ALIGNMENT OF THE ATLAS-AFP DETECTORS*

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The ATLAS Forward Proton (AFP) detectors open new possibilities to expand the reach of the ATLAS Experiment physics and to probe unique physics processes by measuring intact protons produced in diffractive or photon-induced processes. The AFP system uses Roman pots located approximately 210 meters from the ATLAS interaction point on both outgoing beams. These devices enable measurements in the vicinity of the LHC beam. Each AFP station contains a tracking detector, consisting of four planes of silicon pixel sensors. The present study focuses on the alignment of the AFP detector, a critical process to ensure the highest accuracy in proton measurements. Local alignment, the first step in this process, concentrates on accurately determining the relative positions of the pixel planes. Subsequently, global alignment is dedicated to determining the overall position of the AFP detector relative to the beam.

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1. Introduction

The ATLAS Forward Proton (AFP) detector, which is a part of the ATLAS Experiment at the Large Hadron Collider (LHC), is designed to measure intact protons scattered at very small angles in proton–proton (pp) collisions [1, 2]. AFP significantly expands the experimental reach of ATLAS by facilitating studies on exclusive production, where both protons remain intact, and single diffractive dissociative (SDD) processes, where only one proton remains intact. It opens new avenues for testing the Standard Model (SM) and conducting searches beyond the Standard Model (BSM) [3, 4].

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The AFP system uses the Roman pot technology (RP). A pot is inserted into the vicinity of the LHC beam under the stable beam conditions to detect protons travelling through the LHC magnetic lattice, see Fig. 1. The pots are located at longitudinal distances of approximately $z \simeq \pm 205$ m (NEAR) and $z \simeq \pm 217$ m (FAR) on either side of the interaction point. The coordinate system is defined in such a way that z is along the LHC beam, x points outside the LHC ring, and y points up[1].

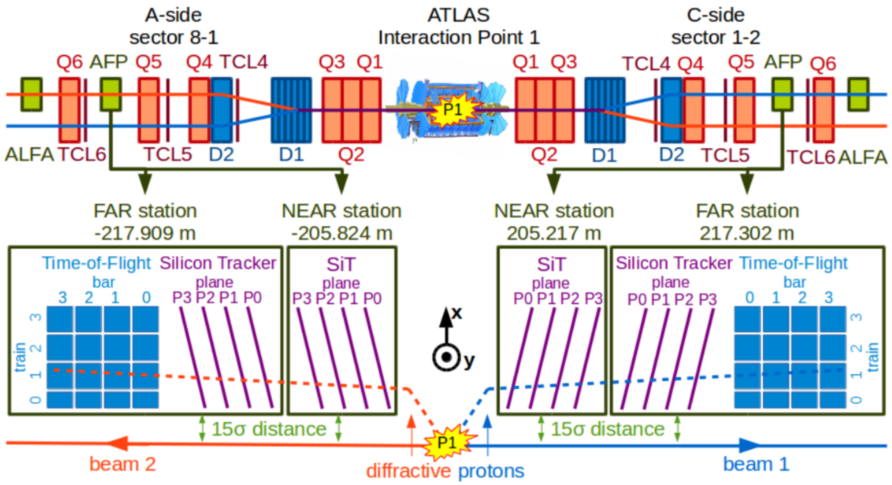

Fig. 1. A comprehensive schematic of the AFP detector system [5].

Each station is equipped with a Silicon Tracker (SiT) module, which houses a four-plane 3D silicon pixel sensor designed to measure the trajectories of the scattered protons. These planes, separated by a distance of 9 mm, are 230 μm thick and consist of 336×80 pixels with dimensions of $50\ \mu\text{m} \times 250\ \mu\text{m}$. The planes are tilted by 14° around the y-axis to achieve a resolution of 6 μm and 30 μm along the x- and y-axis respectively [6]. Furthermore, FAR stations are equipped with a Time-of-Flight (ToF) module that detects Cherenkov radiation emitted by the transversing protons using sixteen L-shaped light-guiding quartz (LQ) bars. The ToF modules offer the timing resolution of 20 ps [7]. This allows for the precise calculation of the position of the longitudinal coordinate of the interaction vertex (z) of a proton pair.

As a proton traverses the SiT detector, it activates pixels within the SiT planes. The reconstruction involves forming clusters from hits belonging to the SiT planes. Usually, due to the tilt 14°, two adjacent pixels are activated.

[1] The pots, also referred to as stations, are positioned such that Side A faces the $-z$ direction from the interaction point, and Side C faces the $+z$ direction.

The cluster position is determined by the energy-weighted average of the positions of the activated pixels. Assuming a linear trajectory for the proton due to the absence of a magnetic field, the reconstruction entails performing a linear regression on the cluster coordinates separately in the (z, x) and (z, y) planes, in order to form a track. The final stage of reconstruction identifies a proton object at one or more stations.

A proper alignment of a detector is an indispensable ingredient of a precise measurement. Although the positions of the RP stations and the SiT planes within them are set according to the design values during installation, data-based alignment is required to account for minor rotations and shifts that may occur during the insertion of the Roman pots. Therefore, in order to obtain the most accurate kinematics of the protons, monitoring the alignment in the AFP detector is a necessity.

2. Local alignment

The local alignment aims at the determination of the relative positions of the SiT planes within a station. In this analysis, the calculation of the alignment parameters is based on minimizing the differences between the cluster and the track positions within each plane. Track positions are taken as a reference, representing the true position of the protons. The relation between the positions of the track ($\vec{r}_{\mathrm{t}}$) and the clusters ($\vec{r}_{\mathrm{c}}$) can be written in terms of the alignment parameters as follows:

$$\vec{r}_{\mathrm{t}} = R(\alpha, \beta, \gamma)\, \vec{r}_{\mathrm{c}} + \delta\vec{r}(\delta x, \delta y, \delta z)\,, \tag{1}$$

where $\delta\vec{r}$ represents the offset corrections along the x, y, and z axes, while $R(\alpha, \beta, \gamma)$ denotes the 3D rotational matrix, corresponding to the rotation angles around the z, y, and x axes, respectively.

Each plane has six degrees of freedom: three rotations and three offsets, implying thus the determination of 24 free parameters for each station. This study adopts a simplified approach that focuses on the adjustments in the x and y directions and rotations about the z-axis, utilizing the small-angle approximation for the rotation matrix as presented in Eq. (1). Furthermore, three degrees of freedom are eliminated by calculating the alignment parameters relative to the SiT plane closest to the collision point — the 0^{th} plane. This also removes one of the weak modes, which is shifting the entire detector[2]. Consequently, only nine free parameters remain to be determined for each station.

[2] A weak mode refers to a rotation or a translation that does not significantly change the residuals or the χ^2 of a track.

The following criteria are applied to the data to facilitate the local alignment in a clean environment: one to two hits are recorded, and one cluster is reconstructed per SiT plane, with only one track reconstructed within a station. In addition, events where the transverse distance between clusters is greater than 0.5 mm are excluded. The slope of the track is set to zero to eliminate the weak mode resulting from the rotation of the entire detector.

Initially, the alignment parameters are set to zero, assuming that no corrections are required. Adjustments to the alignment parameters are made through iterative calculations until a stable state is achieved, at which point no further correction is required. Figure 2 illustrates the offset along the x-axis before and after applying all alignment corrections and the evolution of the offset value with the iteration number.

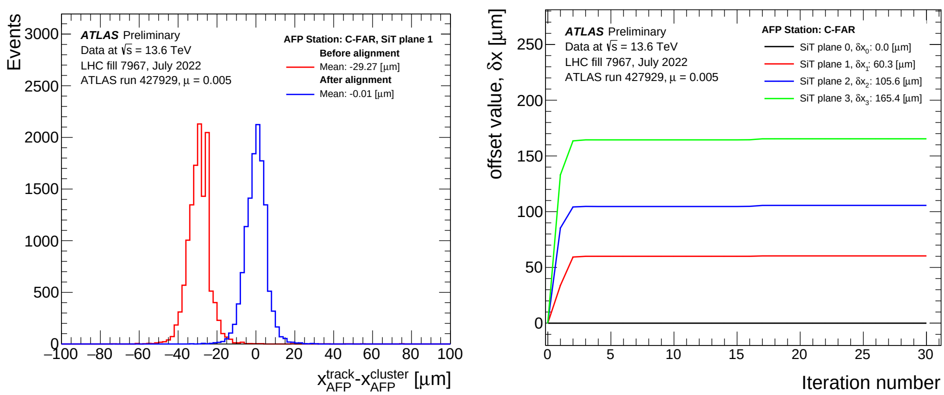

Fig. 2. Left: The distribution of the difference of the x positions of a reconstructed track and a cluster in SiT Plane 1 of the AFP C-FAR station for an exemplary ATLAS run. Right: The evolution of the offset value (δx) along the x-axis as a function of the iteration number [8].

3. Global alignment

Global alignment is crucial for determining the precise position of the AFP detector relative to the LHC beam. The alignment parameters can be obtained using various methods. Prior to data-taking, pots are surveyed in the tunnel using precise lasers. This allows the determination of rotation while pots are inserted. Beam-Based Alignment (BBA) involves aligning the collimators with the beam to determine its nominal position [9]. Beam Position Monitoring (BPM) provides the real-time tracking of the beam position throughout the standard accelerator operations [10]. In addition, dedicated studies of beam optics are performed in order to precisely determine the proton trajectory, as influenced by LHC magnets, from the interaction point to the AFP detector.

A data-driven approach, the dimuon calibration, can also be used for the global alignment. This method involves the process of the exclusive production of muon pairs, wherein two leptons are produced through the photon-fusion mechanism during pp collisions, with the protons remaining intact. The idea behind this method is to compare the x positions of the protons calculated based on the measured dimuon system with those measured by the AFP detector. Results of such an analysis conducted using the LHC Run 2 data are shown in Fig. 3, taken from Ref. [5]. The mean of the distribution signifies the level of misalignment.

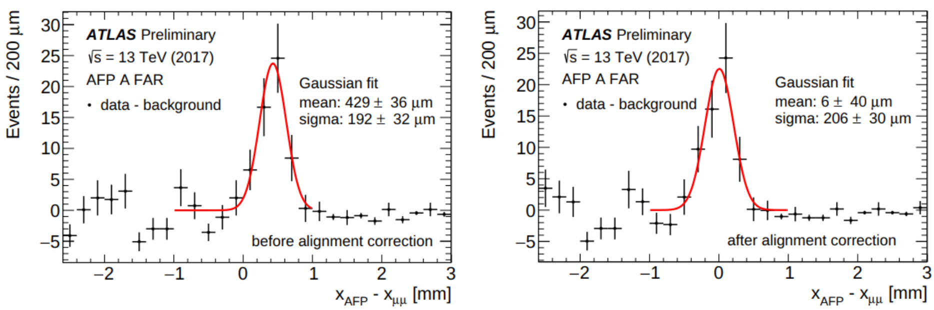

Fig. 3. Distributions of the x positions calculated using the dimuon system and the protons measured at AFP: Left: Before alignment; Right: After alignment. The mean values and uncertainties are from a Gaussian fit.

4. Conclusion

The AFP detector plays a crucial role in extending the ATLAS physics program by detecting the forward scattered protons that remain intact during pp collisions. The alignment of the AFP is essential for achieving precise proton measurements and is divided into two main tasks: local and global alignment. Local alignment was attempted using a method focused on minimizing residuals. Moving forward, the strategy will shift to the Global χ^2 method, a more sophisticated technique that was also applied in the alignment of the ATLAS Inner Detector [11]. Global alignment was initially carried out using the dimuon calibration method. It is the dominant source of uncertainty for the AFP-based data analyses performed so far, taken very conservatively as 300 μm. Efforts to improve global alignment, including BBA, BPM, and RP rotation studies, are actively continuing. Additionally, beam optics studies are underway to determine data-driven corrections to the beam optics, using observables determined with AFP.

Both phases of alignment are essential for enhancing the precision of AFP measurements. The analysis of LHC Run 2 data offered valuable insights, as several methodologies were applied for the first time [5]. Research related to these efforts is now progressing with the LHC Run 3 data.

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