Alignment-related Effects in Forward Proton Experiments at the LHC

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Abstract

The activity in the field of diffractive physics at the Large Hadron Collider has been constantly increasing. This includes the planning for additional dedicated apparatus – horizontal forward proton detectors. This work focusses on the problems related to the alignment of such detectors. The effects of the misalignment of the detectors on their geometric acceptance and the proton kinematics reconstruction is studied. The requirements for the alignment precision is inferred for different types of possible measurements.

Keywords: alignment, forward physics, diffractive, AFP, LHC

1. Introduction

An important part of the Large Hadron Collider experimental programme are studies of the Standard Model physics. One of the least understood branch of the Standard Model is diffraction, and in particular, the hard diffraction.

First surprise about diffraction came from HERA, where unexpectedly a significant contribution of diffraction was observed. Second one was spotted at the Tevatron – the extrapolations based on HERA measurements lead to overestimation of the diffractive cross sections by a factor of about 10. Although today these issues are considered to be understood, the gained experience shows that it should not be taken for granted that the LHC results will agree with the expectations.

Two properties of diffractive events are typically used to discriminate against non-diffractive interactions. First is the presence of large rapidity gaps. In non-diffractive interactions the colour charge is exchanged between the interacting protons. This leads to break-up of the protons and to enhanced production of hadrons in the forward region. In contrast, in the case of diffractive interaction, a colour singlet is exchanged and the forward production is suppressed. This results in rapidity regions completely devoid of particles – the rapidity gaps.

Unfortunately, the size of the rapidity gap is anti-correlated to the energy transferred from the diffractively scattered proton and, in consequence, to the diffractive mass. Moreover, rapidity gaps can be present also in non-diffractive events, where they can emerge due to fluctuation of the distance between neighbouring particles. The size of such a gap will have a steeply falling exponential distribution. The size of the gap

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1Although diffractive interactions are possible in any hadron-hadron collision, in this work we focus on proton-proton interactions at the LHC
in diffractive events drops slower, which makes the rapidity gap method usable for events with large gaps, i.e. small diffractive masses. For high diffractive masses and, in particular, the hard diffraction, the use of this method is problematic.

The second method used for measurements of diffraction is based on the fact that the exchange of a colour singlet may leave the proton intact. Such a proton is characterised by a very steep distribution of the scattering angle. In fact, at the LHC, the diffractive protons are scattered into the beam pipe and traverse the magnetic structures of the accelerator accompanying the proton bunch. However, the kinematics of the diffractive protons is slightly different from that of the protons of the beam (greater transverse momentum or smaller energy). This makes the trajectory of such protons recede from the beam orbit. At far enough distance from the interaction point (more than a hundred of meters), diffractive protons may depart far enough from the beam core to be detected.

Measurements of diffractively scattered protons in the vicinity of the beam require dedicated detectors. To access small scattering angles, the detectors have to be placed inside the accelerator beam pipe. Moreover, it must be possible to vary the distance between the detector and the beam during the operation. This is because the minimal distance depends on the actual condition of the beam. Typically, during the beam injection and acceleration, when the beams are unstable, the detectors must be retracted far away. This is possible by using a dedicated system – the Roman Pot or the Hamburg movable beam pipe. Depending on the nature of the studied process the detectors can be designed to move in the machine plane (horizontal detectors) or along the normal to this plane (vertical detectors).

The procedures of inserting and retracting the detectors imply that the positions of the detectors will vary from one data taking period to another. This makes the apparatus alignment more difficult than for other detectors, since it needs to be performed more frequently – typically for each run. In order to develop the alignment methods one needs to know what is the precision needed to perform the physics measurement. This is the subject of this paper.

2. The AFP Detectors

Presently, at the LHC, the proton tagging detectors are installed at Point 1 (ALFA) and Point 5 (TOTEM). In addition to the existing vertical detectors around LHC Point 1, installation of additional horizontal stations – the AFP (ATLAS Forward Proton) detectors [1] – is considered. In this paper the alignment will be studied for AFP the detectors, however, the results for the TOTEM horizontal pots should be similar.

The ultimate aim of the AFP detectors is to measure diffractive and two-photon process during the periods in which the LHC will work with standard settings, i.e. low $\beta^*$, high luminosity. It is planned to use horizontally inserted detectors placed symmetrically w.r.t. the interaction point at 204 m (near station) and 212 m (far station). The AFP stations will contain silicon pixel detectors [2] with foreseen spatial resolution of 10 $\mu$m in the horizontal direction and 30 $\mu$m in the vertical direction. The far stations will be also equipped with precise timing detectors having the resolution of 30 ps.

The protons scattered diffractively at the interaction point traverse the fields of the LHC magnets together with the beam. For the AFP detectors these are: three quadrupole magnets (Q1, Q2, Q3 – the inner triplet), two dipole magnets (D1 and D2 – separating incoming and outgoing beams) and two additional quadrupole magnets (Q4 and Q5). The trajectory of a scattered proton depends on its momentum and the position of the interaction vertex. Tracking of the proton through the magnetic lattice can be simulated with dedicated tools, like the Mad-X [3] or the FPTrack [4] programs.

For the nominal LHC optics ($\beta^* = 0.55$ m) with beam energy $p_0 = 7$ TeV and the beam emittance of 3.5 $\mu$m-rad, one can calculate the transverse size and the angular spread of the beam. For example, at 212 metres from the interaction point the beam width equals 140 $\mu$m and 430 $\mu$m in the horizontal and
vertical direction, respectively. The information about the beam transverse size at the detector location is of particular interest. This is because the detectors cannot approach the beam too close, due to the radiation hazard for both the detectors themselves and the magnets located behind them. The actual distance depends on the beam intensity and the amount of the halo background. A realistic distance value is between 10 and 20 times the width of the beam at the appropriate location ($\sigma$), depending on the intensity and condition of the beam.

The distance between the detector and the beam is of principal importance for the calculation of the detector geometrical acceptance, which defines the range of the scattered proton momenta accessible to the detectors. Since the considered physics processes are symmetric in the azimuthal angle, it makes sense to inspect the geometric acceptance as a function of two parameters. A common choice is the transverse momentum value $p_T$ and the relative momentum loss of the proton $\xi = 1 - p/p_0$, where $p$ is the scattered proton momentum.

The acceptance of the AFP detectors as a function of the scattered proton $p_T$ and $\xi$ for the nominal settings of the LHC and the beam-detector distance of 15 $\sigma$ is presented in Figure 1. One can see that high acceptance is obtained for $\xi \in [0.02; 0.13]$, i.e. high diffractive mass. To have acceptance for low masses, one needs different LHC optics and vertical detectors. On the other hand, the AFP detectors provide very good $p_T$ acceptance, allowing measurements of the full spectrum range.

3. Reconstruction of proton kinematics

The aim of the forward proton measurement is twofold. First, one can simply check whether such a proton was present in the event, which would imply diffractive nature of the process. Second, measurements of the proton trajectory can be used to determine its momentum, which can be used in the analysis. In this section we briefly describe the method used for proton kinematics reconstruction for the AFP detectors.

The parameters describing the scattered proton trajectory in the vicinity of the forward proton detector – the position and elevation angles ($x, y, x', y'$) – depend on the momentum of proton emerging from an interaction ($p_x, p_y, p_z$) as well as on the interaction vertex position ($x_0, y_0, z_0$).

Figure 1: Acceptance of the AFP detectors.
In a general case, it would be impossible to reconstruct the momentum of a scattered proton from its trajectory measurement, because the trajectory is described by four parameters, while it depends on six: vertex position and proton momentum. However, in the case of the nominal LHC optics, the beam spot size is very small. This makes the vertex dependence sub-leading to the momentum dependence and allows momentum reconstruction.

One of the basic properties of the LHC optics in the neighbourhood of the beam intersection regions is the independence of the horizontal and vertical coordinates. For example, the horizontal position and elevation angle of a trajectory depend only on the energy of the scattered proton and on the horizontal momentum component $p_x$; they do not depend on the vertical component $p_y$. One should note that the presence of magnetic moments higher than the quadrupole one in the multipole expansion of the magnetic field introduces such a dependence. In the case of the LHC magnets the higher order components are a factor of about $10^3$ to $10^4$ smaller than the principal ones [5, 6, 7] and hence can be neglected.

At the end, the main properties of the optics are of the following form:

$$ (\xi, p_x) \leftrightarrow (x, x') \quad \text{and} \quad (\xi, p_y) \leftrightarrow (y, y'), $$

which can be visually presented in terms of the chromaticity plots, see Figures 2 and 3. The grids visible in the plots clearly indicate a one-to-one correspondence between the proton kinematics and its trajectory at the AFP position. Therefore, it is possible to reconstruct the energy and transverse momentum of a proton from the measurements of its trajectory position and elevation angles.

![Figure 2: Chromaticity plot for horizontal direction.](image1)

![Figure 3: Chromaticity plot for vertical direction.](image2)

For the sake of the alignment analysis presented in this paper, a simple reconstruction method presented in [8] is used. For completeness this method is briefly recalled in the following.

The LHC optics between the interaction point and the AFP detectors is parametrised using formulae that assume a linear dependence on the transverse momentum, vertex position and the product of the transverse momentum and the transverse vertex position. This formulae take into account the independence of the horizontal and vertical directions. The energy dependence was approximated by polynomials, with ranks chosen in order to provide the transport accuracy negligible with respect to the assumed detector resolution. For example, the parametrisation formulae for the horizontal position and elevation angle of the proton trajectory at the AFP position are following:

$$ x = a(\xi) + b(\xi) \cdot p_x + c(\xi) \cdot x_0 + d(\xi) \cdot p_x \cdot x_0 + e(\xi) \cdot z_0. $$

$$ x' = A(\xi) + B(\xi) \cdot p_x + C(\xi) \cdot x_0 + D(\xi) \cdot p_x \cdot x_0 + E(\xi) \cdot z_0, $$

4
The ξ reconstruction is performed based on the measurement in the horizontal direction only, by solving numerically the equation:

\[
\left( x - a(ξ) - f(ξ) \cdot z_0 - c(ξ) \cdot x_0 \right) \cdot \left( B(ξ) + D(ξ) \cdot z_0 \right) = \\
\left( x' - A(ξ) - F(ξ) \cdot z_0 - C(ξ) \cdot x_0 \right) \cdot \left( b(ξ) + d(ξ) \cdot z_0 \right),
\]

which is obtained by extracting \( p_x \) from the \( x \) and \( x' \) parameterisation equations, where \( x \) and \( x' \) values are taken from the measurement in the AFP detectors.

Obviously, in order to obtain a numerical solution, one needs to know the vertex position. Since usually this is not the case, one should take the centre of the beam spot instead, keeping in mind that such a procedure contributes to the reconstruction resolution. In this work the stress is put on the issues related to the apparatus alignment. The other contributions to the reconstruction error, including the one due to the interaction vertex spread, are neglected (for more details see [8]). In order to reconstruct the transverse momentum, the parameterisation equation on \( x' \) and \( y' \) are solved. It should be pointed out that in principle the equations on \( x \) and \( y \) could also be used, however, the sensitivity to the transverse momentum is much smaller, as is clearly seen in the chromaticity plots.

4. Effects of misalignment on kinematics reconstruction

Misalignment of the detectors means that their position is known with a limited precision. The AFP detector set-up consists of two stations, which results in four degrees of freedom for the position misalignment: \( \Delta x_{\text{near}}, \Delta y_{\text{near}}, \Delta x_{\text{far}}, \Delta y_{\text{far}} \). Taking linear combinations of these variables, one can define the absolute misalignment, which affects the trajectory position measurement:

\[
\Delta x = (\Delta x_{\text{near}} + \Delta x_{\text{far}})/2, \quad \Delta y = (\Delta y_{\text{near}} + \Delta y_{\text{far}})/2,
\]

and the relative misalignment, which affects the measurement of the trajectory elevation angles:

\[
\Delta X = \Delta x_{\text{far}} - \Delta x_{\text{near}}, \quad \Delta Y = \Delta y_{\text{far}} - \Delta y_{\text{near}}.
\]

Incorrect knowledge about the detectors position will influence the reconstruction procedure. The numerical results presented in the following have been obtained using single diffractive events generated with Pythia [9, 10]. First, diffractive protons present in these events were transported through the LHC magnetic lattice up to the AFP detector. Then, their kinematics was reconstructed with appropriate assumptions on the detectors misalignment. Three cases are considered:

(a) absolute horizontal misalignment of 100 µm (\( x_{\text{abs.}} \)),

(b) relative horizontal misalignment of 100 µm (\( x_{\text{rel.}} \)),

(c) relative vertical misalignment of 100 µm (\( y_{\text{abs.}} \)).

The fourth possible case of absolute vertical misalignment has in fact no impact on the reconstruction. This is due to the reconstruction method, which does not make use of the vertical trajectory position, only of the vertical trajectory angle. The misalignment value has been chosen to 100 µm, but the effect of any, relatively small, misalignment can be easily estimated, because to a good approximation it is linear.

The apparatus misalignment leads to two effects:
(a) **offset** – the reconstructed values are on average different than the true value.

(b) **spread** – the reconstructed values are smeared around the average.

This requires a short comment. Naturally, in the presented procedure there is no randomness – for a given event the reconstructed value will always be the same. The observed spread of the reconstruction error comes from averaging over all kinematic variables. For example, different events with the same value of $\xi$ can have different values of $p_x$ and $p_y$. Then, for each event, the reconstruction error on $\xi$ will be different, contributing to the offset and spread.

Figures 4 and 5 present the resulting errors on $\xi$ reconstruction: the offset and the spread, respectively. One should point out that misalignment in the vertical direction has no effect on $\xi$ reconstruction. This is a simple consequence of the reconstruction method, which does not make use of the vertical measurements in the $\xi$ reconstruction procedure. On the other hand, one can see a contribution due to the horizontal misalignment. The absolute one leads to an error of 4% at small $\xi$, decreasing to about 1% at high $\xi$ values. The error due to the relative misalignment has a flatter dependence and slightly varies between -8% and -6% within the whole range of the accepted $\xi$ values. A similar situation is observed for the spread, however, its magnitude is about one order of magnitude smaller.

![Figure 4](image1.png)  
**Figure 4**: The average reconstruction error of the proton relative momentum loss due to 100 $\mu$m misalignment.

![Figure 5](image2.png)  
**Figure 5**: The spread of the relative momentum loss reconstruction error due to 100 $\mu$m misalignment.

Figures 6 and 7 present the estimated error on the reconstructed $p_x$ value. Misalignment in the vertical direction does not play a role and is not presented in the plots. This is also a consequence of the reconstruction method, which does not use vertical components for $p_x$ reconstruction. The obtained error and spread are dominated by relative misalignment, with magnitude below 300 MeV and 60 MeV, respectively.

Results obtained for the vertical momentum reconstruction are presented in Figures 8 and 9. Here, the effects due to both horizontal and vertical misalignments are present. The horizontal misalignment has a non-zero effect, because it leads $\xi$ error, and reconstructed $\xi$ is used for $p_y$ reconstruction. However, the dominant effect comes from the relative vertical misalignment, which leads to error of about 330 MeV and spread of about 100 MeV.

In a physical measurement it is usually not convenient to use directly the horizontal and vertical momentum components, because of the azimuthal symmetry of proton-proton collisions. Instead, one often uses the four-momentum transfer $t$, related to the magnitude of the transverse momentum ($t \approx p_T^2$). It is therefore important to study how would the reconstruction error affect this observable. Obviously, the results cannot contain any additional effect with respect to what has already been presented; they rather are a different way of presentation. The error and spread for the four-momentum transfer reconstruction is presented in Figures 10 and 11. As one could expect, both are dominated by relative misalignments.
Figure 6: The average reconstruction error of the proton horizontal momentum component due to 100 µm misalignment.

Figure 7: The spread of horizontal momentum reconstruction error due to 100 µm misalignment.

Figure 8: The average reconstruction error of the proton vertical momentum component due to 100 µm misalignment.

Figure 9: The spread of vertical momentum reconstruction error due to 100 µm misalignment.

Figure 10: The average reconstruction error of the proton four-momentum transfer due to 100 µm misalignment.

Figure 11: The spread of four-momentum transfer reconstruction error due to 100 µm misalignment.
As mentioned before, physics processes are symmetric in the azimuthal angle. Therefore measurements of this parameter for processes with a single proton is not of great importance. However, a meaningful and important observable for events where two forward protons are produced is the azimuthal angle between these two protons. Therefore, it is relevant to study the misalignment impact on the azimuthal angle at which the proton was scattered. The results are presented in Figures 12 and 13. Since $\varphi$ is obtained from the reconstructed $p_x$ and $p_y$ values, it is not surprising that its reconstruction is dominated by relative misalignments. The error and spread obtained for misalignment of 100 $\mu$m are of the order of 1 rad.

Figure 12: The average reconstruction error of the proton azimuthal angle due to 100 $\mu$m misalignment.

Figure 13: The spread of azimuthal angle reconstruction error due to 100 $\mu$m misalignment.

5. Effects of misalignment on the cross section measurement

Reconstruction errors are not the only problem caused by the misalignment. Precise knowledge of the detector position is important even if the detectors are used only for tagging of the scattered protons. In this case, the misalignment would lead to a wrong estimate of the detector acceptance and in turn to an error on the cross section measurement.

Figure 14: Distribution of proton horizontal trajectory position for various diffractive processes.

Figure 15: Relative error on the cross section due to 100 $\mu$m absolute horizontal misalignment for several diffractive processes.

For precise estimation of the detector acceptance, the vertical misalignment is not relevant, because the
acceptance is determined mainly by the distance between the detector and the beam centre. A relevant input to the analysis of this problem is the distribution of the proton horizontal position at the detector location. This distribution for the protons scattered in the process of single diffractive dissociation as generated by Pythia and several hard diffractive processes generated with FPMC [11] is shown in Figure 14. The peak around zero comes from events with very small momentum loss, for which the proton trajectory position is determined mainly by the transverse momentum acquired in the interaction. With increasing value of x-coordinate, the influence of \( \xi \) on the position becomes dominant. The x-coordinate distribution flattens off, which reflects the shape of the relative momentum loss of diffractive protons – approximately 1/\( \xi \) distribution. Finally, a rapid decrease is observed for \( x > 20 \text{ mm} \), which is due to the LHC effective aperture.

The error on the cross section measurement caused by the misalignment depends not only on the misalignment value itself but also on the beam-detector distance. If the detector is very close to the beam, the measurement (tagging) is performed in the steeply falling region of the distribution. Therefore, even a small change of the distance would have a large effect. When the detector measures in the flat region of the distribution, the sensitivity to misalignment gets much smaller. Towards the boundary of the acceptance region the error increases again, because the observed cross section is already quite small and even a tiny change is significant. These considerations are summarised in Figure 15 which presents the error obtained for a misalignment of 100 \( \mu \text{m} \) as a function of the detector distance from the beam centre.

6. Rotations

Apart from the linear misalignment discussed above, it is also possible that an unknown rotation is introduced to the detector. In principle, one could consider rotations in three planes: (x, y), (x, z) and (y, z). However, in the case of rotations by a small angle \( \theta \) in the (x, z) and (y, z) plane, the x and y trajectory positions are only modified by \( O(\theta^2) \) term, which can be safely neglected. The change in the z position is also negligible, since it is of the order of \( \theta \) times the size of the sensor (about 20 mm), which should be compared to the 8 m distance between two AFP stations. Therefore, in the following we focus only on rotations in (x, y) plane.

Obviously, the mechanical origin of the rotation can be various. One should keep in mind that a rotation around a given axis is equivalent to a rotation around a different, parallel axis and a translation. Since the translational misalignment has already been discussed, it is sufficient to consider rotations w.r.t. a fixed axis. However, the choice of this axis would affect the reconstruction – for protons close to the rotation axis the reconstruction error should be smaller, and it will increase with distance from the axis.

Contrary to the translational misalignment, it is not possible to define absolute and relative rotations. One can only consider rotations of the near and far station. On the other hand, a rotation of both stations would affect the reconstruction in the same way. Therefore, it is sufficient to consider only the rotation of one selected station. In the following, four cases are considered:

(a) rotation of the near station around the centre of the diffractive pattern at the edge close to the beam,

(b) rotation of the far station around the centre of the diffractive pattern at the edge close to the beam,

(c) simultaneous rotation of both stations around the centre of the diffractive pattern at the edge close to the beam,
Like in the previous section, the impact on reconstruction of different kinematic variables will be presented. The magnitude of all rotations is set to 1 milliradian.

Figures 16 and 17 present respectively the offset and the spread of the $\xi$ reconstruction error. Rotation of the near station has a very similar effect to that induced by the rotation of the far station, except that the offsets have opposite signs. This is a reminiscence of the fact that the change of the trajectory elevation angles has greater impact on the $\xi$ reconstruction than the position change. The change of the trajectory elevation angles due to the rotation of the far station has an opposite sign to the change due to the rotation of the near station. Similar argument is appropriate also for the spread. It is interesting to notice that the errors for the case when both stations are rotated are much smaller than when only a single station is rotated. The difference between different origins of rotation is non-negligible only for the offset – as expected the rotation around the beam centre results in larger errors. The magnitude of the error is below 1 % for the offset and below $1 \permil$ for the spread.

Figures 18 and 19 present the errors in the case of the $p_x$ reconstruction. Both the offset and the spread are of the order of few MeV, when one station is rotated. Rotation around a more distant point increases slightly the offset. Simultaneous rotation of both stations lead to negligible errors. The case of the vertical momentum component reconstruction, presented in Figures 20 and 21, is very similar, however, the errors are larger by approximately a factor of two.

Figures 22 and 23 present the error in the case of the four-momentum transfer reconstruction. Also here, the simultaneous rotation of both stations results in negligible errors. Rotation of a single station leads to an offset of the order of $10^{-3}$ GeV$^2$ and a spread of the order of $10^{-2}$ GeV$^2$. The offset is smaller than the spread due to the fact that a given value of $t$ can be obtained for different combinations of $p_x$ and $p_y$ values. The individual offsets on $p_x$ and $p_y$ nearly cancel on the average.

Finally, Figures 24 and 25 present the error in the case of the azimuthal angle reconstruction. The pattern is similar as before: rotations of the near and the far station give opposite offsets and similar spreads. Simultaneous rotation has much smaller effect. The rotation w.r.t. the beam increases the offset.

7. Summary and conclusions

The numerical results presented above provide a foundation on top of which the demands for alignment can be considered. One could consider three types of measurements:
Figure 18: The average reconstruction error of the horizontal component of the proton momentum due to 1 mrad rotation of the detectors.

Figure 19: The spread of the reconstruction error of the horizontal component of the proton momentum due to 1 mrad rotation of the detectors.

Figure 20: The average reconstruction error of the vertical component of the proton momentum due to 1 mrad rotation of the detectors.

Figure 21: The spread of the reconstruction error of the vertical component of the proton momentum due to 1 mrad rotation of the detectors.

Figure 22: The average reconstruction error of the four-momentum transfer due to 1 mrad rotation of the detectors.

Figure 23: The spread of the reconstruction error of the four-momentum transfer due to 1 mrad rotation of the detectors.
(a) **tag-only measurements** – no information about the forward proton kinematics is used, only the information about its presence in the event,

(b) **differential measurements** – reconstructed kinematics of the forward proton is an essential ingredient of the measurement,

(c) **exclusive measurements** – reconstructed forward proton kinematics is needed to discriminate the signal against the background.

An example of a tag-only study is a measurement of the cross section for a chosen diffractive process. In this case, the only point in which the misalignment can affect the measurement is the estimation of the detector acceptance. This issue has been discussed in Section 5. The error due to a misalignment of 100 µm is 2 % in the worst case of soft single diffractive process. Assuming the aim of cross section measurement with 10 % accuracy, the demand on the absolute horizontal alignment precision can be set at 500 µm.

Examples of differential measurements include the measurements of the $\xi$, $t$ and $\varphi$ distributions, as well as various combinations of these observables and also with properties of the centrally produced state. The requirement of $\xi$ measurement with precision better than 10 % implies the absolute horizontal alignment precision of the order of 200 µm for small $\xi$ values, and 500 µm for high $\xi$ values. The relative horizontal precision needs to be more precise and should not exceed 100 µm.

Measurements of $t$ and $\varphi$ will be dominated by the uncertainty due to the relative misalignment, both horizontal and vertical. The sensitivity of the transverse momentum reconstruction is very high, which leads to the need for the alignment precision of 10 µm. On the other hand, this sensitivity provides also a data-driven method for the relative alignment, see [12].

Exclusive measurements require the kinematic reconstruction not only for the differential measurement, but mainly for the background reduction. For exclusive processes, like exclusive production of jets, the kinematics of the centrally produced system (jets) is correlated with the kinematics of the forward protons due to the energy-momentum conservation. For background processes such correlations do not exist or are much weaker. This allows the selection of very rare exclusive events. In order to best exploit these correlations, the proton kinematics must be correctly reconstructed.

In the case of exclusive QCD processes the most important variable is $\xi$, which can be correlated to the mass and rapidity of the produces jet system. Since exclusive processes are rare, one expects mainly events with small $\xi$ values due to the $1/\xi$ distribution. This leads to the requirement on the absolute horizontal alignment precision better then 100 µm and relative horizontal alignment precision of 25 µm. For QED
processes, like exclusive production of lepton pairs, also $t$ and $\phi$ can be used, because of the possibility of precise $p_T$ measurement of the lepton pair in the central detector. Here, also the relative misalignment plays a role, and the requirement is similar as for the $t$ and $\phi$ measurement: precision of 10 $\mu$m.

Acknowledgements

We gratefully acknowledge Peter Bussey for many stimulating discussions on detector alignment and machine optics.

This work was supported in part by the Polish National Science Centre grant: UMO-2012/05/B/ST2/02480.

References

[1] AFP Collaboration, Technical design report, in preparation, 2015.
[2] S. Grinstein, et al., Beam test studies of 3D pixel sensors irradiated non-uniformly for the ATLAS forward physics detector, Nucl.Instrum.Meth. A730 (2013) 28–32.
[3] F. Schmidt, Mad-X User’s Guide, http://mad.web.cern.ch/mad, CERN, 2005.
[4] P. Bussey, FPTrack Programme, http://ppewww.physics.gla.ac.uk/~bussey/FPTRACK, 2008.
[5] N. Ohuchi, et al., Field Quality of the Low-beta Querupole Magnets, MQXA, for the LHC-IR, Proc. of LHC Project Workshop, Chamonix, France, p. 138, 2004.
[6] O. Brüning, et al., Field Quality Issues for LHC Magnets: Analysis and Perspectives for Quadrupoles and Separation Dipoles, Proc. of LHC Project Workshop, Chamonix, France, p. 178, 2004.
[7] N. Sammut, et al., A Demonstration Experiment for the Forecast of Magnetic Field and Field Errors in the Large Hadron Collider, Proc. of EPAC 2008, Genoa, Italy, p. 2482, 2004.
[8] R. Staszewski, J. Chwastowski, Transport Simulation and Diffractive Event Reconstruction at the LHC, Nucl.Instrum.Meth. A609 (2009) 136–141.
[9] T. Sjostrand, S. Mrenna, P. Z. Skands, A Brief Introduction to PYTHIA 8.1, Comput.Phys.Commun. 178 (2008) 852–867.
[10] T. Sjostrand, S. Mrenna, P. Z. Skands, PYTHIA 6.4 Physics and Manual, JHEP 0605 (2006) 026.
[11] M. Boonekamp, A. Dechambre, V. Juranek, O. Kepka, M. Rangel, et al., FPMC: A Generator for forward physics (2011).
[12] R. Staszewski, M. Trzebinski, J. Chwastowski, Dynamic Alignment Method at the LHC, Adv.High Energy Phys. 2012 (2012) 428305.