FREQUENCY SCANNING INTERFEROMETRY TO MONITOR THE POSITION OF ACCELERATORS COMPONENTS INSIDE THEIR CRYOSTAT FOR THE HL-LHC PROJECT

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Abstract

In the frame of the High Luminosity-LHC (HL-LHC) project, we propose a novel method to monitor the position of accelerators components inside their cryostat, based on Frequency Scanning Interferometry (FSI). We achieve such a determination by installing targets on the internal components and optical fibre behind a viewport or via a feedthrough. This configuration allows performing distance measurements between the optical fibre and the target, at a micrometric accuracy. The final determination accuracy depends on the number of distance measurements and their configuration. We present two examples of application: the position determination of two crab cavities inside their cryostat, in a cold and radioactive environment, and the monitoring of a cold mass inside a dipole cryostat, at cold. In both cases, we introduce the context of measurements, the chosen configuration after simulations, the results achieved and the lessons learnt.

INTRODUCTION

The HL-LHC project [1] aims at increasing the luminosity by a factor 10 beyond the LHC's design value. Such a challenging project requires the development of new technologies among which the monitoring of inner components installed inside a cryostat [2].

The monitoring system adopted for such an inner measurement is the FSI, which provides non-contact measurements between the cryostat and the inner component. This system has been used for the first time for the monitoring of crab cavity components allowing ultra-precise phase control for beam rotation. It was validated on a dedicated test-setup using an LHC dipole, before being implemented for the monitoring of the position of the inner triplet cold masses to cross check its performances in a harsh environment.

This paper describes the FSI position monitoring system and its validation for both applications.

FSI INTRODUCTION AND GLOBAL CONCEPT OF MEASUREMENTS

The FSI allows high precision and simultaneous absolute distance measurements. Only passive components such as optical fibres, collimators and reflective targets are needed. A laser directs infrared light via optical fibres to the collimators installed in the measuring heads. The fibre end is positioned at the focal length of the collimating lens. The light is transmitted to a reflective target that reflects the light back to the collimators.

The FSI distance measurement is deduced from the ratio of the phase change induced in an interferometer reference (stable reference in the form of absorption peaks of an integrated gas cell) and the interferometer measurement (to the reflective target) by frequency scanning [3].

In order to determine the position, the orientation and the scale factor (due to the thermal contraction) of a component inside the cryostat, a minimum of seven FSI measurements are needed. The positions of the reflective targets (Corner Cube Reflector) installed on the inner component have to be known in the inner coordinate system, as well as the position of the FSI collimator installed on the cryostat in the external reference coordinate system (Cf. Figure 1).

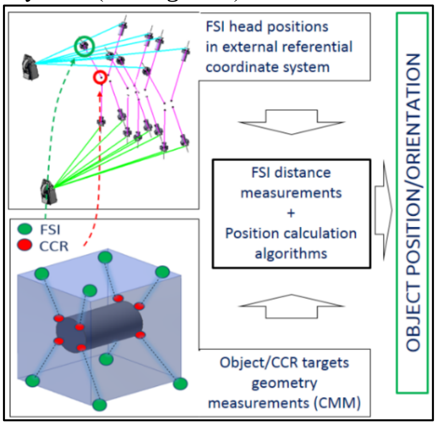

Figure 1 : Sequence of measurements

CRAB CAVITIES CASE

Context of measurement

The first crab cavities, used to rotate the proton bunches of the beam, was installed in the Super Proton Synchrotron (SPS) at the beginning of 2018. Successful operation of the cavities will depend on their correct position and orientation defined from the following alignment constraints, given at 3σ:

- The cavities axes have to be included in a 0.5 mm diameter cylinder w.r.t. the cryostat axis,
- The cavities roll (Ry) w.r.t. the cryostat axis has to be lower than 5 mrad,
- The cavities pitch and yaw (Rx, Rz) w.r.t. the cryostat axis has to be lower than 1 mrad.

The alignment monitoring of the two cavities inside their cryostat is based on a set of absolute distance measurements along multiple lines of sight between reflective targets installed on the cavities flanges and specific optical feedthrough (integrating the FSI collimator) on the cryostat [4]. The absolute distance measurements are performed using the Absolute Multiline Technology developed by the Etalon company providing an uncertainty of measurement of 0.5 ppm between 0.2 m and 20 m. The monitoring system inside the cryostat has to withstand nonstandard operating conditions such as:

- Radiation total ionizing dose of 1MGy per year,
- Vacuum of 10^{-6} mbar
- Cryogenics temperature at 2K.

An additional monitoring system has been deployed and used for the validation of the FSI system prior to the installation of the crab cavities in the SPS accelerator. This system is based on image acquisitions of reflective targets using a specific camera, named BCAM (Brandeis Camera Angle Monitor). It is used as a monitoring system for the HIE-ISOLDE project [5]. The accuracy of a BCAM given by the manufacturer is 50 µrad. This device was only used to crosscheck measurements during the cooling down process, since its radiation hardness was not enough for the crab cavities conditions.

Inter-comparison in a standard environment

Before the closure of the cryostat, the position of the two cavities inside the cryostat was measured with the two monitoring systems FSI and BCAM and compared with laser tracker measurements (Cf. Figure 2).

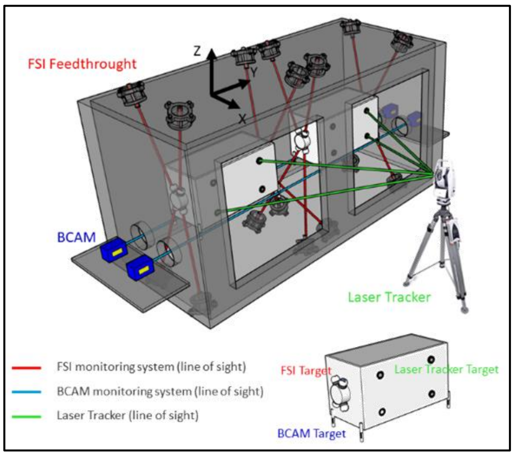

Figure 2 : Crab-cavities setup

For this application, we used Corner Cube Reflectors (CCR) with a centring accuracy of 2 µm for the FSI and laser tracker measurements while we used reflective glass balls with a high refractive index close to 2 for the BCAM system. The positions of the different targets and the mechanical axis of each cavity have been determined with a Coordinate Measuring Machine within an accuracy of 2 µm.

The calibrations of each FSI feedthrough were performed before their installation on the cryostat. It consists in determining the 3D coordinates of the focal point of the collimation lens as well as the direction of the laser beam in the referential frame of the feedthrough [6].

The positions of the FSI feedthroughs and BCAM sensors on the cryostat were determined using laser tracker measurements. The observations resulting from FSI distances and BCAM images allow calculating independently the position of the mechanical axis of both cavities inside the cryostat for each monitoring system.

The following figure (Cf. Figure 3) presents the radial and vertical position of the mechanical axis of each cavity determined by the three systems.

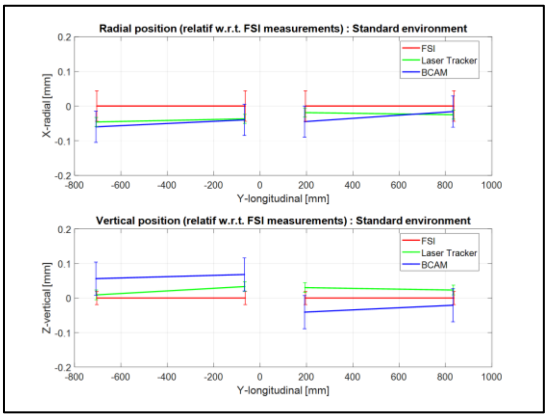

Figure 3 : Inter-comparison in a standard environment

The FSI solution produces a determination of the cavity inside the cryostat within an accuracy of 45 µm in the radial direction (X), 40 µm in the longitudinal direction (Y) and 20 µm in the vertical direction (Z). These accuracies depend on the geometrical configuration of the FSI feedthroughs around the cavity.

Inter-comparison in cold conditions

A vacuum of 10^{-6} mbar inside the cryostat and a cryogenic temperature of 4K were achieved in order to validate both alignment systems in operating conditions.

Figure 4 illustrates the radial and vertical position of the mechanical axis of each cavity for both alignment systems.

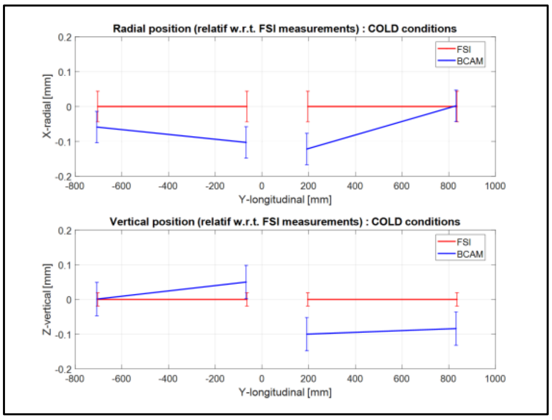

Figure 4 : Inter-comparison in cold conditions

Some differences up to 100 µm are visible, but can be explained by the difference in the thermal expansion coefficients of the supports for both targets. Indeed, the FSI targets were installed around the cavities flanges made of stainless steel, while the BCAM targets were set up on the bottom of the helium tank built in titanium. Despite this, the difference remains acceptable within the uncertainty of measurements of each solution.

Lessons learnt

Several heat-up and cool-down sequences have been conducted prior to the installation in the SPS accelerator. A vertical displacement of the cavities inside the cryostat up to 1.3 mm was observed during the two steady states for both cavities with a repeatability below 10 µm for all the sequences. This displacement was consistent with the thermal contraction simulations of the mechanical support of the cavities.

The scale factor calculated in order to assess the parameters of the Helmert transformation with the aim of defining the positions of the cavities inside the cryostat were identical for both cavities and consistent with the thermal expansion coefficients of the flanges where the FSI targets were installed.

The seven adjusted parameters of the transformation (translation vectors, rotation matrices and scale factor) were assessed from 8 FSI distance observations for each cavity and estimated using the least square method. All FSI observations used a prior standard deviation of 20 µm taking into account the following uncertainty sources:

- the FSI distances,
- the FSI feedthrough calibration,
- the position of the FSI feedthroughs on the cryostat,
- the position of the FSI targets on the cavity.

The seven adjusted parameters of the transformation are presented in the following table (Cf. Table 1).

Table 1 : Measurement uncertainty of the transformation parameters

Parameters	Uncertainty
$\boldsymbol{T_x}$ (mm) radial	0.021
$\boldsymbol{T_y}$ (mm) longitudinal	0.039
$\boldsymbol{T_z}$ (mm) vertical	0.009
$\boldsymbol{R_x}$ (rad) pitch	0.000030
$\boldsymbol{R_y}$ (rad) roll	0.000165
$\boldsymbol{R_z}$ (rad) yaw	0.000069
Scale factor (ppm)	55

The accuracies achieved (at 1σ) were excellent w.r.t. the alignment requirements.

Long term stability measurements at cold

The crab cavities were installed in the SPS accelerator 6 months ago (Cf. Figure 5). The first results from physics showed that bunches of protons could be tilted using these superconducting radiofrequency cavities.

Figure 5 : Crab cavities in SPS accelerator

The following figure (Cf. Figure 6) presents the vertical translation of the main axis of the cavity 1 inside the cryostat during the last 5 months.

We can see the long-term stability below 10 µm during the two steady states and a repeatability in the repositioning of the crab cavities below 10 µm between warm and cold conditions.

A correlation at 99.5 % between the vertical position of the cavities and the temperature is established and consistent with the simulations.

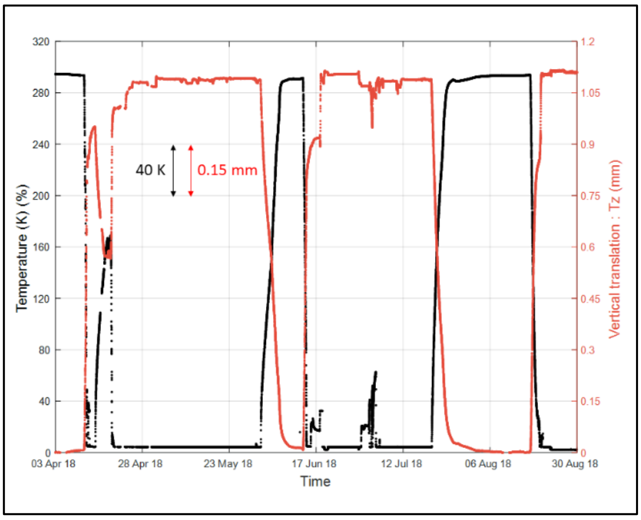

Figure 6 : Vertical translation during the last 5 months

DIPOLE CASE

Context of measurements

For the HL-LHC project, the follow up of the position of the inner triplet cold masses inside their cryostat is a key challenge. An uncertainty of measurement of ± 0.1 mm is required in a harsh environment, including cryogenic temperature of 2K, radiation level of 1MGy per year and vacuum of 10^{-6} mbar. Furthermore, unlike the crab-cavities project, the installation process of the triplet will not be performed in a clean room, so additional issues linked with insulation vacuum cleanness might appear. As the prototype of HL-LHC was still under construction, an LHC dipole (Cf. Figure 7) has been used in order to demonstrate the cold mass monitoring feasibility inside its cryostat [7].

Figure 7 : Dipole test bench

Twelve targets measured by the FSI system were installed on the cold mass. The main challenge was to find a target able to keep its reflective properties in cold and dusty conditions. Different test phases were performed in order to find a target meeting these requirements.

Target positions were chosen along three sections of the LHC dipole (Cf. Figure 8). As in the crab-cavity case, the Absolute Multiline Technology from Etalon was used. Four targets were measured by a FSI feedthrough, while the others were measured through a window. Three different types of targets have been tested.

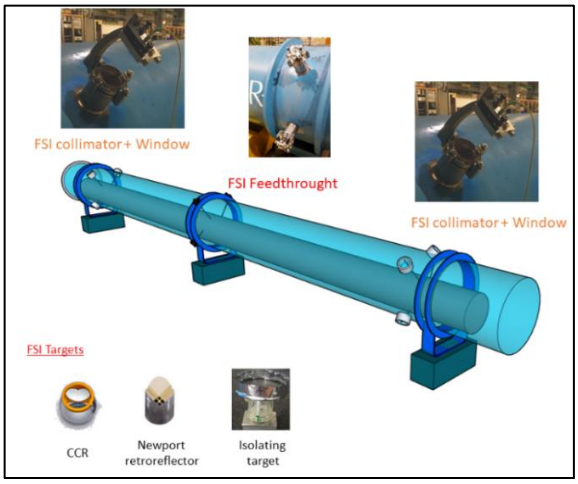

Figure 8 : Dipole test setup

Feedthrough or Viewport

Two different FSI heads were used.

- Four FSI feedthroughs (Cf. Figure 9) developed by CERN were installed directly on the cryostat to provide vacuum isolation (working as a bellow) and to collimate the laser beam. The FSI observation was dependent of only one refractive index: the vacuum one.

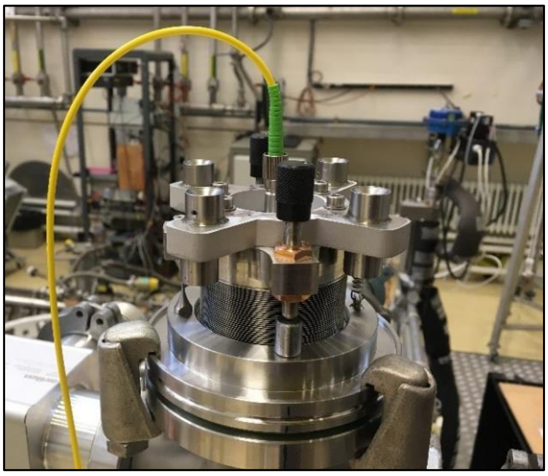

Figure 9 : FSI feedthrough

- The FSI collimator (Cf. Figure 10) was fixed to the viewport flanges. The FSI observations went through three different refractive indexes: the air, the viewport glass and finally the vacuum. The refractive index of the three environments must be known as well as the thickness of the viewport and the distance between the focal point of the FSI collimator and the viewport plane. The FSI observation can then be corrected.

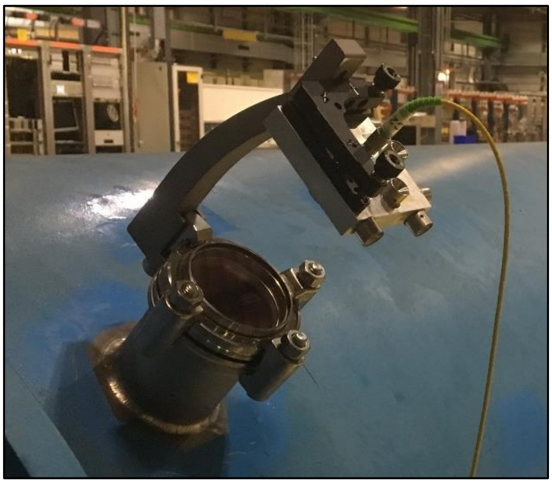

Figure 10 : Viewport + FSI collimator

Both FSI heads were tested and validated. The viewport has the advantage that one can see what is happening on the cold mass and more specifically on the targets.

FSI targets

Three different types of targets were used:

- Corner Cube Reflector (CCR)
- Newport retroreflector
- Insulating target

For the first tests, only the CCR and Newport reflectors were used. During the cool down, the reflective targets became blurry and the reflected signal was non-existent. The pictures (Cf. Figure 11) below show a CCR at warm and cold conditions. The degradation of the surface reflecting properties is due to cryo-condensation. The residual particles of water and oil in the dirty cryostat insulation vacuum froze on the cold reflector surface, creating a barrier for the laser.

Figure 11 : CCR at warm and cold conditions

Using reflective optical components in the dirty vacuum vessel environment (coming from Multi-Layer Insulation (MLI) and the rusty interior of the cryostat) makes it more complicated than for the crab-cavities project, where the cavities were assembled in a clean cryostat. At the residual pressure of the insulation vacuum, every species naturally present in the air condenses at or below 180 K. To solve the cryo-condensation issue, a 3D printed insulated target support was developed in order to keep the reflector above 180K (Cf. Figure 12).

The insulated target consists of an aluminium reflector glued on the insulating support. The support role is to minimize the heat transfer from the reflector to the cold mass. A black coated radiation intercepting plate was attached to the top of the reflector, allowing the interception of the heat coming from the vacuum vessel, and keeping the reflector's temperature above the water point of cryo-condensation. Additional MLI was added below the heat interception plate, to minimize heat radiation to the cold mass.

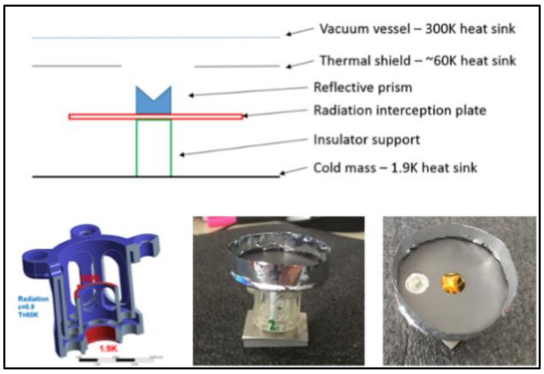

Figure 12 : 3D printed insulated support

Eight insulated targets were printed and fixed to the cold mass. A cool-down to 1.9K was carried out. The insulated targets kept a clear aspect with a good reflection.

Result with insulated targets

The insulated targets were installed on the two extremity sections of the cold mass. The positions of the reflectors and the mechanical axis of the cold mass were determined with laser tracker measurements. Once installed inside the dipole, the eight insulated targets were measured with FSI collimators through a viewport at warm and cold conditions.

The seven adjusted parameters of the Helmert transformation (translation vector, rotation matrix and scale factor) were assessed from the FSI distance observations and estimated using the least square method. Among the observations, only seven FSI observations were kept on the least squares adjustment process, due to a big residual value on one observation. After analysis, the epoxy glue used for the supports of the targets was not strong enough. A second version of insulated targets will be tested in autumn 2018. However, a least squares adjustment process could be carried out with only seven observations: the longitudinal translation was fixed in order to get more observations than equations and to estimate the accuracy.

The following table (Cf. Table 2) presents the relative adjusted parameters between warm and cold conditions.

Table 2 : Relative parameters of the Helmert transformation between warm and cold conditions

Parameters	**Value**	**Uncertainty**
T_x (mm) radial	-0.001	0.066
T_y (mm) longitudinal	0.825	(fixed)
T_z (mm) vertical	-1.078	0.023
R_x (rad) pitch	0.000003	0.000004
R_y (rad) roll	-0.001050	0.001285
R_z (rad) yaw	-0.000022	0.000003
Scale factor (ppm)	-2889	15

The vertical displacement (1.078 mm) of the cold mass, as well as the scale factor (0.002889), are consistent with the simulations. The lack of observations demands a new series of tests with 12 insulated targets scheduled for Autumn 2018 in order to validate this first result.

Preparation of phase 4

The concept of the support of the insulated target is satisfactory and efficient. The phenomenon of cryo-condensation is solved. The new support should be less fragile and more rigid, while maintaining the same thermal characteristics. Two composite materials: Accura Bluestone or the Accura 48 are candidates for validation.

CONCLUSION

The tests performed at CERN on the internal position monitoring of crab cavities and cold mass inside their cryostats demonstrated the micrometric precision of the FSI system in a harsh environment and fulfilled the alignment requirements of the specifications.

During the first cooling down of the dipole, a phenomenon of cryo-condensation was observed on the CCRs. Some specific insulated targets' supports were created and installed to replace the CCR in order to solve this issue. Successful tests achieved with this new target at 2K showed its potential, which should be confirmed by additional tests scheduled in October.

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