Mirror Facet Technologies for the Telescopes of the CTA Observatory

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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 will comprise several tens of large Imaging Atmospheric Cherenkov Telescopes (IACTs) to be operated in array mode. The total reflective surface could be up to 10,000 m^2 requiring unprecedented technological efforts. The R&D status of lightweight, reliable and cost-effective mirror facets for the CTA telescope reflectors is reviewed. The properties of the reflector directly influence the telescope performance and thus constitute a fundamental ingredient to improve and maintain the sensitivity. Current activities, technical and optical requirements for the mirror facets and future prospects are hereafter presented and discussed.**

***Keywords*: IACT, CTA, mirrors.**

I. Introduction

In recent years, ground-based very-high energy gamma-ray astronomy has experienced a major breakthrough demonstrated by impressive astrophysical results obtained with IACTs like HESS, MAGIC or VERITAS [1]. The Cherenkov Telescope Array (CTA) project is being designed both to provide an expansion of the energy range down to a few tens of GeV and up to about 100 TeV and — most importantly — with at least 10 times increase in sensitivity compared to current installations. This can only be achieved by combining a) many telescopes operated in array-mode and b) using telescopes of different sizes. CTA is planned to comprise about a hundred telescopes of $2-3$ different sizes: several small size telescopes (SST) of 6 m diameter, several medium size telescopes (MST) of 12 m and few large size telescopes (LST) of 23 m diameter. However, the number of the telescopes, their size, their configuration and the overall performance are still under investigation and the final layout will come out after Monte Carlo optimization.

Individual telescopes will need reflectors of up to 400 m^2 area tessellated with many light-weight, robust and reliable mirror facets (hereafter mirrors) with adequate reflectance and focusing qualities but demanding very little maintenance. Nevertheless, 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. IACTs are not usually protected by domes and therefore the mirrors are permanently exposed to the environment. Current IACTs mostly use glass or aluminum mirrors, both requiring cost and labor intensive machining. The challenge for CTA is to develop low-cost mirrors of $1-2$ m^2 area with the potential for a high production rate. The technologies currently under investigation pursue different methods such as constructions based on carbon fiber/epoxy based substrates, sandwich concepts with cold-slumped surfaces made of thin float glass or thin aluminum sheets and different core materials like aluminum honeycomb, glass or plastic foams or sandwich structures made entirely from aluminum.

This paper has the following structure: in Section II the technical specifications for the mirrors and the reflective surface requirements are addressed. In Section III, the ongoing development of the different technologies for mirror prototypes by different institutes within the CTA consortium is presented. The paper concludes in Section IV with a short summary.

II. Mirror facet specifications

A. Mechanical specifications

Geometry. The geometry currently favored for the facets of the CTA telescopes is hexagonal in shape, with an increased panel size of $1-2$ m^2 area, well beyond the presently common size of $0.3 - 1$ m^2. Developments are ongoing.

Weight. The weight limit per facet could depend on their size and structure and on the characteristics of the telescope like the mirror alignment system and constraints due to the necessary handling/mounting of the facets. However, weight reduction is an important goal but should not come at the expense of optical quality, stability of the facets or a significant increase in price. For facet handling a total weight of less than 20 kg/m^2 would be desirable.

Rigidity. High rigidity of the mirror panels is a fundamental requirement. First of all, due to the movement of the telescope, 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. Secondly, the mirror should not deform during the estimated 10 years of operation. Thirdly, the facets should not vibrate when exposed to moderate winds (typically, IACTs can operate safely at up to 40 km/h wind speed).

Temperature range. IACTs are normally placed at altitudes of $1,000 - 3,000$ m a.s.l. where the daily temperature changes by several tens of degrees and rapid temperature drops are quite frequent. Mirrors should resist to temperature changes from $-15°$C to $+60°$C and the optical properties (i.e. the focal length) should not change significantly in the range $-10°$C to $+30°$C.

Sphericity. All current IACTs have mirror panels of spherical shape. This is the optimal solution for Davies-Cotton designs [2] and in general for telescopes with diameters below 12 m (SST and MST). However, in case of parabolic profiles, the discrepancy between the two principal radii of curvature for radial distances larger than 6 m becomes relevant, and therefore aspherical mirrors (with different radii of curvature in perpendicular directions), could be an optimal solution for the LST.

Focal length. The focal length depends on the size and design of the telescope. In case of Davies-Cotton designs or spherical profiles, all mirror facets have the same focal length (f). This is normally the best solution for the SST, still acceptable for the MST, and is used in most present installations. In case of a parabolic profile, the reflector can be approximated by not to large spherical mirrors of different focal lengths. Depending on the chosen focal length or the f/D ratio of the main reflector such a solution might be adopted for the LST. Such an approach depends also on the chosen focal length, respectively f/D of the main reflector and allowing for a small panel size.

B. Optical specifications of the facets

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 future CTA reflectors, i.e. the spot size of the reflected light in the focal plane, i.e. in the 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 mirror facets 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 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 mirror facets 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. 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.

C. 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. The test procedures are not finalized yet but will most probably incorporate the following: It is planned to measure the focal lengths at different wavelengths ($250 - 650$ nm) and versus temperature. The surface curvature will be scanned by a 3D measuring device with 1 micron precision. The rigidity will be tested by measuring the spot structure when loading the facets at different points. This test mimics the conditions of mirrors operated at different orientations and under wind pressure. The local reflectivity will be measured by fine-grid scanning the surface between 300 to 800 nm, because the mirror surface reflectivity can be quite inhomogeneous, particularly after protective coating. Measurement of surface micro-roughness will be performed before and after at least 500 thermal cycles and salt/sodium-hydroxide fog tests. From the surface roughness, the reflective properties can be estimated and fully characterize the optical performance of the mirror. The adhesion of the reflecting material and its protective coating will be tested by stripping normal office sticky tape from the surface. The water-tightness will be tested by immersing the mirror in warm water to a depth of at least 1 m. All sun-exposed plastic parts 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.

III. Preliminary review of current techniques for mirror facets

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

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^{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 implifying the design and reducing costs.

Composite mirrors

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. Space Research Centre. The SRC is investigating sheet moulding compound (SMC) technology, in which a composite material (Menzolit®) is formed over a spherical steel mould and then given a reflective coating. Menzolit has a carbon fibre content of 60%, a Young's modulus of $20 - 50$ GPa (depending on fibre direction) and 0% shrinkage. The manufacturing temperature is around 180°C at a pressure of 100 bar, with the moulding process taking 10 min. The whole mirror is made as a single part and of one material, with ribs formed on the rear to increase mechanical stability. A sketch of the composite mirror is shown in Figure 2a.

Institute of Nuclear Physics PAS. Here, a mirror is made in two steps. The first step is fabrication of a rigid sandwich structure, which consists of two flat composite panels separated by perforated tubes of equal length. The second step is the casting of a spherical layer onto the front panel using a master surface. The spherical layer is cast at room temperature and a few bars pressure, obviating the need for extremes of temperature and pressure. Next, the spherical layer will be coated using technologies developed by other groups. 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 facilitate production, while the robustness of the structure ensures easy handling of the mirror. The technology proposed also enables the gluing of thin float glass sheets onto the sandwich structure. A sketch of the proposed design is shown in Figure 2b.

Plastic foam core mirrors

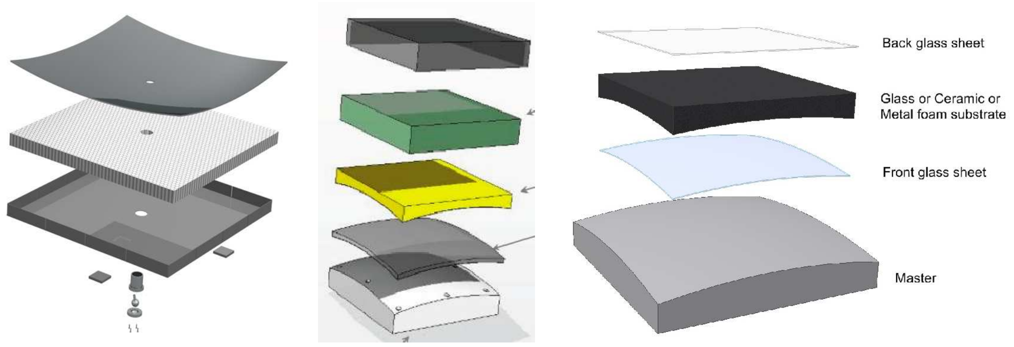
The IRFU group at CEA (Saclay) is developing samples of foam mirrors based on mould replication, as shown in Figure 1b. A sandwich is formed by a composite of a glass sheet, a resin layer, a pre-formed foam block and a glass-fiber envelope, all pressed against a curved metallic high-precision mould. 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.

Glass-replica mirrors

Almost half of the reflector facets of MAGIC II are made using a new concept: cold-slumped glass-aluminum sandwich mirrors [6], [7]. A thin sheet of glass is cold-slumped against a high precision spherical mould. This glass plate, an aluminum honeycomb and a back sheet are then glued together with aeronautic glue. Such mirror blanks are lightweight, reliable, cheap and can be produced quite fast. The shaped blanks are then aluminized under vacuum. For CTA, an R&D activity is going on aiming at improving 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 1c.

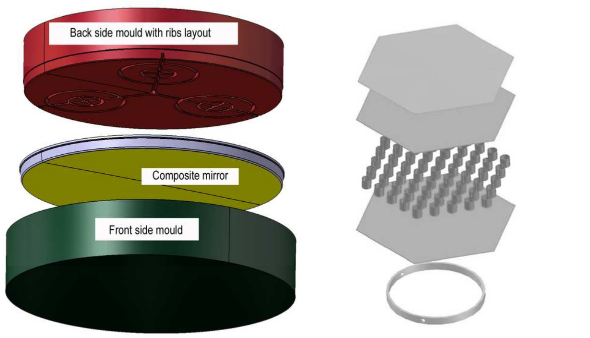
IV. Reflective and protective coating

Reflective coatings. 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



(a) All-aluminum (b) Plastic foam core (c) Slumping foam core

Fig. 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) 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. (c) Cold-slumped foam-glass mirror.



(a) Composite SRC (b) Composite INP

Fig. 2. (a) Composite mirror. 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 from 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

vacuum reached in the caoting 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].

Protective coatings. 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 in collaboration with the Univ. 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). Simple 3-layer designs are already able to increase the reflectance between 300 and 500 nm by 5%. c) Hydrophobic coatings on top of the protective coating to reduce the adhesion of dust and dew formation. In addition, the possibility of using thin back-side 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 ($\leq$ 1 mm) at reasonably low cost constitute quite some challenges and are currently under investigation in collaboration with leading glass producers.

V. SUMMARY

The demand for a few thousand mirror facets totalling about 10,000 m^2 in area for CTA is a major 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 low costs. One of the major constraints is the requirement for a very low aging rate allowing at least 10 years of operation without resurfacing. 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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