Hartmann test of the COMPASS RICH-1 optical telescopes

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The central region of COMPASS RICH-1 has been equipped with a new photon detection system based on MultiAnode PhotoMultiplier Tubes (MAPMT). The Cherenkov photons are focused by an array of 576 fused silica telescopes onto 576 MAPMTs. The quality and positioning of all optical components have been tested by Hartmann method. The validation procedures are described. The quality of the optical concentrators was checked and alignment corrections were made. The upgraded detector showed excellent performances during 2006 data taking.

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1 Introduction

The new central part of the COMPASS RICH-1 [1, 2] photon detection system consists of 576 MultiAnodes PhotoMultiplier Tubes (HAMAMATSU H6568, 4 × 4 pixels per PMT with UV extended glass entrance window). Each MAPMT is coupled to an individual telescope focusing the Cherenkov photons onto active array of the PMTs [3]. For all telescopes, planoconvex field lenses have a 5 ° wedge due a spatial limitations. Biconvex condensor lenses have one aspherical surface [3], see Fig. 1.

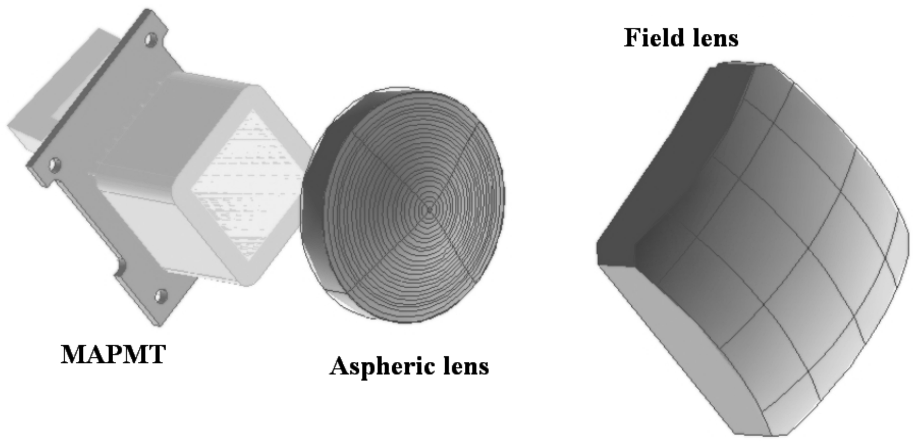

Fig. 1. A MAPMT coupled to a fused silica optical telescope.

Field lenses (SILO; Florence, Italy) are glued onto a 4 aluminum frames (each housing -12 × 12 lenses). Aspheric lenses (ASPHERICON; Jena, Germany) and the PMTs are mounted in soft iron holders. These holders are fixed to the 4 dedicated aluminum frames (each housing 12 × 12 holders). The assembly of the both frames (field lens frame and frame with holders) forms 1/4 of the 576 telescopes.

The most critical parameter is the precise positioning of the lenses especially the aspheric one. The tolerances are in the order of 0.1 mm for the decenter and 0.05 ° for the tilt of the lenses. The irregularities of the surface are less relevant for the condensor optics (order of 3 fringes).

The prototypes of the lenses have been tested by interferometric methods at the Optical Development Workshop of the CAS (Turnov, Czech Rep.). All optical components and the assembled telescopes have been validated by Hartmann method using dedicated setups. This approach offers several advantages: we needed a measurement procedure that allows us fast, real time and precise result even for aspherical surfaces.

2 Experimental setup of the Hartmann sensor

The Hartmann test [4–6] provides a fast, portable and low cost method of wavefront measurement. A dedicated testing device was developed. A blue LED powered by a stabilized power source is used as a "small point" light source. A parallel light beam is created by a telephoto objective; the beam crosses the Hartmann plate, which consists of an opaque plate with a grid of circular holes. The grid of the holes has been optimized for each test exercise. A wavefront of light is sampled into as many spots as the number of holes in the plate, see Fig. 2. A CCD camera detects the spot positions. Any aberrated wavefront causes the spot displacement from the reference position, see Fig. 3. If the displacements of the spots centroids are known, the deviation of the aberrated wavefront from the reference one could be calculated.

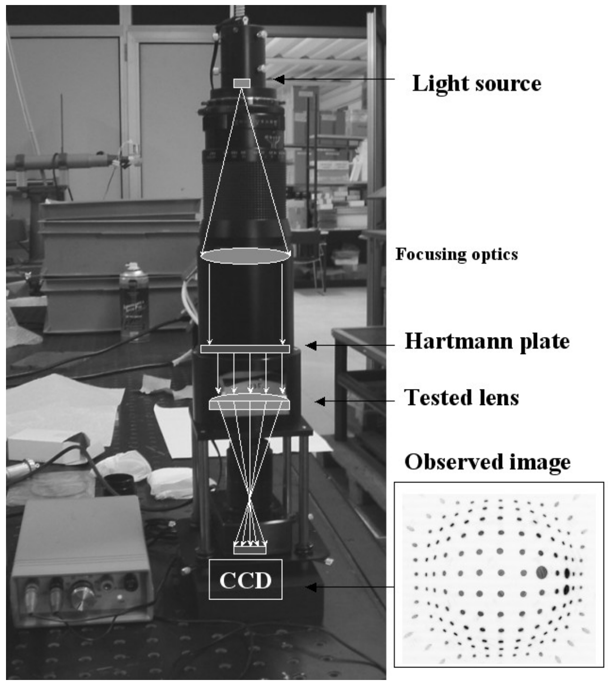

Fig. 2. The principle of the Hartmann test; testing apparatus.

3 Results

The quality and alignment of each lenses and all telescopes has been measured and wavefront distortion has been characterized. One of the common used ways is to describe wavefront approximates by a set of orthogonal polynomials. A very convenient set of possible orthogonal function is the set of Zernike polynomials Z_k(x,y), because the most frequent aberration can be expressed by low order Zernike polynomials [7–9]. Each polynomial is related to a specific aberration (tilt, coma, astigmatism, etc.).

A simulation results obtained using the ZEMAX commercial package has been used as reference. All the real lenses have been compared with the ideal lens placed in the ideal position. The resolution of the Hartmann test is limited by the fact that each aperture measures the average tilt of the wavefront at the hole location. Small-localized defects are not detected if the apertures of the Hartmann plate do not cover them. However all lenses have been visually inspected before testing.

Wavefront deformation (Wx, y) can be expressed by this equation

$$W(x,y) = \Phi_W \Phi_{Wref} = \sum_{k=0}^{\infty} C_k Z_k(x,y)$$

Where ϕ_w is the aberrated wavefront ; ϕ_{Wref} is the reference wavefront; Z_k(x, y) are Zernike polynomials and C_k corresponding Zernike coefficients. Coefficients C_k evaluating corresponding aberration can be obtained by solving the following equation $(\Delta x_i, \Delta y_i)$ is the displacement of the i-th spot from the reference one, see Fig. 3.):

$$(\text{const.}) \begin{pmatrix} \Delta x_0 \\ \Delta y_0 \\ \vdots \\ \Delta x_k \\ \Delta y_k \\ \vdots \\ \Delta x_{N-1} \\ \Delta y_{N-1} \end{pmatrix} = \begin{pmatrix} \frac{dZ_0}{dx}\big|_0 & \frac{dZ_1}{dx}\big|_0 & \cdots & \frac{dZ_{M-1}}{dx}\big|_0 \\ \vdots & \vdots & \vdots & \vdots \\ \frac{dZ_0}{dy}\big|_0 & \frac{dZ_1}{dy}\big|_0 & \cdots & \frac{dZ_{M-1}}{dy}\big|_0 \\ \frac{dZ_0}{dx}\big|_i & \frac{dZ_1}{dx}\big|_i & \cdots & \frac{dZ_{M-1}}{dx}\big|_i \\ \frac{dZ_0}{dy}\big|_i & \frac{dZ_1}{dy}\big|_i & \cdots & \frac{dZ_{M-1}}{dy}\big|_i \\ \vdots & \vdots & \vdots & \vdots \\ \frac{dZ_{-1}}{dx}\big|_{N-1} & \frac{dZ_{-1}}{dx}\big|_{N-1} & \cdots & \frac{dZ_{M-1}}{dx}\big|_0 \\ \frac{dZ_{-1}}{dy}\big|_{N-1} & \frac{dZ_{-1}}{dy}\big|_{N-1} & \cdots & \frac{dZ_{M-1}}{dy}\big|_0 \end{pmatrix} \cdot \begin{pmatrix} C_0 \\ C_1 \\ \vdots \\ C_k \\ \vdots \\ C_{M-2} \\ C_{M-1} \end{pmatrix}$$

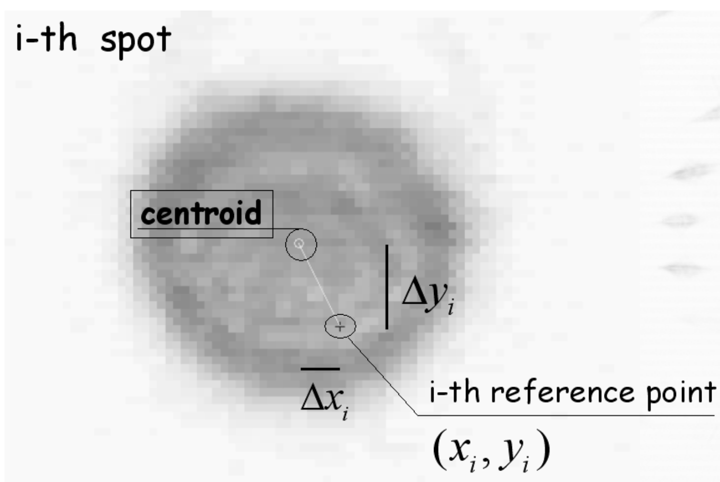

Fig. 3. The displacement of the i-th spot from the reference.

Routines for wavefront deformation calculation have been developed. These routines use as reference a theoretical lens simulated with ZEMAX and also a real reference a prototype lens precisely tested by interferometric methods. These algorithms, based on singular value decomposition, give information about the quality and the position of the tested lens.

The test procedure consists of 4 measurements. The quality of each individual field lens has been tested. 690 field lenses have been quality controlled; we have chosen 576 lenses and glued them onto the 4 frames (4×144 lenses). The quality of their position has also been tested. In this case our testing device is divided into two parts, one with light source and Hartmann plate and the second one with CCD camera. Both parts are fixed to the tool holder of a milling machine. The frame with glued field lenses is fixed to the table of the milling machine. This arrangement allows us to move the testing device with micrometric precision, see Fig. 4. Aspheric lenses have been mounted in their soft iron holders and tested. If these lenses were within tolerances, their holders were fixed with glue and mounted onto the frame (in total 4 frames $\times 144$ aspheric lens holders). After assembling both frames together, a set of 144 telescopes was created. It has been necessary to test each individual telescope (again using the milling machine setup). 26 telescopes exceeded our tolerances and have been corrected by inclining the lens holder with the aspheric lens.

Fig. 4. Measurement of the field lens frame and whole telescopes. The milling machine setup.

4 Conclusion

Testing procedures for the quality control and validation of the optical concentrators of the new COMPASS RICH-1 photon detection system have been developed and implemented in a period of one and a half year. In total we have quality controlled 690 individual field lenses, quality and position controlled the 617 individual aspheric lenses and, position checked the 576 glued field lenses. Also all 576 telescopes have been tested and 26 of them have been corrected to obtain final optical properties within desired tolerances. About 70 % of the telescopes exhibit a shift of the image in the plane of the detectors bellows 50 μm, 20 % bellow 100 μm, 10 % bellow 150 μm, to be compared with the PMT pixel size, which is of $4 \times 4\,\mathrm{mm}^2$ with a gap between pixels of 0.1 mm. Even better achievements could be obtained if a more refined, but extremely time consuming, telescope correction would have been implemented. The results obtained cause a displacement of -less then 5 % of the photons hits to a neighboring pixel. The COMPASS experiment started data taking in July 2006 and the first feedback indicates excellent performance of the new photon detection system of the RICH-1 detector.

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