Overview of ATLAS forward proton detectors for LHC Run 3 and plans for the HL-LHC

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Abstract

Status of the ATLAS Roman Pots (AFP and ALFA) for LHC Run 3 after all refurbishments and improvements done during Long Shutdown 2 is reported. Based on analysis of Run 2 data, the expected performance of the Tracking and Time-of-Flight detectors are described along with numerous hardware and software updates and data taking plans for Run 3. Roman pot position with respect to the beam for Run 3 optics is discussed for two scenarios during luminosity levelling. Finally, the physics interest and the most recent studies of beam optics and detector options for participation at the High Luminosity LHC (HL-LHC) are discussed. [1]

1 Introduction

About half of all proton-proton collisions at the LHC is due to diffractive events. Such interactions result from the exchange of a colourless object (photon in case of electromagnetic and Pomeron for strong interactions). This exchange does not alter the quantum numbers of the interacting particle thus one or both colliding proton may remain intact. In addition, there will be a rapidity gap, which is a space in rapidity devoid of particles. Rapidity gap has traditionally been a common experimental indicator of a diffractive event, but it frequently is obliterated by particles coming from independent collisions happening in the same bunch crossing, usually referred to as "pile-up" interactions. Also, the gap could be outside the acceptance of the detector. Another technique for identifying diffractive events is a direct measurement of the intact proton which is scattered at very small angles (few micro-radians). Dipole and quadrupole magnets of the LHC [1] deflect a proton scattered at the Interaction point (IP) outside the beam envelope [2]. Therefore, "proton detectors" must be located far away from the collision point.

2 ATLAS Forward Detectors

The ATLAS [3] Roman Pot detectors consist of: AFP [4] and ALFA [5]. These detectors are designed to detect forward protons. The ALFA (Absolute Luminosity For ATLAS) system comprises four detector stations at 237 m and 241 (Run 1)/245 (Run 2) m on either side of the IP, which are mounted in RP devices that allow the units to move vertically.

The AFP (ATLAS Forward Proton) detector have four horizontally moving stations installed symmetrically with respect to the ATLAS IP at approximately 205 m (NEAR station) and 217 m (FAR station). The silicon tracker (SiT), which is made up of four planes of 3D silicon pixel sensors [6], is housed inside of the NEAR and FAR stations, with the addition of Time-of-Flight (ToF) devices at the FAR station.

SiT is composed of a single FE-I4B front-end chip [7] that offers 336×80 pixels with a 50×250 μm^2 pixel size. With the sensors tilted 14 degrees in x-axis, the best resolution in the x coordinate is obtained and staggering the planes increases resolution in the y coordinate. The measured resolution is 5.5 ± 0.5 μm for each individual plane and 2.8 ± 0.5 μm for all plane in x and approximately 30 μm in y [8].

The Time-of-Flight (ToF) detectors are designed to measure the primary vertex z-position which can be compared to position reconstructed by the ATLAS tracker to help reduce the background. In Run 3, AFP plans to achieve timing resolution of 20 ps [9] which translates to about 6 mm of spatial resolution.

3 ATLAS Forward Detectors in Run 3

AFP underwent a series of upgrades during LS2. A redesign of the AFP ToF detector was done keeping the Micro-Channel Plate PhotoMulTipliers (MCP-PMTs) outside vacuum in order to reduce the risk of electric arcs. This design allows also easier access to the electronics. Additionally, new MCP-PMT and its back-end electronics designs are introduced to address inefficiencies from Run 2 data collection and to suppress cross-talk. SiT is equipped with newly created tracking modules and new heat exchangers are installed to enhance cooling capabilities. The aforementioned improvements were successfully tested at DESY and SPS [10], and currently the detectors are participating in Run 3 data collection.

ALFA underwent refurbishments needed to keep system operational for Run 3. The major action was exchange of motherboards.

AFP will participate in regular data collection during standard (high-μ) and various low μ runs. ALFA will participate in the $\beta^* = 90$ m run in 2022. In addition, data collection for the $\beta^* = 3/6$ km run with $\sqrt{s} = 13.6$ TeV is scheduled to begin in early 2023 for measurement of elastic scattering at new energy.

3.1 Run 3 Optics

In Run 3, luminosity levelling and Achromatic Telescopic Squeezing (ATS) will be used [11]. Adoption of ATS would result in no change in the magnet settings between IP1 and AFP during β^* levelling, which will help to simplify the unfolding of proton kinematics.

3.2 Roman Pot Position During Luminosity Levelling

In Run 3 two scenarios of RP operation were taken into account. In the first scenario (used in 2022), the jaws of TCT collimator are kept constant and pot position is determined according to the equation [1].

Table 1: Roman Pot position for different β^* for scenario 1 (Left) and 2 (Right). See text for details.

β^*	d_{XRP}^{NEAR} [mm]	d_{XRP}^{FAR} [mm]
30	2.251	1.500
36	2.238	1.500
43	2.241	1.500
51	2.260	1.500
60	2.299	1.500
71	2.362	1.632
84	2.456	1.815
100	2.591	2.045
120	2.784	2.334

β^*	d_{XRP}^{NEAR} [mm]	d_{XRP}^{FAR} [mm]
30	2.251	1.500
36	2.111	1.500
43	1.995	1.500
51	1.902	1.500
60	1.831	1.500
71	1.777	1.500
84	1.742	1.500
100	1.727	1.500
120	1.734	1.500

$$d_{XRP}(\beta^*) = MAX[(8.5 \cdot \frac{\sigma_{TCT}(\beta_0^*)}{\sigma_{TCT}(\beta^*)} + 3) \cdot \sigma_{XRP} + 0.3 \text{ mm}, 1.5 \text{ mm}], \tag{1}$$

where $\sigma_{TCT}(\beta_0^*)$ is the size of the beam at TCT location for the reference value of β^* at 30 cm, $\sigma_{TCT}(\beta^*)$ is for considered β^* and σ_{XRP} is beam width at RP location. A hard limit of 1.5 mm is set for the LHC machine protection.

In the second scenario (to be used in 2023+), the aim is to have minimum possible distance between Roman pots and the beam. All pots should be set to 1.5 mm in the ideal scenario, but due to the LHC machine protection rules in equation [2], this setting is not feasible at the AFP NEAR station as it would need the TCT jaws to be set lower than the minimum permissible value of 8.5σ.

$$n_{TCT} \leq \frac{1.2 \text{ mm}}{\sigma_{XRP}} - 3 \tag{2}$$

Maintaining the TCT at 8.5σ and allowing pots to approach as closely as possible can resolve this issue and pot distance is given by equation [3].

$$d_{XRP}[mm] = MAX(11.5 \cdot \sigma_{XRP} + 0.3 \text{ mm}, 1.5 \text{ mm}). \tag{3}$$

Pot positions calculated according to equations [1] and [3] are summarised in table [1].

4 ATLAS Forward Detectors in HL-LHC

The existence of Roman pots at High Luminosity LHC (HL-LHC) is a topic of ongoing internal discussion within the ATLAS community. At HL-LHC high pile-up and low β^* environment, the key focus is on photon induced processes and Beyond Standard Model searches and the first step for such studies is the determination acceptance of Forward Detectors.

The optics and layout used for studies is HL-LHC v.1.5 with $\sqrt{s} = 14$ TeV, $\beta^* = 15$ cm, vertical and horizontal crossing angle and emittance of 2.5 μm·rad. Crossing angle of $p_x = -250\ \mu rad$ for phase $\phi = 0$ (horizontal) is nominal for Run 4 AFP.

According to the LHC machine layout v.1.5 only few locations are possible for installation of Roman Pots:

- RP1A at 195.5 m, RP1B at 198.0 m (i.e. 2.5 m distance),
- RP2A at 217.0 m, RP2B at 219.5 m (i.e. 2.5 m distance),
- RP3A at 234.0 m, RP3B at 237.0 m, RP3C at 245.0 m (i.e. distances 3, 8 or 11 m, respectively).

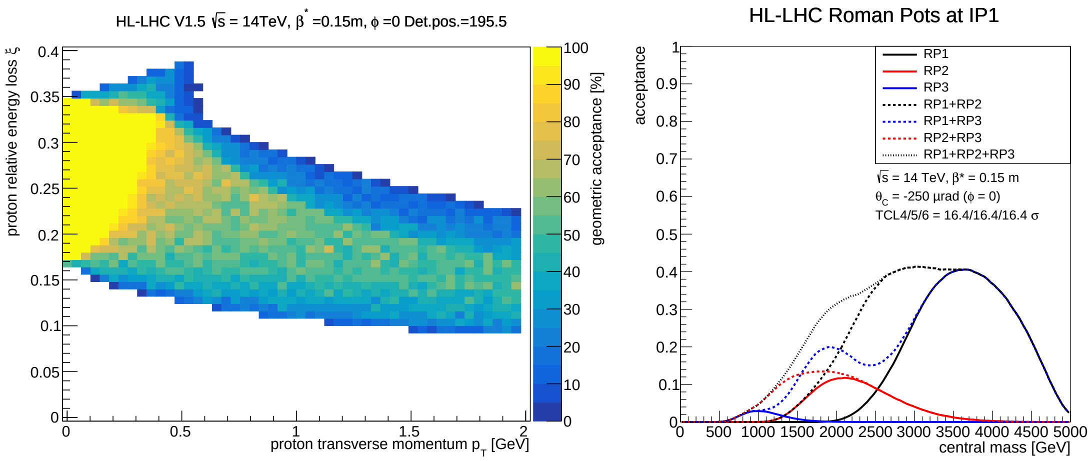

Figure 1: Acceptance for HL-LHC Roman Pots at IP1. **Left:** Geometric acceptance for RP1A and horizontal crossing angle ($\phi = 0$). **Right:** Mass acceptance for considered sets of stations near IP1.

Roman pots were assumed to be inserted at $11\sigma + 0.3$ mm from the beam. The default setting of collimators (TCL4,5,6) is 14.2σ, although this can be increased, *e.g.* to $16.4\ \sigma$.

Figure 1 (Left) shows, as an example, the geometric acceptance of a station at 195.5 m (RP1A). It can be clearly seen that the acceptance is for rather high proton energy losses of $0.17 < \xi < 0.35$. Results of combining stations (like RP1+RP2) assumes the installation of additional pots (at a cost to be taken into account) to enable "enhanced" acceptance. The legends of figure 1 can be inferred as:

- "RP1" means combination two stations RP1A and RP1B on both sides of IP when proton is tagged in all of them,
- "RP1+RP2" means tagged proton in [(RP1A "and" RP1B on side A) "or" (RP2A "and" RP2B on side A)] "and" [(RP1A "and" RP1B on side C) "or" (RP2A "and" RP2B on side C)].

The figure 1 (Right) indicates that mass acceptance is position-dependent, implying that stations closer to the IP have acceptance for higher masses. Optics with vertical crossing angle results in acceptance towards lower masses as compared to horizontal crossing angle.

5 Conclusion

During LHC Run 2, AFP and ALFA collected data-sets during standard and special low-luminosity conditions, and several analyses of the data, including elastic, diffractive, and (semi-)exclusive, are ongoing. Both detectors underwent hardware upgrades before being deployed in the LHC tunnel. Diffractive and minimum-bias studies as well as BSM searches would be conducted using the data AFP collected during Run 3. The presence of Roman Pots in Run 4 is being discussed within ATLAS as forward proton tagging benefits a variety of physics studies, but having forward detectors in the HL-LHC would necessitate an optimization of the beam optics to enhance its acceptance.

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