The Methods of the LHC Magnets' Magnetic Axis Location Measurement

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Abstract - More than 8 thousands LHC magnets of various types will be extensively measured during series magnetic test at both room and superfluid helium temperature. The precise knowledge of the magnetic axis positioning is vital for the alignment of those magnets in the tunnel. The most efficient and cost effective method with rotating pick up coil is chosen currently as a baseline for series measurement. The position of the measuring coil axis herewith is measured with a dedicated optical system. The deflection of the light beam in the air due to temperature gradient either passing through the cold bore when the magnet excited for warm measurement or through the anti-cryostat during cold measurement can reach magnitudes significantly exceeding tolerance and therefore is a critical issue. We present studies of the light deflection in 10m long dipole at warm and cold and propose means to reduce it. The result of the dipole centring powered in Quadrupole Configured Dipole (QCD) or "ugly quad" configuration and correlation with centring based on high order harmonics are presented as well.

1 Introduction

All magnets of the Large Hadron Collider (LHC) must be aligned with respect to the beam orbit with a typical accuracy in the tenth of mm range. This will require a detailed knowledge of the position of the magnetic axis of both the main lattice quadrupole and its end corrector magnets in the Short Straight Section -SSS (MQ, MO, MSCB) and the main dipole with its end correctors (MCS, MCD) with respect to the fiducials mounted on the cryostat in warm and cold conditions. The alignment in warm is necessary for proper installation of those magnets in the cryostat, meanwhile in cold it is needed for their operation.

Actually the dipole magnet has no axis and therefore its alignment is a pure geometric problem i. e. the location of the frame in which the set of harmonics is measured must be known in the reference survey system. The alignment of the corrector magnets having magnetic axes is important because of feed-down effect. Most critical issue is the SSS alignment with respect to the beam orbit.

The cold mass moves with respect to the cryostat during cool-down, and therefore some technique allowing to systematically and reliably measure the displacement of the cold mass with respect to the cryostat needs to be elaborated. Furthermore, during series measurement the SSS and main dipole, lattice magnets, will be equipped with a warm bore, the *anti-cryostat*, that will pass through the magnet and provide the room temperature conditions needed either for scanning the bore with rotating coils in case of SSS or for measuring with a set of 13 coils covering the main dipole. The anti-cryostat will not be mounted in an accurate position with respect to the magnet cold bore, and for SSS it will not be necessarily straight. The typical deviation from straightness can be estimated of the order of one mm, based on present experience on dipole prototype tests. Because of these reasons we cannot simply rely on mechanical precision and reproducibility to correlate the magnetic axis in the reference frame of the rotating coil to its location with respect to the fiducials on the cryostat.

As it was already mentioned above all auxiliary magnets must be matched with the main magnet's magnetic axis during installation in the cryostat. This means that their magnetic axis position should be known prior to mounting in the cryostat. Because at present no device is foreseen to measure location of magnetic axis of those correctors and to transfer it to their own fiducials at cold, this measurement can be done at room temperature only. Despite after assembling their magnetic axes can be measured at cold no simple means are foreseen to align them afterwards except the cryostat total dismounting that is completely unacceptable.

Therefore one can state that for every particular case a reliable and cost effective method is needed. They are described in the following.

1.1 Dipole alignment

The dipole and correctors should be mutually aligned to within some 0.3mm, the dipole itself should be aligned geometrically to some tenths of mm accuracy for mounting reasons. So far it is not clear what will be taken as a criteria for the magnetic axis of the dipole. It can be determined for example as the axis where some even harmonics equal zero (typically b_{10}, a_{10}), or the axis of a quadrupole configured dipole (QCD), as discussed later. In any case the harmonic contents measured at room temperature and cold conditions (1.8K) needs to be attached to some axis. Because of that the transversal position of the field-measuring device must be measured relative to an optically defined reference axis. The position of the auxiliary magnet's axes should be measured as well.

For the field quality measurement at cold a long coil shaft is foreseen [5]. In order to increase the efficiency of the series measurement the technique allowing to measure the magnet in one step has been chosen. A 16 m shaft is obtained by assembling 13 modules of approximately 1.25 m length each. This covers readily the 15 m length of the LHC Dipole and the adjacent corrector magnets. Two of these identical systems are able to measure the twin apertures dipole simultaneously. However, no alignment herewith is possible. Because of that another device – a *mole* is foreseen for the dipole alignment at both warm and cold conditions.

The "mole" system dedicated to warm measurement of the main dipole and correctors is presently under development [2]. This system consists of:

- mole itself – the measuring unit passing through the cold bore including: rotating pick up coil with motor, light source and angular encoder,
- optical system – motorised telescope and acquisition system,
- transporting system.

Figure 1 shows a schematic view of the mole assembly. The main component is the $\varnothing$ 41×750 mm search coil (h), made of two glass-fiber reinforced epoxy half shells enclosing three 11.5 mm wide radial coils. Each coil has 400 turns and an effective surface of approximately 3.4 m^2. The coil surfaces, relevant for the measurement of the dipole strength, have been calibrated to 10^{-4} accuracy in a reference dipole. The central coil is used for dipole bucking.

An optical system tracks the transverse position of the mole in the magnet cross section, so that the magnetic axis measured in the reference frame of the rotating coil can be transferred to external fiducials. A light emitting diode (LED) mounted on the rotating axis of the front coil flange (i) is used to create a small light spot which is viewed from the front reference bench by a fixed, pre-aligned, high quality commercial straightness telescope. This telescope is fitted with a motorized focus, a CCD camera and a Digital Signal Processor (DSP) performing image treatment. Travelling in the bent aperture of a dipole the mole has a pitch and yaw up to

2.5 mrad. At such angles a reference mounted at the front of the coil has a substantial lateral error with respect to the coil center location. For this reason the light spot is viewed through a lens mounted in front of the LED, projecting a virtual image of the light spot into the center of the rotating coil.

Since, however, the bulk of magnet tests at 1.8 K will be made with “long coils” for the dipoles and scanning machines for quadrupoles, moles will only be used for the series test at room temperature of dipoles and for special sample tests of dipoles at 1.8 K. Because of the anti-cryostat needed for cold measurement the “cold mole” being under development now has the same design but a smaller diameter.

1.2 Quadrupole

The principle of the axis measurement method for quadrupoles that we are developing is to use a rotating coil to scan the magnetic field along the SSS and hence obtain the location of the magnetic axis with respect to the rotation axis of the coil as a function of longitudinal position. The coil rotation axis will be marked by a light source (a Light Emitting Diode, LED) accurately positioned with respect to the coil ball bearings. This will allow an optical measurement of the position of the light source (i. e. the rotation axis of the coil) in parallel with the magnetic measurement. The optical measurement will be in the reference frame of the *line of sight* of the telescope. This line must be established prior to scanning the SSS using two reference positions, located on both sides of the SSS. The reference locations will be provided in practice by the magnetic axis of two short reference quadrupoles, whose fiducials are in well-known position with respect to their magnetic axes and periodically checked. The schematic representation of the relative positions is shown in Fig. 2.

Totally the rotating coils set consists of two coils attached to each other via two universal cardan joints. One of them the 600mm-length coil will measure the field quality and field integral, while the second one - 100mm-length coil will be used for the axis measurement. The last coil is instrumented with a LED and encased inside a vacuum container. The external sliding seal of the container provides vacuum in the warm bore part between LED and telescope avoiding deflection of the light (see later discussion).

1.3 Corrector magnets

The training behaviour and magnetic field quality at superfluid helium temperature are foreseen to be done for some part of the magnets during the series tests on a dedicated station, based on a vertical cryogenic Dewar container, as it is routinely done currently for the prototypes. The dedicated test stand for magnetic axis searching and transferring its position to the corrector’s fiducials has been built [1]. The most demanding tolerance is to centre these correctors with respect to the curved axis of the main dipoles to better than 0.3 mm in average. On the other hand, the accuracy of positioning the poles in the MCS or MCD correctors hardly ascertains that mechanical and magnetic axes coincide within 0.1 mm. The "warm" measuring bench is therefore equipped with all the facilities needed to mark the correctors with survey points.

The magnet is first oriented in angle on a positioning table in order to cancel respectively the skew main term and the component one order lower than the main harmonic. After the measurement coil is then replaced by a reference jig having the same rotation axis and equipped with the same reference surfaces. This jig is equipped with fingers in hard metal, able to punch survey marks in the magnet's case. Both the measurement sensitivity and the mechanics including the accuracy between these fingers and the rotation axis or the reference surfaces allow a positioning of the survey marks within 25 μm.

The systematic angular error allowed in the field direction adjustment is 5 mrad. A verification of the parallelism between the reference surface of the measuring shaft and the coils effective surfaces is possible by swopping the shaft top to bottom. The actually measured error of 2.8 mrad can be taken into account in the alignment software. The new benches allowing to remarkably simplify the alignment procedure and dedicated for industry are now under development [6].

1.4 Technological challenges

Concluding this chapter, one should note that there are a few technical problems associated with the LHC magnets alignment discovered during commissioning and qualification of the measuring system. One of them is to meet the required precision, which is rather strict and e. g. in case of SSS is tens of μm, of the measuring or instrument system frame attachment to the survey system linked with the cryostat external fiducials. It includes both the accuracy and the mutual long-term stability of those systems. Actually this is a general problem of 3-D systems, where one dimension, length of the SSS or main dipole cryostat being of the order of 10m, is more than one order longer than other ones. Another problem is deflection of the light.

It was already observed during the quadrupole and dipole cold mass warm measurement [3, 4] that even at relatively low excitation current needed for warm measurement there is a significant deflection (order of 0.4mm) of the light when it passes the cold bore. Because this deflection is much larger than the tolerance required, the measuring system could be accepted only if either the deflection is stable and predictable enough to be taken into account afterwards or if there is some way to avoid or at least essentially reduce the deflection.

The absolute deflection of the light passing the warm bore of the cold magnet displayed very large deflection. This is due to the fact that the anti-cryostat is resting on the cold bore via so-called cryogenic supports placed along the magnet at distance of ~0.6 m. Below those spots the temperature is 1.8K. Obviously due to heat leakage a longitudinal gradients of the temperature occur. In 10m long dipoles, at cold, deflection of the light was 6.3mm, that corresponds to a uniform temperature gradient along the cold bore of $dT°/dy \cong 74.4$ [°K/m]. This deflection is the source of the largest error of the system and therefore we concentrate mainly on this.

2. Light Beam Deflection

To perform the test the 10m long dipole model has been installed onto four jacks allowing to move the magnet vertically by +/- 20mm. The LED herewith was placed onto individual support at one end of the dipole visible through the cold bore with the telescope located at the opposite end of the magnet. In order to measure long-term behaviour of the magnet's parameters, such as the cold mass cooling down, the mutual position of the LED and telescope must be very stable and controlled. Our experience shows that a reference system is needed for that purpose. We employed the reference system, which includes a mirror able to reflect the LED installed on a heavy concrete block. Hereby one can see the image of the LED either through the cold bore or through the outside of the magnet. Thus this system, aligned once before the test, allows checking or even measuring the stability of the relative position of telescope and LED. Moreover, to avoid any unwanted effects, an absolute test has been done a few times during the measurements: the position of the LED image through the aperture has been measured with and without dipole, lifting the magnet up so that a clear view could be obtained.

To analyse the deflection as function of the powering level the magnet was excited with four current values 15, 20, 25 and 30A. The resistance of the dipole at room temperature is ~ 4.06Ω. The energy dissipation inside the cold mass equals ***920W*** at 15A, ***1624W*** at 20A, ***2538W*** at 25A and ***3720W*** at 30A of excitation.

We have measured the temperature of the magnet in two ways: with a temperature gauge inside the second cold bore and by means of the DVM i. e. measuring the voltage drop on the magnet the temperature of the coil. The time dependence of the temperature obtained is a linear function, meaning that the heating process is adiabatic. The time constant of the temperature relaxation for a 10m dipole at room temperature is about $\tau_{cold\ bore} \approx 14\ hours$.

At the same time we have measured the deflection of the light beam passing through the cold bore. The typical behaviour of the deflection of light during both warming up and cooling down of the magnet is presented in Figure 3. The time constants for the light beam deflection heating up and cooling down were calculated from the exponential fit of the experimental data (see Fig. 3). All measurements were done at the same position of the magnet, more precisely for a light beam passing in the center of the cold bore all along the magnet. As it was observed the deflection establishes after beginning of the heating and decays during cooling following the exponential function with more or less the same time constant order of 18 min. Moreover, this time constant is independent from the excitation level. On the other hand we have found that there is a strong correlation between power and light beam deflection. This varies from 0.14mm at 15A to 0.45mm at 30A of current. The average ratio is ~8.7W/μm and is rather linear with variation of ~30μm, close to our estimated accuracy. This result imply that to limit the deflection to less than 50μm the current can not exceed **10A**.

In the attempt to localise the origin of the light deflection effect, the cold bore was scanned with the light in vertical direction Y by moving the magnet with the jacks by approximately +/-19mm from the center. The purpose of this experiment was to study the dependence of the integrated vertical gradient of the temperature over the cold bore length on the vertical position of the light beam with respect to the cold bore. The cold bore axis and the light beam were herewith kept parallel to each other. The dipole was powered at 20A and the scanning step was 2.5mm. The result of the scanning is reported in Fig. 4. The deflection appears to be a strong function of the relative vertical position of the beam in the magnet cold bore.

Another series of experiments was done to localise in the longitudinal direction any region creating large beam deflection. This was done using *"shields"* of different types at different positions along the magnet. A shield serves both as a thermal bridge shorting the temperature gradient along the magnet and as insulator of the air in the cold bore from the wall. Different types of shields have been used. As a most efficient shield a 1m long copper tube, 40mm of diameter and 1mm wall thickness was used for longitudinal scan. The deflection magnitude against longitudinal position of the shield is shown in Figure 5. Leaving the detailed analysis to a later section, we note here that according to this last result (see Fig. 5) the effect of deflection is not evenly spread along the magnet but can be localised at a region 200mm away from the magnet end.

Laminar nitrogen flows have been applied from each side of the cold bore: at the telescope's side and at the LED' s side in order to study the influence of the different directions of the flow on the light deflection. It was observed that the cleansing of the cold bore with high and turbulent flow perturbs the steady state configuration of the air. As a result just after cutting the initial cleansing flow the deflection of the light is zero. The re-establishing of the steady air configuration in terms of deflection appears with a time constant of about 10min**.** The typical dependence of the deflection on the flow rate has a minimum at around 30 – 50 l/h.

The light deflection measurement was repeated with a vacuum level of approximately **1mbar** inside the cold bore. The light beam deflection is proportional to the density of the gas. At constant temperature the density is inversely proportional to the pressure. Therefore the expected deflection equals to $0.45\frac{P_{vacuum}}{P_{normal}}[mm] = 0.45\mu m$ and is much less than our resolution. The measurement confirmed our expectation, i.e. no appreciable deflection was observed during this test.

3. Analysis of the results and comparison with computer simulation

In this chapter we will analyse the results obtained in the experiment, present the result of the computer simulation performed basing on measured boundary conditions and then compare those results.

The light beam deflection in y (vertical) direction is due to a temperature gradient dT/dy. The effect of a non-uniform temperature (and density) gas is that of an optical prism, where higher density gas gives a larger refraction coefficient (the *thick* side of the prism) compared to lower density gas (the *thin* side of the prism). In general the temperature gradient can be a function of position along the length L of the optical path in the magnet. The deflection in this case can be estimated as:

$$\Delta Y \approx 10^{-6}\frac{L}{2}\int_0^L \frac{dT}{dy}dz\,, \qquad (1)$$

where z is the longitudinal co-ordinate.

As one can see from the summary in Table 1, the time constant of the establishment and decay of the light deflection are almost independent from the energy dissipation in the magnet. Moreover the cooling down time constant of the deflection decay is close to the fast component of the cold bore's temperature decay time constant. Thus one can conclude that a deflection is established during the initial phase of the thermal transients that precedes the linear temperature increase associated with the adiabatic heating. This is why the cold bore cool-down time constant essentially differs from the light deflection decay time constant. Similarly the deflection decays during the fast cooling phase that takes place before the slow temperature decrease.

The tests performed with the thermal shields placed at different axial position along the cold bore (see the results shown in Figure 5) indicate that the light beam deflection is a local effect. The vertical temperature gradient appears to be concentrated at the ends of the magnet. The temperature gradient zone is approximately 200 mm long inside the magnet, starting at about 160 mm from the end-caps of the cold mass shrinking cylinder and reaching approximately one aperture length inside the coil.

To explain the deflection we postulate the presence along the cold bore of localised, natural convection cells driven by a longitudinal temperature gradient (i. e. along the magnet). The mechanism generating and sustaining the flow in these convection cells is qualitatively explained below. The Joule heat generated in the coil causes temperature gradients, in particular a gradient will be present along the cold bore between locations close to the coil ends (heated) and locations outside the cold mass (cooled). The end-caps of the cold mass shrinking cylinder acts in effect as a cold heat sink owing to the large thermal inertia. The longitudinal gradient along the cold bore induces a similar longitudinal gradient in the air temperature. This initial temperature distribution is unstable and evolves into a convection cell.

The initial temperature profile, with vertical iso-temperature lines, is skewed by mass convection. In particular in the centre of the convection cell we will have warm gas at the top of the cold bore, and cold gas at the bottom. The net effect of the natural convection cell is therefore to transform a longitudinal temperature gradient dT/dz into a positive transverse gradient dT/dy. This mechanism has been confirmed by simulations.

Based on the measurements performed we can compute the strength of the localised optical prisms (and the associated vertical temperature gradients) in the two magnets ends. For simplicity we assume that the regions with vertical temperature gradient are short, so that we can make a *thin* lens approximation, and that they are identical.

Naming $\Delta\alpha$ the refraction angle through the thin prism, identical for both sides, a first order approximation of the total observed deflection is:

$$\Delta Y_{tot} \approx \Delta\alpha\left(L_{LED} + L_{tel} + L_{mag}\right) \qquad (2)$$

In our measurements $L_{LED} \approx L_{tel} \approx 1.5$m and $L_{mag} \approx 10$m. From the deflection data we have calculated the angle $\Delta\alpha$ for each value of the operating current, reported in Tab. 1. The associated temperature gradient dT/dy, also reported in Tab. 1, was calculated using:

$$\Delta\alpha = \frac{d\Delta y}{dz} = 10^{-6} \cdot \frac{dT}{dy} \cdot \delta z \text{, for } \delta z\text{=200mm,}$$

obtained from Eq. (1) using the thin lens approximation. Finally from the vertical temperature gradient we have estimated in Tab. 1 the vertical temperature difference ΔT_y at a distance of 12.5 mm (half the cold-bore diameter).

The conclusion made above based on the measurement results was entirely confirmed by the computer simulation. The map of the temperature in ZY plane at X=0, the vertical plane passing through the cold bore center for an axial gradient of 5°/m is shown in Fig.6. The final dependence of the integrated gradient of the temperature as a function of the vertical co-ordinate of the light beam passing however parallel to the cold bore axis is shown in Fig. 4. The last curve is entirely consistent with the measured one. Furthermore the calculated maximum integral of gradient is 20K agrees with the measured 18.2K at 25A of excitation (see Table 1). Thus one can conclude that the physical explanation we gave above matches with the computer simulation performed within 10% of accuracy.

Concluding this chapter, one can state that the light deflection can be avoided either by short circuiting the localised convection cells (using a thermal shield), or using a modest flow of dry nitrogen or applying vacuum. Of the three methods to avoid deflection, the second (gas flow) seems the simplest and more attractive. In fact it could be used systematically during series measurements to refer the measured harmonics to an external reference (magnets fiducials). Unfortunately all methods assume some modification of the system.

A different approach consists in a measurement at very low current in the magnet. As we have shown the light beam is deflected proportionally to the Joule power input, so that using a current level of the order of 1 A should not produce any noticeable effect in a dipole. A dipole axis measurement at low current could be performed in different ways, e.g. using the quadrupole configured dipole (QCD) configuration or AC excitation. Let us consider the QCD method for the axis measurement in the LHC dipoles.

4 QCD configuration

The applied rotating coil technique to search the location of the magnetic axis has much higher sensitivity to quadrupole field than to dipole one. Despite the supeconducting dipole design supposes internal connection of the upper and lower half-coils in series the existence of voltage taps allows us to inject small current there in opposite direction. The calculation of the QCD field performed with ROXIE6.0 code gives rather bad quality of the quadrupole field – this is why it is called "ugly quadrupole". However, because the magnetic axis only is essential there, high order harmonics do not matter. The main benefit of QCD is the larger sensitivity of the rotating coil to offset:

$$\frac{S_1^{ugly}}{S_{n-1}^{dipole}} \cong \frac{3000}{(n-1)} \cdot \frac{I_{u.q.}}{I_d}$$

According to the above equation one can state that for typical n=11 used for alignment at cold the equal sensitivities could be reached at $I_d \geq 300\ I_{u.q.}$. In other words it means that QCD method gives us power reduction factor of 10^5. The requirement to the current imbalance for 50μm centring accuracy is: $\frac{\Delta I}{I} \leq 1.7 \times 10^{-3}$, that is not very strict and can be reached with commercial power supply.

More than seven 1m long models were intensively measured in QCD configuration in order to study the measurement accuracy and stability of QCD axis position at different temperature. The influence of the thermal cycle was considered as well. The result of this investigation allows to state that expected instability of this axis in the range of 1.8K to 300K is less than **24μm** (for comparison the measured random spread of the offset at warm is order of 1mm). This total spread includes the random error of the measurement itself and pick up coil / dipole mutual position instability.

Because the QCD method is supposed to be used as a reference for cold and warm centring, establish the correlation between QCD and some axis defined in pure dipole configuration at cold is a very important issue. The lowest even harmonic equal to zero in LHC dipole is C10. It is valuable, that next to it the odd harmonic C11=0.61unit is comparable with C5 and C7. Because the accepted centring is based on feed-down phenomenon these couple of harmonics was chosen as a baseline for the centring at high field. The correlation between QCD and axis where C10=0 is shown in Fig. 7.

Basing on those dipoles statistics one can conclude that QCD and C10=0 axes are consistent each other with accuracy of ~**70μm**, that is less than tolerance.

5 Conclusion

The alignment of the magnetic axis of the superconducting magnets in the LHC is one of the critical issues in the project. We have described here the systems that we are developing to measure and verify the alignment of the lattice elements. Although based on the same principle of the rotating coils, the systems are independent and individually calibrated, so that cross checks will be possible. This is of paramount importance to guarantee a minimum of systematic and random errors.

Among the technological challenges to be mastered, we have found that air turbulence and air stratification are by far the most critical. To overcome the systematic errors introduced by temperature gradients in the air inside the bore of the magnet under alignment we have devised several solutions. During cold tests we plan to evacuate the optical path for the survey inside the magnet bore, thus avoiding any systematic error due to temperature gradients. For warm tests we try to avoid the vacuum option, for obvious reasons of simplicity. The alternatives discussed in this paper appear then to be promising candidates, and in particular the low power excitation of the magnets for centring purposes (dipoles in QCD configuration) followed by higher current measurement of harmonics.

The systems are either recently commissioned (mole) or in the final stage of procurement (bench for SSS alignment, bench for corrector alignment). The coming months will therefore be critical for the qualification of the systems and the establishment of suitable and efficient measurement procedures.

6. References

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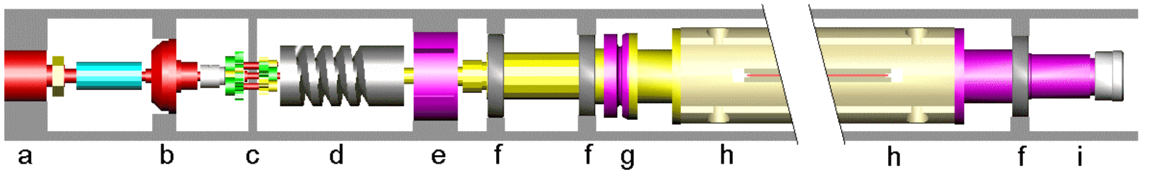

Figure 1. Schematic drawing of main mole components: (a) multiturn potentiometer, (b) piezo-motor, (c) 3:1 reduction, (d) helical coupling, (e) encoder, (f) ceramic ball bearing, (g) Ti coupling, (h) coil, (i) LED and optics.

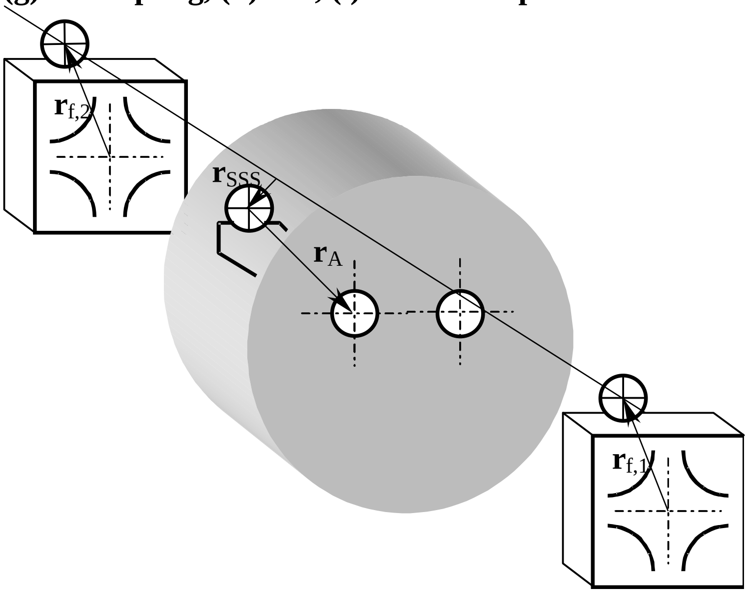

Figure 2. Schematic view of the position of the SSS cryostat with respect to the line passing through the axis of the reference quadrupoles, where r_A is wanted coordinate of the SSS axis in fiducials frame, vector r_{SSS} defines the SSS position in the reference frame and $r_{f,1}$, $r_{f,2}$ are the reference quads fiducial positions with respect to the magnetic axis.

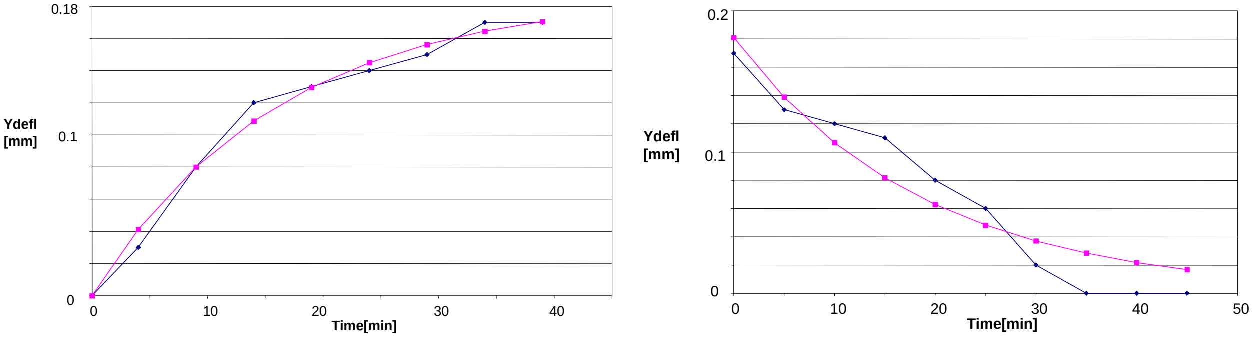

Figure 3. Measured light beam deflection (diamonds) and exponential fit (squares) during heating up and cooling down at 20A powering.

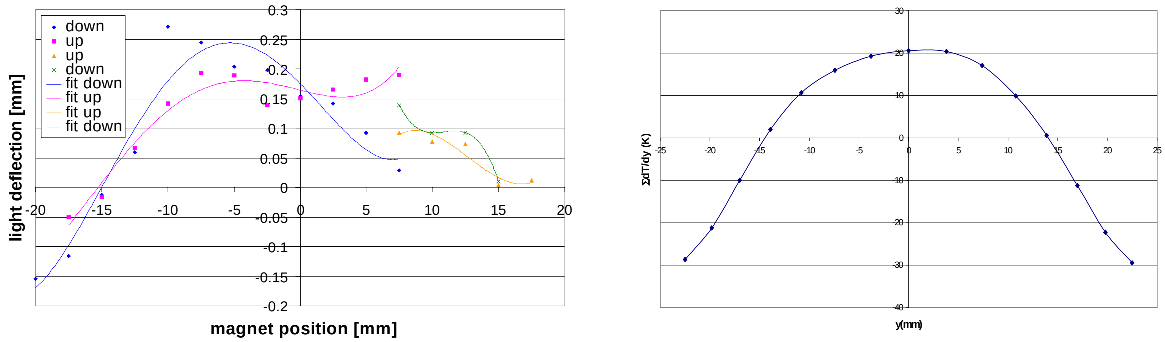

Figure 4. Measured light deflection and calculated integral of gradient against position of the magnet at 20A of excitation

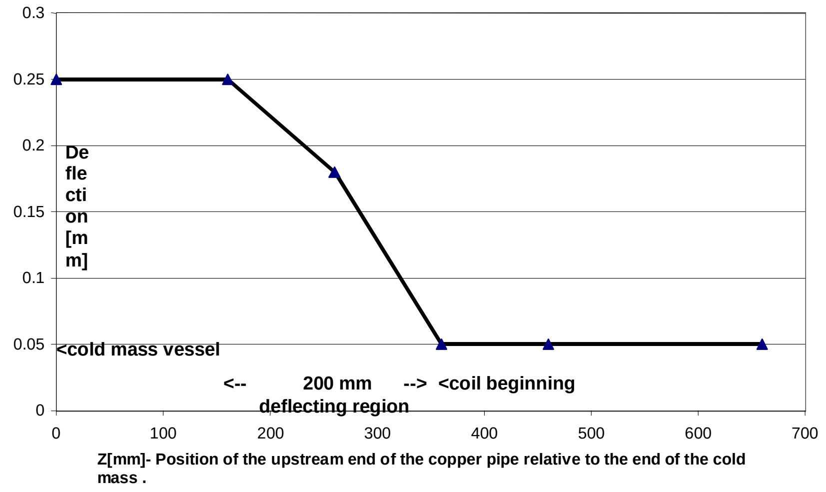

Figure 5. Deflection as a function of the position of the thermal shield (copper pipe).

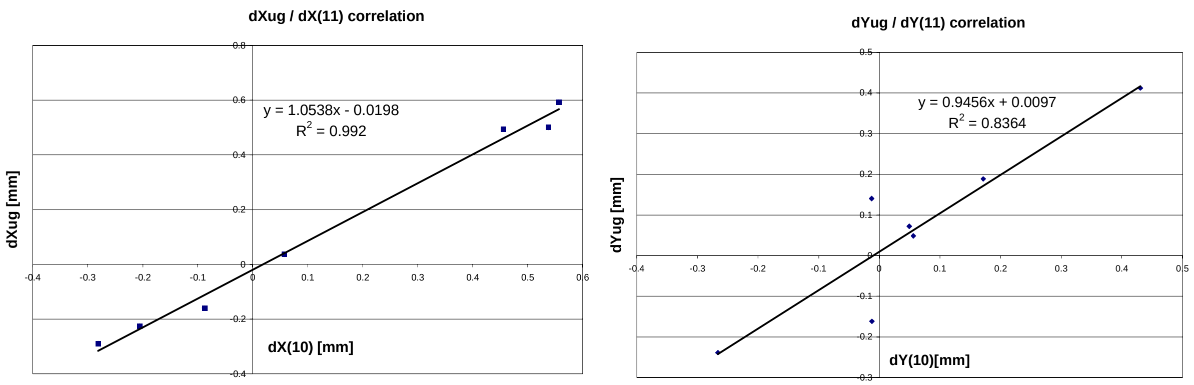

Figure 7. QCD / C10=0 axes correlation, QCD axis was measured at warm.

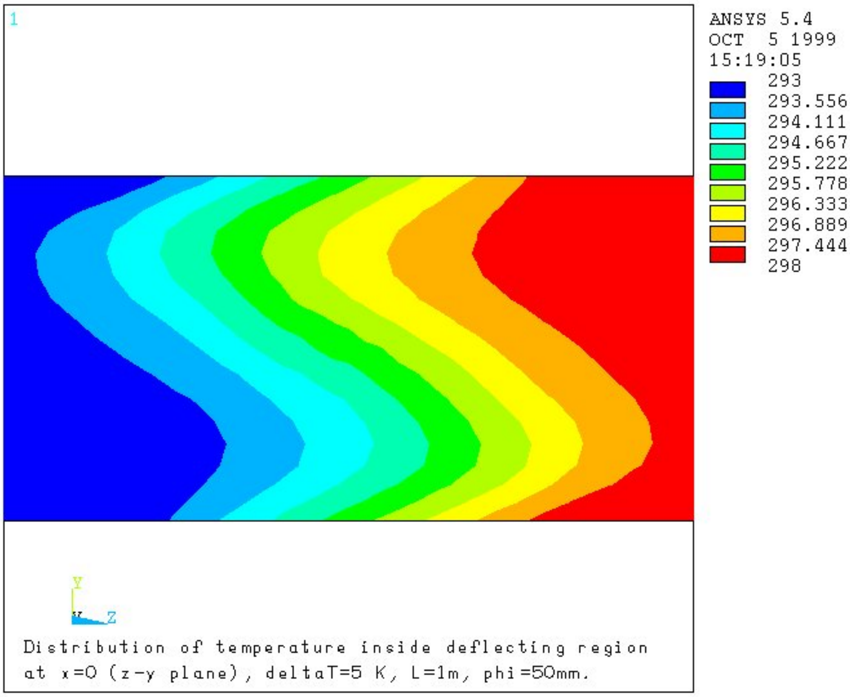

Figure 6. Map of the temperature in ZY plane.

Table 1. Deflection angle, associated vertical temperature gradient and temperature difference as a function of the operating current in the magnet.

Current	[A]	15	20	25	30
$\Delta\alpha$	[mrad]	0.0107	0.0131	0.0192	0.0346
dT/dy(*)	[°C/m]	53.5	65.5	91	173
ΔT_y at 12.5mm(*)	[°C]	0.67	0.82	1.14	2.2

*) over 200mm length of the deflecting region