IMPROVEMENT OF THE ALIGNMENT PROCESS OF SUPERCONDUCTING MAGNETS AND LOW-β-SECTIONS

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1. INTRODUCTION

CERN plans to build a new collider, the LHC, to bring protons into head-on collision. In order to reach the nominal energy, a high magnetic field is required. The machine is therefore to be based on superconducting magnets. The aperture, maintained as small as possible, is a severe constraint on the design of the magnets, and also implies the need for an extremely high quality orbit. The machine will be installed in the existing LEP tunnel, above the LEP machine, and two new experimental areas are planned to be built, with strong focussing quadrupoles installed around these areas.

Among the several problems which can be considered as "classical" for the alignment of the components of an accelerator, particular attention must be paid to two major points which are not new, but which are important because of the specificity of the machine. As we use reference targets for the positioning of the magnets, we have to be sure of the stability of the geometric relationship between the reference targets and the magnetic axis in the time going, and in the case of superconducting magnets the targets are not fixed directly to the magnet itself. This is the first point. The second one concerns the alignment of the low beta quadrupoles because of the disproportionally severe effect of a small misalignment of these elements on the orbits.

This paper will present the solution given to these problems at CERN, and the status of the studies which are presently under way.

2. REFERENCE TARGETS AND MAGNETIC AXIS

Until now, the magnets of an accelerator have been aligned from reference targets which are installed on the magnet itself. Many type of targets can be used. Some can support instruments, and we thus call them "active" targets. Others are "passive" targets, in that they are only used for sighting to [1]. In any case, as these targets can be considered as the image of the magnetic axis -from a geometric point of view-, it is necessary to be sure that the geometrical relationship is stable.

2.1 Comparison between Classical Magnets and Superconducting Magnets

With the classical magnets, the targets are directly mounted on the yoke and even if some targets can also be inserted into the gap of the magnet, the link between these reference points and the magnetic axis is definitively established during the measurements of the magnetic field. It is difficult to imagine what can change the position of the targets with respect to the magnetic field. The only movements which can be expected - apart from a crash - are very small and are in the longitudinal direction because of the variation of the length of the magnet itself during its use, and these induce no significant effect on the alignment.

The consequence of such a stability is that it is advantageous to fix the targets at constant dimensions for a same type of magnet.

A superconducting magnet is enclosed in a cryostat and is therefore not directly accessible. The role of this cryostat is to insulate the cold mass of the magnet which is cooled down to 1.5 K from the normal temperature. It also forms the support of magnet, and the reference targets are fixed on this support. Thus the relationship between the targets of a super-conducting magnet and its magnetic field can change in the course of time for several reasons:

- The magnet is put through important internal thermal constraints. Its contraction is very large when it is cooled down and it is possible that movements of few centimeters longitudinally in the support could create significant random displacements;
  the same problems can occur during quenches;
- interconnection of magnets, by means of bellows which partially lose their flexibility at cryogenic temperatures, can also cause movements of the cold mass in the cryostat;
- long term stability of the cold posts which are built in composite material is not perfectly known;
- vibrations during transport are also sources of movements.

2.2 A Method to Survey the Movements of the Cold Mass

CERN has decided to measure the movements of the cold mass with respect to its cryostat on the prototype magnets which are built for the LHC. For this purpose, a non-contact solution have been choosen. The geometric relationship between the reference targets and the magnetic axis can be decomposed in two parts. The first one comes from the monitoring of the movements of the cold mass with respect to the cryostat, and the second one comes from the control of the possible deformation of the cryostat itself, for example because of the variations of pressure or temperature.

To check the first relationship, a small bar is suspended from the cold mass and hangs inside each post. It is assumed to follow regularly the cold mass. A shaft, equipped with 9 capacitive detectors and clamped to a flange inside the cryostat, allows the relative position of the small bar and of the cryostat to be measured in translation and tilt (fig. 1). The capacitive detectors are mounted around the bar at two levels so they can measure a tilt angle of the bar. At each level, two capacitive detectors are installed in the opposite direction so it is possible to control the values given; the sum of a couple of values must be constant. A nineth detector installed in front of the end of the bar measures the vertical translation.

The required accuracies requested are as follows:

- rod-tilt in the longitudinal plane of the magnet (Phi): RMS=0.30 mrd;
- rod-tilt in the magnet transverse plane of the magnet (T): RMS=0.07 mrd;
- translation with respect to the X (radial) and 2 (vertical) axis: RMS=0.05 mm;
- translation with respect to the Y (longitudinal) axis: RMS=0.10 mm.

The range of measurements is limited to 30 mm in translation according to the Y axis, 4 mm in translation according to the X and 2 axis, and 12 mrd for the tilt angles T and Phi.

Because of the distance between the flange of the cryostat and the reference target, the possible deformation of the cryostat must be controlled also. This check can easily be made by using of a simple mechanical jig. Thus, the geometrical relationship between the targets and the magnetic axis is described by the same data set as for the classical magnets, with the addition of the data set of the two complementary relationships. At any moment it is possible to re-compute the main relationship by measuring the two others and comparing the data with the original ones obtained when the magnetic field was measured. The consequence is that for this type of magnet, it is not necessary to fix the targets at a constant distance from the magnetic axis.

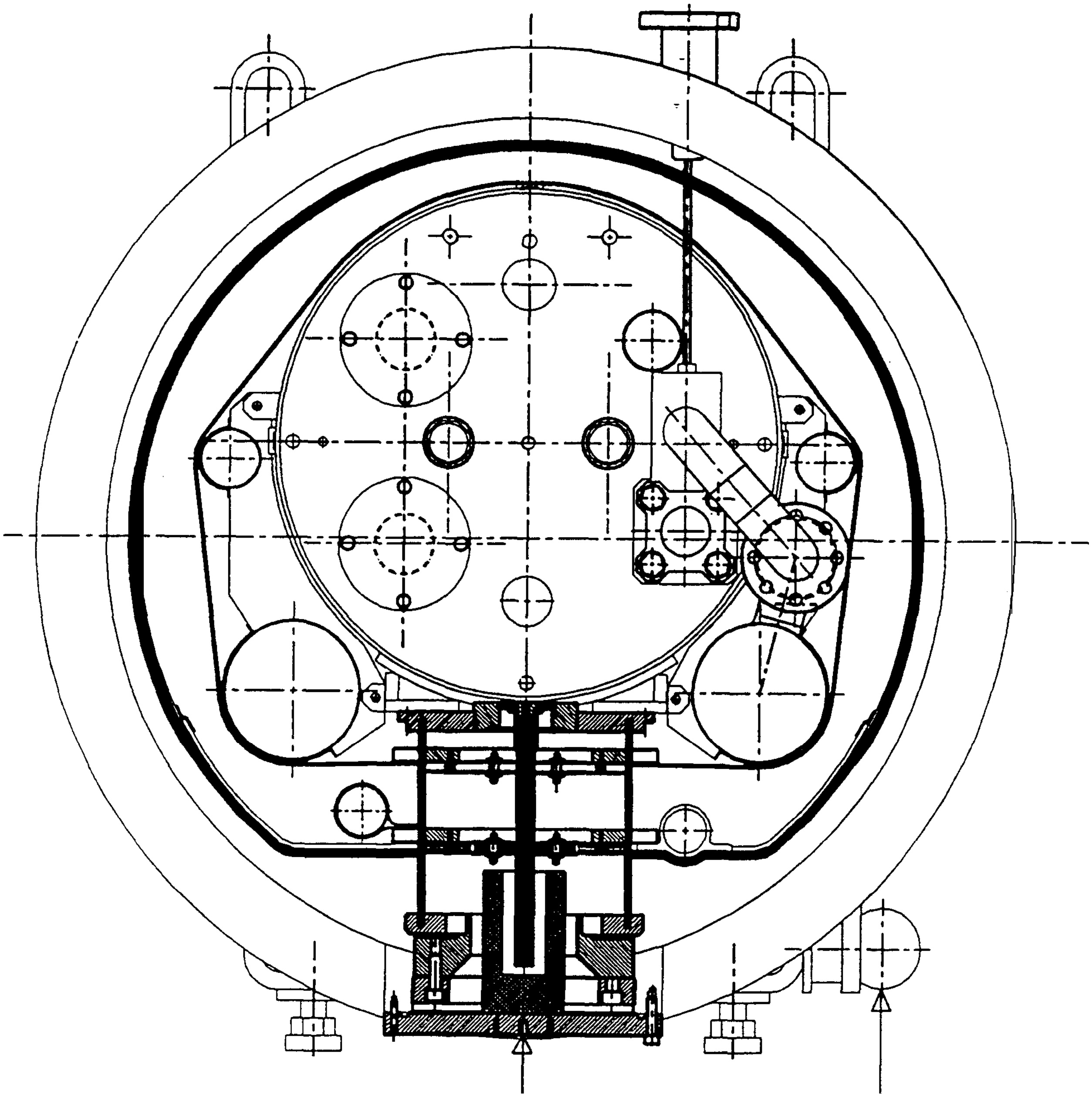


Fig 1. Cross section of a LHC superconducting magnet

Such a method presents major advantages. It is possible to continuously measure the displacements as the element is cooled, under vacuum and to try to understand the behaviour of the cold mass and its support. The components are sensitive neither to the cryogenics nor to the radiations. The electronics are outside, and the only elements located in the cryostat are the electrodes and the bar which is made of silica or of “Zero Dur” because of the high stability of these materials at cryogenic temperatures. There is no contact between hot and cooled elements and thermic losses are minimised by the choice of the material of the bar. Special attention is paid to the electronics which are self-calibrated. The measurements can be made either in the workshop or when the magnets are already aligned in the tunnel.

3. ALIGNMENT OF LOW BETA QUADRUPOLES

The alignment of the low beta quadrupoles is always a challenge for surveyors. Their location around the experiments, in especially cluttered areas, make them particularly difficult to position. Nevertheless, the alignment of these elements is critical for the beam orbits. For the LHC project, CERN is studying a new optical method of alignment which could be used in any straight section of the accelerator.

3.1 Goals and Constraints

The area concerned incorporates the experimental area which is about 25m long, and two 35m long low beta insertions. The total length of the vector to be aligned is about 100m long. The accuracy required is ± 0.1mm for each element radially along this vector. The components of this vector -low beta quadrupoles, pick-ups and the experimental detector- must be aligned correctly not only with respect to this vector but also with respect to the rest of the machine.

It must be possible to apply the method both locally and as a remote procedure from the control room during short stops of the machine.

Because of the high level of radioactivity which is expected in these areas close the beam line, all the component must be resistant to the radiations, or must have a low cost.

3.2. Description of the Method

As it is impossible to keep free a space through the detector for a direct line of sight, and not accurate enough to measure around the experimental detector, it is suggested to use the only place kept free through the detector: the vacuum pipe itself where the particle beams are circulating. Consequently, this method takes advantage of the elimination of the problems due to the refraction, because the reference straight line is located in the vacuum, and of equal ease of determination of the offsets vertically and radially.

Thus the method involves installing a laser beam into the vacuum chamber all along the the vector to be aligned, and measuring some internal reference targets located each side of the experimental detector with respect to the laser beam line. If the internal targets are mechanically well known with respect to external references, measuring the relative alignment of the internal targets is equivalent to measuring that of the external ones, which can be considered as geodetic reference targets of a linear network and used for the alignment of the other elements by classical methods.

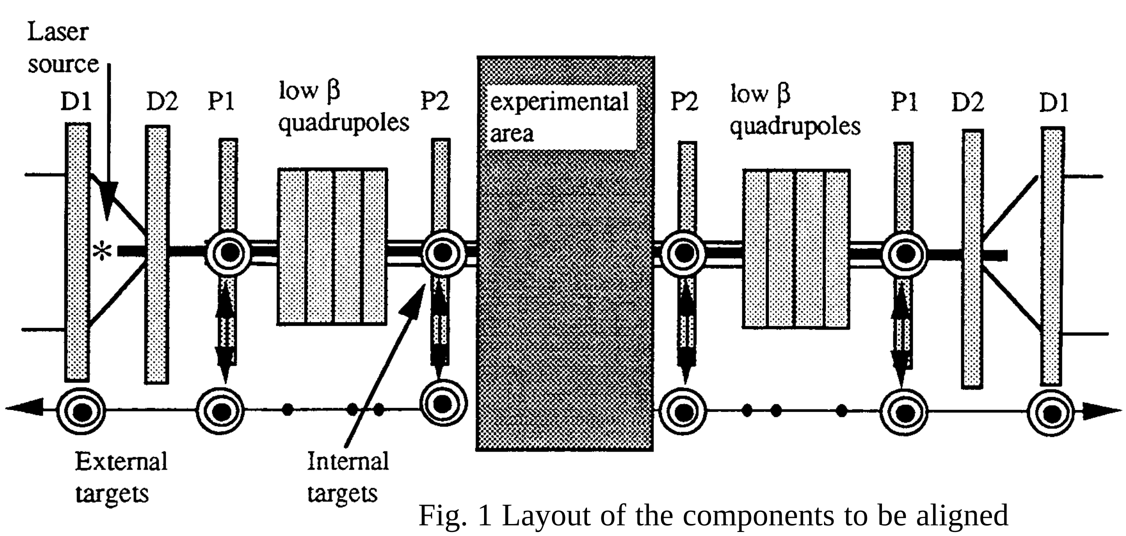


Fig. 1 Layout of the components to be aligned

These internal targets are installed into vacuum tanks (P1 and P2 on the figure 1) which are included in the vacuum system of the machine, and these tanks are also equiped with two external reference targets, as it is the case for the components to be aligned. Of course, as the measuring system must be out of the beam when the experiment is running, the internal targets and the laser source must be movable with a repeatable positioning system with respect to each tank. A ceramic screen with fiducial marks constitutes the internal target.

3.2.1 The Laser Source

Due to the divergency, the radius of the laser beam increases with the propagation distance. The following formula describes the propagation of the Gaussian beams and gives the minimum size of the beam [2].

$$w(z)^2=wo^2(1+(\lambda z/\pi wo^2)^2)$$

z : The distance propagated from the plane where the wavefront last time was flat
λ : The wavelength
wo : The radius of the $1/e^2$ contour at the plane where the wave front is flat
$w(z)$: The radius of the $1/e^2$ contour after the wave has propagated a distance z

By differentiating this formula, we can find the optimum condition for the variation of $w(z)$ on some z interval.

$$z = \pi wo^2/\lambda$$

Using a HeNe laser source implies a minimum beam waist radius (*wo*) of 3.17 mm when z = 50 m, and the beam radius at 100 m is w = 4.48 mm. This is compatible with the inner diameter planned for the vacuum chamber which reaches its minimum of 20 mm in two places due to the presence of radiation shielding.

The optimum beam is achieved by using a Galilean designed beam expander.

The source must be located outside the vacuum chamber and the beam goes into the vacuum chamber through a window. A movable prism can deflects the beam, so that it is approximately parallel to a vacuum pipe. As the beam is installed in the vacuum, its straightness is not affected by atmospheric effects. Its exact position is not critical and the only important points are the gaussian repartition of the light and the fact it must not touch the side of the pipe.

3.2.2 The Detector

Because of the high level of radiations, PSD sensors, fiber optics and silica components cannot be used. The laser spot and the fiducial marks are therefore observed through a window using a CCD camera (Pig. 2 and 3)

The system consists of a Sony XC-77CE camera which works according to the CCIR signal system with 50 half images per second. The CCD sensor has a resolution of 756 (horizontally) x 581 (vertically) square pixel elements of 11.0 x 11.0 µm each. and the camera provides the pixel sampling clock as an output signal. The video signal is transfered to an analogue-digital unit and then stored on a Data Acquisition Main Board located in a PC.

The CCD camera is installed as far as possible from the vacuum chamber -one meter or more - and can be protected against radiation by a special shielding. The focal length chosen is 75 mm, with a magnification ring of 1.5X, which gives us a width object of 78 mm inspected from a distance of 1 m.

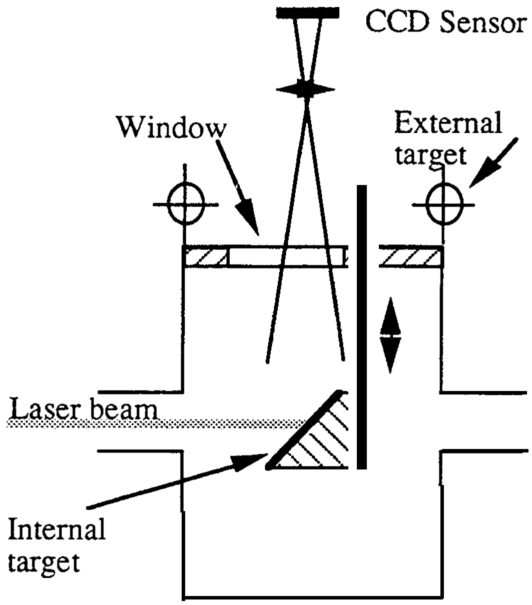


Fig. 3 : Layout of the detector

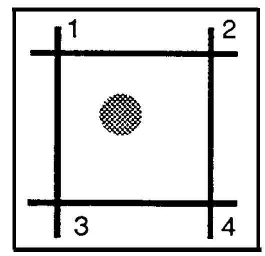


Fig. 4 Internal target

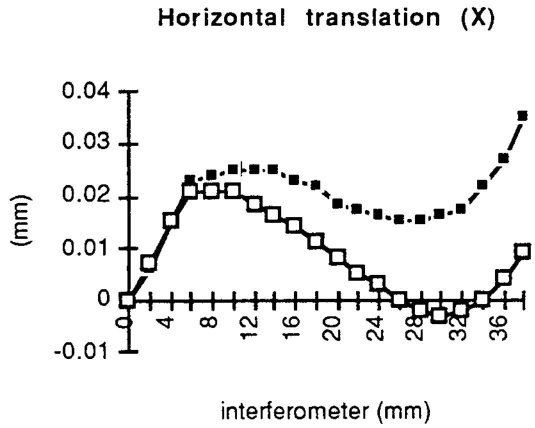
3.2.3 Measurements and Results

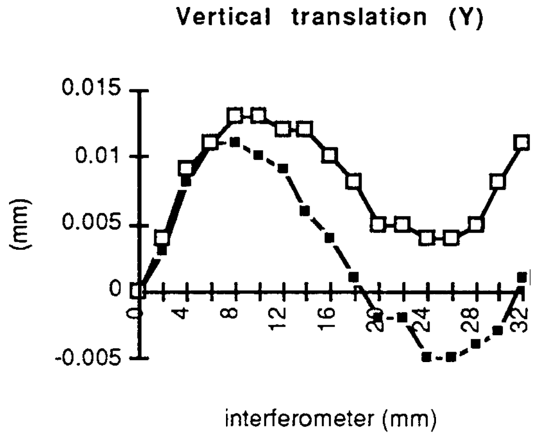
The target prototype is made of ceramic, on which four crosses are drawn by the mean of deposit of copper oxyde under vacuum. So the thickness of the lines is quite nul, to avoid the errors due to the shadow effect on the side of the lines. The figure of the crosses is measured by means of an interferometer and the relative accuracy of each cross is 3 µm. Such a grid of 225 crosses has been built, for the calibration of the system. This specific target can be used to determine not only the distortion of the optical system, due to the lenses, and also to the crossing through the window from the vacuum to the air [3].

The rms of the measurement of one cross with the CCD camera is 0.01 pixel, or 1µm at the scale of the object, with the use of a specific subpixel measurement software based on the determination of the edges of the crosses [4]. The Direct Linear Transformation (DLT) approach, or Homographic Transformation is used to give the respective orientations of the object and image planes [5]. Four points are a minimum to give the solution of the system, but the method has also been tested with the special grid of 225 crosses. The measurement of such a target can also give the internal calibration of the camera. Tests have been made by moving the targets over 35 mm, recording the displacements with the interferometer, and measuring the displacements with the CCD camera.

The following graphs show the comparison between the interferometer and the CCD camera measurements, and it should be noticed that the distortion has not been taken into account in this test and that the curves obtained are the influenced by this error. Nevertheless, the results of the measurements stay within the specification without taking the distortion corrections into account in this test.

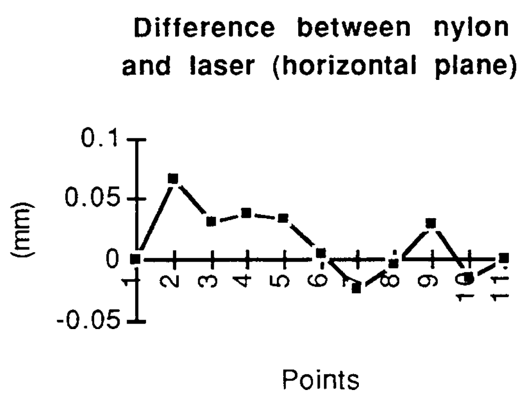
The study of the laser spot is also an important point. The regularity of the surface is important because of the speckle, and only a random grainy effect does not affect the barycenter of the spot [2]. The speckle effect is the granular appearance of the spot due to the phase differences between light coming from different parts of the surface because of the irregularity of it. It can be minimised by moving the target at high frequency (vibration) or by making the laser hit the CCD sensor directly.

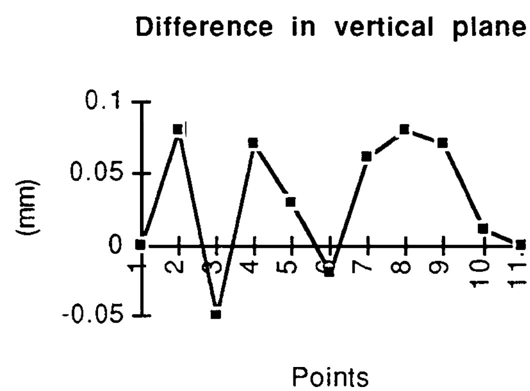




These solutions are neither convenient nor possible in our case, and the solution of an extensive averaging of the images has been chosen. The choice of the black-level of the image and the environment light may also influence the determination of the barycenter of the spot. It has been verified that, with the target used, the image position of the gravity center of the laser spot can be determined and stay stable within 11μm (rms) when moving the target in its plane in the range of 35 mm..

The last test made consisted of measuring the relative misalignment of eleven points regularly installed along 10 m. The laser source was located 15 m upstream this line, to try to detect some effects of the laser stability. The horizontal offset alignment of the points were measured by CERN nylon offset device. All the possible arrangements of nylon measurements were carried out and were adjusted by least square method. The r.m.s. of the residuals of the 165 observations was 0.02 mm [6]. The vertical measurement was made by direct levelling and we can estimate that the accuracy is of the same order. The comparison of the offsets obtained with the laser and CCD camera method - applied in the air - with those obtained with the classical methods are shown on the following graphs. The r.m.s. of the difference between the nylon and laser measurements is 0.03 mm in the horizontal plane. In the vertical plane, the rms is 0.047 mm. The small instability of the CCD camera observed during the measurements in the vertical plane is confirmed by these results.





These very preliminary results were obtained with very simple equipment, in the air, (so with a high probability of refraction effects) and by moving the CCD camera to each point, which is an important factor of instability. They are very promising and confirm the feasibility of the method.

5. CONCLUSION

The capacitive method described for the control of the cold mass is well adapted to measure everywhere its displacement inside the cryostat, and, in conjunction with the optical or mechanical methods previously used only at normal temperature and in workshop, will complete the knowledge of the behaviour of such magnets. As we still use reference targets for the alignment of the magnets, it is absolutely necessary to be sure of their positions with respect to the magnetic field, and this is the preliminary step for a good alignment.

The proposed method of alignment through the vacuum pipe brings an efficient solution to the problem of the alignment of the magnetic elements located around the detectors of particle accelerators. It is simple, accurate, very similar to that used by the machine physicists for the detection of the particle beams with TV pickups, and it takes advantage of the only space kept free by the physicists through their detectors.

This method can also be used in the air, of course, with a loss of accuracy due to the influence of the atmosphere on the straightness of the light, and is very suitable for remote control measurements in hostile areas (radiation, noise, heat...)

REFERENCES

[l] E. Menant & J.P. Quesnel, Reference Target Positioning, CERN, CAS Montreux (March 1992).

[2] H. Petersson, Laser Alignment System using CCD-Camera and Digital Signal Processing, CERN, (Sept 1993).

[3] T. Luhmann & W. Wester-Ebbinghaus, Image Recording with Opto-Electronical Matrix Sensor for On-Line Processing, FIG, London, (Sept. 1987).

[4] P. Seitz and J.M. Raynor, Optische Überauflösung mit CCD-Kameras und digitaler Bildverarbeitung in Optical 3-D Measurement Techniques, A. Gruen & H. Kahmen (Eds.), Herbert Wichmann Verlag GmbH, Karlsruhe (1989).

[5] H.M. Karara, Non-Topographic Photogrammetry, American Society Of Photogrammetry (1979).

[6] C. Rigaud, T. Dobers, Test sur les Dispositifs d'Alignement au Fil, Note Interne CERN, (1993).