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CTAO MST back-coated mirrors development

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Back-coated mirrors offer an alternative to the standard front-coated mirrors, enhancing durability and long-term reflective properties by placing the exposed front coating behind a thin protective glass layer. This design ensures a long-term protection of the reflective layers, mitigating the effects of environmental exposure on the soft protective coating (typically quartz) and reflective aluminium, which commonly affect front-coated mirrors. Additionally, the mechanical properties of the thin front panel in back-coated mirrors improve the overall durability of the mirror segment. In this contribution, we present a comparison of front- and back-coated composite mirror prototypes that have recently been developed for CTAO MST telescopes. We present mirror designs and discuss the mechanical properties, optical performance, scratch and surface hardness tests, in relation to mirror durability and lifespan. Enhancing the durability of the mirrors impacts the operating costs of telescopes and reduces the environmental footprint of the project by eliminating the need for mirror removal or re-coating during the lifetime of the project. The back-coated mirror technique is currently being tested as prototypes for the CTAO MST.

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1. Introduction

Ground-based detection of very high-energy (VHE) gamma-ray photons primarily relies on Imaging Atmospheric Cherenkov Telescopes (IACTs), used by current observatories such as H.E.S.S. [1], MAGIC [2], VERITAS [3], and the forthcoming Cherenkov Telescope Array Observatory (CTAO) [4]. The IACT technique leverages the collection of Cherenkov radiation generated by primary VHE gamma rays interacting with the atmosphere, offering superior angular and energy resolution compared to other ground-based detectors (e.g., HAWC [5]). Given its reliance on optical detection of atmospheric ultraviolet light at peak intensity at around 350 nm, the quality of the telescopes' optical elements is paramount. Key optical components include mirrors, optical filters, light detectors, and light-guides. The system's initial angular resolution is primarily determined by the field of view, optical point spread function (PSF), and camera pixel size. For individual mirrors, the PSF (influenced by shape and surface roughness) and the spectral reflectance of the reflective coating are critical imaging parameters in an IACT. The reflective coating in mirrors installed in currently operating IACTs typically consists of an Al layer applied to the front surface of a glass panel, additionally protected from oxidation by a thin layer of quartz. Due to exposure to environmental conditions, the optical performance of such front-coated mirrors degrades over the telescope's operational lifetime, necessitating their continuous monitoring and periodic replacement or re-coating. Mirrors with coatings applied to the back surface of the glass panel – so-called back-coated mirrors, help mitigate these issues while offering comparable optical performance. Here, we present a comparison of front- and back-coated mirror prototypes recently manufactured for the CTAO MST telescopes at the Institute of Nuclear Physics Polish Academy of Sciences (IFJ PAN), in collaboration with the Joint Laboratory of Optics (JLO) and DESY-Zeuthen.

2. Mirrors for CTAO MST telescopes

The CTAO is a next-generation facility for very high-energy gamma-ray astronomy, designed to dramatically enhance sensitivity – by a factor of ten compared to current instruments – and extend the observable energy range from a few tens of GeV to over 100 TeV. The array will consist of around one hundred IACTs of different sizes, requiring a total reflective surface area of approximately 10,000 m^2.

The Medium-Sized Telescopes (MSTs) form the core of CTAO, covering the 150 GeV to 5 TeV energy range. The telescopes feature a modified Davies-Cotton design with a $f = 16.0$ m focal length and the mirror dish of 12 m diameter composed of 86 hexagonal, 1.2 m flat-to-flat wide spherical mirror facets, with a nominal radius of curvature of 32.14 m. To meet optical requirements, at least 80% of the reflected Cherenkov light must be focused within a $d_{80} = 24$ mm diameter spot at $2f$, with over 85% total reflectivity in the 300–550 nm range. Spot reflectivity must remain above 60% over several years of operation.

MST mirror designs are based on a sandwich concept and utilize cold-slumping replication technology for production, offering a cost-effective solution. The use of lightweight mirror substrates alleviates the weight constraints associated with traditional solid-glass mirrors, which limit the structural rigidity and motion dynamics of the telescope dish. The incorporation of innovative

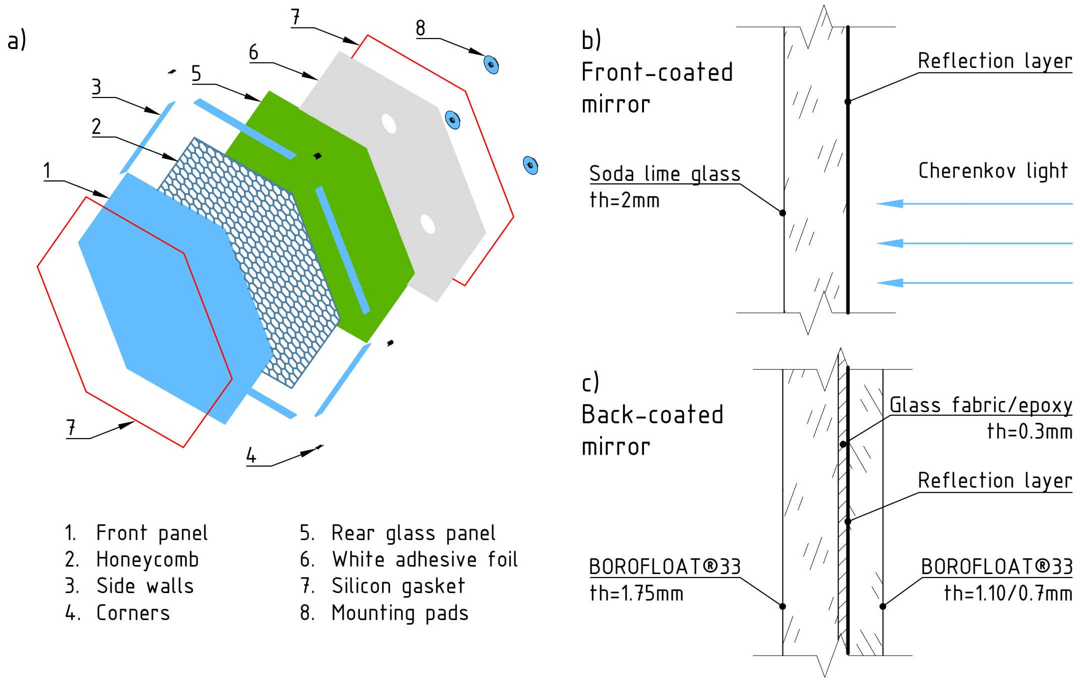

Figure 1: Schematic structure of composite mirrors designed for CTAO MST telescopes (a). Panels (b) and (c) show the front panel design of front-coated and back-coated mirrors, respectively.

back-coated mirror technologies, featuring more stable and durable reflective layers, represents a further advancement in composite mirror design.

The schematic of the composite front- and back-coated mirror designs is shown in Figure 1a. The mirror consists of front (1) and rear (5) hexagonal panels connected by a 35 mm high aluminum honeycomb spacer (2) made from 50 μm foil. The structure is enclosed by 4 mm thick custom-shaped glass side walls (3), which match the mirror's curvature, and stainless-steel corner plates (4). All components are laminated together using epoxy resin at room temperature on a convex metal mould. The edges of both the front and rear panels are sealed with a protective UV- and temperature-resistant silicone rubber gasket (7). The rear panel is additionally covered with a white protective foil (6) to shield it from solar UV exposure and overheating. Three stainless steel mounting pads (8) are attached to the rear using silicone adhesive.

Table 1: List of 9 prototype back-coated mirrors of the IFJ–MBF series presented in this work, detailing the front glass panel design and its thickness.

mirror ID	front-surface	mirror ID	front-surface
IFJ–MBF–01	mosaic 4 el. thick=1.1 mm	IFJ–MBF–02	mosaic 7 el. thick=1.1 mm
IFJ–MBF–13	full hexagon thick=1.1 mm	IFJ–MBF–14	full hexagon thick=1.1 mm
IFJ–MBF–15	mosaic 4 el. thick=1.1 mm	IFJ–MBF–16	mosaic 4 el. thick=0.7 mm
IFJ–MBF–17	mosaic 6 el. thick=1.1 mm	IFJ–MBF–18	mosaic 6 el. thick=1.1 mm
IFJ–MBF–19	mosaic 4 el. thick=0.7 mm		

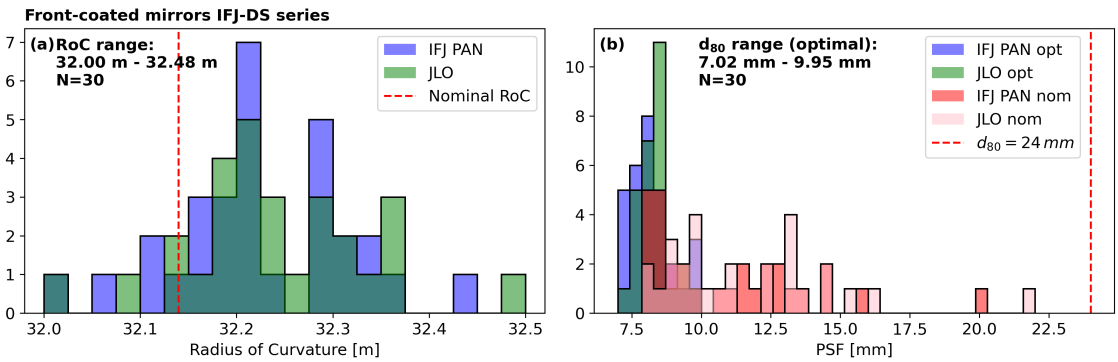

Figure 2: Histograms showing the measured radius of curvature (= $2f$; a), and the PSF (d_{80}) at both the optimal focus and the nominal $2f$ distance of 32.14 m (b) for front-coated mirrors of the IFJ–DS series.

Two mirror technologies have been developed: front-coated and back-coated designs. They differ in the glass type and the construction and production technology of the front panel (Figure 1b and 1c). The front-coated mirrors, is the joint Polish-French concept, developed by the IFJ PAN, CEA-Saclay, and DESY-Zeuthen [6]. They use soda-lime glass and feature a single 2 mm-thick front glass sheet with the reflective coating applied directly to its outer surface (Figure 1b). The back-coated mirrors – developed by IFJ PAN, JLO and DESY-Zeuthen – use Schott Borofloat® 33 glass for all components [7]. The reflective surface consists either of a thin, full hexagonal glass panel or a mosaic of thin, coated glass tiles, with the gaps between them filled with silicone glue. The full panel or assembled mosaic is then laminated with fiberglass fabric and epoxy. This front panel is mounted onto a pre-fabricated sandwich support structure, similar to that of the front-coated mirror, but with the glass pane adjacent to the honeycomb measuring 1.75 mm thick instead of the 2 mm pane used in the front-coated design (compare Figure 1b and 1c). In the back-coated design, the reflective layer is thus protected within the mirror assembly.

A large series of 30 front-coated mirrors was recently manufactured in collaboration with an industrial partner, under industrial assembly conditions. The front glass panels of these IFJ–DS–01 to –30 series mirrors were coated with reflective and protective layers by KERDRY Thin Film Technologies SMB. These mirrors are compared here to nine back-coated mirror prototypes, which feature either full hexagonal glass tiles or mosaics composed of four, six, or seven elements in their front panels (see Table 1). The tile thickness varies between 1.1 mm and 0.7 mm. The full glass tiles in the IFJ–MBF–13 to –19 series were coated at KERDRY, while the mosaic tiles were metallized at JLO. The IFJ–MBF mirrors were produced at the IFJ PAN laboratory. Details of the reflective coating and manufacturing technology are provided in references [6] and [7].

3. Optical performance and tests of mechanical properties

To compare the front- and back-coated mirrors and verify their compliance with MST specifications, we measure their focal length, PSF, spectral reflectance, and mechanical properties.

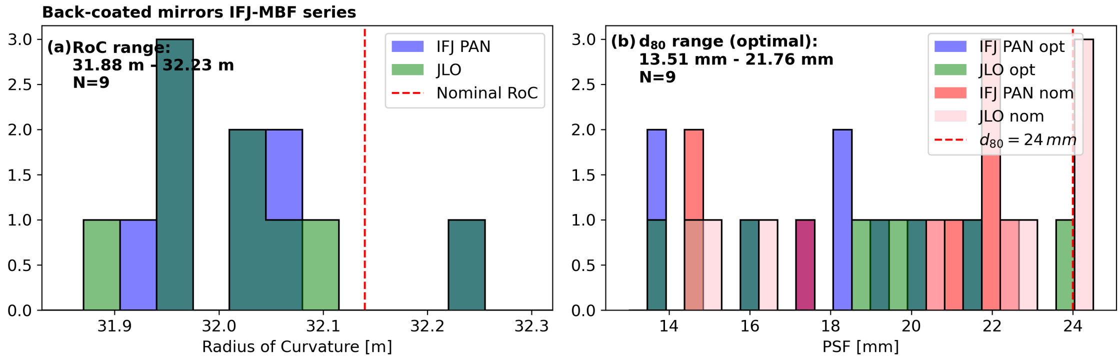

Figure 3: Histograms showing measurements for back-coated mirrors of the IFJ–MBF series (see Fig. 2).

3.1 Focal length, PSF and encircled energy

The quality of mirror facets depends on the substrate shape, surface microroughness, and the optical transmittance and reflectance of the materials used. The overall shape determines the PSF, while microroughness affects the balance between specular reflection and scattering. These contributions to the PSF can be measured separately or together using dedicated methods. Surface shape can be assessed via contact or non-contact techniques, and reflectance measured locally or with non-contact spectrophotometers. Combining these measurements allows for simulation of the final PSF. A more direct and commonly used method involves placing a point-like light source at a distance of 2f (twice the telescope focal length) along the optical axis of the mirror. The reflected light is either detected directly by a large-area CCD camera or projected onto a screen and then captured by the camera. The PSF is quantified by the encircled energy within a defined radius around its center of gravity. The focal length is determined by measuring the PSF at different distances between the mirror and camera and identifying the position with the smallest spot size.

The focal length and PSF (= d_{80}; see Section 2) of the mirrors were measured using $2f$ test benches at IFJ PAN and JLO (for details, see [7]). Here, we compare the results of these independent measurements.

Figure 2 shows histograms of the radius of curvature (RoC= $2f$), PSF at best focus (optimal RoC), and the PSF at the nominal MST $2f$ distance of 32.14 m for front-coated IFJ-DS series mirrors, comparing measurements from IFJ PAN and JLO setups. The results from both setups are in good agreement. All front-coated mirrors have PSF values at both the optimal and nominal RoC well below the specification of $d_{80} < 24$ mm, with an average optimal PSF of $\langle d_{80} \rangle_{2f} \approx 8.16$ mm (measured with the IFJ PAN setup; $\langle d_{80} \rangle_{2f} \approx 8.37$ mm at JLO), and all PSF values not exceeding $d_{80,2f} = 10$ mm. The mirrors therefore exhibit excellent optical performance and fully comply with the MST specification. While most RoC values are close to the nominal, some deviations arise because the current production was not optimized for precise focal length matching. However, the RoC can be adjusted by tuning the mould curvature, allowing corrections within ±0.30 m. Fine-tuning is planned during the initial phase of serial production.

Histograms for back-coated IFJ–MBF mirrors are shown in Figure 3. All mirrors achieve optimal-focus PSF values below the $d_{80} = 24$ mm threshold, meeting the MST specification. The best PSFs (∼ 13.6 – 15.9 mm) were obtained for mosaic mirrors IFJ–MBF–15, –17, and –18 with

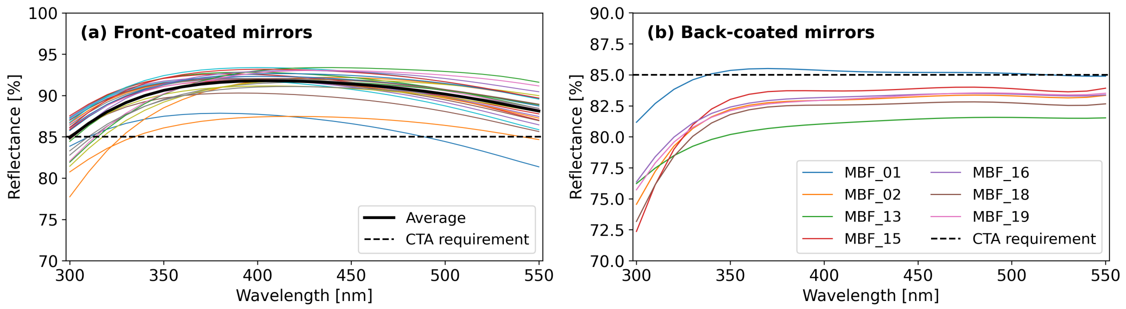

Figure 4: Spectral focused reflectance for front-coated IFJ–DS series mirrors (a) and selected back-coated IFJ–MBF series mirrors (b). The dashed line at 85% indicates the CTAO specification threshold.

1.1 mm-thick front tiles. Mirrors IFJ–MBF–01 and –02, also with 1.1 mm tiles, show higher PSFs of 20.3–23.75 mm; they were produced at an early development stage before the manufacturing technology was fully optimized. Full-hexagon mirrors and mosaics with 0.7 mm tiles exhibit PSFs between 17.5 and 20.3 mm. Values reflect measurements from both IFJ PAN and JLO setups.

3.2 Spectral focused reflectance

We measure the spectral reflectance of the mirrors using the same $2f$ setup configuration as for the PSF measurements, with the point-like source replaced by an optical fiber connected to a broadband UV–visible light source. A variable iris in front of the fiber defines the beam's solid angle to illuminate the entire mirror facet. An integrating sphere and fiber spectrophotometer measure the reference signal and the light reflected from the mirror at 2f. Their ratio yields the mirror's spectral reflectance.

Figure 4a shows that the majority of front-coated mirrors maintain reflectance above 85% across the full 300–550 nm wavelength range. A few mirrors exhibit slightly lower reflectance (by ~1–4%) in the 300–330 nm range, with one outlier at 77.7% reflectance at 300 nm. Overall, all mirrors exhibit excellent reflectivity in the Cherenkov wavelength range, with the average reflectance remaining above 85% across the entire band (thick solid line in Fig. 4a).

Due to the UV–VIS transmittance properties of the thin borosilicate glass protecting the reflective layer, back-coated mirrors show lower reflectance than front-coated ones. Nevertheless, all mirrors with mosaic front panels exhibit focused reflectance above ~82.5% for wavelengths above ~350 nm, while the full hexagon mirror (IFJ–MBF–13) exceeds ~80% in the same range. Below 350 nm, reflectance drops due to reduced glass transmittance [7], but remains above 72.5%. Performance in this band is ~2-5% better for mosaics with 0.7 mm-thick tiles compared to those with 1.1 mm tiles. Mosaic mirrors also outperform full hexagon mirrors overall. Variations among mirrors of the same type likely arise from differences in coating quality, glass transmittance and reflectance, surface microroughness, and support structure. Further studies are needed to quantify the impact of these factors. Averaged focused reflectance in the 300–550 nm range lies between 83.6% and 84.9% for the IFJ–MBF mirrors, with a median around 82%, comparable to front-coated mirrors after several years of operation. Their performance also clearly exceeds earlier results reported in [8].

3.3 Mechanical properties of the front and back-coated mirror samples

Measurements of mechanical and tribological properties were performed using a fully calibrated NanoTest instrument (Micro Materials, UK). Nanoindentation with a pyramidal Berkovich indenter under loads of 1 and 10 mN was used to determine hardness and reduced modulus values, evaluated using the standard method [9] with corrections for thermal drift and frame compliance. Adhesion and cohesion were assessed using scratch tests with spherical indenters of radii 10μm and 5μm under progressively increasing loads: up to 100 mN and 250 mN for the 10μm indenter, and up to 500 mN for the 5μm indenter. Scratch tracks were evaluated visually using a confocal microscope (LEXT 5000, Olympus, Japan) in combination with depth–load–displacement recordings. Measurements of mechanical properties were carried out using two different loads. A load of 1 mN ensured surface sensitivity, allowing characterisation of the top layer with minimal influence from the substrate. In contrast, a load of 10 mN induced greater deformation, enabling testing of deeper regions of the surface and primarily reflecting the substrate's properties.

Front-coated samples (FC) exhibit significantly lower hardness compared to back-coated samples (BC) (Fig. 5a). This lower hardness persists even at higher indentation loads, indicating the strong influence of the softer aluminum layer. However, hardness is a more localised property, while the reduced modulus reflects broader material behavior. At a 10 mN load, both front-coated and back-coated samples show nearly identical reduced modulus values (Fig. 5b).

In scratch tests using a 10μm spherical indenter at maximum loads of 100 and 250 mN, front-coated samples exhibit gradual penetration through the coating down to the substrate. In contrast, back-coated samples show no coating failure and only surface smoothing, even at scratch load of 250 mN (Fig. 5, right), indicating significantly higher scratch resistance. For back-coated samples tested with a 5μm indenter at 500 mN, glass cracking was observed, with maximum scratch groove depths of $3 - 5\mu$m and glass crack depths of $17 - 27\mu$m. This damage is negligible relative to the glass thickness (0.7 or 1.1 mm).

Overall, the back-coated mirrors demonstrate much higher mechanical resistance, supporting longer durability and operational lifetime.

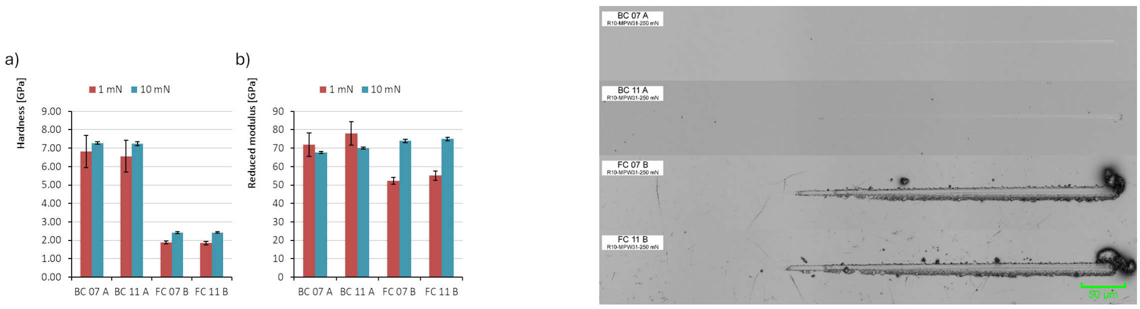

Figure 5: Top left: Indentation results for back- and front-coated samples showing (a) hardness and (b) reduced elastic modulus. Right: Surface images after scratch tests with a 10μm spherical indenter at a maximum load of 250 mN. The back-coated samples (two upper tracks) show almost no damage, while the front-coated samples (two lower tracks) exhibit significant penetration through the coating layers down to the coating–substrate interface.

4. Conclusions

This paper compares front-coated and back-coated composite sandwich mirrors developed for the MSTs of CTAO. We demonstrate that the updated joint Polish–French technology for front-coated mirror production has been successfully implemented under industrial conditions in Poland. These mirrors exhibit excellent optical performance and fully meet MST specifications. The novel back-coated mirrors, based on a similar design, also show excellent focusing and mechanical properties, along with very high reflectivity in the Cherenkov wavelength range. As the back-coated technology is expected to maintain reflectivity throughout the mirror's lifetime, it represents a promising solution for enhancing the performance and efficiency of future telescopes or upgrades of existing IACTs used in ground-based gamma-ray astronomy.

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