Production and test of BI-RPC detectors for ATLAS Phase II upgrade

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The NEW 1mm RPC

The mechanical constraints and radiation environment posed by the ATLAS experiment layout in the Barrel Inner region required the design of a new thinner gauge RPC detector with a rate capability order of 10 kHz/cm_2.

The RPCs installed in the current ATLAS trigger system are characterized by gas gap and electrode thickness respectively of 2 mm and 1.8 mm. The maximum counting rate they can support is 1 kHz/cm_2 and are certified to work for 10 ATLAS years at a maximum rate of 100 Hz/cm_2.

Designing a detector in line with the new requirements was a great challenge

To meet the mechanical requirements, the gas gap was halved from 2 mm to 1 mm with a consequent positive contribution in terms of time resolution (1 ns → 0.4 ns) and rate capability, widely improved thanks to the introduction of new FE electronics.

Thinner gap → less charge in avalanche discharge !
Less charge on read-out panels

- increase the electric field moving the working point from 4.8 kV/mm to 5.8 kV/mm
  - increase in the force exerted between the electrodes
- Reduce the electrode thickness increase the charge collection efficiency;
- Improve the electronics FE to 2 fC threshold;

compromise is required

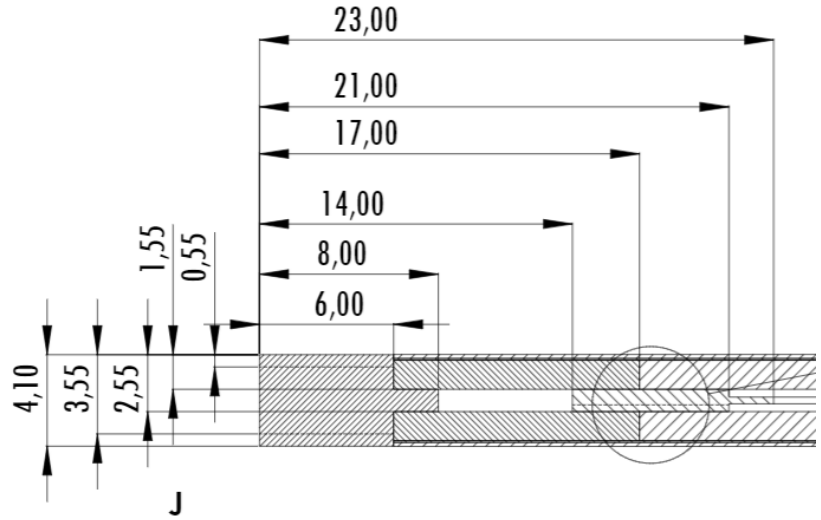
Lower High Voltage

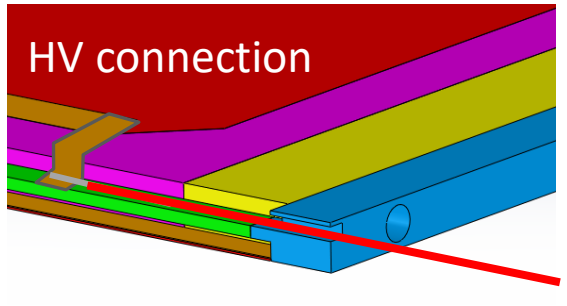
- Improvement of the high voltage connection;
- Reduction of the spark discharge on the read-out panels and power system.

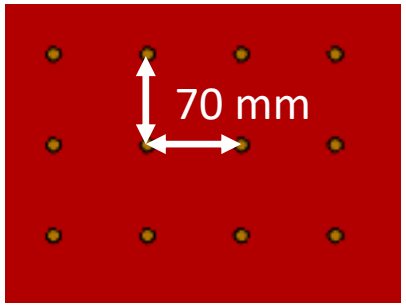
See presentation “The ATLAS RPC Phase II upgrade for High Luminosity LHC era” for upgrade details
https://indico.cern.ch/event/1291157/contributions/5876889/

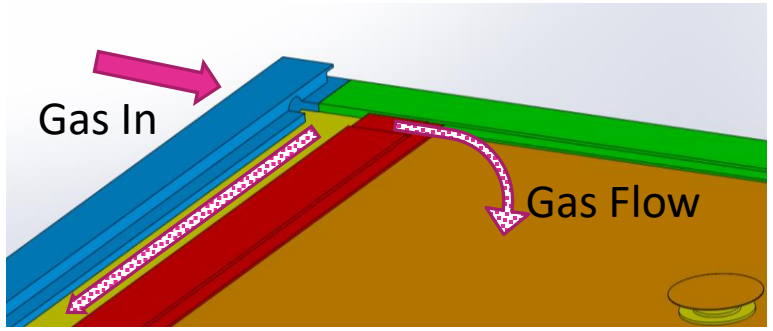
Gas volumes description

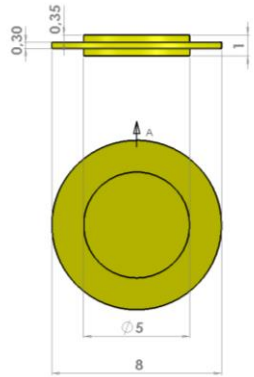
- **Many improvements with respect to ATLAS Legacy RPC detectors:** Gas gap thickness reduced from 2 mm to 1 mm: new polycarbonate pillars has been designed with 1 mm thickness and 1 cm diameter.
- **Electrodes thickness reduced from 1.8 mm to 1.5 mm:** after many test with 1.2 mm thick electrodes, the nominal thickness has been changed to 1.5 to reduce the electrode deformation due to electric field. The pillars matrix pitch has also been reduced to 7 cm x 7 cm to increase the pillars density.
- **Redesigned gas distribution**: with respect to ATLAS old RPC the new gas volume has an internal gas distributor composed by a channel 6 mm times 1 mm wide connected to the gas volume through small window (section 4.5 mm times 0.45 mm). Distributors are located along the short sides and have 2 gas inlet/outlets each
- **New HV cable connection**: the HV connection was moved from the top to the side of the gas volume to eliminate conflicts with read-out panels, the HV wire was replaced with a 1 mm, 18 kV rated wire.
- **Graphite layer**: causes a potential drop proportional to the calculated resistance between the HV connection point and the point where the discharge occurs. It was decided to reduce the layer resistivity since the detectors in the BI region will draw significant current. The best compromise between low resistivity and cluster size was evaluated to 320 kΩ/□;









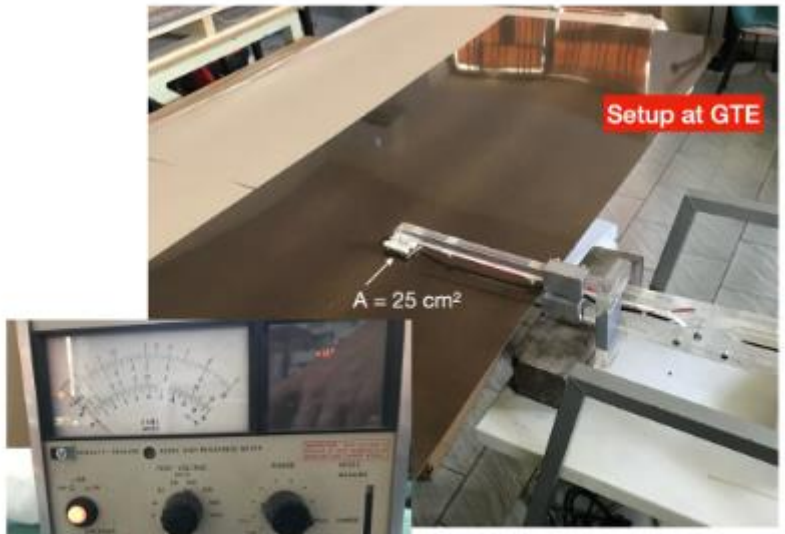


Bakelite plates

Bakelite plates are the main element of the gas volume, and their properties determine the response of the detector

- thickness and dielectric constant have a decisive impact on the charge collection efficiency on read-out panels.
- resistivity affect the rate capability of the detector according to the charge per count delivered in the gas

For the RPC-BI upgrade, to cope with the HL-LHC environment, a nominal value of 1.5 mm thickness and a resistivity of about 10^{10} Ωcm were chosen.



Bakelite plates are purchased from Teknemica s.r.l. with the following specifications:

- nominal thickness 1.50 mm + 0.00 mm - 0.18 mm;
- tolerance on linear dimensions ±0.5 mm;
- difference between the two diagonals less than 1 mm;
- bulk resistivity between 1.5 x 10^{10} Ωcm and 6 x 10^{10} Ωcm, measured at 20 °C and 50% of relative humidity.

After the first production batch the resistivity upper limit has been moved to 10^{11} Ωcm.

Resistivity is certified by the manufacturer and by INFN on sample plates, with a pico-amperometer or a high resistance mater connected to a pliers with large surface conductive electrodes. Value are corrected for temperature T effect with the formula $\rho_{20^\circ} = \rho_T e^{\frac{T-20}{8.1}}$

FAT and production of gas volumes

PRODUCTION

- About **700** gas-volume will be produced over 2 years 2023-2025 by **General Tecnica Engineering (GTE).**
  206 gas volume produced and tested of BIL A-B and BIS A-B type.
- **240** gas-volumes will be produced by **Max Plank Institute for Physics (MPI**) **in cooperation with industrial partners**:
  - Technology transfer to industry ongoing with two new additional manufacturers (Mirion Technologies and PTS Maschinenbau);
  - Small scale RPC produced and under test in GIF++ since April;
  - Preparation of real scale RPC production at external company;

  Serial production start planned for end 2024.
- **72** gas volume will be produced and qualified in **University of science and technology of China (USTC):**
  - Production procedures were developed
  - Small scale RPC produced and qualified
  - Planned delivery of produced gas volume to CERN for GIF++ tests

QUALIFICATION

Factory Acceptance Tests (FAT):

- Spacers gluing resists to a traction force of 30 N;
- Bakelite oiling: scratch test on dummy gas volume;
- Graphite layer: to check surface resistivity (350±100 kΩ/□);
- Gas tightness: p_{start}=3 mbar, Δp < 0.1 mbar after 3 min;
- Envelope dimensions
- Mechanical rigidity: injected air 1% of gas volume, after 1 min Δp > 2 mbar)
- Current leakage: measured with both electrodes at 7 kV on long sides. I_{leak} < 0.2 for BIS and I_{leak} < 0.3 µA for BIL
- Visual inspection
  - Absence of bubbles larger than 2-3 mm^2
  - Absence of scratches
- Quality control tests under the CERN-INFN responsibility:
  - Gas tightness test (Δp < 0.1 mbar after 3 minutes);
  - I-V Characterization;
  - Conditioning at GIF++ working at 4800 V in position D4.

  Tests performed by collaboration finds leaky gas volumes
  Investigations with stress tests ongoing!

Infrastructures for gas volume certification

HV splitter and sensors

Custom device to collects all the components for gas and high voltage distribution and monitoring sensors have been designed to test 24 gas volumes simultaneously. The device consists of:

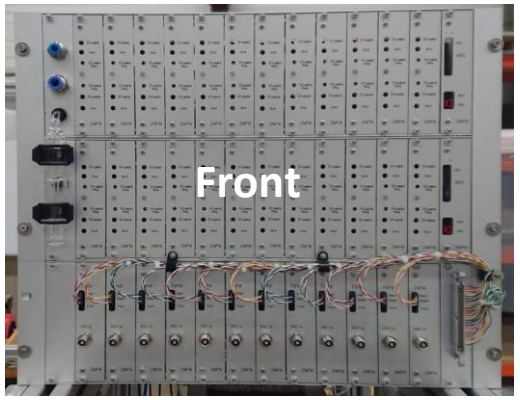
- 12 HV splitters with 24 100 kΩ shunt resistors;
- 24 Gas sensor boards equipped with Omron D6FP0010A and signaling LED with two adjustable threshold;
- 2 Mainboards providing for sensors power supply and signal concentrator.

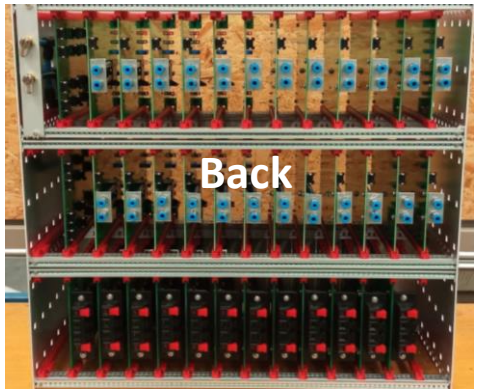
5 instrumented crates have been produced from INFN in collaboration with Max Planck Institute and USTC

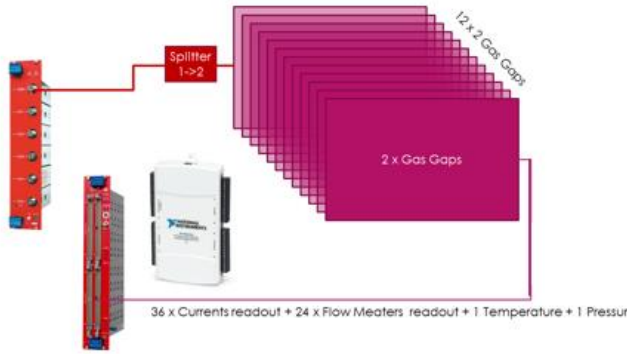
Trolley and packs

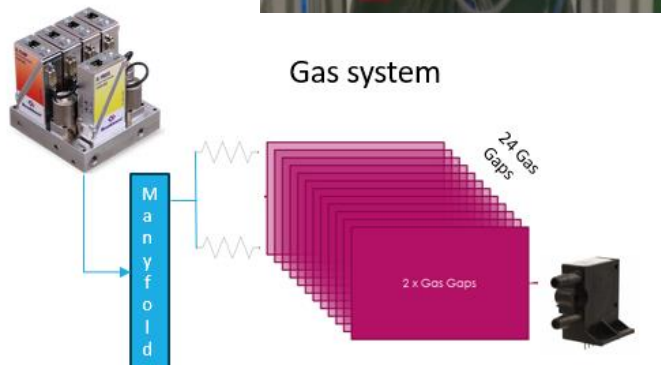
Two trolleys for each production site have been produced for the main gas volume form factors (BIL - BIS). The trolley can host the HV splitter and sensors crate and are equipped with gas manifolds.

Gas volume are delivered to different production sites closed in packs made of pre-bent aluminum honeycomb plates equipped with shock sensors of different sensitivity. There is a pack for each gas volume form factor.







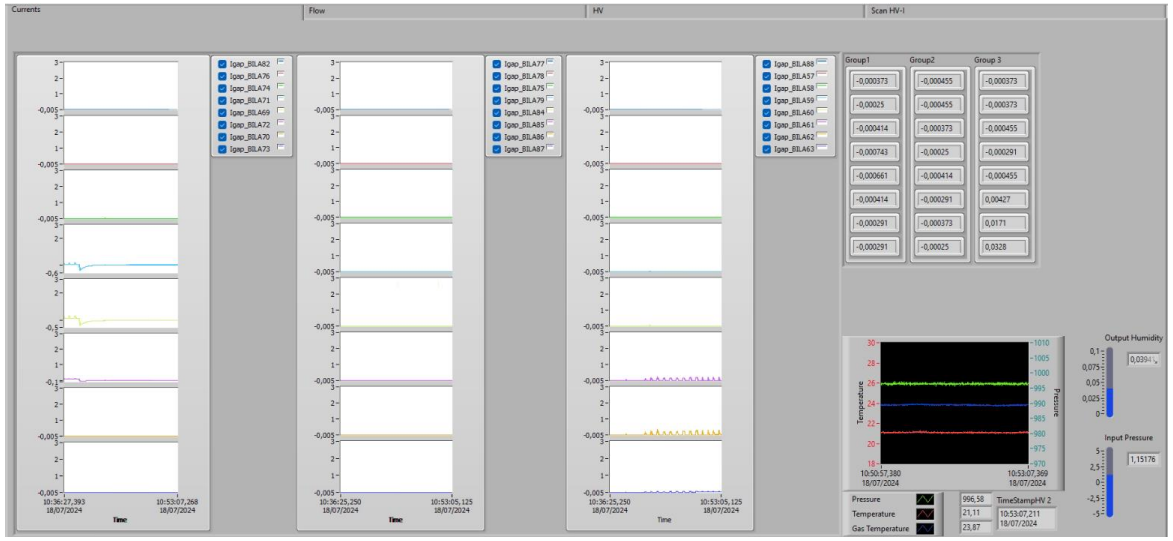


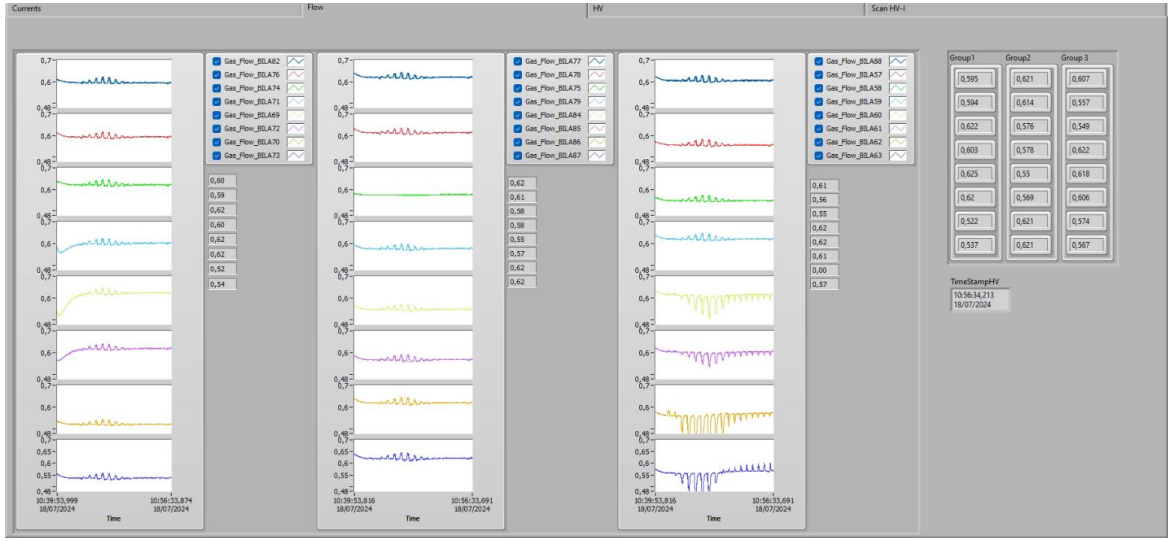
Gas volume qualification
DCS monitor

A data control system has been developed in LabView to monitor and perform I-V characterization of gas volume.
The software interfaces with sensors through two National Instruments USB-6218 ADC boards and samples signals at 0.3 sps sampling rate. Data are typically saved under sampled at 0.03 sps.
Different parameters are monitored:

- Gas volume absorbed current (2 nA sensitivity)
- Gas flux out of each gas volume (0,08 l/h margin error without calibration)
- Gas temperature at the manifold input
- Room temperature
- Humidity
- Atmospheric Pressure
- Pressure of the gas at the manifold input

Transient induced signals allow the system map to be verified.
The gas sensors have sufficient sensitivity to observe the small flow variation caused by the deformation of the electrodes during voltage variations even with a Rump Up of only 30 V/s.





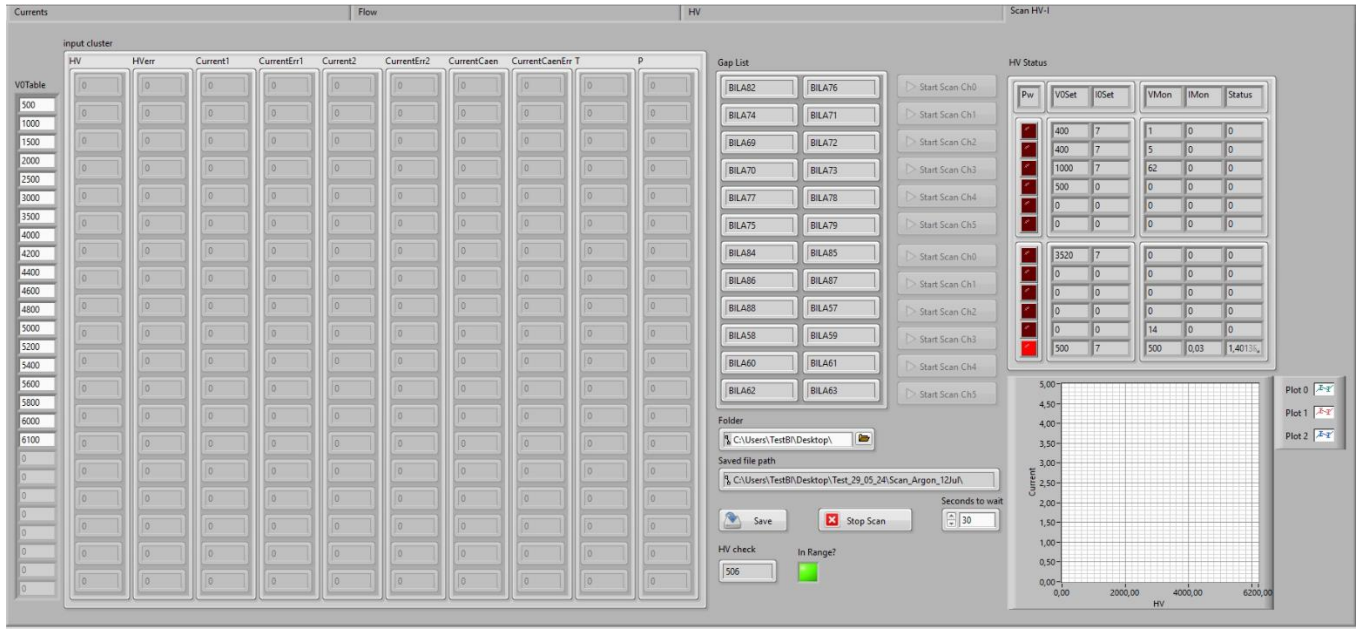
I-V Characterization

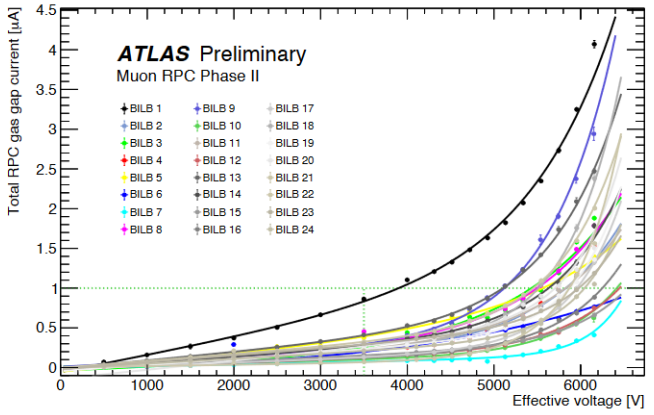
Each gas volume is characterized by performing a voltage scan and measuring the current flowing inside the gas gap through a 100 kΩ resistor in series with the device.
The scan is carried out in 500 V steps up to 4 kV and 200 V steps up to a voltage of 6.2 kV.
The effective voltage HV_{eff} is calculated by rescaling the voltage applied by the generator HV_{gen} for temperature and pressure according to

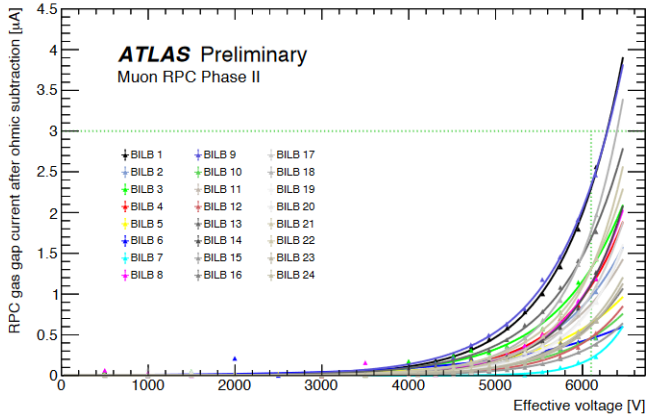
$$HV_{eff} = HV_{gen}\frac{T}{T_0}\frac{P_0}{P}$$

with $P_0 = 1010\,mbar$ and $T_0 = 293\,k$, lab reference value.
Acceptance limits: max 3 µA at 6.1kV after ohmic subtraction and max 1 µA at 3.5kV. Ohmic contribution evaluated with a linear fit in the range [0,3] kV.

The control software allows to carry out automatic scans of pairs of gas volumes, saving the data in a format compatible with the production database





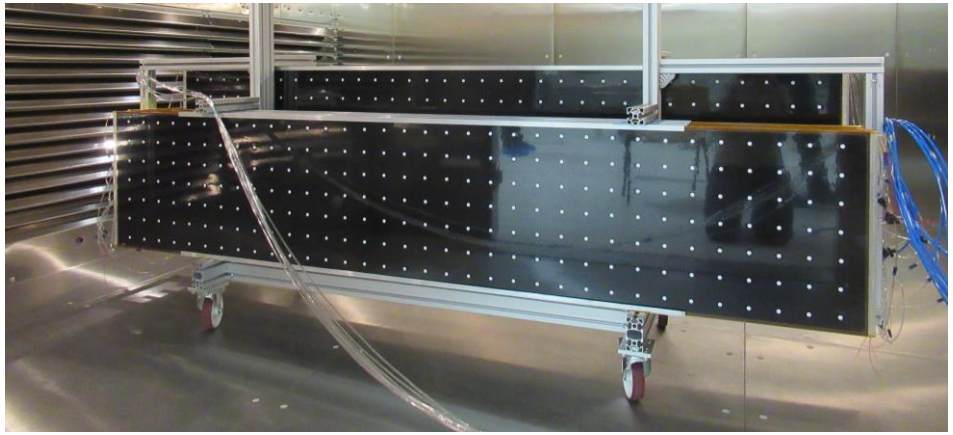


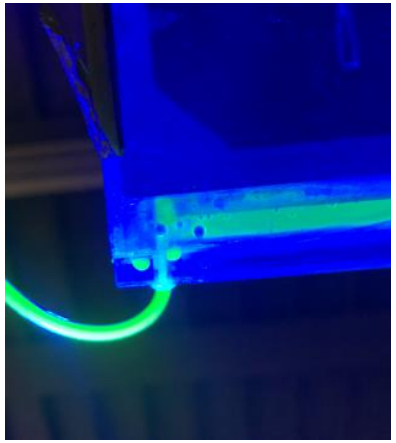
Hermetic sealing and investigation on mechanical property

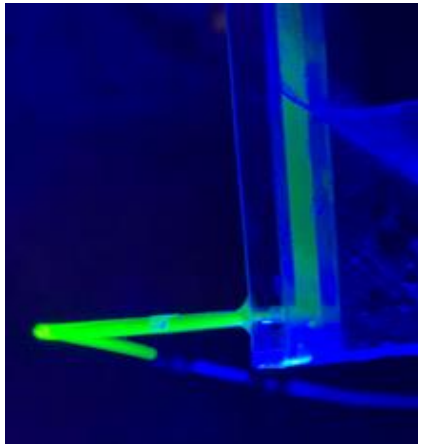
After the production of the first two gas volume batch, quality control tests revealed gas leaks.
The mechanical property and the hermetic sealing of the gas volumes have been investigated. Special tools have been developed to investigated weak points of the assembly procedure.

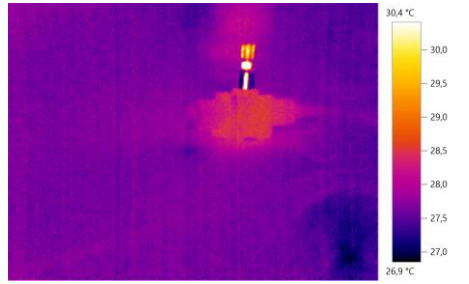
Gas volumes were exposed to mechanical stress tests through thermal expansion cycles. The measurements were carried out on 12 samples (8 at the ITk thermal chamber at INFN national laboratories of Frascati, 4 at the thermal chamber of the University of Cambridge). Cycles in the range [-20,30] °C was repeated multiple times checking for appearance of leaks. Tests in Cambridge still in progress to increase statistics.

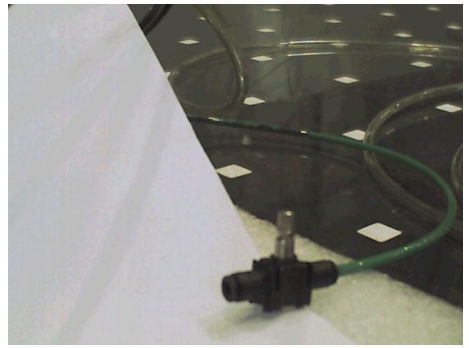
New tools to find gas leaks were introduced. Florescent tracer made it possible to identify the critical points. Detection tests through a thermal camera have been carried out.











Read-out panels production

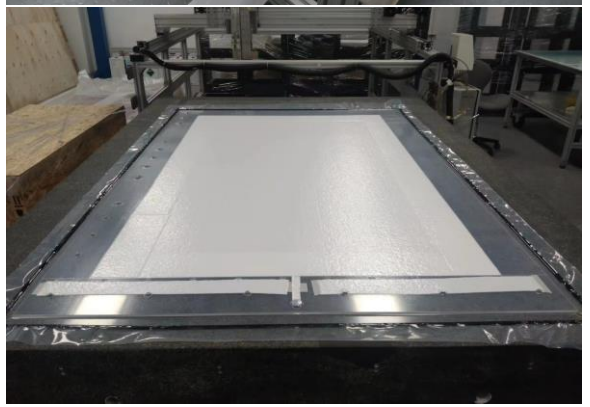
New read-out panels consisting of 3 layers glued with Araldite 2011 glue:

- **One layer of aramid paper honeycomb 3 mm thick;**
- **Two layers of copper-plated FR4 0.4 mm thick on which read-out strips are produced through a photoengraving process.**

Cosenza site will produce about 1000 readout panels using the vacuum bag on a granite table technique for strip panel assembly
→ maximum production rate = 4 BIL or 2 BOM panels/day.

Production chain:

- Single side copper clad halogen free FR4 plates produced by MDT srl (Milan, IT);
- Single side copper clad FR4 photo-incision by Eltos (Arezzo, IT)
- Paper honeycomb impregnated with phenolic resin produced by IMATEC srl (Milan, IT).
- Panels assembly and QC tests in Cosenza
- Dedicated transport from Cosenza to CERN in batch of 90 strip panels about every 2 months.



Production status: 330 BIL strip panels corresponding to 49.1% of the total BIL has been produced. Transferred to CERN 38.7%.

All BIS panels are produced in China, about 100 BIS1 and 500 BIS2-6 types, using the vacuum bag on a granite table technique and qualified in USTC.

Production status: 142 BIS 2-6 panels produced; 2 panels rejected; production rate 4 panels/day

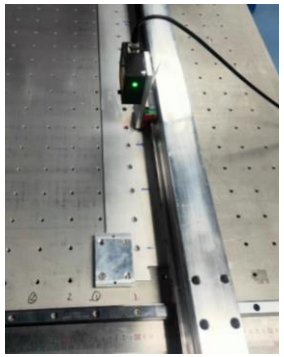
Read-out panels qualification

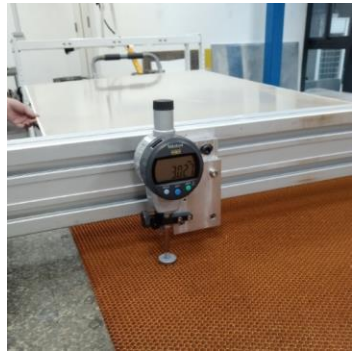
Produced panels and components are qualified with test on

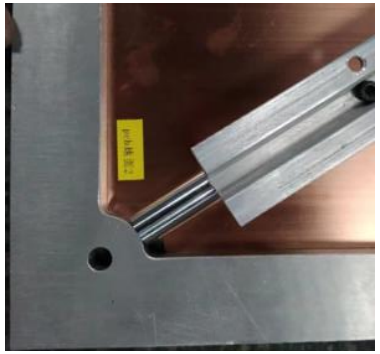
- Aramide paper thickness with gauge comparator;
- FR4 single side copper clad and assembled panel thickness:
  - Cosenza with gauge comparators sampling the surface on a 7 cm x 7 cm pitch matrix;
  - China with a laser sensor sliding along a rail taking data continuously; sampling point (7 cm interval) achieved by a mask with holes;
- Dimensional measurements with in 2 points by means of digital micrometer which measure the deviation from stain steel reference bars.

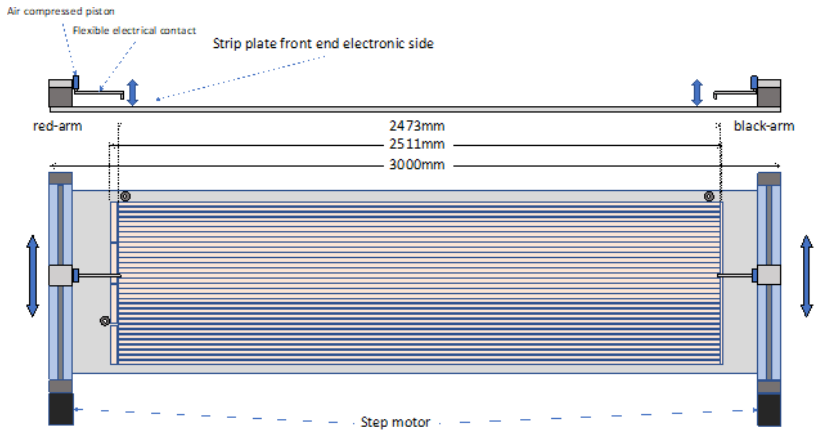
Tolerance on length and width of the FR4 plates are 0.5 mm and 0.3 mm, respectively, while those of the strip panel is 2.0 mm and 1.0 mm respectively. Tolerance on thickness is 0.16 mm.

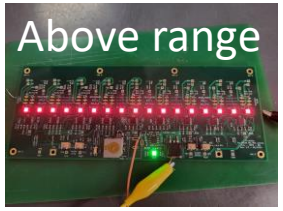
SMD matching resistors are soldered to the ends of each strip and each decoupling wire. To verify the value of the resistors, a 17-channels test board was developed and produced by Bologna.

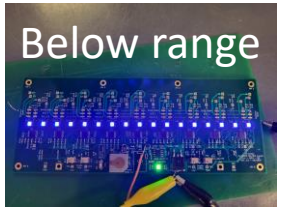












FE Electronics status and qualification

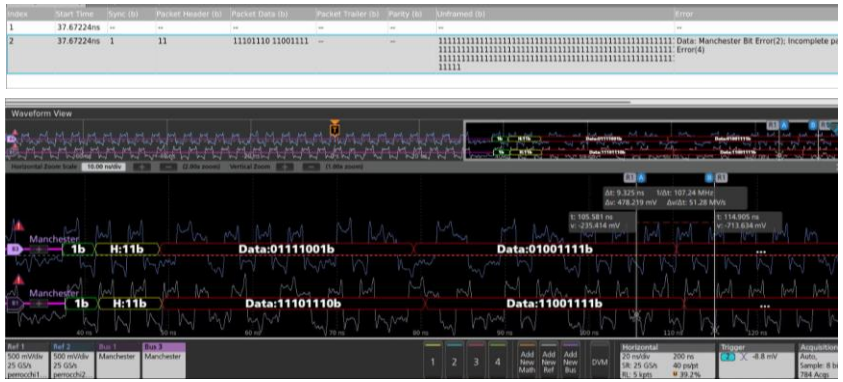
For BI-RPC, an ASIC chip has been developed by INFN Rome Tor Vergata integrating preamplifier, discriminator and TDC. Main features of the FE board are: detectable signal of **1-2 fC**; Voltage Controlled Oscillator (VCO) defining the TDC time resolution (**50-150 ps RMS**); data encoded using the Manchester code.

FE- board test is shared between Rome 2, USTC and HK. A test station has been designed and is under construction in Rome 2. A test signal will be sent on each individual channel while the output will be analyzed under different power conditions through**:**

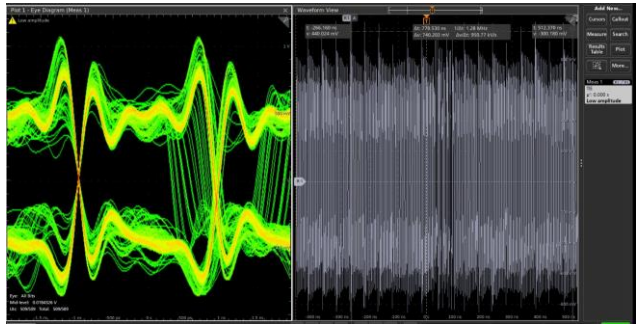
- Digital acquisition of Manchester coded waveforms for performance qualification
- Analog acquisition whit LVDS probe from each channel for signal integrity (on sample boards)

Almost all the equipment has been purchased and is in the programming phase. The board will be hosted during the test in a fixture being produced by INGUN Prüfmittelbau GmbH and customized in collaboration with MOTECO Swiss GmbH (ready in 12 weeks).

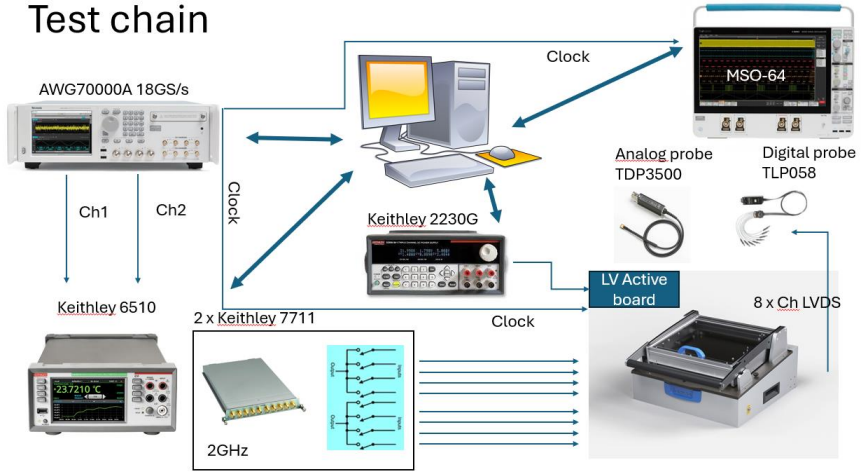
Manchester decoding of preliminary waveform



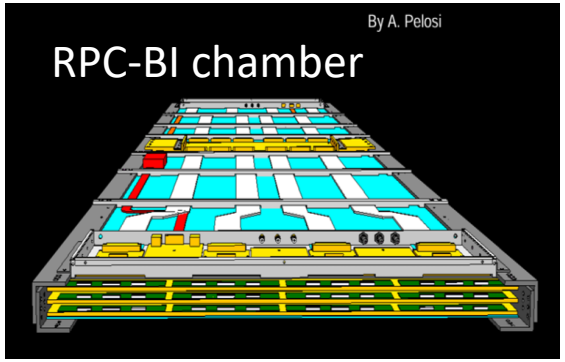
Eye diagram of preliminary waveform with advanced jitter analysis



Test chain



Singlets and Chambers production



The ATLAS RPC-BI chamber consists of 3 independent singlets sharing the same mechanics and services. Singlets and chambers (Triplets) will be assembled in different production sites:

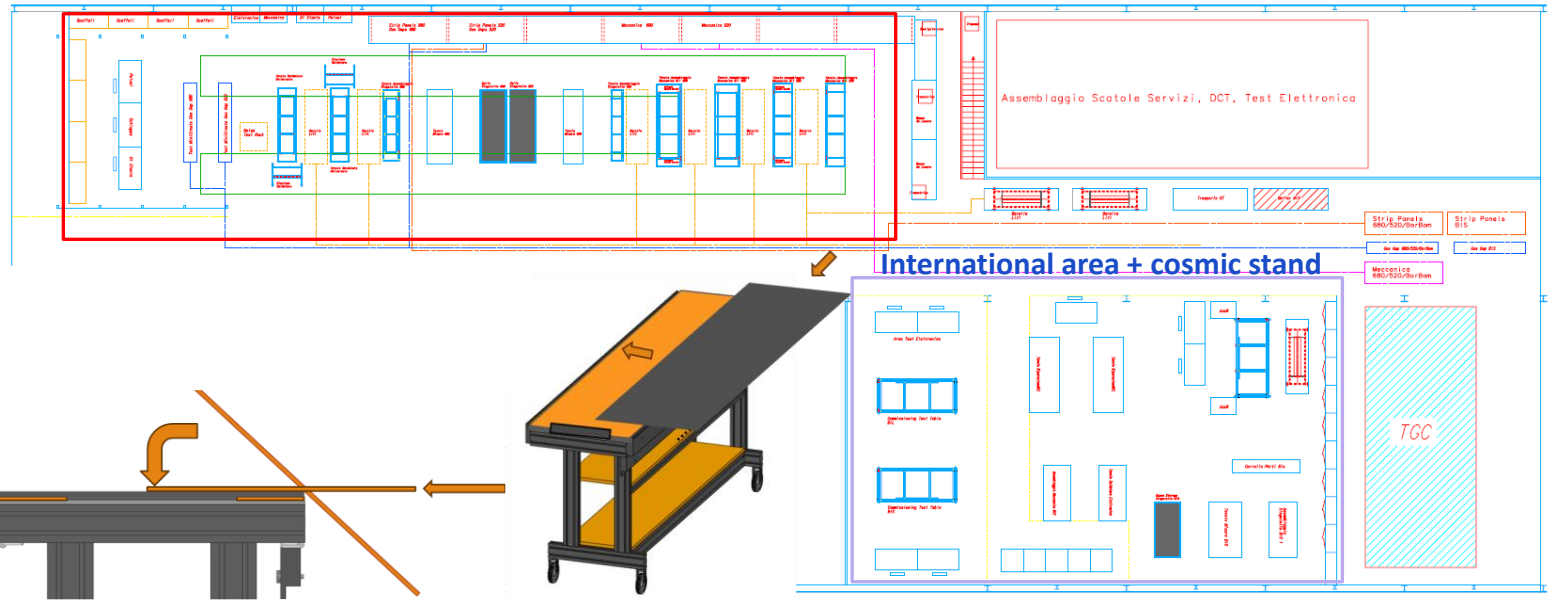
- INFN will assemble and tests all BIL singlets and triplets excluding S7 + 50% BOM/BOR + 50% BIL-7 in the CERN-BB5 site;
- MPI will assemble and test all BIS triplets in Munich;
- USTC: BIS singlets, 50% BIL-7 + BIL-9 singlets and triplets; BIS singlets are delivered to Munich for triplets production.
- Hong Kong University: 25% BOR/BOM triplets;
- Istinye University, Turkey: 25% BOR/BOM singlets and triplets.

INFN production line is almost ready. Special tables and tools are ready for singlet assembly. Singlets are tested for envelop dimension with micrometric gauge comparators and HV leak before FE-boards welding.

A cosmic ray test station has been designed and is in construction to perform QC tests on singlets and triplets.

Test stands are in preparation also in other institutes for BIS certification.

INFN production line

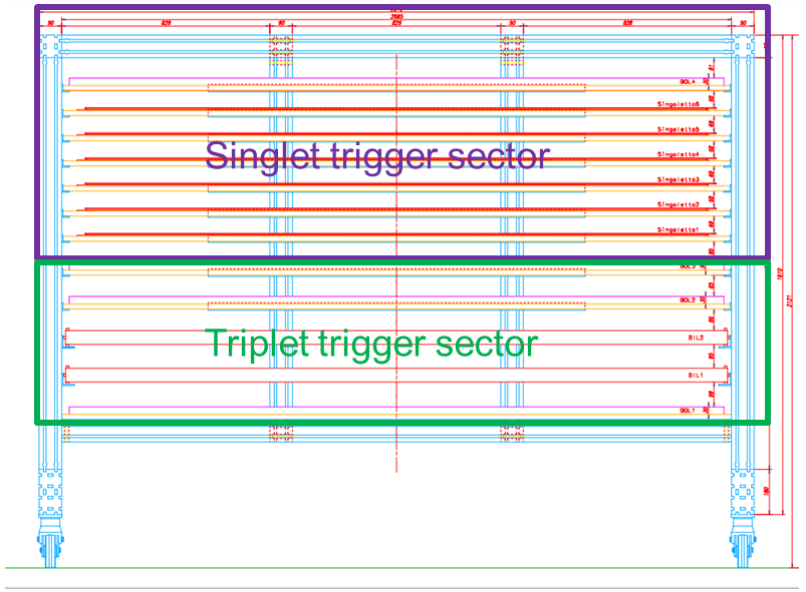


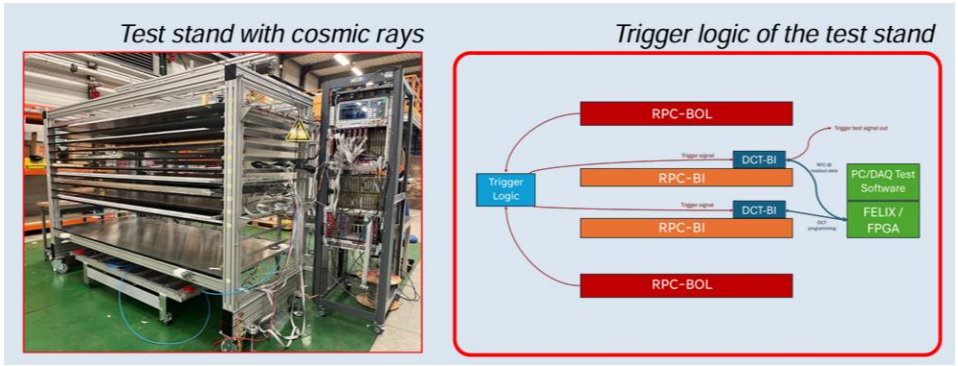
Cosmic ray test stand

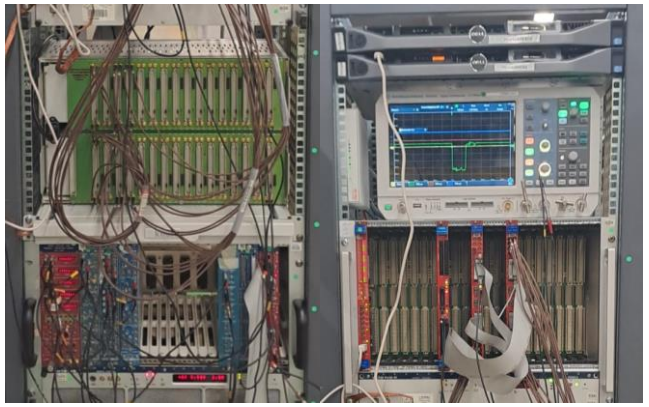
A cosmic ray test stand is in preparation at the INFN BIL production line in CERN-BB5. The infrastructure will certify all RPC BIL singlets and triplets produced by the Italian community: about 100 BIL triplets and 300 singlets, plus BOR/BOM chambers.
Trigger detectors are 4 x RPC BOL Atlas Singlets (2 mm RPC detectors) with active area of 2430 x 1010 mm each and a total of 448 Channels. This solution allows to perform integration tests of new BMBO-DCT on ATLAS Legacy detectors.

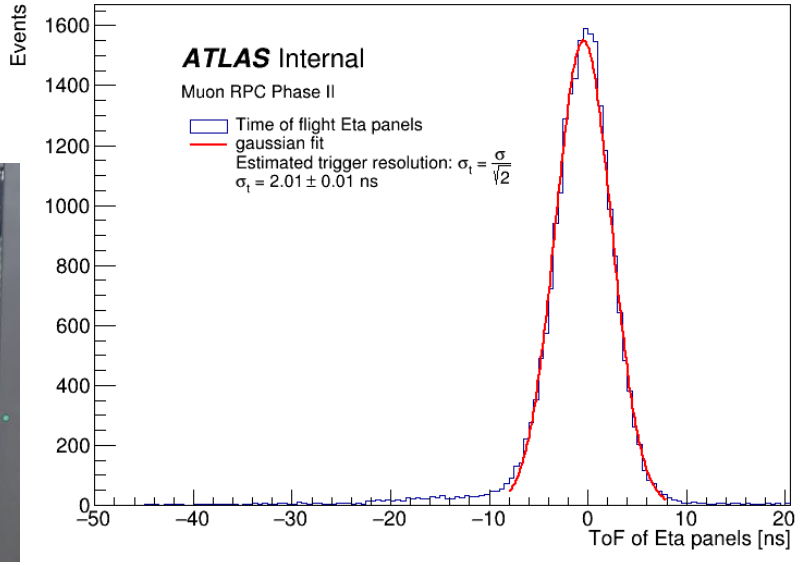
Trigger chambers Read out system is based on TTL translator with NIM fast OR for each FE board (Granularity 1x1 Chs → 8 x 8 Chs)
Trigger Logic: implemented on CAEN V2495 Altera Cyclon V Translator/Logic Unit

All trigger tyles have been installed and acquired. Trigger has been implemented on 2/4 Trigger tiles and tested for timing performance, firmware using all trigger tyles for RoIs definition under development.







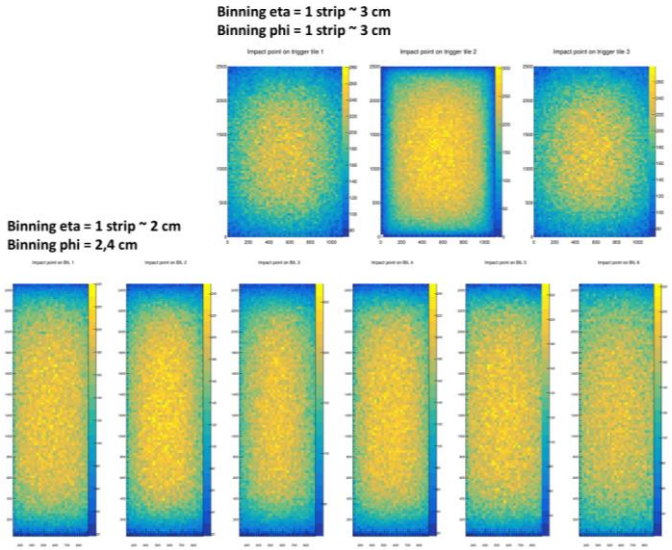


QC tests on Singlets and Triplets

Different tests will be performed on singlets and Triplets to qualify all the figure of merit. The cosmic stand allows to test up to 6 Singlets and 2 triplets simultaneously.

The FPGA allows to implements up to 130 topological trigger configurations to comply with different chambers form factor. One of the trigger tiles could be read-out directly by the BMBO-DCT to improve tracking capabilities.

A preliminary trigger rate have been simulated implementing a triple coincidence to estimate the qualification schedule. We expect about 170 entries/hour in $\Delta\eta \times \Delta\varphi$ about 5 cm^2



Test type	RPC	Trigger	Scan Over	Output Plot	Runs
Performance	Singlet	No	HV	HV-I curve	1
Performance	Singlet	Cosmic	• HV@Fixed Vth • Vth@Fixed HV	Efficiency; Cluster size; TOT; σ_x, σ_y @Working point	8 + 1 high Statistics 6 + 1 high Statistics
Noise	Singlet	Random	• HV@Fixed Vth • Vth@Fixed HV	Rate vs HV	• 8 + 1 high Statistics • 6+ 1 high Statistics
Performane	Singlet	Cosmics	Fixed HV and Vth	Tomography	1 Very High Statistics
Noise	Triplet	Random	2 HV OFF & 1 HV ON	Rate @Working point	3 + 1 (All ON)
Noise	Triplet	Cosmics	Vth – Fixed HV@50% Working point	Efficiency, Cluster size, ToT	3 High Statistics
Noise	Triplet	Auto	Vth @ Fixed HV	Efficiency, Coincidence Rate	6 + 1 High Statistics

Conclusions

✓ Production of the RPCs for Phase II upgrade of the Atlas spectrometer has begun.
All production sites have created assembly lines and infrastructures for the storage and qualification of components.

✓ **Quality control protocols** have been established for almost all components.

✓ **Production of gas volumes** has already started in GTE and quality controls are underway.
New partners and manufacturers are completing the final steps to qualify as gas volume producers in Germany and China.

✓ **Production of readout panels** started in both Cosenza and China sites. BIL readout panels production 50% complete; BIS2-6 readout panels production 30% complete.

✓ **FE-board test stand** in preparation, preliminary tests concluded, 12 weeks for fixture customization.

✓ **Cosmic ray stand** almost ready in CERN-BB5 production site, double coincidence large area trigger just available

Back-up slides

Production Database

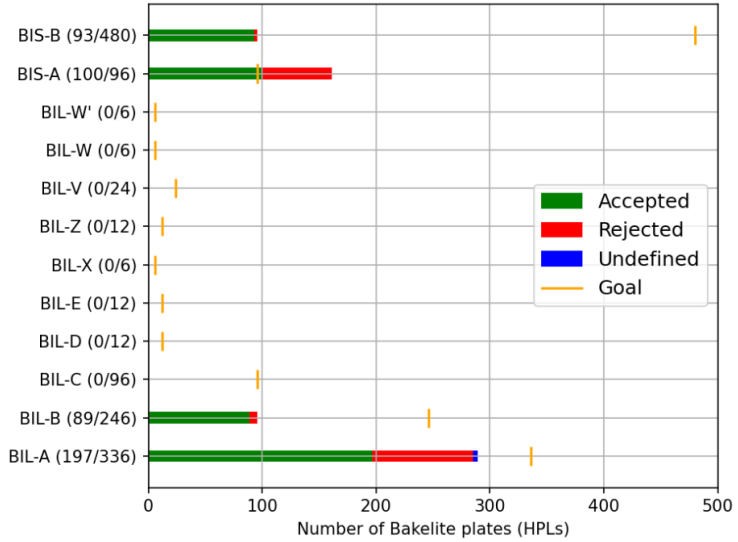
All components are identified in the production database with an ID code at the time of purchase or manufacturing.

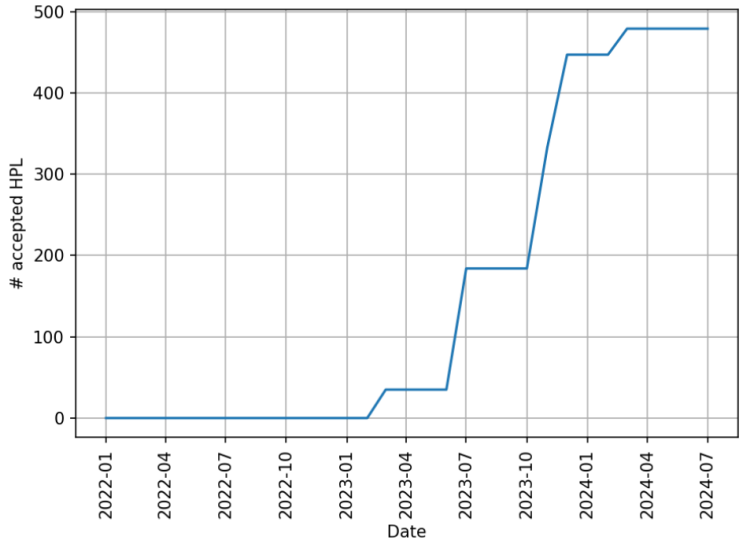
Database contains results of quality control tests and allows you to trace the components in the various production sites. Data are stored in .json format and can be plotted through embedded scripts.

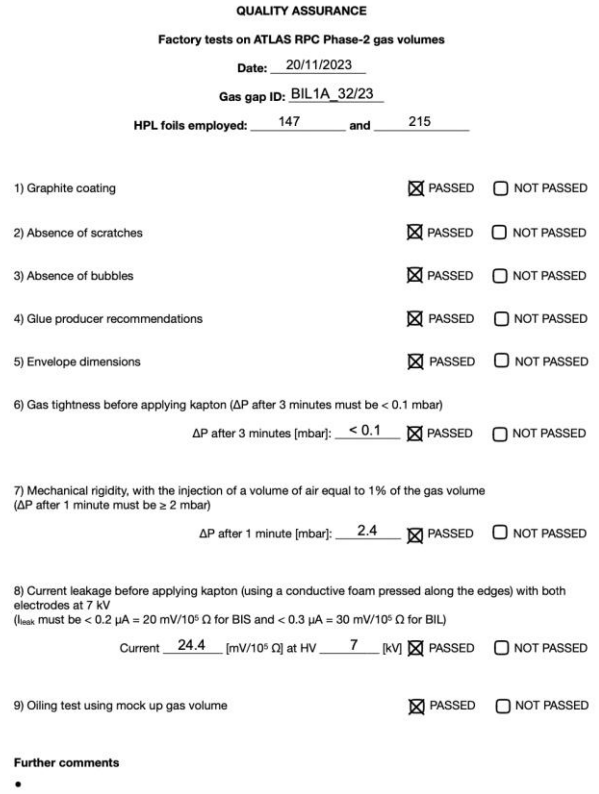
An overview of the production progress is also available.

Status:

- Management of panels and gas gaps ready;
- next step: implement singlets;
- Long-term: triplets, chambers.







QUALITY ASSURANCE

Factory tests on ATLAS RPC Phase-2 gas volumes

Date: 20/11/2023

Gas gap ID: BIL1A_32/23

HPL foils employed: 147 **and** 215

1) Graphite coating ☒ PASSED ☐ NOT PASSED

2) Absence of scratches ☒ PASSED ☐ NOT PASSED

3) Absence of bubbles ☒ PASSED ☐ NOT PASSED

4) Glue producer recommendations ☒ PASSED ☐ NOT PASSED

5) Envelope dimensions ☒ PASSED ☐ NOT PASSED

6) Gas tightness before applying kapton (ΔP after 3 minutes must be < 0.1 mbar)

ΔP after 3 minutes [mbar]: < 0.1 ☒ PASSED ☐ NOT PASSED

7) Mechanical rigidity, with the injection of a volume of air equal to 1% of the gas volume (ΔP after 1 minute must be ≥ 2 mbar)

ΔP after 1 minute [mbar]: 2.4 ☒ PASSED ☐ NOT PASSED

8) Current leakage before applying kapton (using a conductive foam pressed along the edges) with both electrodes at 7 kV
(I_{leak} must be < 0.2 μA = 20 mV/10⁵ Ω for BIS and < 0.3 μA = 30 mV/10⁵ Ω for BIL)

Current 24.4 [mV/10⁵ Ω] at HV 7 [kV] ☒ PASSED ☐ NOT PASSED

9) Oiling test using mock up gas volume ☒ PASSED ☐ NOT PASSED

Further comments

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Factory Acceptance Tests Documents