Quality Assurance and Quality Control of Gas Volumes for the Upgrade of the ATLAS RPCs for HL-LHC Operation

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on behalf of the ATLAS Muon community

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Outlook

- Introduction
- A summary on the QA/QC tests of Legacy RPC gas volumes at the production site
- Description of the RPC-system extension for the Phase-II operation of the ATLAS experiment
- Features of the QA/QC tests at the production site and at CERN
- Problems that were met during the gas-volume production and workarounds
- Conclusion

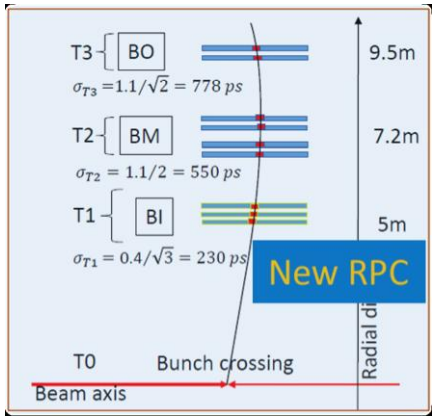
Summary of the QA/QC test of ATLAS Legacy RPC gas volumes

- Preliminary Ar-conditioning test followed by a I-vs-V test were carried out at the production site using a TFE-isoC_4H_{10} binary gas mixture
- These tests were carried out from 2002 till 2006
- Over 3200 gas volumes were tested, of BM and BO types
- 90 % of the produced gas volumes were accepted for being installed in the ATLAS RPC subdetector

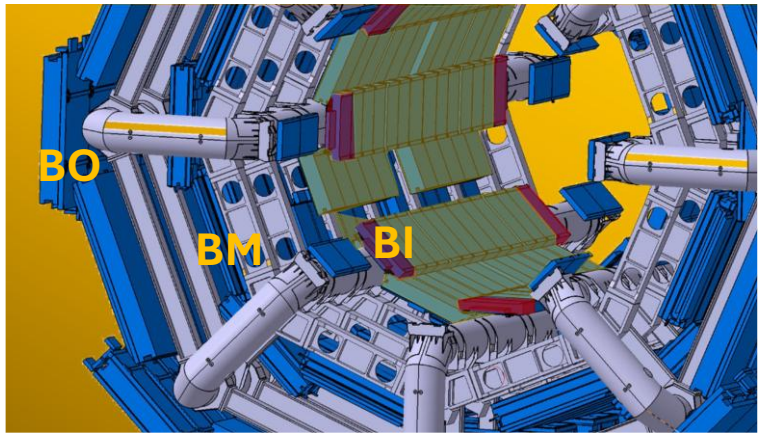
The ATLAS RPC upgrade for Phase II

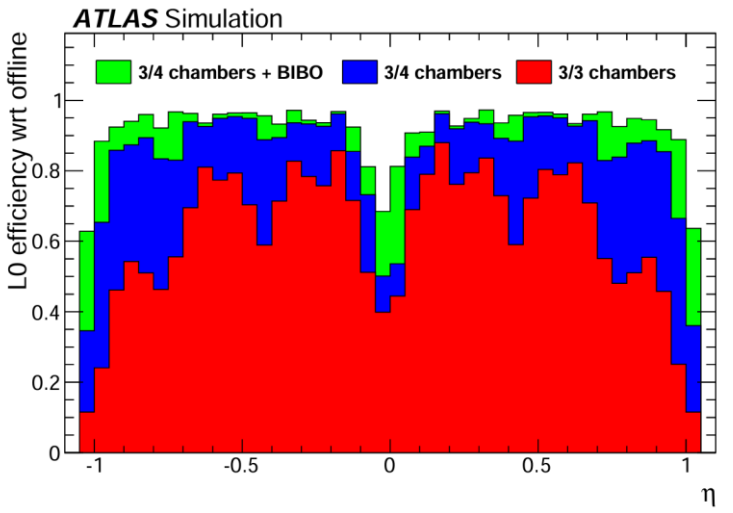
The HL-LHC luminosity increase ($7.5 \cdot 10^{34}$ cm^{-2} s^{-1} at $\sqrt{s} = 14$ TeV pp , average number of interactions per bunch crossing $\langle\mu\rangle = 200$) foresees a major upgrade for the ATLAS Muon Trigger system. About 300 new-generation RPC chambers will be inserted in the Barrel Inner region (BI), and the old on-detector trigger boards will be replaced with new ones

- Improved trigger redundancy (from 6 to 9 layers)
- Increased trigger acceptance (from 78% to 92%, and to 96% by requiring BI-BO coincidence, see Table 3.2 of the Phase II Muon TDR: https://cds.cern.ch/record/2285580/files/ATLAS-TDR-026.pdf)
- Improved time resolution for time-of-flight measurements: new thin-gap RPCs (1 mm) and new read-out electronics (0.4 ns for BI RPCs, from 2 ns to 1.1 ns for legacy RPCs)



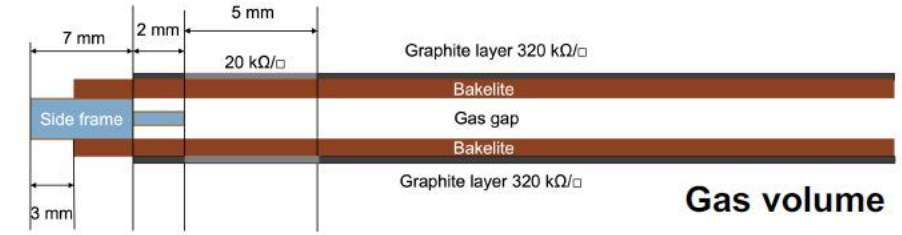
- BI RPC detector surface: 472 m^2
- 306 BI RPC chambers
- 8262 new front-end boards

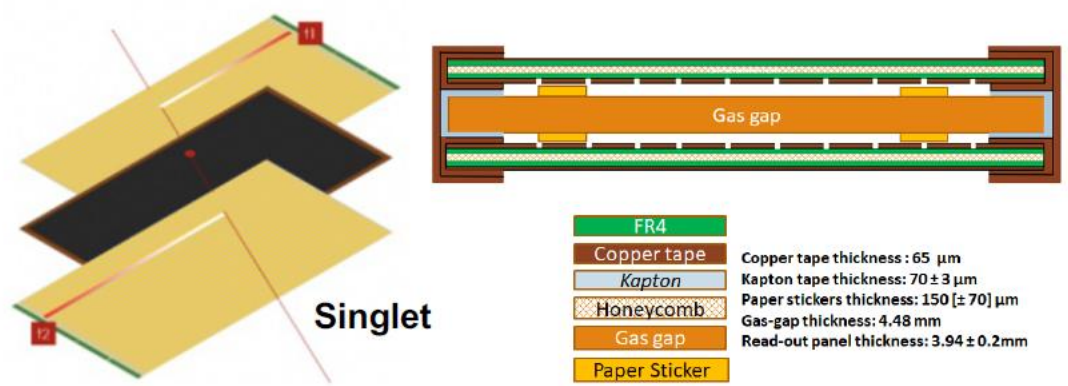


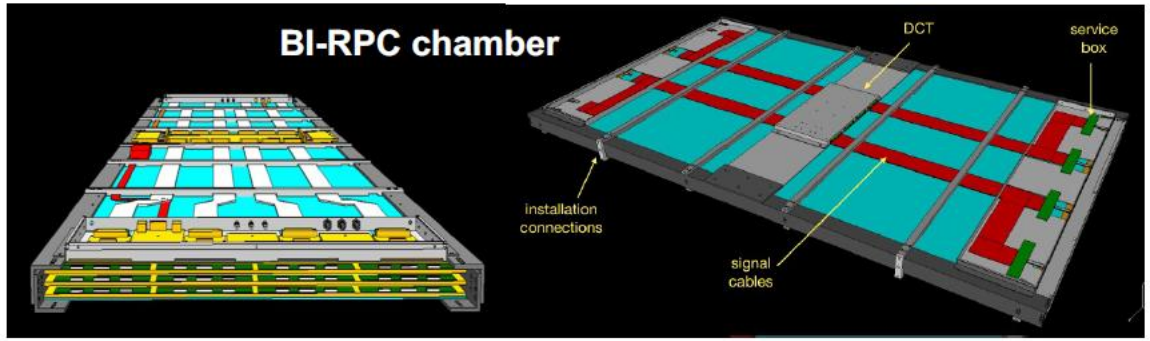


BI-RPC: gas volumes, singlets and chambers

- **Gas volume:** a gas volume is composed of a gas gap enclosed between two High-Pressure Laminate (HPL) plates. A graphite layer is deposited on the external face of each HPL plate. Total gas-volume thickness: about 4.5 mm
- **Singlet:** the gas volume is enclosed between two read-out panels with η-oriented strips (parallel to the long side of the chamber), forming a «singlet». The gas volume with the read-out panels is enclosed in a Faraday cage consisting of the outer faces (copper) with their edges connected by conductive copper tape. Singlet thickness: about 13 mm
- **BI chamber:** three singlets (a «triplet») are inserted within a suitable mechanical structure to form a BI chamber. BIL-RPCs will be inserted in the Large sectors, while BIS-RPCs will be inserted in the Small sectors. BI chamber thickness: about 65 mm

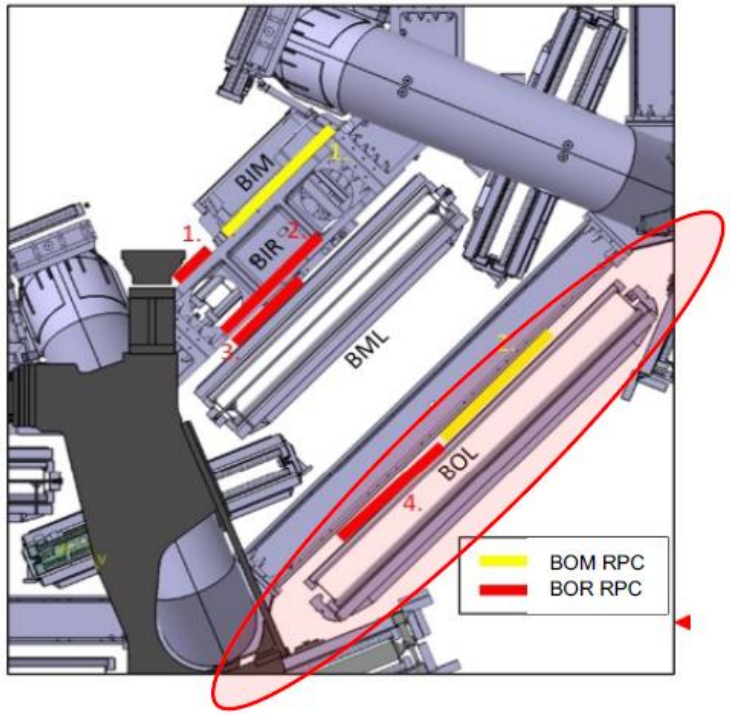


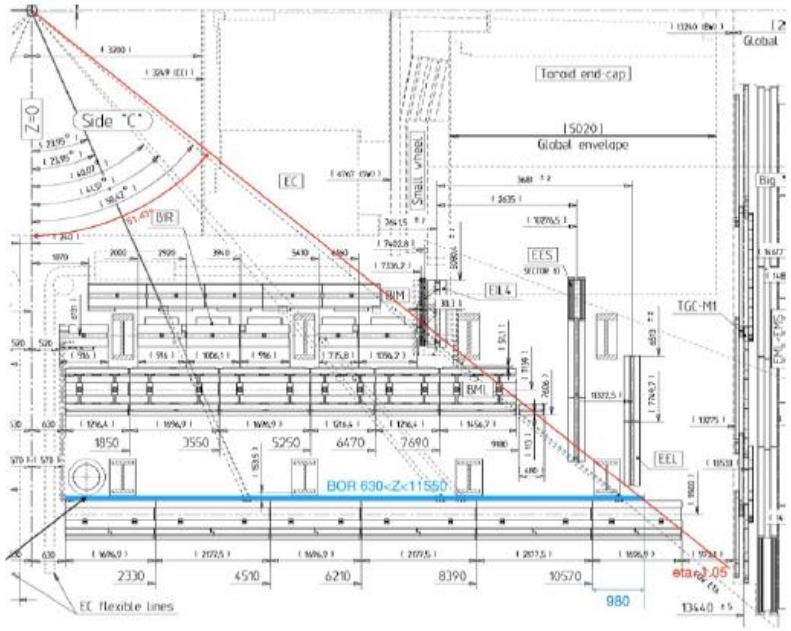




Layout of the BI-RPC chambers

- The design of the BI-RPC mechanics has been defined for all the main chambers (4 BIL types: BIL 680S – BIL 680L – BIL 620S – BIL 520S covering 75% of the BIL sectors; 2 BIS types: BIS1 and BIS from 2 to 6, covering all the BIS sectors involved in the Phase-II upgrade) and other special cases.
- In the feet sectors (S11 and S15) new chambers will be installed in the Barrel Outer region: 80 identical BOR-BOM chambers without overlapping, of BIS-like size.





New gas volumes

- A new design for the gas volumes has been used, with several changes with respect to the ATLAS legacy RPC detectors:
- Gas-gap thickness: 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
- New HV-cable connection on the the gas-volume side
- The 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 footprint was redesigned to reduce the risk of possible current leaks
- Electrode thickness: reduced from 1.8 mm to 1.4 mm

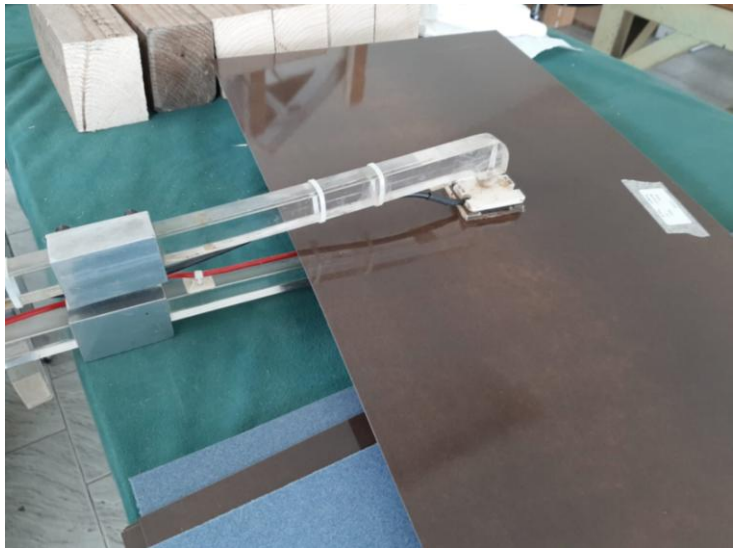
The production of the gas volumes in Italy has started in 2023 and will end in 2027, carried out by General Tecnica Engineering (GTE).

Two new production centers underwent a qualification process and started the production:

Munich (Max Planck Institute, MPI) and Hefei (University of Science and Technology of China, USTC)

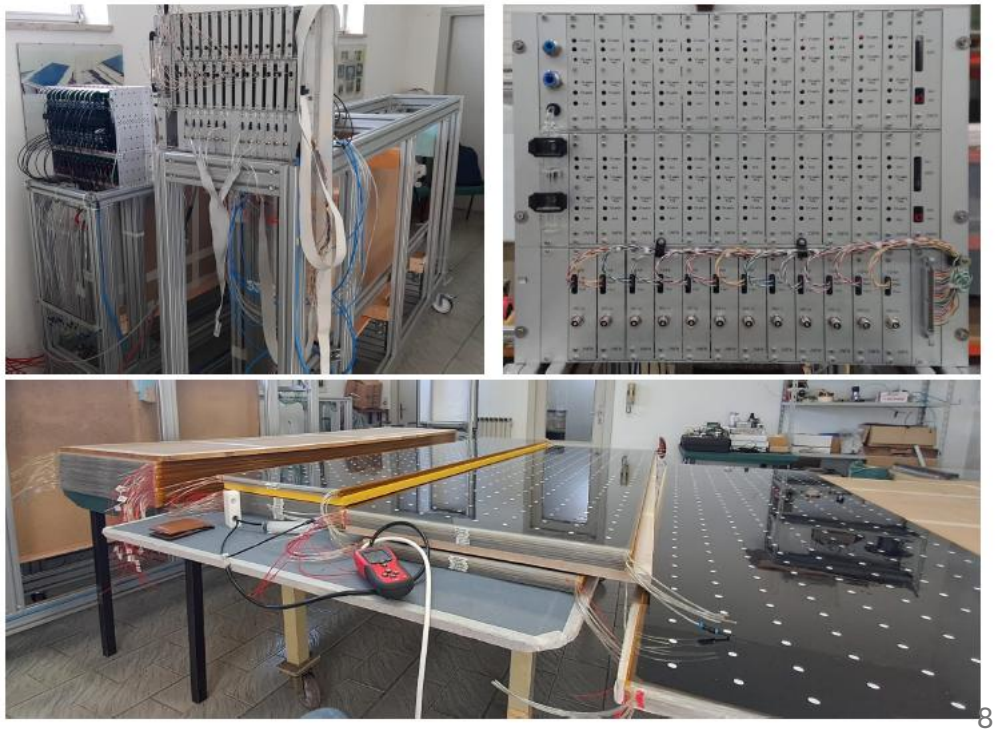
Qualification of gas volumes

- **Tests of HPL plates are carried out by INFN at GTE:**
- Measurement of the HPL bulk resistivity (maximum value accepted: 10^{11} Ω cm)
- Sample measurement of plate thickness
- Visual inspection for detecting any possible macroscopic defects



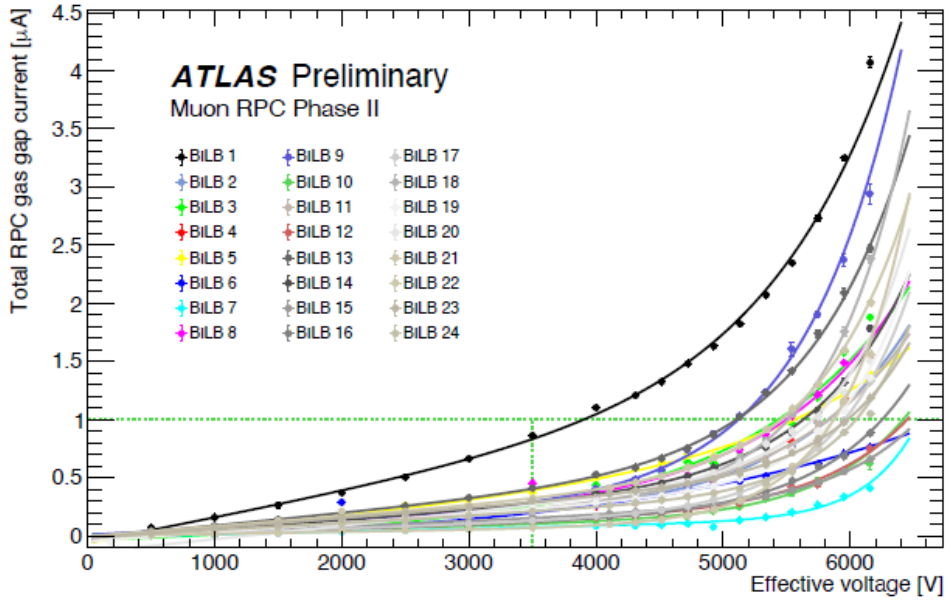
Gas-volume tests are carried out at GTE and CERN:

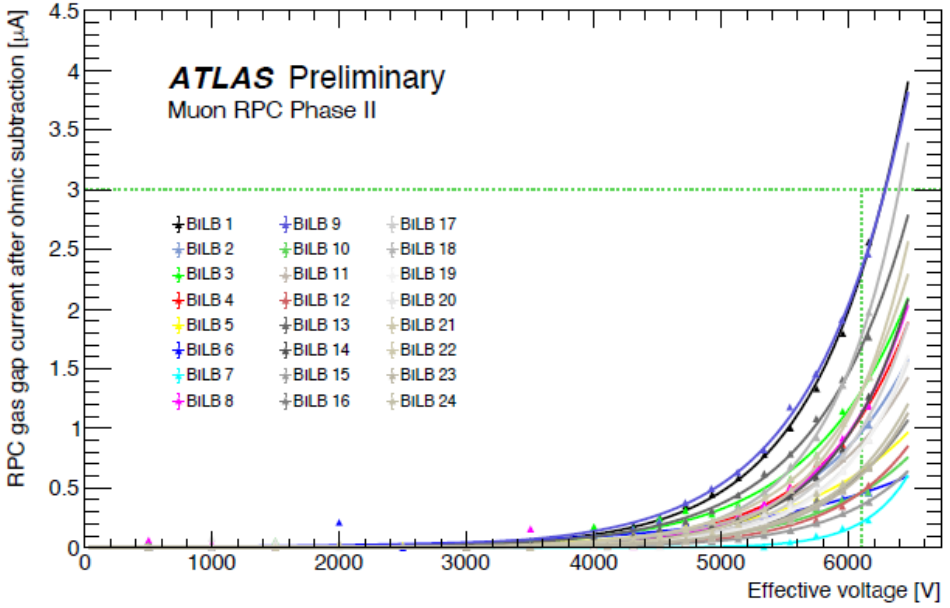
- 9 tests are carried out by the manufacturer
- 3 tests are carried out by CERN-INFN
  - Current vs Voltage (I-V) characterization (max 1 μA @ 3.5 kV – max 3 μA @ 6.1 kV after ohmic-current subtraction)
  - Gas-tightness test ($\Delta p < 0.1$ mbar after 3 minutes)
  - Current-leak test
- Conditioning at GIF++
  - The I-V curve is measured again with the source off
  - The gas volumes are exposed to γ radiation from a ^{137}Cs source, at approximately 4800 V (max 20 $\mu A/m^2$), before repeating the I-V test



Current vs voltage test of gas volumes

- The BI-RPC gas volumes are in production. In agreement with the tender requirements, gas volumes are accepted if the measured total current is less than 1 μA at 3.5 kV and a measured current less than 3 μA at 6.1 kV after subtracting the ohmic component, extrapolated by performing a linear fit in the [0 – 3] kV range
- All gas volumes must undergo this test before invoicing. The plots below show the **total current (left)** and the **recalculated current after subtracting the ohmic component (right)** as a function of the applied voltage, for a whole production batch of BIL gas volumes
- This tested production batch met the acceptance requirements





A first problem

- During the production of the BI gas volumes at GTE, after the initial positive QA/QC tests at the firm, some units were found to have gas leak ($\Delta p > 0.1$ mbar after 3 minutes).
- This issue was met in the spring of 2024 during tests at CERN and it took a few months to be addressed.
- After very careful checks, it was found that this leaks were due to an imperfect connection of the gas-distribution block at the edge of the gas volume, which affected a number of units. This block is an additional part with respect to Legacy RPC gas volumes which had a simpler structure.
- Refurbishment on the already produced gas volumes was made at CERN to fix the problem.
- Additional careful glueing on specific parts of the gas volumes during the production allowed to solve this problem in the summer of 2024.

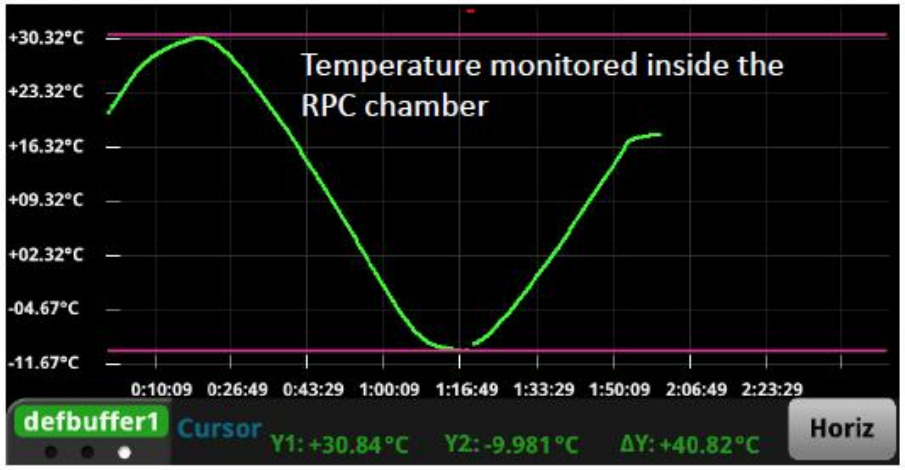
Gas-volume thermal tests

- Stress tests were carried out on 4 BIL-type gas volumes with thermal cycles in the climatic chamber of the ATLAS laboratories at INFN Frascati. Additional tests were performed on BIS-type gas volumes at the Cambridge University.
- Several cycles were carried out:
- 5 x [10 °C – 30 °C]
- 4 x [0 °C – 30 °C]
- 3 x [-10 °C – 30 °C]
- 3 x [-20 °C – 30 °C]

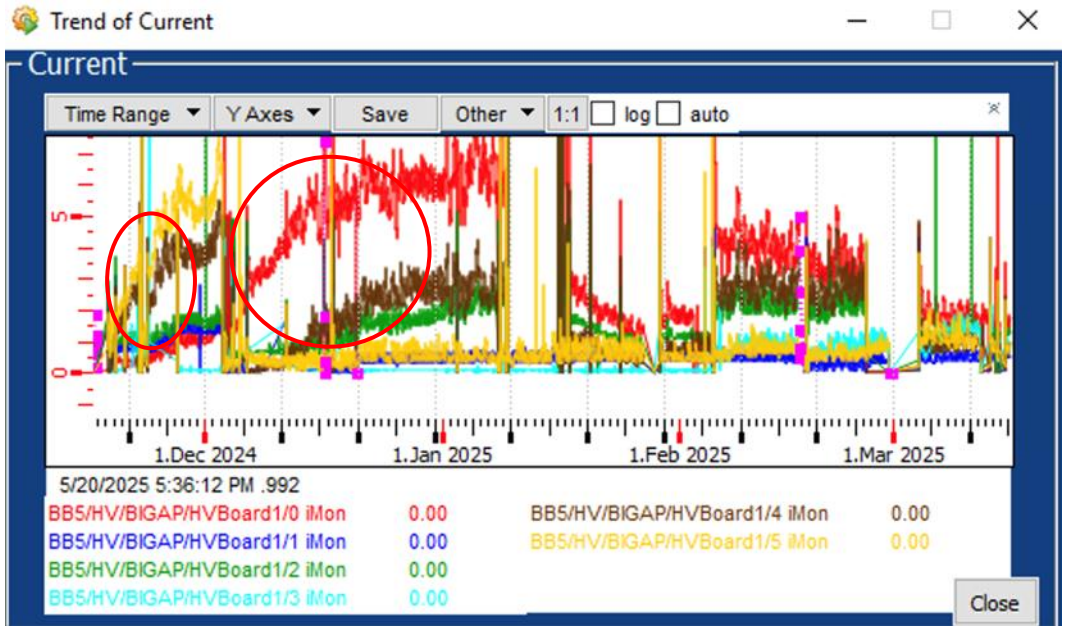
The gas volumes were flushed in parallel during the thermal cycles with low dew point dry air, applying 1.8 mbar overpressure at the gas inlet:

- 2 temperature sensors were inserted into the gas gaps to evaluate the delay in temperature variation and the attenuation of the cycle range
- At the end of each cycle, the thermal-equilibrium conditions were verified after 15 minutes
- Mechanical strength and gas tightness were monitored during the thermal cycles
- In the test performed at Frascati no gas leak was observed after the thermal cycles





A second problem [1]



Long-term current monitoring of 6 BI gas volumes at CERN from December 2024 till March 2025. The «current drifts» are circled

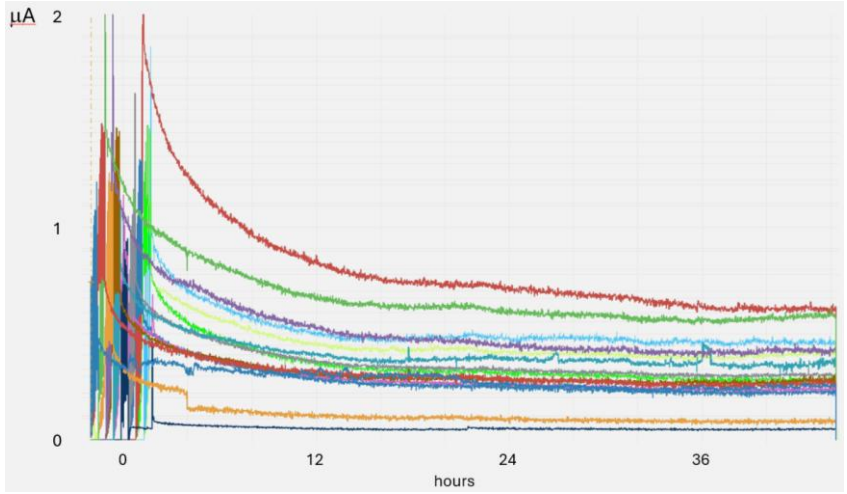
- A number of gas volumes, which were re-tested at CERN after being shipped from GTE (having passed the QA/QC tests at the firm) showed increasing absorbed current («current drift») some time after the start of the test at the operating voltage.
- Although the current which each ATLAS RPC gas volume is expected to absorb during the HL-LHC runs at high luminosity will be considerably higher than a few μA, a current significantly greater than the upper limit established for the QA/QC acceptance must be avoided in order to guarantee slower ageing for the gas volume.

- Due to this, the gas-volume production at GTE was stopped for some time in the spring of 2025 in order to study this issue very carefully and find a final reliable solution.

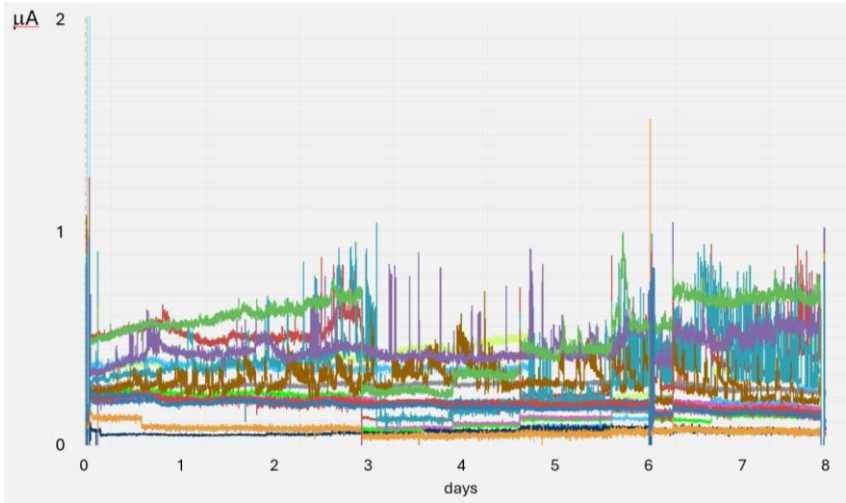
A second problem [2]

- The main reason for that behaviour was found to be related to unwanted glue intrusions on the inner edges of a number of gas volumes, after manual edge glueing. This modifies the edge profile inside the gas volume and enhances the magnitude of the electric field locally, leading to «hot spots» on the inner edge which may get worse with time.
- Also bakelite pre-washing with heptane, argon curing before oiling and an extended air-drying period were introduced in the production.
- In every gas volume with current drift, the measured current always reaches a «plateau» with time, which is however considerably greater than the maximum QA/QC acceptable value.
- The workaround was to extend the use of the automatic glue dispenser to edge glueing. Before then, it was used only for inner spacer glueing. This procedure was introduced in the summer of 2025.

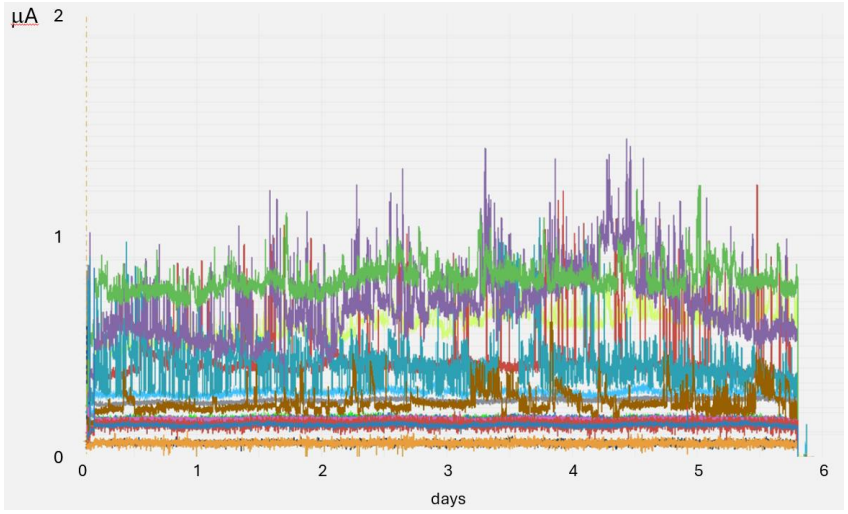
A second problem [3] – long-term current monitoring on 15 BIS 2B gas volumes



Beginning: 44 hs (16 - 18 September 2025)



Monitoring: 8 days (18 - 26 September 2025)



Monitoring: 6 days (26 September - 02 October 2025)

- This is a typical behaviour for the long-term current monitoring at 5.8 kV of BI gas volumes produced starting from the summer of 2025.
- In this specific batch (15 BIS 2B gas volumes) all the currents stayed lower than 1 µA during the whole test, well below the maximum value allowed for QA/QC acceptance.
- No more significant currents drifts were observed on the end-2025 and 2026 BI gas-volume production.

Gas-volume production status at General Tecnica Engineering (September 2026 update)

TYPE	ORDERED	EXTRA ORDER	TOTAL ORDER	ASSEMBLED	TO BE MADE	% MADE
BIL1A	168	9	177	170	7	96
BIL1B	126	8	134	89	45	66.4
BILC	24		24	0	24	0
BILE	6	1	7	6	1	85.7
BILX + BILZ	9	2	11	9	2	81.8
BILY	6	1	7	4	3	57.1
BILD + BILYB	12	2	14	10	4	71.4
BIS2A	51	14	65	62	3	95.4
BIS2B	240	6	246	162	84	65.9

The BI gas-volume production at GTE will be completed in 2027

Conclusions

- The assembly and the QA/QC qualification of the BI RPC gas volumes for extending the ATLAS RPC subdetector in view of Phase-II operation has been in progress since 2023
- Two potentially serious problems which showed up (gas leak, current drift) were solved by improving the glueing procedure of the gas volumes
- We are working to increase the qualification speed so that this task will be completed in due time for the installation in 2027

Backup

BIL and BIS dimensions

BIL-RPC

		Mechanics					Singlet		Panels		Gas gap		Bakelite	
Factory Name	TC Name	L (sliders included)	Total sliders	hole	W	chamber	L	W	L	W	L	W	L	W
BILA	680	2650	16	0	680	2634	2542	658	2511	658	2466	658	2432	652
BILB	520	2650	16	0	520	2634	2542	498	2511	498	2466	498	2432	492
BILC	680C	2216	16	0	680	2200	2108	658	2077	658	2032	658	1998	652
BILD	520C	2216	16	0	520	2200	2108	498	2077	498	2032	498	1998	492
BILE	680Z	2360	16	0	680	2344	2252	658	2221	658	2176	658	2142	652
BILX	520X	2650	916	900	520	1734	1642	498	1611	498	1566	498	1532	492
BILY	520Y	2650	136	120	520	2514	2422	498	2391	498	2346	498	2312	492
BILYB	520YB	2650	376	360	520	2274	2182	498	2151	498	2106	498	2072	492
BILZ	520CZ	2216	476	460	520	1740	1648	498	1617	498	1572	498	1538	492
V	520S	1440	16	0	520	1424	1332	498	1301	498	1256	498	1222	492
BILW	360S	1518	16	0	360	1502	1410	338	1379	338	1334	338	1300	332
W'	360SS	1840	16	0	360	1824	1732	338	1701	338	1656	338	1622	332

BIS-RPC

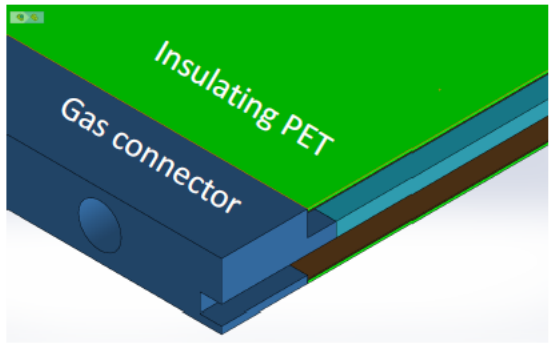
		Mechanics					Singlet		Panels		Gas gap		Bakelite	
Factory Name	TC Name	L (sliders included)	Total sliders	hole	W	chamber	L	W	L	W	L	W	L	
BIS1							1736	1072	1705	1072	1660	1072	1626	1066
BIS2-6							1736	890	1705	890	1660	890	1626	884

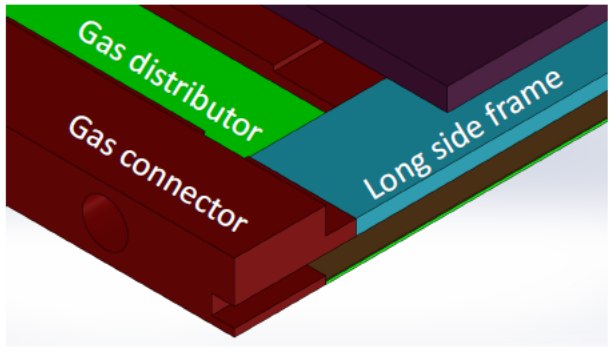
BIS78-RPC

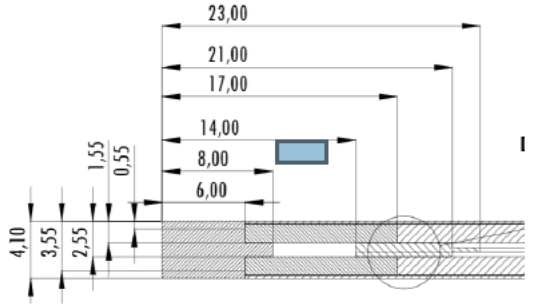
	Singlet		Panel eta		Panel phi		Gas Gap		Bakelite	
	L	W	L	W			L	W	L	W
BIS7L	1817	1157	1784	1157	1817	1124	1779	1107	1745	1101
BIS7S	1817	967	1784	967	1817	934	1779	917	1745	911
BIS8L							1773	367		
BIS8S							1653	367		

Length (L) and Width (W) in mm.

Details of BI-RPCs







Transversal view on the gas distributor side