Production and test of RPC detectors for the large sectors of the ATLAS Inner Barrel (BIL) Phase II upgrade

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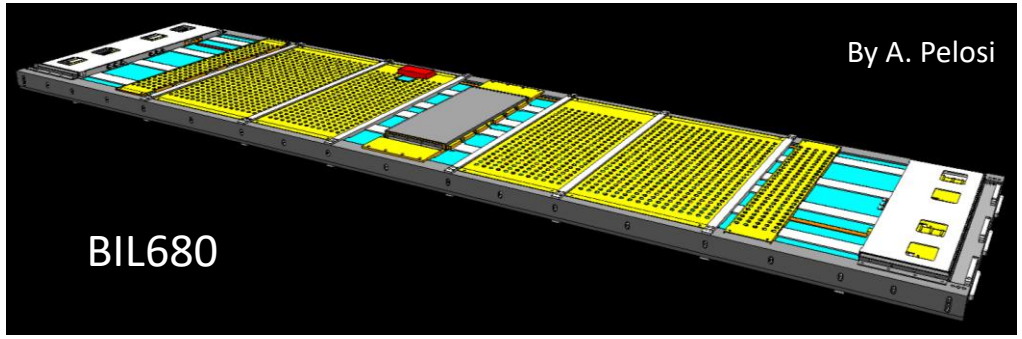
on behalf of the ATLAS Collaboration

XVII Conference on Resistive Plate Chambers and Related Detectors

New generation RPC (1/2)

- 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 they have been certified to work for 10 ATLAS years at a maximum rate of 100 Hz/cm^2.
- The new RPC layer to install in the muon spectrometer during LS3 (2026-2029) has to cope two principal constraints: rate capability order of 10 kHz/cm^2 and chamber thickness of 70 mm in which 3 independent detectors are placed, each of them made of a gas gap sandwiched between two readout panels with strips equally oriented and the FEE soldered only on one side of each panel. In the singlet the two panels are assembled with the FEE on opposite side. The strip gives the eta coordinate, while the difference in time arrival of the signal to FEE is proportional to the orthogonal coordinate (named phi).
- **Designing a detector in line with these requirements has been a great challenge**

New generation RPC (2/2)



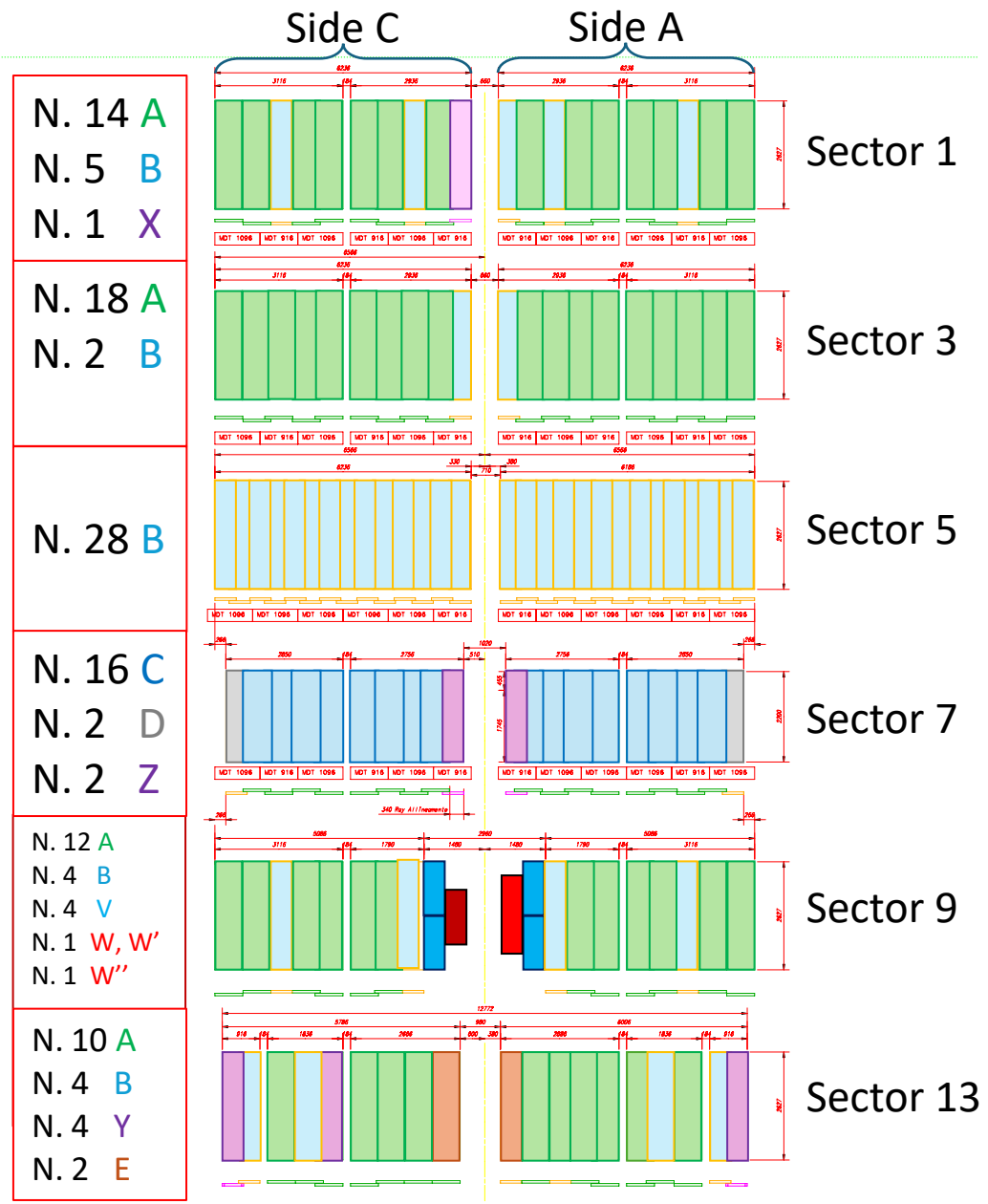
- To meet these requirements
  - the gas-gap width has been halved from 2 mm to 1 mm
    - Advantages: better time resolution (1 ns → 0.4 ns) and higher rate capability
    - Disadvantages: less charge in avalanche discharge and consequently on the readout strip -> working point from 4.8 kV/mm to 5.8 kV/mm
  - the electrode thickness has been reduced from 1.8 mm to 1.5 mm to increase the charge collection efficiency;
  - the electronics FE threshold has been reduced to 2 fC;
- With a gas gap of 1 mm and a wp of 5.8 kV/mm
  - the high-voltage connections are improved;
  - the charge produced during discharge is reduced with the evident benefit for the FEE and the power system.
- See presentation “The ATLAS RPC Phase II upgrade for High Luminosity LHC era” for upgrade details https://indico.cern.ch/event/1354736/contributions/6098757/

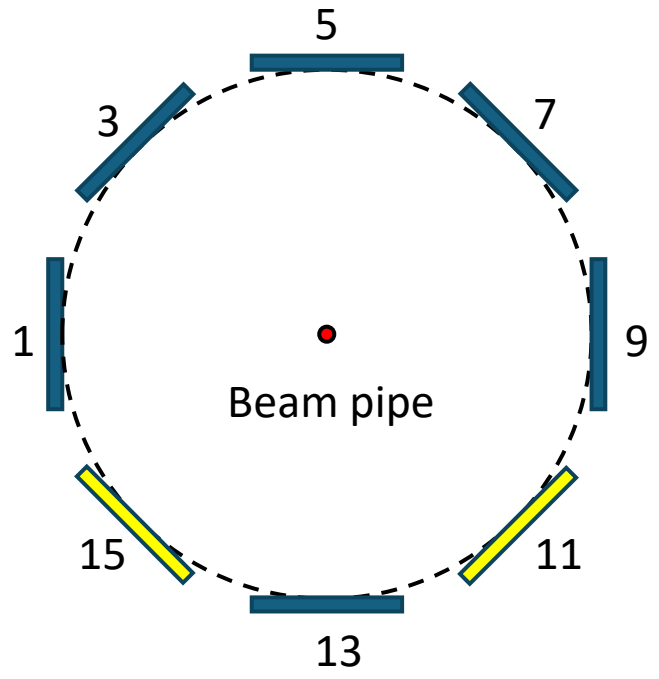
RPC geometries in the inner barrel sectors 1, 3, 5, 7, 9, 13

N. of ch.	Type	dimensions (WxL mm)
N. 56	A	680x2650
N. 41	B	520x2650
N. 4	Y	520x2530
N. 1	X	520x1750
N. 16	C	680x2216
N. 2	D	520x2216
N. 2	Z	520x1756
N. 4	V	520x1440
N. 1	W	360x1518
N. 1	W’	360x1840
N. 1	W’’	520x2290

Naming on TCn drawings

A = 680; B = 520; C = 680C;
D = 520C; E = 680Z; V = 520S;
X = 520X; Y = 520Y; Z = 520CZ;
W = 360S; W’ = 360SS;
W’’ = 520YB

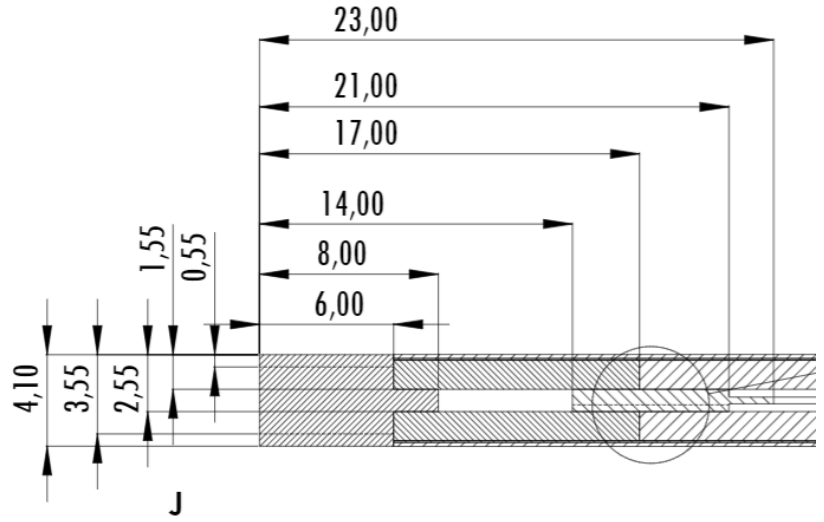


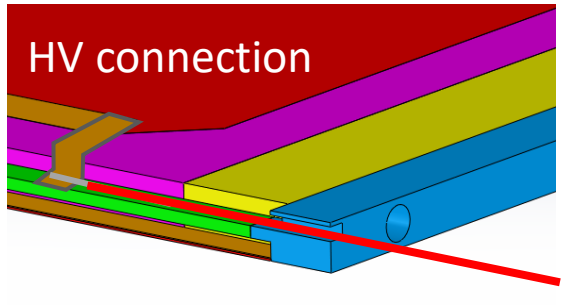


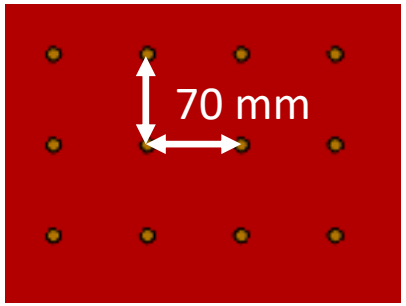
Sectors 11 and 15 under study

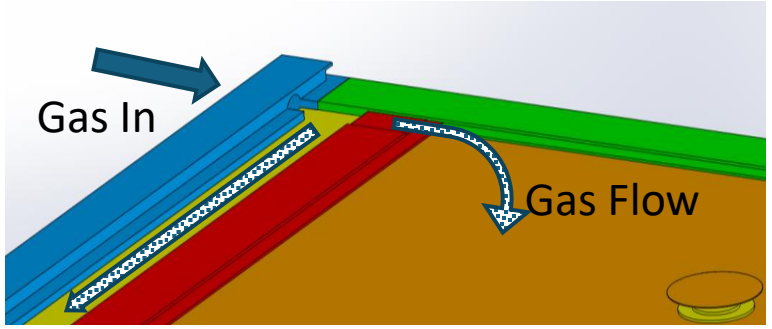
Gas-volume description

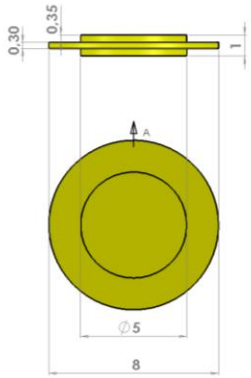
- **Improvements with respect to ATLAS Legacy RPC detectors**
  - Polycarbonate pillars with 1 mm thickness and 1 cm diameter
  - Pillars matrix pitch reduced to 7 x 7 cm to reduce electrode deformation
  - Gas distributor composed of a channel 6 mm large, and 1 mm thick connected to the gas volume through a small window. Distributors are located along the short sides and have 2 gas inlet/outlets each
  - The HV connection was moved from the top to the side of the gas volume to eliminate conflicts with the read-out panels, the HV wire was replaced with a 1 mm, 18 kV rated wire
  - The 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/□;







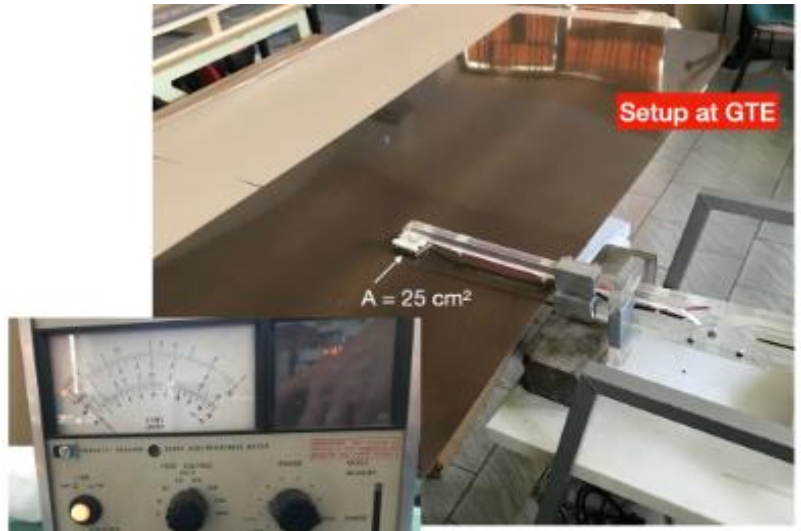




Bakelite plates

- 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^{11} Ω cm 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} Ω cm and 10^{11} Ω cm, measured at 20 °C and 50% relative humidity.
- The resistivity is certified by the manufacturer and INFN at random, with a picoammeter or a high-resistance material connected to a clamp with large surface conductive electrodes. The values are corrected for the effect of the temperature T using the formula

$$\rho_{20^\circ} = \rho_T e^{\frac{T-20}{8.1}}$$



FAT and production of gas volumes (1/2)

Factory Acceptance Tests

- Spacer gluing must resist 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 and absence of scratches

- Quality-control tests under the CERN-INFN responsibility:
  - Gas-tightness test (Δ*p* < 0.1 mbar after 3 minutes @ 3mbar overpressure);
  - I-V characterization;
  - Conditioning at GIF++ working at 4800 V in position D4.

FAT and production of gas volumes (2/2)

PRODUCTION

- About **700** gas-volume are being 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 so far.

For all the details concerning the production of BIS-RPCs, see F. Fallavollita and G. Proto's talks

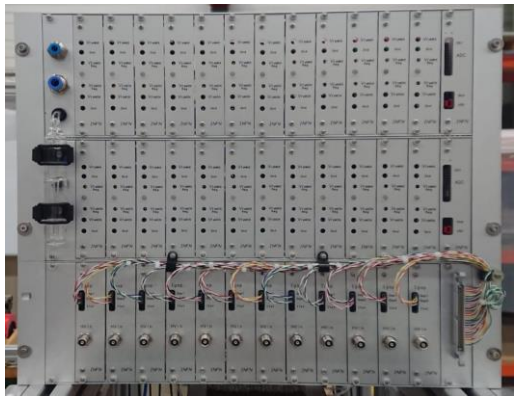
Infrastructures for gas volume certification

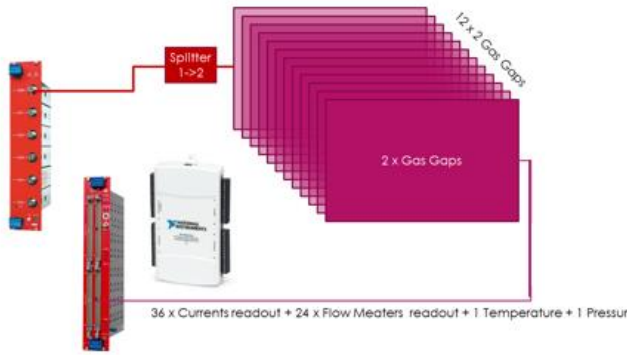
Crate

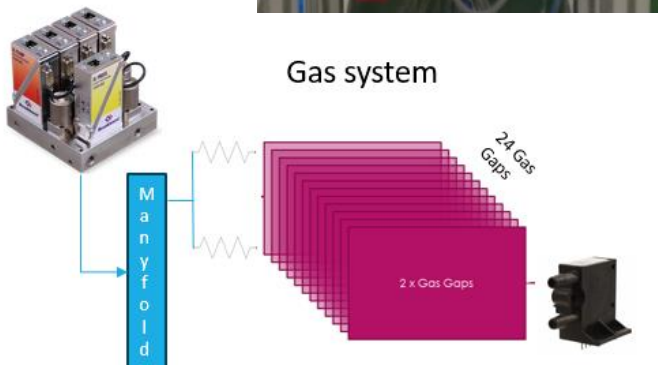
Custom device for gas and high voltage distribution, and monitoring sensors to test 24 gas volumes simultaneously:

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



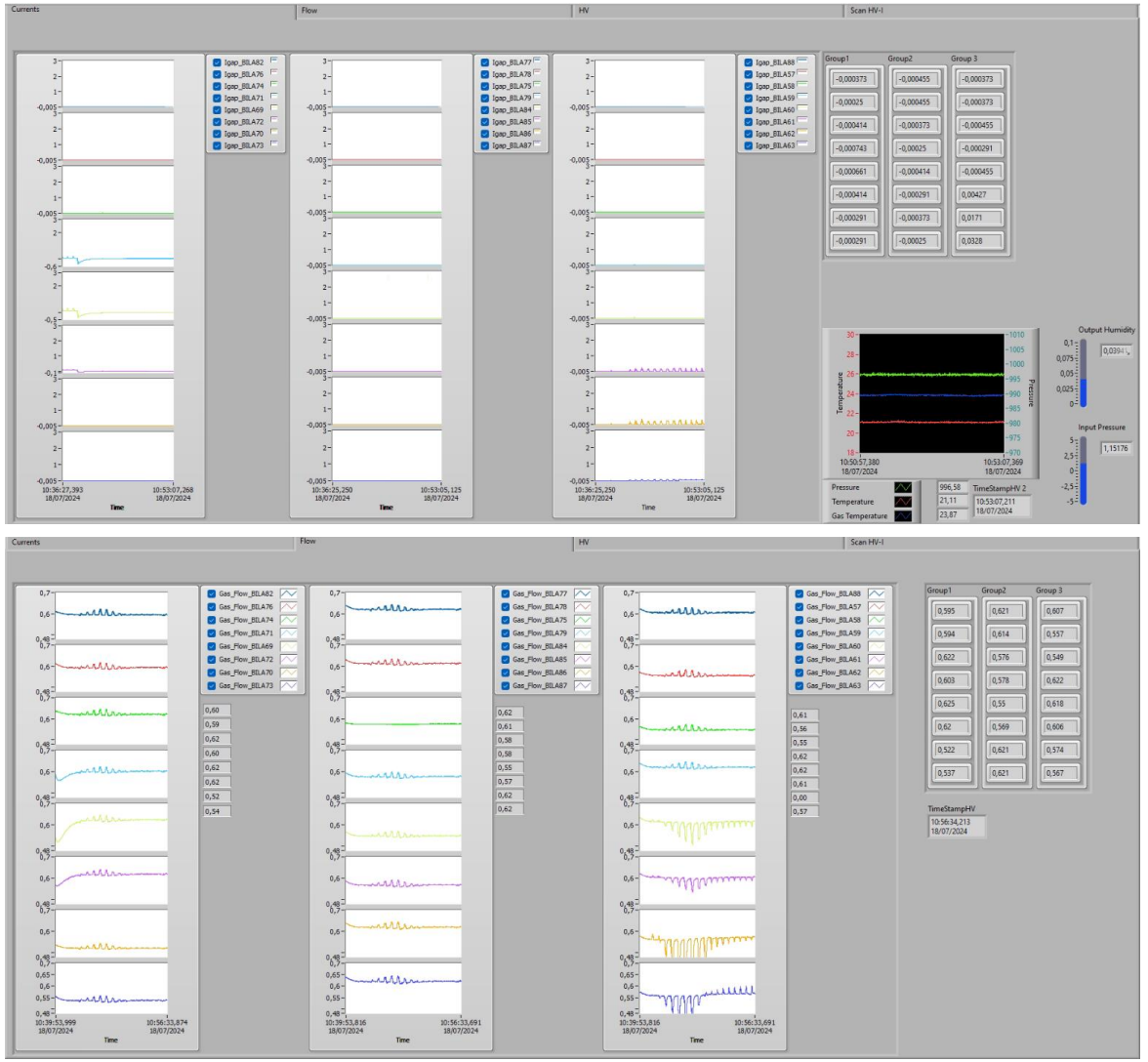




Gas-volume qualification DCS monitor

A data control system monitors and performs I-V characterization of gas volume.
Two National Instruments USB-6218 ADC boards are used for the I-V curves (data are saved at 0.03 Hz).
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 and pressure at the manifold input
- Environmental parameters

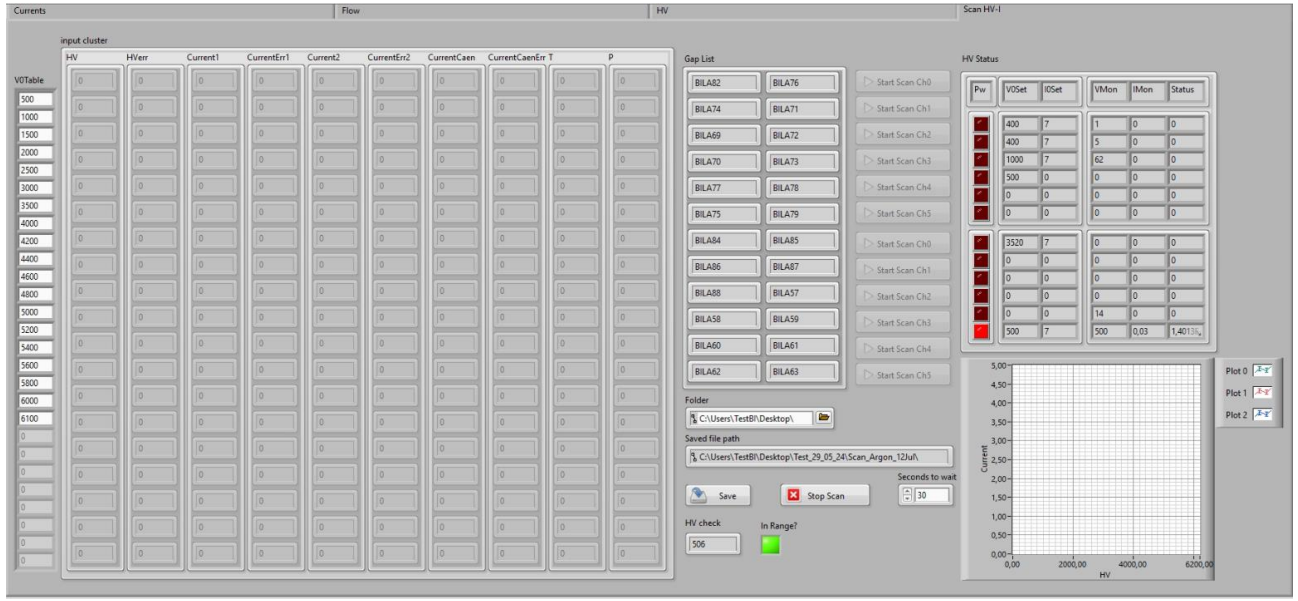


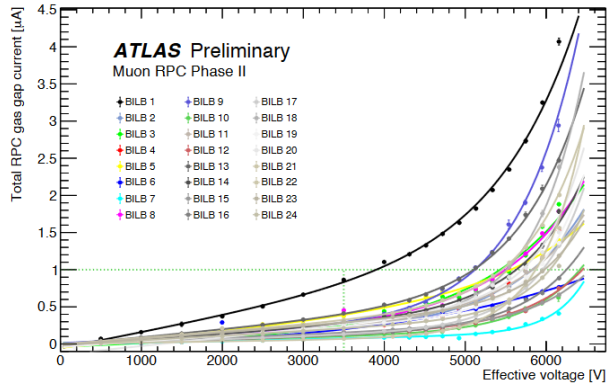
I-V Characterization

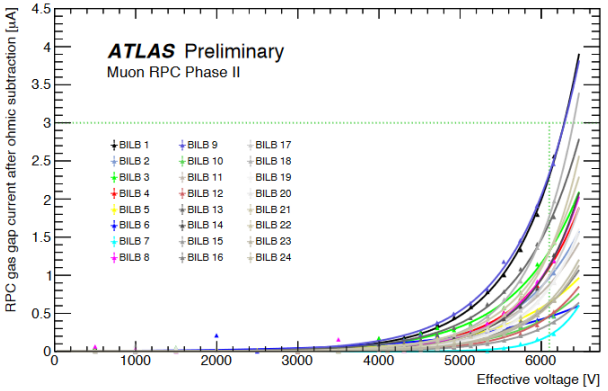
For each volume of gas, a voltage scan up to 6.2 kV is performed to measure the current flowing through the gas gap. The voltage drop across a 100 kΩ resistor in series with the cathode is measured.
The effective voltage HV_{eff} is calculated by rescaling the voltage applied by the generator HV_{gen} 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.







Read-out panels production

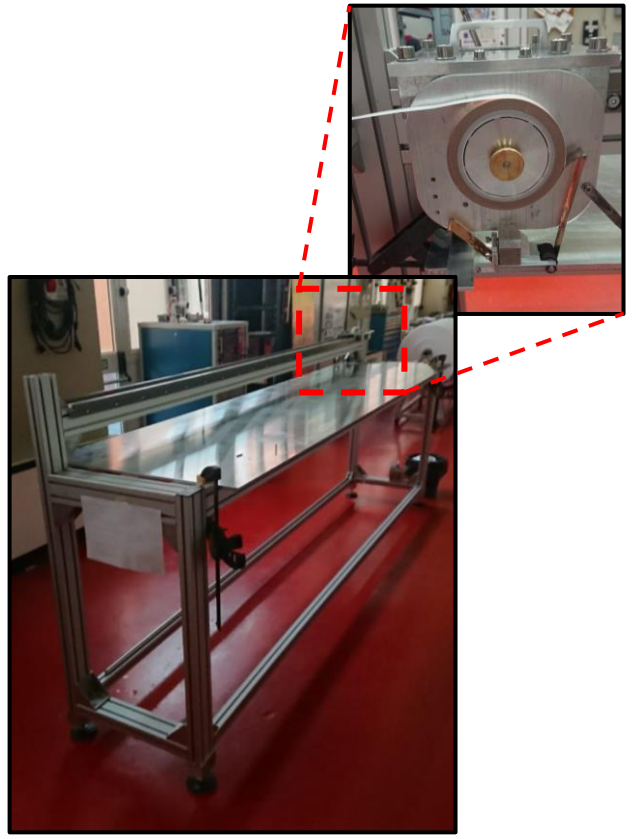
The read-out panels consist of a 3 mm thick honeycomb aramid paper sheet sandwiched between two 0.4 mm thick halogen-free copper-coated FR4 plates. On one of the two plates the strip pattern is obtained by photoengraving process

Cosenza site is producing about 1000 readout panels using the vacuum bag technique on a granite table → maximum daily production rate = 4 BIL or 2 BOM panels.

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 dep. of Physics of UNICAL
- Dedicated transport from Cosenza to CERN in batch of 90 strip panels about every 2 months.

Production status: **400** BIL strip panels corresponding to 60% of the BIL has been produced. Transferred to CERN 95%.



Read-out panels qualification

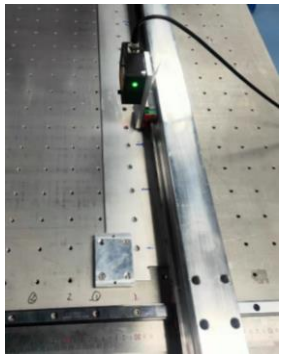
Produced panels and components are qualified with test on

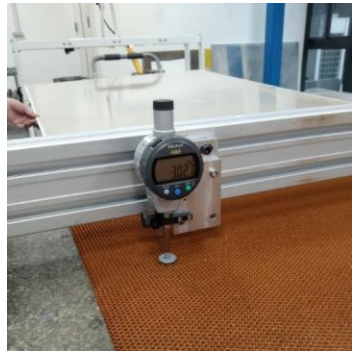
- Aramide paper thickness with gauge comparator;
- FR4 single side copper clad and assembled panel thickness:
  - Cosenza with gauge comparators sampling the surface on a 7 cm x 7 cm pitch matrix;
- Dimensional measurements between 2 points by means of a digital micrometer which measures the deviation from stainless-steel reference bars.

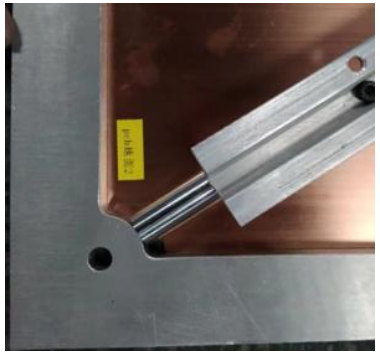
Tolerance on length and width of the FR4 plates are 0.5 mm and 0.3 mm, respectively, while those of the strip panel is 2.0 mm and 1.0 mm respectively. Tolerance on thickness is 0.16 mm.

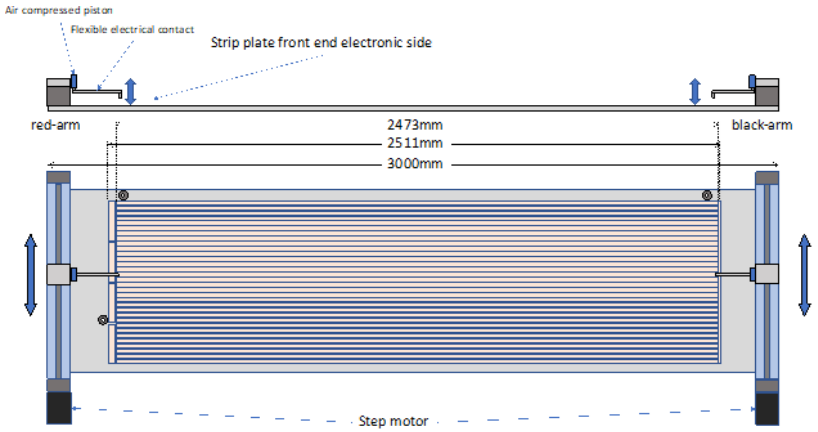
SMD matching resistors are soldered to the ends of each strip and each decoupling wire. To verify the value of the resistors, a 17-channel test board was developed and produced

For the mass production of the read-out panels for BIS-RPCs, see D. Du's talk









FE Electronics status and qualification

For BI-RPC, an ASIC chip has been developed by INFN Rome 2 integrating preamplifier, discriminator and TDC. Main features of the FE board are 1) detectable signal of **1-2 fC**; 2) Voltage Controlled Oscillator (VCO) defining the TDC time resolution (**50-150 ps RMS**); 3) 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 at 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 prob from each channel for signal integrity (on sample boards)

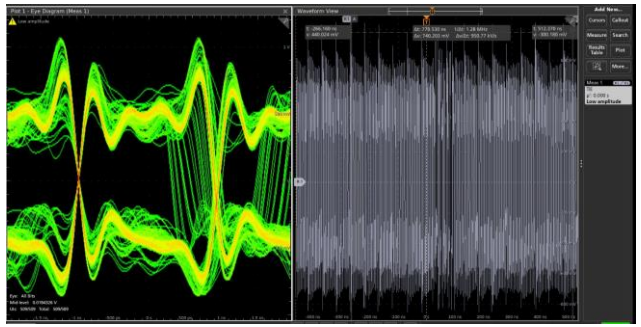
Almost all the equipment has been purchased and is in the programming phase. The board will be hosted during the test in a fixture being produced by INGUN Prüfmittelbau GmbH and customized in collaboration with MOTECO Swiss GmbH (ready in winter 2024).

Software licenses for Manchester decoding and advanced jitter analysis are being purchased

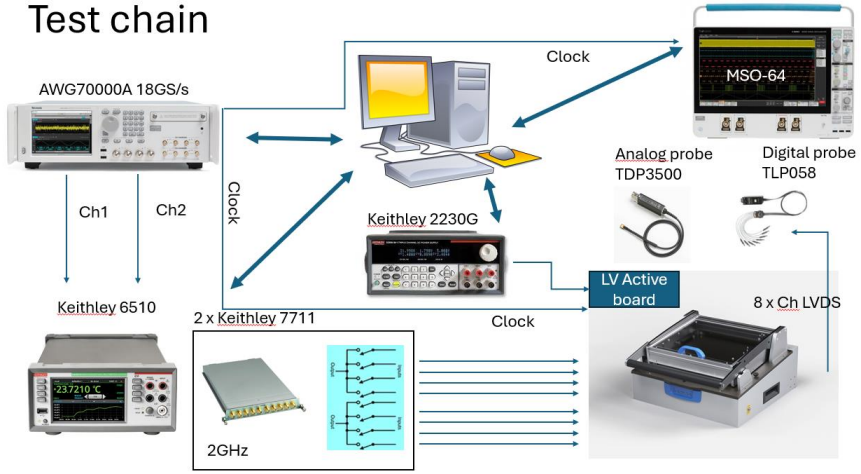
For more details on the FEE for BI-RPCs, see L. Pizzimento's talk

Manchester decoding of preliminary waveform

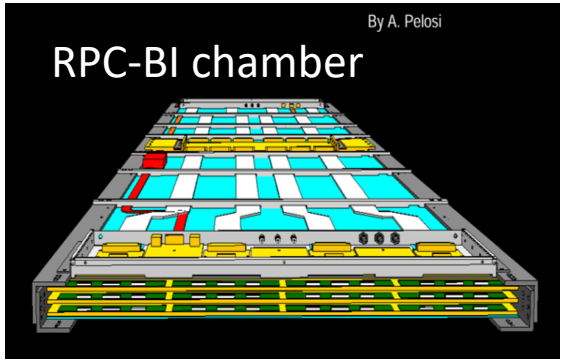
Eye diagram of preliminary waveform with advanced jitter analysis



Test chain



Singlets and Chambers production



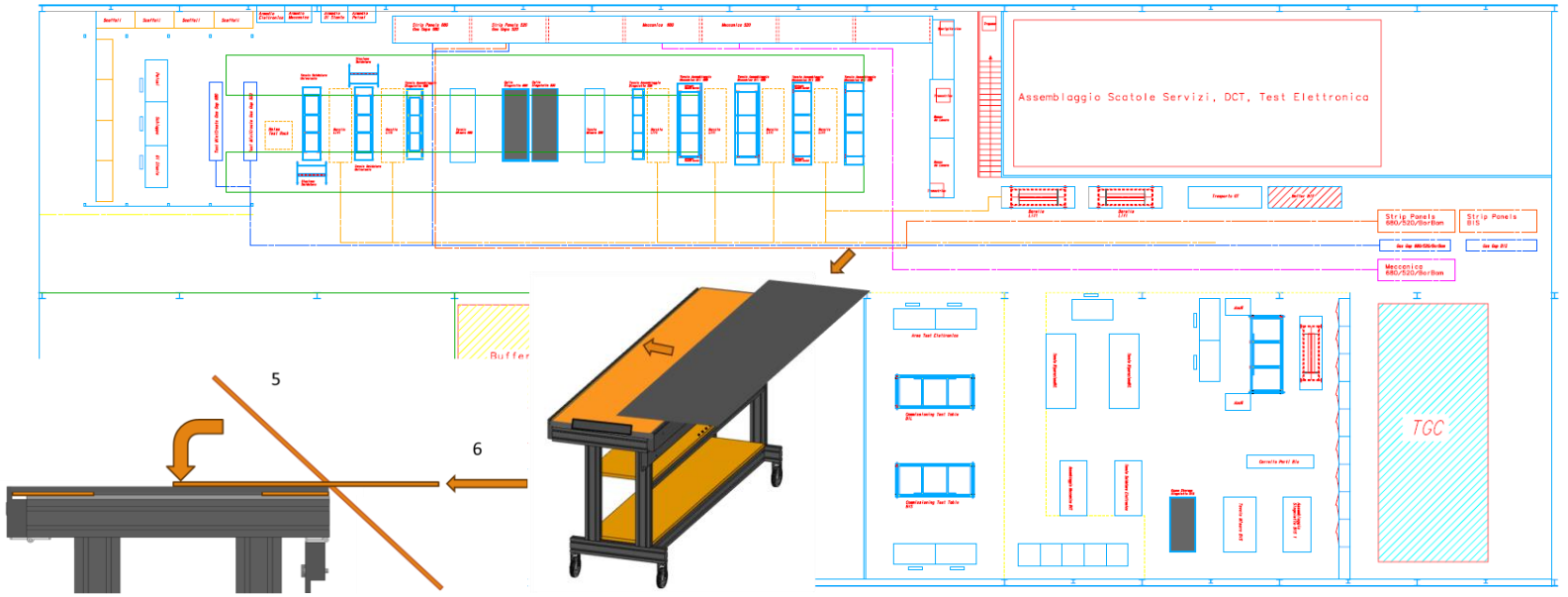
The ATLAS RPC-BI chamber consists of 3 independent singlets sharing the same mechanics and services. Singlets and chambers will be assembled in different production sites:

- INFN will assemble and tests all BIL singlets and chambers excluding 7 chambers of the sector 7 and 50% BOM/BOR in the CERN-BB5 site;
- MPI will assemble and test all BIS chambers in Munich;
- USTC will assemble the BIS singlets, BIS singlets are delivered to Munich for chambers production. The 7 chambers BIL sector 7 and the 8 chambers BIS1 will be assembled in CERN-BB5;
- Hong Kong University: 25% BOR/BOM chambers in CERN-BB5;
- Istinye University, Turkey: 25% BOR/BOM chambers in their institute.

INFN production line is ready. Tables and tools are ready for singlet assembly and test.
Singlets are tested for envelop dimension with micrometric gauge comparators and for current leak @ 7kV before FE-boards welding.

A cosmic-ray test station is working. It was designed to perform QC tests on BI singlets and chambers.

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



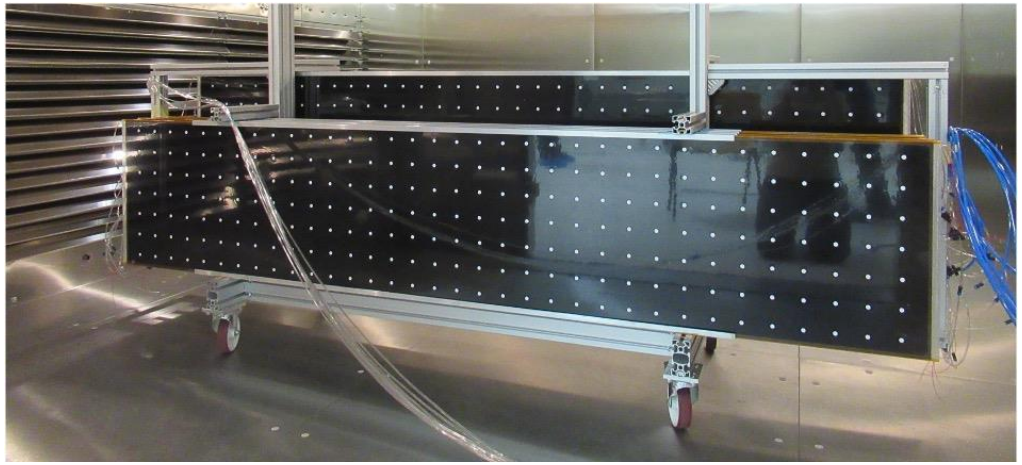
Unexpected events and investigations

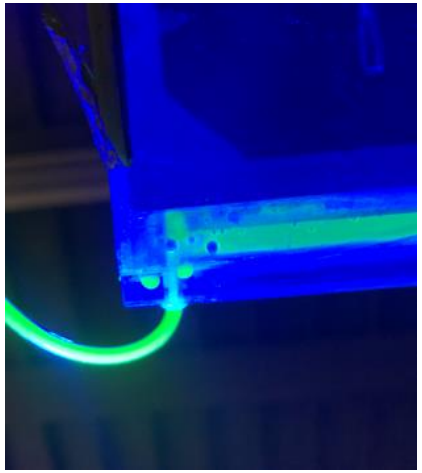
After the production of the first two gas volume batch, quality control tests revealed gas leaks in few gas volumes.
Accurate investigations were performed to identify the causes and highlight the weak points of the production process.

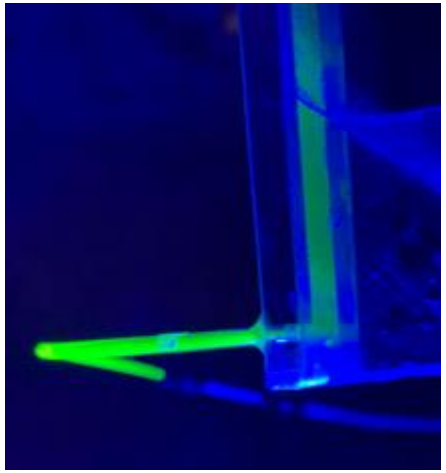
Gas volumes were exposed to mechanical stress tests through thermal expansion cycles. The measurements were carried out on 16 samples (8 at the ITk thermal chamber at INFN national laboratories of Frascati, 8 at the thermal chamber of the University of Cambridge).
Cycles in the range [-20,30] °C was repeated multiple times checking for appearance of leaks. Tests in Cambridge still in progress to increase statistics.

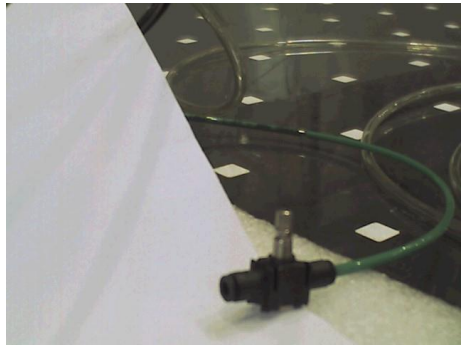
New tools to find gas leaks were introduced. Fluorescent tracer made it possible to identify the critical points.
Detection tests through a thermal camera have been carried out, the possibility of purchasing a
Gas Imaging (OGI) cameras designed to detect hydrocarbons.

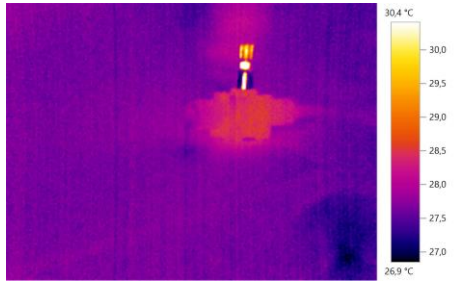
Activity in progress to eliminate this problem: gas volumes with slightly modified gas-distribution system produced at GTE and defective gas volumes repaired at CERN.





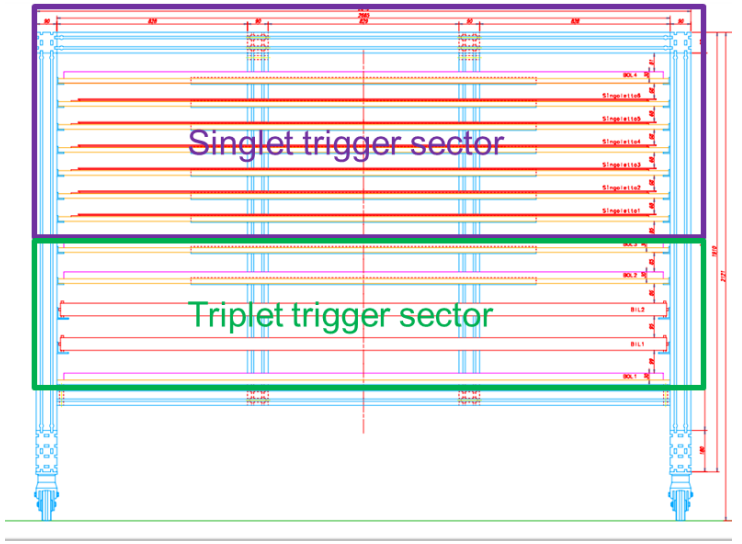






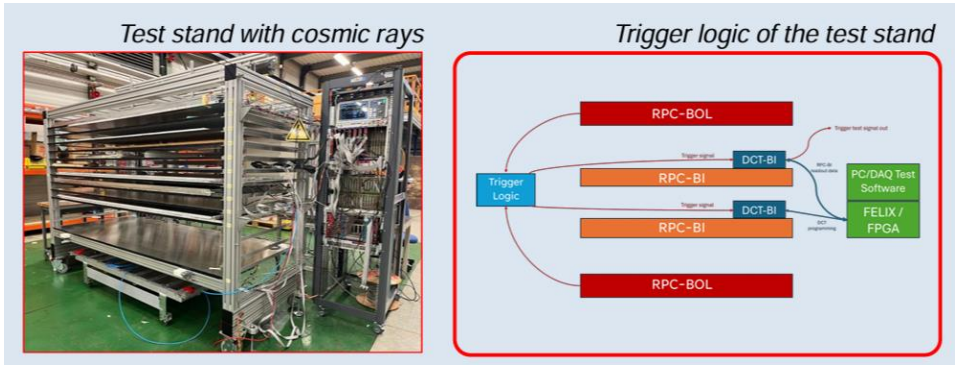
Cosmic-ray test stand

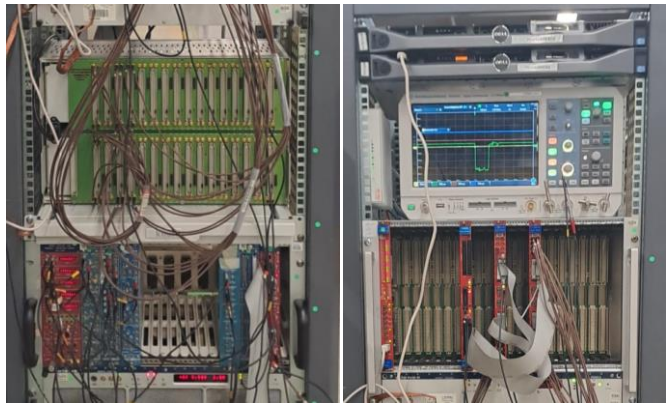
A cosmic-ray test stand has been completed on the INFN BIL production line at CERN-BB5. The infrastructure will certify all BIL-RPC singlets and chambers produced by the Italian community: 120 BIL chambers and 360 singlets, plus 40 BOR/BOM chambers.
Trigger detectors are 4 x BOL-RPC Atlas Singlets (2 mm RPC detectors) with active area of 2430 x 1010 mm^2 each and a total of 448 Channels. This solution allows to perform integration tests of new BMBO-DCT on ATLAS Legacy detectors.

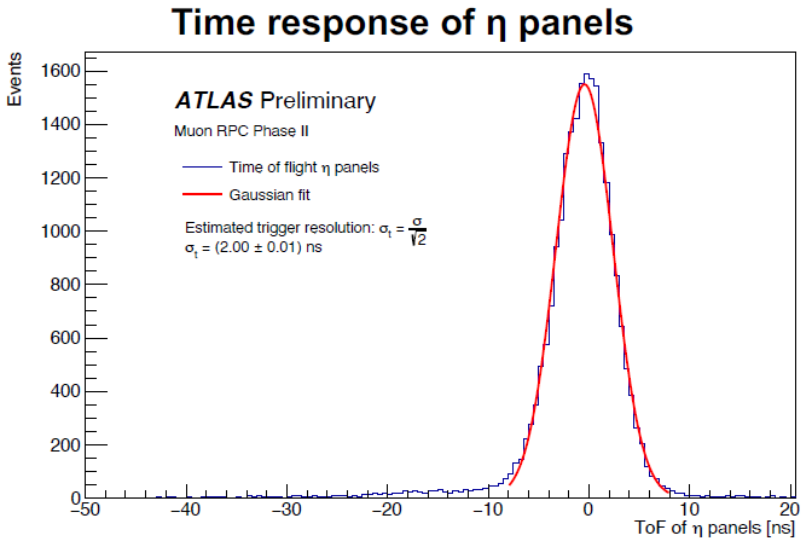


Trigger chambers read-out system is based on TTL translator with NIM fast-OR for each FE board (Granularity 1x1 Chs → 8 x 8 Chs)
Trigger Logic: implemented on FPGA CAEN V2495 Altera Cyclon V Translator/Logic Unit

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







Conclusions

- ✓ Production of the RPCs for Phase II upgrade of the Atlas spectrometer has begun. **Assembly lines and infrastructures** for the storage and qualification of the detectors is ready.
- ✓ **Quality control protocols** have been established for almost all components.
- ✓ **Production of gas volumes** has already started in GTE and quality controls are underway. USTC and MPI are completing the final steps to qualify as gap gas producers.
- ✓ **Production of readout panels** started in both Cosenza and USTC sites. BIL readout panels production 50% complete; BIS2-6 readout panels production 30% complete.
- ✓ **FE-board test stand** in preparation, preliminary tests concluded.
- ✓ **Database** ready to store gas-volume and panels information, production status available. Other components interface under development
- ✓ **Cosmic ray stand** almost ready in CERN-BB5 production site, triple (quadruple) coincidence large area trigger just available

Back-up slides

Additional consideration on BIS-RPCs

- **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 at GIF++ since April;
  - Preparation of real-scale RPC production at external company;
- Serial-production start planned for the end of 2024.
- **72** gas volumes will be produced and qualified at **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

Mechanical structures for storage and shipping

- **Trolley and packs**
- Trolleys have been produced for the main gas volume geometries (BIL and BIS). The trolley host the crate and is equipped with gas manifolds.
- Gas volume are delivered to different production sites in packs made of pre-bent aluminum honeycomb plates equipped with shock sensors of different sensitivity. There is a pack for each gas volume geometry.

BIS read-out panels

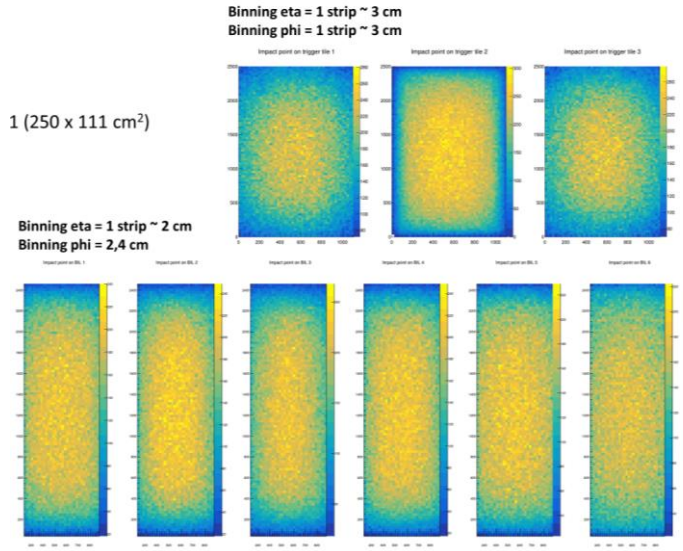
- **All BIS panels are produced in China**, about 100 BIS1 and 500 BIS2-6 types, using the vacuum bag technique on a granite table and qualified in USTC. The assembly is made in a company
- **Production status:** 50 BIS-1 and 150 BIS 2-6 panels produced; 2 panels rejected; production rate 4 panels/day
- FR4 single side copper clad and assembled panel thickness:
  - China with a laser sensor sliding along a rail taking data continuously; sampling point (7 cm interval) achieved by a mask with holes;

QC tests on Singlets and Chambers

Different tests will be performed on singlets and chambers to qualify all the figures 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 geometries. One of the trigger tiles could be read-out directly by the BMBO-DCT to improve tracking capabilities.

A preliminary trigger rate has been simulated implementing a triple coincidence to estimate the qualification schedule. We expect about 170 entries/hour in $\Delta\eta$ x $\Delta\phi$ 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
Performance	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

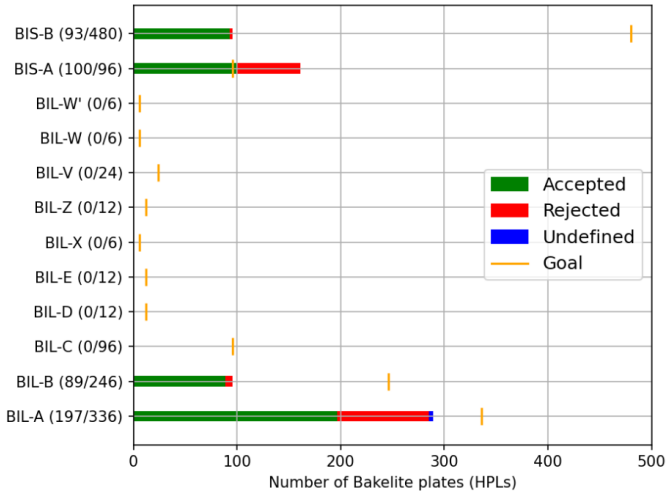
Production Database

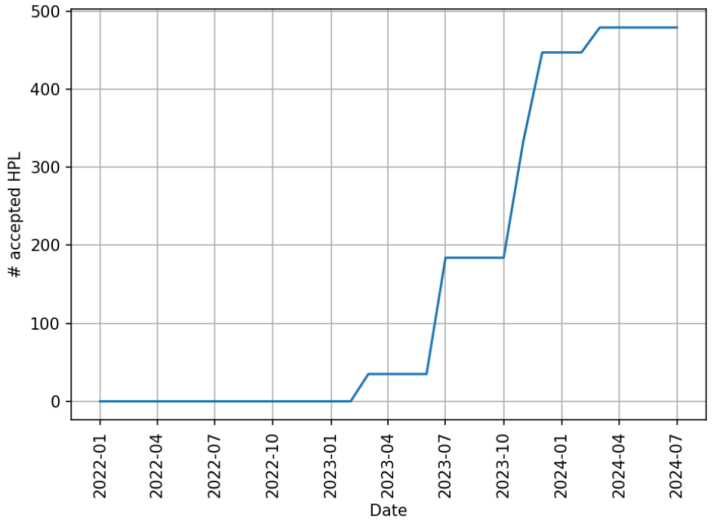
All components are identified in the production database with an ID code at the time of purchase or manufacturing.

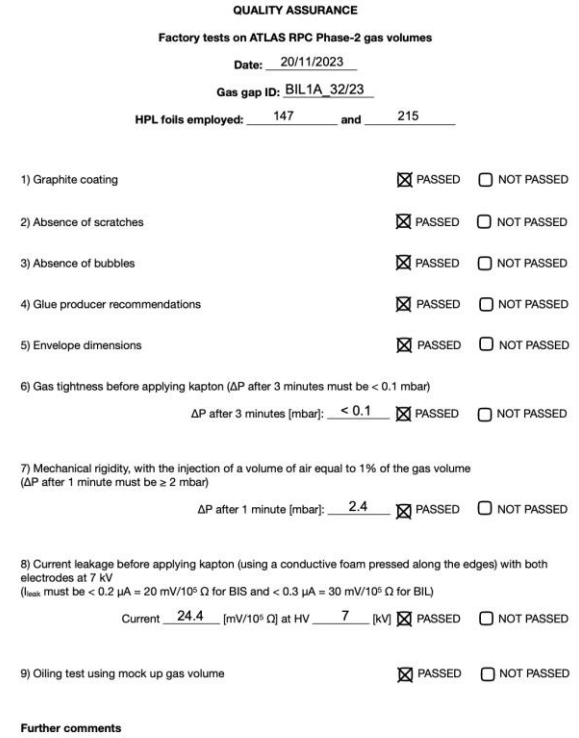
Database contains results of quality control tests and allows to trace the components in the various production sites and time. Data are stored in .json format and can be plotted through embedded scripts.

Status:

- Management of panels and gas gaps ready;
- In the near future will be implemented the singlets;
- In 2025 will be implemented the 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

Factory Acceptance Tests Documents