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Multi-target frequency scanning inteferometry to determine the position of components inside a vessel at a cryogenic temperature

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Abstract

At CERN, the high accuracy alignment of components installed in a hermetically sealed steel container (called vacuum vessel), can quickly become a challenge as normally the equipment inside the vacuum vessel has to undergo thermal cycles from room temperature to cryogenic temperature (down to 2 K). For the high luminosity Large Hadron Collider (HL-LHC) project, a measurement method, based on multi-target Frequency Scanning Interferometry (MT-FSI), consisting of redundant absolute distance measurement between the vacuum vessel and the internal component, solves this issue. The vacuum vessel is equipped with feedthroughs inserting and positioning the optical ferrule inside the vessel, while measurement targets (glass sphere with an aluminium coating) are installed on the internal component. In this paper, the concept of measurement is introduced and applied on one example: a vacuum vessel housing a magnet cold mass.

Large scale metrology, frequency scanning interferometry, internal monitoring, cryogenic temperature, collider

Introduction

To increase by more than 10 times the luminosity reach w.r.t the first 10 years of the LHC lifetime, the HL-LHC project will replace nearly 1.2 km of the accelerator during the long shutdown scheduled in 2024 [1]. Such a challenging project requires the development of new technologies among which the internal position monitoring of key components. It is required to measure continuously the position of components inside a sealed container, under vacuum, at cryogenic temperature (2 K), within ± a 0.1 mm uncertainty of measurement with respect to external targets located on the sealed container. Several possibilities to perform such measurements were investigated, based on optical or RF solutions [2][3]. A solution based on multi-target Frequency Scanning Interferometry (MT-FSI), developed by CERN, was retained and will be implemented on the HL-LHC project. This paper introduces this concept of measurement and illustrates its application on one HL-LHC component needing internal monitoring: the magnet cold mass of specific quadrupoles located just before the collision point to focus the particle beam.

1. Multi-Target Frequency Scanning Inteferometry

MT-FSI performs absolute distance measurements between the extremity of an optical fiber ferrule and the reflecting targets within an uncertainty of measurement of a few micrometers over distances below the meter [4]. The interference signal between the reflected beam from the ferrule tip (acting as a mirror) and the target is analysed, and more specifically its beat frequency. The beat frequency is proportional to the distance between the ferrule tip and the target : if the laser sweeping speed is constant, the distance can be deduced using a Fourier transform technique.

To implement such a technique for internal monitoring, the fiber tip ferrule is inserted in a feedthrough which is a leaktight interface between the vacuum vessel (at the technical vacuum of 10^{-6} mbar) and the accelerator tunnel (at atmospheric pressure) where the component is installed.

The position of the fiber tip ferrule is measured during a calibration process w.r.t. external targets installed on the external part of the feedthrough and defining a measurable referential frame. Once the feedthroughs have been installed on the vacuum vessel, the targets of the external part of the feedthroughs are measured with a laser tracker. The position of the fiber tip ferrules (defining the startup of the distance) are then determined in the coordinate system of the vacuum vessel [5], [6]. See Figure 1

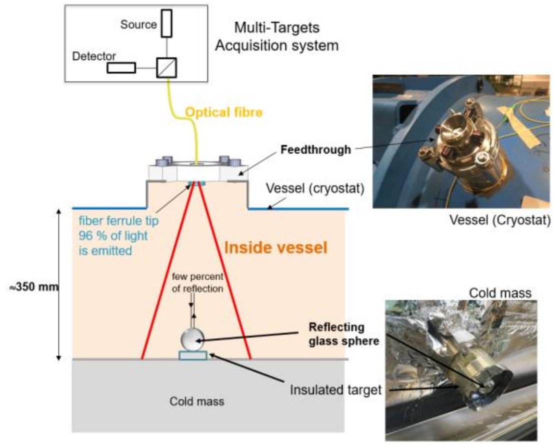

Figure 1. Configuration of FSI distance measurement

The chosen reflector is a 0.5'' diameter glass sphere, with a micrometric sphericity and a small coating of aluminium to be detected by other instruments as the AT960 Laser Tracker (from Hexagon Metrology). The spheres are installed on the internal component and their position w.r.t. the mechanical axis of the component is measured before their installation in the vacuum vessel. Their position is later measured again once the component has been inserted inside its vessel, through the openings foreseen for the feedthrough, by laser tracker measurements, in order to control the position of the inner component inside the vacuum vessel [6]. See Figure 1.

2. Internal position determination of the cold mass

Four low beta quadrupoles located on each side of two LHC collision points will be equipped with the MT-FSI technology to determine continuously the position of their magnet cold mass with respect to the external vessel, to have an accurate determination of the position of each cold mass (and as a consequence of their mechanical and magnetic centre that are relevant for the beam steering). The magnet cold mass can be approximated to a cylinder with a diameter of 0.80 m and a length of 10 m. The vacuum vessel can be approximated as a cylinder of a diameter of 0.94 m and a length of 11 m. The magnet cold mass is supported inside its vessel by 3 feet. The central foot is fixed while the two others allow a longitudinal translation of the cold mass for the thermal contraction. The thermal contraction is determined by a scale factor in the similitude (see chapter 2.2.).

The vacuum vessel will remain at a temperature of 300 K while the cold mass will reach 2 K with a contraction of more than 15 mm on both extremities.

2.1. Validation setup description

To validate our solution, we used a similar component, as the low beta quadrupoles are still under manufacturing: an LHC dipole, a bit longer and installed in a vaccum vessel not originally forseen to host the MT-FSI and therefore not assembled with the same cleaniness specification that will be adopted in future. Its cold mass was equipped with glass spheres installed on an insulated support to avoid cryo-condensation [7] along 2 sections (closed to the 2 extremities called IN and OUT), with 4 glass spheres per section, allowing to reconstruct with redundancy the position of its internal cold mass. See Figure 2.

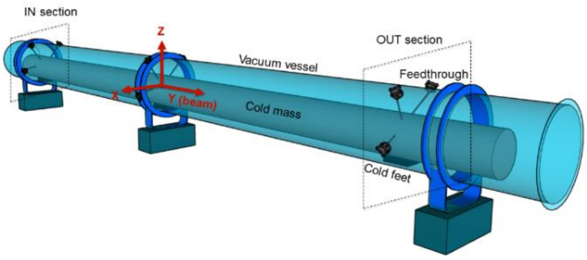

Figure 2. Dipole layout

2.2. Results obtained

Three thermal cycles, ranging from 300 K to 4 K were performed over 2 months, see Figure 3. The two first ones were quite short (duration of a few days), while the last one was longer (3 weeks) to see long-term impact of cold measurements on the MT-FSI system. At each warm / cold state, the position of feedthroughs in the vessel frame was redetermined. No significant deformation (less than 40 µm) of the vacuum vessel has been observed between the different states (measurement done with laser tracker).

Such a configuration allows the determination of 6 unknowns: 3 translations, 1 scale factor, the pitch and yaw motions (the roll was constrainted with an uncertainty of 100 µrad) from 8 observations. The residuals obtained after a least square adjustment on the 8 distance measurements are all below 40 µm. Figure 3 presents the vertical coordinate of the center of cold mass (OUT section) calculated for each state. At the beginning, the vacuum vessel was at ambient pressure. The vacuum vessel was then placed under vacuum. No displacement of the inner component w.r.t. the vessel has been observed during the vacuum pumping (less than 30 µm). Three thermal cycles (300K / 4K) were carried out. A repeatability of less than 50 µm of the position determination of the IN and OUT centers of the inner component w.r.t. the vacuum vessel between the 3 thermal cycles (300 K / 4 K) was obtained. At the end of the test, a return to atmospheric pressure was completed showing no significant displacement.

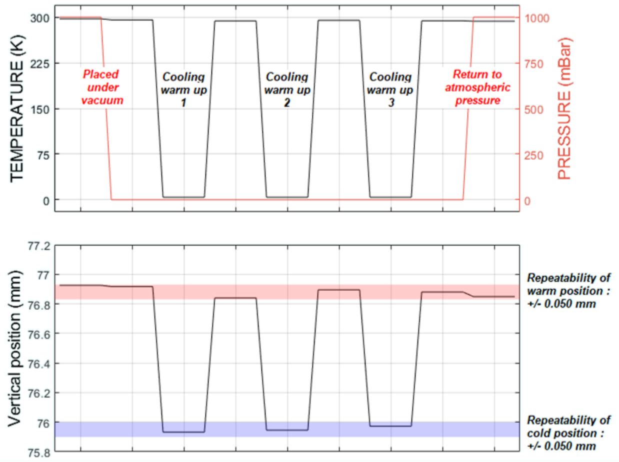

Figure 3. Results of the 3 thernal cycles (OUT section)

Table 1 presents the accuracy associated in the 3 directions far below the initial requirements. The third thermal cycle at 4 K lasted more than 3 weeks. During this period, no cryo-condensation impact on the targets was observed.

Table 1. Accuracy of section determination

Direction	Accuracy (mm)
X : Radial	0.060
Y . Longitudinal	0.085
Z : Vertical	0.030

5. Conclusion

CERN will use MT-FSI to determine the internal position of cold masses inside their vacuum vessel during the operation of LHC collider. The final configuration of the system has been qualified on a similar component, with glass sphere targets installed on an insulated support and the FSI ferrule tip inserted in a simple feedthrough. No cryo-condensation was observed during the thermal cycles at 4 K and a very good repeatability in the determination of the coordinates of the centre of the two sections was demonstrated.

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