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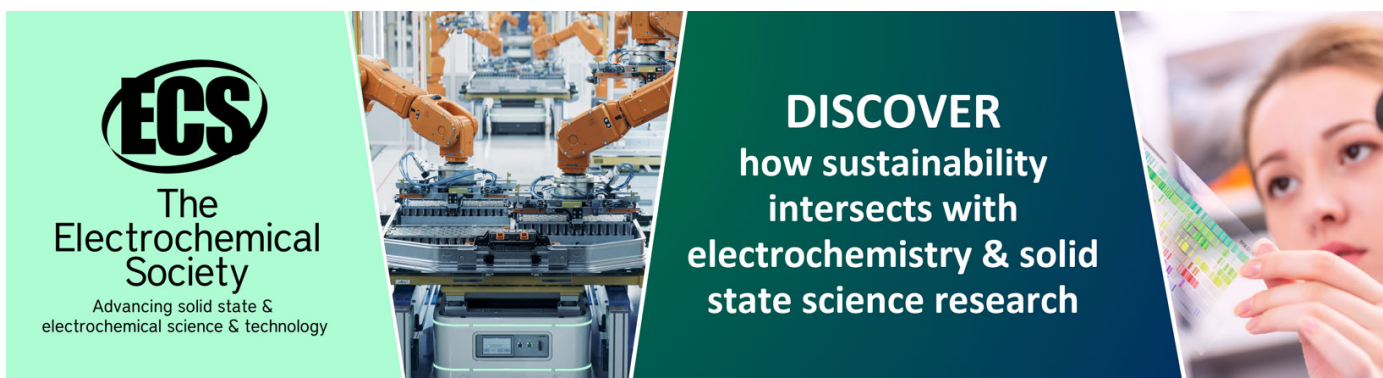
Thermal engineering of optical mirrors for use at cryogenic temperature inside a LHC magnet cryostat

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Thermal engineering of optical mirrors for use at cryogenic temperature inside a LHC magnet cryostat

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Abstract. In the frame of the HL-LHC project, innovative technical solutions are sought to measure accurately the position of the magnet helium vessel inside the cryostat. To this end, a system based on laser-interferometry is being designed to monitor the displacement of the vessel through dedicated openings in the new HL-LHC magnet cryostats. In order to test such a system on a full-scale setup in representative operating conditions, a LHC dipole cryostat was modified to integrate the system optical lines of sight and the reflective mirrors were mounted onto the magnet helium vessel.

Upon the first cool down of the magnet to 80 K, severe ice-like condensation started forming on the reflective surface of the mirrors hence making the system unusable at cold. This was attributed to the condensation of the residual gas remaining in the cryostat insulation vacuum on the mirror surface. In this configuration the mirrors acted as local “cold spots” since they were purposefully sticking out of the multi-layer insulation (MLI) that is otherwise covering the magnet helium vessel.

In order to cope with this condensation issue, a dedicated study was carried out to design and manufacture a passive temperature regulation system based on a thermal insulating support and a thermal radiation intercept in order to keep the mirrors just above the expected freezing temperature in operational conditions.

This paper details the thermal engineering study leading to the design of the insulated mirrors and presents the technical solution retained as well as the latest test results.

1. Introduction

1.1. LHC cryostat alignment

Critical elements of particle accelerators such as magnets or RF cavities, often require a very precise position alignment in order to fulfil their function. During the LHC design phase, this need for precision has guided the implementation of a complete strategy to ensure that the magnet position can be known precisely and that they can be realigned when required (see Ref. [1]).



In the case of the main LHC magnets, systematic measurements have been performed to measure the magnet helium vessel position inside their cryostat and test campaigns were conducted to quantify their displacement relative to the cryostat upon cool down.

During the accelerators operation, the helium vessels are enclosed inside their cryostat, so the actual position of the magnet helium vessel in operational conditions is not measured in-situ but inferred from the cryostat position.

In the frame of the HL-LHC project, it is now planned to replace the LHC inner triplet magnets of the LHC interaction point 1 (Atlas) and point 5 (CMS) by innovative Nb₃Sn quadrupole magnets in order to increase the particle collision rate by decreasing further the beam diameter at collision. Therefore the knowledge of the magnetic position of these magnetic elements will become even more stringent than it used to be for the LHC.

In order to provide a measurement of the magnet position, in addition to the cryostat position, a method was sought to measure in-situ the position of the magnet helium vessel inside the cryostat.

A possible way to achieve this is the use of optical measurement techniques by interferometry (see Ref. [2] for more details).

1.2. The Frequency Scanning Interferometry (FSI) system layout

The FSI system allows absolute distance measurement between the focal point of the interferometer and the centre of a corner cube reflector (CCR). In the case of the FSI implementation on the LHC magnets, the CCR mirror is fixed onto the magnet helium vessel and the optical head is looking through a feedthrough located on a flange opening on the cryostat vacuum vessel (see Fig. 1).

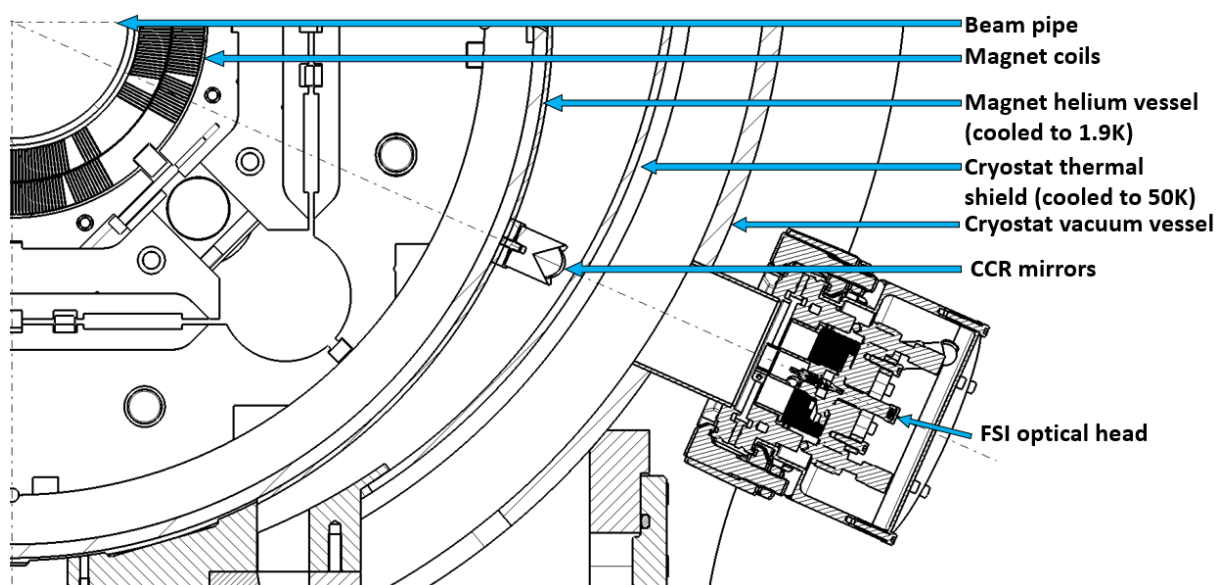


Figure 1- Project of implementation of the FSI system on the MQXFB quadrupole magnet – ¼ cross section

The CCR mirror will then be cooled down along with the magnet helium vessel and follow its movements while the optical head is fixed to the cryostat flange. Thus the continuous monitoring of the CCR position with the FSI system will give a continuous measurement of the helium vessel position relative to the cryostat.

In order to compute the helium vessel position all along its length, a series of four FSI interferometers are positioned at three different longitudinal planes along the cryostat.

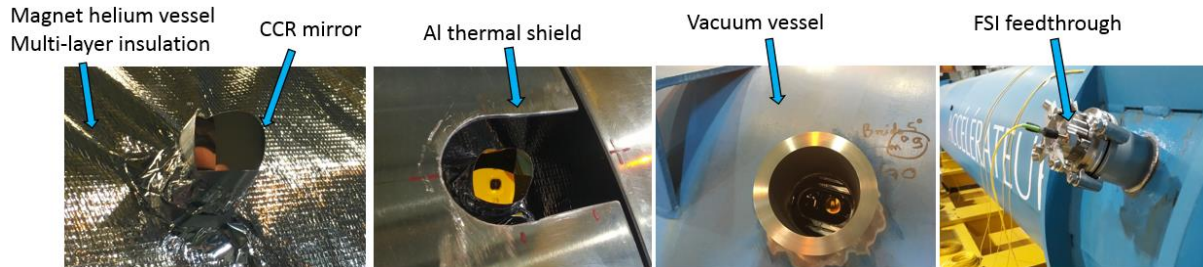


Figure 2 Actual implementation of the FSI system on the LHC dipole magnet for testing

Fig.2 details the implementation of the system with the CCR mirror that is rigidly attached to the cold mass and sticking out from the multi-layer insulation (MLI) cover in order to be visible from the outside. The aluminium thermal shield plate, where openings have been prepared to open the line of sight between the outside and the reflector, is then placed on top. Eventually this assembly is put inside the LHC dipole cryostat where flanges have been added at the position of the reflectors.

2. First cool magnet down

In August 2018, the dipole magnet fitted with the FSI system was cooled down to 80K. During the magnet cool down, the optical signal on the reflectors was progressively lost. A look at the CCR through the viewports showed that the reflective surface were covered with some thick deposition (see Fig. 3).

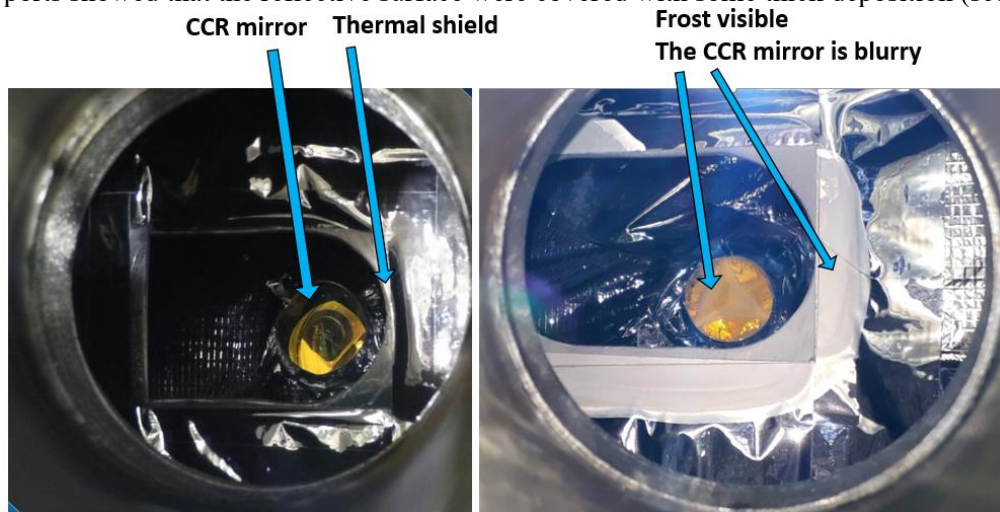


Figure 3 View of the CCR through the view port under vacuum (top) and after cool down to 80K (lower)

From Fig. 3, we can see that the deposit on the surface of the CCR seems to show a crystal-like shape and looks similar to frost. After the subsequent warming up of the magnet helium vessel, but still under insulation vacuum, the “frost” had disappeared, the CCR were reflective again and the signal could be processed.

In order to reduce the potential effect of gaseous impurities initially present in the insulation vacuum volume, the vacuum vessel was vented with gaseous nitrogen several time in order to rinse the impurities as much as possible. A subsequent cool down showed slightly more favourable results initially with a degraded but acceptable residual reflection on the CCR after cool down. However the situation progressively degraded in the next days until the reflection signal was lost again.

3. Further investigations

From the cool down observations, there is a visible deposition on the reflective surface of the CCR at cold conditions (Fig. 3) that is evaporating when warmed up again. From Fig. 3 we can see that this deposit is also visible on the edge of the thermal shield.

Thus it is supposed that a phenomenon of gas condensation is happening on the cold surfaces. Although this phenomenon is usually favourable in the LHC operation, since it helps to improve the performance of the insulation vacuum by trapping residual gas on the cold spots, it is here clearly detrimental to the performance of the FSI system by preventing any usable light reflection from the CCR mirror.

From Fig.4, we can see the gas condensation temperature for each gas specie naturally present in ambient air at the corresponding vapour pressure.

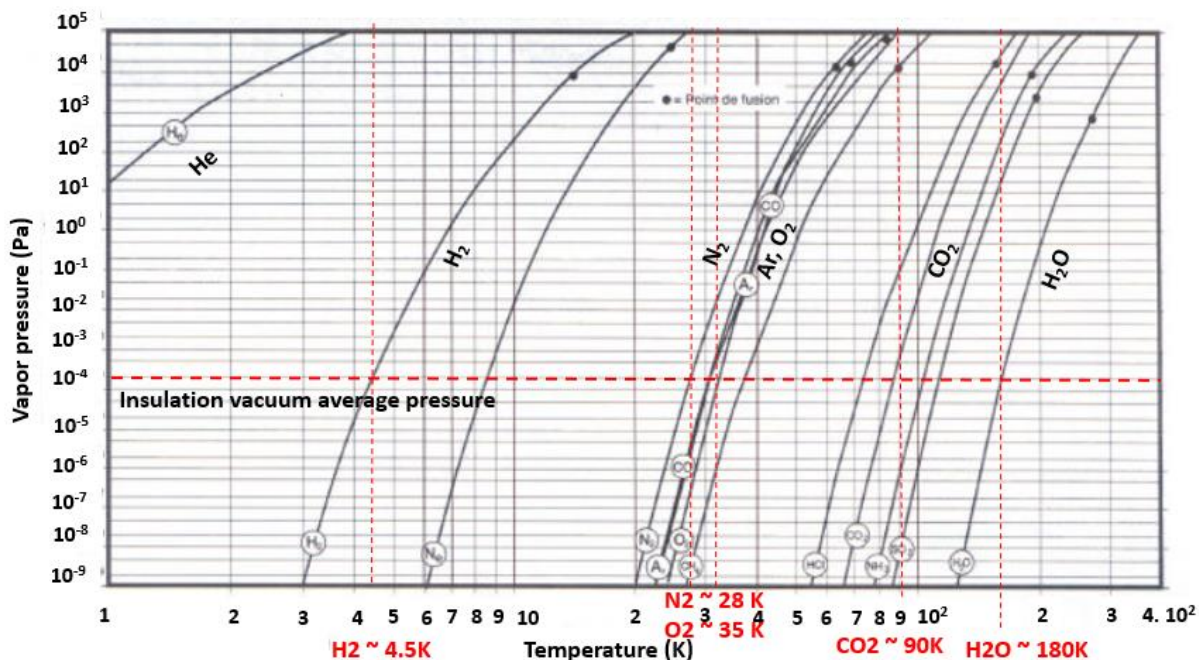


Figure 4 Table of the condensation temperature of various gas at different partial pressure – Adapted from Ref. [3]

From Ref. [4], we know that the main outgassing happening in the insulation vacuum is due to water vapour being trapped inside the layers of the MLI insulation itself.

In addition, some further analysis of the magnet cool down showed that the freezing of the target was happening around 200 K of helium vessel temperature, hence strongly suggesting that the pollution of the reflective surfaces was principally due to water vapour freezing.

4. Strategy to cope

By conservatively assuming that the insulation vacuum residual pressure is composed of 100% of gaseous water, we can see from Fig. 4 that, at the insulation vacuum residual pressure of $1E-6$ mbar, the vapour condensation should happen at a temperature of around 180 K.

This implies that managing to keep a CCR mirror temperature above 180 K should in principle keep us free from the water vapour condensation.

In order to heat up the CCR to close to 200 K while keeping the heat in-leak to the cold mass to a minimum, it was decided to make use of the thermal radiations from the vacuum vessel to keep the reflector at 200 K while insulating the reflector from the cold mass as much as possible. A sketch of the concept principle is visible in Fig. 5.

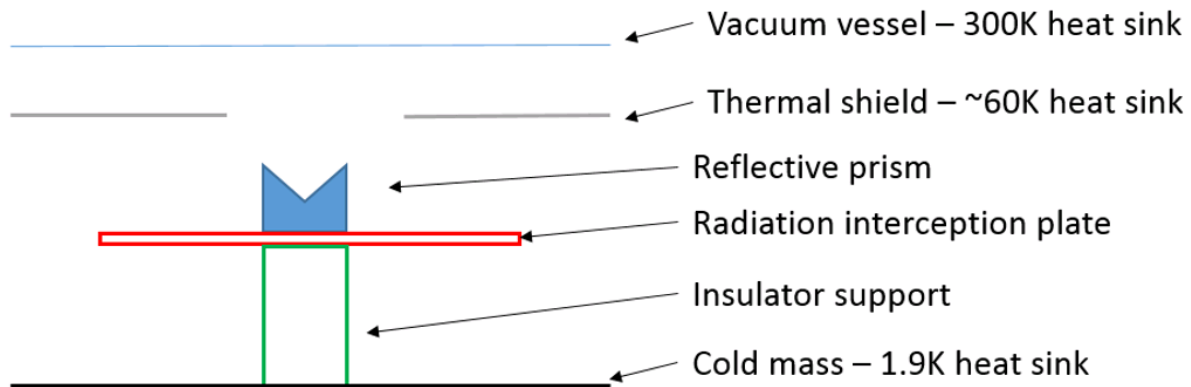


Figure 5 Conceptual sketch of the insulated reflector

In order to warm up the CCR mirror, we have decided to make use of the heat irradiated from the vacuum vessel, which will be deposited on a radiation interception plate. An insulated support will then provide a rigid link between the reflector and the cold mass while limiting the conducted heat flux to a minimum.

5. Temperature regulation system design

5.1. Design guidelines

The heat inlet of the system is driven by the thermal radiation emitted from the vacuum vessel inner skin and passing through the opening of the thermal shield. Unfortunately only a portion of this heat will irradiate the radiation interception plate, the rest shall be lost through the gap between the radiation plate and the thermal shield.

In order to estimate this power inlet, we can write Stephan-Boltzmann equation in a simple way:

$$q_{i \rightarrow j} = \sigma \cdot \varepsilon_i \cdot \varepsilon_j \cdot S_i \cdot f_{i \rightarrow j} \cdot (T_i^4 - T_j^4) \quad (1)$$

Where $q_{i \rightarrow j}$ is the power irradiated on the radiation plate from the thermal shield opening, σ is the Stephan-Boltzmann constant, ε_i the emissivity of the vacuum vessel inner surface, ε_j the emissivity of the radiation plate, S_i the surface area of the thermal shield opening, $f_{i \rightarrow j}$ the view factor between the thermal shield opening and the radiation plate, T_i the temperature of the vacuum vessel and T_j the temperature of the radiation plate.

This power is expected to be extracted through conduction of the insulator support to the cold mass as well as secondary radiation emission of the setup (from the back of the radiation plate and outer surface of the insulator plate) to the volume between the cold mass surface and the thermal shield inner surface.

$$q_{j \rightarrow \text{lost}} = \frac{S}{l} \cdot \int_{1.9K}^{T_i} \lambda(T) dT + \sigma \cdot \varepsilon_{jb} \cdot S_j \cdot (T_j^4 - T_k^4) + \sigma \cdot \varepsilon_l \cdot \int (T_l^4 - T_k^4) dS \quad (2)$$

Where $\frac{S}{l}$ is the cross-section to length conduction ratio of the insulator support, $\int_{1.9K}^{T_i} \lambda(T) dT$ is the thermal conductivity integral of the insulator support material, ε_{jb} is the emissivity of the back of the radiation plate, S_j is the visible surface of the radiation plate, T_j the temperature of the receiver plate, T_k the equivalent temperature of the cold mass volume, ε_l the emissivity of the insulator material surface, T_l the temperature of the insulator surface.

Therefore, by choosing the right set of parameters as described by eq. (1) and eq. (2), we can then tune the system to give it a steady state temperature T_j of 200 K which will then prevent water vapor deposition on the CCR mirror.

5.2. System design

The insulator support was produced by 3D printing of epoxy polymer material through stereolithography. Of all available materials, epoxy resin showed the best balance between material stiffness and low thermal conductivity. However its surface emissivity is high (~ 0.9) which is detrimental to the radiation thermal performance of the system.

The design was made in order to increase the conduction thermal resistance as much as possible while keeping a low total height in order to fit in the thermal shield enclosure.

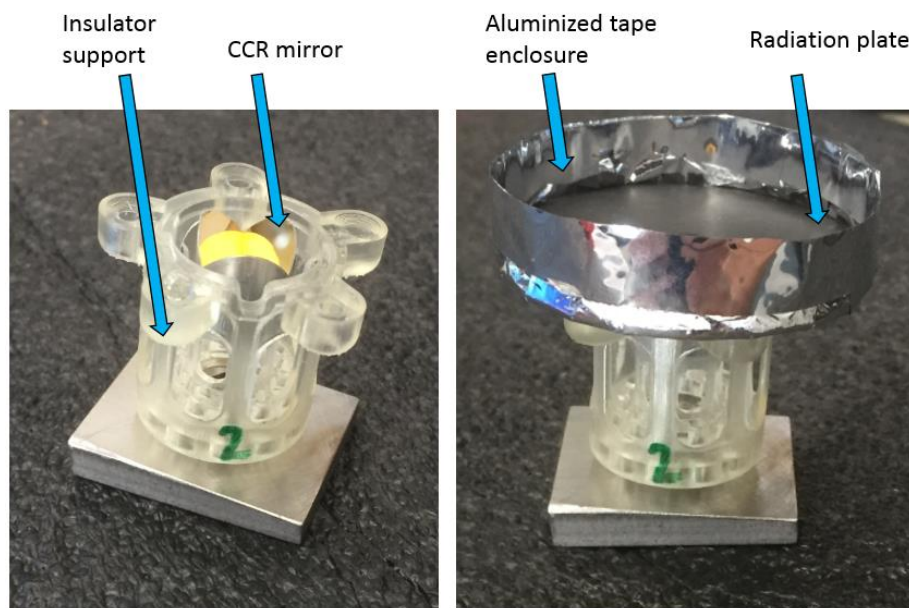


Figure 6 Insulating system design (left) with the CCR mirror attached (right) fitted with the interception plate

On Fig. 6, the radiation plate is visible. It is an aluminium plate with a high emissivity paint on the top surface (to increase ε_j in eq.1) and it is covered with Mylar aluminized tape on the underneath to avoid the parasitic heat loss by self-emission of the plate (in order to reduce the term ε_{jb} of equation 2).

The aluminized tape is also used to increase the apparent height of the setup in order to close as much as possible the gap between the thermal shield and the radiation plate. The fact that it is almost perfectly reflective enables a high effective view factor $f_{i \rightarrow j}$ (eq. 1).

The diameter of the radiation plate in the current setup is 40 mm and is equal to the thermal shield opening. This was deemed sufficient after the FE simulations check but can be modified in necessary for future applications.

5.3. Thermal analysis

In order to maximise the power inlet of the system, the top surface of the radiation plate is covered with a high emissivity black paint with an emissivity of 0.9, the aluminized tape allows to increase the view factor by reducing the residual opening of the thermal shield to a minimum, the radiation plate and the thermal shield opening both have a diameter of 40 mm. The inner vacuum vessel is expected to have an emissivity of 0.3.

From this set of parameters, a view factor calculation gives us the available inlet power (see table 1) provided that the radiation plate has a surface temperature of 200 K.

Table 1 Estimation of the incident power on the radiation plate

Radiation plate to thermal shield gap (mm)	Power deposited on the radiation plate (mW)	Power lost in the gap between radiation plate and thermal shield (mW)
5	106	26
10	77	65
15	62	86

These results outline the importance of closing the residual gap in order to get enough irradiation of the receiver plate, with the beneficial aspect of reducing further the power irradiated inside the thermal shield volume.

A set of finite elements simulations was then carried out to get the insulator system thermal performance with the insulator support actual geometry. This takes into account the conduction and radiation thermal resistance of the mirror support.

Table 2. Estimation of the power inlet required to maintain the CCR mirror at a given temperature

CCR mirror temperature (K)	Power loss through insulator conduction (mW)	Power loss through epoxy insulator radiation emission (mW)	Power loss through plate radiation emission (mW)	Total power required (mW)
150	20	8	0.7	28.7
200	26	30	2	58
250	44	62	6	112

From the comparison of table 1 and 2, we can see that with the system in its current design state it is possible to maintain a temperature above 200 K on the CCR mirror as long as the thermal shield gap opening is below 15 mm.

Table 2 also shows that at 200 K more than half of the heat loss comes from self-emission of the epoxy resin. Therefore subsequent effort to improve further the system performance should aim to address this point, possibly by enclosing the insulator in an aluminized cage to reflect back its own radiation.

During operations of the system, the system actual temperature and insulator contraction behavior will be unknown to a certain extent. This adds an uncertainty to the CCR mirror position.

Further thermomechanical FE analysis showed that a temperature uncertainty of ± 50 K of the insulator may bring a position variation of the CCR of ± 10 μ m through different thermal contraction of the support.

6. Final cool down testing

The system was eventually installed on the dipole magnet for testing (see Fig. 8) along with several reference mirrors (not insulated) and the magnet was then cooled down to 1.9 K, its operational temperature.

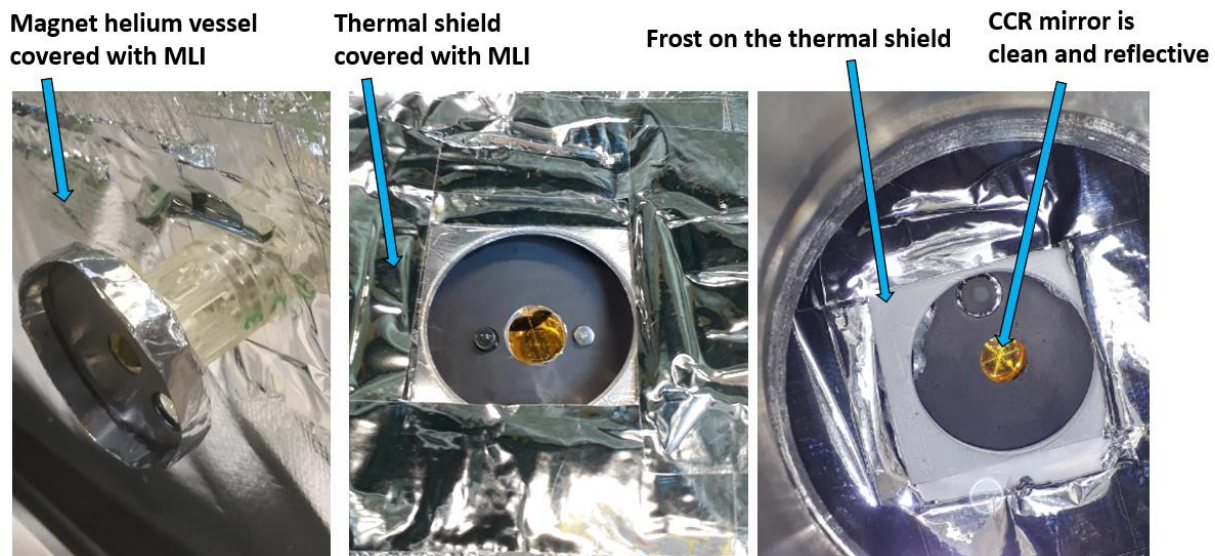


Figure 7 Insulated CCR mirror installed on the magnet helium vessel (left) with the thermal shield put on top (centre) and cooled down to 1.9K (right)

After cool down to 1.9 K, no frost deposit was visible on the reflective surface of the CCR mirror while the reference non-insulated mirrors did show a similar frost deposit as before. This situation was stable as no loss of reflection occurred in the following weeks.

7. Conclusion

In the frame of the development of an innovative position monitoring system for the superconducting magnets, an issue of mirror surface contamination at cryogenic temperature was encountered. After dedicated investigation, this was attributed to the condensation of residual gas, suspected to be principally water vapour, directly on the mirrors reflective surface.

In order to cope with the issue, a system aiming at keeping the mirror temperature above the water freezing temperature by making use of the radiations from the vacuum vessel was designed and implemented, with a successful outcome.

8. References

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