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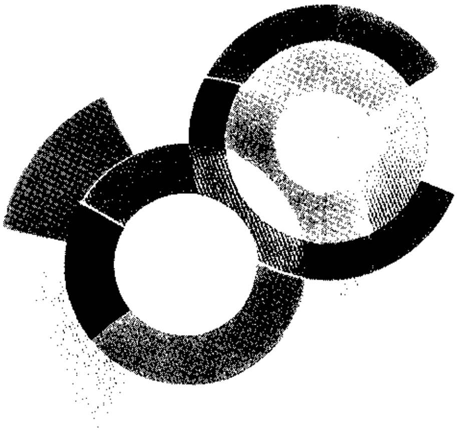

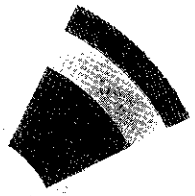

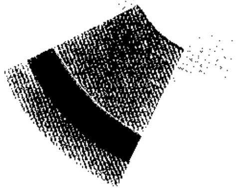

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DEVELOPMENT OF A TRANSPARENT OPTICAL TELESCOPE FOR THE ABSOLUTE POSITIONING WITH RESPECT TO A REFERENCE LASER BEAM

**J.-Ch. Barrière, O. Cloué, C. Guyot, P. Ponsot,
J.-C. Saudemont , J.-P. Schuller, Ph. Schune, S. Sube**

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Département d'**A**strophysique, de Physique des **P**articules, de Physique **N**ucléaire et de l'**I**nstrumentation **A**ssociée
CEA/Saclay F-91191 Gif-sur-Yvette Cédex

Couverture Sylvie Cabrit et Marc Sauvage

Development of a Transparent Optical Telescope for the Absolute Positioning with respect to a Reference Laser Beam

J.-Ch. Barrière, O. Cloué, C. Guyot, P. Ponsot, J.-C. Saudemont,
J.-P. Schuller, Ph. Schune, S. Sube

CEA Saclay, DSM/DAPNIA, F-91191 Gif sur Yvette Cedex, France

ABSTRACT

We have developed an optical system which permits the absolute positioning of an element with respect to a reference laser beam. The resolution is of the order of 10 µm in translation and 50 µrad in rotation. It is highly transparent (>90%) permitting several elements to be aligned. A calibration procedure has also been studied in order to be independent of internal deformations.

Keywords: alignment, CCD, transparent position sensor, absolute positioning, pigtail laser

1. INTRODUCTION

A new optical sensor has been developed[1] for the alignment of the muon chambers of the ATLAS[2] experiment (a). The momentum measurement in the ATLAS muon spectrometer aims at a precision of the order of 10% for muons of momentum 1 TeV. It proceeds from a sagitta measurement using triplets of precision chambers with a mean inter chamber distance of 5 meters. The target degree of accuracy for the precision chamber alignment is such that the alignment contribution to the final sagitta measurement error stays below the intrinsic chamber measurement error which contributes at a level of 50 µm.

In the alignment scheme foreseen for the end-cap chambers[2], a reference set of 3 to 4 carbon fibre bars are connected by several laser beams. The relative positioning of the bars is done via a laser beam and transparent telescope precisely mounted on the bars.

The optical alignment sensor useful area should be typically 30x30 mm^2 combined with a transparency above 90% and with a resolution ~10 µm in translation and below 50 µrad in rotation. Up to 180 optical systems with these requirements are foreseen in the end-cap system. An other requirement concerns the price of such a unit which should not exceed € 400.

Finally, the accelerator environment imposes that the system tolerates high particle fluence and dose rates[3].

For further author information
Ph.S. (correspondence): e-mail: schune@hep.saclay.cea.fr; Telephone: +33 1 6908 7061; Fax: +33 1 6908 6428
J.-Ch.B.: e-mail: barriere@hep.saclay.cea.fr
O.C.: e-mail: cloue@dapnia.cea.fr
C.G.: e-mail: guyot@hep.saclay.cea.fr
J.-P.S.: e-mail schuller@hep.saclay.cea.fr

(a) ATLAS is an LHC (Large Hadron Collider) experiment, located at CERN (European Laboratory for Particle Physics), CH - 1211 Geneva 23, Switzerland.

2. PRINCIPLE OF OPERATION OF ONE OPTICAL TELESCOPE

2.1 Principle

Our optical sensor, called STAMP for Saclay Telescope for the Alignment of Many Points, allows the accurate positioning transversally with respect to a laser beam used as a reference (or equivalently, provides the laser beam position and direction with respect to a reference frame attached to the sensor).

The laser beam is created by a mono-mode pig-tail diode laser at a wavelength of 680 nm. The chosen wavelength is not an issue, but it is strongly desired that it be visible, for simplicity of operation and for safety reasons. The output beam diameter should not exceed 5 mm at distances up to 15 meters (the maximum chamber distance from the laser). Its profile follows a TEM_{00} gaussian law. Finally the output power needed must be less than 1mW (see 3.3).

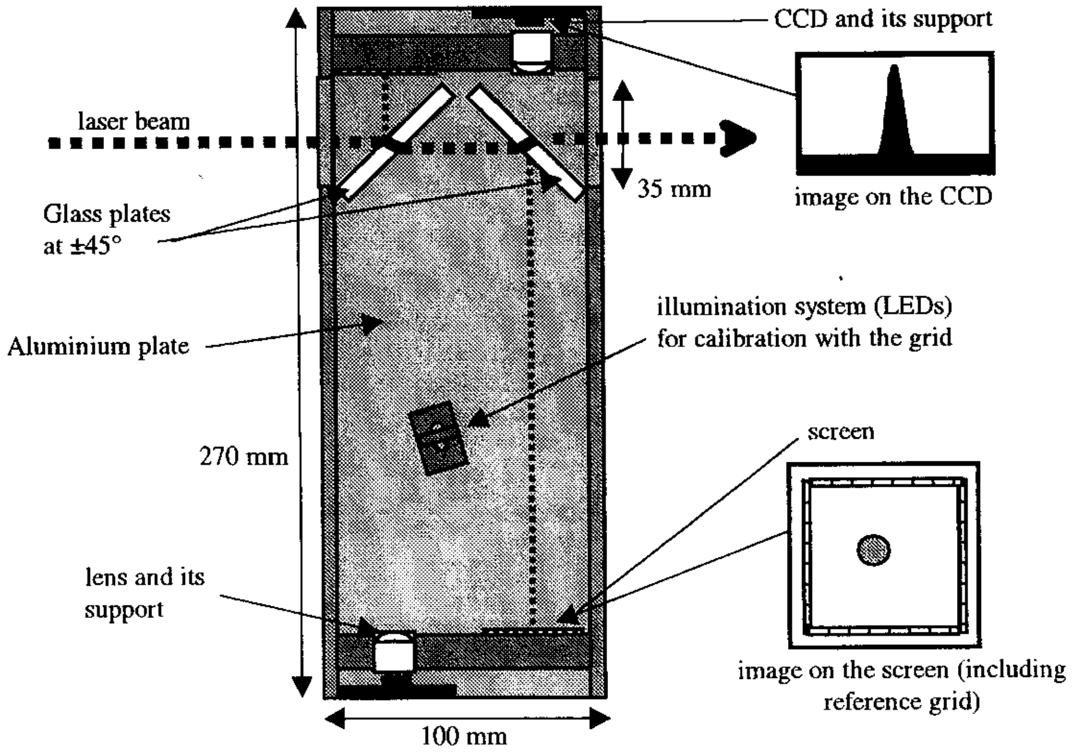

Figure 1: Sketch of a STAMP showing the two arms. The three-points kinematic mount are under the aluminium plate (see Sections 3 and 4). The role of the reference grid is explain in Section 4.

A STAMP is composed of two arms mounted on the same aluminium plate (see Fig. 1 and 2). The first arm consists of a glass window at +45°. This allows to pick up and project a fraction (4%) of the laser beam to a screen seen by a CCD via a lens operating with a (de)magnification g of the order of 1/10. This magnification is necessary since the range of the displacements is 30 mm and for typical inexpensive CCDs the active surface is only ~3x4 mm^2.

The second arm, head to foot with respect to the first one, works on the same principle with the remaining light: another glass window at –45° projects a fraction of the laser beam to a screen, seen with a magnification of 1/10 by a second CCD.

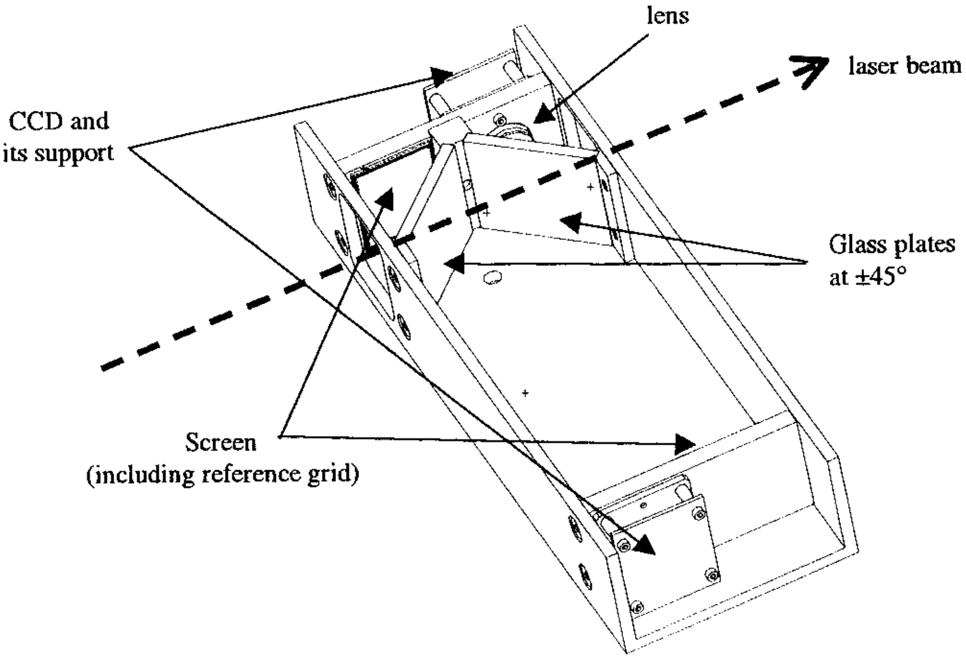

Figure 2: 3D view of a STAMP. The LED system for the calibration is not shown on this view.

The beam spot on each CCD is recorded and fitted, after the separate summation of all rows and all columns, by a gaussian law for each projection (see Fig. 3).

2.2 Reconstruction of the laser beam position and direction

Using the information from both CCDs allows us to reconstruct the beam with respect to the STAMP transverse position. Assuming a resolution Δd on each CCD, the resolution on the laser spot barycenter is $\Delta d/(\sqrt{2}g)$. The two beam angles with respect to the STAMP reference frame are also accessible to our system because the measurement position from each arm (i.e. the screen position) is different. The angular resolution is simply: $\Delta\theta = \sqrt{2}\Delta d/(gL)$, where L is the distance between the mirror images of the two screens with respect to the reflecting plane of the glass plates. With $\Delta d \sim 1$ µm and $g \sim 0.1$ the resolution in translation is below 10 µm. Thus, a distance $L \sim 20$ cm is needed in order to have an angular resolution below 50 µrad.

Thanks to the high transparency of each system, the positioning of further STAMPs along the same laser beam is possible.

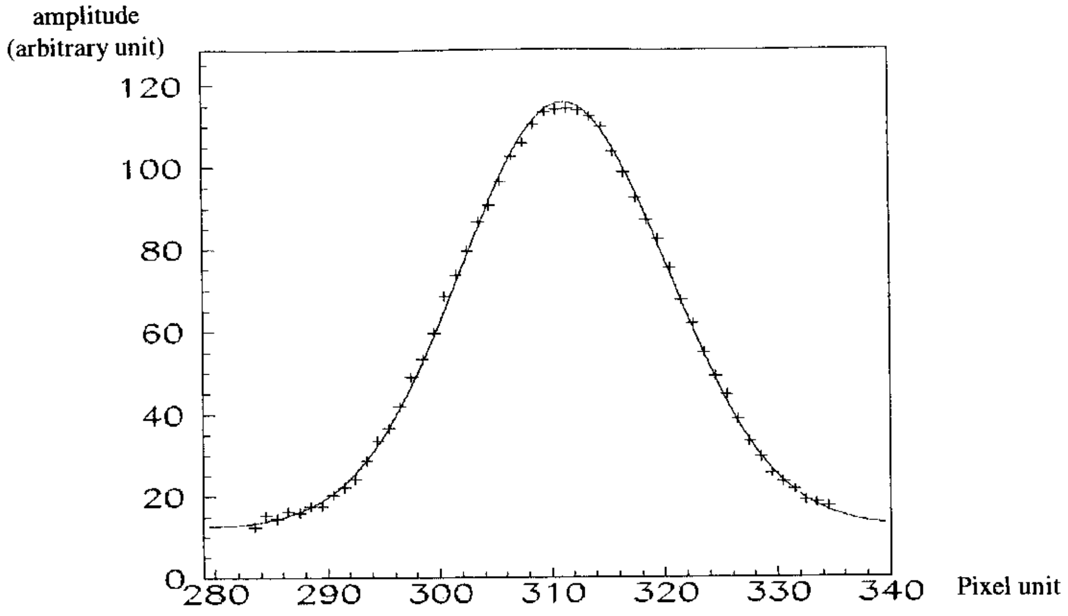

Figure 3: Example of a laser spot reconstruction (solid line) summing of the pixel rows of the CCD (crosses). The pixel receiving the maximum of light has an ADC value around 200 ADC count.

3. REQUIREMENTS ON OPTICAL, MECHANICAL AND CCD ELEMENTS

3.1 Optical elements

There are strong requirements on each element in order to reach the expected resolution (<10 µm on each arm) and the required transparency without distortion of the laser beam in case of multiple element alignment.

For high transparency and parasitic image attenuation, an antireflective coating on the exit of the window is optimised for a wavelength of 680 nm. To avoid distortion of the beam, the glass window must have a flatness tolerance of $\lambda/10$ with a wedge angle as small as possible. Since windows will be used in pairs (one per arm) with angles of ±45°, the angular deflection cancels completely if we can use pairs of windows, cut from a single plate, with the same parallelism. Then the required tolerance is only ~2 arc minutes. Standard surface quality for laser application are required (60–40 scratch and dig or better).

For the lens, the requirements are the following: centration of ~3 arc minutes and a focal length precision of ±2% for the mounting on the system. To avoid a speckle pattern on the CCD, the lens diaphragm diameter is ~ 4 mm for a focal length of 20 mm. A larger aperture may lead to uncontrolled aberrations with a singlet lens.

3.2 Mechanics

To avoid a too big deformation due to temperature variations in the experimental hall (typically ±2°) or during installation, the length of the aluminium plate supporting all the equipment should be as small as possible. Also, the available space in the experiment for each telescope is small. The present overall length of our prototype is about 27 cm and the distance between the screen and the CCD's pixel plane is about 22 cm (this fixed the focal length of the lenses to be 20 mm).

A three-point kinematic mount is used for supporting the plate. It will be helpful for the absolute calibration.

3.3 CCD

For the prototype development phase, we have used video CCDs associated with a 8 bit frame-grabber. With a 1mW pig-tail laser, the laser spot gives up to 200 ADC counts on the CCD, while the dark-current level is about 10 ADC counts. Thus, the contrast is good enough for fitting the spot position with the required precision (~ 1 µm on the CCD).

To avoid interference between the pixel frequency (~9.5 MHz) and the sampling frequency (aliasing) we have used a low-pass Butterworth third order filter. Then, we digitise the signal at ~14.7 MHz, well above the chosen cut-off frequency *fc*. The latter, $fc \approx 3$ MHz, is about one third of the pixel frequency but ten times above the gaussian signal bandwidth in order to avoid phase shift.

4. AN OPTICAL REFERENCE: THE GRID

4.1 Grid characteristics and function

In order to achieve an absolute positioning (see section 6) and also to be independent of the stability (below 1 µm) for the lens–CCD system, an optical reference has been added on the screen.

This optical reference is made of a photo-lithographic fishbone grid deposit all around the 40x40 mm^2 screen (see Fig. 1 and 4). It has a fixed pitch of 1000 µm and a line width of 250 µm. The resolution on the drawing with this technique is better than 0.5 µm.

In standard running conditions, we will alternate laser spot measurement and grid illumination using a LED (for the grid reconstruction algorithm, see 4.2). This grid plays different roles:

- the laser spot reconstruction will be done with respect to the grid position independently of the CCD position,
- we can calibrate distortion/aberration of the lens (the grid is regular all around the screen),
- it can be used to calibrate out the imperfect positioning of the optical element (see Section 6),
- in case of CCD failure, since the screen (including the grid) stays in position, one can replace a CCD without re-calibrating the STAMP.

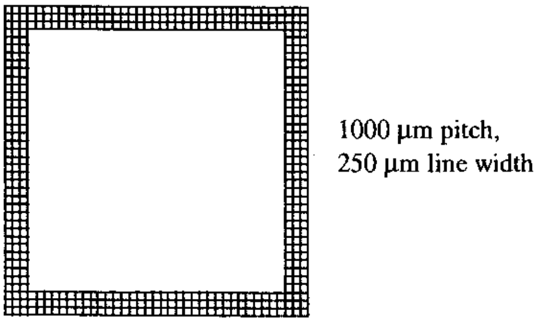

Figure 4: View of the photo-lithographic fishbone grid deposit all around the screen. The external grid dimensions are about 40x40 mm^2. The useful screen area for the laser spot reconstruction is the inner part of the grid.

4.2 Grid reconstruction on the CCD

We have developed a simple algorithm in order to reconstruct the grid parameters on the CCD. By searching minima along lines and columns of the pixel array, we can reconstruct the grid segments. Combining these segments allows us to determine the crossing points in horizontal and vertical pixel units. By performing a χ^2 minimisation on all these crossing positions (~300) and using only the grid pitch information, we fit:

- i) the magnification *g*,
- ii) the grid position and angle with respect to the CCD axes,
- iii) 5 parameters describing the distortion of the lens (9 parameters in total).

To check the consistency of such a fit, we have reconstructed a full square grid (see Fig. 5) on the screen (with the same pitch: 1 mm), fitting these parameters using all the crossing positions or only the border ones. The results are compatible for both fits at a precision level of 3 μm on the screen.

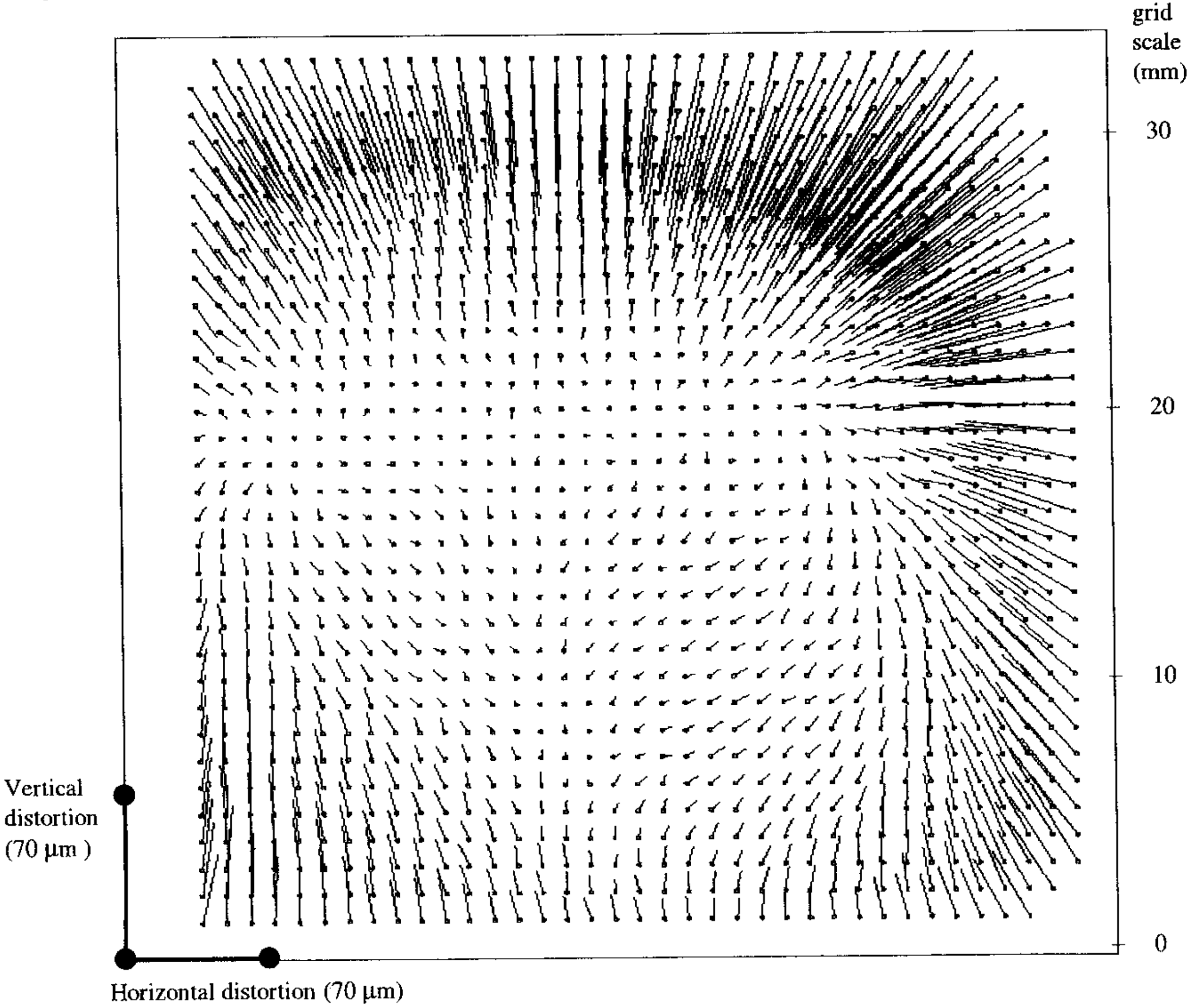

Figure 5: Calculated distortions, on the screen, using the reconstructed grid on the CCD: the length of each line (horizontally and vertically) gives the amplitude of the distortion at each crossing positions (dots). The precision at each crossing positions is below 3 μm. The pattern of the distortion can be precisely (2 μm r.m.s.) fitted by 5 parameters (see text).

5. EXPERIMENTAL SET-UP AND RESULTS

5.1 Stability

Every minute, during one day, a laser spot from a pig-tail laser diode has been reconstructed on a STAMP at a distance of 20 cm. In this way, the laser pointing and reconstruction stability can be evaluated: on each CCD, the r.m.s. resolution is below 1% of a pixel, which gives a stability on the screen below 1 μm.

5.2 Resolution when moving the laser

For this test, the laser has been positioned on two perpendicular micro-metric stages. The laser has been displaced in a plane perpendicular to the STAMP at different known positions over a range of ±15 mm. By fitting each reconstructed position on one CCD and by using the laser positions we obtained a resolution on the screen below 10 μm r.m.s. (see Fig. 6). This resolution is corrected for the lens distortion and for the laser's yaw coming from the stages (controlled by an auto-collimator with a resolution of 2 arc-second).

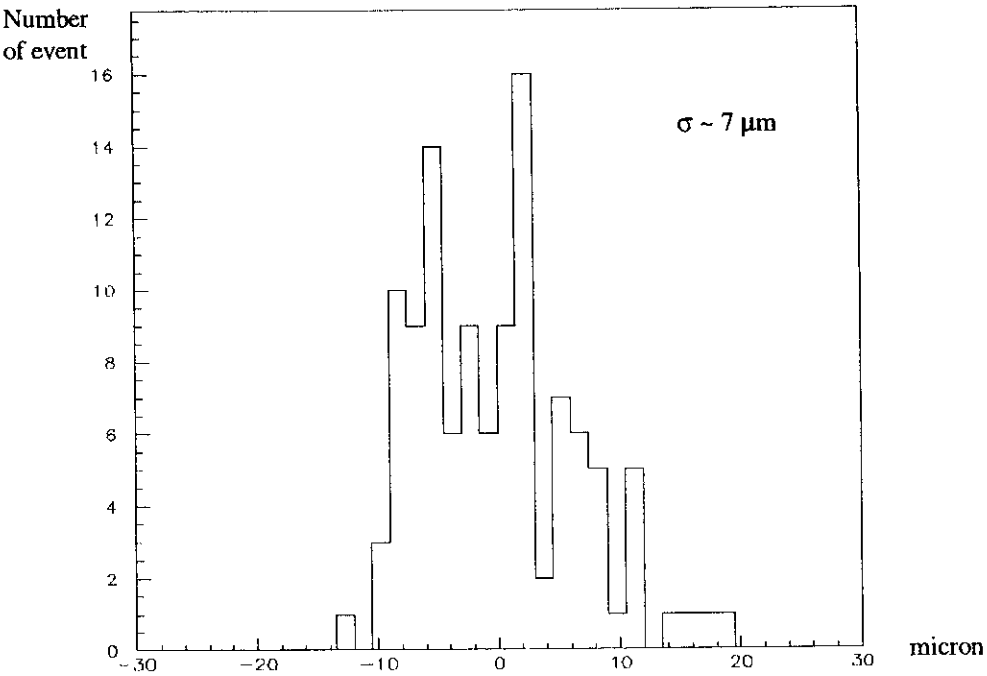

Figure 6: Reconstructed relative position from one CCD on the STAMP compared to the laser positions from the two perpendicular micro-metric stages. The resolution is below 10 μm.

5.3 Influence of one STAMP on the following one

A test bench consisting of three STAMPs (see Fig. 7) has been used for testing the influence on the spot deflection due to the displacement of one STAMP with respect to the following one. The first STAMP is fixed and controls the laser pointing stability during the acquisition. The middle one which is moveable deflects the laser due to the induce rotation of its two glass windows. Its relative position is measured by six mechanical probes with a resolution below 2 μm. The last

STAMP is fixed and measures the deflection of the laser beam coming from the middle one. The distance between two STAMP is 1 meter.

We have compared the displacements of the middle STAMP over ±4 mm and ±20 mrad, measured by the mechanical probes and by the STAMP itself. For translations the resolution is below 3 μm r.m.s. and for rotations the resolution is below 20 μrad r.m.s. .

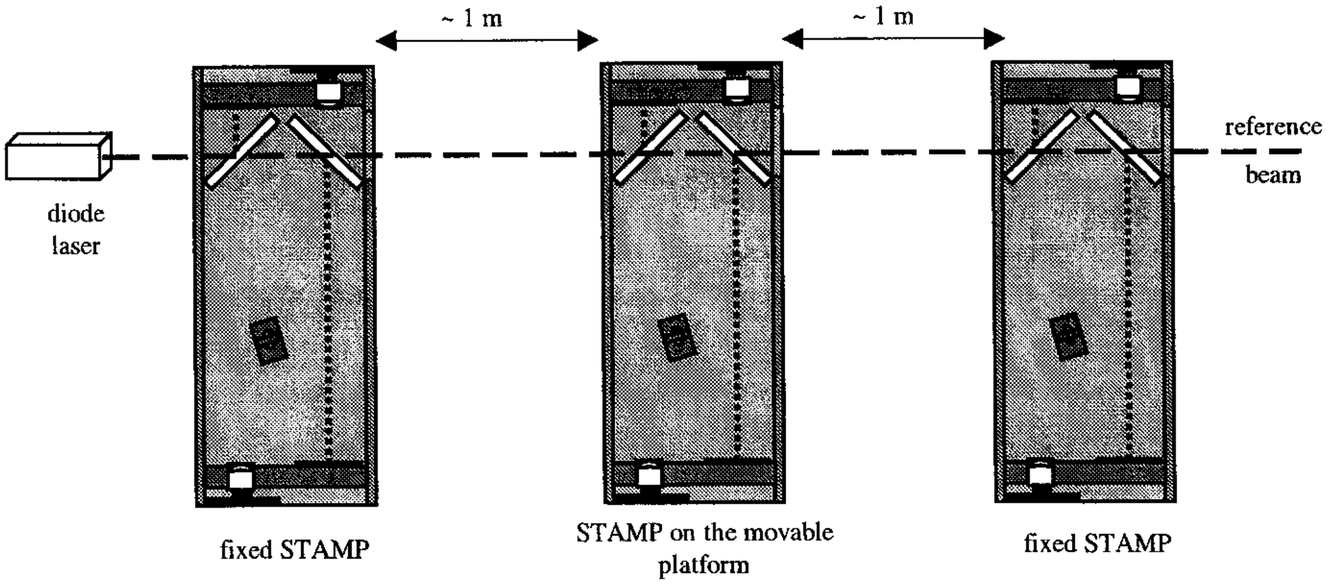

Figure 7: Test bench with the three STAMP: the first STAMP controls the laser pointing, the middle one is moveable and deflects the laser and the last STAMP measures the deflection of the laser beam coming from the middle one.

The laser spot displacement on the last STAMP is measured with a resolution of 4 μm r.m.s. .

6. ABSOLUTE ALIGNMENT PROCEDURE

The goal of the absolute alignment procedure is to provide the spot barycenter reconstruction with respect to an external mechanical reference fixed to the STAMP. Again the photo-lithographic grid will be useful.

Fig. 8 shows the set-up for such a calibration. An external CCD records alternatively each grid, illuminated uniformly by an external light source, of a STAMP to be calibrated (using two different lenses). A complete photo-lithographic grid precisely fixed on an external support is taken as a reference. This support has known dimensions and positions with a precision of few microns with respect to the balls supporting the STAMP (not shown).

We compare the reconstructed position of each grid of the STAMP with respect to the reference grid placed at the two reference positions (see Fig. 8 for the 2nd reference position). In this way, each sub-system grid/glass window will also be positioned/oriented with respect to the ball bearings supporting the STAMP, with the same precision as the mechanical support.

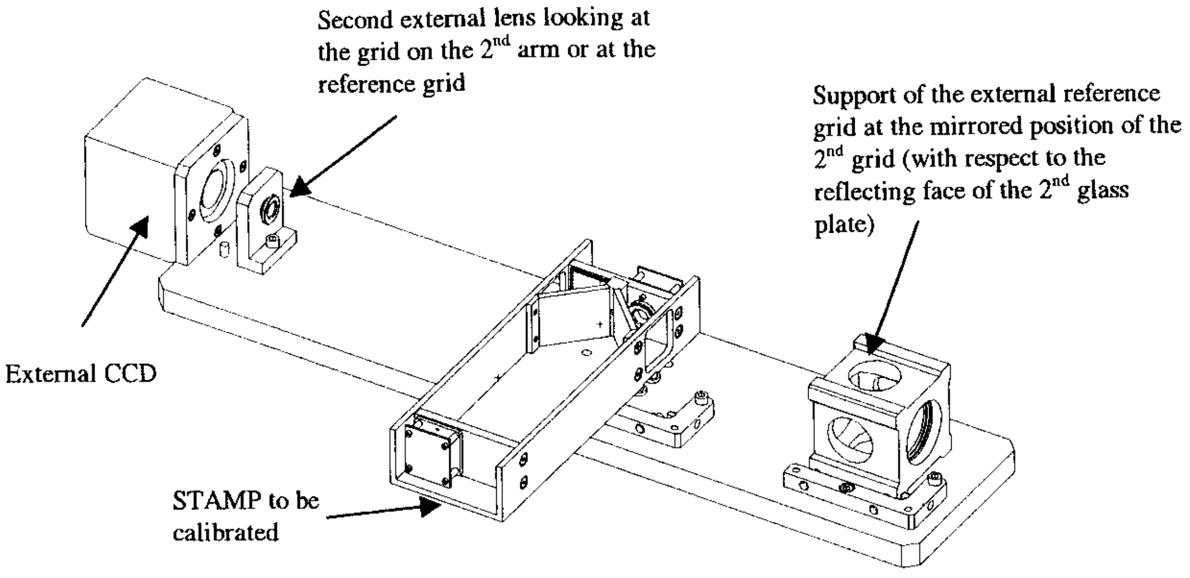

Figure 8: Set-up for the absolute calibration of a STAMP. The external light sources for lightening successively the three grids are not shown. The figure corresponds to the reference grid at the second reference position

This procedure is planned to be experimentally tested in the near future.

7. NEXT TESTS AND FUTURE DEVELOPMENT

We plan to use 12 STAMPs in a test bench, simulating a skeleton of an end-cap muon chamber sector, called DATCHA (Demonstration of the ATLAS Chamber Alignment [2]). It will include all other alignment sensors developed for the ATLAS muon chambers [4], for comparison. The experimental hall will be stabilised in temperature at ±0.5°.

7.1 Tests to be performed at the DATCHA test bench

For this test, the STAMPs will be associated three by three on the same laser beam (four beams in total) with a mean distance between two STAMPs close to 2.5 m. They will be positioned on carbon fibre bars at known positions, with a relative resolution below 5 μm in all directions. Thus the absolute calibration procedure described in Section 6 will be tested.

7.2 New CCDs

New CCDs [3] will be used on the DATCHA STAMPs. We have chosen remote driven pixel CCDs in order to control time exposure, clock speed transfer and real spatial sampling. A special VME electronic board has been designed for this application. It includes multiplexing for large camera readout.

8. CONCLUSION

We have developed a new type of highly transparent sensor able to reconstruct a TEM_{00} laser beam profile with a precision of 10 μm in translation and less than 50 μrad in rotation, transverse to the beam. All the components used for this application are well known industrial products available at a total price already below € 500. It may be reduced further.

Future studies in real conditions at the DATCHA test bench will be an important milestone for the absolute calibration procedure.

9. ACKNOWLEDGEMENTS

We would like to thank H. Blumenfeld and M. Bourdinaud for fruitful discussions during the development of this project and also H. v.d. Graaf and K. Hashemi for useful discussions on CCD.

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