Light concentrator for LHAASO-WFCTA

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Abstract: In order to avoid loss of Cherenkov signal resulting from the dead area among photomultiplier tubes (PMT) and invalid fringe of each PMT, the compound parabolic light concentrator (CPLC) used as front window of PMT array is considered to improve detective efficiency. On the basis of the edge-ray principle and features of Wide Field Cherenkov Telescope of LHAASO, a CPLC, with 1.46 in concentration ratio and 15.6mm in length has been designed. Moreover, its optical performance by simulation is presented in this paper.

Keywords: light concentrator, Winston cone, WFCTA.

1 Introduction

Most modern Cherenkov telescopes, such as HESS, FACT, use non-imaging light concentrators, usually called "Winston cone", in front of the cameras which are composed of many pixelized photomultiplier tubes (PMT)[1, 2, 3]. The light concentrators help retrieving the loss of insensitive areas at the outer edges of PMT cathodes and dead areas result from spaces among neighboring PMTs due to their circular shape. Furthermore, the light concentrators also shield the cameras from stray light with large incidence angles.

It has been proved that the compound parabolic light concentrator (CPLC) comes very close to being an ideal concentrator comparing with a cone concentrator or a paraboloid of revolution concentrator[4] . The CPLC provides maximum concentration ratio and almost ideal angle-area tradeoff. It is constructed by overlapping two offset, truncated parabolic reflectors by applying the edge-ray principle.

Light concentrator requires that all rays entering at the extreme collecting angle θ_i shall emerge through the rim point of the exit aperture. Since it is well known that a parabolic shape with its axis parallel to the direction θ_i and its focus will do this, as shown in figure 1 , its focus must be at the rim point of the exit aperture. The complete concentrator must have an axis of symmetry if it is to be a 3D system, so the reflecting surface is obtained by rotating the parabola about the concentrator axis rather than about the axis of the parabola.

The symmetry of CPLC determines the overall length. The CPLC is defined by the input angle θ_i and the output radial size *a'*. The maximum length of the CPLC is:

$$L = \frac{a'(1+\sin\theta_i)\cos\theta_i}{\sin^2\theta_i} \quad (1)$$

All rays incident into the CPLC at angles less than the input angle will pass and rays beyond the collection angle are rejected. The focal length of the CPLC is:

$$f = a'(1+\sin\theta_i) \quad (2)$$

The radial size of the input aperture is:

$$a = \frac{a'}{\sin\theta_i} \quad (3)$$

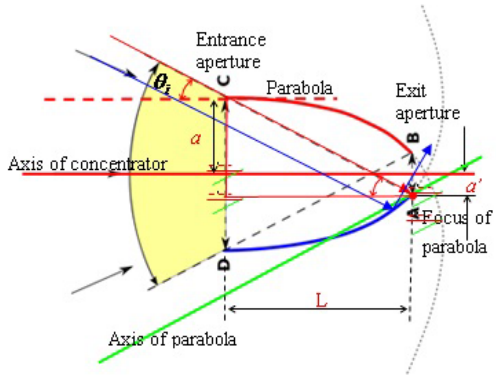

Fig. 1: Construction of the CPLC profile from the edge-ray principle.

In this case, the CPLC would have the maximum theoretical concentration ratio

$$C_{max} = (\frac{a}{a'})^2 = (\frac{n}{\sin\theta_i})^2 \quad (4)$$

where n is the refractive index of the material of solid CPLC. It may be 1(air) for hollow light concentrator or larger than 1 for dielectric solid light concentrator.

2 Design considerations

The wide field of view Cherenkov telescope array (WFCTA) is a major component of the Large High Altitude Air Shower Observatory project (LHAASO).The telescope is enclosed in a one third shipping container so that it is not only compactable but also an effective shield against dust and part of stray light. The optical system of WFCTA is a single spherical reflector segmented with 27 hexagonal concave mirrors. And the camera with 1024 pixels would be candidate PMTs of 25.4mm diameter, while their maximum sensitive diameter of the PMT cathode is 21mm shown as figure 2. The total invalid areas of a camera including insensitive areas of the PMT cathode and dead neighboring space among PMTs are more than 30%. Hence, measures must be taken to avoid loss of Cherenkov signal projecting on these areas. For WFCTA, we also apply the efficient compound parabolic light concentrator, just like HESS, FACT etc., but with different design considerations due to different requirements of telescope.

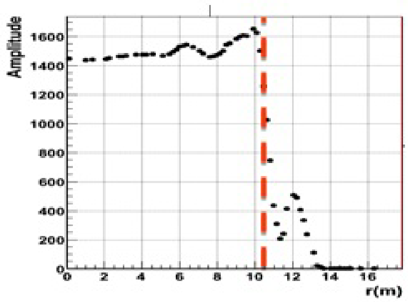

Fig. 2: PMT sensitivity as a function of the distance from the center of the PMT.

The telescope of WFCTA has a focal distance to diameter ratio f/D of 1.1 which implies a desired cutoff angle per pixel of approximately 25° that is the limit of input angle of CPLC. Assuming only less than 25° of the incident signal light can enter the CPLC, and the light collector is desired to reach the maximum collection efficiency, according to formula (1), the length of CPLC extends to 75.6mm and the maximum concentration ratio is 5.6. Under such a high concentration ratio, however, the diameter of the input aperture of CPLC is 49.6mm, nearly the double of the diameter of a PMT. That means the total area of the CPLC arrays is almost four times larger than the total area of PMT arrays. This is unreasonable for WFACT because the camera is located before the reflector and inevitably blocks some incident light. Hence, there is no longer any obstacle larger than area of the PMT arrays in the incident light path before the reflective mirror. Therefore, considerations for the optimization of the light concentrators of the WFCTA camera are:

- the output area of a CPLC coincides with the sensitive area of the PMT cathode;
- the angular cutoff guarantees all incident rays at angles less than 25° will pass;
- the total input area of CPLC arrays must not exceed the total areas of PMT arrays, and individual CPLC has a hexagonal shape so as to cover the focal plane with minimal structural losses;
- the CPLC inner surfaces must provide high reflectivity.

3 Simulation

To meet the above restrictions, we deliberately enlarge the collecting angle in original design in order to overcome the disadvantage of long length and large input aperture of CPLC. On the basis of ray-tracing simulations, a basic CPLC geometry with a circular input aperture of 12.7mm radius, a circular output aperture of 10.5mm radius, and a length of 15.6mm was adopted, shown as figure 3. Its output area is just keeping with the sensitive area of a PMT cathode while its input aperture is also same as the physical dimension of a PMT that will not cause additional shielding. However, a reasonable length and input area of CPLC is obtained by exchange of expanding the collecting angle. Fortunately, the whole system of a telescope of WFCTA is assembled in a container which walls can baffle stray light from outer environment. As a result, the large collecting angle of CPLC is practical in an enclosed telescope.

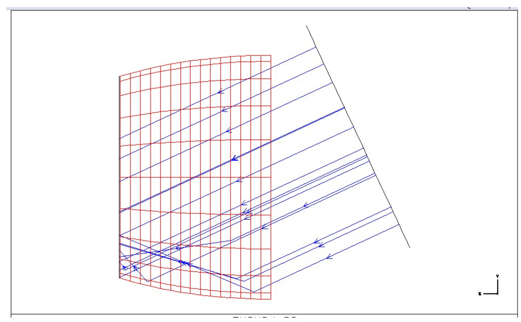

Fig. 3: A basic CPLC layout with input aperture of 12.7mm radius and output aperture of 10.5mm radius and a length of 15.6mm, the extreme collecting angle is 56° .

The concentration ratio of CPLC with 15.6mm in length is 1.46 which indicates additional 46% signal light can be concentrated on the sensitive area instead of invalid fringe of each PMT. The image of incident light at different angles passing through the CPLC is shown as figure 4. The diameter of spot is 21mm equivalent to the sensitive area of a PMT cathode.

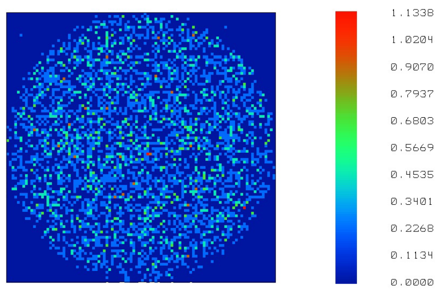

Fig. 4: The output image on detector for incident light at different angles .

The transmission properties of a CPLC are given by the transmission-angle curves. These curves of CPLC with a length of 75.6mm and 15.6mm are shown in figure 5. The CPLC of 75.6 millimeters-long exhibits a fairly sharp cutoff at about 25° , while the CPLC of 15.6 millimeters-long at about 56° .They both approach very closely the ideal rectangular cutoff that a concentrator with maximum theoretical concentration ratio should have. Although the CPLC with a length of 15.6mm allows more rays of wide angle to pass, within the range from 0° to 25° , both CPLCs have no difference on collection efficiency.

In addition, the input area of a CPLC should be a hexagonal shape in order to cover the focal plane with minimal losses. For parabolic walls of Winston cone, no difference in the transmission-angle curves can be detected between cones with circular input and output area and other shapes, such as hexagonal area if they have same concentration

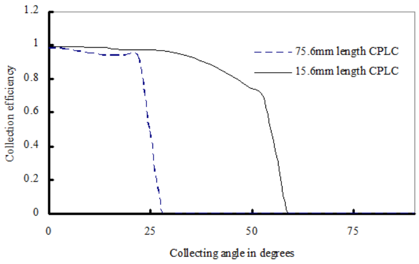

Fig. 5: Transmission-angle curve for CPLCs with different length .

factor[2] . Therefore, the principal parameters of the CPLC coinciding to the needs of WFCTA and its properties of concentration are settled.

Moreover, our CPLC is the hollow cone design, just like classical Winston cone, which has the advantages of being a very practical layout, minimum material absorption loss and easy to make for all wavelengths, since it depends on reflection rather than refraction, and not requiring any extreme material properties.

As the verification and test, a simple light concentrator is made of aluminum foil with a thickness of 1mm. For the convenience of making, the light concentrator only has flat walls and hexagonal entrance and exit (Figure 6). Its collection efficiency was tested by using photomultiplier black-box testing system. And testing results show that the collection of light signal is increased obviously even using light cone with plane surface.

Fig. 6: The photomultiplier black-box testing system and insertion is a simple light cone made of aluminum foil.

4 Optical crosstalk

There is phenomenon of optical crosstalk between neighboring pixels, in which light belong to one pixel could enter another one and be detected by wrong pixel. The causes of this error may be walls of CPLC and optical aberrations.

Due to light concentrator arrays are placed in the focal plane position, all rays coming from reflector enter the light concentrator at converged beams and incident aperture angle is less than 25° . Hence, as angle resolution of 0.5° , each light concentrator receives its own converged beams. Only those beams projecting between adjacent centers of light concentrator could be split into two parts. Obviously, the intensity of light split is not strong and the angle resolution of these images is less than 0.5° , as a result, it has little impact.

Another reason of optical crosstalk is caused by optical aberrations which is independent of light concentrator. For wide field of view telescope, the aberrations inevitably become worse with the increasing of field of view. For incident light with large angle, their image spot will deviate from the chief ray so that some of rays hit the adjacent pixels and be detected by neighboring PMT. But according to the simulation results of optical design, the maximum deviation is about 20% for 7° in field of view which will not change the trace of spots.

5 Summary and outlook

Light concentrators are considered for candidate PMT applications of WFCTA in LHAASO, increasing the effective area of camera. The light concentrator should be hollow cone which walls adopt compound parabolic structure and inner surfaces have high reflectivity, in addition, a hexagonal area is used to input and output aperture. The next steps relating to the CPLC are being studied, such as:

- The fabrication method and techniques should be considered not only for function of concentrating light, but also mass production and low cost. Compression molding is the preferred making method and inner sides of the CPLC are coated with aluminums.
- Easy installation, accurate and stable fixation is also important. Combined with the structure of focal plane, complete the installation design of the CPLC arrays.
- A prototype of the CPLC is scheduled to produce and test, which then guides well the scheme improvement.

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