



Hot-spot method for alignment of ATLAS Forward Proton detectors at the LHC

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Abstract

ATLAS Forward Proton detectors (AFP) are placed inside LHC beampipe. They aim to measure very forward protons that have not yet been measured in ATLAS detector. The very precise knowledge of their position – called the alignment – is required for trustworthy data analysis. The aim of this paper is to describe the hot spot alignment method which involves looking for high density spots in proton position distribution.

1 Introduction

One of the goals of LHC physics programme is to measure properties of so called diffractive processes.

These processes can happen when protons interact strongly by exchanging the colorless object called Pomeron. From this kind of collision one or two protons can remain intact or loose a small amount of their energy.

It is a common situation when one proton remains intact and second dissociates. This we call single diffractive proton scattering. Feynman diagram for this process is presented on figure 1.

This kind of events has two very distinctive experimental signatures. This is namely: large rapidity gap – a suppression of radiation in certain area of phase-space - and an intact forward proton.

Scattering angle of diffractive processes is very small and because of this they cannot be seen in ATLAS main detector.

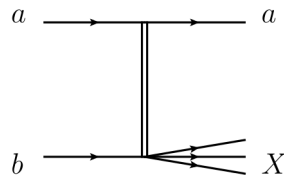


Figure 1: Feynman diagram for single diffractive dissociation of proton. One can observe intact proton.

With this in mind the forward detectors are build. They are usually placed in the beam pipe with a proximity to the proton beam and very far from interaction point. Thanks to this it becomes possible to detect protons with very large pseudorapidity ranges.

ATLAS Forward Proton

For ATLAS the newest addition in forward region is the AFP detector [[1]]. These detectors can work with normal collision optics, contrary to older ALFA detectors.

AFP station consists of four-layer pixel tracker and time-of-flight detector in outer station. The resolution of pixel tracker is of $10\mu\text{m}$ in horizontal axis and $30\mu\text{m}$ in vertical plane. Time resolution of ToFs is 30 ps. The horizontal resolution is higher because it plays the leading role in reconstruction process [[?]].

Ultimately there will be four stations, two for each side of the interaction point. Currently only one arm is installed. It is actively taking data.

Each of the stations is placed in so called Roman Pots. This is widely used technology which allows the detector to be safely put inside the beam pipe. This is the case for AFP which is put to the beam pipe from the side. Both roman pot and AFP detector are presented on figure 2.

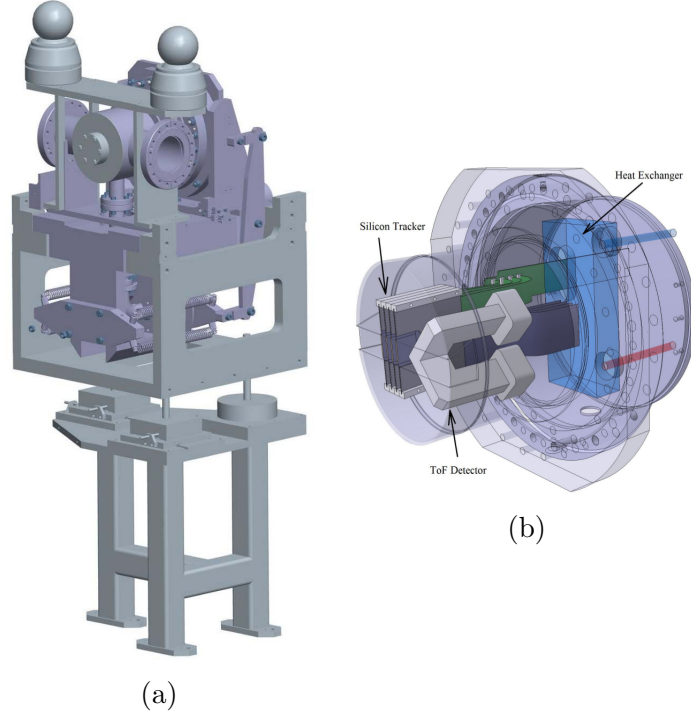


Figure 2: (a) – Roman Pot construction, (b) – structure of AFP station.

Alignment

Forward proton detectors can measure the position and the direction of scattered proton. With these momenta can be reconstructed. As this calculation heavily depend of measured position precise knowledge of their position, called alignment, is crucial.

Moreover, alignment method should be data driven, as beam conditions may change during the run. This is the case with AFP, which has to be removed from the beam pipe during early stages of the run. Later on they are put inside the beam pipe in the very proximity to the proton beam.

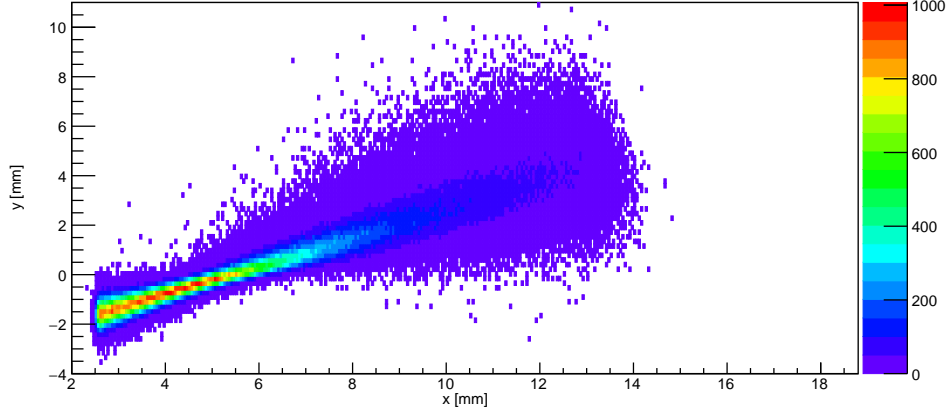
Separate alignment has to be done for each run in order to successfully compare results between runs.

2 Hot Spot alignment

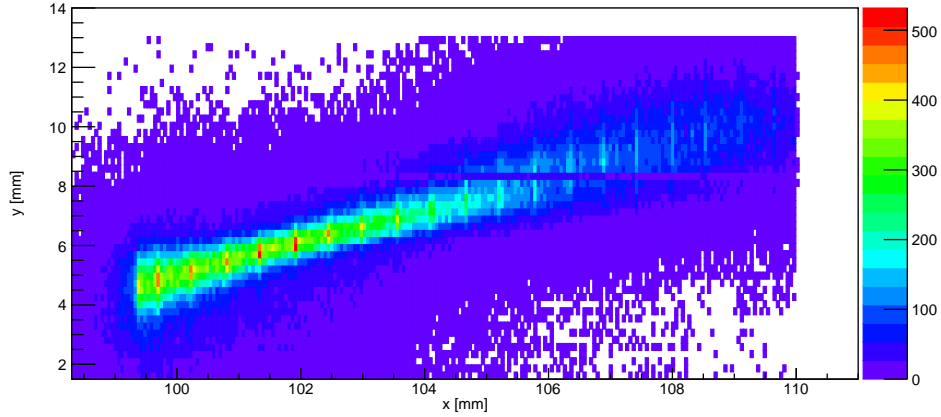
Hot spot is purely data driven alignment method. It can be performed separately for each station or even pixel tracker. Dominating process is single diffractive proton dissociation, which has large cross section and because of this statistics needed to perform alignment can be gathered in very short time (order of seconds). It does not use reconstructed values and because of this can be used in early stages of data analysis.

This method involves looking for high density areas (called the hot spot) in the proton distribution in x-y plane (fig. 3). This corresponds to the search of the narrowest area in this distribution.

The principle of the hot-spot method is to align the detector with respect to this region. The position of this narrow region with respect to the beam is known from the simulation. In data registered with the detector, the beam-centre itself is not observed while hot spot region can clearly be seen. A comparison between the data and the simulation provides information about the position of the detector during the data taking.



(a)



(b)

Figure 3: (a) hitmap for MC for AFP station 2 and (b) hitmap for reconstructed tracks.

The origin of received shape is not yet fully understood. It is known that it is connected to proton momenta distribution and LHC optics. Less energetic particles¹ are swept away by dipole magnets and in result they can end up further away from the centre of the beam than highly energetic particles. Due to stability of LHC optics hot spot method is viable - the narrowest regions position does not change over time.

¹

With lower ξ (called *relative energy loss*), which is calculated as $\xi = 1 - \frac{E_p}{E_b}$

The measurement of width of the proton position distribution is an important part of the hot spot method. It can be done in several various ways.

In each of these width measurement methods the very first step is to divide the distribution to thin 'slices' along y axis. The chosen width of this slice is of pixel size. The consequences and uncertainties associated with the changes of slice width will be studied in the future.

1. "RMS" - for each slice RMS is calculated². The main issue for this method is that it is highly susceptible to background noise of protons that appear far from the main 'axis' of the proton distribution. It could potentially be used in runs with special optics, where the cross-section of the proton position distribution is not Gaussian.
2. "Gauss" - For each slice Gaussian fit is performed, the σ -width is then taken as the measured width. The main issue with this method is that the proton position distribution cross-section shape does not follow the gauss statistics for the majority of slices. This leads to heavy dependance on statistics. When it is too low the fit quality is too low and thus the error is much larger.
3. "Combined" - for each slice RMS is calculated and then Gaussian is fitted on range proportional to the measured rms (fig. 4). This method aims to remove weaknesses of previous two methods. It is dependent on only one parameter: $\mathcal{A} = \sigma \cdot RMS$.

Main concern for this method was/is that it fails to perform correct fit in wide regions of the proton position distribution. It may happen but this does not affect whole method because these regions are far from the hot spot. In the near future additional studies will be performed on this topic.

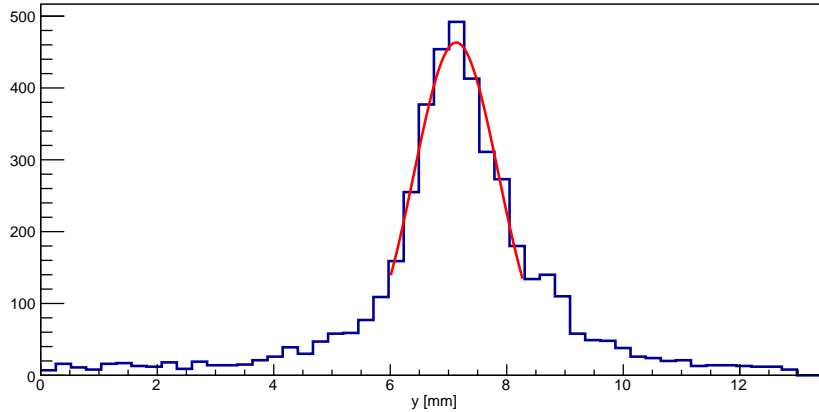


Figure 4: Measurement of width with partial Gaussian fit (fit range: $\sigma = 1.32$, $\mathcal{A} = 2.29$ [mm], $x = 103.4$ [mm]).

²Standard deviation: $S_y(x) = \sqrt{\frac{1}{N} \sum_{i=1}^N (y_i - \bar{y})^2}$

When this step is completed finding the narrowest slice is performed with polynomial fit (fig. 5).

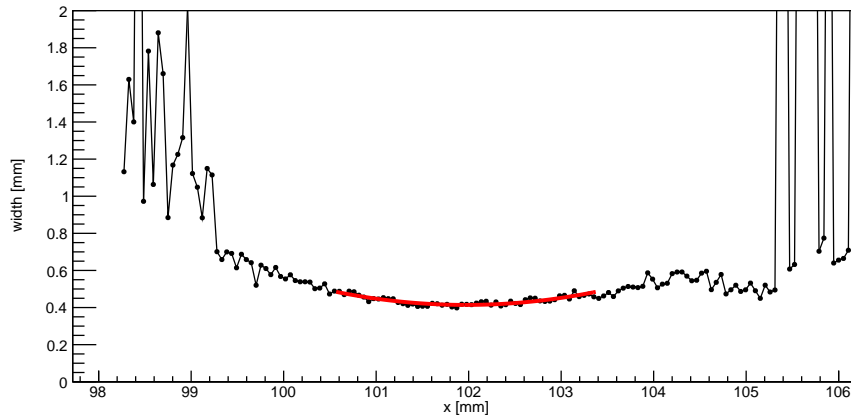
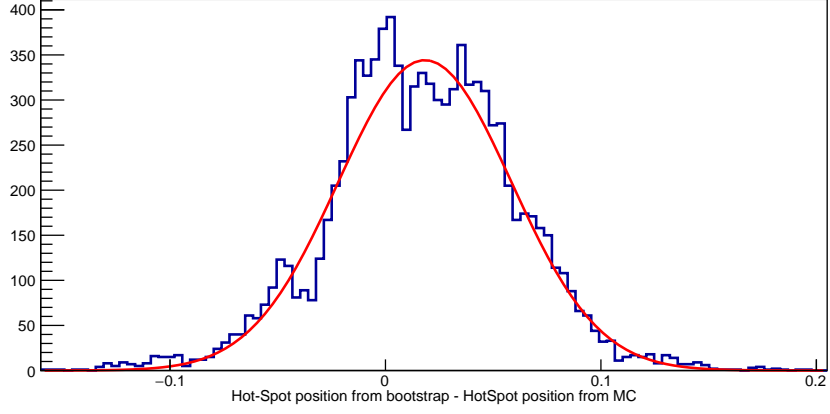


Figure 5: Polynomial fit is performed to find the position of the hot spot. Position of the minimum of this function is the wanted hot spot position.

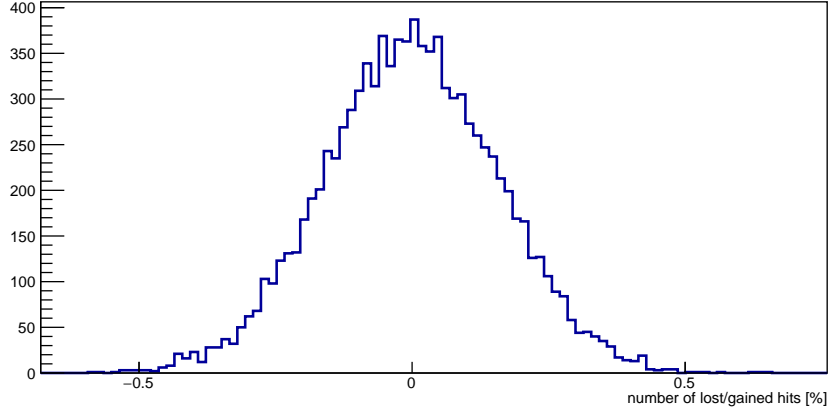
3 Statistical uncertainty

To estimate statistical uncertainties the bootstrap method was used. It is a statistical method of obtaining statistical uncertainty. For every bin of proton position distribution histogram a new value is chosen according to the poisson distribution with the mean of original value of the chosen bin.

On average the bootstrapping method does not introduce new events and it was proven that samples generated with this method are statistically independent (see fig. 6).



(a)

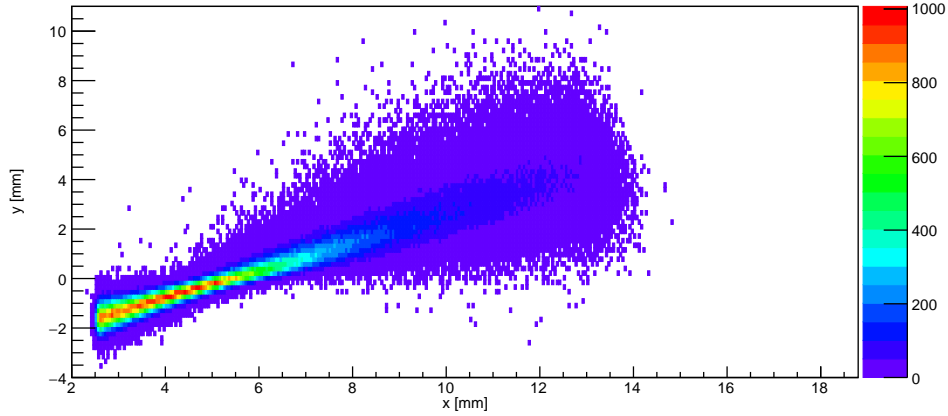


(b)

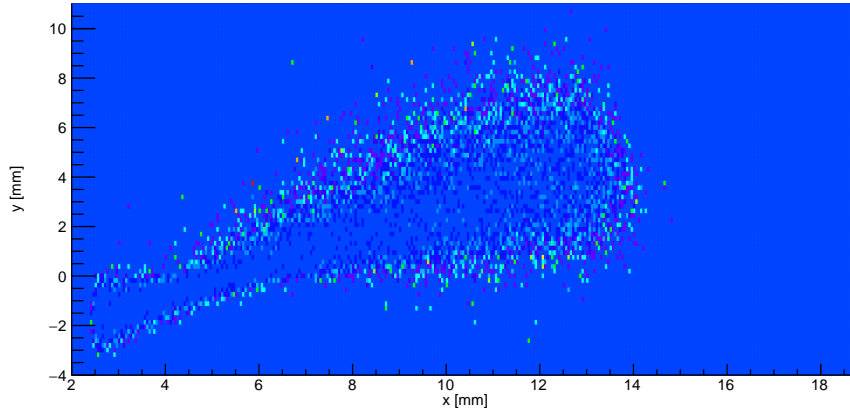
Figure 6: The spread of hot spot positions obtained via bootstrapping is presented on (a). Both width ($\sigma = 0.040$ [mm]) of this distribution and shift ($\delta = 0.018$ [mm]) can be treated as estimate of statistical uncertainty. On (b) one can notice that bootstrap does not introduce new events.

Bootstrapping is equivalent to generation of new MC simulation. The hot spot search algorithm is repeated on obtained sample. The spread and the shift from original hotspot position can be treated as statistical uncertainty. One can notice that bootstrap effectively introduces smearing-like background (fig. 7) which explains the origin of this uncertainty.

This uncertainty has sub-pixel size of 40 [μm].



(a)



(b)

Figure 7: (a) MC sample and (b) background introduced by bootstrapping. One can notice that it mostly affects the edges of proton position distribution. This is analogous to performing a smearing of momenta of generated particles.

Systematic uncertainties were not studied during DESY summer school 2016 programme.

4 Data

For both MC and data the algorithm showed stable. The data sample used originated from physics run for AFP where hot spot is clearly visible. Only part of the available statistics was used and it was proved that method works correctly with such a small statistical sample. Algorithm does not need any cuts, because it needs to be stable and repeatable and having defined its parameters is enough.

The influence of cuts is to be studied further in the future.

The result of the algorithm is a set of numbers. It is information about hot spot positions

for MC and for provided data sample. With this the alignment correction is calculated (table ??).

Station	MC hot spot position [mm]	Data hot spot position [mm]:	Correction [mm]:
2	101.97	4.89	97.08
3	100.95	3.59	97.37

Table 1: Numbers obtained by hot spot search algorithm.

5 Summary

The "hot-spot" method of alignment uses the characteristic proton hit pattern which was observed in forward proton detectors. It does not require enormous computing effort and is simple to use. The cross section of dominating process is big and because of this the method does not require long detector runs. The method is also independent on other detectors and can measure alignment of each sub-detector separately.

The detector is aligned according to the narrow region – so called "hot-spot". Hit pattern width can be measured with several methods. The Narrowest area is found by fitting a quadratic function to the width-distance function.

First results with AFP data were produced. Hot spot method will be applied to future data and it will be under continuous development.

References

- [1] ATLAS Collaboration, “Technical Design Report for the ATLAS Forward Proton Detector”, CERN-LHCC-2015-009, ATLAS-TDR-024.
- [2] R. Staszewski and J. Chwastowski, “Transport Simulation and Diffractive Event Reconstruction at the LHC”, Nucl. Instrum. Meth. A **609**, 136 (2009).