# METROLOGY OF SUPERCONDUCTING MAGNETS
## LHC Test String First Experience

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## 1. INTRODUCTION

The Large Hadron Collider project (LHC) incorporates novel design features which are particularly challenging: twin aperture superconducting magnets with a stored energy higher than 5 MJ per magnet and working in a bath of superfluid helium. It was therefore decided in 1991 to order several full length prototype magnets and install them in a test string, to demonstrate the feasibility of the LHC. From the alignment point of view, new problems need to be solved and the Survey Group took the opportunity to experiment some techniques on the cryostats of the test string.

This paper presents the test string and then describes the tests the Survey Group made during the "Run 1" of the String.

## 2. DESCRIPTION OF THE TEST STRING

The test string was originally foreseen to correspond to a full LHC half-cell, i.e. one short straight section and four dipole magnets, as designed in 1991, when the project started.

However, as the delivery of the 10 m long dipole was delayed, it was decided to install the string with the short straight section and only two dipoles.

The string starts with the string feed box (SFB), which is a large tank necessary for feeding the superconducting magnets with the different cryogenics fluids.

The short straight section (SSS) cryostat contains the quadrupole but the correction elements such as sextupoles, tuning quadrupoles and closed orbit correctors, normally present in the SSS, are here replaced by dummies. It is directly connected to the SFB on one side and to the dipole magnets on the other side. The weight of the SSS is roughly 10 t, while the dipoles are heavier (30 t).

The string ends with the string return box (SRB), which closes the string cryostat vacuum and contains the short circuits for the electrical busbars as well as some cryogenic valves.

To reproduce the conditions of the LEP tunnel in which the LHC will be installed, the String was built on a concrete girder as wide as the LEP tunnel and with a slope of 1.4%. As it was originally foreseen to install the LHC above the LEP collider, all the string elements are mounted on Γ shaped supports which bring the cryostat axes to about 1.7 m above the floor.

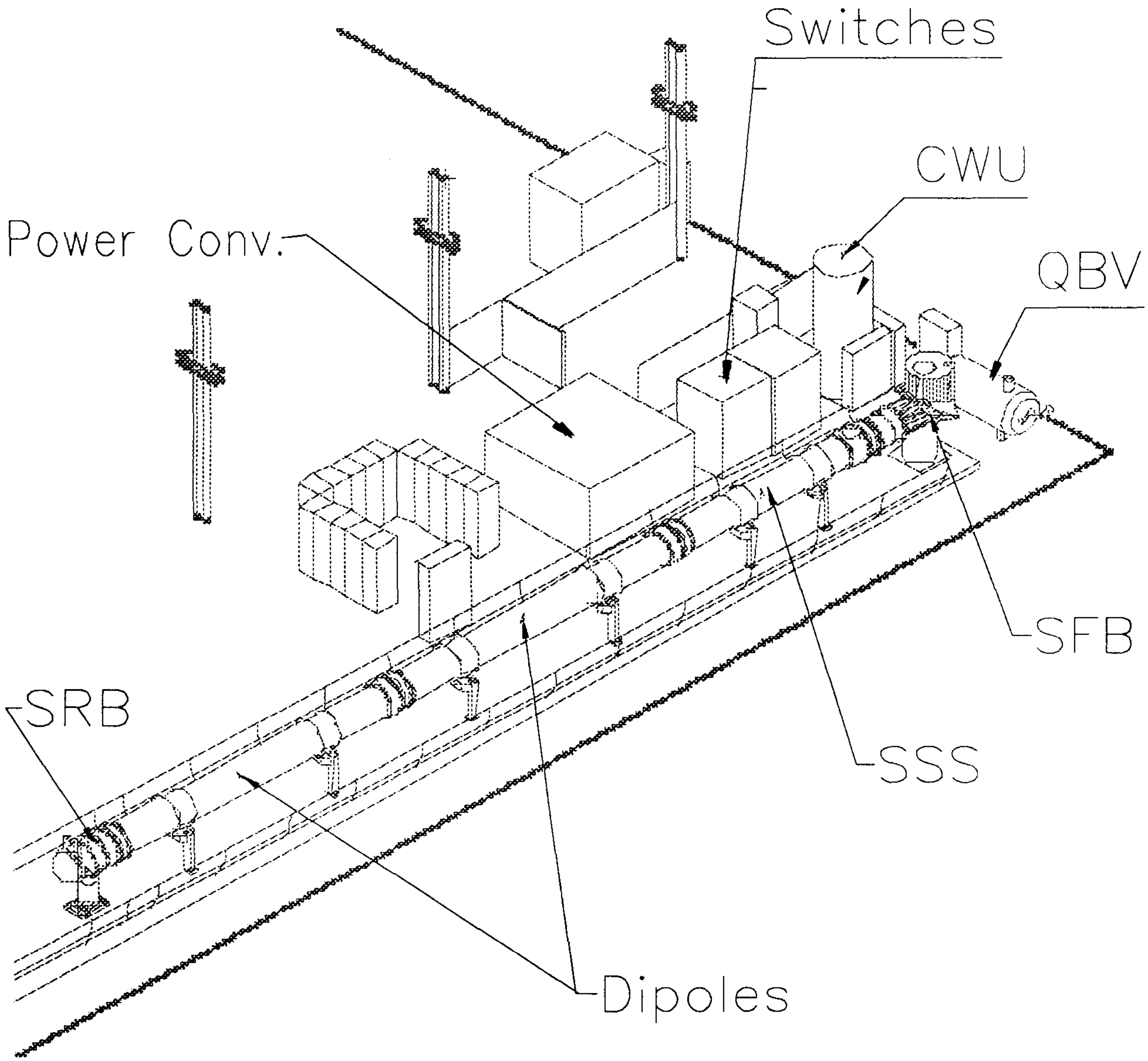


Fig 1. An overview of the String Test

## 3. THE SURVEY IMPLICATION

For the “classical” magnets, the fiducials used for their alignment are located directly on the laminations and therefore their position, once measured, is not susceptible to change.

In the LHC, the alignment of the superconducting magnets will be done using the fiducials located on the cryostat and according to the magnetic or the geometrical axis of the cold mass. The cold mass, located inside the cryostat, is supported by two cold feet. One of the two is fixed, the other one is free in the longer direction of the cryostat to allow the contraction of the cold mass during the operation of the “cooling down” and its elongation during the “warming up”.

Once the cold mass is installed into the cryostat, the position of the fiducials is measured according to the cold mass. Then, the cryostat is transported to its final position and is subjected to the cooling down and eventually to quenches.

In order to register movements of the cold mass according to the cryostat, and therefore to be sure that the position between the fiducials and the axis of the magnet does not change during the life cycle of the magnet, a measuring system has been developed in collaboration with industry.

## 4. MEASURING THE MOVEMENTS OF THE COLD MASS ACCORDING TO THE CRYOSTAT USING A CAPACITIVE SENSOR SYSTEM

### 4.1 Description of the system

The hardware part of the system is composed of three main components :

- **the active positioning detector,** which is a cylinder made in stainless steel with a rectangular hole running through it. The inner part of the hole, made in ceramic because of its stability, is equipped with nine capacitive sensors. These sensors are installed as described below :
    - four in the longitudinal direction (length of the cryostat) with a range of 1.5 mm and an accuracy of 0.022 mm;
    - four in the radial direction (perpendicularly to the main dimension of the cryostat) with a range of 4 mm and an accuracy of 0.005 mm;
    - the last one in the vertical direction with a range of 4 mm and an accuracy of 0.05 mm.

  This cylinder is fixed to the cryostat, inside the latter.

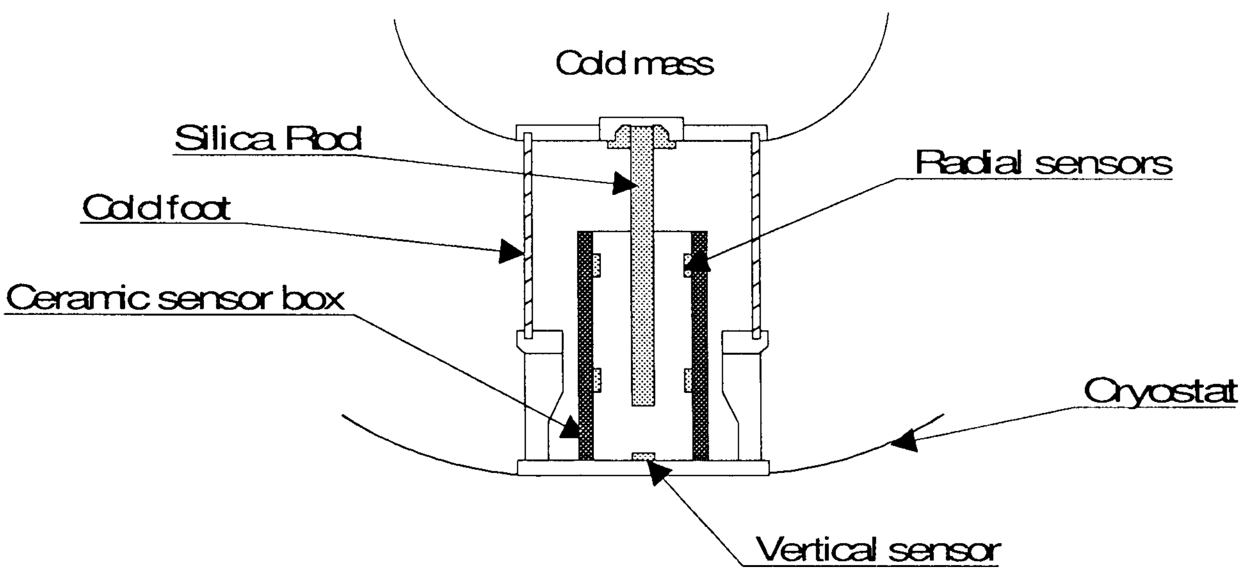


Fig. 2. The Capacitive sensor system

- **the passive detected object** is a silica cylindrical rod whose external surface has been covered by a thin layer of metal. One of its extremities is fixed to the cold mass, while the other fits into the hole of the active positioning detector. The position of the rod can then be determined with respect to the detector. Movements can be detected for three translations and two rotations. It has to be noticed that the combination detector box/rod has to be calibrated.
- As the system is based on capacitive measurements between the active positioning detector and the rod acting as a target, it needs **a readout and calculating device.** This is composed by an ADC, a multiplexer and finally a PC.

The software part of the system consists of a program running on the PC that collects the data and calculates the distances in the three directions and the two angles from the incoming tensions and the results of the calibration. It has to be noticed that, for every measurement of the nine sensors, three reference capacities are also measured.

The calculation is done using a calibration function for each combination of sensor box/rod, the whole measuring range being divided into four sectors of measurements to avoid “shadows zones”. The distances are then determined by using the values of the lower or upper row of sensors, the angles using values of both lower and upper rows.

## 4.2 Preliminary tests

Before installing the system inside the cryostats, some tests were done in a laboratory in order to verify the accuracy of the system, during a short period of time as well as during a long time.

For all the translations and the two rotations, the accuracy was better than the specifications asked for by CERN.

On the other hand, in order to see if a drift occurs on the sensors after a certain time, a long time test was carried out with registration of tensions every 10 mn on a period of about 100 hours. The results show no drift in the longitudinal and radial direction.

In the vertical direction, some movements were detected which cannot be considered as typical drifts but as temperature influences on the framework, as the place where the test took place was not air-conditioned. In the same way, no drift could be seen during the hundred hours of tests on the rotation angles.

## 4.3 The system in the cryostats of the LHC Test String

The feet of the quadrupole (SSS), as well as these of the second dipole (I2), are equipped with the detector system. The first dipole (I1) arrived at CERN before the system was operational and was so badly manufactured that it was impossible to install the system inside the cryostat.

Two kinds of measurements were done with the system :

- long term stability;
- during quenches.

## 4.4 Stability measurements

Run 1 of the LHC String Test started on the 30th of September 1994 and ended in the middle of June 1995. During this period, the operations on the string were as follows :

- pumping in the beginning of October 94;
- cooling down from 300K to 1.8K;
- warming up to 300K (Christmas shut-down);
- cooling down again in February 95;
- warming up in June 95.

At all these stages, measurements were made and the results are shown in the figures below :

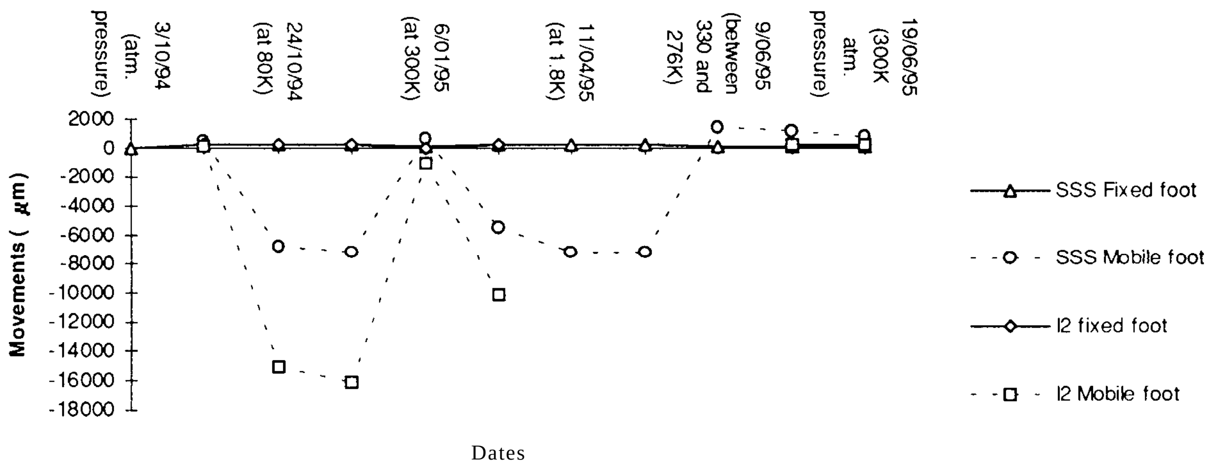


Fig. 3. Longitudinal movements of the cold mass

On figure 3, it can be noticed that, during the cooling down and the warming up, the two mobile feet are moving in the range of what was foreseen by the calculations and according to their length (6 mm for SSS and 16 mm for 12). However the two other feet are also moving in the range of 200 µm, which was not expected.

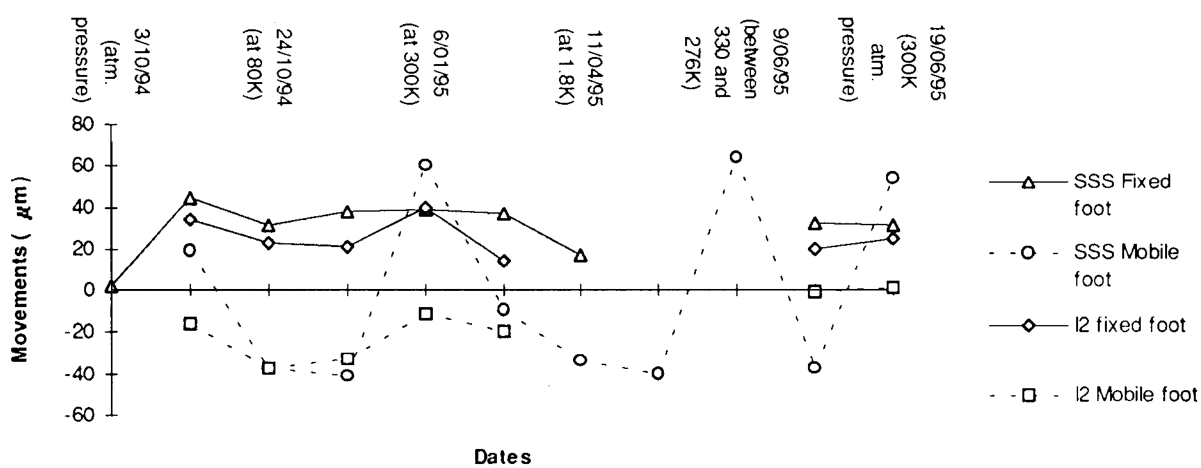


Fig. 4. Radial movements of the cold mass

On figure 4, very small movements (in the range of 30-40 μm) can be seen for all the feet except the mobile foot of the SSS which has moved in a stranger manner, going from ± 50 μm around its original position. This strange movement has not been explained yet.

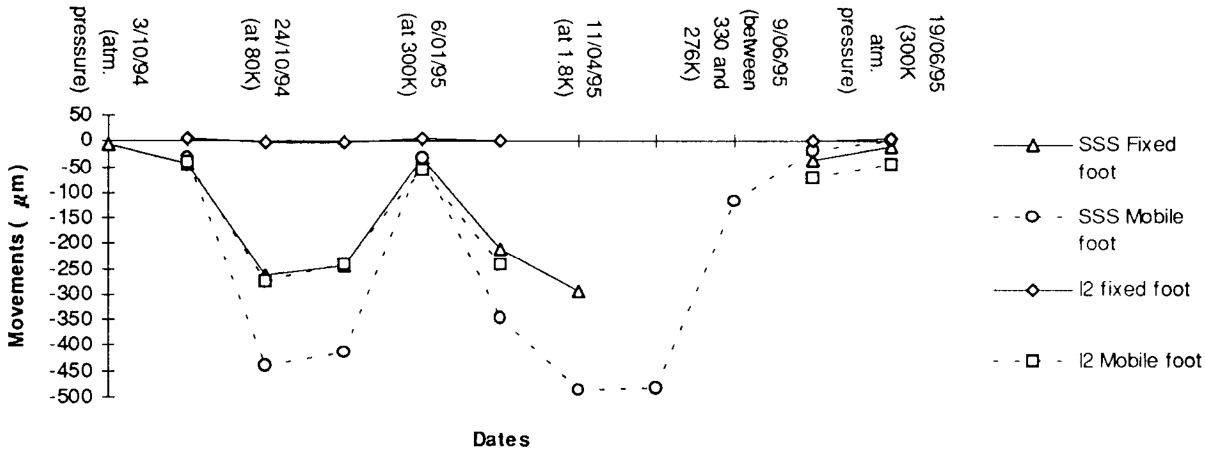


Fig. 5. Vertical movements of the cold mass

Figure 5 shows important movements (between 250 and 450 μm) on all the feet except on the fixed foot of I2.

The four cold feet on which measurements were taken are not made with the same fiber angles and therefore the contraction coefficients are not the same. This is the reason why the movements in the vertical direction are so different.

A general remark about the three latter figures is that the “fixed” feet are not as fixed as they are called. They seem to be flexible, reacting like a spring.

The other important thing to be noticed is that after one year of measurements on these two cryostats in the three directions, the positions are not exactly the same than the ones measured one year ago. This is summarized in the table below.

Table 1 : Variations of the cold mass position from May 94 to June 95

| | Longitudinal (μm) | Radial (μm) | Vertical (μm) |
|---|---|---|---|
| SSS : Fixed foot | 126 | 9 | -13 |
| SSS : Mobile foot | 377 | 62 | 10 |
| I2 : Fixed foot | 177 | 73 | 4 |
| I2 : Mobile foot | 163 | -10 | 139 |

The variations are not really big but they could not be considered as negligible.

The relative alignment, in the vertical and the radial direction, of three consecutive quadrupole of the future LHC should be realized with an accuracy of 0.1 mm, therefore the position of the cold mass with respect to the cryostat should be known with a better accuracy. This accuracy cannot be obtained in the actual cryostat.

### 4.5 Measurements during quenches

*What is a quench* ?- A quench is a resistive transition, i.e. when a magnet changes from the state of superconductivity to the state of resistivity; it occurs when either the critical temperature or the critical current or the critical field is by-passed. It can also occur in case of beam loss.

The studies of the behaviour of the cryostat during a quench were done on a test bench located very close to the string. The measurements were done on all the cryostats that composed the string. The string, itself, was useful for studying the propagation of a quench.

#### *4.5.1 Studying the movements of the cold mass of a cryostat during a quench in this cryostat*

The three following figures show the movements of the cold mass of the cryostat I2 during a quench that occurs in I2. The quench was generated by increasing the current with a high ramping rate, from 0 to 13 kA in about 2 mn. A variation of about 150 microns can be observed on Figure 6. It is due to the elongation of the cold mass because of the rise of the current. The curve of the square of the current is rigorously parallel to the curve of the longitudinal movement.

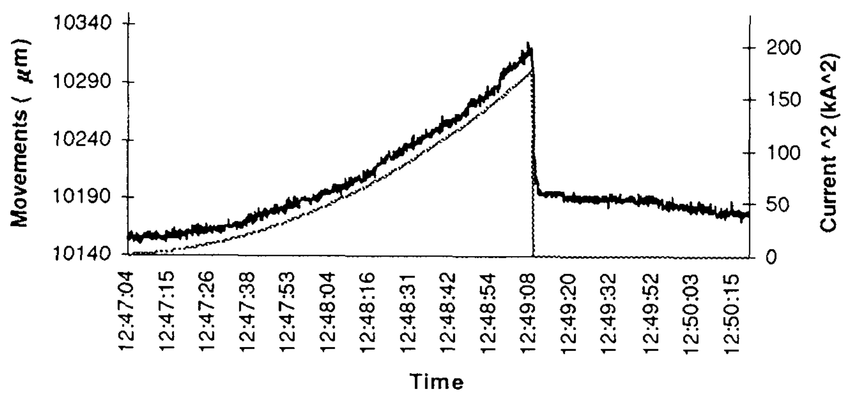


Fig. 6. Longitudinal movements of the cold mass of the I2 (mobile foot) during a quench in I2

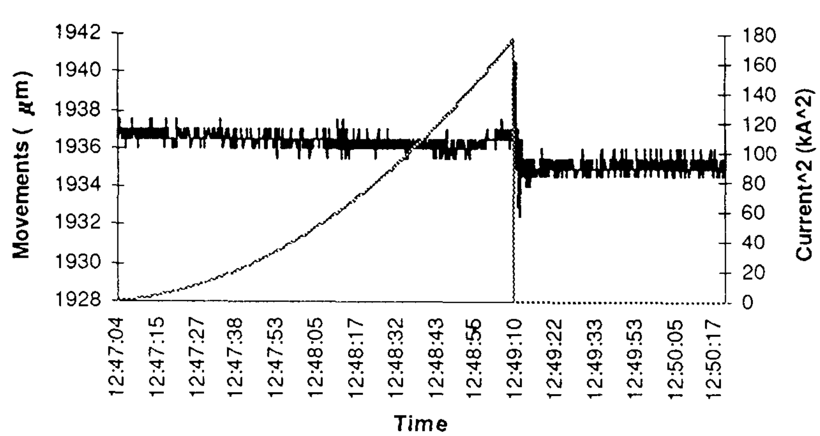


Fig. 7. Radial movements of the cold mass of the I2 (mobile foot) during a quench in I2

On figure 7 a very small movement of several microns can be observed.

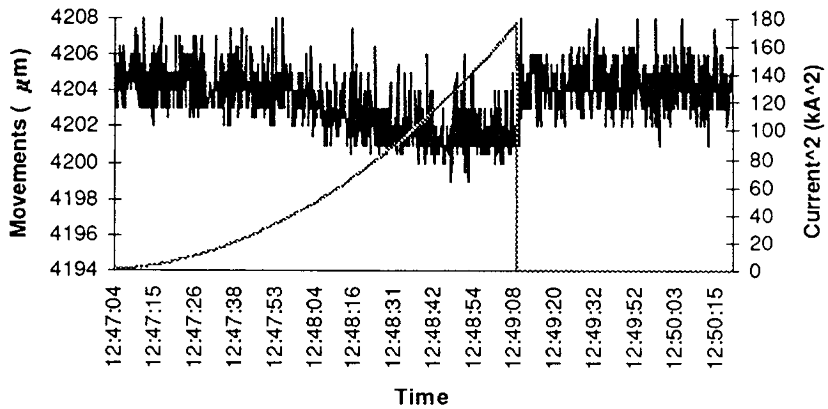


Fig. 8. Vertical movements of the cold mass of the I2 (mobile foot) during a quench in I2

No real vertical movement was detected by the system. This last figure proves that the electronic of the system is not perturbed by the effects of the quench as it could have been implied by figure 7.

On the three preceding figures, because the period of time displayed is too small (about 3 mn), the beginning of the ramping is not on the graph and it cannot be seen that the cold mass comes back exactly to its original position after several minutes.

*4.5.2 Studying the movements of the cold mass of a cryostat during a quench in another cryostat*

The figures below shows the movements of the cold mass in the cryostat SSS on the mobile foot in the three directions during a quench that occurred in I2.

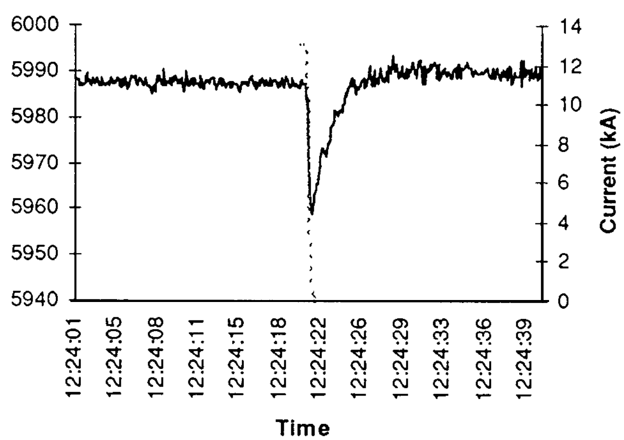


Fig. 9. Longitudinal movements of the cold mass of the SSS
(mobile foot) during a quench in I2

The graph of the longitudinal movement is different from the graph of the figure 6, because as the quench occurred in I2, no elongation of the cold mass can be observed. But a movement, like a shock wave, that seems to come from the origin of the quench (12) towards the extremity of the string can be observed.

A few seconds after the quench, the cold mass returns to its position.

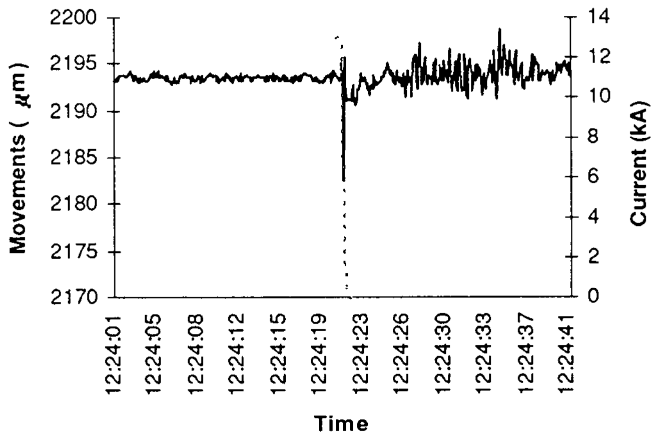


Fig. 10 Radial movements of the cold mass of the SSS
(mobile foot) during a quench in I2

As for the quench inside I2, a small movement (about I2 microns) was detected and an oscillation is to be noticed after the quench. This oscillation stops after several seconds.

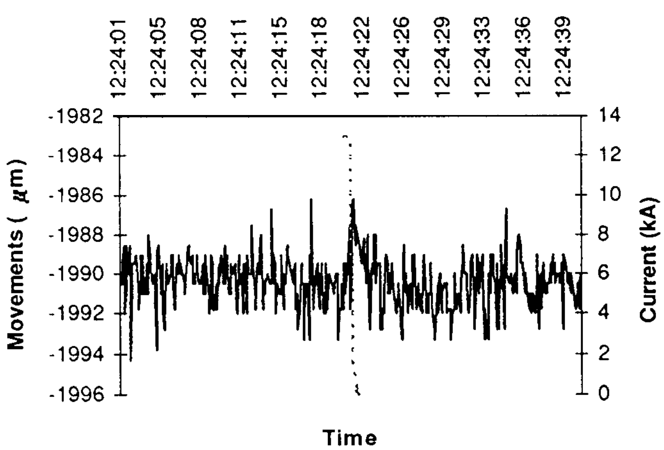


Fig. 11 Vertical movements of the cold mass of the SSS
(mobile foot) during a quench in I2

No significant movement was detected in the vertical direction.

## 5. MEASURING VIBRATIONS OF THE COLD MASS USING THE CAPACITIVE SENSOR SYSTEM

In the future LHC, a vibration of the cold mass at a frequency of 2 kHz can generate a loss of the beam.

In order to try to detect vibrations at such a frequency, the system was modified to be able to get data from one sensor at a time at a frequency of 10 kHz, instead of eight times a minute for all the sensors originally.

The acquisition was done on a Mac using Labview and the calculations using the Fast Fourier Transform.

The measurements were taken on the nine sensors during a period of time of 0.8 s at a frequency of 10 kHz, one sensor after the other because of the acquisition problems mentioned before, but exactly in the same temperature and current conditions of the string and with all the pumps stopped.

In the longitudinal and in the radial direction, the results are exactly the same for the four different sensors, it is the reason why only the results of one are presented.

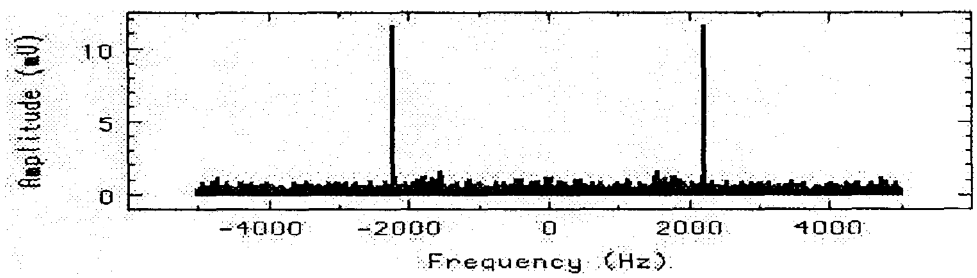


Fig. 12. Vibrations in the longitudinal direction (1 mV = 3 μm).

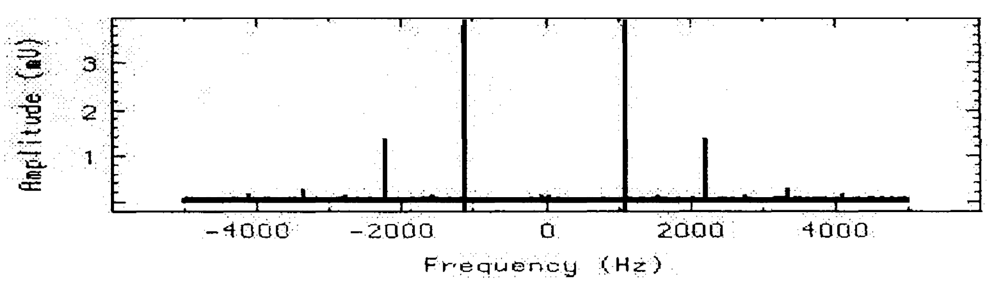


Fig. 13. Vibrations in the radial direction (1 mV = 0.4 μm).

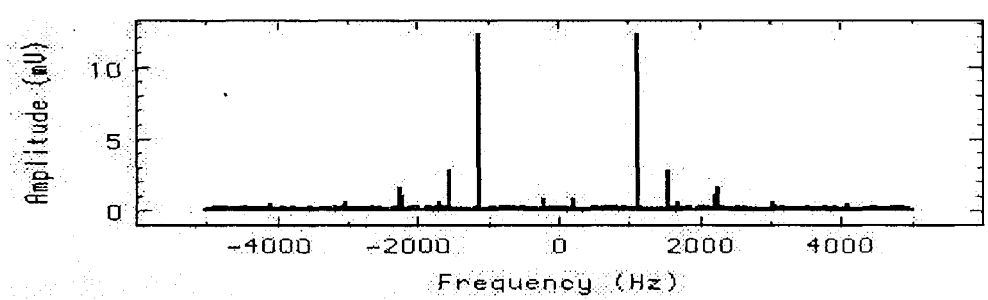


Fig. 14. Vibrations in the vertical direction (1 mV = 0.4 μm).

Some oscillations were observed in the three directions : at 2.2 kHz in the longitudinal direction but with a lot of noise, at 1.1 kHz and an harmonic at 2.2 kHz in the radial direction and roughly at the same frequency in the vertical direction.

The problem is that the system measures the vibrations of the silica rod fixed on the cold mass with respect of the cryostat on which the system is fixed. So, does the system measure the proper frequency of the rod which seems to be in the range of 1 kHz, the vibrations of the cryostat itself, or really the vibrations of the cold mass which interests the physicists ?

With the actual system, it is currently impossible to answer this question and this is the reason why it has been decided to install accelerometers on the cold mass of the SSS and of Il. The measurements will be done during “Run 2” of the string.

## CONCLUSION

It is the first time that, in a cryomagnet, the position of the cold mass with respect to the cryostat is very well known. The capacitive sensor system is very satisfactory for its accuracy as well as for its reliability.

The results of the measurements show that the feet move as expected in the longitudinal direction, are less stable than foreseen in the vertical direction but don’t move at all in the radial plane. After a quench, the cold feet come back to their original position.

The results of the measurements on this first series of cryomagnets are very interesting, first of all for the surveyors who will have to align the superconducting magnets in the future LHC, but also for the designers of the cold feet who can appreciate what progress needs to be done on the feet, and for the mechanical engineers who are designing the supports for the magnets.

At the beginning, it was foreseen to install the capacitive system only in the prototype cryomagnets, in order to prove the stability and the repeatability of the position of the cold mass during all its life cycle, from the insertion inside the cryostat to the installation into the tunnel and during the operation of the LHC.

Now, taking into account the results of these measurements and the fact that a vacuum barrier will be located very close to the SSS, very light comparatively to a dipole, the decision has to be taken if a system for checking the position of the cold mass has to be installed in all the SSS of the LHC.

As a matter of fact, it must be admitted that the system presented in this paper is not really appropriate to large series because of the high heat inloads generated (150 mW) in the cryostat and also because of its price.

## ACKNOWLEDGMENTS

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## REFERENCES

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