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ROBUST OPTICAL INSTRUMENTATION FOR ACCELERATOR ALIGNMENT USING FREQUENCY SCANNING INTERFEROMETRY

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Abstract

The precise alignment of components inside particle accelerators is an important engineering challenge in high-energy physics. Optical interferometry, being a precise, optical distance measurement technique, is often a method of choice in such applications. However, classical fringe-counting interferometers present several drawbacks in terms of system complexity. Due to the increasing availability of broadband, high-speed, sweeping laser sources, Frequency Scanning Interferometry (FSI) based systems, using Fourier analysis of the interference signal, are becoming a subject of growing interest. In the framework of the High-Luminosity LHC project at CERN, a range of FSI-based sensor solutions have been developed and tested. It includes the optical equipment for monitoring the position of cryogenic components inside their cryostats and FSI instrumentation like inclinometers and water-based levelling sensors. This paper presents the results of preliminary tests of these components.

INTRODUCTION

In the framework of the High-Luminosity LHC (HL-LHC) project at CERN [1], a range of new solutions using Fourier analysis based Frequency Sweeping Interferometry (FSI) [2, 3] is under development. This technique was chosen as it allows to simultaneously measure absolute distances to multiple targets and it is less sensitive to intensity variations of the reflected optical signal, providing the possibility to create simple and robust sensors and sensor networks. The FSI has become a workhorse of HL-LHC position monitoring, allowing to deploy novel applications like monitoring of the position of superconducting magnets and crab cavity cold masses inside their cryostats. For this purpose, specifically designed divergent beam FSI vacuum optics and low-cost glass ball reflectors were developed. Furthermore, a new family of cost-optimized, optical sensors (hydrostatic levelling, inclinometer, distance) is under development and their tests are realized under the same coordinated effort.

Frequency Sweeping Interferometry

The Fourier analysis based FSI uses similar interferometer layout as the Michelson interferometer. The constant frequency laser is replaced by a sweeping laser source (cf. Fig. 1) [3]. To simplify the optical architecture of the interferometer, the configuration shown in Fig. 1 uses a single mode optical fibre, with the ferrule used as a reference mirror. Its polished tip reflects ~4% of incident light back towards the source, thus forming the reference arm of the interferometer. The remaining ~96% of light is emitted towards the reflective target(s), using additional collimating optics.

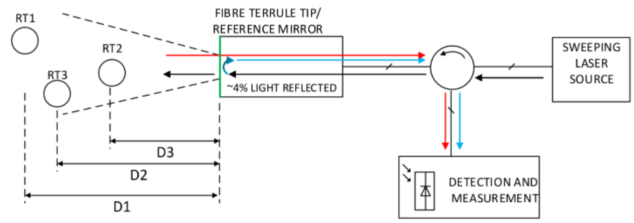

Figure 1: Multi-target Frequency Sweeping Interferometer schematic.

The reflecting targets placed within the emitted beam reflect part of the light back to the fibre and via the circulator to the photodetector, where the reference beam (ferrule tip reflection) and the light reflected from the target are recombined, creating an interference signal (consisting of the mix of the interference beat frequencies). If the laser sweep speed is constant, the beat frequencies become proportional to the reflective target distances and can be retrieved from the sampled photodetector output using Fast Fourier Transform (FFT) and converted into proper distance values. This approach provides the possibility to measure multiple distances to the targets in a single laser scan.

SENSOR DESIGN

The alignment of HL-LHC components will consist of approximately 600 different interferometric sensors: hydrostatic levelling sensors, inclinometers and distance measurement sensors (inside and outside cryostats) [2, 3]. Most of them will perform a short distance (< 0.5 m) measurement, achieving an uncertainty of measurement better than 10 µm. All the sensors will operate in a radioactive environment, where human interventions are very limited; hence their construction shall be simplified and should allow maintenance-free operation. Considering these conditions and the large amount of equipment involved called for the design of simple and robust sensors, based mainly on divergent laser beams and low-cost glass ball reflectors.

For most of the sensors, the divergent Gaussian beams are emitted directly from fibre ferrule tips, which reduces the cost of the optical components. The beam divergence angle is defined by the numerical aperture of the fibre [3].

A fully remote position monitoring system requires the permanent presence of reflectors in hundreds of points. Conventional reflective targets, like Spherically Mounted Retroreflectors (SMRs), used during survey works, tend to be very expensive due to tight machining tolerances and precise pre-sale characterization. In order to reduce the overall cost of the system, a low-cost type of reflector, consisting of a glass ball with a refractive index n = 2 is

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used [3]. Such reflectors have the shape of precisely machined TAFD55 glass balls (cf. Fig. 2) and can be equipped with a reflective coating on the back side to improve the reflected signal intensity.

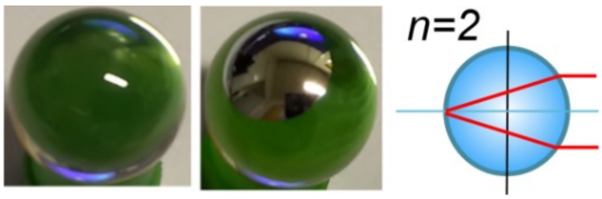

Figure 2: Glass ball reflector (uncoated, coated, principle).

Intra-cryostat Position Monitoring

The position monitoring of components installed inside a cryostat [4] requires measurements of cold components (T ≈ 2 K: magnet cold masses, crab cavities) from the warm vacuum vessel level, which requires the use of non-contact methods to avoid thermal losses. The monitoring system adopted for such an inner measurement uses multiple FSI distance measurements. To determine the position, the orientation and the thermal movement (due to the thermal contraction of the parts) of a component inside the cryostat, a minimum of seven FSI measurements is required. The positions of the reflective targets (cf. Fig. 3): Corner Cube Reflector (CCR) or glass ball reflectors, installed on the inner component, have to be known in the inner coordinate system, while the positions of the FSI measurement heads installed on the cryostat has to be known in the external reference coordinate system.

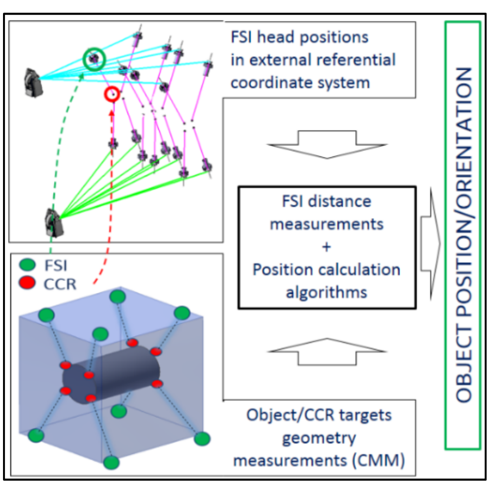

Figure 3: Sequence of measurements for intra-cryostat position monitoring.

The development of such internal monitoring system instrumentation at CERN started from the crab cavities monitoring systems [4, 5], where a standard optical approach (tip-tilt adjustable optical collimators and CCRs) was initially tested. The next development step, targeted for the HL-LHC Inner Triplet [4], allowed to decrease the system cost through the use of simple (adjustment-free), divergent laser beam heads and glass ball reflectors (cf. Fig. 4). A big effort was made to develop and test special cryo-compatible reflector supports (cf. Fig. 4c), to suppress effects of cryo-condensation on the reflectors, which may appear inside the cryostat insulation vacuum [6].

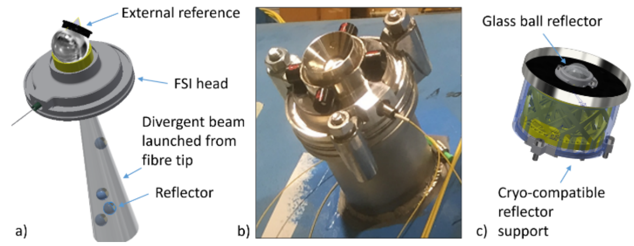

Figure 4: Intra-cryostat position monitoring instrumentation: a), b) FSI divergent beam head; c) cryo-compatible FSI reflector.

Hydrostatic Levelling Sensors

Hydrostatic Levelling Sensors (HLS) are used to measure the vertical position of accelerator components w.r.t. the water surface of a hydraulic network. The FSI-HLS sensor developed at CERN (cf. Fig. 5) consists solely of a bare fibre ferrule for laser beam delivery. A part of light is always reflected back from the water surface (only incident rays perpendicular to the water mirror) giving the absolute ferule-water distance measured by the FSI.

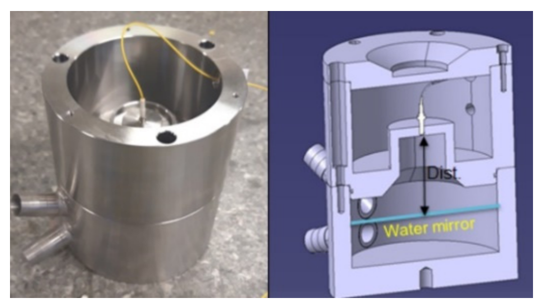

Figure 5: FSI-HLS sensor and its operation principle.

Inclinometers

An optical inclinometer consists of a pendulum suspended on a flexural hinge, with a single glass ball reflector placed on the bottom of the pendulum (cf. Fig. 6). The inclination of the sensor is given by a differential FSI measurement of distances between the ferrules (located on both sides of the pendulum, to suppress the thermal effects) and the glass reflector.

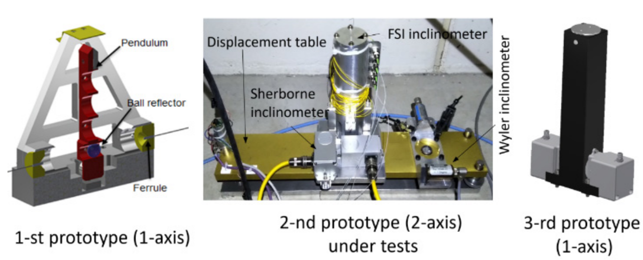

Figure 6: Family of FSI inclinometers developed and tested at CERN.

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Particular emphasis was given to the development of a proper damping system for the pendulum, compatible with the radiation conditions [3] foreseen for HL-LHC. Several prototypes were designed and tested, including magnetic, oil, gas (air) dampers, leading to the conclusion that air based dampers are most suited for the final HL-LHC solution.

TEST RESULTS

Radiation Testes of Optical Components

All optical position monitoring solutions for HL-LHC systems shall withstand up to 2 MGy of Total Ionizing Dose (TID). Two irradiation campaigns, in 2015 and 2018, were performed in the Fraunhofer Institute in Germany to qualify the systems. The first campaign (irradiation steps between 0.1 and 10 MGy) aimed at qualifying the optical collimators and the CCRs and allowed the pre-selection of optical components for the crab cavity application [5]. The second campaign (irradiation steps between 0.3 and 10 MGy) focused on the irradiation of the FSI heads (consisting of fibres, ferrules, collimating optics) and glass ball reflectors. This test confirmed the performance of the selected materials. It was found that the impact of irradiation, on the precision of the FSI measurement head, was less than 10 µm. Shifts ranging from 2 to 4 µm were found during post-irradiation measurements of TAFD 55 glass ball reflectors w.r.t. non-irradiated samples.

Intra-cryostat Position Monitoring Instrumentation

Divergent beam FSI optical heads and cryo-compatible FSI targets were tested during laboratory calibrations and during several measurement campaigns on a dipole magnet prototype in 2018 and 2019 [4].

The calibrations of FSI heads, based on combined FSI measurements with laser tracker measurements, showed an uncertainty of the FSI head at the level of 20 to 30 µm.

The overall system deployed on a test dipole allowed to observe changes of the position of the cold mass inside the cryostat, during cool-down/warm-up cycles, with a precision of 23 µm in vertical and 66 µm in the radial direction [4].

Hydrostatic Levelling Sensors

The performance of FSI-HLS sensors was compared to commercial capacitive HLS sensors using a 100 m long water network installed in a stable underground environment. Data from both types of sensors were logged during approximately 35 days. An example of comparison between the two types of sensors is presented in Fig. 7.

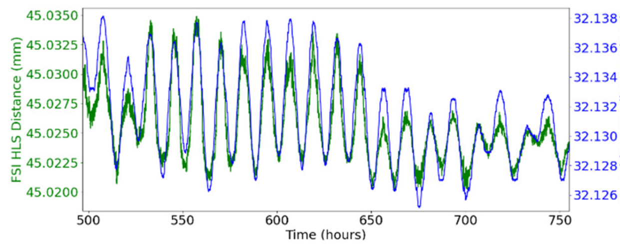

Figure 7: Comparison between an FSI-HLS sensor and a commercial capacitive HLS sensor.

The oscillations in Fig. 7 come from lunar/solar tides in the water network. The measurements of both types of HLS sensors were coherent within 2 to 4 µm.

Inclinometers

The performance of the FSI inclinometer was compared with two commercial inclinometers (Sherborne LSOC-1 and Wyler ZEROTRONIC). The three sensors were placed on a motorized displacement table (cf. Fig. 6), which was continously inclined forwards and backwards by 7 mrad during approx. 35 days. Figure 8 presents the error between the FSI and Sherborne inclinometers.

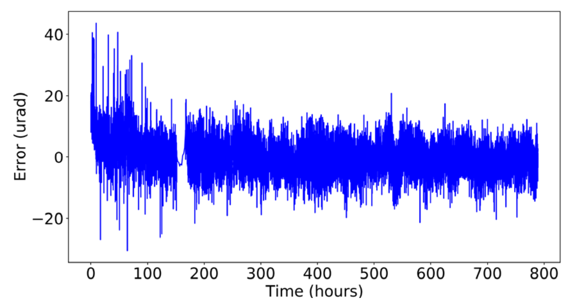

Figure 8: Error between the FSI inclinometer and Sherborne LSOC-1 inclinometer.

The standard deviation of error between the readings of the FSI inclinometer and both reference inclinometers, during ~35 days, is approximately 5 µrad.

CONCLUSION

The tests performed at CERN on the family of simple and cost optimized FSI instrumentation prototypes, demonstrated the robustness and satisfactory accuracy of the FSI based sensors in a harsh environment and fulfil the alignment requirements of the specifications. The design work to launch the production of the series components for the HL-LHC FSI based sensors will be finalized in 2022.

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