THE ATLAS UPGRADE PROGRAM* **

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In 2018 he ATLAS detector started the preparations for an ambitious physics project, aiming at the exploration of very rare processes and extreme phase spaces, an endeavor that will require a substantial increase in the amount of data to be taken. To accomplish this purpose, a comprehensive upgrade of the detector and associated systems was devised and planned to be carried out in two phases. The Phase-I upgrade program, completed in 2021, includes new features for the muon detector, for the electromagnetic calorimeter trigger system, and for all trigger and data acquisition chain. For the heavy-ion program, a new Zero Degree Calorimeter (ZDC) with improved radiation hardness will be installed. Upon reaching an integrated luminosity of 350 fb^{-1}, the LHC will undergo a new upgrade, becoming the High-Luminosity LHC (HL-LHC).

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1. Overview of ATLAS upgrades

After 9 years of successful data-taking in proton–proton and heavy-ion collisions at a variety of energies, in 2018 the ATLAS detector started the preparations for an ambitious physics project, aiming at the exploration of very rare processes and extreme phase spaces, an endeavor that will require a substantial increase in the amount of data to be taken. To accomplish this purpose, a comprehensive upgrade of the detector and associated systems was devised and planned to be carried out in two phases. The Phase-I upgrade program foresees new features for the muon detector, for the electromagnetic calorimeter trigger system, and for all trigger and data acquisition

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chain. These upgrades are expected to be fully functional in 2022 and will enable ATLAS to carry on its physics program at a two-fold increased luminosity. Of particular interest for the heavy-ions program, a refurbished Zero Degree Calorimeter (ZDC) with improved radiation hardness will be installed. In addition to the improved radiation hardness, the existing calorimetric capabilities are complemented by a transversely-segmented position sensitive Reaction Plane Detector (RPD).

Upon reaching an integrated luminosity of 350 fb^{-1}, the LHC will undergo a new upgrade, becoming the High-Luminosity LHC (HL-LHC). The HL-LHC will reach an instantaneous luminosity of 7.5×10^{34} $\mathrm{cm}^{-2}\mathrm{s}^{-1}$, which will enable the experiments to accumulate 4 ab^{-1} of integrated luminosity in about 10 years of operation. The challenges the ATLAS experiment will face during the HL-LHC stage are paramount, as it will have to cope with more than 200 simultaneous collisions per bunch crossing with many subsystems exposed to very high radiation levels. To preserve its performance, the ATLAS detector will require a major upgrade program, known as the Phase-II upgrade program. During the Phase-II upgrade, a completely new all-silicon tracker with extended rapidity coverage will replace the current inner tracker detector; the calorimeters and muon systems will have their trigger and data acquisition systems fully redesigned, allowing the implementation of a free-running readout system. A new subsystem called the High Granularity Timing Detector will aid the track-vertex association in the forward region by incorporating timing information into the reconstructed tracks. Finally, the ZDC will be rebuilt as the HL-ZDC for compatibility with the beam optics of the HL-LHC. The aforementioned projects are here summarized with a focus on the upgrades relevant to the heavy-ion program.

2. Zero degree calorimeters for ATLAS in Run 3

2.1. Detector

The ZDCs are located 140 m downstream of the ATLAS interaction point, in the Target Absorber for Neutrals (TAN). Charged particles are swept away by the bending magnets, but neutral particles — most importantly, spectator neutrons from heavy-ion collisions — reach the ZDC. Measuring the spectator neutrons is crucial for both minimum bias and ultra-peripheral collisions triggering and event selection. The ZDCs are modular sampling calorimeters whose sensitive region is instrumented with alternating layers of tungsten and fused-silica rods. High-energy particles impinging on the tungsten induce showers which radiate Cherenkov photons in the fused-silica rods. These photons are transported in the rods to a PMT at the top of the detector. In the previous operation, rather than fused-silica rods, the detector used fused-quartz rods whose light-transmission properties were dramatically degraded due to the formation of radiation-induced color centers in the material. A dedicated R&D campaign led to the choice of highly H_2 doped fused-silica rods whose transmission properties are expected to be stable up to dosages of a few hundred MRad, comfortably higher than the approximated 130 MRad exposure expected from the Run 3 heavy-ion running. The ZDC were refurbished with the improved rods in the summer of 2021.

2.2. Trigger and data acquisition capabilities

For the upcoming Run 3 operation, new all digital readout and triggers have been implemented with the LUCROD board [1]. Each LUCROD board has 16 input channels and is capable of baseline subtraction, pulse detection, and signal summing. Further, it enables trigger decisions encompassing multiple thresholds across both ZDC sides, which were previously unavailable. In addition to the upgrade electronics, newly installed air-core cables will reduce the effects of pile-up in the detector data. These upgrades were tested in the 900 GeV pilot beam in 2021. Figure 1 shows the far more precise signal waveforms from the pilot beam running compared with waveforms from the 2018 data taking.

2.3. Reaction plane detector

The purpose of the RPD is to measure the transverse (to the beam axis) deflection of spectator neutrons generated in ion–ion collisions. It is located between the first two modules of the ZDC. The RPD is based on a novel "Pan Flute" design, which consists of an approximately 4×4 cm^2 active region at its base, where charged particles, produced in the showers stimulated by neutrons or other forward particles in the first ZDC module, generate the Cherenkov light in a staggered array of fused-silica fibers. The active region of the detector is comprised of 256 overlapping fibers arranged as a virtual 4×4 array of square tiles which provide spatial sensitivity to incident charged particles in the x–y plane. Each channel is comprised of 16 synthetic fused-silica fibers that run vertically in the x–y plane and terminate at the same depth. A tile is reconstructed as a 9.60 mm^2 area, defined in the transverse dimensions by the fiber channel spacing within the support harps, and in the vertical dimension by the depth of each fiber within the harps. The overlap of the fibers is known allowing a position-sensitive signal to be extracted in either an explicit or machine-learning-based algorithm. The active region and the signal extraction are illustrated in figure 2.

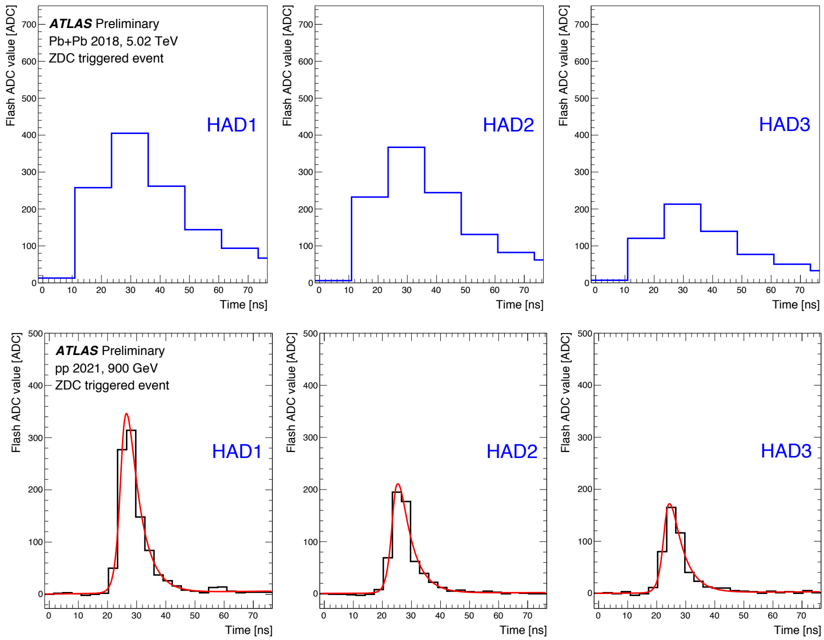

Fig. 1. (Color online) Flash ADC samples as a function of time read-out from the three ZDC calorimeter modules, HAD1-HAD3, for a single event. Top: Samples read-out from the Run 2 electronics during 2018 lead–lead collisions data-taking by ATLAS. Bottom: Samples read-out from a LUCROD FEE board during the proton–proton pilot beam data-taking. The baseline is measured in the first sample and subtracted from the other samples. The red/gray curves show fits to the pulses that are performed as part of the standard ZDC offline analysis. The pulses have shorter rise and fall times, compared to those during Run 2, thanks to the installation during LS2 of air-core cables that carry the signals from the tunnel to USA15.

3. HL-LHC upgrades

3.1. Central detector upgrades

One of the major upgrades to ATLAS is the replacement of the inner tracking detector with a new all-silicon Inner Tracker (ITk) [2]. It is composed of a Pixel Detector surrounded by a Strip Detector. The Strip Detector has four strip double-module layers in the barrel region and six end-cap disks, covering the pseudorapidity range of $|\eta| < 2.7$. The Pixel Detector consists of five flat barrel layers and multiple inclined or vertical ring-shaped end-cap disks, extending the coverage up to $|\eta| = 4.0$, as compared to $|\eta| < 2.5$ in the current ATLAS detector. This increased acceptance is especially useful for

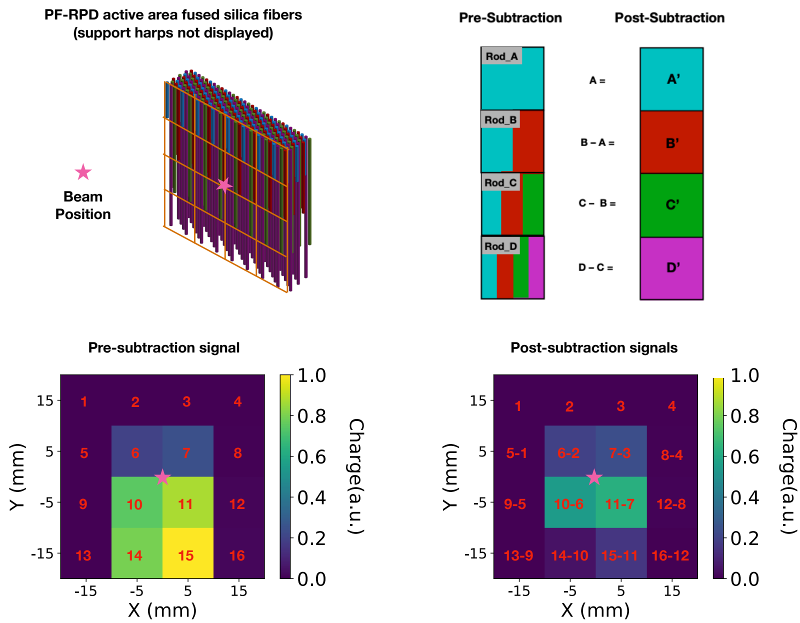

Fig. 2. Top left: The fibers that make up the active area of the RPD, shown with a depiction of the virtual tiles. Top right: A schematic illustration of the subtraction procedure. Bottom: The subtraction procedure illustrated on the virtual tiles.

correlation and fluctuation measurements, a key part of the heavy-ion program in which the larger acceptance will be more valuable than increased luminosity. Complementing the ITk is the High Granularity Timing Detector (HGTD) [3]. The HGTD, located at $2.5 < |\eta| < 4.0$, provides a timing-information key for pileup rejection at high luminosity. Of more direct concern for the heavy-ion program, the detector will play a role in the minimum bias event and triggering definition of heavy-ion collisions.

3.2. HL-ZDC

The ATLAS ZDC project will evolve into the Joint ZDC Calorimeter Project (JZCaP) HL-ZDC for the HL-LHC. This is a collaborative project between ATLAS and CMS, presently engaged in a joint R&D program and expected to culminate in detectors for both experiments. Due to the changes in beam optics in the transition from the LHC to the HL-LHC, the TAN where the ZDCs are currently located will be replaced by the TAXN, 13 meters closer to the interaction point. Although the basic instrumentation and measurement capabilities will be similar to the existing ZDC, the available mechanical envelope for the HL-ZDC necessitates a change in the basic design of the detector: the HL-ZDC will be monolithic rather than modular and will have a width only half as large as the ZDC. The design of the HL-ZDC and the TAXN slot are shown in figure 3. In addition to the mechanical redesign, R&D is ongoing to further improve radiation hardness and measurement capabilities of the HL-ZDC.

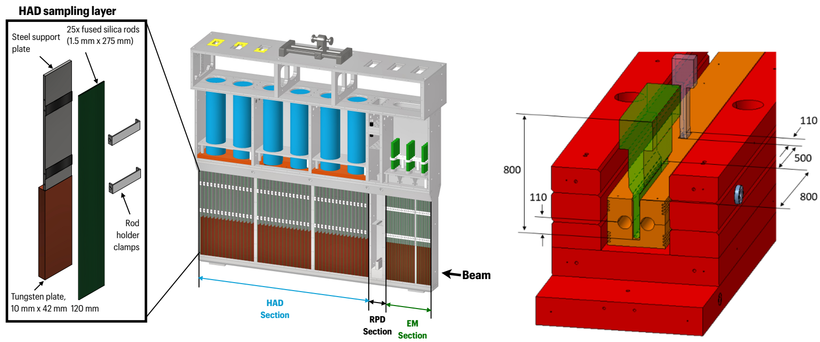

Fig. 3. (Color online) Left: The design of the HL-ZDC shown with an expanded view of a sampling layer. Right: The TAXN, with the HL-ZDC envelope shown in green in the center.

4. Summary

The ATLAS upgrade program will prepare ATLAS for a continuation of its physics program in the next decades. This includes both high-energy physics measured in proton–proton collisions and the heavy-ion program. Although they are primarily designed for high-luminosity proton–proton collisions, the HL-LHC upgrades, in particular the ITk and HGTD, will benefit of the heavy-ion program as well. The ZDC and within it the RPD, are designed for the heavy-ion program and are expected to contribute to the program already in the LHC Run 3, and in a redesigned form in the HL-LHC.

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