POSITION MONITORING SYSTEM FOR HL-LHC CRAB CAVITIES

M. Sosin, T. Dijoud, H. Mainaud-Durand, CERN, Geneva, Switzerland
V. Rude, ESGT-CNAM, Le Mans, France

Abstract

The high luminosity upgrade for the LHC at CERN (HL-LHC project) will extend the discovery potential of the LHC by a factor 10. It relies on key innovative technologies like superconducting cavities for beam rotation, named "crab cavities". Two crab cavities will be hosted in a superconducting cryostat working at a cold (<3 K).

The position of each cavity will be monitored during the cool-down and the operation in order to comply with the tight alignment tolerances: the misalignment of a cavity axis w.r.t. the other will have to be lower than 0.5 mm and each cavity roll w.r.t. the cryostat axis will have to be lower than 1 mrad. Moreover, the monitoring system will have to be radiation hard (up to 10 MGy) and maintenance free.

We propose a solution based on the Frequency Scanning Interferometry to provide the position monitoring of the crab cavities. This paper describes the design and study of such a solution, including the engineering approach, the issues encountered and the lessons learnt.

INTRODUCTION

The goal of the high luminosity upgrade for the LHC at CERN (HL-LHC project) is to increase the luminosity to the level of 300 fb-1 per year, which requires smaller beam sizes and reduction of non-zero crossing angles at interaction points (IP). To correct the geometric effects of the reduced beam sizes crossing angles the use of transverse deflecting cavities (also called "crab cavities") was proposed. A crab cavity imparts transversal rotation to the bunch, which continues to rotate outside the cavity, allowing reduction of the crossing angles at the IP.

The HL-LHC upgrade assumes installation of 8 crab cavities (paired by 2 in 4 cryostats) on each side of ATLAS (IP 1) and CMS (IP 5) detectors. Each pair of cavities dressed in helium tanks will be suspended inside the cryomodule (Fig. 1) using a suspension system to perform a precise adjustment of the cavities position. The cavity operational temperature will be around 2 K provided by liquid helium cooling.

Successful operation of the RF cavities depends on their correct position and orientation. The alignment constrains result from the transverse and longitudinal alignment tolerances derived from the LHC performance requirements [1], which impose:

- the cavity rotation in the X-Y plane to be lower than 0.3° (3σ) per cavity (R_Z - Fig. 2);
- the cavity roll w.r.t. the cryostat axis should be lower than 1 mrad (3σ);
- the transverse displacement of the cavities w.r.t. each other inside a cryostat; intra-cavity alignment in the transverse plane w.r.t. the cryostat axis should not exceed the 0.5mm (3σ);

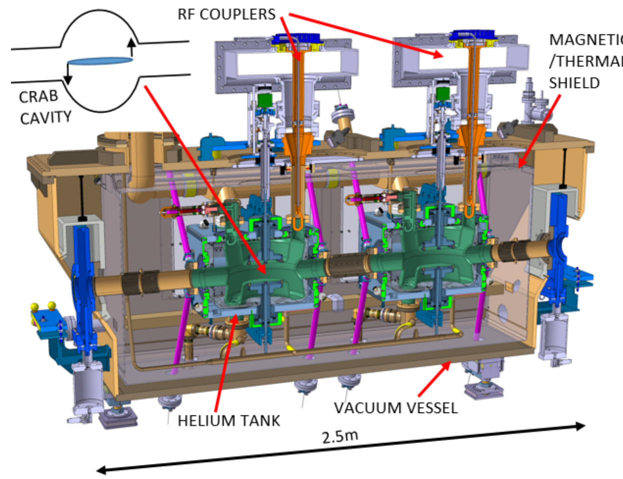

Figure 1: Double-Quarter-Wave (DQW) cryomodule prototype.

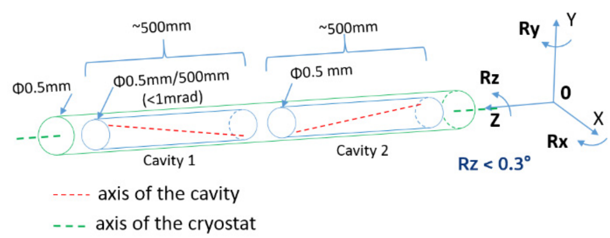

Figure 2: Crab cavities alignment tolerances.

To be able to monitor the alignment of the cavities w.r.t. external references at the tolerance of 0.5 mm (3σ) the position monitoring system needs to be 5 to 10 times more accurate, hence its required accuracy was defined as 50 to 100 μm. Furthermore, the monitoring system has to be compatible with cryogenic, vacuum and radiation conditions, which drastically increases the difficulty of implementation of such a system.

At the beginning of 2015 the research and development project on monitoring system for crab cavities started at CERN.

DESIGN CONSTRAINTS

One of the challenges to design this position monitoring system is the measurement of the position of the cryogenic components (crab cavities at T ~2 K) w.r.t. a warm cryostat (room temperature). Moreover the position of the referential frames of the cavities and cryostat will have to be determined w.r.t. each other through absolute measurements.

The main issue concerning cold objects measurements is that the crab cavities (helium tanks) geometry can only be measured accurately by a Coordinate Measuring Machines (CMM) at room temperature. After cool-down the geometry of the components changes (thermal contraction), so the CMM data will have to be corrected by models using proper materials contraction coefficients. This is not trivial considering nonlinear behaviour of the materials contraction and the complex design of the cavities making simulations imperfect. In addition, the gradient of temperature between vacuum vessel and cavity may have an impact on the result of the distance measurements, hence non-contact methods are preferred (as an additional benefit it will also limit the heat transfer by conduction).

The second challenge is the future operation of the cavities in high radiation conditions. The components of the monitoring system will have to be radiation hard and keep stable properties over their work period. Preliminary estimations of total ionising doses (TID) for HL-LHC operation are: 10 MGy for the components installed close (5 cm) to the cryomodule beam tube; 1 MGy for the components installed at the level of the vacuum vessel [2].

MONITORING SYSTEM SOLUTION

Taking into the account the above-mentioned constraints, the Frequency Scanning Interferometry (FSI [3]) was chosen as a baseline solution. The FSI system offers absolute interferometric distance measurement with a sub-micron accuracy. Only passive components (mirror, collimator, fibres) are needed in the measurements zone, which makes the application suitable for a high radiation level operation.

Monitoring System Layout

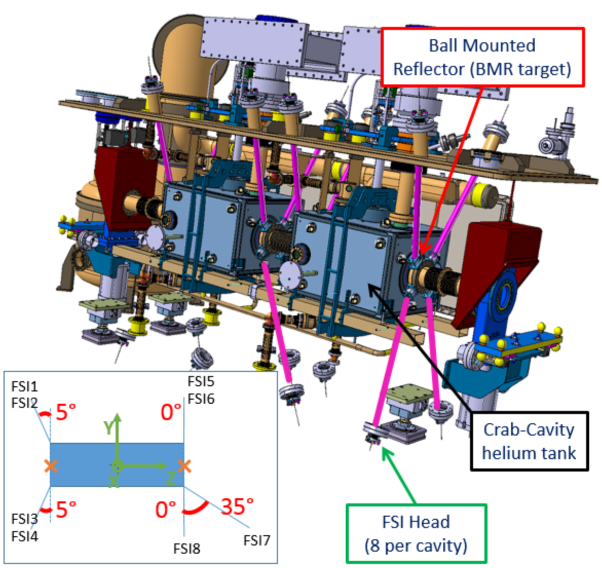

Figure 3: Crab cavities cryomodule - monitoring system components.

To measure the position and orientation of the crab cavities, a minimum of 6 distances have to be measured. Considering the need of high reliability of the system (with a maintenance time reduced to a minimum due to radiation) a redundant configuration with 8 distance measurements was selected (Fig. 3), increasing also the measurement accuracy. The measurement chain consists of a ball mounted reflector (BMR) installed on the flange of the crab cavity (4 BMR-s per flange, 8 per cavity) and assigned to the FSI head installed on the vacuum vessel. FSI head has several functions: to provide vacuum isolation (works as a vacuum fibre feedthrough), to collimate the laser beam and to link the FSI collimator interference point with external coordinate system.

Position Monitoring Strategy

To calculate the cavities position the detailed information concerning the geometry of all components of the system and their thermal contraction models have to be known. Figure 4 shows the main computation steps.

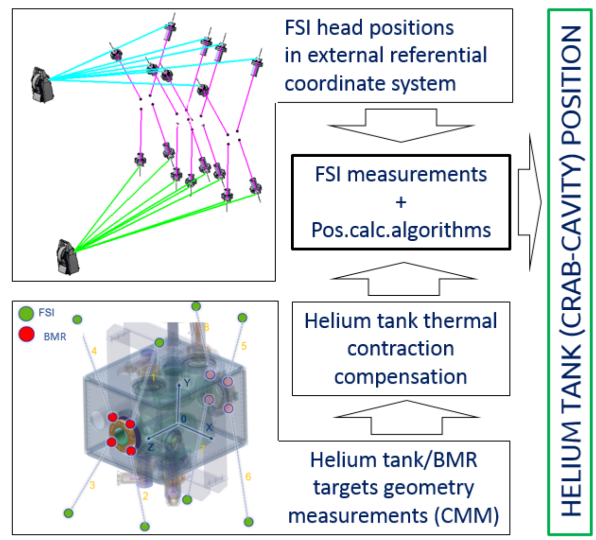

Figure 4: Position monitoring strategy.

The determination of the position of the reference axis of the cavities w.r.t. external alignment references (flanges' BMR-s) – cavity fiducialisation [4] - is performed using a CMM.

The FSI heads optical interference points (FSI heads 'zeros') are determined w.r.t. the heads fiducial marks (integrated on the head atmospheric side) during the calibration process. Using the FSI heads calibration data and laser tracker measurements – the optical interference points (FSI heads 'zeros') can be known in the external coordinate system.

The above measurement results, together with the thermal contraction models of the objects and FSI distance measurements allow for a computation of cavities position in an external to the cryomodule coordinate system.

STRATEGY VALIDATION RESULTS

To validate the strategy undertaken and to check if the required accuracy at the level of 50-100 μm can be reached, we had to verify several main issues:

- the system components stability under radiation and cryogenic conditions;

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- the FSI heads calibration accuracy;
- the impact of the FSI head displacement pattern on measurements accuracy (choice of optimal heads displacement geometry);
- the impact of the thermal contraction models imperfections on the final calculations;
- the long term shape stability of vacuum vessel (all FSI heads are embedded in the vessel).

Radiation Tests

The optical components to be used for the cavities measurement chain (retroreflectors, collimators - Fig. 5) were a subject to an irradiation campaign performed in Fraunhofer Institute in Germany between December 2015 and March 2016. The samples were exposed to the gamma irradiation with the doses of 0.1, 0.5, 1, 2, 5, 7, 10 MGy. Between each irradiation step the optical parameters stability and mechanical resistance of components were verified.

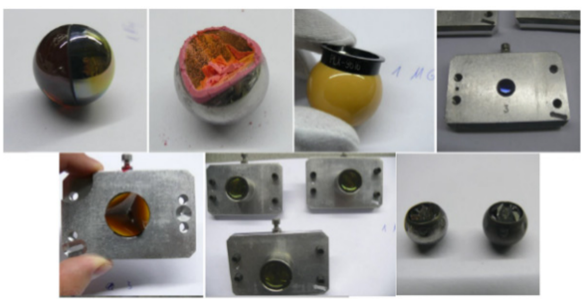

Figure 5: Irradiated optical samples.

The results of the tests have shown a good performance of most of the samples. For the validated BMR-s, the maximum change of the measured distance with total ionising dose of 10MGy was less than 20µm. No changes of properties were observed on the collimators planned to be used in the FSI heads.

FSI Head Calibration Accuracy

The accuracy of the calibration method linking the position of the collimator origin (interference point - vacuum side) to the outer head reference fiducials (atmosphere side) had to be verified. The FSI head calibration relies on multiple FSI measurements of the distances to the same reflecting target (Fig. 6 – "K"). In parallel to these measurements the positions of the head fiducials w.r.t. the reflector "K" are measured and determined in the external coordinate system. Having series of measurements and using distance equation (Fig. 6 – "Dist") we are able to determine the collimator origin position w.r.t. the head fiducials.

To perform the method validation the head test mock-up was constructed (Fig. 6) and the calibration was performed using a AT401 laser tracker. The calibration uncertainty for the X direction (axis of the collimator) of FSI head was below 10 µm (1σ), which is a very good result, as X is the direction of the distance measurement. For Y, Z directions the calibration accuracy was assumed to be 200 µm (accuracy of machining of the mock-up collimator interface).

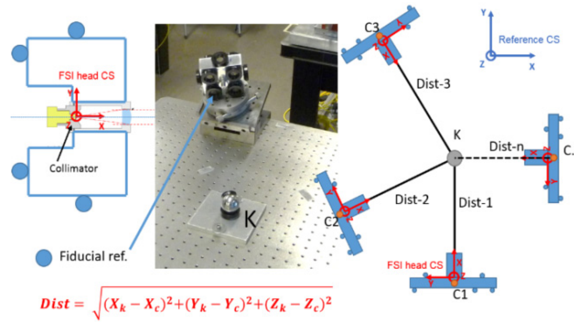

Figure 6: FSI head calibration.

FSI Heads Displacement Pattern

The way of arrangement of the FSI heads around the measured cavities has an impact on cavities position and orientation determination accuracy. Due to the integration limits (cryostat space constraints) the heads were regularly displaced around the cavities flanges (Fig. 3). To achieve better accuracy in longitudinal (beam) direction - 5° and 35° longitudinal inclinations of FSI heads were applied.

The impact of the above configuration on the cavities position/orientation calculation (least square Gaussian fitting method used) uncertainty was verified by numerical simulations, taking as input CMM, AT401 and calibration uncertainties. The possible errors coming from the material contraction coefficients were not taken into account. The results were the following: X→19 µm; Y→7 µm; Z→25 µm; R_X→17 µrad; R_Y→ 44 µrad; R_Z→142 µrad (all 1σ, according to Fig. 2 axis descriptions).

CONCLUSIONS

The results of the tests performed up to now in the frame of the crab cavities alignment monitoring project are promising. The optical components selected passed the radiation tests. The initial simulations concerning the expected uncertainty of the chosen method confirm the measurements strategy assumptions and fit the requirements.

There is still a need to check the components and method under cryogenic conditions and vacuum - the tests are planned to be done in second half of 2016. The overall, cooled-down system tests are planned for the end of 2017.

REFERENCES

[1] P. Baudrenghien et al., Functional specification of the LHC prototype crab cavity system, CERN-ACC-Note-2013-003, 2013
[2] F. Cerutti, L.S. Esposito: Energy deposition for HL-LHC v1.1: TAN/D2/Q4 (http://indico.cern.ch/event/326148/session/17/contribution/43), pp. 34-35.
[3] J. Dale et.al, Multi-channel absolute distance measurement system with subppm-accuracy and 20m range using frequency scanning interferometry and gas absorption cells, Optics Express Vol.22, 2014
[4] S. Griffet et al., "Strategy and validation of fiducialisation for the pre-alignment of CLIC components," IPAC2012, WEPPD073, pp 2693-2695, New Orleans, USA