PROCEEDINGS OF SCIENCE

Overview of ATLAS Forward Proton Detectors for LHC Run 3 and Plans for the HL-LHC

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A key focus of the physics program at the LHC is the study of proton-proton collisions after the interaction. An important class of processes that can be studied are the ones where protons remain intact. In such cases the electromagnetic fields surrounding the protons can interact producing high energy photon-photon collisions. Alternatively, interactions mediated by the strong force can also result in intact forward scattered protons, providing probes of quantum chromodynamics (QCD). In order to aid an identification and provide a unique information about these interactions, instrumentation to detect and measure protons scattered through the very small angles is installed in the beam-pipe far downstream on both sides of the interaction point. In this paper, the description of the ATLAS Roman Pot Detectors (AFP and ALFA), their performance to date and expectations for the upcoming LHC Run 3 is discussed. The physics of interest, beam optics and detector options for the extension of the programme into the High-Luminosity LHC (HL-LHC) era are also discussed.

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1. Introduction

Located at the Large Hadron Collider (LHC) [1], the ATLAS experiment [2] has been designed to measure the products of proton–proton collisions in a full azimuthal angle coverage and a large acceptance in pseudorapidity. For measurements of colliding protons that escape the acceptance of the main detector, the ATLAS Roman Pot (ARP) detectors are used.

Located far away from the ATLAS interaction point, the ATLAS Forward Proton (AFP [3]) and Absolute Luminosity For ATLAS (ALFA [4]) detectors were successfully installed in 2009 and 2016 respectively and successfully took data since. The main focus of ALFA are special runs with a very low pile-up (μ) and (very) high β^* optics [5]. The purpose is to measure elastic scattering and soft diffraction. The first results from ALFA have been published, see Ref. [6] and [7].

The AFP detectors were designed to study hard diffractive (*e.g.* double Pomeron exchange di-jet production) or BSM processes (*e.g.* anomalous quartic couplings). AFP takes data both in low-μ runs and in the "regular" high-μ ones. First results from AFP have been published *e.g* in Ref. [8] and [9].

2. AFP and ALFA Detectors

Both the ALFA and AFP detectors have two stations on both sides of ATLAS. In order to measure protons scattered at very small angles (so-called *forward protons*) both detectors need to be very close to the beam. Since the beam conditions are not stable at all times, the detectors must be movable. In both cases the Roman Pot (RP) technology is used to enable the insertion of the detectors into beam pipe. The one difference is that the AFP detectors are inserted horizontally whereas the ALFA vertically.

The AFP Roman pot stations are located around 210 m from the ATLAS Interaction Point (IP). In case of non-stable beams pots are retracted to a "safe" storage position, which is about 40 mm from the beam. When the beam is stable, the detectors can be moved 2-3 mm close to the beam centre. Each RP consists of four Silicon Trackers (SiT) [10]. Additionally, stations located furthest from the IP host Time-of-Flight (ToF) detectors [11].

The ALFA stations are located around 237 and 245 m from the IP, with each position hosting two detectors (commonly called upper and lower) consisting of 20 layers of 64 scintillating fibre detectors.

Operating at a long distance from the interaction point demands the analysis of the LHC optics (settings of the magnetic fields). The trajectories of the scattered forward protons are bent differently according to the energy lost during the collision: $\xi = 1 - \frac{E_{proton}}{E_{beam}}$. Protons having $\xi = 0$ will be very close to the beam and in the low-β^* optics would not be able to be detected by the detectors. With increasing values of ξ, trajectories are further from the beam and may reach the detectors. At large ξ, the proton trajectories will diverge from the beam so far that they will be filtered by the LHC collimators. The magnet optics has been carefully studied and ATLAS Roman Pots measurement potential in changed for Run 3 and HL-LHC data taking conditions will be discussed in the next sections of this paper.

3. Geometric Acceptance in Run 2 and Run 3

As mentioned above, the proton trajectory depends on its energy loss. However, it also depends on proton transverse momentum. The geometric acceptance of the "forward" proton is typically shown as dependence on these two variables.

The AFP geometrical acceptance for typical low-β^* optics during Run 2 is presented in Figure 1 (left). The accepted energy loss is limited to the region of $0.03 < \xi < 0.1$, which corresponds to the mass acceptance of $390 < M_{central} < 1300$ GeV for $\sqrt{s} = 13$ TeV. The lower limit is due to the distance from the beam to which AFP can be inserted whereas the upper one is due to collimators and beampipe aperture. During Run 2 data taking the detector-beam distance varied between 2 and 4 mm, depending on the station and optics.

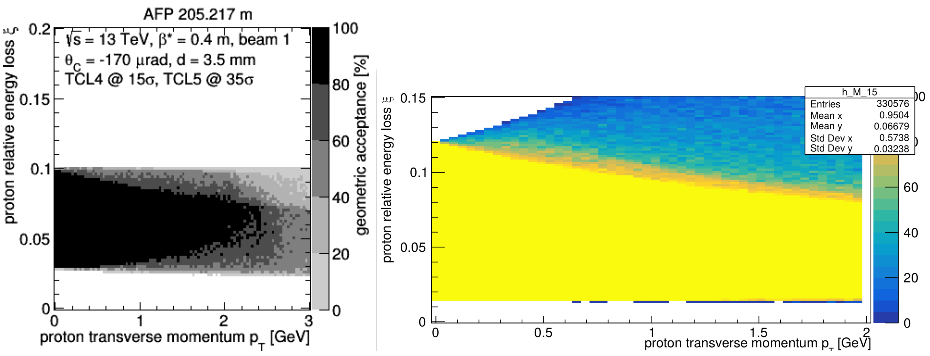

Figure 1: Geometrical acceptances for AFP detector in Run 2 (left) and Run 3 (right).

In Run 3 the optics was further optimized and thus the acceptance of the detectors is changed. The predicted geometrical acceptance is shown in Figure 1 (right). In Run 3 the AFP insertion distance varies between 2.3 and 2.8 mm for stations closer to the interaction point (Near stations) and from 1.5 to 2.3 mm for further stations (Far stations). This results in a geometric acceptance that is slightly improved on Run 2: $0.02 < \xi < 0.12$ and the mass acceptance of $260 < M_{central} < 1560$ GeV.

Since ALFA takes part only in special runs at the high-β^* a dedicated optics is needed to achieve the measurement requirements. The first version of $\beta^* = 90$ m optics was already prepared, but adjustments were clearly needed. Optics settings with $\beta^* = 3/6$ km are being developed as well. Once available, the geometric acceptances will be calculated.

4. Detector Upgrades During LS2

After the Run 2, there was period of time without data taking, the so-called Long Shutdown 2. This time was dedicated to the detectors upgrades. The ALFA detector went through a minor change of the motherboards, as the old ones were damaged due to radiation.

More modifications were done to the AFP detectors. The most visible change was to apply an Out-of-Vacuum solution, where photomultipliers were taken out of the pot vacuum to allow the operation in atmospheric pressure. In Figure 2 on the left the detector package in Run 2 is visible. On the right is detector package after the upgrade. The upgrade also included the new photomultipliers and new glue-less quartz bars to guide Cherenkov light. For the readout the possibility to trigger on a single ToF train[1] was added. There is also a possibility to cross check the full signal path after the installation and between the runs, thanks to the set of installed pulser modules. All these settings can be fully controlled remotely. The ToF upgrade was successfully tested at DESY and SPS in 2020.

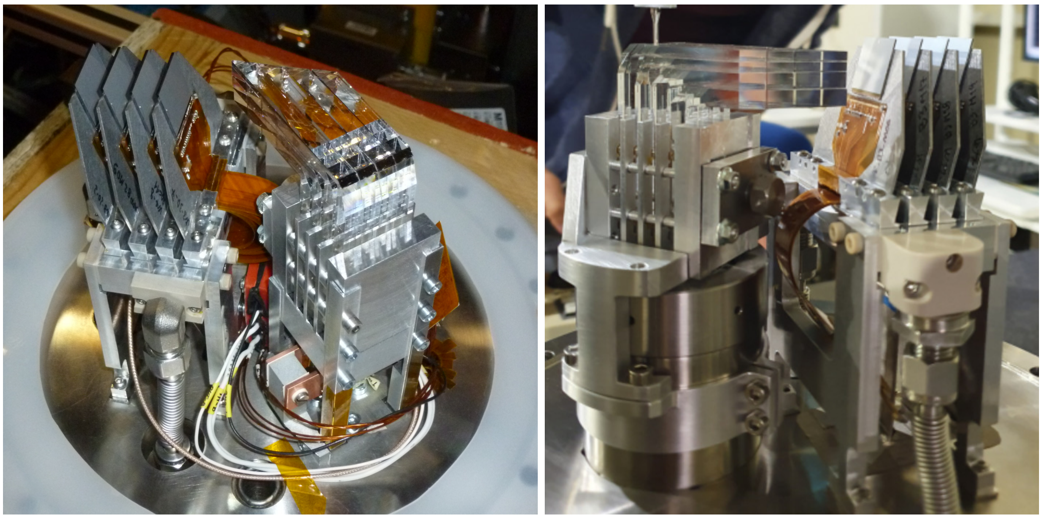

Figure 2: **Left:** AFP detector package in Run 2. **Right:** AFP detector package after upgrade.

Additionally, the AFP silicon detector cooling was improved by installing new heat exchangers. With the upgrades, the AFP detectors are expected to run smoothly during the Run 3 data taking, aiming at the ToF timing resolution of 20 ps (25 ps in Run 2, [11]).

5. Run 3 Data Taking Plans

The AFP schedule during Run 3 data taking will be rather busy. The detector will take data regularly during high-μ runs. The AFP integrated luminosity is expected to match that of ATLAS. The goal is to measure high p_T exclusive processes and enable BSM searches.

The soft diffraction and low p_T hard diffraction protons will be measurable during low-μ runs ($0.005 < \mu < 1$). Such conditions will be obtained by the beam separation at the collision point. It should be mentioned that in 2022 the AFP took data together with LHCf [12], with β^* of 19.2 m. These data can be used for diffractive studies and cosmic ray physics.

There is also interest in participation in the medium-μ runs ($\mu \sim 2$), where $\sim$1/fb of data can be collected. This could be an excellent event sample for studies of medium/high p_T hard diffractive processes. Finally, a sample for diffractive studies at lower energy can be collected during proton-proton reference run for PbPb collisions.

The ALFA detector will gather important data for its elastic scattering measurements in a new energy $\sqrt{s}$ = 13.6 TeV, running with β^* = 90 m run and runs with β^* = 3/6 km. Both are scheduled for 2023.

[1] Set of ToF LQ bars.

6. ATLAS Roman Pots at HL-LHC

At high pile-up and low β^* environment the main physics focus would be on photon induced processes and BSM searches (*e.g.* ALP/DM/anomalous couplings in $\gamma\gamma \to WW/ZZ/t\bar{t}/...$).

For the HL-LHC different position in the tunnel of the ATLAS Roman Pots needs to be considered, as the space in the tunnel for the stations is reduced due to the LHC upgrade. There are seven potential locations for Roman Pots (RP) on each side of ATLAS. The distance from the interaction point for them is:

- RP1A/B: 195.5/198.0 m
- RP2A/B: 217.0/219.5 m
- RP3A/B/C: 234.0/237.0/245.0 m.

The three scenarios are considered. For each scenario with different pot locations the mass acceptance was calculated and shown in Figure 3 (left). In the first scenario, four pots are considered (solid black, blue and red lines). The closer the RP are to the IP the wider mass acceptance is and it is shifting towards higher masses. In the next scenario, eight stations are proposed and marked on the plot with the doted black, blue and red lines. In the last scenario, twelve stations are considered (dashed black line) resulting with the widest range of mass acceptance.

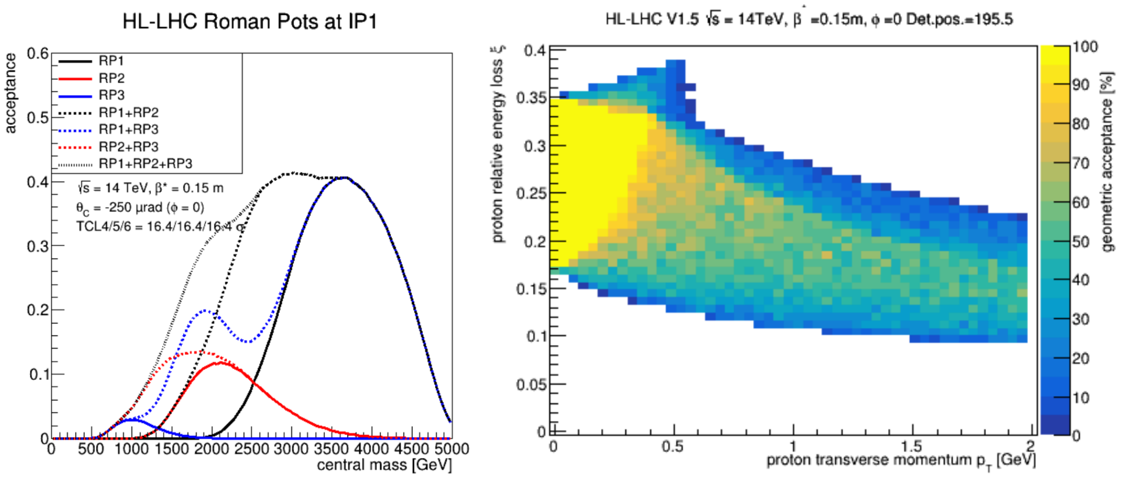

Figure 3: **Left:** predicted mass acceptance of RPs in Run 3. **Right:** predicted geometrical acceptance of RPs in Run 3.

Other issues that must be taken into account is the beam crossing plane. At the LHC the beam crossing planes at the IP1 and IP5 must be perpendicular (vertical at IP5 means horizontal at IP1). The vertical crossing angle results in the extension towards lower masses and this setting is strongly preferred by CT-PPS. The geometric acceptance for the horizontal crossing angle and RP1A position is shown in Figure 3 (right). The range of the proton energy loss that could be measured is much different from what was presented for previous data taking periods and is varies from 0.15 up to 0.35.

7. Summary

The Run 2 data provided excellent samples for physics studies with ongoing elastic, diffractive, and (semi-)exclusive analyses. For the current Run 3 data taking both the ALFA and AFP detectors went through important upgrades during LS2. The AFP ToF system had successful test beams at DESY and SPS and the aim is to reach 20 ps resolution. With the upgraded ToF and cooling systems the AFP will take part in both high-μ and special low-μ runs, providing the data for BSM searches and studies of exclusive processes and soft/hard diffraction. The ALFA detector with new motherboards will take part in very high β^* runs to study properties of elastic scattering at new energy.

The proposal for the RP participation in HL-LHC run has been made. The new locations in the tunnel, possible number of stations and plane of crossing angle have been considered. The possible mass and geometric acceptances were shown. With this conditions the main physics of interest would be on photon induced processes and BSM searches. It should be mentioned that at the moment of writing these proceedings, the decision was made to defer the presence of Roman pots in ATLAS at least until after Run 4.

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