THE LASER TRACKER : A MAJOR TOOL FOR THE METROLOGY OF THE LHC

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1. INTRODUCTION

The Large Hadron Collider (LHC) requires the fabrication of about 2000 superconducting magnets produced in different locations all over the world.

Inside these magnets, the particle beam will circulate in a vacuum chamber so small that the loss of beam/mechanical aperture is rather important. The interconnection of all the tubes of two adjacent magnets is also a challenge. The positioning of the alignment targets, used during the alignment in the tunnel, with respect to the axis of the magnet is also to be done with a high accuracy even for the dipoles magnets.

To realise all these measurements the 3D laser tracker technology has been introduced at CERN. This paper presents briefly the instruments and methodology used in the past, the methodology for taking all the benefits of the laser tracker and the experience gained at CERN during the measurements made on all kind of LHC components.

2. THE OBJECTS TO MEASURE

2.1. The cryo-dipole

A cryo-dipole is a magnet that produces the required magnetic field to deflect the particles along a circular trajectory. It is composed by a cold mass, which is the magnet operating at 1.9K, inserted into a vacuum vessel, also called cryostat. It can be seen as a long bended cylinder of 15 m long, 1 m diameter and 35T. The geometry of this object is defined by the geometry of the two particle beam channels, also called Cold Bore Tubes.

In order to satisfy the mechanical aperture, the axis of each cold bore tube has to be contained within a torus of 1 mm radius around its theoretical axis. On the other hand, in the interconnection area, the maximum offset tolerable by the below linking the cold bore tubes of two adjacent dipoles is 4 mm. Ground movements, detected in the existing tunnel, as well as arm lever effects and security margin for the alignment necessitates that the positioning of the cold bore tubes extremities has to be realised with a tolerance of 0.6 mm (3 σ). The measurement during which the shape of the magnet is checked, the positioning of the tubes is done and the position of the fiducials determined is called “fiducialisation”.

A beam screen, installed inside the cold bore tube to protect it from synchrotronic radiation, has to have its extremities aligned with an accuracy of 1mm (3σ). Moreover, the position of all the other tubes at each extremity has to be measured with a good accuracy and the tubes aligned within specified tolerances. This measurement is called “beam screen measurements”

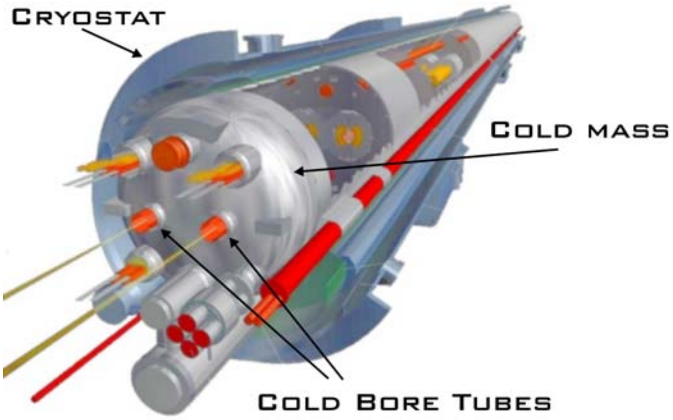


Figure 1: the cryo-dipole

2.2. The Short Straight Section (SSS)

A short straight section is composed of a cryo-quadrupole, whose main function is to focus, defocus and drive the particle beam. Installed in a vacuum vessel, it has a length of 5.5m, a diameter of 1m and its weight is 10T. The geometry of this object is defined by the position of the magnetic axis of the quadrupole.

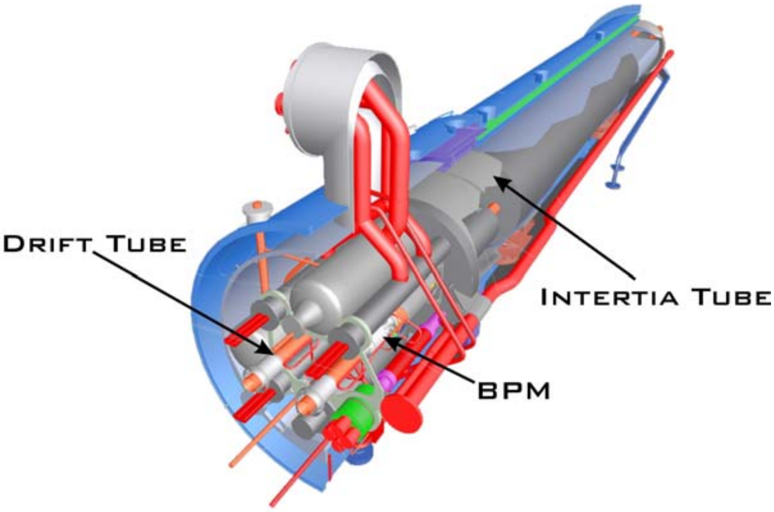


Figure 2 : the Short Straight Section

The SSS is equipped with a Beam Positioning Monitor (BPM) to measure the position of the beam during operation. The position of the center of this BPM with respect to the magnetic axis of the quadrupole has to be known with an accuracy of 0.2 mm (1σ) in order to know the position of the axis of the quadrupole with respect to the beam.

This BPM is connected to the adjacent magnet through a Drift Tube. For the same reasons as mentioned for the dipoles, the extremity of this drift tube has to be aligned with a tolerance of 0.6 mm ($3\ \sigma$). Similarly to the dipoles, the position of all the tubes at the extremities have to be checked.

3. A BIT OF HISTORY

The “fiducialisation” of the cryo-dipoles was the first operation developed and the most difficult to achieve. A lot of instruments were tested during the phase of the manufacturing of the prototypes magnets in the years 1996-1997[1]. The first system developed was an electronic “mole”, able to materialize the axis of the tube inside which it is located, and detected by a laser beam located on translation XY tables, materializing a “mechanical” co-ordinate system. The main difficulty with this system was the alignment of the laser beam inside the tubes of 15 m in order the laser beam to pass through the magnet. This operation was really time consuming.

Figure 3 : the electronic "mole" and the laser

Another measuring system was an auto-centering “mole” equipped with a LED and measured by a Taylor-Hobson lens located also on translation tables XY.

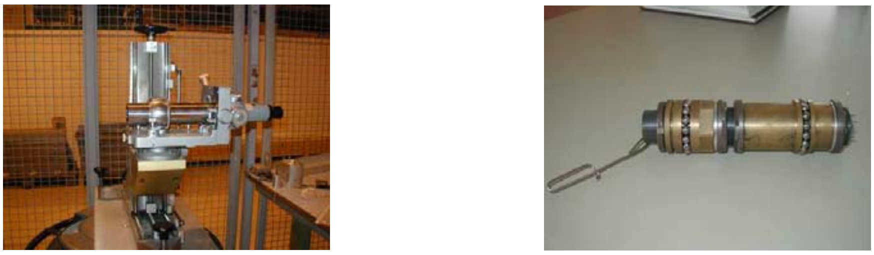


Figure 4 : the Taylor-Hobson lens and the mechanical mole

In addition, to realise measurements at the ends of the magnets during the assembly phase, a 3D (6 axis) measurement arm was used, resecting itself on reference points determined by the previous mentioned system.

The big disadvantages of these systems was that we have to rely on the stability of the XY tables, as they were materializing a co-ordinate system, and the fact that it was not possible to make redundancy measurements. Another negative point is the fact that the measurements were done with many various instruments with heterogeneous accuracy. They were more “mecanician” oriented than “topographic” systems.

The laser tracker technology was existing since the beginning of the 90s but using only interferometer distance measurements, making it difficult to use in the frame of industrial context. In 1998, the new laser tracker appeared with the Absolute Distance Measurer. After a first trial, it was obvious that it was the ideal instrument to realize all the operations on the LHC magnets.

4. THE LASER TRACKER TECHNOLOGY

The reasons of choosing a laser tracker are the following :

- An accuracy better than 0.1 mm and reliability;
- Ability to control the measurements through redundancy;
- Fully automatic tracking system as a huge amount of magnets has to be measured;
- Ability to measure inside a tube of 50 mm and 15 m length for the geometry of the dipoles;
- Transportability as the works take place in different halls;
- A powerful software.

5. MAKING GOOD MEASUREMENTS WITH THE LASER TRACKER : THE FIDUCIALISATION EXAMPLE

As the laser tracker is a fully automatic system, it seems to be a “push-button” instrument which can be used by non-specialised persons. This chapter describes what was done by the Survey group to get all the benefits of the laser tracker taking as an example the “fiducialisation” of the LHC dipoles magnets.

5.1. Verification that the instrument is within the specifications

Before buying the instrument, a selection test was specified in order to check that the requested accuracy could be achieved by the laser tracker [2]. This test was representing the worse configuration of measurements to be done with the LHC dipole magnets during the fiducialisation operation. In other words measuring a network of points badly configured, because long and narrow, with an accuracy better than 0.1mm at 1σ [1]. Two firms passed the test with success and one was chosen to provide CERN with instruments.

The same test is used for the acceptance of a new-arriving laser tracker in the Survey and Magnetic Measurements groups. Among five laser trackers received, one of them didn’t pass this test after several trials. Finally, the manufacturer decided to provide CERN with another one which passed successfully the test at the first trial.

5.2. Calibration of the instrument

The manufacturer specifies a “full” calibration of the instrument every year or after an important transportation of the instrument. At CERN, we do it every three months. Also it has been noticed that there is a deterioration of the measurements when there is an important change of temperature. In this case, we also recalibrate the instrument.

A weekly calibration of the “mole” is also done by rotating the “mole” inside a calibrated tube and it has to be repaired when the deviation to the mean value exceeds 0.07 mm at 1s.

5.3. The network of common points

As measurements have to be taken from different positions of the laser tracker[, commons points have to be measured in order to link them[3]. These points, called network points, have to be located all around the object and in different planes. Simulations have given the best possible places for the network points. These points have to be very stable during the measurements. Therefore, some of them were sealed on the floor, others on top of tripods higher (in blue on figure 5) than the magnet to measure.

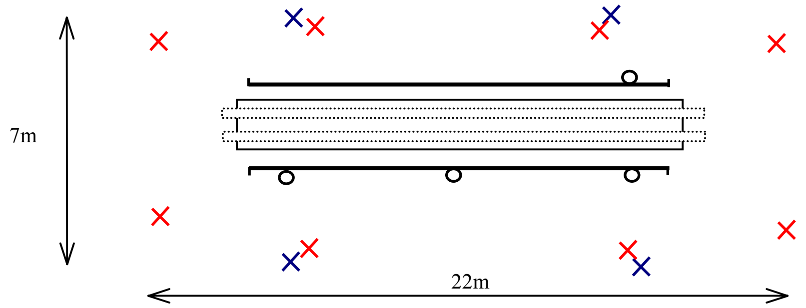


Figure 5 : the network of points

5.4. Redundancy measurements

The determination of the magnet axis is done with measurements inside the two cold bore tubes. In theory, measurements taken from one side of the magnet for each cold bore tubes should be enough but in order to have a better homogeneity of the measurements all along the magnet, measurements are done from both sides from four positions of the laser trackers. Similarly, the fiducials are measured from two positions, on each side of the magnet, as one position should have been enough.

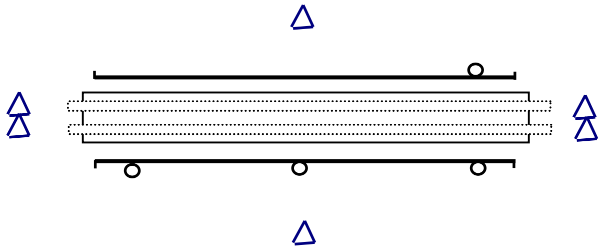


Figure 6 : the laser tracker positions

Making redundancy measurements doesn't necessary improve very much the accuracy but gives a great confidence in the measurements and an estimate of the errors. Measurements taken from well chosen positions of the laser tracker, also strengthen a bit more the network. When doing the calculation using the bundle adjustment, it is not advisable to suppress measurements except if there is a good reason, a point that has moved during the measurements for example. From our experience and the manufacturer specification, a limit of 0.08 mm at 1s has been put on the bundle adjustment of the network points. If this value is exceeded, the measurements from this position of the laser tracker have to be redone.

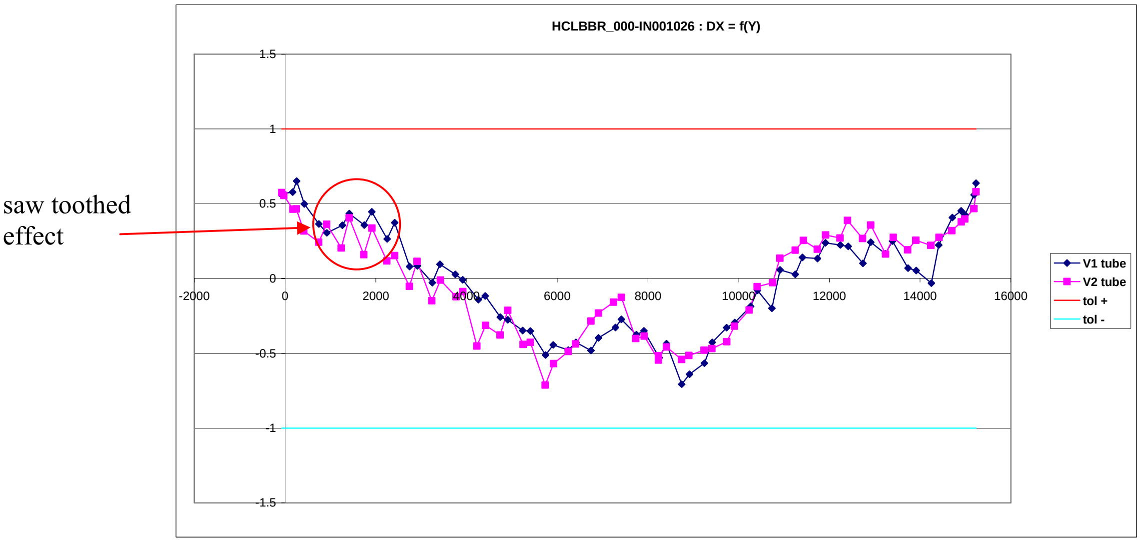
5.5. Accuracy obtained

5.5.1. Repetition test

In order to determine the accuracy of the method, the same magnet has been measured five times and the deviation of the co-ordinates of the fiducials didn't exceed 0.04 mm at 1s.

5.5.2. The "saw toothed" effect

Measurements from both sides of the magnets give also a good estimate of the errors. As the measurements are not taken in the same longitudinal position, a "saw toothed" phenomena may appear as shown on figure 7.



saw toothed effect

Figure 7: saw toothed effect on the horizontal shape

This phenomena is due to a combination of errors which can be listed as :

- Linkage of the laser tracker positions characterised by the bundle adjustment ***ba*** limited to 0.08 mm at 1σ
- Measurement error ***me*** of a point by the laser tracker given by the manufacturer to 5 ppm at 1σ

- Centering error ***ce*** of the “mole” inside the cold bore tube measured at 0.07 mm at 1σ

Therefore, the maximum tooth saw effect should not exceed

$$\text{dev} = 3 * \sqrt{ba^2 + (d1 * me)^2 + (d2 * me)^2 + 2 * ce^2}$$

where :

$d1$: distance from a point to the Tracker at position 1

d2 : distance of the same point to the Tracker at position 2

This gives a limit of 0.47mm at 3σ. If the deviations exceed these values, the measurements have to be redone.

6. MEASURING THE MOVEMENT OF THE CRYO-DIPOLE INSIDE ITS CRYOSTAT

After a beam screen has been inserted inside the cold bore tube in order to protect it from the synchrotronic radiation, the ends of the beam screen have to be checked with respect to the axis determined during the fiducialisation. During this operation, the fiducials are measured as well as references of the cold mass and the beam screen extremities.

By using a 3D Helmert transformation of the fiducials measured during the fiducialisation on the co-ordinates of the ones measured during the beam screen measurements, it is possible to determine the movement of the cold mass between these two stages[4].

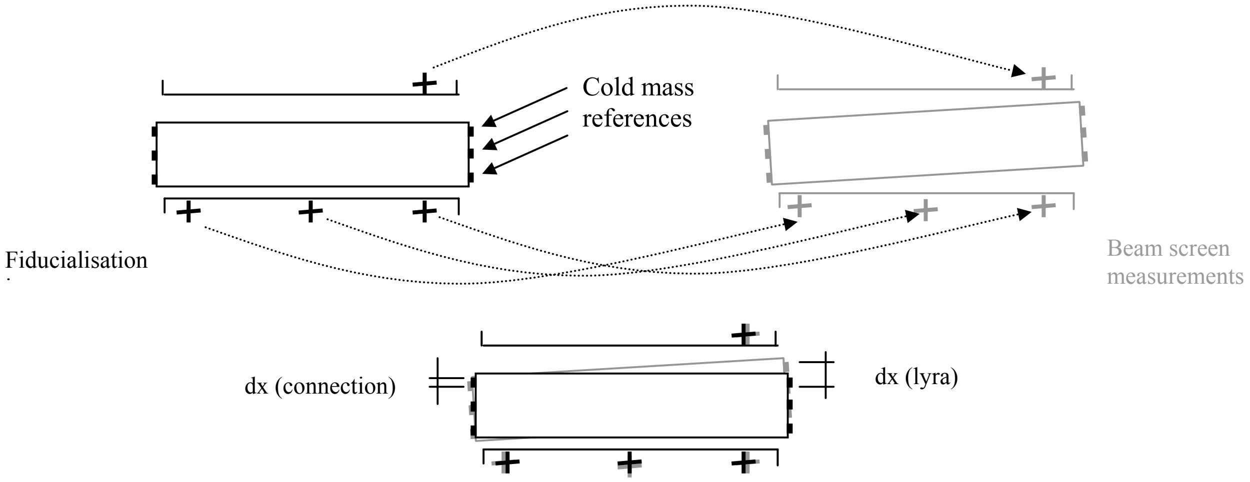


Figure 8 : movement of the cold mass

The dx dy, dz of co-ordinates of the cold mass references gives directly the movement as shown on figure 8.

As there will be a lot of time between the fiducialisation and the beam screen measurement, specially storage on an outside parking, the determination of an eventual movement is of great interest.

7. CALCULATING THE CHANGE OF SAGITTA OF CRYO-DIPOLES

More over, using the same measurements it is also possible to calculate an eventual change of the shape of the magnet. As a matter of fact, a 3D Helmert transformation can be done on the co-ordinates of the cold mass references measured during the fiducialisation and the ones measured for the beam screen measurements. In this case new vales of the fiducials are calculated as shown on figure 9

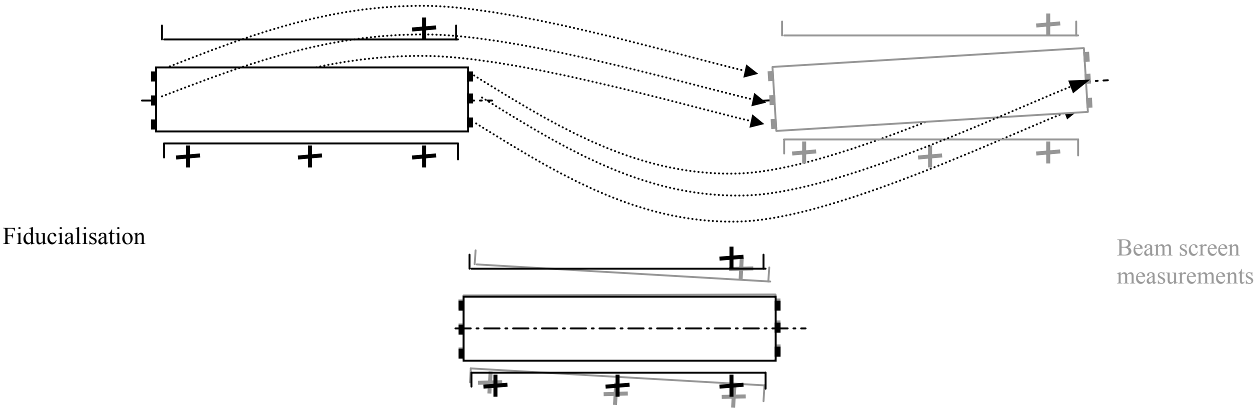


Figure 9 : new fiducials can be calculated

During the beam screen measurements, no measurements are made inside the cold bore tubes, therefore the shape is not measured. Only the cold mass references, also called d points, and fiducials are measured. A way of calculating the change of sagitta is the use of longitudinal(Y) deviations of the d9 and d10 between measurements of fiducialisation and beam screen extremities[4]. These deviations are issued from the 3D transformation mentioned above. From the longitudinal deviations, an angular deviation (dα1 and dα2) can be calculated at each extremity. It has to be noted that dα1 and dα2 should have an opposite sign but an absolute value in the same range of order, if the cold mass acts like a regular circle.

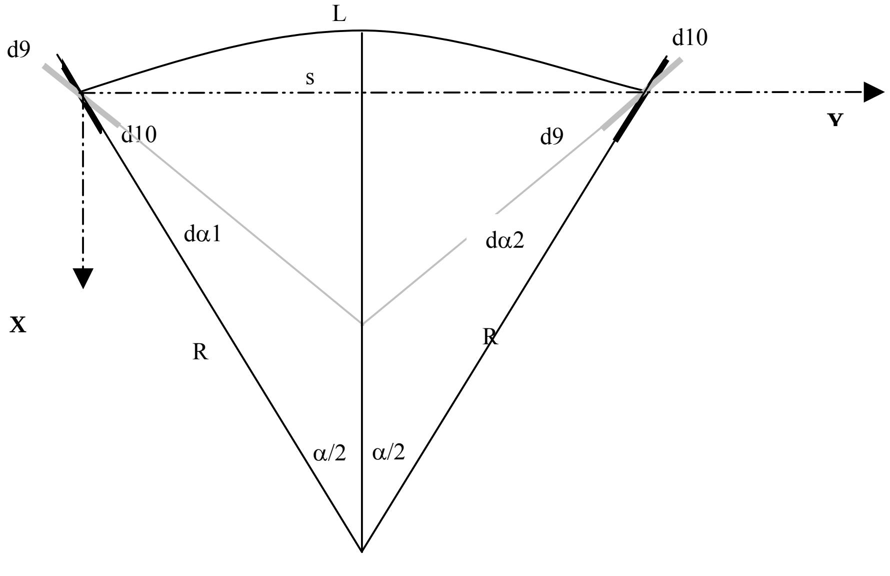


Figure 10: change of sagitta

From figure 10 : dα = dα1- dα2

and the sagitta $s = \dfrac{L\left(1-\cos\left[\dfrac{\alpha}{2}\right]\right)}{\alpha}$

a change of sagitta $ds = \left(-\dfrac{L\left(1-\cos\left[\dfrac{\alpha}{2}\right]\right)}{\alpha^2} + \dfrac{L\sin\left[\dfrac{\alpha}{2}\right]}{2\alpha} \right) * d\alpha$

It could appear surprising to do this calculation using very small longitudinal movements over a distance of 494 mm (d9-d10) to extrapolated a change of sagitta on the whole length of the cold mass. But it has to be said that the laser tracker used the maximum accuracy of its interferometer while doing the measurements along this direction. The absolute accuracy is in the range of 0.02 mm at 1σ. The relative accuracy when measuring the two points is certainly better. It leads to an accuracy of 0.06 mrd for dα and 0.1mm on the chang 1 f sagitta, all values given at 1σ.

For 14 magnets, the change of sagitta, calculated using the above mentioned method, was compared to the real measured change of sagitta. The deviation was 0.2 mm at 1σ, which proves that the beam screen measurements and calculation can give a good estimate of the deformation of a dipole without measuring inside the tubes.

8. THE SSS MEASUREMENTS

The SSS reference axis is determined by the magnetic axis of the quadrupole. Therefore the “fiducialisation” is realised with a specific “mole” measuring at the same time the mechanical axis of the cold bore and the magnetic axis, the position of the whole system being determined by the laser tracker technology. All the experience gained during the cryo-dipole tests (calibration, network of points, redundancies) has been used to develop the methodology of this measurement. The network (fig 11) has a better configuration as the SSS is shorter than the dipole. This allows to reach the accuracy of 0.1 mm at 1 σ which correspond to the error budget allocated for this measurement.

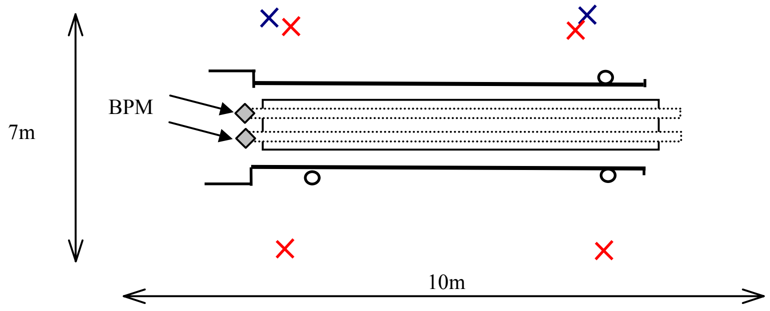


Figure 11 : the SSS measurements set up

For the position of the Beam Positioning Monitor (BPM) at the connection side of the SSS, the laser tracker is also used, relocating itself on the fiducials determined during the fiducialisation. The measurement of the position of all the tubes at each extremity is realised during the same operation using the same technology.

9. CONCLUSION

In order to produce the future LHC magnet cryo-dipoles and SSS within very tight mechanical tolerances, a new instrument using 3D technology has been tested and the relevant method developed. Both instrument and methodology have been used on the first 150 magnets and it has been proved that the measuring specifications can be reached using this measuring system.

Despite the fact that this instrument is fully automatic and seems to be “press button” and easy-to-use by non-experienced manpower, it is not so obvious to get all the benefits of this marvellous technology and its use requires really good topographical background.

References

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[2] Supply of Portable 3-D Measuring Systems Allowing the On-Site Dimensional Inspection of the Cold Masses of LHC Dipole Magnets, Annex A1 and A2, M. Bajko and al, June 1999

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