Mirror development for CTA

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ABSTRACT

The Cherenkov Telescope Array (CTA), currently in its early design phase, is a proposed new project for ground-based gamma-ray astronomy with at least 10 times higher sensitivity than current instruments. CTA is planned to consist of several tens of large Imaging Atmospheric Cherenkov Telescopes (IACTs) with a combined reflective surface of up to 10,000 m^2. The challenge for the future CTA array is to develop lightweight and cost efficient mirrors with high production rates, good longterm durability and adequate optical properties. The technologies currently under investigation comprise different methods of carbon fibre/epoxy based substrates, sandwich concepts with cold-slumped surfaces made of thin float glass and different structural materials like aluminum honeycomb, glass foam or PU foam inside, and aluminum sandwich structures with either diamond milled surfaces or reflective foils. The current status of the mirror development for CTA will be summarized together with investigations on the improvement of the reflective surfaces and their protection against degradation.

1. INTRODUCTION

In recent years, ground-based very-high energy gamma-ray astronomy has experienced a major breakthrough demonstrated by the impressive astrophysical results obtained with IACTs like HESS, MAGIC or VERITAS.[1] The Cherenkov Telescope Array (CTA) project is being designed to provide an increase in sensitivity of at least a factor ten compared to current installations along with a significant extension of the observable energy range down to a few tens of GeV and up to about 100 TeV, preferrably in two locations to cover the northern as well as the southern hemisphere. The final layout of the arrays such as the exact number of telescopes, their sizes, their configuration and the overall performance are still under investigation using detailed Monte Carlo simulations as well as technical feasability studies for individual components. To reach the required sensitivity several tens of telescopes will be needed with a combined mirror area of up to 10000 m^2. To cover the intended range in gamma-ray energies $2-3$ different telescope sizes might be useful. Current design studies investigate three telescope sizes: small sized telescopes with a diameter of approximately 6 m, several medium sized telescopes (12 m) and large sized telescopes (23 m).

The individual telescopes will need reflectors of up to 400 m^2 area. The requirements for the focal point spread function (PSF) are more relaxed compared to those for optical telescopes. Typical PSF below a few arcmin per single mirror are acceptable which makes the use of a segmented reflector consisting of small individual mirror facets (called mirrors in the following) possible. IACTs are usually not protected by domes, the mirrors are permanently exposed to the environment. The design goal for the mirrors is to develop low-cost, light-weight, robust and reliable mirrors of $1-2$ m^2 in size with adequate reflectance and focusing qualities but demanding very little maintenance. Current IACTs mostly use polished glass or diamond-milled aluminum mirrors, both requiring cost, time and labor intensive machining. The technologies currently under investigation for CTA

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pursue different methods such as constructions based on carbon fiber/epoxy based substrates, sandwich concepts with cold-slumped surfaces made of thin float glass and different core materials like aluminum honeycomb, glass foams or plastic foams as well as sandwich structures made entirely from aluminum.

This paper has the following structure: in Section 2 the technical specifications for the mirrors and the reflective surface requirements are addressed. In Section 3, the ongoing development of the different technologies for mirror prototypes by different institutes within the CTA consortium is presented. Section 4 summarizes the activities concerning the reflective and protective surface coatings and Section 5 concludes with a short summary.

2. MIRROR SPECIFICATIONS

2.1. Mechanical specifications

Geometry. The mirrors for the CTA telescopes will be hexagonal in shape, with an anticipated size between $1-2$ m^2, well beyond the common size of $0.3-1$ m^2 of the currently operational instruments.

Weight. Weight reduction compared to the currently widely used solid glass mirrors is an important goal but should not come at the expense of optical quality, stability, long-term durability or a significant increase in price. For ease of handling a total weight of less than 20 kg/m^2 is desirable.

Rigidity. High rigidity of the mirrors is a fundamental requirement. The orientation of the mirrors changes between facing 40° down and 90° up with respect to the horizontal. The mirror deformation under gravity must be small enough to maintain the specifications for the PSF and the alignment. The same holds for moderate wind loads (typically, IACTs can operate safely at up to 40 km/h wind speed). The mirrors should not deform during the estimated 10 years of operation.

Temperature range. IACTs are normally placed at altitudes of $1,000-3,000$ m a.s.l. where significant temperature changes between day and nighttime as well as rapid temperature drops are quite frequent. All optical properties should stay within specifications within the range -10°C to $+30$°C. Further, the mirrors should resist to temperature changes from -15°C to $+60$°C with all changes of properties being reversible.

Surface shape. Current IACTs have mirrors of spherical shape. For small and medium-sized telescopes which usually have a Davies-Cotton design[2] the resulting overall optical properties are satisfying. For large telescopes the reflector will most probably approximate a parabolic shape. In these cases the discrepancy between the two principal radii of curvature for radial distances larger than 6 m becomes relevant. Depending on the final design spherical mirrors might still be feasable but aspherical mirrors (with different radii of curvature in perpendicular directions) might be an interesting option.

2.2. Optical specifications of the mirrors

Point spread function. Intrinsic aberrations in the Cherenkov light emitted by atmospheric showers limit the angular resolution to values of around 30 arcsec.[3] However, the final requirements for the resolution of the reflectors of future CTA telescopes, i.e. the spot size of the reflected light in the focal plane (camera), will depend on the pixel size of the camera and the final design of the telescope reflector. There is no real need to produce mirrors with a PSF well below the half of the camera pixel size, which is ordinarily not smaller than 5 arcmin. A diffuse reflected component is not critical as long as it is spread out over a large solid angle.

Reflectance. The reflectance into the focal spot shall exceed 80% for all wavelengths in the range from 300 to 600 nm, ideally close to (or even above) 90%. The Cherenkov light intensity peaks between 300 and 450 nm, therefore the reflectance of the coating should be optimized for this range.

Durability. CTA will be operated for at least 10 years. Therefore, the mirrors should maintain their performance for that duration, i.e. the PSF and the reflectance should not degrade by more than a few percent. Most critical is the long-term stability of the reflectance under the prevailing environmental conditions. Current glass mirrors are front-coated with aluminum and overcoated by a protective layer. Such mirrors have shown reflectance losses of 4-5% per year and need re-coating after about 5 years. Such a rapid degradation is not observed in diamond milled aluminum mirrors (AlMgSi 0.5 and AlMgSi 1 alloys, overcoated with SiO_2 with some carbon admixture) mounted on the MAGIC telescopes[4] for which the reflectivity loss is about 1%/year.

2.3. Testing facilities

Two independent test-facilities are foreseen for *a*) a complete qualification of all mirror prototypes until a decision for the final design is made, *b*) automated measurements of the essential parameters of each mirror to be installed on the CTA telescopes.

All Prototypes will undergo a common extensive testing procedure to characterize their optical and mechanical properties as well as their long-term durability. The test procedures are not finalized yet but will most probably incorporate the following:

The surface curvature will be scanned by a 3D measuring device with 1 micron precision and the micro-roughness of the surface will be measured. The focal lengths at different wavelengths ($250 - 650$ nm) will be measrued optically. The spot size will be checked with a 2f-setup illuminating the mirror with a point light source placed twice the focal distance away and imaging the resulting spot a the same distance, separately for different wavelengths. For the reflectance three tests are envisaged: a) reflectance measurements using spectrophotometers on small samples coated together with the mirrors, b) pointwise reflectance measurements with reflectometers on the mirrors surface, c) most important, the measurement of the directed reflectance into the focal spot using the same 2f-setup as for the determination of the spot size.

The rigidity will be tested by loading the mirrors with weights at different points during the 3D measurements. The tests for long-term durability will include extensive temperature and humidity cycling, salt fog and and sodium hydroxide tests and abrasion tests, all followed by renewed optical testing. The coating has to pass a standard Scotch-tape adhesion test. The water-tightness of the sandwich structures will be tested by immersing the mirrors in warm water to a depth of at least 1 m. All parts exposed to the sun need to be checked for UV-resistance. An important requirement for sandwich mirrors is a high heat conductivity between the front- and back-plane to avoid radiation cooling and in turn dew or ice formation during clear windless nights. Suitable test methods are under study.

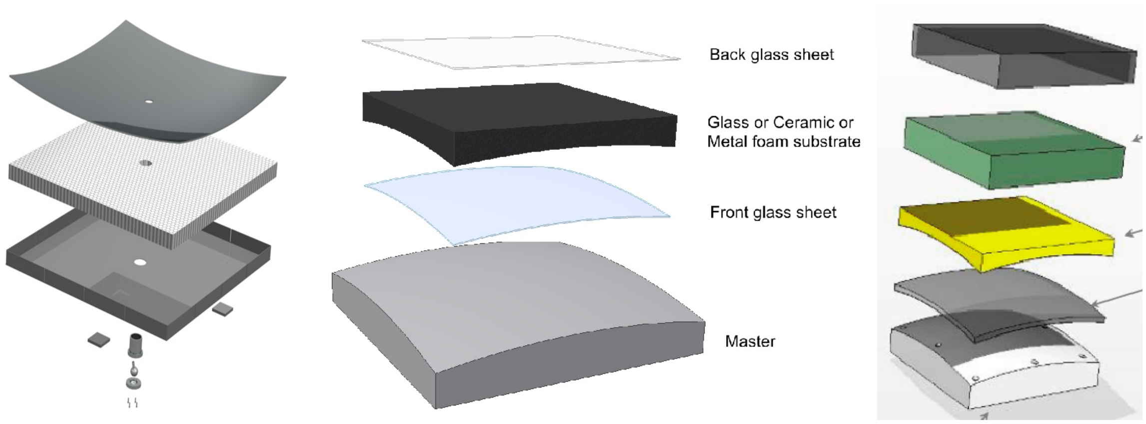
For the series production a fast but reliable highly automised test prcocedure checking the basic properties of the mirrors will be set up to ensure a constant quality of all mirrors mounted on the telescopes of the array.

3. TECHNOLOGIES UNDER INVESTIGATION FOR CTA MIRRORS

Different institutes within the CTA consortium are developing prototypes testing different techniques. In this section, these technologies are presented.

3.1. All-aluminum mirrors

The entire reflector of MAGIC I and more than half of the MAGIC II mirrors are made of a sandwich of two thin aluminum layers interspaced by an aluminum honeycomb structure that ensures rigidity, high temperature conductivity and low weight, as shown in Figure 1a.[4] The aluminum parts are interspaced with the 3M$^{\mathrm{TM}}$Scotch-Weld structural adhesive AF-163-2K specifically for aeronautic applications. The assembly is then sandwiched between spherical moulds and put in an autoclave, where a cycle of high temperature and pressure cures the structural glue. The reflective surface is then generated by precision diamond milling, which provides also high reflectivity. Depending on the facet position in the main dish slightly different focal lengths are machined to fit the overall parabolic shape on the MAGIC reflectors. The final roughness of the surface is around 4 nm and the average reflectivity 85%. The aluminum surface is protected by a thin layer of quartz (with some admixture of carbon) of around 100 nm thickness for protection against corrosion and acid rain, and is deposited by a plasma process of a few Torr pressure. Most of the reflected light of MAGIC I mirrors is focused within $0.5 - 1$ mrad corresponding to a PSF of 17 mm at the camera focal plane. For CTA, the technique will be further developed in order to provide *a*) mirrors of larger size, up to 1.9 m^2 and *b*) aspherical mirrors, as described above. Particular attention will be paid to simplifying the design and reducing costs.



(a) All-aluminum (b) Glass replica, INAF (c) Glass replica, CEA

Figure 1. (a) All-aluminum mirror. Two thin aluminum layers are sandwiched together with aeronautic glue, interspaced by a honeycomb layer. The surface is diamond-machined and quartz-protected. (b) Cold-slumped foam-glass mirror. (c) Plastic-foam core mirror. From top to bottom: a glass-fiber envelope (or a glass-sheet), a pre-formed foam block, resin, a second glass-sheet and the spherical mould.

3.2. Composite mirrors

Carbon fibre/epoxy based substrates have good meachanical properties and show the potential of fast and economical production in large quantities. The challenge is to produce mirrors with good surface qualities without labor-intesive polishing. This technique is under development at the Space Research Center and Institute of Nuclear Physics of the Polish Academy of Sciences (PAS).

Space Research Center, PAS, Warsaw The SRC investigates the sheet moulding compound (SMC) technology, in which a composite material (Menzolit®) is formed in a spherical steel mould at high pressures (100 bar) and high temperatures (180°C). Menzolit has a carbon fibre content of 60%, a Young's modulus of $20 - 50$ GPa (depending on fibre direction) and 0% shrinkage. The moulding process takes approximately 10 min. The whole mirror structure is made as a single part and of one material, with ribs formed on the rear to increase mechanical stability. The spherical surface is formed by an in-mould coating process (IMC) during the forming process of the structure itself. A sketch of such a composite mirror and the respective mould is shown in Figure 2a.

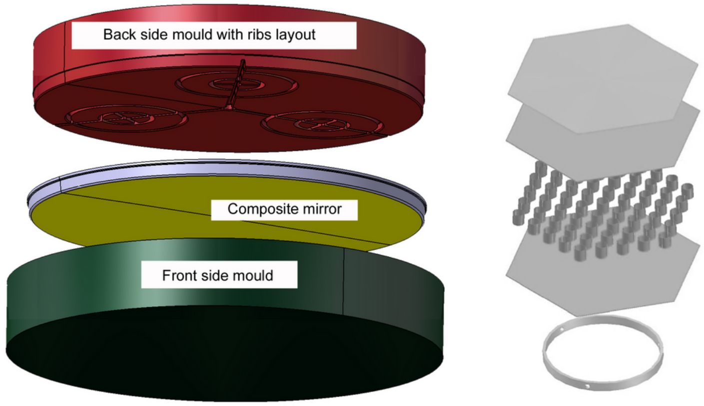
Institute of Nuclear Physics, PAS, Krakow The carbon fibre / epoxy sandwich structure under investigation are rigid sandwich structures, which consist of two flat composite panels separated by perforated tubes of equal length. In a second step a spherical epoxy layer is cast onto the front panel using a master surface. This process happens at room temperature and a few bars pressure, avoiding the need for extremes in temperature and pressure. The open sandwich structure enables good cooling and ventilation of the mirror panels and avoids trapping water inside the structure. The flatness and uniform thickness of the sandwich structure facilitates production, while the robustness of the structure ensures easy handling of the mirror. The technology also enables the gluing of thin float glass sheets onto the sandwich structure. A sketch of the proposed design is shown in Figure 2b.

3.3. Glass replica mirrors

The basic concept of this method is to form a thin sheet of glass on a high precision mould to the reuired shape of the mirror and glue a structural material and a second glass sheet or other material to its back to form a rigid sandwich structure. This concept is persued by two instituts (INAF Brera, Italy and CEA Saclay, France) for different types of structural material.

INAF Brera, Italy

Almost half of the reflector facets of MAGIC II are cold-slumped glass-aluminum sandwich mirrors.[6,7] A thin sheet of glass is cold-slumped on a high precision spherical mould. This glass sheet, an aluminum honeycomb and



(a) Composite SRC (b) Composite INP

Figure 2. (a) Composite mirror SRC. The front and rear side steel moulds are pressed against the composite which retains the shape. The surface (yellow part) need aluminization and coating (b) Composite mirror INP. From top to bottom: a spherical layer to be coated (cast on the front panel), the flat front panel, perforated tubes of uniform length interspacing front and rear panels, the flat rear panel and an example of mounting interface

a back sheet are then glued together with aeronautic glue. The shaped substrates are coated in the same way as traditional glass mirrors. For CTA R&D activities are going on to improve the process. In this regard, the possible use of FoamGlass® instead of Al honeycomb is being investigated, in order to avoid print through problems and increase the rigidity. This material has a low weight, $(0.1 - 0.165)$ g/cm^3, very low CTE $\simeq 9\,\mu$m K/m, it is water tight, can easily be machined, has high strength and is very competitively priced. A sketch of the mirror is shown in Figure 1b.

CEA Saclay, France

A similar method based on mould replication is being developed by the IRFU group at CEA (Saclay). A sandwich is formed by cold-slumping a glass sheet sheet on a high-precision mould and creating a sandwich using a resin layer, a pre-formed foam block and a glass-fiber envelope. The mirrors show very good geometrical properties; some test pieces are almost ready and will be tested soon at the HESS site. In addition, an hexagonal mould 1.2 m flat-to-flat is under design to accomplish with the CTA requirements. A sketch of the mirror is shown in Figure 1c.

4. REFLECTIVE AND PROTECTIVE COATING

4.1. Reflective coating

The need to have a good reflectance between 300 and 600 nm wavelengths makes aluminum the natural choice as reflective material. The adhesion and long-term durability of the reflective coating depends on the quality of the substrate cleaning and vacuum reached in the coating chamber. Compared to standard processes operating at approximately at 10^{-6} Torr and using a glow discharge before aluminization ultra-high vacuum (10^{-8} Torr) and electron beam cleaning might help to improve the quality by avoiding water deposition on the surface but has to be confronted with the resulting increase in overall cost. It is also planned to study new coating techniques, based on different thickness, deposition time and/or new materials, or the use of intermediate layers like chromium or SiO to increase the adhesion.[5] In addition purely dielectric coatings without any metalic layers and optimized for the required wavelength band are under investigation.

4.2. Protective coating

Current IACT mirrors are protected by vacuum deposited SiO_2 in the case of H.E.S.S., SiO_2 with carbon admixtures for MAGIC and Al_2O_3 obtained by anodizing the reflective Al layer in the case of VERITAS. The Max-Planck-Institut für Kernphysik, Heidelberg, in collaboration with the University of Tübingen and industrial partners is performing studies to enhance both the reflectance and the long-term durability of mirror surfaces. Coatings under investigation include: *a*) A "tropicalized" SiO_2 coating with the SiO_2 being applied in two steps with intermediate surface treatment to avoid pinholes appearing at the same position in both layers. *b*) Multilayer layer dielectric coatings of alternating layers of materials with low and high refractive index (e.g. SiO_2/HfO_2 or SiO_2/Y_2O_3) on top of the aluminization. Simple 3-layer designs are already able to increase the reflectance between 300 and 500 nm by 5%. *c* Purely dielectric coatings without any metallic layer avoiding the rather low adhesion of aluminum on glass. *d*) Hydrophobic coatings on top of the protective coating to reduce the adhesion of dust and dew formation. In addition, the possibility of using thin backside aluminized glass-sheets of high UV transmittance is under investigation. Such an approach would result in good protection of the reflective layer, the requirements for good transmission down to 300 nm combined with sufficiently low surface roughness, suitability for cold slumping, low solarization effects, minimized emissivity leading to reduced dew and ice formation on the mirror surface and availability in large sizes ($1-2$ m^2) at low thickness (≤ 1 mm) at reasonably low cost constitute quite some challenges and are currently under investigation in collaboration with leading glass producers.

5. SUMMARY

The demand for a few thousand mirrors with a total reflective area of up to 10,000 m^2 for CTA is a challenge in quite a few aspects such as: production of large size facets of up to 2 m^2 in area, low weight ($\simeq 20$ kg/m^2), high optical quality, easy and rapid series production and especially low costs. One of the major constraints is the requirement for a very low aging rate allowing at least 10 years of operation without recoating. Currently, quite a few options, nearly all based on sandwich concepts, are under study. The goal is to improve the performances substantially and lower the costs of the designs currently under investigation and to come to a final selection within the next 1 to 2 years.

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