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COMPUTER VISION TECHNIQUES USED TO MONITOR THE ALIGNMENT OF CAVITIES AND SOLENOIDS IN THE PIP-II PROTOTYPE SSR1 CRYOMODULE*

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Abstract

The alignment of the SRF PIP-II string components is studied as the acceptable beam deflection, offset and defocusing, which may otherwise cause beam loss. Simulations and measurements established that the maximum deviation of the beam pipe from the reference orbit should not exceed a small fraction of the beam aperture. To observe the translations and rotations of each single component within the cryomodule, optical instruments (H-BCAM) surveying highly reflective targets, installed in the internal assembly of the module were used. The alignment monitoring concept for the PIP II SSR1 prototype cryomodule, along with relevant measurements of the components' position monitoring during coldmass cooldown is presented in this contribution. This development paves the way to new computer vision applications in the field of cryomodule assemblies in clean-room environment, in which robotically-assisted operations have the potential to dramatically reduce the risk of chemical and particulate contamination.

INTRODUCTION

The PIP-II project [1] is a substantial upgrade of Fermilab accelerator complex. The PIP-II linac includes 23 cryomodules containing five different types of accelerating structures: HWR, SSR1, SSR2, LB650, and HB650. SSR1 was the first prototype cryomodule (CM) to be fully designed, built, and successfully tested at Fermilab [2–5]. SSR1 CM consists of eight 325 MHz superconducting accelerating cavities (single spoke resonator "type 1"), and four focusing lens (solenoids) equipped with beam position monitors (BPMs). H-BCAMs® [6] were employed on SSR1 to monitor the position of cavities and solenoids throughout the entire assembly sequence, transportation, and testing qualification phase. The same technology will be used for alignment monitoring purposes also for the other PIP-II cryomodules. H-BCAMs are optical instruments, developed by Brandeis University, intended to monitor the geometry of large structures such as particles detectors and accelerators. Prior to SSR1, this technology was employed in the HIE ISOLDE experiment at CERN [7], which inspired the alignment monitoring strategy developed for SSR1 and presented in [8].

ALIGNMENT PROCEDURE

Cavities and solenoids are mechanically aligned during the assembly process. The geometric axis of cavities and solenoids is identified and referenced to external fiducials using, respectively, Bead Pull [9, 10] and Stretched Wire [11] techniques. The external fiducials are later used to align cavities and solenoids in the assembly with the laser tracker [12,13]. The final alignment must comply with PIP-II alignment requirements reported in Table 1. It is necessary to take into account the shift due to the cooldown of the components from ambient temperature to 2 K. H-BCAMs are used to monitor the displacement of cavities and solenoids during each phase following the final alignment.

Table 1: PIP-II Alignment Requirements

Cavities	Value
Transverse cavity alignment error, mm RMS	<1
Angular cavity alignment error, mrad RMS	≤10
Solenoids	**Value**
Transverse cavity alignment error, mm RMS	<0.5
Angular solenoid alignment error, mrad RMS	≤1

Measurement Principle

H-BCAMs look at targets, which are detected as spotlight sources. Their positions are projected onto the CCD (charge coupled device) sensor. Each target consists in two high reflective index glass balls contained into a cylindrical tube (as shown in Fig. 1), which is rigidly connected to cavities and solenoids. The nominal distance between glass balls is $d = 12\,\text{mm}{+}0.003\,\text{mm}{-}0.009\,\text{mm}$. This calibrated distance is used as a scale factor to convert displacements of targets measured as pixels on the CCD sensors, to displacements in mm. The length of the SSR1 cryomodule is ~ 5.2 m.

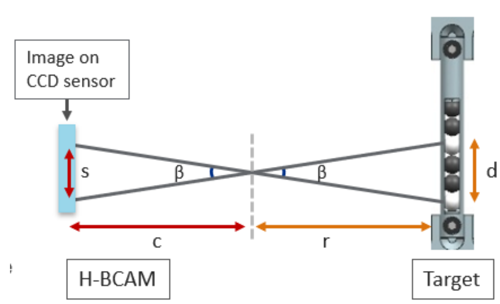

Figure 1: H-BCAMs Measurement Principle. d is a calibrated dimension (d = 12 mm, for this design); s is the distance as measured on the charge coupled device (CCD) sensor in the H-BCAM. The ratio d/s defines the scaling factor.

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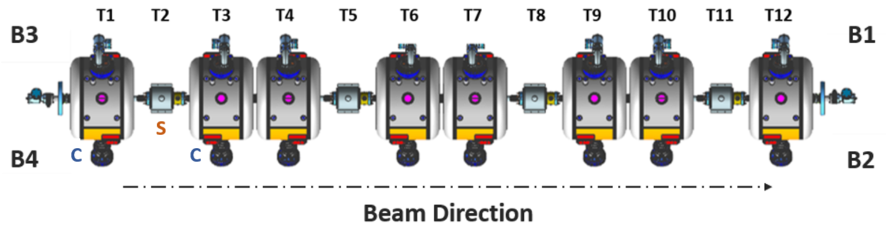

Figure 2: CAD model of prototype SSR1 string assembly. C stands for cavity, S stand for solenoid; the sequence C-S-C is repeated four times in the string assembly. The picture includes the H-BCAMs location, and targets numbering.The letter *B* defines the location of the four H-BCAMs.

Hardware Setup and Data Acquisition

Four H-BCAMs are used to monitor the alignment of the string assembly: two cameras are located on the upstream side and two on the downstream side of the cryomodule (see Fig. 2 for reference). Two targets are placed on the two sides (left and right) of each cavity and solenoid. A schematic of the cryomodule lattice is shown in Fig. 2. Glass balls are inserted into cylindrical tubes supported by frames rigidly attached to reference surfaces on cavities and solenoids. Figure 3 shows how glass balls are mounted into the support frame and how they look like as seen from the H-BCAM's perspective.

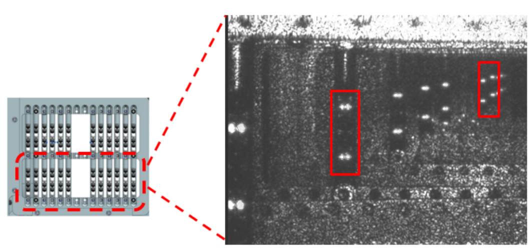

Figure 3: Glass balls mounted into the support frame and image of targets as acquired by one H-BCAM.

The data acquisition procedure is fully automated: a MATLAB® script prompts the user for geometrical details and create an *Acquisifier* scripts, which is passed down to a data acquisition tool provided by the LWDAQ® (Long-Wire Data Acquisition) software [14]. This software acts as a controller, which runs the subsequent steps of a data acquisition cycle and adds a timestamp for each step. The output of the LWDAQ software is a text file: the file is passed to a MATLAB script which post processes the data, filters eventual outliers, calculate the displacements, and sort the elaborated data. The set of data imported into R-Studio® for plotting and statistical analysis.

RESULTS AND DISCUSSIONS

During the cooldown cavities and solenoids are expected to move due to shrink. The vertical displacement was estimated with finite element analysis as equal to 1.2 mm. Therefore, this quantity is applied as a vertical offset on cavities and solenoids at the last phase of alignment at room temperature. Figure 4 shows almost 300 hours of cooldown. Temperature is monitored by means of 20 temperature sensors located on the upper and lower side of each cavity and on the solenoids. During the considered time frame, the temperature goes down from ambient temperature to 2 K. The vertical displacement of targets from T2 to T11 monitored by B3 and B1 is shown in Fig. 4: a positive displacement means that targets are moving down.

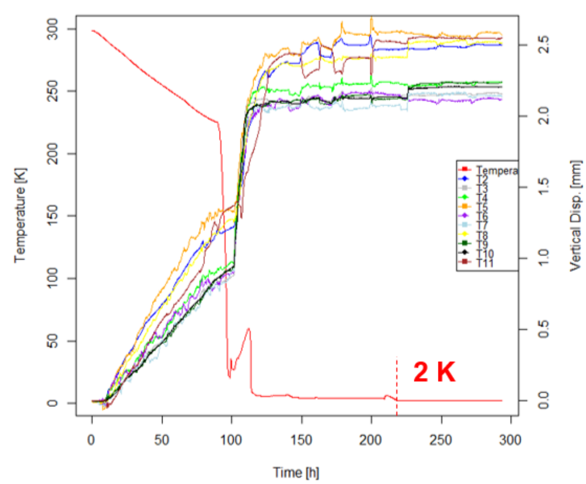

Figure 4: Targets' vertical displacement and temperature as a function of time.

The slope of the vertical displacement curves is proportional to the slope of the temperature profile. The delay between the displacement curves and the temperature profile curve is due to the position of the temperature sensors, that are mounted on the helium jackets of the cavities and on the solenoids. The targets monitored by the H-BCAMs' are instead mounted on frames connected to cavities and solenoids. Therefore, the targets' temperature is not the one measured by the temperature sensors at the same timestamp. A comparison between the temperature profile resulting from one sensor mounted on a specific cavity/solenoid, and the vertical displacement of that cavity/solenoid, shows a correlation between bumps in the displacement curves (more evident for solenoids) and pronounced temperature changes. Furthermore, it is worth noticing that targets T2, T5, T8,

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and T11 displaced more than targets T3, T4, T6, T7, T9, and T10. The former targets are mounted on solenoids, while the others are mounted on cavities. The targets' support frames are different for cavities and solenoids, thus the ~0.3 mm gap in the vertical displacements, visible in Fig. 4, results from the differences in the thermal shrinkage of the support frames. After subtracting the linear shrinkage, the vertical displacement of cavities and solenoids, when the temperature stabilizes at 2 K, gets closer to the value of 1.2 mm resulting from Finite Element simulations, as shown in Fig. 5.

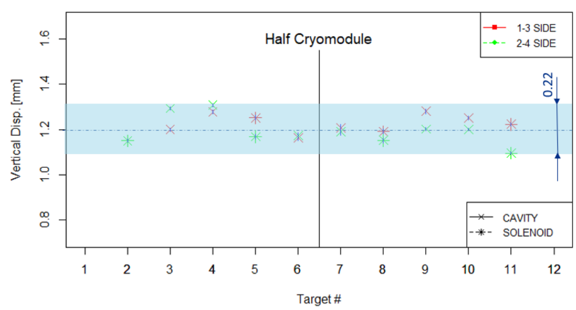

Figure 5: Targets' vertical displacement at the end of the cooldown. A positive displacement means that targets are moving down.

The maximum misalignment range between the cavities and the solenoids in the vertical direction is ±0.11 mm.

Figures 6 and 7 show the horizontal displacements of targets during the cooldown, on the B1-B3 and B2-B4 side, respectively (see Fig. 2 for reference). Positive values on the B1-B3 side and negative values on the B2-B4 side mean that targets are moving towards each others. Figure 8 shows targets' horizontal displacements when temperature stabilizes at 2 K, after compensating the linear contraction of the support frames.

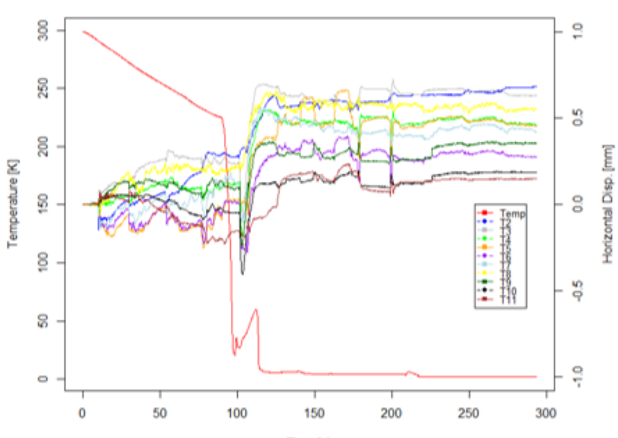

Figure 6: Targets' horizontal displacement and temperature as a function of time, B1-B3 side.

The maximum misalignment range of cavities and solenoids in the horizontal direction is lower than ±0.22 mm.

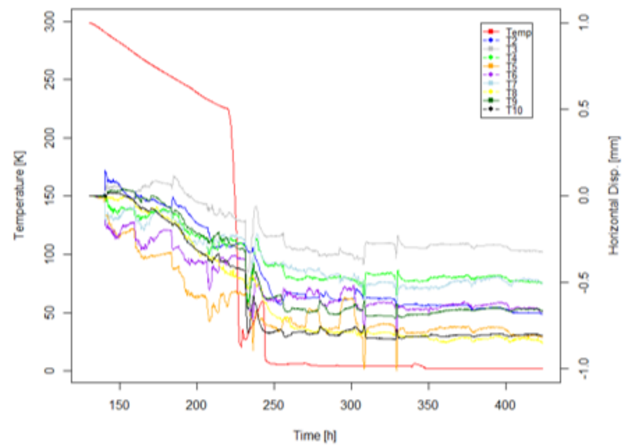

Figure 7: Targets' horizontal displacement and temperature as a function of time, B2-B4 side.

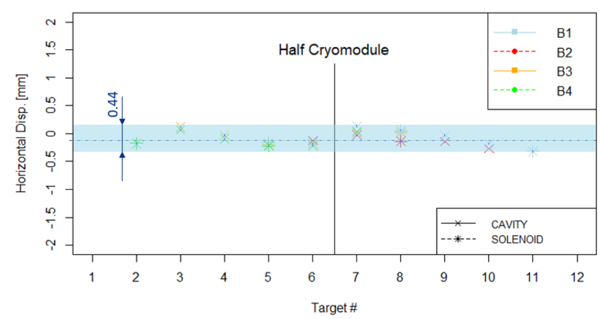

Figure 8: Targets' horizontal displacement at the end of the cooldown.

CONCLUSIONS

H-BCAMs were proven to be a valid technology for PIP-II cryomodules alignment monitoring purposes. A demonstration of the alignment monitoring system was given for the first cooldown test of prototype SSR1. The results of the data analysis were compared with the PIP-II alignment requirements. The data acquisition process is fully automated, while the post processing of the data could be further improved to allow the measurement of the pitch of cavities and solenoids, and to eventually achieve a "live" monitoring capability.

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