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3D monitoring of the LHCb SciFi detector

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Abstract

The SciFi detector is one of the new particle trackers of LHCb, which is one of the four main experiments installed on the LHC at CERN. This detector is composed of three stations each formed by four 'six by five meters' planes covered by scintillating fibres.

The LHCb dipole magnet powering cycles and the environment conditions such as humidity and temperature variations may affect the geometry of the detectors leading to loss of precision for the tracking of the particles.

During the second-long shutdown of the LHC (LS2), the CERN Survey team (BE-GM-ESA) in collaboration with the LHCb Technical Coordination and the EPFL (Ecole Polytechnique Fédérale de LAUSANNE, CH), developed a near real time 3D monitoring system in order to follow the possible movements and deformations of the detector. It should allow for the 3D position measurement of three sets of a dozen of points spread over each of the three detector stations, reaching a precision of 150 µm at the one sigma level.

The new system is based on intersecting lines of sight of opto-electronic BCAM (Brandeis CCD Angle Monitor) sensors, following the movements of reference marks attached to the detector.

It will use eight BCAM sensors per station. They will be fixed on the LHCb concrete 'bunker' via adjustable supports. Their lines of sight will intersect in 10 different positions where targets will be installed.

Some 4 mm diameter glass spheres of index 2 will materialize the measured points. The spheres allow a wide range of intersection angles. They are maintained in place by low (density) material holders, minimising the interference with the physics of the detector.

The system will be installed in 2022.

This paper summarizes the studies of the proposed system, its configuration and integration in the experiment, as well as the first tests and current results obtained.

Monitoring, Image, Laser, Accuracy

1. Introduction

The SciFi detector is a new particle tracker of LHCb [1] (Figure 1), one of the four main experiments installed on the CERN Large Hadron Collider [2].

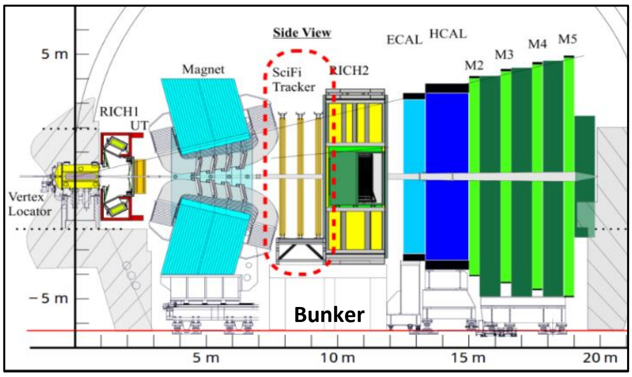

Figure 1. LHCb layout [3]

This detector is composed of three stations. Each formed of four connected layers. Each station opens in half around the beam pipe. Every layer is made of 5 or 6 modules (Figure 2). The modules are approximately 5 m high, 600 mm wide and 40 mm thick and contain several layers of scintillating fibres reinforced by honeycombs and carbon fibre.

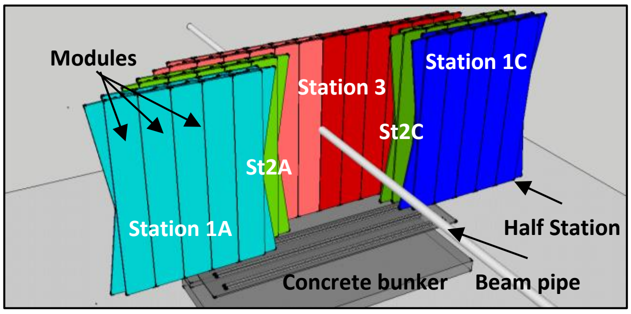

Figure 2. SciFi detector parts

From previous trackers it is known that the LHCb dipole magnet powering cycles and the environmental conditions may affect the position and geometry of the detectors leading to loss of precision for the tracking of the particles [4].

In order to identify those movements and deformations, a near real time 3D monitoring system has been developed since the end of 2019 during the second-long shutdown and technical stop of the LHC.

The system must keep track of the position of about a dozen of points per station (Figure 3). The measurement of the relative movements should have a precision of 0.1 mm at one sigma level. The accuracy of the determination of the absolute position should be better than 0.5 mm in three dimensions. The system should be made of a limited use of materials, work in 1 Tesla magnetic field, survive in the radioactive environment of the experiment and be low cost.

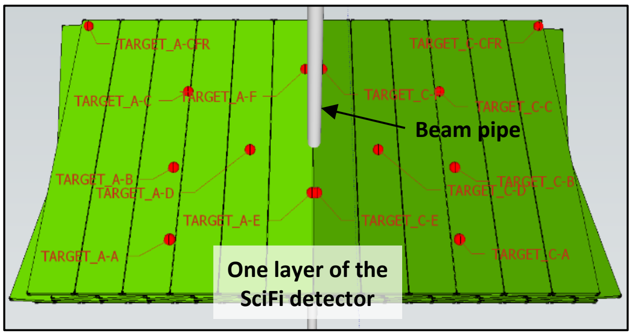

Figure 3. Distribution of the monitored points for station 3

Previous LHCb trackers were already equipped with a similar system [5]. On each station, a single point materialised by a reflective sticker has been observed by 2 cameras subtending an angle close to 90°. Simple trigonometry has been used to compute the point coordinates.

The new system uses eight cameras per station, installed on stable structures, having their lines of sights intersecting at the points of interest.

This research work will explain the choices and designs used for the cameras, the targets and their installation as well as the computation of the point 3D coordinates.

2. Principle

Points of interest of the detector, materialised by targets, are visible from fixed cameras. Each camera sees a few targets and tracks their angular movement (direction of the line of sight). Coupled with data from a second camera, the intersection gives the 3D coordinates of the observed point.

The main hypothesis of the system is the stability in time of the cameras, especially during the physics run.

2.1. Targets and their supports

Each monitored point is materialised by a physical reflective target visible from the cameras.

There are two main constraints. It should be visible at a distance of up to 9 m and it must be contained in the lines of sight of at least two cameras, which should subtend an angle as close to 90° as possible. The quantity of material is kept to a minimum to limit the physical interaction with the particles that are tracked. In addition, for practical reasons, the target has been designed to be slightly adjustable in position and to be interchangeable with laser tracker targets.

Therefore, 4 mm diameter glass balls with reflective index 2 have been selected. They are maintained in place by a kinematic plugin system that consist of a holder equipped with 8g6 pin and a receptacle equipped of 8H7 holes, both made of PEEK (Polyetheretherketone). The receptacle can be inserted in five different positions into a support made of 'Delmat EP GC 203' which is glued directly on the detector (Figure 4).

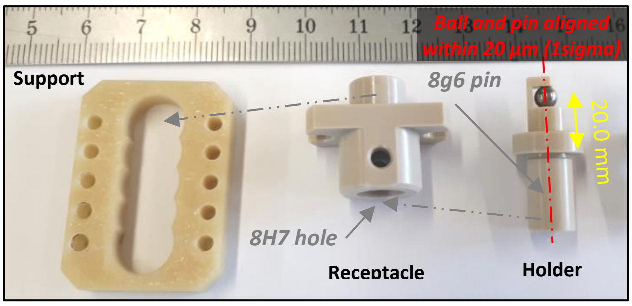

Figure 4. Target/glass ball adjustable holder

2.2. Cameras and their supports

The system uses single sided *Brandeis CCD Angle Monitors* (BCAM). They are robust, isostatic, non-magnetic, working in magnetic field and can accept a total radiation dose of 400 Gy [6] (Figure 5).

For cost reasons, the recycled first generation devices with a field of view of 30 mrad x 40 mrad and a precision of 5 µrad have been used.

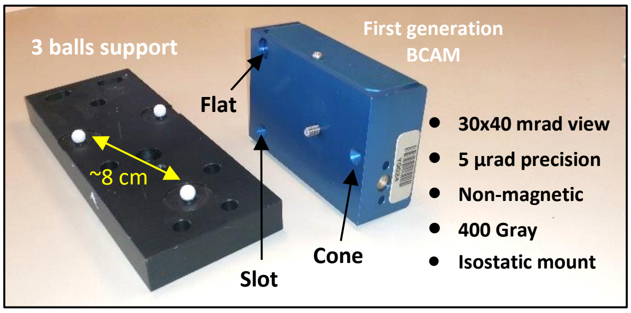

Figure 5. Camera, fixation and specifications

The cameras are equipped with laser sources that are reflected by the targets.

Beneath each BCAM there are three depressions: a flat, a slot, and a cone (Figure 5). These allow the BCAM to sit isostatically on three quarter-inch (6.35 mm diameter) ceramic balls. The centres of these balls define a mount coordinate system (also called BCAM coordinates system) [7]. The calibration procedure allows to determine the position of the camera pivot point and the direction of the camera axis, the rotation of the CCD and the position of the laser light sources in the mount coordinates. That way, the determination of the vector between the camera and the target has been achieved with a precision of 50 µrad (Figure 6).

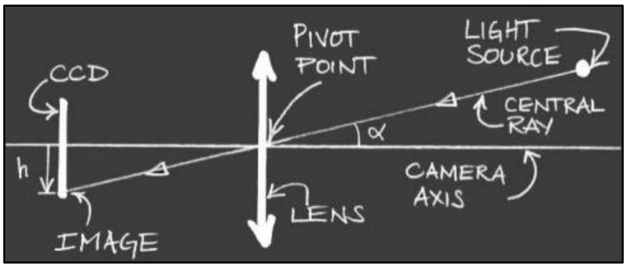

Figure 6. Schematic drawing of the optical principle [5]

The most stable area in the zone from where the detector is visible is the concrete bunker on which the SciFi is installed. The BCAMs will be placed there, on supports (Figure 7) that allow the camera adjustment in translation and rotation in order to find their nominal positions. During the monitoring operation the zone will be closed and the temperature controlled. To verify the stability of the support, an additional camera will be fixed at the extremity of one of the arm of the support to look at a stable target placed on one of the concrete wall of the LHCb cavern.

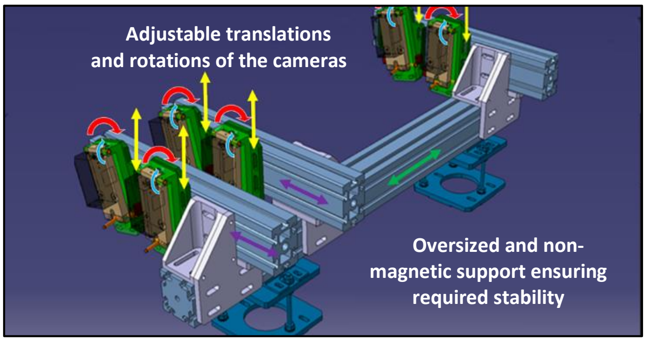

Figure 7. Camera support

2.3. Observations / geometry

The aim is to monitor a maximum number of points, as equally spread as possible over the detector plane (with special interest in the centre of the detector plane where a maximum of particles passes), with a limited number of cameras placed on the available stable area.

In Figure 8, the chosen geometry is illustrated. It is a compromise maximizing the number of modules covered while minimizing the number of cameras. Twelve targets are observed in 3D by eight BCAMs. Two points are only observed in 2D by a single camera, they are on a module that has already 2 other positions monitored in 3D, to identify a possible bent shape of the X–Y plane of the module. The same configuration is used for each of the three stations.

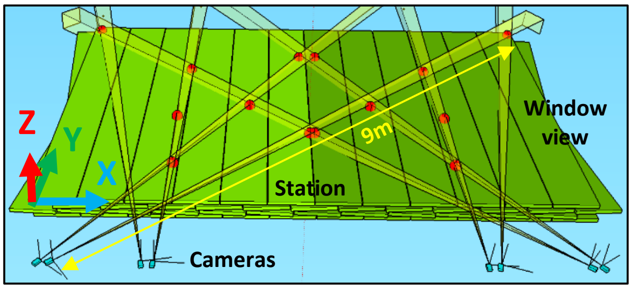

Figure 8. Cameras and targets distribution for one station

The camera axes are coplanar, the plane is inclined by 5° w.r.t. the detector plane, allowing the targets not to hide each other and to ease the target identification on the camera images.

Thanks to the known mounting system (equipped with reference marks) of the cameras and to the compatibility of the target holders, the starting positions of the cameras and targets can be measured in the detector system with a laser tracker.

2.4. Computation

Each vector between the cameras and the targets can be computed (§2.2) in the detector coordinate system with an a priori precision of 50 µrad. In the worst case with a camera to target distances up to 9 m, this is equivalent to 450 µm on the target coordinates. It is due to the extrapolation between the BCAM base length of ~80 mm and the distance between the camera and the target. This precision will be improved with a calibration of the system using precisely measured positions of all targets and cameras with a laser tracker.

The system is slightly redundant so that a least squares adjustment of the 3D positions will be performed. In practice, we benefit from existing CERN software developed such as MATHIS [7] to perform the acquisition of images and analysis, and LGC [8] for the least squares compensation.

The computation will loop, with data acquisition time of approximately 1 minute per station.

3. One to one (1:1) scale mock-up

In the validation procedure, a 1:1 scale model simulating the system for one layer has been done on a concrete floor.

The positions of the cameras and the targets have been determined using an Absolute Laser Tracker (AT) with an estimated precision of 40 µm along X, Y and Z axes (Figure 8). For each test, two positions of the targets have been measured using both systems to compare relative displacements.

3.1. Measurement repeatability

A repeatability test of 30 measurements of the 14 targets took place. The standard deviation when considering all points of interest is 6, 9 and 5 µm (Figure 9) for the position along X-, Y- and Z-axis, respectively.

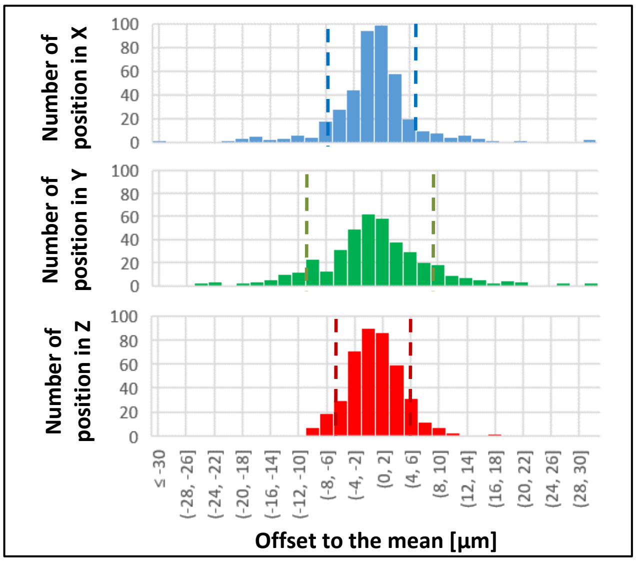

Figure 9. Precision per axis.

The 3D precision for each point can be computed as follow:

$$\sigma_{3D} = \sqrt{\sigma_X^2 + \sigma_Y^2 + \sigma_Z^2} \tag{1}$$

Where:

$\sigma_{X,Y,Z}$ = the standard deviation of the 30 measurements along X-, Y- and Z-axis respectively, for a given target.

The precision varies from 5 to 25 µm depending on the distance between the target and the camera and the intersection angle between the camera lines of sight (Figure 10).

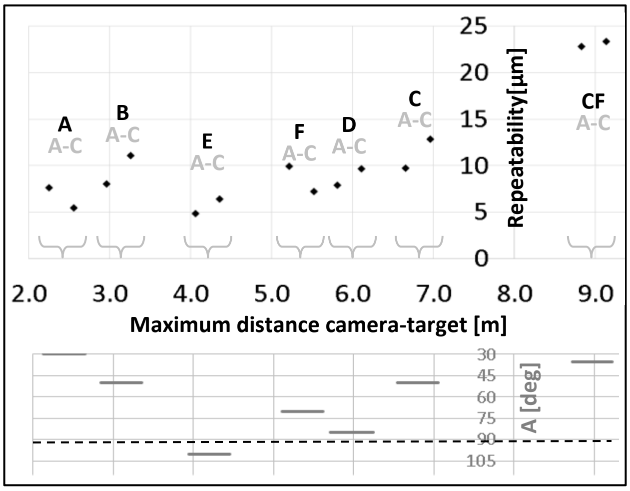

Figure 10. Repeatability per point of interest (top) and camera line of sight intersection angle A (bottom) in function of the camera-target distance.

3.2. Accuracy on the coordinates

The accuracy is determined by the comparison of the coordinates given by the BCAM system and the laser tracker (AT) measurements. The accuracy (d) and its uncertainty along each axis are given by:

$$d_W = W_{AT} - W_{BCAM} \quad \text{and} \quad \sigma_{d_W} = \pm\sqrt{\sigma_{W_{AT}}^2 + \sigma_{W_{BCAM}}^2} \tag{2,3}$$

With

- W = X, Y or Z;
- d_W = the coordinates difference between AT and BCAM along the W axis;
- W = the X-, Y- and Z-coordinates provided by the AT and BCAM measurements, respectively.

And the 3D accuracy (d_{3D}) and its uncertainty by:

$$d_{3D} = \sqrt{d_X^2 + d_Y^2 + d_Z^2} \quad (4)$$

and

$$\sigma_{d_{3D}} = \pm\left(\left(\frac{d_X}{\sqrt{d_X^2+d_Y^2+d_Z^2}}\right)^2 \sigma_{d_X}^2 + \left(\frac{d_Y}{\sqrt{d_X^2+d_Y^2+d_Z^2}}\right)^2 \sigma_{d_Y}^2 + \left(\frac{d_Z}{\sqrt{d_X^2+d_Y^2+d_Z^2}}\right)^2 \sigma_{d_Z}^2\right)^{\frac{1}{2}} \quad (5)$$

The accuracy is similar along the X-, Y- and Z-axis and the 3D accuracy varies from 50 to 150 µm depending on the geometrical configuration of targets and cameras (Figure 11).

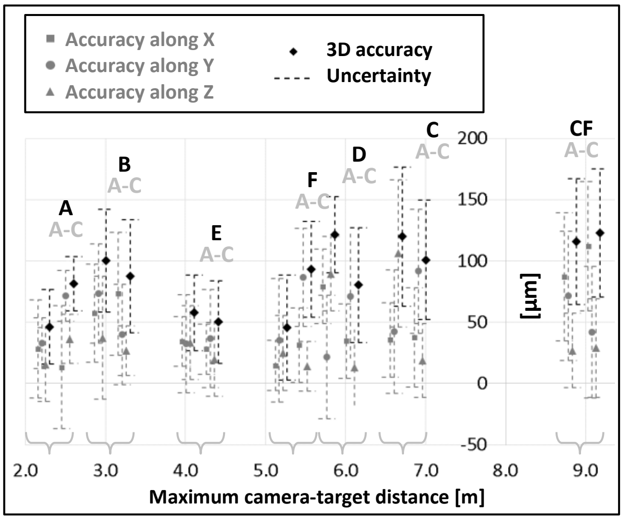

Figure 11. **Accuracy of 3D coordinates per point of interest**

3.3. Accuracy of relative displacements

Thanks to the two different positions of the targets measured with the two independent systems, an accuracy on the relative displacements (D) and its uncertainty can be estimated along each axis by:

$$D_W = d_{W_{BCAM}} - d_{W_{AT}} \text{ and } \sigma_{D_W} = \pm\sqrt{\sigma_{d_{W_{BCAM}}}^2 + \sigma_{d_{W_{AT}}}^2} \quad (6, 7)$$

Where:

$$d_{I_{sys}} = I_{P2_{sys}} - I_{P1_{sys}} \text{ and } \sigma_{d_{I_{sys}}} = \pm\sqrt{\sigma_{I_{P2_{sys}}}^2 + \sigma_{I_{P1_{sys}}}^2} \quad (8, 9)$$

With:

- *I = X, Y or Z*
- *sys = BCAM or Tracker*
- $d_{I_{sys}}$ *= difference in coordinates between the two positions for one of the systems along a given axis.*

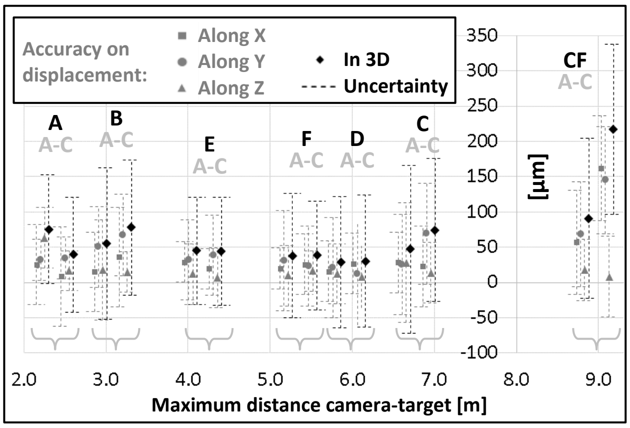

Figure 12. **Accuracy of relative displacements measurement**

The accuracy in 3D and its uncertainty is given by:

$$D_{3D} = \sqrt{D_X^2 + D_Y^2 + D_Z^2} \text{ and } \sigma_{3D} = \sqrt{\sigma_X^2 + \sigma_Y^2 + \sigma_Z^2} \quad (10,11)$$

The accuracy on relative displacement detection is mostly below 50 µm along the X-, Y-, and Z-axis.

In 3D, the accuracy varies from 40 to 100 µm except for one of the targets, which is the furthest away from its associated cameras (Figure 12).

4. Conclusion

The system being studied looks very promising. The simulation of one SciFi plane with a 1:1 scale model using first generation BCAMs as cameras, 4 mm glass balls with refractive index 2 as targets and MATHIS software for computation give results in the expected range of measurement precision and accuracy. A 3D precision better than 20 µm and an accuracy better than 150 µm is achieved. The accuracy of relative displacement is around 50 µm for most of the target-camera configurations.

An improvement of the system could be to add other cameras looking at existing targets from further stable positions. In addition, more points could be monitored inside the field of view of existing cameras by adding more constraints to the computation such as known distances between points on a same module.

The system will be installed at the end of the ongoing maintenance and upgrade period of the CERN LHC. The system relies on the stability of the cameras which is assumed during the LHC runs when the cavern is closed and the access forbidden and that was checked by the previous existing monitoring system. The knowledge of the movements of the detectors with the monitoring system precision and accuracy will help to determine the particles tracks with more reliability.

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