PROCEEDINGS OF SCIENCE

Development of a new backside reflection mirror technologies for ground-based gamma-ray astronomy

PoS(ICRC2023)816

Jerzy Michałowski,[a] Markus Garczarczyk,[b] Tomasz Gieras,[a] Dusan Mandat,[c] Krzysztof Nalewajski,[a] Jacek Niemiec,[a,*] Miroslav Pech[c] and Paweł Świerk[a]

[a] *Institute of Nuclear Physics Polish Academy of Sciences, PL-31342 Krakow, Poland*

[b] *Deutsches Elektronen-Synchrotron, DE-15738 Zeuthen, Germany*

[c] *Institute of Physics of the Czech Academy of Sciences, 17. listopadu 50, Olomouc & Na Slovance 2, Prague, Czech Republic*

E-mail: jerzy.michalowski@ifj.edu.pl, jacek.niemiec@ifj.edu.pl

Imaging atmospheric Cherenkov telescopes (IACTs) are often used for detection of high-energy gamma rays from the ground. The reflector of an IACT is typically tessellated into smaller mirror segments. The mirror segments are made of a glass or sandwich structure substrate with the front side coated typically with aluminum (Al) and a thin quartz protective layer. Direct exposure to harsh environmental conditions causes rapid degradation of optical performance of this type of mirrors and forces their regular replacement or re-coating that entails significant operational cost for the observatories. Mirrors with a thin front glass panel coated on a back surface, adjacent directly to the mirror substrate, can solve this problem. We report on our recent development of various technologies to build a reflective back-coated front glass surface with a composite mirror support structure manufactured with the cold glass slumping technique. We show that a decrease in optical efficiency due to the transmission of Cherenkov light reflected through the glass layer can be significantly compensated by selecting a special type of glass with appropriate thickness. We present full-size mirror prototypes that fit the specifications for the Medium-Sized Telescope mirrors for the Cherenkov Telescope Array. We also show first results of the laboratory tests of mechanical stability and focused reflectivity in the spectral range of the Cherenkov light.

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

*Speaker

1. Introduction

The detection of very high-energy gamma-ray photons at ground level is frequently accomplished through the utilization of IACTs. These telescopes collect Cherenkov radiation emitted by extensive air-showers generated by primary gamma rays or protons in the GeV/TeV energy range. The Cherenkov light spectrum reaches its peak intensity in the UV wavelength range at around 350 nm. Optical mirror segments, arranged in a tessellated way on the telescope reflector, are used to reflect the light towards the telescope camera. The reflectors of individual IACTs have surface areas ranging from several tens to hundreds of square meters. Due to costs reasons, the telescopes are not protected by domes.

The reflective surface of mirrors installed in currently operating IACTs is either diamond-milled Al or a glass panel coated with a thin Al layer on its front surface. The Al layer is additionally protected from oxidation by a thin layer of quartz, whose thickness is determined through a trade-off between the highest reflectivity throughout the Cherenkov spectrum and durability of the protection. The direct exposure of the mirrors to harsh weather conditions, including pronounced diurnal and seasonal temperature variations, precipitation, ice, winds, and dust deposition at desert and high-mountain altitudes, leads to accelerated degradation of the protective layer and a significant loss of reflectivity. This forces the replacement of the mirrors or their re-coating every few years, which entails significant operational cost for the observatories.

The implementation of mirrors featuring a thin front glass panel coated on the back surface, directly adjacent to the mirror substrate, can offer a solution to this problem. Will et al. [1] have recently presented the first solution of this kind. It uses a 0.4 mm glass sheet adhered on the coated side to the support structure of the mirror. The so-called *back-coated* mirror can then be easily cleaned, and environmental factors should not deter its optical performance. Several prototypes with a square shape and a surface area of 1 m^2 have been manufactured for the MAGIC[1] telescopes located on the Canary Island La Palma.

The use of an ultra-thin glass panel in the above mentioned solution necessitates careful handling and poses challenges in the mirror production process. Moreover, the transmission of light for the glass used in [1] causes the mean surface reflectivity to be reduced to below 70% at wavelengths shorter than 350 nm. Further advancements are therefore required to identify solutions for back-coated mirrors that offer improved reflectivity optimised for the Cherenkov waveband, while maintaining an easy and cost-effective manufacturing. Here we present the first results of our research on novel backside reflection mirror technologies developed at the Institute of Nuclear Physics Polish Academy of Sciences (INP PAS), in collaboration with the Joint Laboratory of Optics (JLO) and DESY-Zeuthen.

2. New backside reflection composite mirrors

2.1 Mirrors for MSTs of the CTA Observatory

The back-coated mirrors described here are designed to fit the specifications for the Medium-Sized Telescopes (MSTs) for the Cherenkov Telescope Array (CTA)[2]. MST sub-arrays will perform

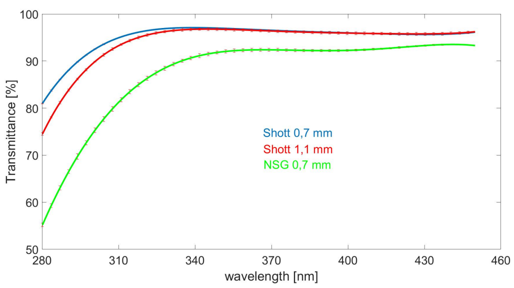
[1] magic.mpp.mpg.de
[2] www.cta-observatory.org

observations in the core energy range of CTA between 80 GeV and 50 TeV. The MSTs utilize a modified Davies-Cotton design, with a reflector diameter of 12 m and a focal length of 16.0 m. The reflector is composed of 86 hexagonal facets with the spherical profile and the flat-to-flat size of 1.2 m. The MST mirror specifications require the individual mirror segments to collect 80% of the reflected Cherenkov light in a spot of $d_{80} < 12$ mm at the nominal focal distance of 16.07 m. The overall focused reflectivity inside the spot shall be greater than 85% at any wavelength in the range between 300 and 550 nm.

2.2 Glass selection

The primary factor determining the optical performance of a back-coated mirror is the ultraviolet (UV) and visual light (VIS) transparency of the front glass panel. We have selected the float glass from two manufacturers: Schott Borofloat® 33 and NSG glanova ™. The thickness of the glass sheets is ranging between 0.5 mm to 1.75 mm. The samples were coated with a reflective Al layer of 100 nm, covered with the 150 nm protective layer of Cr. The extra Cr layer is applied due to its superior adhesion to the glue used for assembling the thin glass panel to the mirror support structure. It also protects the Al against oxidation immediately after the deposition process. Both materials were deposited using the Physical Vapor Deposition (PVD) technology at a pressure of 5×10^{-4} Pa and at room temperature, to prevent the reflectivity deterioration of the Al in the UV region. After careful cleaning, the thin glass substrates were subjected to a 10-minute Argon discharge to enhance adhesion prior to the deposition process. Al was deposited via thermal evaporation on tungsten boats, while chromium (Cr) was deposited using an electron gun.

Figure 1 shows the comparison of spectral transmittance (left) and reflectance (right) for the UV-VIS light of the selected samples of different thickness. The reflectivity of all samples remains above 85% for wavelengths longer than 350 nm and maintains a minimum of 70% for shorter wavelengths down to ~300 nm. In the range from 300 nm to 350 nm the Schott Borofloat® 33 glass performs much better than the NSG glanova ™ glass. This is due to much higher transmittance of the borosilicate glass in this waveband (compare measurements for the 0.7 mm-thick glass). Due to the better performance, the Schott Borofloat® 33 glass was selected for manufacturing of the first mirror prototypes.



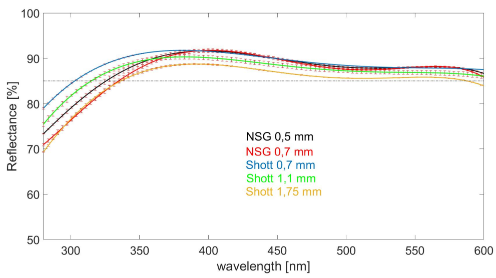


Figure 1: Comparison of spectral transmittance (left) and reflectance (right) in the UV-VIS waveband of thin glass samples of SCHOTT Borofloat® 33 and NSG glanova™ glass. The samples are coated with Al on their back surfaces.

2.3 Mirror design and production technology

Figure 2 shows a schematic view of the composite sandwiched backside reflection mirror designed at INP PAS. The mirror is produced based on the co-called cold-slumping technology [2]. Its design is based on various developments and improvements of composite mirrors made at INP PAS [3] in the past years. The mirror design planned to be used for the MSTs at the southern observatory site in Chile, developed jointly by the INP PAS, CEA-Saclay and DESY-Zeuthen [4], is based on the same technology. The back-coated mirror differs mainly in the construction of the front panel (a single hexagonal glass sheet is used in the Polish-French solution) and the glass type (instead of soda-lime glass, all glass elements are made of Schott Borofloat® 33).

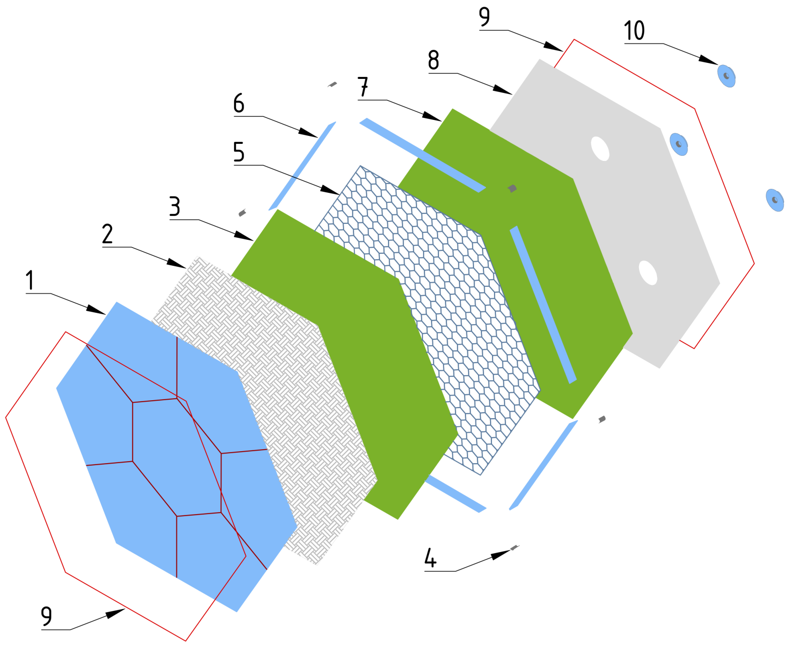


Figure 2: Schematic structure of composite a back-coated mirror. Front panel: metallized mosaic glass sheets (1), and glass fiber-epoxy resin laminate (2). Mechanical support structure: front glass tile (3), honeycomb (5), rear glass tile (7), glass side walls (6) and corner elements (4). Protection and fixation measures: white adhesive foil (8), silicon gaskets (9), mounting pads (10).

The back-coated mirrors are composed of two primary components: the front panel (items (1-2) in Figure 2) and the mechanical support structure (3-7). The front panel is built of a mosaic (1) of 7 or 4 elements (see Figure 3) that have a thickness of 1.1 mm and are coated with the Al and Cr layers, as described in section 2.2. During the mirror production process, the mosaic components are placed on a flat table with the metallization layer facing upwards, separated by 1 mm plastic spacers. The gaps between them are filled with silicone glue, which is allowed to cure. Once the glue is set, the components are laminated with the glass fiber fabric and epoxy resin (2). The lamination serves to mechanically join the mosaic pieces and protect the fragile metallization layer from damage during subsequent manufacturing stages. The complete panel (1) has a thickness of $\sim$ 1.4 mm and size of 1.2 m (f-t-f). After curing, the panel is transferred to a convex metal mold and suctioned to it using a vacuum system. In the next step a rigid support structure is glued to the mosaic laminated panel on the mould, in which way the mirror receives the spherical profile of the mould. The support structure has a similar shape and structure to a front-coated MST mirror [4], but it lacks the reflective coating. The production process of the support structure differs in the way that for the back-coated mirror the support sandwich structure is fabricated in advance on the same metal mould.

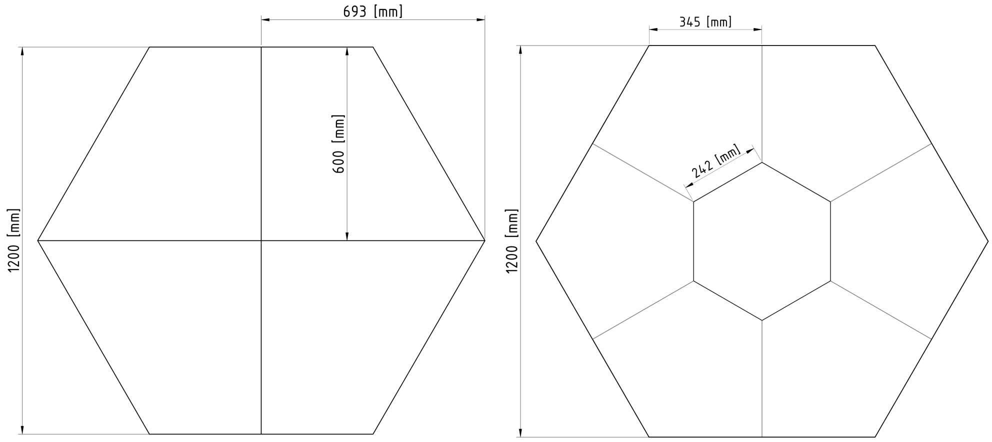


Figure 3: Schematic drawing of the front glass panel made of a mosaic of 4 (left) or 7 (right) elements.

The mirror support structure is constructed using the front (3) and the rear (7) haxagonal glass tiles, with a thickness of 1.75 mm and 2.0 mm, respectively. They are connected using a spacer structure (5), which is a commercial honeycomb made of thin 50-micron Al foil with a height of 35 mm. The mirror structure is enclosed with six 3.3 mm thick glass side-walls (6) that are shaped to match the desired curvature of the mirror. They are joined at the mirror corners with 1 mm thick stainless steel shaped plates (4). These components are laminated together at room temperature on a metal mould using the epoxy resin.

The edges of both the front and the rear panels are covered with a special silicone rubber (9), resistant to UV and durable over a wide temperature range (from −60°C to +230°C). This gasket protects the mirror edges against damage during transportation and installation on the telescope. It also aids supporting the sealing of the mirror front side glued layers. The rear panel is covered with a white protective foil (8) to protect the back side of the mirror, which faces the Sun during daytime, from excessive UV exposure and heating. Three stainless steel pads (10), used to mount the mirror, are securely attached to the rear side using silicone adhesive. Figure 4 shows the first MST-size back-coated mirror prototypes. The total weight of each mirror is 20 kg.

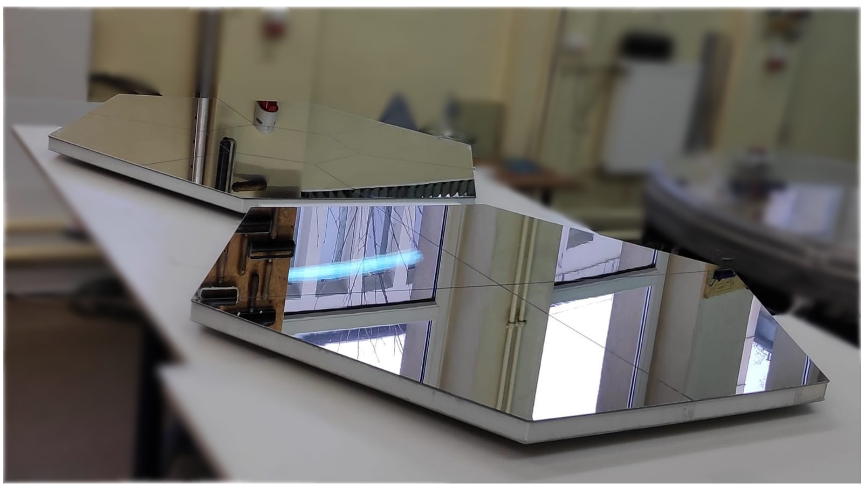


Figure 4: Full MST-size prototypes of back-coated mirrors whose front reflective panels are composed of the mosaic of 7 (top, MBF 2) and 4 (bottom, MBF 1) elements. The protective silicone gasket is not yet applied to the edges of these mirrors.

The composition of the mosaic requires the technology of cutting and grinding of 1.1 mm-thick Borofloat 33 glass at specific angles between the edges. We have developed and constructed a custom-made device specifically for this task. The device utilizes a small wheel/knife and a linear guide. The pressure applied to the knife is achieved through a gravity load, resulting in controllable and repeatable cuts.

3. Tests of optical performance

To assess the optical performance of the prototype mirrors and verify their compliance with the MST specifications we measured their focal length, PSF and spectral reflectance.

3.1 Focal length and PSF

The focal length and PSF (= d_{80}, see section 2.1) of the mirrors were measured using $2f$ setups available at INP PAS and JLO. These setups use a point-like source positioned along the optical axis of the mirror, illuminating the mirror from a distance of roughly twice the focal length. The reflected light is projected onto the screen and captured by a CCD camera equipped with software for image analysis. In the INP PAS test bench, the light source is a red laser with a wavelength of 635 nm, whereas the JLO setup utilizes a standard white LED with 50 μm pin hole and aperture system to obtain a point-like source without additional background. The focal length of a mirror is determined by measuring the PSF at various distances between the mirror and the CCD camera, and identifying the distance that yields the smallest spot dimension.

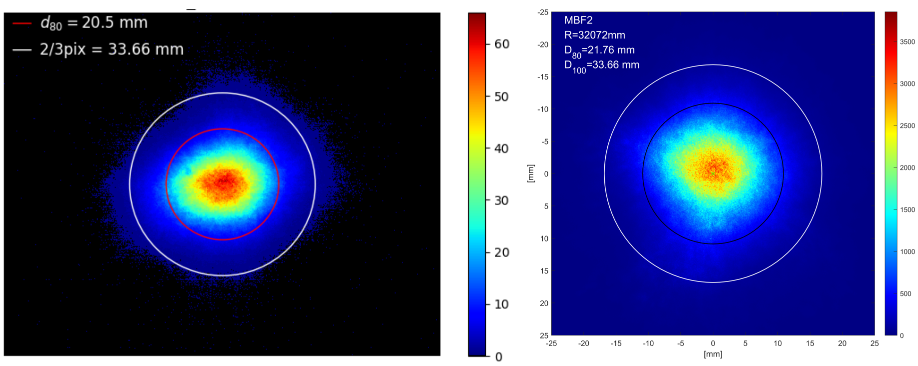


Figure 5: PSF at best focus of the MBF 1 mirror (mosaic of 4 elements) measured using the INP PAS testing setup (left, red circle) and the MBF 2 mirror (mosaic of 7 elements) measured with the JLO test bench (right, blue circle). White circles show d_{100} = 33.66 mm containment radius.

Figure 5 shows the results obtained on the INP PAS test bench for mirror MBF 1, whose front panel is a mosaic of 4 elements. The radius of curvature is $R_{\mathrm{M1}} = 31.93 \pm 0.05$ m, and the PSF at best focus is $d_{80,\mathrm{M1}} = 20.5$ mm, as marked in the figure with a red circle. The results for mirror M2 read: $R_{\mathrm{M2}} = 32.05 \pm 0.05$ m and $d_{80,\mathrm{M2}} = 21.1$ mm. The measurements on the JLO setup yield compatible curvature radii and very similar PSF: $d_{80,\mathrm{M1}} = 20.1$ mm and $d_{80,\mathrm{M2}} = 21.8$ mm. Measurements on the $2f$ setup result in a spot size twice the one expected for a parallel beam of light. To compare the d_{80} measurements with the MST specification one needs to divide the measured value by two. The mirrors thus very well meet MST PSF specification. The mirrors maintain their focusing properties over time. The measurements conducted immediately after production and after 5 months of production show results consistent with systematic errors of the test setup. During this time both mirrors spent 5 or 6 days in a climate chamber and underwent temperature cycles from −20°C to +40°C with a rise of 10°C/h. They were also transported between Krakow and Olomouc for measurements during the winter season.

3.2 Spectral reflectance

Figure 6 shows the mean surface reflectance of the back-coated mirrors, compared to the front-coated MST mirror. The data were taken with a CT7 reflectometer/scatterometer[3]. Data points are averaged from several hundred measurements on the mirror surface. Both back-coated mirrors maintain reflectance above 85% for wavelengths longer than ∼350 nm and above 74% for wavelengths down to ∼300 nm, showing similar behaviour. Their averaged reflectivity in the 300-550 nm waveband is ∼87%, very similar to the reference front-coated mirror (∼91%).

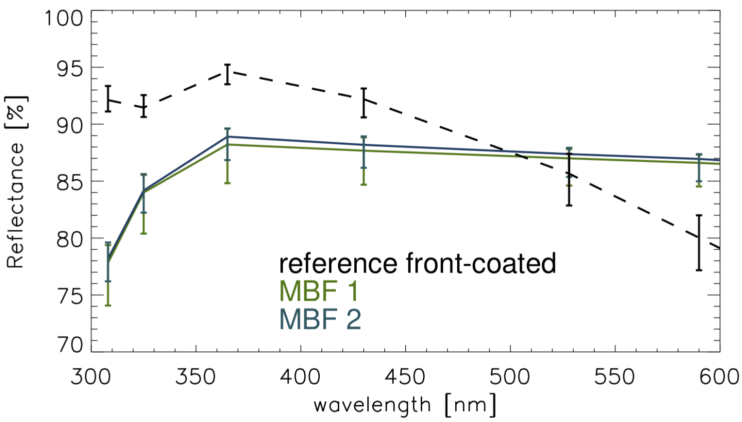


Figure 6: Mean surface reflectance of the MBF 1 and MBF 2 mirrors. Data for one of the front-coated MST mirrors produced at INP PAS are shown for comparison.

Measurement of the focused reflectivity was performed using the JLO $2f$ setup. The LED was replaced by an optical fibre connected to a wide spectral range light source covering UV-VIS waveband. An integrating sphere was placed at the focal distance of the mirror. Measurement of the ratio between the light source and the integrated light in the sphere gives the spectral reflectance of the mirror.

Figure 7 shows that the MBF 1 mirror exhibits the focused light reflectance above 85% at all wavelengths above ∼350 nm. The value is only 2-3% lower than the mean surface reflectance within this wavelength range. The reflectance below 350 nm decreases, but remains higher than 70% above ∼300 nm. The reflectivity loss can be explained by the reduced transmittance of the glass in this waveband. The MBF 2 mirror exhibits similar spectral dependence, though its reflectance is 2-3% smaller than that of the MBF 1 mirror. This difference cannot be fully explained by either a larger dead-space in the 7-elements mosaic panel (0.36% of the total surface area for MBF 2 mirror and 0.26% for MBF 1 mirror) or the quality of the coating, which appears to be better for the MBF 2 mirror compared to the MBF 1 facet (see Figure 6). Further studies are ongoing to understand this discrepancy. To conclude, the averaged focused reflectivity in the waveband between 300 and 550 nm is about 83.5% and 81% for the MBF 1 and MBF 2 mirrors, respectively. It is significantly higher, when comparing to the results reported in [1].

[3]OPO | Optical metrology

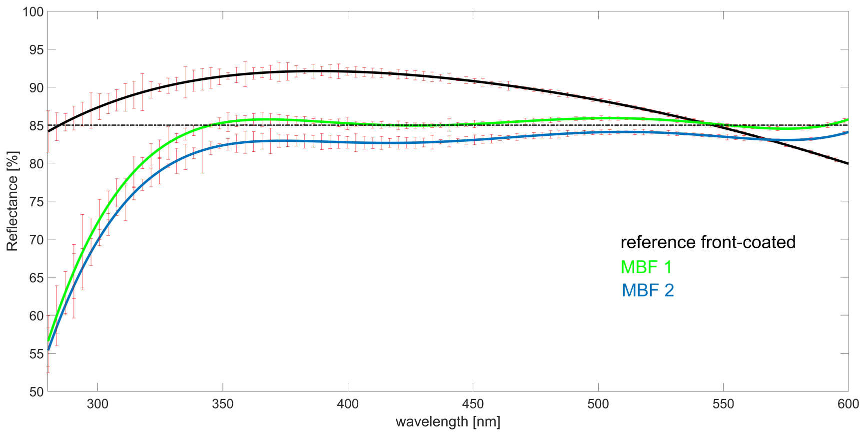


Figure 7: Spectral focused reflectance for MBF 1-2 and the reference mirrors (see Figure 6). Dashed line at 85% marks the CTA requirement.

4. Conclusions and outlook

This paper presents the first two ever-built prototype MST mirrors that utilize novel back-coated technologies. The mirrors exhibit excellent focusing properties and very high reflectivity in the Cherenkov waveband. The technology promises no reflectivity loss during the mirror lifetime. Currently, additional prototype mirrors are being constructed, featuring different types of front glass panels, including single hexagonal panels and mosaic panels with varying glass thicknesses. The use of mosaic will likely allow the technology to be applied for mirrors of much larger size and/or with significantly smaller radii of curvature. These studies aim to identify the optimal back-coated mirror solutions for improved performance and efficiency for future telescopes (or updates of existing IACTs) for ground-based gamma-ray astronomy.

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. The work is also co-financed by the Ministry of Education, Youth and Sports, MEYS LM2015046, LM2018105, LTT17006, EU/MEYS CZ.02.1.01/0.0/0.0/16_013/0001403, CZ.02.1.01/0.0/0.0/18_046/0016007.

SCIENCE FOR THE SOCIETY

References

[1] Will, M., et al. 2019, PoS, ICRC2019, 823.

[2] Canestrari, R., et al. 2013, Optical Engineering, 52, 051204.

[3] Michałowski, M., et al. 2015, PoS, ICRC2015, 988.

[4] Michałowski, M., et al. 2023, PoS, ICRC2023, 818.