**PRODUCTION OF 300 PARABOLOIDAL MIRRORS WITH HIGH REFLECTIVITY
FOR USE IN THE BARREL RICH COUNTER IN DELPHI AT LEP**

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ABSTRACT

Mirrors have been produced industrially by heat-forming 6 mm thick float-glass at about 610°C, followed by vacuum deposition of a 50 nm thick layer of Al and a 60 nm thick protective layer of MgF₂, using a fabrication method first developed at CERN. The successful implementation of this method for industrial production, and the quality control of the mirrors, are described. An average reflectivity of more than 85% in the wavelength region 165–200 nm has been achieved in the production. The focal spot obtained by shining parallel light on the mirrors contained, on the average, 98% of the light within a circle of 1.2 mm diameter.

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1. INTRODUCTION

The DELPHI detector [1] at the LEP Collider will be equipped with Ring-Imaging Cherenkov (RICH) counters to enable full particle identification over a wide momentum range. These RICH counters consist of a cylindrical Barrel RICH detector and two end-cap Forward RICH detectors, as shown in Fig. 1.

Figure 2 shows the basic principle of a RICH counter. The Cherenkov light emitted by a relativistic charged particle traversing the radiator medium is reflected by a focusing mirror to form a ring image in the detection plane of a single-photon position detector. This detector consists of drift chambers of the Time Projection Chamber (TPC) type, with tetrakis(dimethylamine)ethylene (TMAE, ionization threshold 5.4 eV) as the photoionizing agent mixed into the gas. The drift chambers are equipped with quartz windows that are transparent to VUV light. The emission angle of the Cherenkov light, from which the velocity of the traversing particle can be derived, is obtained by geometrical reconstruction from the ring image registered by the photodetector.

When RICH counters of this type were first proposed [2] for high-energy physics requirements at colliders, the overall geometry of the detector—and therefore also of the focusing mirror—was that of a spherical shell. It was subsequently shown [3] that by decomposing the spherical shell into small sectors, the overall shape could be given a cylindrical geometry without significantly impairing the accuracy in the measurement of the Cherenkov-light emission angle. Further analysis demonstrated [4] that the optimal shape of the mirror sectors was paraboloidal rather than spherical.

The DELPHI Barrel RICH has been designed along these basic lines and contains 288 paraboloidal mirror sectors. The subdivision into mirror sectors, the choice of focal lengths, and the orientation of the focal axes of the paraboloidal mirrors were optimized under the condition that, on the one hand, the Cherenkov angular error due to the limited position resolution of the photodetector dominated over the angular error due to geometrical aberrations, and on the other hand, that the total number of mirror sectors was kept to a minimum. This led to a design with a row of six different types of paraboloidal mirrors covering $\Delta\phi = 15^\circ$ in azimuth and $40^\circ < \theta < 90^\circ$ in polar angle of the Barrel RICH, implying a total of 288 mirrors to cover the full azimuth and $40^\circ < \theta < 140^\circ$ in polar angle. The dimensions of the six mirror types are given in Table 1.

The radiator gas in which the Cherenkov light is generated (C_5F_{12}) is transparent for light of wavelengths above 165 nm only, and the photoionizing agent (TMAE) has a significant quantum efficiency only below a 200 nm wavelength. To keep the number of detected photons as high as possible, it was required that the reflectivity of the mirrors should be not less than 80% for light in the range 165–200 nm.

The limitations in Cherenkov angular resolution due to the limited position resolution of the photodetector were such that an additional angular dispersion of up to ± 1.5 mrad, due to angular deviations in the mirror surface from the exact paraboloidal design shape, could be accepted without significantly degrading the overall Cherenkov angular resolution. With a focal length of about 0.4 m, this condition is equivalent to requiring that the mirrors should focus parallel light to a spot in which most of the light would be contained in a circular area of 1.2 mm diameter.

The 288 mirrors (plus 12 spares) satisfying these requirements have now been successfully produced for the Barrel RICH, using a slumping and coating method first developed at CERN [5]. Below we will describe the implementation of this method for industrial production, the quality control of the mirrors produced, and the results obtained in terms of VUV mirror reflectivity and mirror-shape accuracy.

2. IMPLEMENTATION OF THE METHOD FOR INDUSTRIAL PRODUCTION

2.1 General

When implementing the slumping and coating process at Bofors Aerotronics AB (BAAB), some adjustments had to be made to meet the requirements of industrial series-production. Otherwise, the transfer of the prototype method from CERN was made with as few changes as possible. Some key tools were borrowed from CERN in order to ensure fast and safe technology transfer. On several occasions, key CERN personnel inspected the installations at BAAB and suggested important improvements. In addition to this, some steps in the process were developed at BAAB, such as the sawing and the packing, and other steps were developed further, such as the heat-slumping and the vacuum-deposition.

2.2 Raw materials

The glass blanks were made of float-glass delivered as circular disks of 836 mm diameter and 6 mm thickness (from Pilkington). The surface roughness of the blanks was measured to be no more than 0.2 nm r.m.s. Visual inspection and the subsequent successful production operation also served as a quality control.

The aluminium used for mirror coating was 1.5 mm wire of 99.999% purity (Balzers BD 481 534-T). The magnesium fluoride used for the protective layers was of 99.99% purity (Balzers BD 481 373-T).

2.3 Slumping

The six paraboloidal moulds used for the slumping of the mirror blanks were fabricated at CERN [5]. The oven (Hofmann Industrieofenbau, Linz, Austria, type TSL 1,5) used to heat the moulds with the blanks has an inner floor space of 1 m × 1 m and an inner height of 1.5 m, and is large enough to accommodate two moulds, together with their accessories, in a two-storey arrangement. Hence it is possible to slump two 836 mm diameter mirror blanks per cycle. To reach a temperature in the region of 600 °C, about 55 kW of heat power has to be dissipated in the air, which is circulated inside the oven by a fan.

The oven is controlled by a processor (Digit 200) that allows a temperature-time function to be programmed with sufficient freedom for our purpose. The function for the complete heating-slumping-cooling cycle was worked out with the following requirements in mind.

- i) For reasons of production scheduling, the time for loading flat blanks, plus the complete heat cycle, plus the time for unloading slumped blanks, had to be less than 24 hours. Here, the only adjustable variable was the complete heat cycle, which had to be brought down to 22–23 hours.
- ii) The heating-up and cooling-down rates had to be kept low enough to avoid build-up of stress in the glass material: too much stress remaining after cooling causes the glass to crack during the subsequent sawing operation. In particular, the transformation temperature of the glass was determined, using a dilatometric method, to be at 520 °C, and the cooling rate through the transformation-temperature range between 550 °C and 450 °C, was chosen to be very low (about 12 °C/h).
- iii) The two critical parameters for obtaining a satisfactory mirror-shape accuracy in the moulding are: a) the maximum temperature $T_{\max}$ at which the glass blank is kept for a certain period of time before the vacuum is applied between the blank and the mould in order to slump; and b) the minimal length Δt of this time period. These parameters were varied, and the resulting accuracy in mirror shape was measured by observing the size of the focal spot on an optical bench, as described in subsection 3.1. It was found that the optimum value of $T_{\max}$ should be chosen in the interval (600–620) °C, in accordance with the results of the prototype work at CERN. Some

mirror types appeared to be more critical than others, and these required a $T_{\max}$ in the upper part of this interval. The time period Δt was found to be about two hours.

After this optimization, all mirror types could be slumped to their desired shapes with satisfactory accuracy, with the exception of type number 3; for obscure reasons, which we did not have time to investigate, this mirror type always suffered a 50% rejection rate at the shape testing. The heat cycle used in the production is illustrated in Fig. 3.

2.4 Sawing and chamfering

Successful sawing at proper measurements and angles, without cracking the glass, necessitated the use of specially designed tools for mounting the mirror blanks on the numerically controlled saw (type MAHO MH 600 E). The set-up is shown in Fig. 4. The fixture holding the blank can be inclined so that the correct angle is formed between the mirror surface and the saw-blade. The concave surface of the blank, facing downwards, is supported in its entirety by polyurethane foam in order to avoid cracking, and is held in position by four rubber bellows attached to a vacuum system.

Three of the six Barrel RICH paraboloidal mirror types do not contain the axis of the paraboloid within the mirror contour. In these cases, two similar mirrors could be sawed out of one blank, essentially halving the number of blanks needed for such mirrors.

As the Barrel RICH photon detectors are designed to operate at high voltages up to 150 kV, special care had to be given to the smoothness of the chamfers in order to avoid corona effect at the edges of the mirrors. The edges of the sawed mirror substrates were rounded using a brass-diamond wheel which had a peripheral groove of 3 mm radius of curvature. The wheel was mounted on a simple milling machine with a support suited to the curved shape of the substrates. In order to join the rounded edge smoothly to the large surfaces of the substrate, it was necessary to finish the chamfer by hand with a whetstone.

2.5 Coating

Before coating, the mirror substrates were cleaned by conventional methods. The evaporation plant used for the coating (type Balzers BA 710) was equipped with a rotation pump and an oil diffusion-pump. In order to produce an Al layer of the high purity and particular thickness required for high-vacuum ultraviolet reflectivity, the following conditions had to be met. The vacuum in the plant had to be high enough, and the evaporation speed fast enough, to avoid any oxidation or contamination of the Al before the protective layer of MgF_2 was applied. The thickness of the Al layer had to be carefully monitored and optimized in balance between two negative effects: if the layer is too thin it will be transparent to the VUV light used (wavelengths around 170–180 nm); if it is too thick, it will scatter the VUV light owing to the formation of crystallites on the surface. The thickness of the protective MgF_2 layer had to be carefully monitored also, and optimized so that the optical thickness of the layer was equal to about one half of the wavelength of the VUV light used, thus avoiding losses in reflectivity due to destructive interference.

To meet these requirements, the following modifications of the standard evaporation plant were necessary.

- i) The ordinary diffusion-pump oil had to be replaced by polyphenyl ether (commercial name Santovac 5) in order to generate a sufficiently high and clean vacuum. We were informed that, unlike ordinary diffusion-pump oil, polyphenyl ether is not expected to impair the reflectivity of mirrors in the VUV region [6].
- ii) All vacuum rubber seals in the plant had to be replaced with either copper seals or special high-vacuum rubber seals (type Viton) in order to maintain satisfactory vacuum conditions.

- iii) The inside walls of the vacuum chamber had to be covered with protective steel-sheet screens, which needed to be regularly exchanged and cleaned.
 - iv) A specially sensitive high-vacuum pressure-gauge (Balzers type 1 MG 060B) was installed.
- With these modifications it was possible to pump a clean vacuum of 10^{-7} Torr in three hours.

- v) To allow rapid and well-controlled evaporation of the Al and the MgF_2 layers, the following items had to be installed:
 - a) a second heat-filament power-control unit (Balzers Evaporation Control, type BSV 203), making it possible to control the evaporation of the Al and the MgF_2 independently;
 - b) a quartz-crystal thickness monitor (Balzers type QSG 301, crystal holder type QSK 135), with autostop at a given frequency;
 - c) a pneumatic shutter assembly (Airco Temescal Model PA-2) for fast and automatic shutting off of the Al coating by an autostop function;
 - d) electronics to control units (a), (b), and (c) for automatic operation of the Al coating;
 - e) an ultra-high vacuum feedthrough (Balzers type UDD 135) for fast rotation of the mirror substrate.

The operation involving these items is as follows. First, keeping the shutters closed, the Al and MgF_2 heating-power controls are set manually to 25% and 100% of full power, respectively. The Al melts and wets the tungsten heat-filament. When the trigger is pulled, the heating power for the Al is increased to its full extent; one second later, a relay opens the pneumatic shutter (c), thus uncovering the Al source. After approximately one more second, the appropriate thickness of the Al layer is reached, and the thickness monitor (b) closes the pneumatic shutter (c) and turns off the Al evaporation power (a) through the autostop function. Immediately after this, the MgF_2 coating shutter is opened manually, and is kept open until the thickness monitor signals an appropriate MgF_2 thickness, about 12 seconds later.

At first, a slower evaporation speed for the Al coating was used. Under these conditions an Al-layer thickness of satisfactory accuracy could be obtained with manual control of the process. It was, on the other hand, not possible to reach a VUV reflectivity above 80% at this slower evaporation speed. Full automation for the Al coating therefore proved necessary, as the fast process with a high evaporation power could not be controlled manually with sufficient accuracy. The fast rotation feedthrough (e) allowed the substrate to rotate several complete turns during the short Al coating period, thereby providing a homogeneous layer over the whole substrate surface.

Figure 5 shows the readings of the pressure gauge (p) and of the crystal thickness-monitor frequency (f) as functions of time t over the full coating cycle, corresponding to the standard conditions applied during production of the mirrors.

The thickness monitor was calibrated to measure the thickness of the Al layer in the following way. Glass plates were coated with Al, and their light reflectivity and transmittance were measured in the 400–500 nm wavelength region. The results of these measurements were compared with the results of numerical calculations for the same wavelength region, where the optical constants of Al are well known. From this comparison we obtained the crystal frequency as a function of layer thickness.

After this calibration, a series of test-coatings were made with Al layers of different thicknesses and with an MgF_2 layer of constant thickness; the resulting reflectivity as a function of wavelength was measured with a VUV spectrophotometer (see subsection 3.2). A clear maximum in the reflectivity for light of ~ 175 nm wavelength was found around a calibrated Al layer thickness of ~ 50 nm. Using a Talystep profilometer, the same layer thickness was measured to be 56 ± 10 nm.

The thickness-monitor calibration for MgF_2 was made by measuring the crystal frequency at which a MgF_2 test-layer could be observed to have a minimum reflectivity for light of ~ 350 nm wavelength, corresponding to an expected maximum for light of wavelength ~ 175 nm. The corresponding physical MgF_2 layer thickness was calculated to be ~ 60 nm.

The final adjustment of the MgF_2 thickness, as read by the monitor, was made by performing a series of test-coatings with different MgF_2 thicknesses and constant Al layer thickness, and measuring the resulting reflectivity as a function of wavelength in the VUV region.

The Talystep profilometer was also used to measure the surface roughness of the float-glass surface, of the Al coating, and of the combined Al + MgF_2 coatings, respectively. Each surface type was scanned in five different places over a length of 50 μm with a 0.3 μm stylus radius and 0.5 mg stylus loading. The r.m.s. roughness was determined to be 0.18 ± 0.02 nm, 0.28 ± 0.02 nm, and 0.27 ± 0.03 nm, respectively, for the three types of surface mentioned above.

2.6 Packing

Special packing for transport and storage was developed and tested in order to comply with requirements appertaining to transport-environment resistance, manageability, and cleanliness. In particular, the inner packing, which consists of a plastic bag filled with dry nitrogen, contains a small packet filled with a desiccating agent. Before putting the paraboloidal mirror into the bag, an Al plate, slightly larger than the mirror itself, was taped to it to prevent the bag from coming into contact with the concave mirror surface. The rest of the packing consisted of conventional corrugated cardboard boxes stuffed with shock-absorbing material.

3. QUALITY CONTROL

3.1 Shape-control optical bench set-up

The paraboloidal shape of each mirror was tested with the requirement that at least 90% of the light passing through the focal region must be contained within a circle of 1.2 mm diameter. Some mirror types were more difficult than others to slump correctly. These mirrors were shape-tested before the VUV coating was applied. During shape-testing they had a simple Al coating for visible light, which was later washed away. The reason for this procedure was that the schedule could not allow badly shaped mirrors to take up time in the evaporation plant, which was the bottleneck in the production line.

The optical bench set-up is shown schematically in Fig. 6. The light source A, about 0.4 mm in diameter, is located at the focus of the spherical collimator B. Collimated light from B hits the paraboloidal mirror M under test, and is focused at point C. The photodetector D, located behind C, receives the light, the power of which is shown by the photometer at E. The mechanics for the adjustment of the position of M are arranged at F. Screens S, with holes of various diameters, are adjusted in the focal region at C until a maximum reading is obtained at E. The 100% level is read when there is no screen at C. The rear side of S—which is turned towards D—is black, so that essentially no stray light can reach D by reflection from S.

This measuring principle is basically very simple and has few sources of systematic error. Two similar set-ups were used, one at BAAB before delivery of the mirrors, and another at CERN after delivery. At BAAB, the collimator had a focal length of 3000 mm and a diameter of 500 mm; at CERN, the focal length was 2673 mm and the diameter 560 mm. As the diagonal of the largest mirror type was 555 mm, the BAAB measurement had some systematic limitation, discussed below in subsection 4.1.

3.2 The vacuum ultraviolet spectrophotometer for reflectivity measurement

The test procedure used for the measurement of reflectivity, before delivery of the mirrors, was as follows. During each coating cycle, one paraboloidal substrate and four planar witness pieces (size 25×25 mm²), of the same surface quality (maximum roughness 0.4 nm r.m.s.), were coated. The reflectivity of one witness piece was measured in a VUV spectrophotometer, which had been developed for other purposes at the Institute of Physics, University of Uppsala [7]. The reason for

using witness pieces was that this spectrophotometer was not large enough to contain the full-size paraboloidal mirrors. The reflectivity was measured at three different wavelengths: 165 nm, 180 nm, and 200 nm. If the reflectivity of the witness piece at these three wavelengths was above 80%, it was assumed that the reflectivity of the full-size mirror was acceptable in the whole region 165–200 nm.

After delivery at CERN, the reflectivity of each mirror was measured at 15 wavelengths over the range 140–280 nm, using a VUV spectrophotometer that was large enough to contain the full-size paraboloidal mirrors. This spectrophotometer was designed to serve in the present project and is described elsewhere [8].

4. RESULTING MIRROR QUALITY

4.1 Focal spot-size

Figure 7 shows a histogram corresponding to 229 mirrors as measured at CERN after the first delivery; it displays the number N of mirrors that have $P\%$ of the focused light within a circle of 1.2 mm diameter. Of the 229 mirrors, 99 have P between 99% and 100%. The remaining 130 mirrors are distributed in a long tail, and 14 of them have P below 90%; the latter were rejected and new ones were fabricated at BAAB.

Figure 8 is the corresponding histogram for the 300 final mirrors as measured at BAAB. Here, 155 of the 300 mirrors are between 99% and 100%, and all mirrors with P below 90% have been eliminated. The average value is 98.0%.

A systematic error exists in the BAAB measurement, the origin of which was mentioned in subsection 3.1. The light beam from the spherical collimator does not cover the corners of the paraboloidal mirrors under test. This could theoretically imply that the light contained within the 1.2 mm diameter hole is overrated by an order of 2.5%, assuming that no light came from these corners for the mirror types having the longest diagonals. However, in practice these corners would reflect a substantial amount of light, and some mirror types have shorter diagonals, implying a theoretical maximum overrating of the order of 1%. The average overrating in the BAAB measurement should therefore be lower than 1%.

4.2 Vacuum ultraviolet reflectivity

The result of the reflectivity measurements of witness pieces for all 300 mirrors are presented in Figs. 9a–c as histograms showing the number N of witness pieces having reflectivity $R\%$ at wavelengths 165 nm, 180 nm, and 200 nm, respectively; in Fig. 10, the histogram shows the number N of witness pieces having a reflectivity $R_M\%$ at the same three wavelengths, where $R_M = (R_{165} + R_{180} + R_{200})/3$. The average reflectivity R_{AV} for the sample of 300 mirrors delivered is 84.9%, 87.5%, and 88.5% at 165 nm, 180 nm, and 200 nm, respectively.

In Fig. 11 is shown the average reflectivity, as measured at CERN, of all 300 mirrors at 15 wavelengths in the range 140–280 nm. The curve shows a flat maximum of about 88% over the range 220–180 nm and a marked drop to about 82% at 140 nm. The agreement between the measurements of witness pieces at BAAB and those of the final mirrors at CERN is good at 200 nm, whereas at 180 nm the witness-pieces results are $\sim 1\%$ lower, and at 165 nm they are $\sim 3\%$ lower. One explanation for this discrepancy between the two measurements could be that the witness pieces were positioned outside the periphery of the mirror during the coating, thus far from the centre of the coating plant.

5. CONCLUDING REMARKS

A mirror slumping and coating process, first developed at CERN, has been successfully implemented for industrial series-production at Bofors Aerotonics AB, and used there to produce 300 paraboloidal mirrors for the Barrel RICH counter in DELPHI. Certain steps in the process were

further developed during the implementation and production phases. The quality control measurements performed at BAAB and at CERN show good consistency and thereby consolidate the conclusion that an average reflectivity of at least 85% for light in the 165–200 nm wavelength range, and a focal spot containing on the average 98% of the focused light within a 1.2 mm diameter circle, have been achieved in the series production of these 300 mirrors. At the time of writing, the 120 spherical mirrors required for the Forward RICH in DELPHI are under production at BAAB, using essentially the same process.

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Table 1

Dimensions of the six mirror types.

The mirrors have the approximate shape of symmetric trapezoids of height H, larger parallel side A, and smaller parallel side B as projected on a plane perpendicular to the axis of the paraboloid (all in mm).

Type	Focal length	H	A	B
1	401	275	484	481
2	390	271	485	477
3	373	264	486	473
4	356	255	486	467
5	345	248	486	461
6	377	260	487	448

Figure captions

- Fig. 1 General view of one quadrant of the DELPHI detector at LEP (CERN), showing the Barrel and Forward RICH counters and their focusing mirrors.
- Fig. 2 Schematic picture showing the basic principles of the Ring Imaging Cherenkov (RICH) counter.
- Fig. 3 The finally chosen heat cycle for slumping.
- Fig. 4 A slumped mirror blank mounted on its fixture, with the numerically controlled saw used for obtaining trapezoidally contoured mirror substrates from the blank. The oval structure near the centre of the blank is one of the rubber bellows for applying the vacuum to hold the blank.
- Fig. 5 Pressure-reading p in the evaporation chamber and frequency f of the thickness monitor as functions of the time t during the coating.
- Fig. 6 Optical set-up for mirror-shape inspection. The details are described in the text.
- Fig. 7 Result of mirror-shape control measurements at CERN of the first delivered 229 mirrors.
- Fig. 8 Result of shape control measurements at BAAB for the final 300 mirrors.
- Fig. 9a,b,c Results of the reflectivity measurement of witness pieces for the 300 mirrors at BAAB, for light of wavelength a) 165 nm, b) 180 nm, and c) 200 nm.
- Fig. 10 The mean reflectivity R_M at the three wavelengths as defined in the text.
- Fig. 11 Average reflectivity as a function of wavelength for all 300 mirrors as measured at CERN.

Fig. 1

Fig. 2

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Fig. 4

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Fig. 8

Fig. 9

Fig. 10

Fig. 11