator), the two RICH detectors, the dipole magnet, the four tracking stations (TT, T1 to T3), the ScintillatingPad Detector (SPD) and Preshower, the Electromagnetic (ECAL) and Hadronic (HCAL) calorimeters, and the five muon stations M1 to M5.

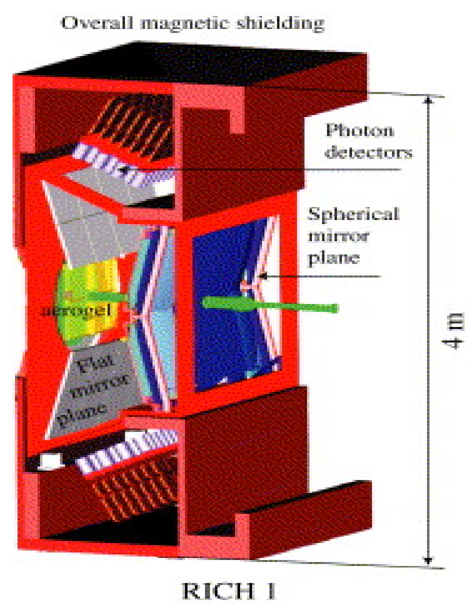


Figure 2. Schematic of the RICH1 detector, showing the planar and spherical mirror setup. The elementary particles coming from the right side.

2. MIRROR SYSTEM REQUIREMENTS AND SPECIFICATIONS

The RICH1 mirror system consists of 4 rectangular mirrors of ~835 mm x 640 mm. The mirror surfaces should be identical spherical reflectors with 2700 mm radius of curvature (R_{oc}). Specified tolerance on the R_{oc} was 1%. The mirrors are mounted in pairs as shown in figure 2. Each mirror of a pair is aligned to the same center of curvature. The two pairs direct the radiation to separate flat mirrors and their respective detector systems. The gaps between mirrors was specified as 5mm maximum. The surface optical quality is that the returned radiation from a total illumination from the center of curvature must refocus to a spot size with 95% of the light within 2.5 mm diameter (referred to as a D0 test). The wavelength of interest is visible light and UV out to 200 nm.

These mirrors are located within the particle beam so the goal is to keep the projected mass as low as possible. An areal density of 8 Kg/m_2 was specified as the upper limit to the density. The goal was to make this areal density as low as possible but maintain the necessary rigidity to meet the optical requirements. Each mirror is mounted from three points at the outside edge which is outside the acceptance area of the mirror and beam. In the center of the 4 mirror system is a circular cutout for the beam pipe. The central region of the mirror system must be kept free of adjusters and any extra strengthening material. The frame which mounts these mirrors must separate as two c-shaped sections so that the system can be positioned around the existing beam pipe without disturbing the existing pipe. This requires that the mirrors must be mounted and adjusted on the assembled frame, then separated to mount around the beam pipe, and return to the initial mirror alignment after reconnecting the c-fame system together again. The c-frame with mirrors are mounted and guided on a track system which is mounted in the gas box.

Since the RICH1 mirrors are located within a C_4F_{10} fluorocarbon gas radiator and radiation environment, a testing program on smaller mirror samples was undertaken to verify that the CFRP mirrors would not be affected by this environment. These sample mirrors were 150 mm diameter and have spherical reflector surfaces. The results of these tests are discussed in section 5. The mirror samples have shown no aging effects from either the fluorocarbon gas exposure or the radiation exposure. One should note that this radiation exposure is similar to the radiation exposure for satellites in low earth orbit.

In addition to the testing sample mirrors, an engineering demonstrator mirror was fabricated for evaluation. The goal of the engineering demonstrator was to test mirror fabricated as close as possible to the final mirror design. To maintain a rapid project schedule, this engineering model was fabricated on existing tooling and mandrels at CMA. This engineering model was roughly the same size as the final mirrors but had a different ROC for the spherical surface. The test results of the engineering prototype were positive. The CFRP mirror technology provided a clear, attractive solution to the RICH1 mirror requirements.

The mirrors and mounting frame were designed at CMA using Solidworks CAD programs. An FEA (finite element analysis) using COSMOS was run on both the frame and one of the mirrors. The FEA analysis was used to verify the design concept. Particular attention was paid to the mounting points for the mirrors and the resonant frequencies of the system. The load conditions on this system are static and rather benign.

The details of the mirror mounting and adjustment on the frame assembly were particularly important in the design process. Each of the 3 attachment points (per mirror) uses a stainless steel rod end linkage. This allows a stress free, 3-point mount of the mirror to the frame. One mount provides a reference x-y location of the mirror. The other 2 mounting points provide adjustment of the mirror in tip-tilt about the first point.

3. MIRROR SYSTEM FABRICATION

The CFRP mirrors are fabricated using a replication process. The front mirror surface formed over a mandrel with the desired (opposite) curve. This process is described in previous papers by CMA [1]. A glass mandrel is used for the mirror surface replication because it provides a hard, stable, smooth surface. Considerable effort is put into the fabrication of this mandrel since they are a defining step in the final quality of the CFRP mirror's optical surface.

The borosilicate glass blank for the mandrel was supplied by Hextek Corporation, Tucson, AZ. The grinding and polishing of this blank was done at the CMA facilities by R. Royce of Royce Optical. Classical glass grinding and polishing methods are used to figure the glass surface. The mandrel diameter is ~1100 mm, with a convex surface of

2700 mm radius of curvature. Figure 3 shows the final mandrel. The final convex surface is checked using a spherometer.

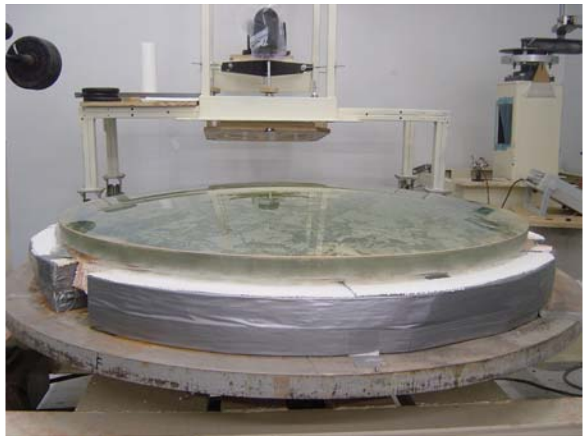


Figure 3. The polished glass mandrel for replication of the CFRP mirrors.

Figure 4. The final mirrors and frame assembly after alignment at CMA

The CFRP mirrors are designed around a sandwich construction (also referred to as torsion box construction). Curved face sheets of CFRP are used front and back. Between the face sheets is a core construction of CFRP cells. This provides a rigid, lightweight construction. CFRP tabs (of T-shaped or L-shaped plates) are bonded to the rear of the mirror for the 3 mounting points. The resulting areal density of the mirror is ~5 kg/m^2, which is well below the specified requirements.

Unidirectional CFRP prepreg is used in the fabrication of both the mirror and the frame. The prepeg material is supplied by Brite Technologies and consists of M46J fibers in Ex1515 cyanate ester resin. By using one material for all of the frame and mirror system, the material testing program (for C_4F_{10} and radiation exposure) was simplified.

The mirror mounting frame was fabricated using square cross section tubes and plate elements. The final assembly is illustrated in figure 4. During final assembly at CMA, the mirrors were aligned and tested for alignment repeatability using the adjustment system. The final mirror and frame assembly has a total mass of ~17 Kg, is extremely rigid, and holds the mirrors repeatability to the desired specification.

4. MIRROR SURFACE COATING

The specification for the RICH1 mirrors is that the reflectivity is greater than 85% in the range $250 \leq \lambda \leq 600$nm, and greater than 70% in the range $200 \leq \lambda \leq 250$nm, for average incidence angle of 25° and over the entire mirror surface.

An Al+MgF_2 coating was chosen for the mirrors to obtain a good reflectivity in the UV range. The coating was done at SESO (Société Européenne de Systèmes Optiques, Aix-en-Provence, France), which has developed aluminum protected coatings for UV applications and has a large coating chamber to hold the RICH1 mirrors. Simulation studies [2] of the coating thickness layers were done both at SESO and CERN. These studies showed that a coating consisting of 80nm of aluminum protected by an 80nm thick layer of MgF_2 gave the required reflectivity curves. However the coating applied at SESO is of varying thickness; 160nm at the mirror centre thinning down to 80nm at its periphery. This is done ensure the required reflectivity performance over the entire mirror surface without the need to develop surface uniformity coating tools which are costly and require time to prepare. Figure 5 shows the simulated and measured reflectivity curves.

The reflectivity curves are for 3 CFRP and 3 glass samples placed at different radial distances from chamber center (BALZERS SCS 1131 with internal diameter of 1130 mm). This coating test was done at SESO before the final coating of the RICH1 production mirrors. The CFRP and glass samples give comparable results indicating that there is no problem coating the carbon fiber mirror substrates in the chamber. Outgassing tests proved that CFRP outgassing is negligible. The simulation curves for the thickest and thinnest MgF_2 layers are also shown for comparison. The reflectivity is very good and fully satisfies the RICH1 specifications. The average reflectivity of the samples is ~90%. The witness samples placed in the chamber during the coating of the RICH1 production mirrors confirm these results.

The reflectivity curves are for 3 CFRP and 3 glass samples placed at different radial distances from chamber center (BALZERS SCS 1131 with internal diameter of 1130 mm). This coating test was done at SESO before the final coating of the RICH1 production mirrors. The CFRP and glass samples give comparable results indicating that there is no problem coating the carbon fiber mirror substrates in the chamber. Outgassing tests proved that CFRP outgassing is negligible. The simulation curves for the thickest and thinnest MgF_2 layers are also shown for comparison. The reflectivity is very good and fully satisfies the RICH1 specifications. The average reflectivity of the samples is ~90%. The witness samples placed in the chamber during the coating of the RICH1 production mirrors confirm these results.

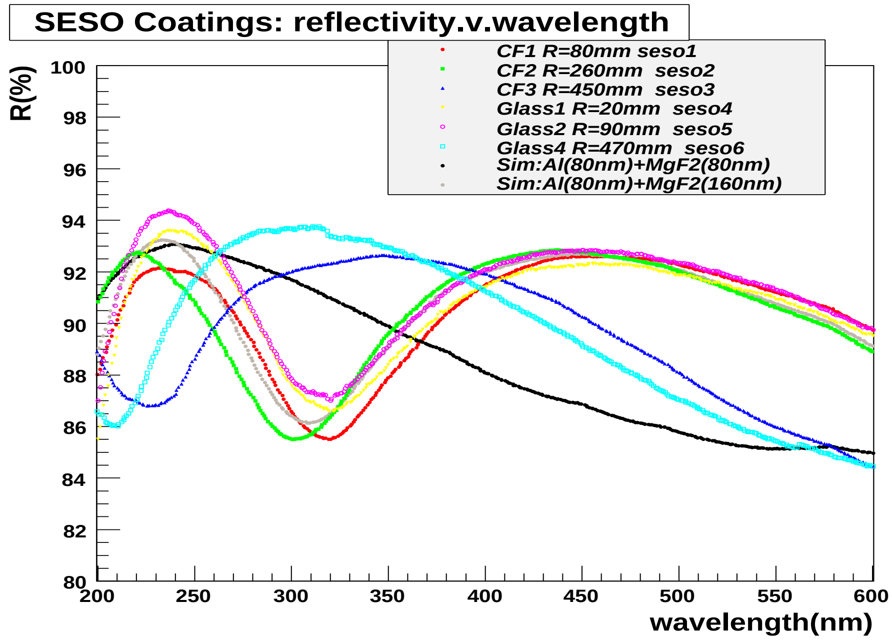


Figure 5. Reflectivity curves of 6 samples (glass and carbon fiber) coated with Al+MgF2 at SESO. The samples are placed at different radial distances from the nominal mirror center. Also the two simulation curves for the thickest and thinnest MgF2 layers are shown.

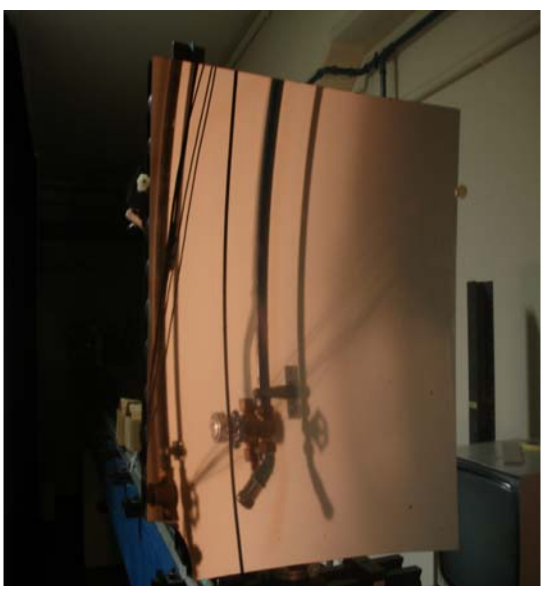


Figure 6. Photos of the coated RICH1-CMA mirrors. Left; coated mirror at SESO. Right, the 4 coated mirrors assembled in the carbon fiber onto the alignment rig at CERN in July 2007.

5. TESTING RESULTS

Throughout the duration of this project, a series of tests were undertaken to verify the compatibility of the CFRP technology with C_4F_{10} fluorocarbon gas and radiation. The tested CMA samples were made of the same CFRP material as for the final RICH1 mirrors. The samples tested are listed here below. Photos of samples are shown in Figure 7.

1. One 600mm x 600mm demonstration mirror (RoC~2200 mm) produced from existing mandrel at CMA for fluorocarbon testing;
2. Two 150mm diameter mirror samples (RoC~1890 mm) for fluorocarbon and radiation testing, named mirror 1 and mirror 2;
3. Two ~100mm x 100mm x 0.5mm flat carbon-fiber samples without coating for mechanical tests, named flat sample A and flat sample B;
4. One ~100mm x 100mm x 0.5mm flat sample for CERN fire safety tests

The testing consisted first in measuring the optical and mechanical characteristics of the samples upon their arrival at CERN and then exposing one set of samples (mirror 2 and flat sample B) to radiation and another set to C_4F_{10} gas (demonstration mirror, mirror 1 and flat sample B). Each set is exposed to either radiation or to C_4F_{10} but not to both.

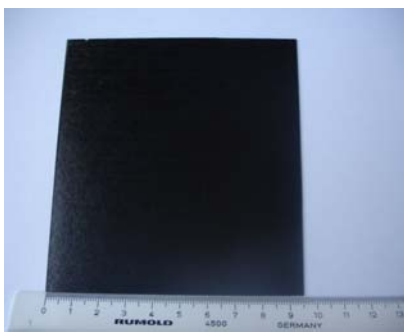


Figure 7. Photos of the CMA samples. Left, the demonstration mirror; center, a flat sample; right, mirror samples 1 and 2.

The measured optical characteristics of the mirror samples are the D0, radius of curvature (R_{oc}) and the reflectivity curve; where D0 is the diameter of the circle at the mirror centre of curvature which contains 95% of the light intensity reflected from a point source at the centre of curvature. The measured mechanical properties of the flat samples are the surface roughness, tensile (pulling), flexural (bending), weight, and physical dimensions.

For the radiation testing, the samples (mirror 2 and flat sample B) were exposed to radiation in three separate steps with a total absorbed dose of 1 kGy, 4 kGy and 10 kGy. 1 kGy is equivalent to one year radiation in RICH1 for part of mirror closest to beampipe (highest radiation area). Gamma radiation was used. The samples were irradiated at Ionisos (IONISOS**,** ZI les Chartinières **,** 01120 Dagneux, France), a cobalt-60 facility near Lyon in France.

For the fluorocarbon testing (C_4F_{10}), the samples (demonstration mirror, mirror 1 and flat sample B) were exposed to C_4F_{10} for a period of one year and measured at regular intervals. The samples were placed in a gas tank filled with C_4F_{10} at room temperature with overpressure of ~100mbar.

Figure 8 shows the setup for the D0 and R_{oc} measurement. The laser and a CCD camera are fixed to a sliding table and move together along the line of the mirror axis. The point-like source illuminates uniformly the whole mirror surface and the reflected image (spot) is measured by the CCD camera. At each 1mm step, the CCD takes a photograph of the spot image. At the end of the scan a LabView program analyzes all the photographs and finds the smallest spot image using a center of gravity method, from which the mirror D0 and R_{oc} are obtained. The radius of curvature R_{oc} of the mirror is defined as the distance between the mirror reflective surface center and the CCD sensor for the smallest spot size.

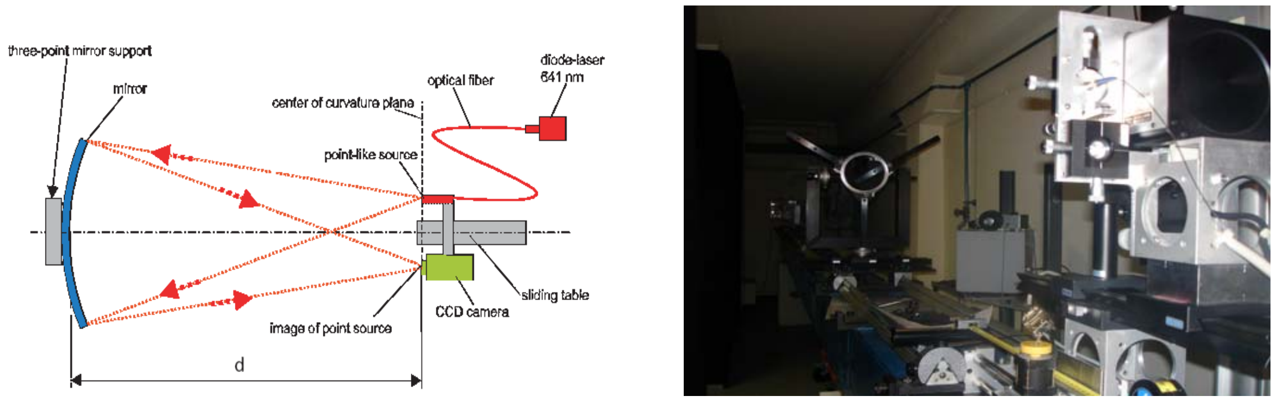
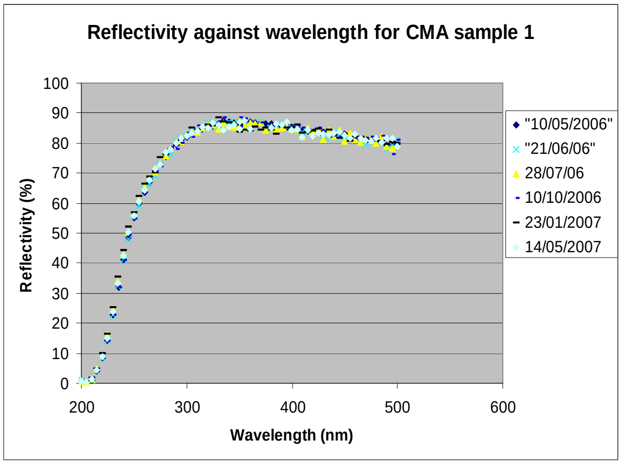


Figure 8. Schematic (left) and photo (right) of the lab setup at CERN for the D0 and R_{oc} measurement.

The results of these test indicate that there is no significant change in the opto-mechanical characteristics of the samples due to exposure to radiation up t0 10 kGy or C4F10 gas for a year. The results are summarized below.

1. The measured D0, R_{oc} for mirror 1&2 are D0~0.9mm and R_{oc}~1890mm respectively, while for the demonstrator mirror: D0~1 mm, R_{oc} ~2200 mm.
2. The reflectivity curves for mirrors 1 and 2 are shown in Figure 9. The mirror coating is 70 nm Al + 70 nm of SiO which gives a low reflectivity in the UV. The demonstrator mirror is too large to fit in the reflectometer so its reflectivity has not been measured. It has the same coating as the small mirrors.
3. The average surface roughness (arithmetic average of roughness), Ra, for flat samples A and B is: ~1.8 µm+/-0.1 µm. The flat samples do not have a mirror surface finish. This test is not indicative of the mirror finish but only general material property of raw, processed CFRP plate.
4. The weight, dimensions and microscope photos taken at a magnification of 10X and 100X, of the flat samples is unchanged.
5. The tensile tests give an average tensile rigidity of ≈ 7000 N/mm, while the flexural tests give an average flexural rigidity of ≈ 33 N/mm for samples A and B respectively, see Figure 10.
6. The third flat sample was used by CERN safety for fire testing. The X-ray spectrometer analysis results in it being halogen and sulphur free. The fire test was successful: i.e. the flame is not propagated along the carbon fiber, but when it is burning, it produces black smoke. The CMA carbon fiber sample material fulfills the CERN safety requirements and can be used in LHCb.



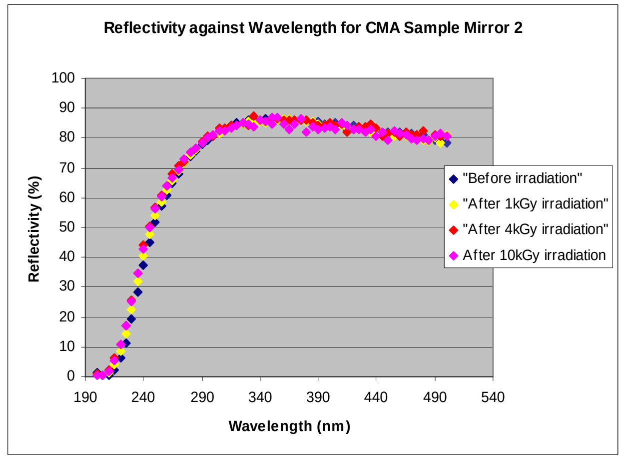


Figure 9. Reflectivity curves for mirror sample 1 (left) and mirror sample 2 (right) before and after exposure to C4F10 gas and radiation.

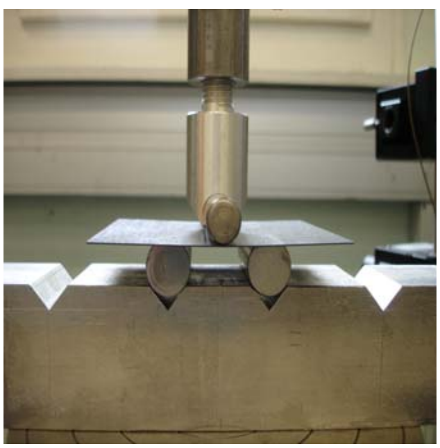


Figure 10. Setup for flexural (left) and tensile tests (right).

The 4 RICH1 production mirrors arrived at CERN in February 2007. The D0, R_{oc} of the four mirrors were measured to be D0 ~0.6+/0.1mm with R_{oc} ~2708+/-1mm. They were re-measured after the coating at SESO in March 2007 and the D0 increased slightly for 3 of the mirrors to D0 ~0.9-1mm. Another measurement in June 2007 shows again a slight increase in the D0. Table 1 tabulates the results. The mirrors are all well within specifications, i.e.: D0 <2.5mm and R_{oc}=2700mm(+/-1%).

Table 1.

Mirror number	D0(mm)	R(mm)	D0(mm)	R(mm)	D0(mm)	R(mm)
	Feb07(before coating)		March07(after coating)		June07	
#1	0.66	2708	1.06	2706	1.07	2710
#2	0.48	2709	0.91	2707	1.15	2710
#3	0.68	2707	0.96	2707	1.38	2709
#4	0.53	2708	0.50	2707	1.18	2710

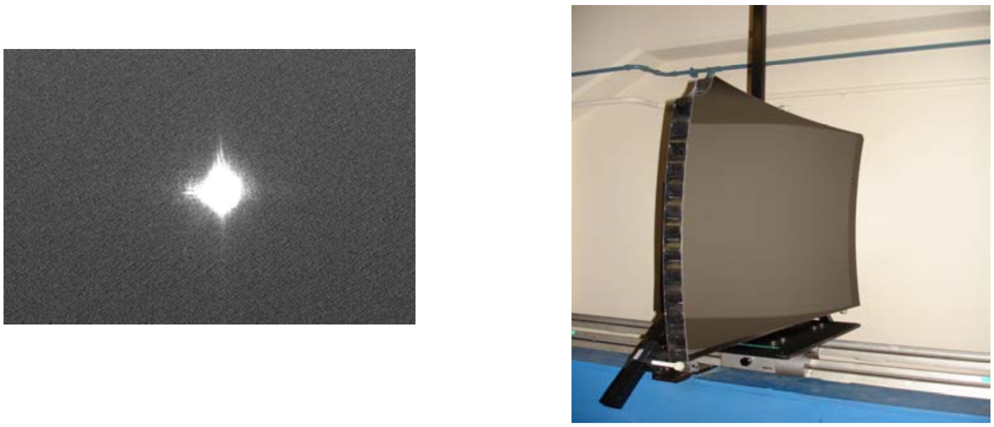


Figure 11. Image of spot at center of curvature for mirror 2 (left) and uncoated mirror (right) on the optical stand during the D0, R_{oc} measurements. Photos taken during the February 2007 measurements.

6. SUMMARY AND CONCLUSIONS

The design and fabrication of CFRP mirrors and frame support for the RICH1 system have been described in this paper. This project completed in a relatively short timescale. The design, material verifications, testing, fabrication and delivery were completed within about 1 year.

The CFRP mirror technology has proven to be well matched to the needs of this project. For all major specification areas, the specifications were exceeded. Table 2 summarizes these results. The radiation exposure testing is relevant to other applications of this technology. In particular, low and mid earth orbit satellites receive similar radiation doses as tested for these mirror samples (without any degradation in optical performance). The mirror technology demonstrated in this project is relevant for many other areas which require precise, light weight optics.

Table 2. Comparison of specifications to fabrication results.

Item	**Project Specification**	**Performance achieved**
R_{oc}	2700 mm ±1%	2708 mm ±0.08%
D0	≤ 2.5mm	≤1.3mm
Arial Density ()	≤ 8 Kg/m^2	~5 Kg/m^2
Gaps between panels	≤ 5 mm	~3 mm
Coating reflectivity (250-600 nm)	85%	90%

REFERENCES

1. R. C. Romeo and R. N. Martin, "Progress in 1m-class lightweight CFRP composite mirrors for the ULTRA telescope", *Proc. SPIE*, **6273**, 62730S (2006).
2. Simulation program: MacLeod and FILMSTAR from FTG Software