



## Full Length Article

## The ATLAS RPC Phase-II upgrade for high-luminosity LHC era

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## ARTICLE INFO

## Keywords:

Resistive Plate Chambers  
ATLAS experiment  
High-luminosity LHC

## ABSTRACT

RPC detectors play a crucial role in triggering events containing muons in the central region of the ATLAS experiment. In view of the High-Luminosity LHC program, the existing RPC system, consisting of six independent concentric cylindrical detector layers each providing a full space time localization of hits, is currently facing a significant upgrade. In the next few years, 306 triplets of new generation RPCs will be installed in the innermost region of the ATLAS Muon Barrel Spectrometer, increasing from 6 to 9 the number of tracking layers, doubling the trigger lever arm. This allows a substantial enhancement of the present trigger redundancy, increasing the geometrical acceptance from 78% to 96% approximately. The new chamber design is based on a very efficient integration of an innovative front-end electronics within the detector Faraday cage, allowing to operate the RPCs with an order of magnitude lower of average charge per count, correspondingly increasing rate capability and longevity. Fitting new chambers in the narrow space left in ATLAS inner barrel was a challenge, achieved by optimizing RPC materials and thickness, featuring a 1 mm gas gap (instead of 2 mm), and 1.4 mm resistive electrodes (instead of 1.8 mm). Both sides of RPCs are readout by strip panels oriented to measure the bending coordinate of the muon spectrometer, while the second coordinate is reconstructed from the difference of the propagation time. To achieve such results, a 100 ps precise TDC has been integrated in the front-end electronics ASIC. The expected time resolution of a single 1 mm RPC gas gap is approximately 300 ps, and the possibility of a stand-alone Time-of-Flight measurement will have a huge impact on ATLAS searches for massive long-lived particles. An overview and the present status of the ATLAS RPC Phase II project will be presented.

## 1. Introduction

The ATLAS experiment at CERN [1] will have to undergo a major upgrade for its muon-trigger system, due to the luminosity increase foreseen for the Large Hadron Collider leading to the High-Luminosity LHC operation phase (HL-LHC) [2]. At a luminosity as high as  $7.5 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$  with a center-of-mass energy of 14 TeV in proton–proton collisions, the average number of interactions per bunch crossing will be about 200. For this reason, about 300 new-generation triplets of Resistive Plate Chambers [3] will be added in the barrel inner region of the ATLAS muon subdetector (the pseudorapidity region  $|\eta| < 1.05$ ), and the old on-detector trigger boards will be replaced with new ones. This upgrade will give increased redundancy (from 6 to 9 layers), increased barrel trigger geometrical acceptance (from 78% of the legacy barrel trigger up to 96% with the addition of the new RPC chambers by requiring the coincidence of inner and outer layers [4]) and improved time resolution for time-of-flight measurements (0.4 ns for the new thin-gap RPCs, and 1.1 ns for legacy RPCs). The new thin-gap (1 mm)

RPCs will cover a 472 m<sup>2</sup> area, and will be arranged into 306 triplets containing 8262 new front-end boards. Fig. 1 shows a scheme of the transverse section of a part of the ATLAS muon trigger in the barrel region for high-luminosity operation: the Barrel Inner (BI), Barrel Middle (BM) and Barrel Outer (BO) muon-trigger stations are evidenced, while TO indicates the LHC bunch-crossing timing; the BM and BO muon-trigger stations are the ones already used since the beginning of the ATLAS operation, while the BI muon-trigger station will be added for the Phase-II operation. The Phase-II upgrade for RPCs was preceded by a pilot project consisting in the installation of an additional layer or RPCs in the transition region between the barrel and the end cap of the ATLAS muon spectrometer (pseudorapidity interval  $1.0 < |\eta| < 1.3$ ), where a high rate of fake triggers is expected; this was the BIS78 project [4], which led to the installation of RPCs extremely similar to the ones foreseen for the Phase-II upgrade. The commissioning and some preliminary results concerning the performance of the BIS78 RPCs were reported in [5].

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<https://doi.org/10.1016/j.nima.2025.170590>

Received 31 January 2025; Received in revised form 1 April 2025; Accepted 29 April 2025

Available online 17 May 2025

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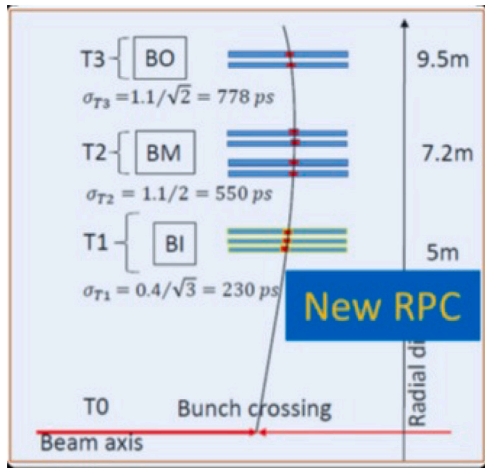


Fig. 1. Geometry of a part of the transverse section of the ATLAS RPC system in the barrel region for high-luminosity operation, indicating the expected time resolution for every trigger station: inner (BI), middle (BM) and outer (BO). T0 indicates the LHC bunch-crossing timing. BM and BO indicate the existing RPC stations installed at the beginning of the ATLAS operation.

## 2. BI resistive plate Chambers

A gas volume of a Resistive Plate Chamber is composed of a gas gap enclosed between two High Pressure Laminate (HPL); a graphite layer is deposited on the external face of each HPL plate; the total gas-volume thickness is about 4.5 mm for the new-generation RPCs to be added.

A singlet is the assembly of a gas volume enclosed between two read-out panels with strips parallel to the long side of the chamber. The singlet is enclosed in a Faraday cage consisting of the outer faces (copper) with their edges connected by conductive copper tape. The thickness of a singlet is about 13 mm.

Finally, three singlets (named a triplet) are inserted within a suitable mechanical structure to form a BI chamber, to be installed in the inner station of the ATLAS muon spectrometer. The BI RPCs which will be inserted in the Large sectors of the ATLAS toroidal magnet where the muon spectrometer is located are named BIL RPCs, while the BI RPCs which will be inserted in the Small sectors are named BIS RPCs. The BI chamber thickness is about 65 mm.

Fig. 2 shows the schemes of the transverse sections of a BI-RPC gas volume, of a BI-RPC singlet and a schematic view of a BI-RPC chamber (triplet).

In view of the upgrade of the ATLAS muon-trigger system for the HL-LHC operation, a new design for the gas volumes has been used, with several changes with respect to the ATLAS legacy RPC detectors: the gas-gap thickness was reduced from 2 mm to 1 mm; the gas distribution was re-designed, with 4 inlets for connecting the gas pipes on the corners of the gas volume, drilled in the profile; a new high-voltage cable connection was designed on the gas-volume side; 6-mm diameter gas pipes were replaced with 3-mm diameter gas pipes; the graphite-layer resistivity was reduced from 500 kΩ/□ to 320 kΩ/□ and the corners of the gas volumes were redesigned, by introducing a 45° cut, to reduce the risk of possible current leaks; finally, the electrode thickness was reduced from 1.8 mm to 1.4 mm.

The production of the gas volumes in Italy has started in 2023 and is expected to end in 2025, carried out by General Tecnica Engineering (GTE, at Monte San Giovanni Campano). Two new possible production centers are undergoing a qualification process, at Munich (Max Planck Institute, MPI, Germany) and Hefei (University of Science and Technology of China, USTC, People's Republic of China).

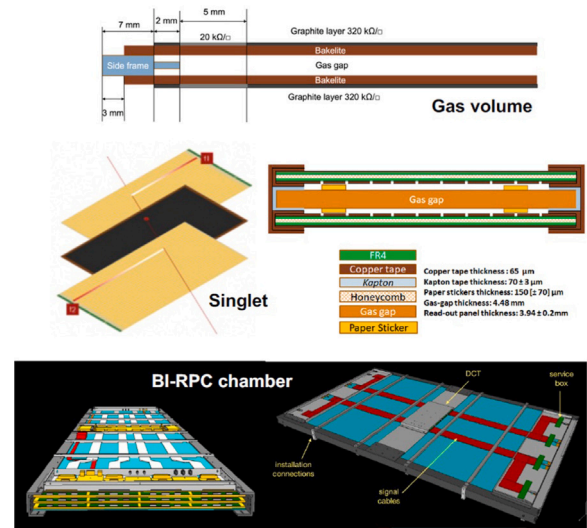


Fig. 2. Top: schematic view and geometry of the transverse section of a BI-RPC gas volume. Middle: schematic view of a BI-RPC singlet (gas volume enclosed between two  $\eta$  read-out panels). Bottom: schematic view of a BI-RPC chamber (triplet) in its mechanical case.

## 3. Qualification of RPC gas volumes

The qualification of BI RPC gas volumes is carried out at the GTE factory by INFN research groups.

Each HPL plate is accepted if its bulk resistivity does not exceed  $10^{11}$  Ωcm, if the plate thickness is within the specifications and uniform, and if a visual inspection does not detect any possible macroscopic defects.

After a gas volume has been produced, and after preliminary tests carried out by the factory technicians (including current-leak tests), final acceptance tests are carried out by INFN research groups. The following certification criteria for the gas volumes of the BI ATLAS RPCs were chosen on the basis of the experience made during the qualification of the legacy ATLAS RPCs, which was described in [6]:

- the current absorbed by every gas volume as a function of the applied voltage; a current less than  $1 \mu\text{A}$  at 3.5 kV, and a current less than  $3 \mu\text{A}$  at 6.1 kV after ohmic-current subtraction are required for each gas volume;
- tightness against gas leaks; after applying an overpressure of 3 mbar, the measured gas leak must not exceed 0.1 mbar after 3 min.

The ohmic component of the current is extrapolated by performing a linear fit in the [0–3] kV range, and then is subtracted to obtain the current due to the electric discharge at higher voltage. Fig. 3 shows the current vs effective voltage curves for 24 gas volumes of BIL type (top) and the current vs effective voltage curves for the same gas volumes after ohmic-current subtraction (bottom). The effective voltage is defined as the equivalent voltage to be applied at a reference temperature of 295 K and a reference atmospheric pressure of 1013 mbar to have the same Townsend coefficient in the gas discharge, and is introduced to account for changes in the environmental parameters in different measurement sets. After shipping the qualified gas volumes to CERN, these will undergo final tests at the GIF++ facility, where they will be exposed to  $\gamma$  radiation from a  $^{137}\text{Cs}$  source so that the absorbed current will be about  $20 \mu\text{A}/\text{m}^2$ , and the current vs voltage behavior will be measured again after that for final qualification and acceptance.

## 4. Gas-volume thermal tests

In the spring of 2024, mechanical stress tests were carried out on 4 BIL-type gas volumes with thermal cycles in the climatic chamber of

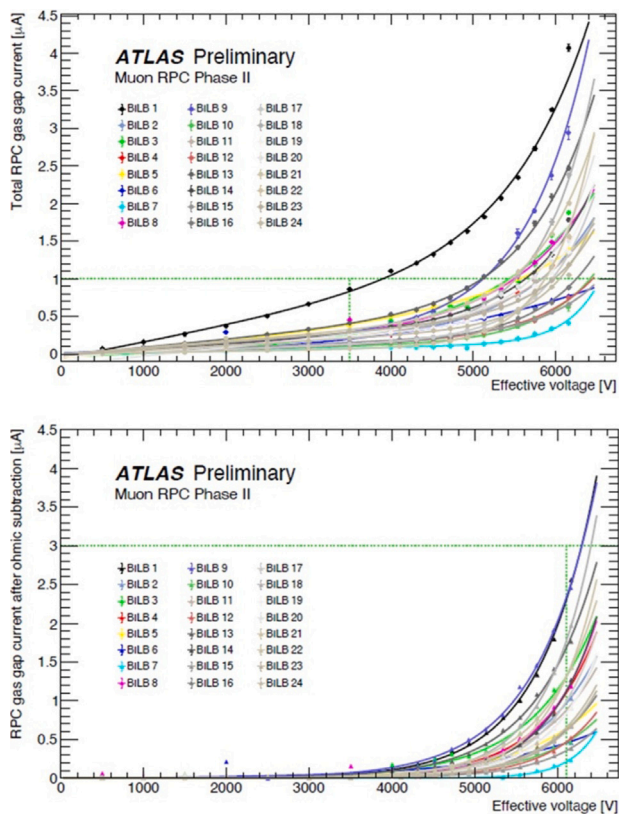


Fig. 3. Top: current vs effective voltage curves for 24 gas volumes of BIL type. Bottom: current vs effective voltage curves for the same 24 gas volume after ohmic-current subtraction. All these gas volumes matched the acceptance criteria.

the ATLAS laboratory at INFN Frascati. Additional tests are performed on BIS-type gas volumes at the Cambridge University. The thermal tests were only aimed at stressing the gas-volume mechanical structure and checking its robustness against gas leaks. Several thermal cycles were performed: 5 cycles between 10 °C and 30 °C, 4 cycles between 0 °C and 30 °C, 3 cycles between -10 °C and 30 °C, 3 cycles between -20 °C and 30 °C. The gas volumes were flushed in parallel during the thermal cycles with low dew point dry air, applying 1.8-mbar overpressure at the gas inlet. Two temperature sensors were inserted into the gas gaps to evaluate the delay in temperature variation and the attenuation of the thermal excursion. At the end of each cycle, the thermal-equilibrium conditions were verified after 15 min. The mechanical robustness and the gas tightness were monitored during the thermal cycles; in particular, the test for gas tightness was carried out as described in Section 3, and no effect on the gas-volume tightness due to the thermal cycles was observed. The temperature range from -10 °C to 30 °C was chosen only to test the gas-volume mechanical robustness against possible temperature changes while the detector is stored in non-conditioned CERN buildings before the commissioning of the Phase-II upgrade. No such temperature time variations are expected inside the ATLAS cavern, where the temperature is by far more stable than in the thermal tests (from 19 °C to 26 °C in the barrel region of the muon spectrometer).

### 5. Read-out panels

BI RPCs will have purposely-designed read-out panels [7] consisting of 3 layers: one layer made of 3 mm-thick aramid paper honeycomb, and two layers made of 0.4 mm-thick copper plated FR4 (a composite of glass-fiber reinforced epoxy resin) on which the read-out strips are made by photo-engraving. The panel thickness and the materials are

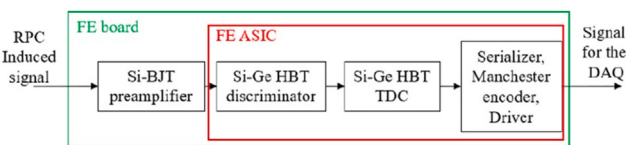


Fig. 4. Scheme of one channel of the new front-end circuit for BI-RPCs.

chosen to optimize the strip impedance and the detector weight. A termination resistor is soldered to the ends of each strip and guard wire.

The construction of the read-out panels is shared between INFN Cosenza (BIL) and Hefei China (BIS). The INFN Cosenza site production capability is 800 panels/year, also carrying out the following tests: thickness measurement of FR4 panels, thickness measurement of aramid paper honeycomb, thickness measurement of the assembled panel surface (7 cm × 7 cm matrix), Panel length and width plus strip-width measurement, and electrical continuity measurements for strips and guard wires.

### 6. Front-end electronics

For BI-RPCs, a custom ASIC chip has been developed [8]. It has Si-technology preamplifier and SiGe-HBT ASIC, with embedded discriminator and TDC. This new design results in improved stability and sensitivity compared to the BIS-78 [4] front-end chips and also allows the  $\phi$ -coordinate reconstruction. Here are the main features: detectable signal of 1–2 fC, minimum discrimination threshold of 0.3 mV, Voltage-Controlled Oscillator (VCO) defining the TDC time resolution driving the scaler (50–150 ps RMS), data encoded using the Manchester code, 8 channels for each ASIC chip (each with its own serial transmission line). Fig. 4 shows the basic scheme for one channel of the new front-end circuit for BI-RPCs.

Ten ASIC chips were irradiated with a neutron flux of  $10^{13} n_{eq}/cm^2$  at the China Spallation Neutron Source (Dongguan) to check the chip radiation hardness: no change was observed in the discriminator and in the VCO response after the irradiation, and no Single Event Upsets (SEU) or other radiation-induced effects were seen.

### 7. $\phi$ -coordinate measurement

The BI-RPC detectors have only  $\eta$ -oriented read-out strips, equipped with FE electronics using a TDC with 100-ps time resolution at the opposite ends. The  $\phi$ -coordinate reconstruction is obtained from the propagation time of the signals on the strips and from the propagation velocity. The signal propagation velocity on the strip can be measured by measuring the time difference on the opposite read-out strip ends.

A test measurement has been carried out at CERN with cosmic muons, by placing 2-cm wide trigger scintillators orthogonal to the strip, at different positions. Fig. 5 shows a scheme of the test experimental layout. A signal propagation velocity of 20 cm/ns was measured on a BIL-RPC equipped with BIS-78 like front-end boards. The resulting spatial resolution for the  $\phi$  reconstructed coordinate was about 2 cm, driven by the scintillator geometry. The spatial resolution for the  $\eta$  coordinate clearly depends on the event cluster size.

### 8. Layout of the ATLAS BI-RPC chambers

The design of the BI-RPC mechanics has been defined for all the main chambers. There are two main BIL types: BIL 680 (with a width of 680 mm) and BIL 520 (with a width of 520 mm) covering 75% of the BIL sectors. There are 2 BIS types: BIS1 (with a width of 1092 mm) and BIS2-6 (with a width of 910 mm), covering all the BIS sectors involved in the Phase-II upgrade. In addition, there are other special types, including BIL 320 (with a width of 320 mm), in one sector of the ATLAS muon spectrometer.

In the feet sectors (Sector 11 and Sector 15) new chambers will be installed in the Barrel Outer region: 80 identical BOR-BOM chambers without overlapping, of BIS-like size (1950 × 1092 mm<sup>2</sup>).

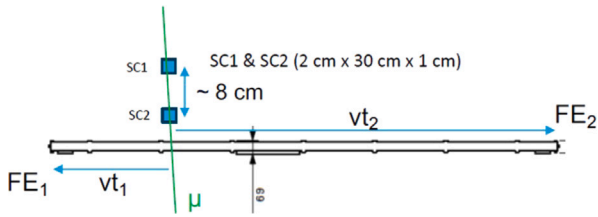


Fig. 5. Scheme of the transverse view of the test setup for  $\phi$ -coordinate measurement. A cosmic-ray trigger is provided by the coincidence of the two scintillator bars SC1 and SC2; the time measurements  $t_1$  and  $t_2$  at the ends of one strip, as a function of the trigger position along the strip, provide the signal propagation speed  $v$  along the strip.

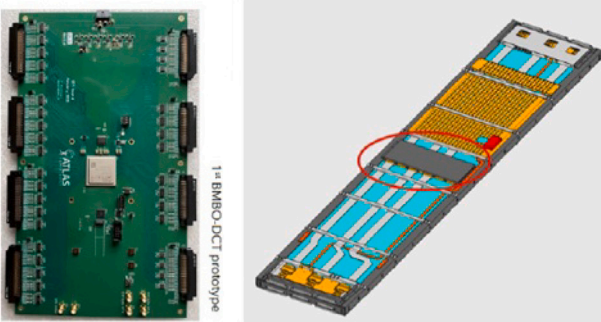
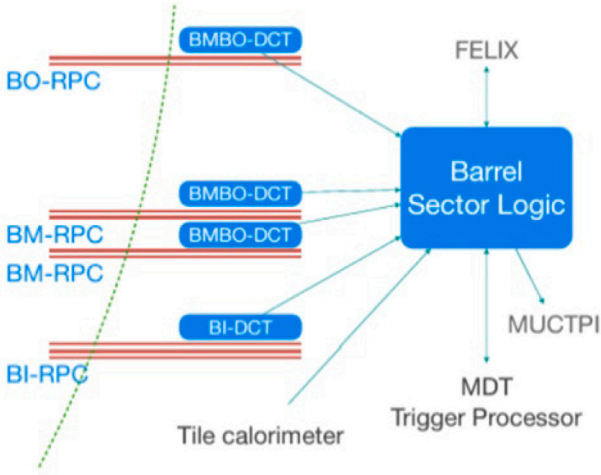


Fig. 6. Top: logical scheme of the connection between the RPC DCT boards and the Sector Logic trigger processor in the ATLAS barrel region. Bottom left: photograph of one of the BMBO-DCT prototypal boards. Bottom right: scheme of the position of the DCT board on one RPC chamber.

### 9. Production database

In order to keep track of every single detail of the production chain for the ATLAS BI-RPCs, a production database has been prepared. The database infrastructure is based on MySQL, and is managed via a web interface to keep track of the components (e.g. gas gaps, HPL plates, etc.), including the relationships among these. The web interface also displays QA/QC test results for the components (e.g., current vs voltage curves).

At the moment (October 2024) the database management of read-out panels and gas volumes is ready. Singlets will be implemented soon, and subsequently triplets and full chambers will be included as well.

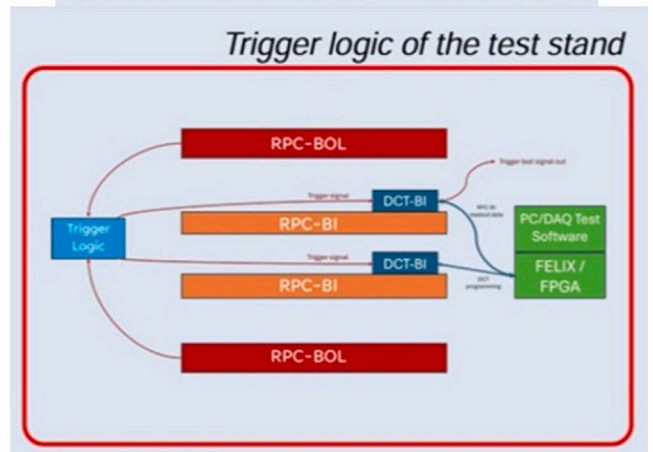


Fig. 7. Top: Photograph of the cosmic-ray test stand for BIL RPCs installed at CERN. Bottom: logical scheme for the trigger logic of the test stand; the legacy BOL RPCs used for the cosmic-ray trigger are colored in red, the BI RPCs to be tested are colored in orange.

### 10. Data collector and transmitter (DCT)

The DCT connects the detector FE with the ATLAS Barrel Sector Logic (SL), where trigger logic operations are carried out. Two kinds of DCT are developed:

1. BMBO-DCT (new boards for the legacy RPC system): receives hit analog pulse from the FE, measures the arrival time with FPGA-TDC and sends time data to the SL. The first prototype has been extensively tested (both hardware and software): successful communication test with the SL, and read-out tests with a BML-RPC at the INFN laboratory of Roma Tor Vergata; the results of the latter test were the following: 0.8 ns time resolution for cosmic-ray time of flight between two RPCs, and 0.24 ns TDC time resolution on  $\eta$ - $\phi$  panels facing the same gas volume. A second prototype is under test. 1208 BMBO-DCT boards are foreseen to be installed on the ATLAS legacy RPC chambers.
2. BI-DCT (BI-RPC): receives hit time digital data from FE-TDC, decodes and sends “Bunch Crossing ID” tagged time data to SL, reconstructs  $\phi$  coordinate from the time difference of two opposite  $\eta$ - $\eta$  time hits on the same strip. The schematics are ready and the first prototype is going to be produced. The communication test between the front-end electronics and the DCT is in progress. The new DCT board will be tested soon in the cosmic-ray station installed in the BB5 building at CERN. 338 BI-DCT boards are foreseen to be installed.

Fig. 6 shows a logical scheme of the connection between the RPC DCT boards and the Sector Logic trigger processor in the ATLAS barrel region (top), a photograph of one of the BMBO-DCT prototypal boards (bottom left) and a scheme of the position of the DCT board on one RPC chamber (bottom right).

## 11. Cosmic-ray test stand for BIL

A cosmic-ray test stand has been constructed and installed in the BB5 building at CERN. This facility will carry out the test of the BIL-type BI-RPC singlets and triplets after their construction. In the test-stand structure, two trigger sectors available for QA/QC test: the upper sector is designed to certify up to 6 BIL singlets; the lower sector is designed to certify up to 2 BIL chambers (triplets). The test stand has a tower-like structure, with four refurbished legacy RPC detector used to provide the trigger for cosmic rays. The height of the trigger detectors can be adjusted depending on the number of detectors under test and to optimize the certification speed during the production. Fig. 7 shows a photograph of the test stand (top) and a logical scheme for the trigger logic of the test stand.

## 12. Conclusions

In order to meet the requirements for the muon trigger in view of the high-luminosity operation phase of the Large Hadron Collider at CERN, new state-of-the-art RPC detectors have been devised and developed for the ATLAS experiment. Due to the lower-resistivity HPL plates and the new high-performance front-end chips and DCT boards, the ATLAS BI-RPC chambers will have improved rate capability up to 10 kHz/cm<sup>2</sup>, which is about 100 times higher than the rate observed by the ATLAS legacy RPCs in the barrel region. The production and test of gas volumes has already started in Italy, with two additional producers under qualification in Germany and China. The read-out

panel assembly and test has started at INFN Cosenza (Italy) and USTC at Hefei (China). The front-end boards are close to the completion of the integration tests: ASICs have been partially produced. The DCT is also well on its way: the second prototype of BMBO-DCT for ATLAS legacy RPCs is under validation, while BI-DCT is getting close to production. Finally, the construction of the prototype of the chamber mechanical structure has been started. The production of all the required BI-RPCs is scheduled to be completed in 2026.

## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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