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ALIGNMENT AND MONITORING SYSTEMS FOR ACCELERATORS AND EXPERIMENTS BASED ON BCAM - FIRST RESULTS AND BENEFITS OF SYSTEMS DEVELOPED FOR ATLAS, LHCB AND HIE-ISOLDE

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Abstract

In the last few years alignment and monitoring systems based on BCAM cameras active sensors, or their HBCAM evolution, have been developed at the request of the Technical Coordination of LHC experiments and HIE-ISOLDE facility Project Leader. ADEPO (ATLAS DEtector POsition) has been designed to speed up the precise closure - 0.3 mm - of large detector parts representing in total ~2500 tons. For LHCb a system has been studied and installed to monitor the positions of the Inner Tracker stations during the LHCb dipole magnet cycles. The MATHILDE (Monitoring and Alignment Tracking for HIE-ISOLDE) system has been developed to fulfil the alignment and monitoring needs for components of the LINAC enclosed in successive Cryo-Modules. These systems have been in each case configured and adapted to the objectives and environmental conditions: low space for integration; presence of magnetic fields; exposure to non-standard environmental conditions such as high vacuum and cryogenic temperatures. After a short description of the different systems and of the environmental constraints, this paper summarizes their first results, performances and their added value.

INTRODUCTION

The evolution of the alignment and position monitoring needs for physics experiments or facilities generates new demands for integrated systems from experiment Technical Coordinators and beam facilities Project Leaders. In this frame, alignment and monitoring systems based on Brandeis CCD Angle Monitors (BCAM) cameras [1] - originally created by Brandeis University, to equip the Muon system of ATLAS - or their HBCAM version, have been developed in the past few years. This paper summarizes first results, performances and benefits of three of them: ADEPO (ATLAS DEtector POsition) designed to speed up the precise closure of large detector parts; the LHCb Inner Tracker (IT) monitoring system created to check the positions of the IT stations during the LHCb dipole magnet cycles and detector operation; MATHILDE (Monitoring and Alignment Tracking for HIE-ISOLDE) developed for the alignment and monitoring of components of the LINAC enclosed in successive Cryo-Modules.

ADEPO SYSTEM

At the end of each maintenance period of the ATLAS experiment the ADEPO system increases the precision of the relative re-positioning of six sub-detectors representing in total ~2500 tons and speeds up the process. The previous method of positioning was based on geodetic measurements and was time consuming due to difficult access to detector reference points.

The technical coordination defined the following specifications for ADEPO [2]. The system must provide a position measurement for the detector adjustment relatively to the previous “run” position. The measurement range has to be of ~50 mm in 3D directions with a demanded accuracy of 0.1 mm along transverse and longitudinal axis. The measurement time should not exceed 30 seconds.

Environmental Constraints

The system works for the follow-up of the experiment closure and as a monitoring system during the run period. The constraints are a magnetic field of 1 Tesla and the necessity of sensor protections to avoid accidental damages. Another challenging point is the limited space for sensors, for retroreflectors and for integration of lines of sight in the experiment. The entire conception, installation and commissioning of equipment had to be done in the maintenance configuration during the Long Shutdown 1.

Design Concept

BCAMs combined with glass corner cube retroreflectors as targets [3], have been chosen as non-contact measurement sensors as they are proven systems for ATLAS environment.

The system consists of: 24 sensors distributed in the experiment mounted on fixed part of the experiment like the ATLAS feet; 44 passive corner cube retroreflector targets mounted on the moving parts of the detector. The independence of each sensor in combination with a redundant installation increases the reliability of the system. Statistical tests based on the Iterative Least Square Adjustment (ILSR) as described by [4] have been added to identify damaged components in the results.

System Validation

To validate the configuration and the software, as well as to confirm that the system is within the specifications, a test setup close to scale one representing three detector parts has been constructed. BCAM and Laser Tracker measurements have been compared. The repeatability tests show excellent results that are below the BCAM specifications. For the reproducibility, the result of 35 µm [5] is obtained but it is impacted by the precision of the laser tracker and the exchange of targets between laser tracker and BCAM measurements.

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Measurement Results

ADEPO has been intensively used for the iterative positioning of the sub-detectors since the maintenance 2015/2016. Due to small support plates and large lever arms, the coordinates, measured by the BCAMs, have a limited precision in ATLAS global reference frame but a high accuracy for the measurements of movements.

During the closure, the team in charge of the detector adjustment stops the movement when the offsets in the monitored directions are below 0.3 mm – measured with a 10 times better accuracy by ADEPO – w.r.to the previous detector position or if the detector is closer than before to the nominal position. The ADEPO results have been confirmed by in-field laser tracker measurements of each subdetector [6].

Over a period of 30 days the measurement stability for different detectors is at the level of ± 15 µm if the magnetic field didn't change during the period. The 1σ precision for an individual BCAM is ~3 µm.

In the monitoring mode the movements caused by the ramp up or ramp down of the ATLAS magnetic field influence the precision of the measurement results that decreases but stays within the specification of 0.1 mm.

Added Value of the System

The Technical Coordination of ATLAS appreciates ADEPO as a valuable tool that saves up to 20% of the total time in the schedule over the complete closing procedure of three weeks.

The time saving for the survey team represents, up to 25%. In addition, the survey intervention could be shifted as shadow operation in the planning.

LHCB INNER TRACKER MONITORING

The LHCb Inner Tracker (IT) monitoring system has been developed to permanently monitor two detector boxes on each of the three LHCb IT stations [7] in order to estimate movements while they are exposed to dipole magnetic field as well as other effects during the physics data taking, and to control the closure of the detector.

A 3D position accuracy in the LHCb reference frame better than 0.5 mm was desired in an area very close to the beam pipe. This area is characterised by the presence of magnetic field (up to ~0.5 T), radiation and low material budget allowed.

Design Concept

The required measurements are obtained by intersection of BCAM lines of sight (triangulation) on passive reflective targets. The cameras are placed on adjustable and measurable supports fixed on stable concrete structures allowing precise knowledge of their positions and rotations (few µm and µrad). The BCAM lines of sight intersect with angles as close as possible to 90°. Additional flashes have been developed and attached to the camera in order to highlight new, very light and reflective circular targets placed on existing reference marks of the tracker boxes. The targets are seen as ellipses from any position within a view angle of ± 45 °.

Software

The image acquisition and analysis are done by a Tcl/Tk script ran by LWDAQ [1]. This script sets up parameters for every image acquisition. It also runs: 'QTargetExtraction' [8] to detect the centre of the ellipses; Helmert transformations between camera coordinate system and LHCb coordinate system; and least-square 3D adjustments to calculate the target coordinates. The computed positions are integrated and archived in the LHCb supervisory control and data acquisition system.

Measurement Results, Performances

An acquisition cycle, sequential image acquisitions followed by one adjustment, is lasting approximately 20 seconds. In the least favourable case, longest distances and smallest intersection angles, the accuracy of relative movement measurement is 75 µm. This accuracy can be further improved to approximately 5 µm by averaging measurements over periods of one hour. Real movements of the detector structure during the averaging time have been checked to be not larger than the obtained resolution.

Added Value of the System

With the excellent performances achieved with the BCAM system, it was possible to measure accurately the movements of the Inner Tracker during operations of the detector and use this information to validate the detector alignment procedures. Displacements due to the magnetic field of up to 10 mm along the LHC beam line were studied, and smaller movement of ~30 µm caused by the powering of the detector electronics could be identified (Fig. 1).

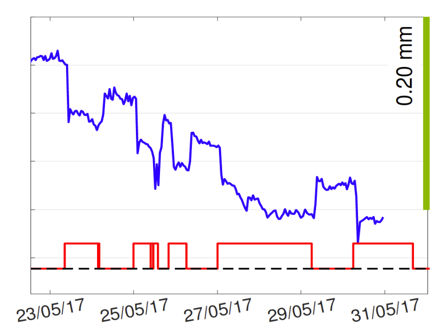

Figure 1: Evolution of the position (top blue line) of one of the LHCb A side Inner Tracker detector boxes along the beam direction z during a period of approximately one week in May 2017. The vertical green line on the right shows the scale corresponding to 0.2 mm. The detector electronics status (ON/OFF, bottom red line) is also shown. A clear correlation between the detector position and the electronics powering can be seen. The corresponding to variations are at the level of ~30 µm.

In addition, slow movements of up to a few 100 µm over one year of operation could be measured. All these movements have been positively correlated with the software alignment constants obtained from tracking particles

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through the detector, providing thus a validation of these alignment constants. In future applications, it is expected that the BCAM measurements can be used as constraints to improve the track-fit resolution and the stability of the alignment software. It is already anticipated that such a system could be used for the upgraded LHCb detector.

MATHILDE SYSTEM

To run the HIE-ISOLDE LINAC in the optimum conditions the MATHILDE (Monitoring and Alignment Tracking for Hie-IsoLDE) system was designed to align and monitor the five RF cavities and one superconducting solenoid enclosed in each LINAC Cryo-Module (CM) within a precision of respectively 0.3 mm and 0.15 mm at 1σ level along the directions perpendicular to the beam. The active elements are operating under vacuum (10^{-11} mbar level) and cryogenic (4.5 K) conditions.

Design Concept

MATHILDE uses a set of specifically upgraded double-sided BCAMs called HIE-ISOLDE Brandeis CCD Angle Monitor (HBCAM) [9]. The optical sensors are placed on metrological tables between the CMs. The measurement scheme [10] includes observations on:

- Other HBCAMs placed on different metrological table or on reference pillars linked to the Nominal Beam Line.
- High Index (n ≈ 2) glass balls [9] associated to the active elements (eight glass spheres per element).

Four precise optical viewports are installed on each CM permitting measurements inside or through it. This design creates a closed geometrical network continuously measured in which the position of the HBCAMs and of the active elements are reconstructed in the datum for every acquisition sequence.

Software

A specially developed Monitoring and Alignment Tracking for HIE-ISOLDE Software (MATHIS) [11] manages the acquisition, the corrections (temperature, viewport crossing, etc.), the 3D adjustment computation and the links to the different databases. The observation scheme and geometrical inputs are fully flexible and therefore easily upgradable for new CM installations or adaptable for totally different projects.

Measurement Results and Added Value

The MATHILDE system is used for a number of different phases during the CM life cycle.

At the end of the assembly step MATHILDE is used to perform the final fiducialisation. After transportation of the CM in the LINAC zone, the system allows the control of the stability of the alignment of the RF cavities and solenoid which was done during the assembly of each CM.

The system is used to pre-align and to align precisely the active elements on the Nominal Beam Line, respectively at room and at cryogenic temperature (down to 4.5 K). Then the positions are monitored during operation.

At steady temperature states, the system allows a 1σ precision against the datum of about 0.1 mm for the position reconstruction of most active elements beam port centres.

In addition, the movement induced by the cool-down or warm-up of the Cryo-Modules are monitored online. Throughout cool-down, the active elements move up by about 4.3 mm.

After installation of three CMs out of four, MATHILDE has proven to be reliable, robust and easily configurable. The 4th CM has been installed in the beginning of 2018 and will be aligned later this year.

CONCLUSION

The BCAM based alignment and monitoring systems developed at CERN for ATLAS, for LHCb and for HIE-ISOLDE have proven to be precise, robust and reliable in different configurations and environments.

The facts that BCAMs have a kinematic mount, that they are delivered with calibrated geometrical parameters and that they allow BCAM to Target as well as BCAM to BCAM observations, facilitate the implementation of adequate geometrical configurations. The redundant observations obtained can produce 3D coordinates once processed with 3D least square adjustment.

These alignment systems increase the amount of available positioning data for physics. In addition to measurements done during the run periods when no access is possible, the number and time of surveyor interventions is reduced as well as the potential exposure to radiation.

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