PROCEEDINGS OF SCIENCE

Composite mirrors for Medium-Sized Telescopes of the Cherenkov Telescope Array – a joint Polish-French design

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The Cherenkov Telescope Array (CTA) is the next-generation observatory for very high-energy gamma rays in the energy range from 20 GeV up to 300 TeV. It will consist of two arrays of imaging atmospheric Cherenkov telescopes of three different sizes. The CTA core energy range of 150 GeV – 5 TeV is covered with the Medium-Sized Telescopes (MSTs), whose segmented reflective mirror dish has a diameter of 12 m and is composed of 86 hexagonal mirror tiles. Here we present a final-design composite mirrors developed for MSTs jointly by the Institute of Nuclear Physics PAS in Krakow, CEA-Saclay and KERDRY Thin Film Technologies SMB enterprise, in collaboration with DESY-Zeuthen. The mirrors are made with the cold glass slumping replication technology. We present features of the mirror substrate design, mirror production technology and results of optical performance tests of the recently manufactured full-size mirror pre-production series.

38th International Cosmic Ray Conference (ICRC2023)
26 July - 3 August, 2023
Nagoya, Japan

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https://pos.sissa.it/

PoS(ICRC2023)818

1. Introduction

In recent years, ground-based very-high-energy gamma-ray astronomy has made significant progress, as demonstrated by the remarkable astrophysical discoveries achieved with experiments such as H.E.S.S. [1], MAGIC [2] and VERITAS [3]. These ground-based observatories detect gamma-ray photons using Imaging Atmospheric Cherenkov Telescopes (IACTs). In the coming years, even greater breakthroughs are anticipated with the introduction of the Cherenkov Telescope Array Observatory (CTAO). The goal of CTAO is to significantly improve flux sensitivity, aiming for a ten-fold increase compared to current installations, and expand the range of observable energy from a few tens of GeV to over 100 TeV. This objective will be realized through the deployment of IACT arrays consisting of telescopes of three different sizes of reflective dishes: Large-Sized Telescopes (LSTs) with a diameter of 23 m, Medium-Sized Telescopes (MSTs) with a 12 m mirror diameter, and Small-Sized Telescopes (SSTs) with a 4 m primary mirror diameter. The telescope arrays will be located at two different sites, one in the northern and one in the southern hemisphere.

The core energy range of CTAO between 150 GeV and 5 TeV is covered with the MST sub-arrays. The MSTs feature a modified Davies-Cotton design, with a focal length of $f = 16.0$ m. The mirror dish consists of 86 hexagonal facets, each with a spherical profile and a flat-to-flat size of 1.2 m. The baseline configuration of CTAO contains 9 MSTs in the Northern Array and 14 MSTs in the Southern Array, requiring a total of nearly 2000 mirror tiles for the MSTs. To meet this demand, various groups within the CTA consortium have developed and improved different mirror technologies, aiming for lightweight and cost-effective solutions [4, 5]. Most of these technologies are based on a sandwich concept and utilize cold-slumping replication technology for manufacturing [6].

The technologies of mirror production for CTA using cold-slumping methods have been developed independently at the Institute of Nuclear Physics Polish Academy of Sciences (INP PAS) in Poland and at the Institute of Research into the Fundamental Laws of the Universe of CEA-Saclay in France for about 15 years. In particular, INP PAS has conducted research on open-structure composite mirrors as a potential solution. Sandwich mirror support structures proposed utilized V-shaped aluminum plates [7] or aluminum tubes [8] as spacers and had side walls made of stiff stainless steel or aluminum mesh. Front and rear mirror panels were made of two glass panels interspaced with a thin fiber glass fabric and a layer of epoxy resin. CEA-Saclay investigated and developed solutions based on a glass closed sealed support structures [9, 10]. Aluminum honeycomb as a spacer, aluminium and glass side walls, and mirror panels made of layers of different materials have been tested and validated. Mirror prototypes of these designs were produced, including large pre-production series, which passed extensive tests of their mechanical stability, including climate chamber cycles for ageing validation and various tests of the reflecting coating quality and durability. Mirrors were deployed and exposed to the environmental conditions at the MST prototype in Berlin for almost eight years, including one-year real-condition test in Chile. Improvements of the coating composition and quality assurance during the manufacturing process were adapted.

In 2017, the groups from INP PAS and CEA-Saclay initiated collaborative efforts, together with DESY-Zeuthen, to develop a joint Polish-French mirror design that combines expertise of both teams. Here we present the final Polish-French composite mirror design and show preliminary tests of optical performance of the pre-series mirrors.

2. Polish-French mirror design

2.1 Mirror design and manufacturing technology

Figure 1 illustrates the schematic view of the joint Polish-French mirror design. The mirror is built of two 2 mm thick soda-lime float glass sheets, front and rear (items (1) and (3) in Figure 1), connected by a 35 mm high honeycomb spacer (2) made of thin 50-micron aluminium foil. The honeycomb structure is punched to allow free air circulation within the mirror substrate. The glass panels have a hexagonal shape, 1200 mm flat-to-flat in size. The mirror structure features custom-shaped soda-lime glass side-walls (4) that align with the desired curvature of the mirror. The thickness of the side-walls is 4 mm. The side-walls merge at the mirror corners with specifically designed stainless-steel plates (5). These components are laminated together at room temperature on a metal mould using epoxy resin. The desired 32.14 m radius of curvature is achieved through the cold slumping technique, utilizing vacuum suction on spherical mould with a specific curvature.

This new Polish-French mirror design features a completely sealed support structure. The use of glass side walls, shaped to match the mirror's curvature, and the incorporation of a punched honeycomb are among the innovative elements in this design. The features were developed during the last years at CEA-Saclay and KERDRY [9, 10]. Free air circulation inside the mirror sandwich is important for the coating process inside vacuum and for maintaining the mechanical stability of the mirror against temperature changes and during transportation to high-altitude observatory sites. To ensure pressure equalization, a special valve is integrated into one of the side walls or corners of the mirror substrate.

The front glass panel is coated with an aluminum reflective layer and a three-layer protective stack (SiO_2 + HfO_2 + SiO_2). The coating is made by KERDRY Thin Film Technologies SMB enterprise – an industrial partner of CEA-Saclay, who aluminized mirrors of earlier designs developed in France. In the current technology, the coating can be applied either on the finished mirror substrate or on a bare glass sheet prior to the mirror assembly. It has been observed that the time needed to glue and remove the holding pads on the bare glass sheet does not offset the longer vacuum time required for coating the complete sandwich in the coating chamber. As a result, the production costs associated with both methods are comparable, when the mirrors are fabricated and coated at the same location.

One of the last steps of the fabrication process, with the front glass coated, is that the edges of the front and rear glass panels are sealed with a UV-resistant silicone rubber (6) that can withstand a wide temperature range (from −60°C to +230°C). This gasket, specific to the Polish construction, provides damage protection during transportation and installation on the telescope. The rear glass panel is covered with a white protective foil (7) to prevent excessive internal heating and degradation of the epoxy resin, when the mirror faces the Sun with its rear side during daytime. Three stainless steel pads (8) are affixed to the rear mirror panel using PVC glue. The pads provide an interface between the mirror and the mirror mount structure.

2.2 Technology adjustments

Ordinary soda-lime float glass, with a thickness of 2 mm, shows a relatively significant surface waviness that varies among different glass sheets and among glass from different providers. This waviness leads to an enlargement of the point-spread-function (PSF) spot size and its elongation

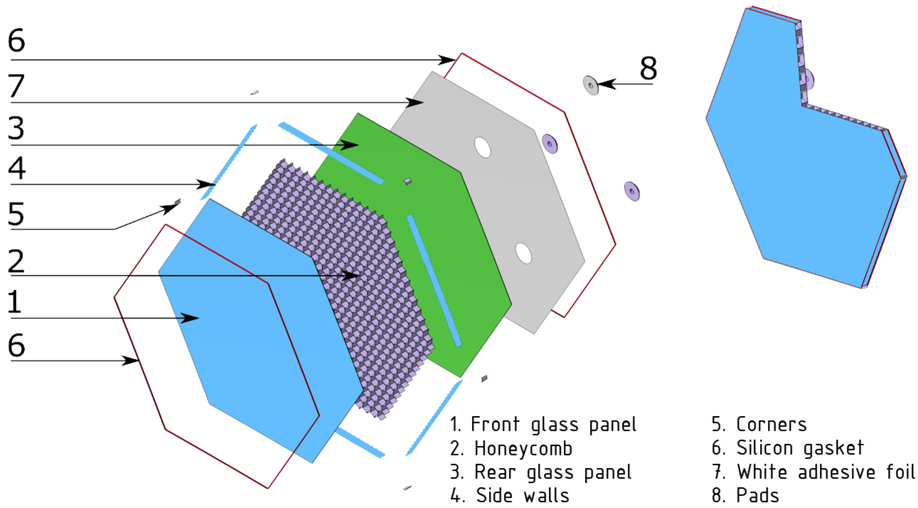

Figure 1: Schematic composite mirror structure of the Polish-French design.

along one axis. To address this issue, INP PAS has developed a test bench that examines raw hexagonal glass sheets before metallization and mirror assembly. The test assesses the magnitude of surface waviness by utilizing partial reflection of light (a few percent) from the non-coated glass surface and analyzing the PSF spot shape and size. This allows for the identification and selection of glass panels with satisfactory spot shapes, which are then selected for the front mirror panels to undergo coating. The glass sheets with lower quality are used for the rear mirror panels. This procedure allows for an improved production yield and ensures the attainment of a high mirror quality. It will be implemented during the mass production of the mirrors for the MSTs.

3. Production of the test mirror series

To verify and validate the final mirror design described above and the mirror fabrication and quality assurance processes, we have run test series production of mirrors. The mirrors were manufactured at two production sites: 6 mirrors at INP PAS and 10 mirrors at KERDRY. We used different providers of the float glass sheets - one from Poland and one from France. All glass sheets have been checked for waviness. The honeycomb spacer structures were manufactured at the same producer in France.

Figure 2 and Figure 3 show example PSF images and focal length measurements for one of the mirrors produced at INP PAS and one at KERDRY, respectively. Table 1 and Table 2 show the list of the mirrors produced at INP PAS and KERDRY, respectively, along with their optical characteristics. Mirrors IFJ-KERDRY 5-7 are made using glass supplied by a Polish provider, whereas mirrors IFJ-KERDRY 8-10 are produced using glass from the French supplier. Similarly, the first four KERDRY mirrors, KS-PS-01 to 04, are fabricated using glass from the same Polish company, the subsequent four, KS-PS-05 to 08, use French glass, and the last two are constructed using French glass from a different glass batch. All mirrors produced at INP PAS use front glass panels that are coated before the mirror assembly. This is also the case for the four mirrors KS-PS-01 to KS-PS-04, which are made of Polish glass. The remaining mirrors had their metallization applied

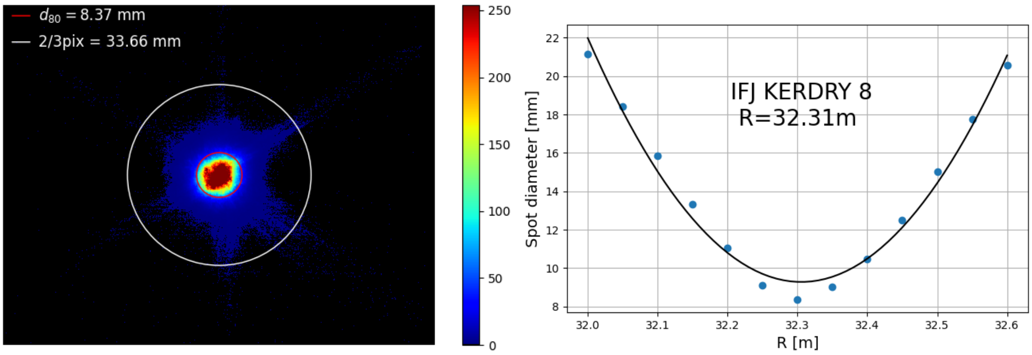

Figure 2: Left: PSF at best focus (red circle) of the IFJ KERDRY 8 mirror produced at INP PAS. White circle shows d_{100} = 33.66 mm containment radius. Right: PSF scan along the optical axis for mirror IFJ KERDRY 8. Data points are fitted with a parabola to determine the radius of curvature. Measurements were obtained using the INP PAS testing setup.

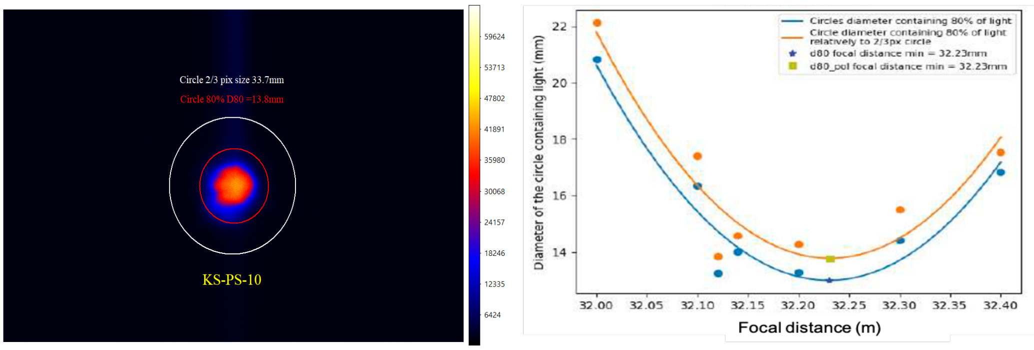

Figure 3: Left: Measurement of d80 at best focus (red circle) for KS-PS-10 mirror produced at KERDRY enterprise. Right: d80 scan along the optical axis for the KS-PS-10 mirror. Measurements were obtained using the CEA-Saclay testing setup.

after the manufacturing of the mirror substrates. It is important to note that mirror manufacturing at both sites achieved a 100% production yield, meaning that no rejection of mirrors has been carried out after production.

4. Tests of optical performance

The MST mirror specifications require that *(i)* the diameter of the circle that includes 80% of the reflected Cherenkov light shall be not greater than d_{80} = 24 mm at a focal distance of 32.14 m, and that *(ii)* the reflectivity within the PSF spot is greater than 85% at any wavelength in the range between 300 and 550 nm. The spot reflectivity should remain above 60% for the lifetime of the mirror, estimated to be several years. Moreover, the mirror should not suffer any irreversible change after being exposed to extreme weather conditions, such as temperatures in the range from −25°C to +60°C and a 200 km/h wind load.

The optical performance of the pre-series mirrors was evaluated by conducting measurements of their focal lengths and PSFs. These tests were carried out using $2f$ setups available at INP PAS and CEA Saclay. The setups involve positioning a point-like light source along the optical axis of

Table 1: List of prototype mirrors produced at INP PAS and the results of laboratory measurements of their radius of curvature (= $2f$), and the PSF (d_{80}) at the twice the focal distance and near the nominal $2f$ distance of 32.14 m.

Mirror ID	$2f$ (m)	d_{80} (mm) @ $2f$	d_{80} (mm) @ 32.15 m
IFJ KERDRY 5	32.30	10.48	14.69
IFJ KERDRY 6	32.26	10.22	12.56
IFJ KERDRY 7	32.19	9.96	10.48
IFJ KERDRY 8	32.31	8.37	13.31
IFJ KERDRY 9	32.23	10.13	11.11
IFJ KERDRY 10	32.17	9.38	9.38

Table 2: List of 10 prototype mirrors produced at KERDRY Thin Film Technologies SMB enterprise in Lannion. The results of laboratory measurements of their radius of curvature and the PSF (d_{80}) at the twice the focal distance and the nominal 2f distance of 32.14 m are performed at CEA Saclay.

Mirror ID	$2f$ (m)	d_{80} (mm) @ $2f$	d_{80} (mm) @ 32.14 m
KS-PS-01	32.03	16.1	17.3
KS-PS-02	32.34	18.8	22.5
KS-PS-03	32.39	15.3	21.3
KS-PS-04	32.40	13.8	20.7
KS-PS-05	32.38	13.7	20.0
KS-PS-06	32.10	14.2	14.4
KS-PS-07	32.11	16.6	16.8
KS-PS-08	32.05	16.2	16.7
KS-PS-09	31.92	12.1	14.9
KS-PS-10	32.23	13.8	15.2

the mirror, illuminating the mirror from a distance adjustable around twice the focal length. The reflected light is captured by a CCD camera equipped with image analysis software. At the INP PAS test bench, a red laser with a wavelength of 635 nm is used as the light source. On the other hand, the CEA-Saclay setup utilizes a 2 mm-diameter LED with a wavelength of 465 nm. To ascertain the focal length of a mirror, the PSF is measured at various distances between the mirror and the CCD camera. The focal length is determined by identifying the distance that yields the smallest PSF.

The optical characteristics in Table 1 and Table 2 list the focal lengths of the pre-series mirrors, their PSF (= d_{80}) at best focus, and the PSF close to/at the nominal MST $2f$ distance of 32.14 m. One can see that all mirrors produced in Poland and France have PSF at the optimal and nominal radius of curvature much smaller than the specification of $d_{80} < 24$ mm. The mirror parameters comply with the MST specification. Both sets of mirrors have similar optical performance, although the average PSF for the INP PAS mirrors, $\langle d_{80} \rangle_{2f} = 9.8$ mm, is smaller compared to the industrialized-CEA-KERDRY mirrors, $\langle d_{80} \rangle_{2f} = 15.1$ mm. The effect is caused by small differences in the production process at both production sites, which will be further investigated in order to improve the serial production performance. It should be noted that the PSF distribution within each set is relatively uniform, indicating that the production technology at both sites is well controlled. It shows that there is no significant difference in the optical performance between the mirrors produced using Polish or French glass suppliers.

The CEA-KERDRY mirror batch construction was focused on the delivery of a 10 mirror batch under industrial conditions to meet the d_{80} specification at the MST nominal distance of 32.14 m. The average value of the $2f$ distance is 32.19 m. The yield of 100% of this production demonstrates the readiness of CEA-KERDRY for mass production of MST mirrors.

The radius of curvature of several INP PAS mirrors deviates from the nominal $2f$ distance of 32.14 m by more than the focal length measurement error, approximately ±0.05 m. This is because the current production runs were not optimized to match the desired focal length. However, the mirror radius can be adjusted by controlling the radius of curvature of the mould using a system that was initially designed and implemented at INP PAS. Similar system was later developed for the laboratory at KERDRY. These systems allow for adjustments of the mirror radius of curvature within a range of ±0.30 m. Fine-tuning of the moulds is planned to be carried out with the first mirrors of the serial-production phase.

The measurements presented in Table 1 for INP PAS mirrors were conducted a few weeks after the mirrors were manufactured. A comparison with the measurements taken immediately after production reveals an average increase in the radius of curvature by approximately 0.05 m. The corresponding change of the PSF is $\sim \pm 1$ mm at best focus, which is comparable to or below the precision of the measurement setup. The impact of the change in mirror radius will be addressed through the final adjustment of the mould shape during the serial production phase.

5. Summary and outlook

This paper presents a joint Polish-French design for composite sandwich mirrors for MSTs of CTAO. With the mirror prototypes we demonstrate that the new updated common technology is successfully applied at two production sites managed by two different teams. Both sites can deliver mirrors that well comply with the MST specifications.

Acknowledgments

Publication co-financed from the Polish state budget under the program of the Minister of Education and Science under the name "Science for the Society", project number NdS/536498/2021/2022, amount of co-financing 1 558 884,80 PLN, total value of the project 1 558 884,80 PLN. LZ, EM, BP, YP, JMR greatly acknowlege the support of CEA-DRF/IRFU, France The industrial partnership between CEA Saclay and the KERDRY Thin Film Technologies enterprise is gratefully acknowledged.

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