The ATLAS RPC Phase II upgrade for High Luminosity LHC era

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on behalf of the ATLAS Collaboration

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ATLAS EXPERIMENT
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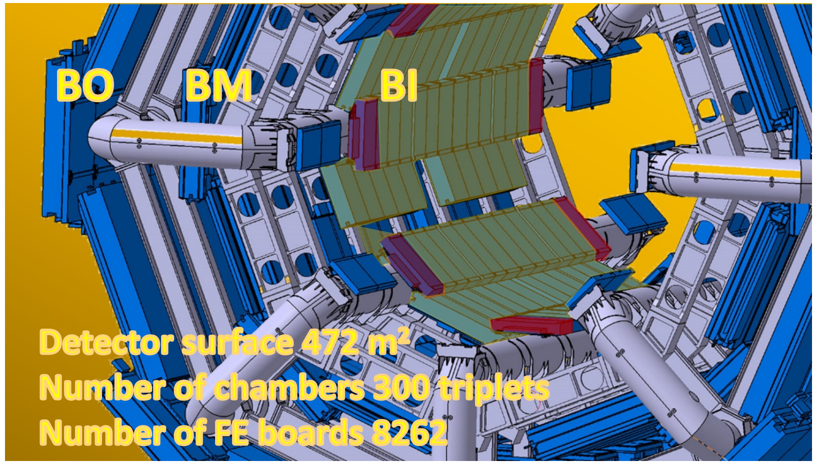
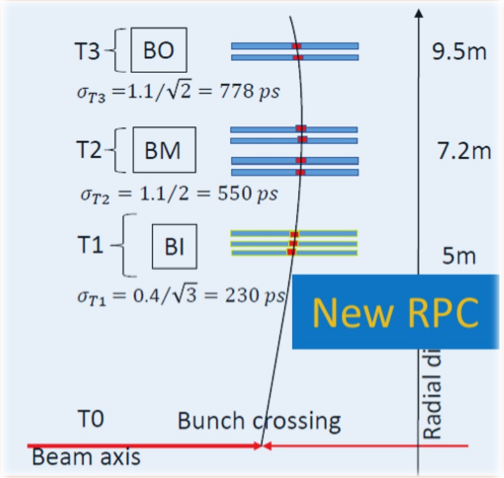
ATLAS RPC system upgrade for Phase II

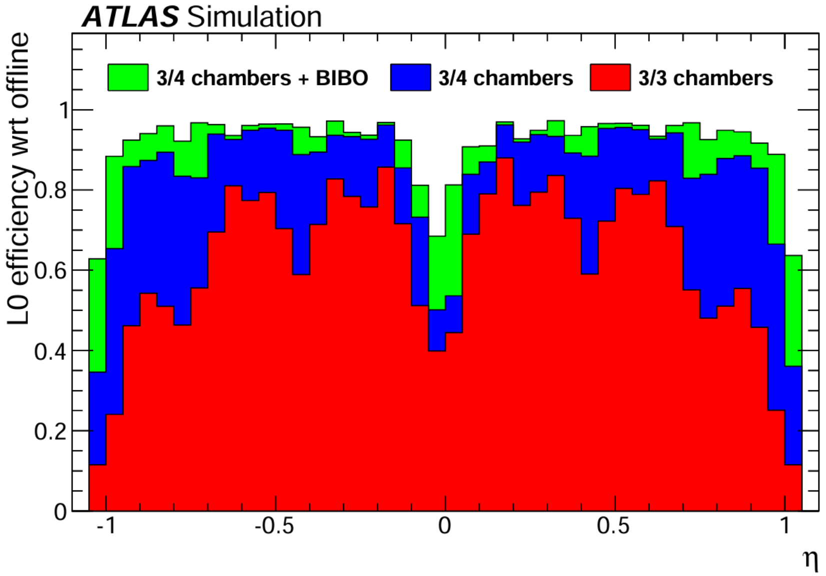
The ATLAS Muon Trigger system needs major upgrades in view of the HL-LHC luminosity increase (7×10^{34} $cm^{-2}s^{-1}$ at $\sqrt{s}$ =14 TeV *pp*, $<\mu>$ = 200). The RPC system will be upgraded adding about 300 new generation RPC detectors with 10 kHz/cm^2 rate capability in the Barrel Inner (BI) and replacing the old on-detector trigger boards with new boards.



Improvements:

- **Trigger Redundancy (6 → 9 layers)**
- **Acceptance (78% → 92%, 96% with BI-BO coincidence)**
- Spectrometer lever arm (2.3 m → 4.5 m)
- Improved time resolution for ToF measurements due to new thin-gap RPCs and readout electronics (0.4 ns for BI-RPCs, 2 ns → 1.1 ns for Legacy RPCs)



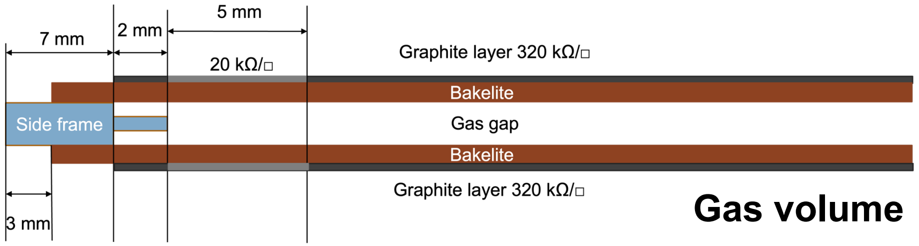


Projects and activities

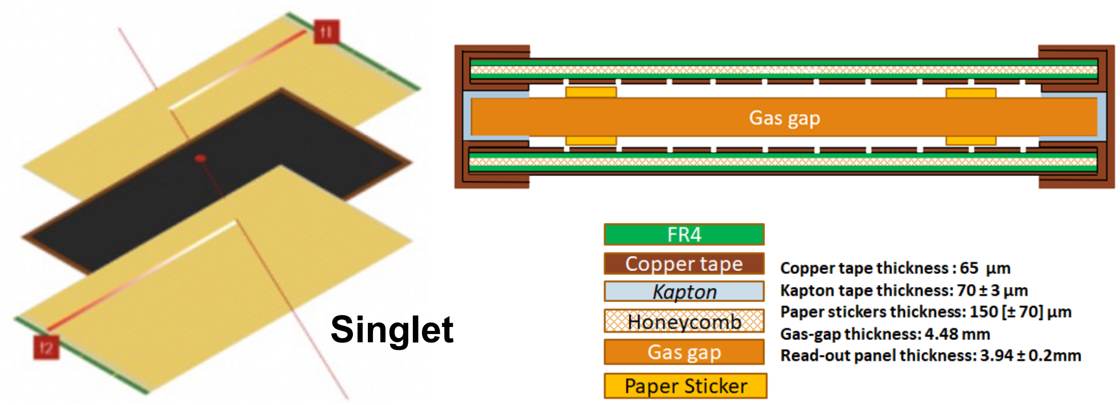
- **BI-RPC:** Installation of an inner layer of RPC triplets with new FE ASIC to increase trigger acceptance.
- **Readout electronics**: Replacement of the on-detector trigger boxes with new trigger boards. New on-detector trigger boards for BI-RPC.
- **Power system:** Replacement of the RPC Power System.

BI-RPC: gas volumes, singlets and chambers

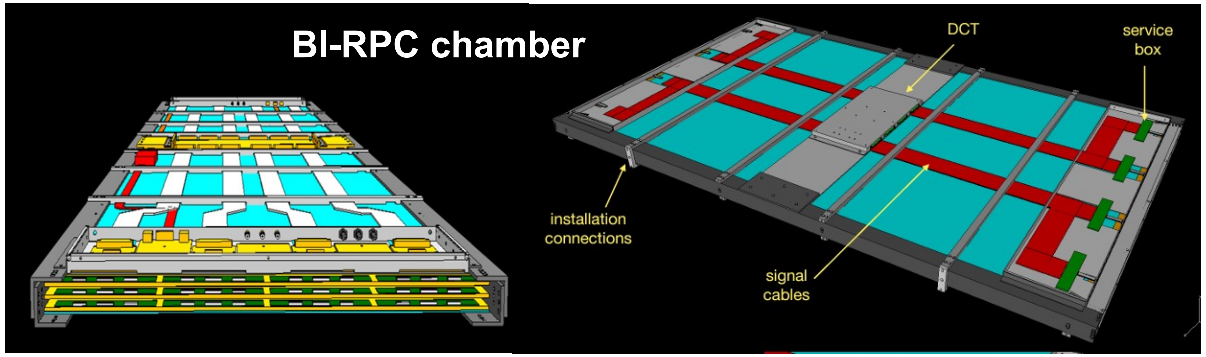
Gas volume: a gas volume is composed of a gas gap closed by two High-Pressure Laminate (HPL) bakelite plates. A graphite layer is placed on top of each HPL plate. Gas volume thickness about 4.5 mm.



Singlet: the gas volume is contained between two readout panels with η-oriented strips (along the long side of the chamber) forming a singlet.
The sandwich composed of the gas volume and the readout panels is closed in a Faraday cage consisting of the outer faces, made of copper material, connected by conductive copper tape on the edges.
Singlet thickness about 13 mm.



BI chamber: three singlets (a triplet) inserted inside the containment mechanics to form the BI chamber.
BIL-RPC will be inserted in Large sector while BIS-RPC will be inserted in Short sectors.
BI chamber thickness about 65 mm.

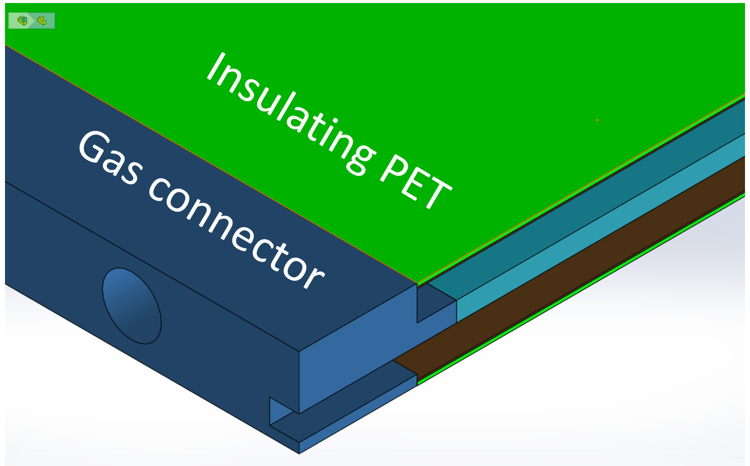


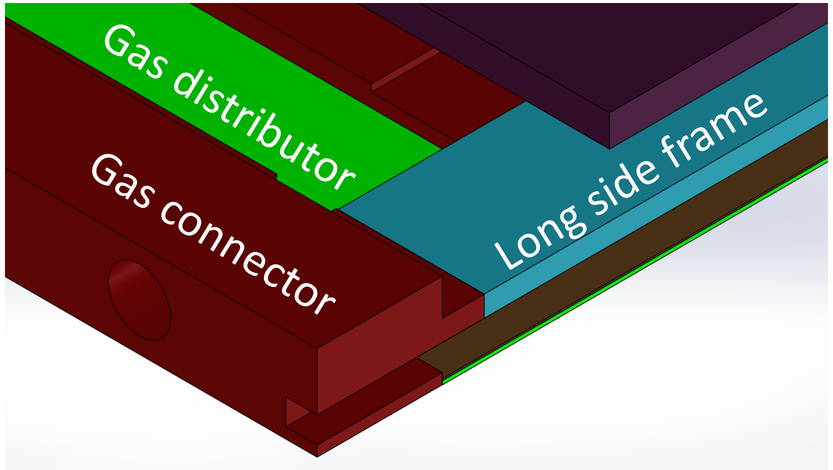
New gas volumes

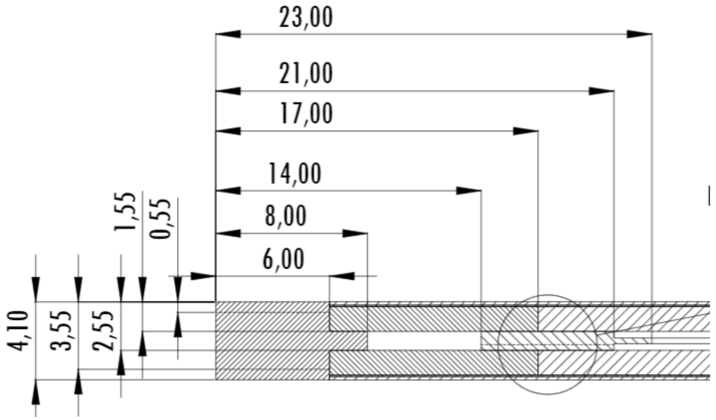
A new gas volume has been developed. Many improvements with respect to ATLAS Legacy RPC detectors:

- **Gas gap thickness reduced from 2 mm to 1 mm;**
- Redesigned gas distribution with 4 holes for connecting the gas pipes placed on the 4 corners of the detector and drilled in solid profile. The profile closes the internal gas distributor channel along the short side of the gas volume;
- New HV cable connection on gas volume side;
- 6 mm diameter gas pipes replaced with a 3 mm pipes;
- Graphite layer resistivity reduced from 500 kΩ/□ to 320 kΩ/□ and footprint redesigned to reduce current leaks;
- Electrodes thickness reduced from 1.8 mm to 1.4 mm.

Production in Italy of the gas-gaps expected over 2 years 2023-2025 by General Tecnica Engineering (GTE).
Two new producers that could produce a fraction of gas volumes are in the phase of qualification: Munich (Max Planck Institute, MPI) and Hefei China (University of Science and Technology of China, USTC).







Transversal view on the gas distributor side

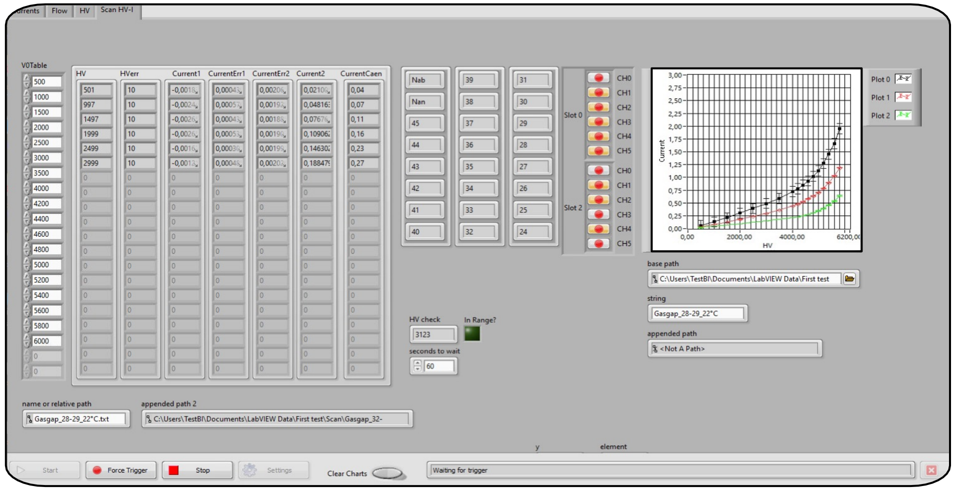
Qualification of gas volumes

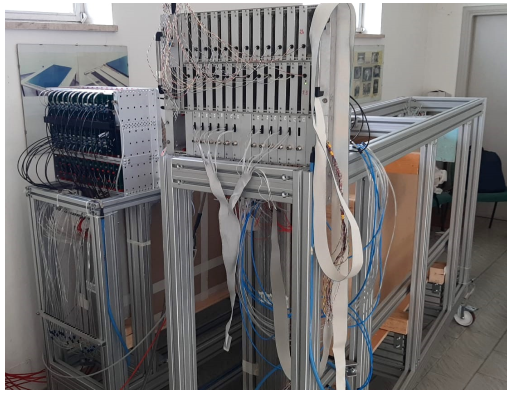
Tests of bakelite plates are carried out by INFN at GTE:

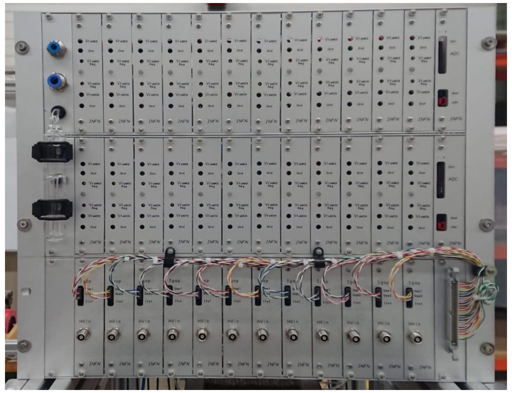
- Sample measurement of the resistivity of the sheets (max 10^{11} Ωcm).
- Sample measurement of plate thickness.
- Visual inspection for the detection of any macroscopic defects.

Gas volumes tests are carried out at GTE:

- 10 Tests under the responsibility of the manufacturer.
- 3 Tests under CERN-INFN responsibility:
  - Current-voltage (I-V) characterization (max 3 μA@6.1kV after ohmic subtraction – max 1 μA@3.5kV).
  - Gas tightness test (Δp < 0.1 mbar after 3 minutes).
  - Current leak test.
- Conditioning at GIF++:
  - The I-V curve is measured again with the source off.
  - Gas volumes are exposed to gamma radiation working at approximately 4800 V in GIF++ position D4 (max 20 μA/m²).

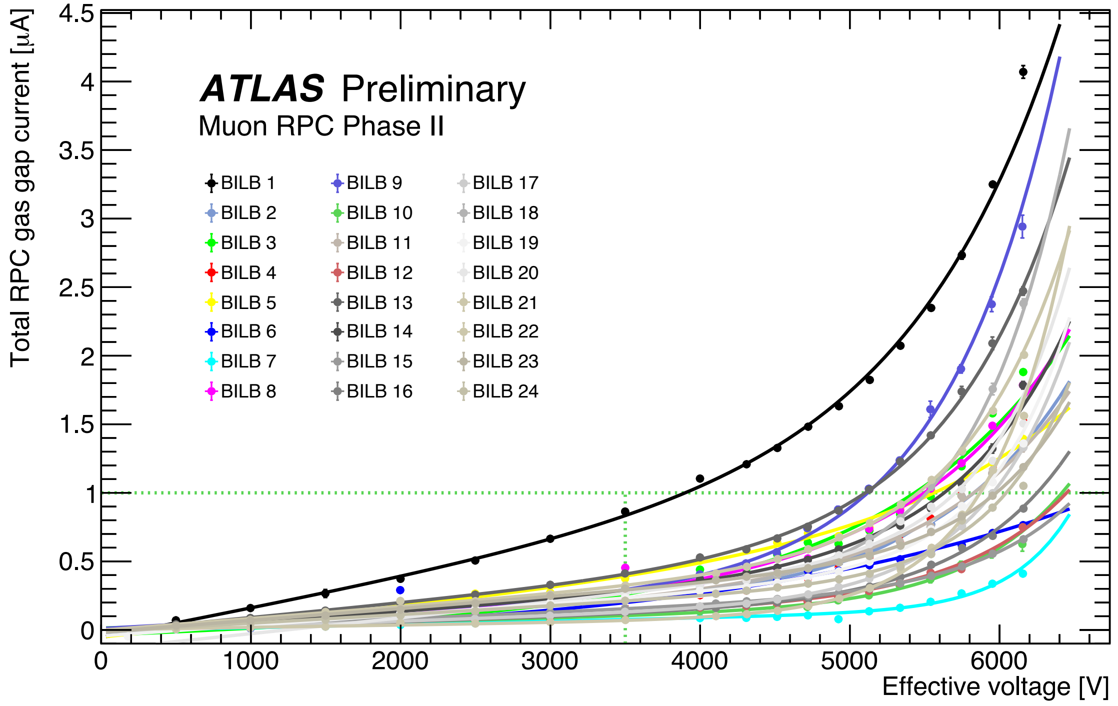


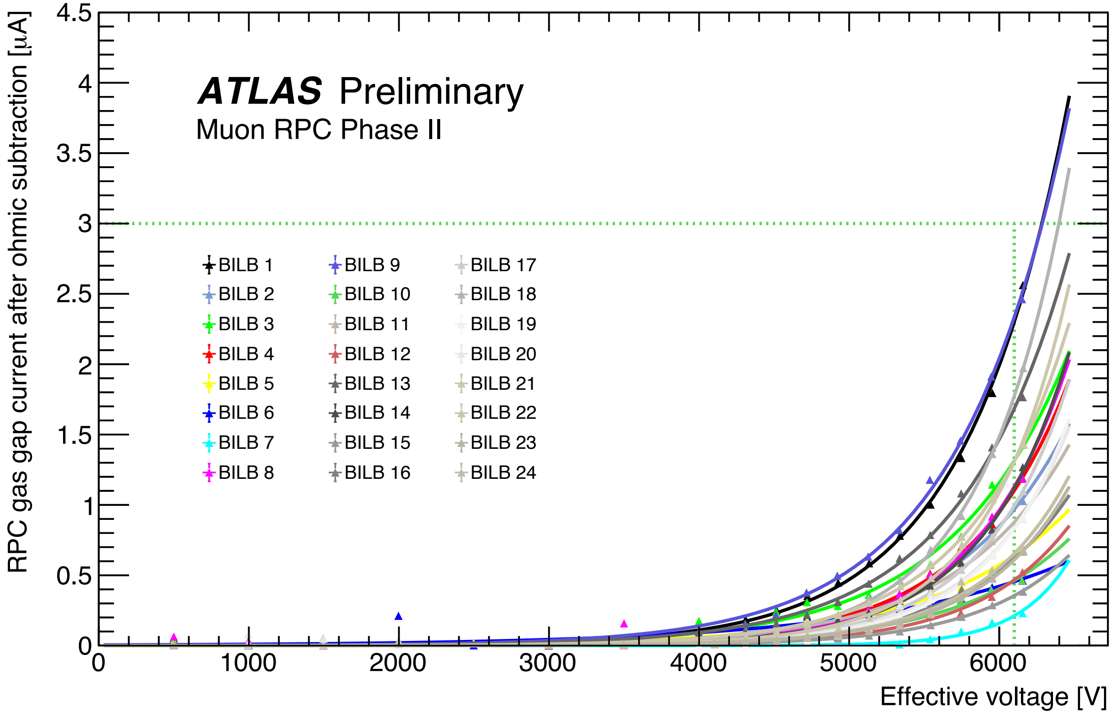




Current Vs Voltage of gas volumes

- BI-RPC gas volumes are in production. According to the tender, volumes are accepted if they show a total current of less than **1 μA at 3.5 kV** and a current after subtracting the ohmic component less than **3 μA at 6.1 kV**. The ohmic component is estimated by performing a linear fit in the [0-3] kV range.
- All volumes undergo an I-V characterization before invoicing. The plots show the total current and the current recalculated after subtracting the ohmic component as a function of the voltage for an entire production batch.
- The tested production batch meets the production requirement.

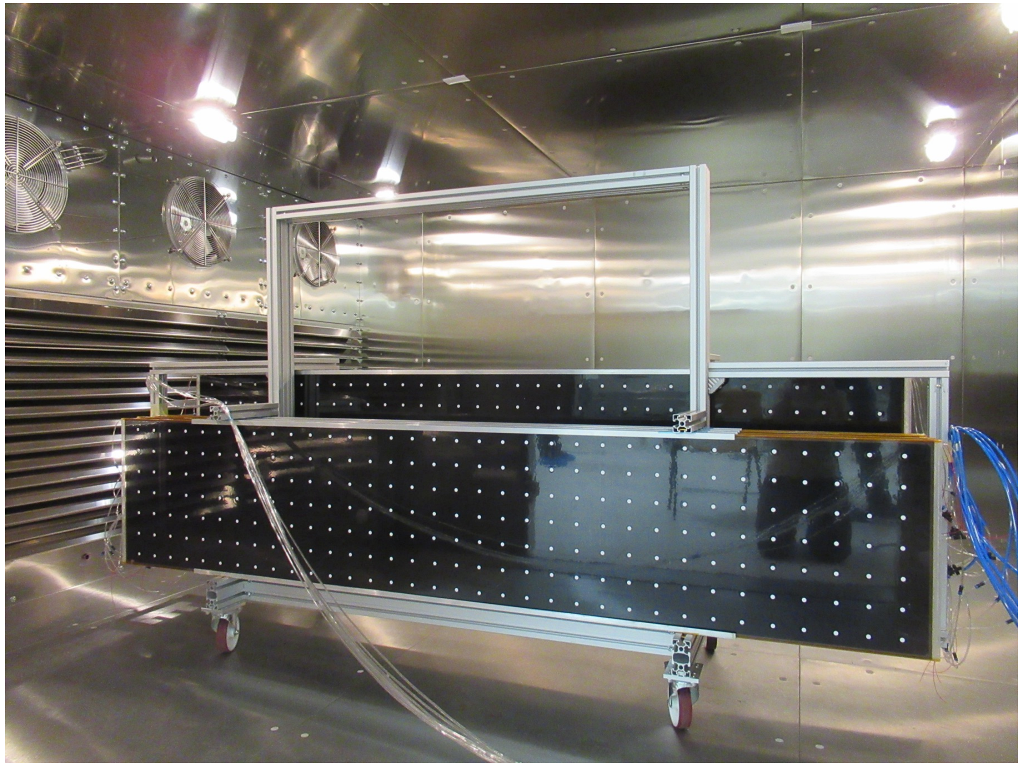




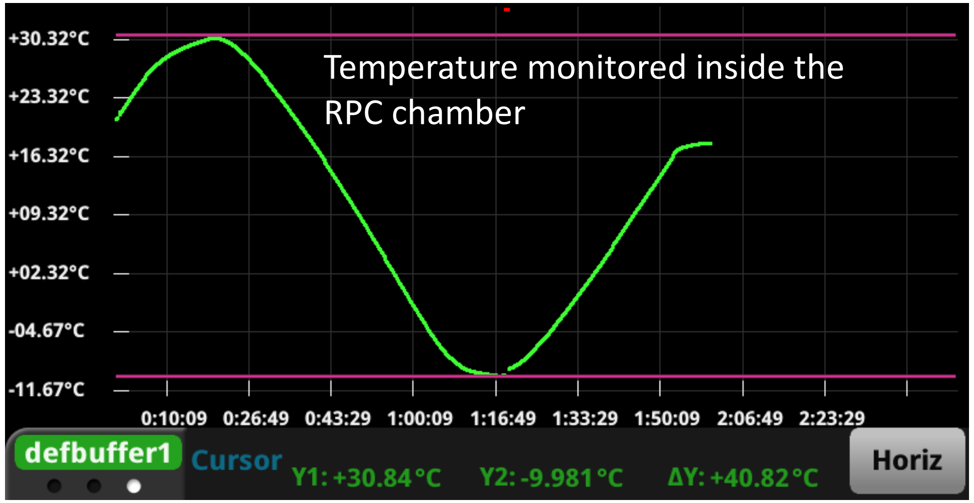
Thermal chamber tests

Stress tests were carried out on 4 gas volumes of BIL type performing thermal cycles in the climatic chamber of the ATLAS laboratories at INFN Frascati.
Additional tests on BIS chambers performed in Cambridge University.

Different cycles have been performed:
- 5 x [10 °C – 30 °C];
- 4 x [0 °C – 30 °C];
- 3 x [-10 °C – 30 °C];
- 3 x [-20 °C – 30 °C].



Gas volumes have been flushed in parallel during heating/cooling cycles with low dew point dry air, applying 1.8 mbar overpressure at gas inlet:
- 2 temperature sensors are 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, a time of 15 minutes was waited to reach the thermal equilibrium.
- Mechanical strength and gas tightness have been monitored during cycles.



Read-out panels

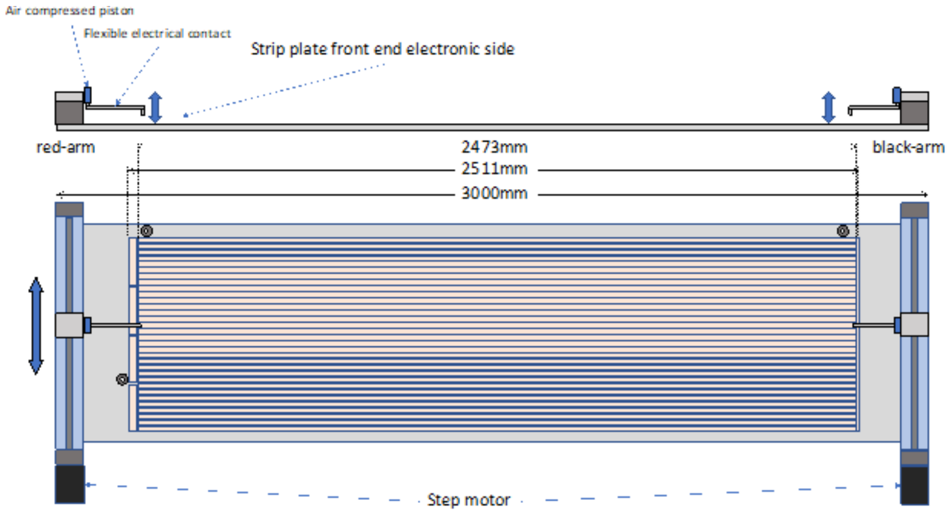
New read-out panels consisting of 3 layers:

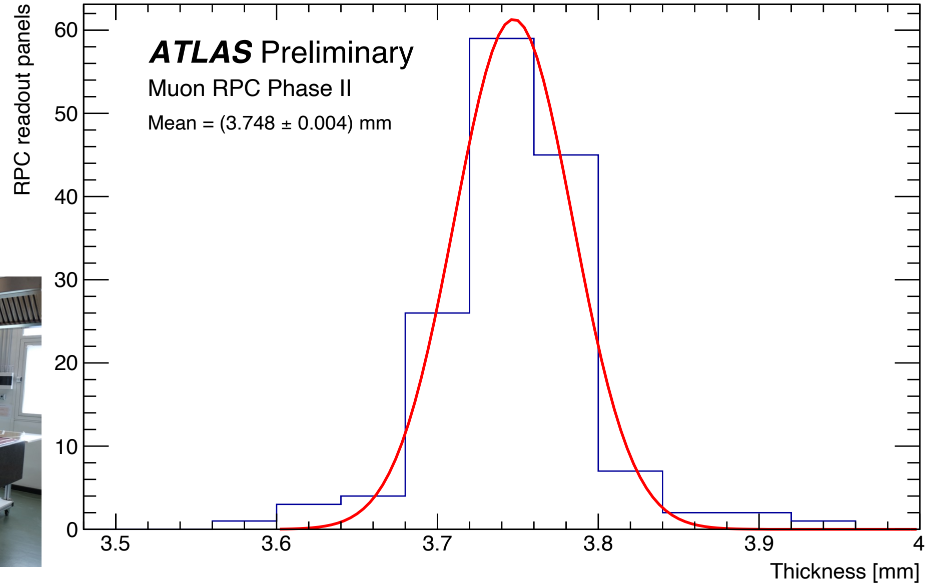
- **One layer of aramid paper honeycomb 3 mm thick;**
- **Two layers of copper-plated FR4 0.4 mm thick on which read-out strips are produced through a photoengraving process.**

Panels thickness and materials are selected to optimize the impedance of the strips and the weight of the detector. A termination resistor is welded to the ends of each strip and guard wire.

Construction of the read-out panels is divided between INFN Cosenza (BIL) and Hefei China (BIS).
INFN Cosenza site capability = 800 panels/year with following tests:

- Thickness measurement of FR4 panels;
- Thickness measurement of Aramid paper honeycomb;
- Thickness measurement of the assembled panel surface (7 cm x 7 cm matrix);
- Panel length and width + strip width measurement;
- Electrical continuity measurements for strips and guard wires.

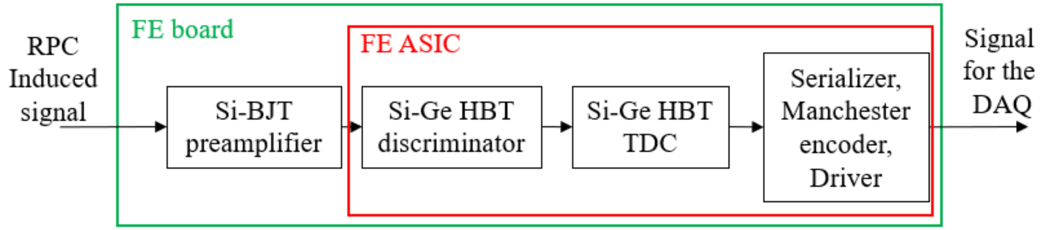




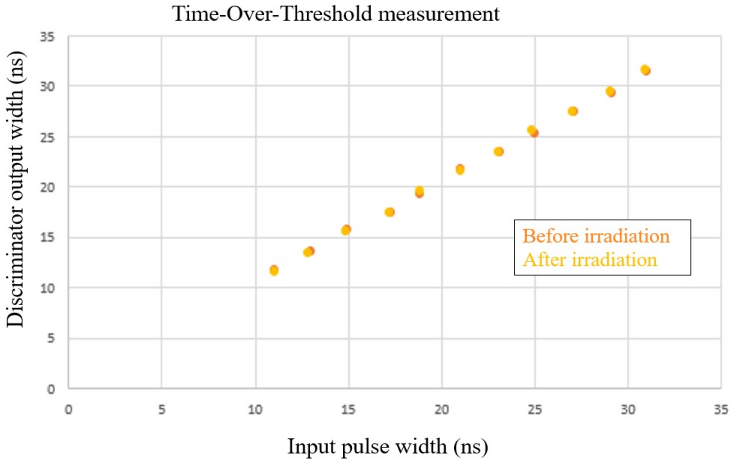
FE Electronics

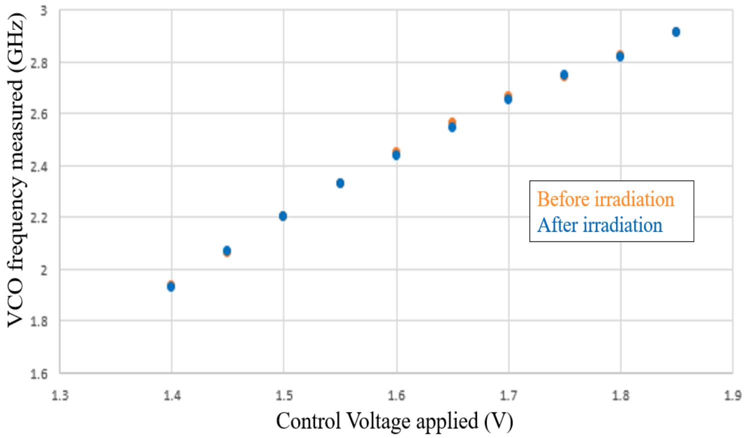
For BI-RPC, an ASIC chip has been developed by INFN Rome Tor Vergata integrating preamplifier, discriminator and TDC. The project provides for an improvement in stability and sensitivity compared to the BIS-78 FE and allows the φ coordinate reconstruction:

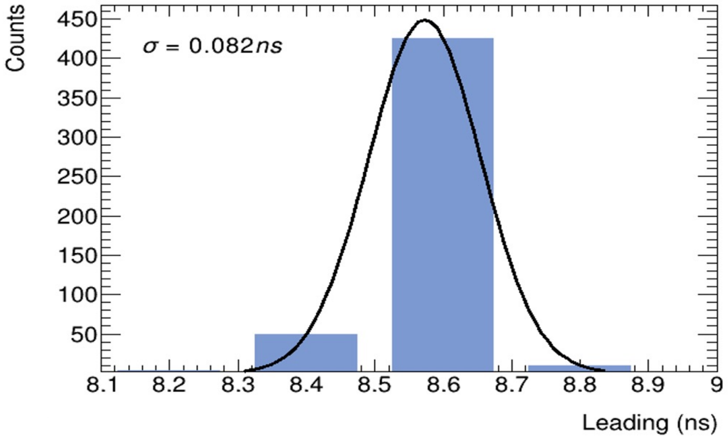
- Detectable signal of **1-2 fC**;
- Minimum discrimination threshold of 0.3 mV;
- Voltage Controlled Oscillator (**VCO**) defining the TDC time resolution driving the scaler (**50-150 ps RMS**);
- The data is encoded using the Manchester code.
- Each ASIC chip of 8 channels, each channel has its own serial transmission line.



10 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 in the discriminator and in the VCO response after the irradiation.**



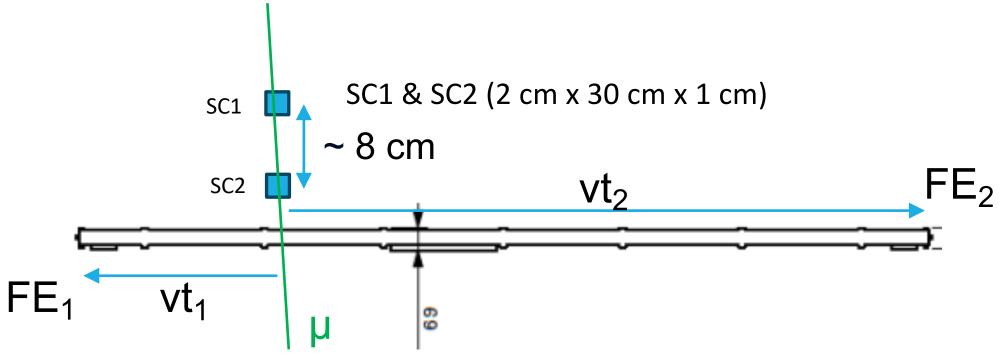


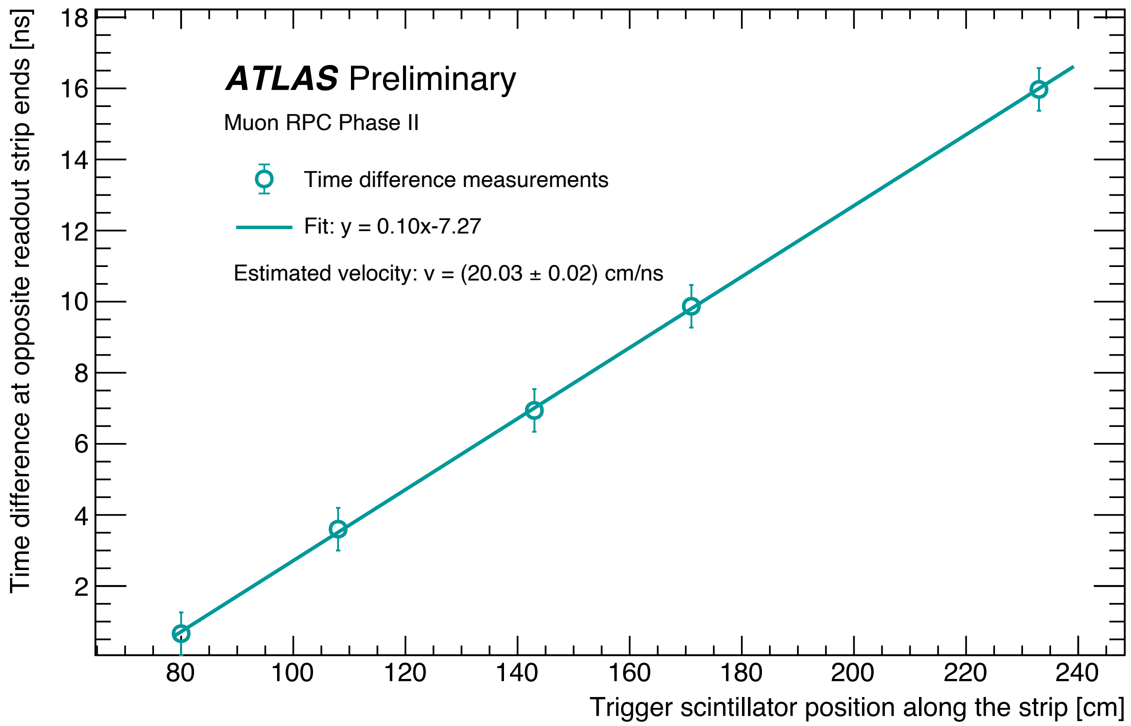


Measurement of φ coordinate

The BI-RPC detectors have only η-oriented readout strips, which are equipped with FE-electronics with a 100 ps TDC temporal resolution at the opposite ends.
The reconstruction of the φ coordinate is obtained from the propagation time of the signals on the strips and the velocity.

- The signal propagation velocity on the strip can be measured by measuring the time difference on opposite readout strip ends.
- The measurement has been performed by placing 2 cm narrow trigger scintillators in different orthogonal positions with respect to the strips.
- A **signal propagation velocity of 20 cm/ns** was measured with a BIL-RPC equipped with a BIS-78 like FE- board;
- The obtained spatial resolution in the φ reconstructed coordinate was about 2 cm, driven by trigger geometry;
- The spatial resolution on the η coordinate depends on the cluster size of the event.

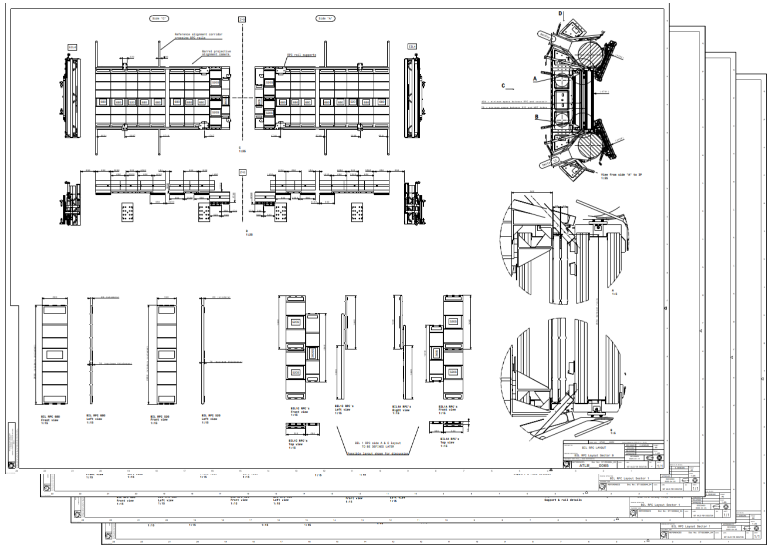


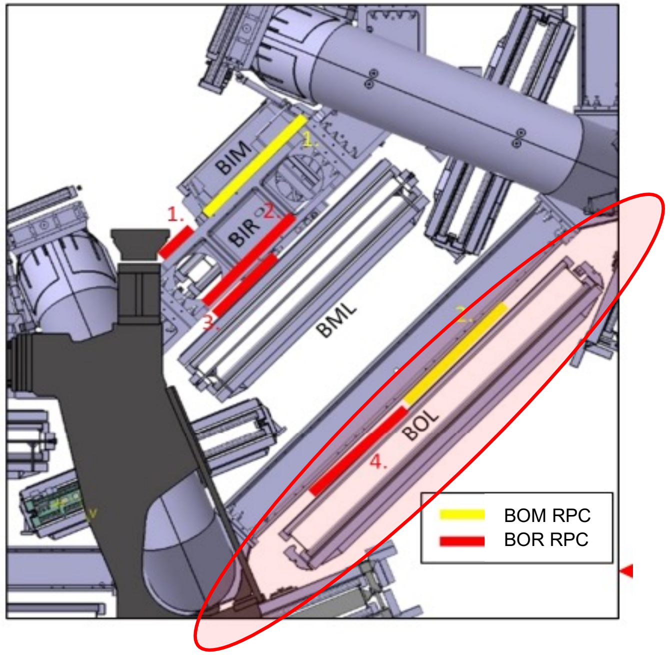


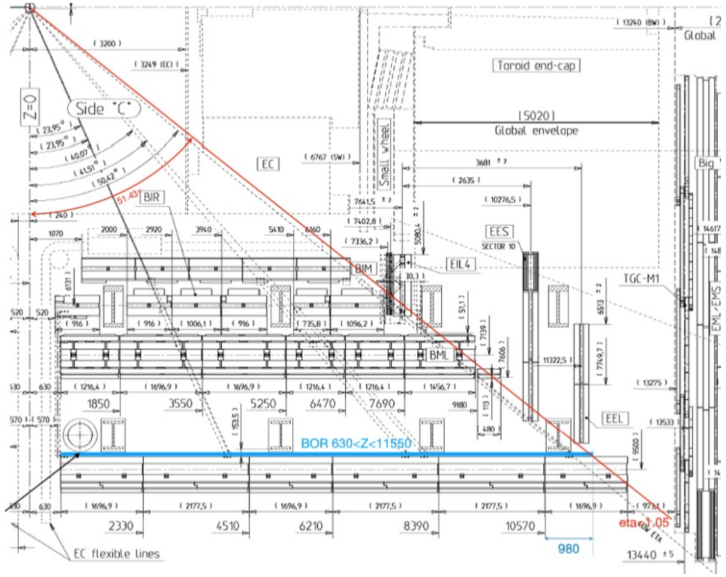
Layout of the new chambers

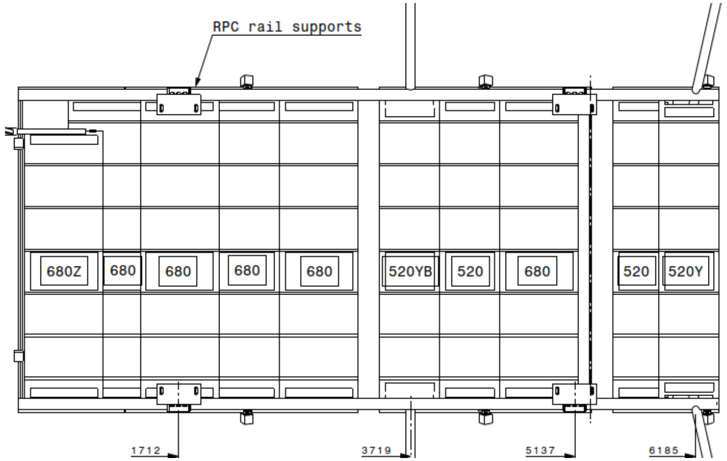
The design of the containment mechanics have been defined for all the main chambers (4 BIL types: BIL 680S - BIL 680L - BIL 620S - BIL 520S covering 75% of BIL sectors, 2 BIS types: BIS1 and BIS from 2 to 6, covering all the BIS sectors involved in Phase-II upgrade) and other special cases.

In the feet sectors (S11 and S15) new chambers will be installed in the Barrel Outer: 80 identical BOR-BOM chambers without overlapping of BIS-like size.



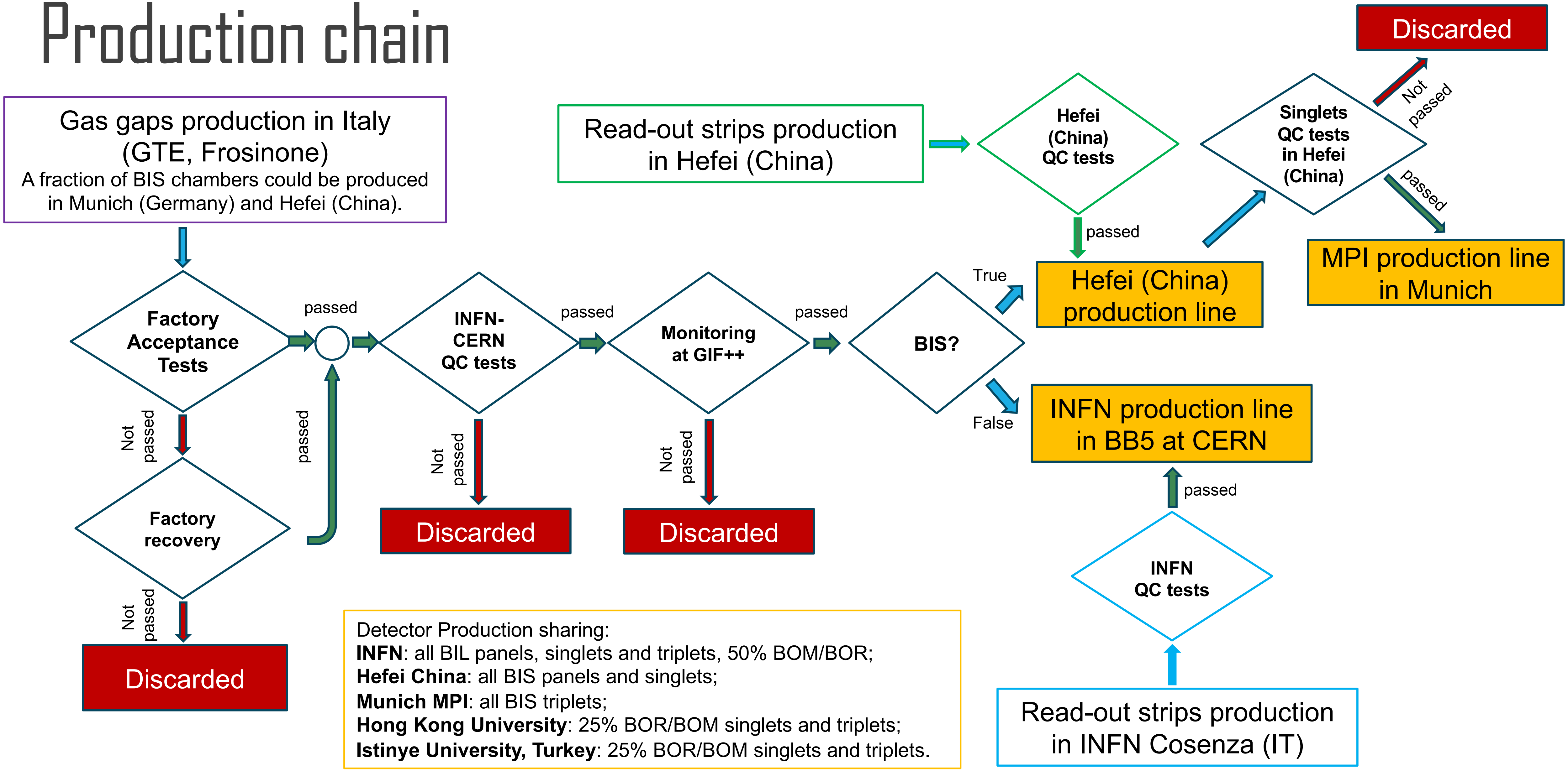






Standard Layout Sector 13A as an example

Production chain



Detector Production sharing:
INFN: all BIL panels, singlets and triplets, 50% BOM/BOR;
Hefei China: all BIS panels and singlets;
Munich MPI: all BIS triplets;
Hong Kong University: 25% BOR/BOM singlets and triplets;
Istinye University, Turkey: 25% BOR/BOM singlets and triplets.

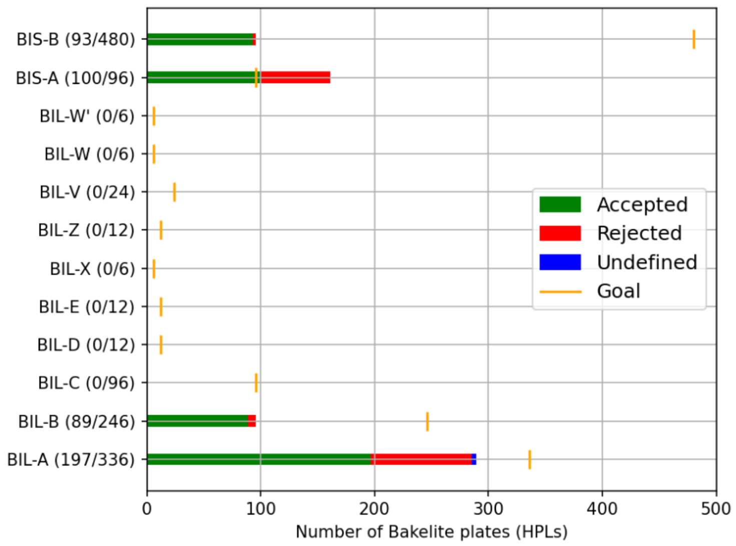
Production Database

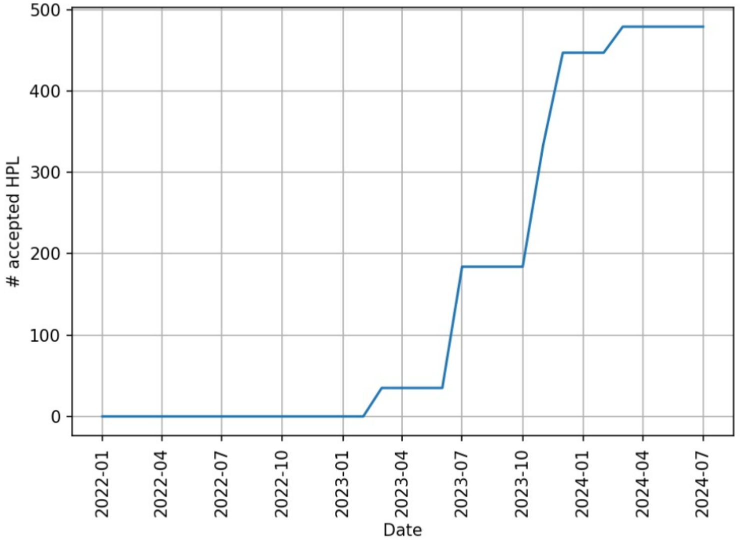
Infrastructure

- mySQL DB managed via a web interface to keep track of components (gas gaps, bakelite plates)
    - Including relationships (i.e. what goes into what).
- Web interface for presenting QAQC test results (e.g. I-HV curves) for components.
- Based on CERN-login, now restricted to users involved in the activity.

Status:

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





Factory Acceptance Tests Documents

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/10^5 Ω for BIS and < 0.3 μA = 30 mV/10^5 Ω for BIL)

Current 24.4 [mV/10^5 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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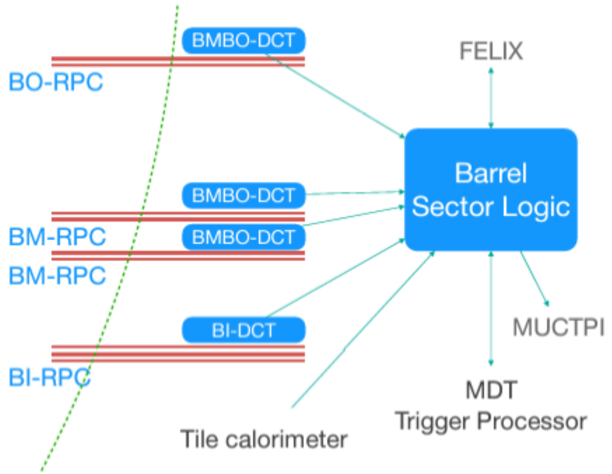
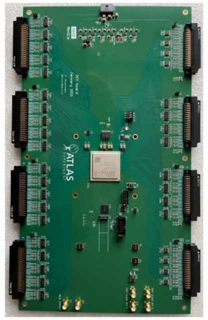
Data Collector and Transmitter (DCT)



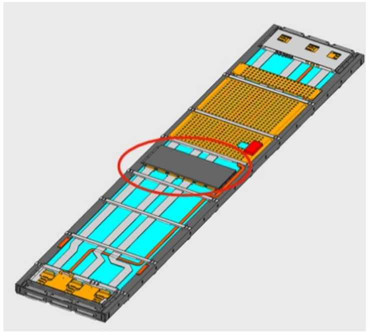
DCT connects detector FE with Barrel Sector Logic (SL), where trigger logic operations are performed. Two kinds of DCTs are developed:

- **BMBO-DCT (Legacy RPC system):** receives hit analog pulse from FE, **measures arrival time with FPGA-TDC** and sends time data to the SL.
  - **1° prototype HW and SW extensively tested:**
    - Communication test with SL;
    - Readout test with a BML chamber in INFN Rome Tor Vergata:
      - 0.8 ns time resolution on time of flight of cosmic between two RPCs;
      - 0.24 ns TDC time resolution on η-φ panels facing same gap.
  - **2° prototype under test, irradiation test completed.**

  1208 BMBO-DCT foreseen to be installed.

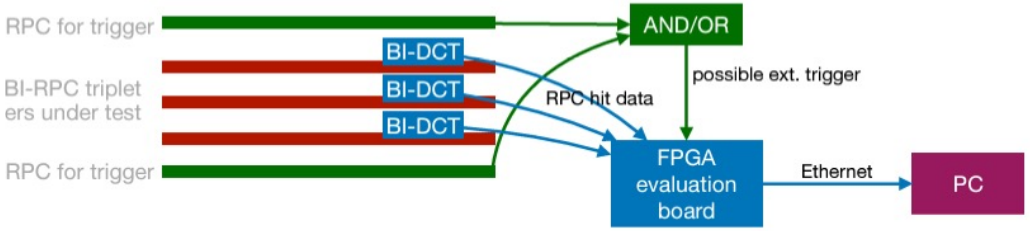


1st BMBO-DCT prototype

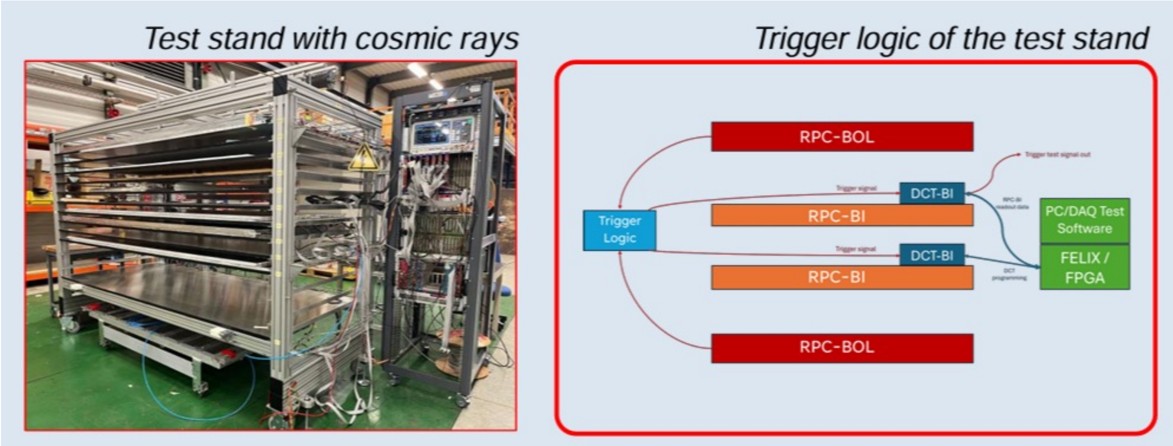


- **BI-DCT (BI-RPC):** receives hit time digital data from FE-TDC, decodes and sends BCID tagged time data to SL, reconstruct φ coordinate from time difference of two η-η readouts.
  - Schematics ready, first prototype being submitted.
  - FE-DCT communication test ongoing.
  - Planned to be tested in cosmic ray test station at CERN BB5.

  338 BI-DCT foreseen to be installed.



Cosmic ray test stand



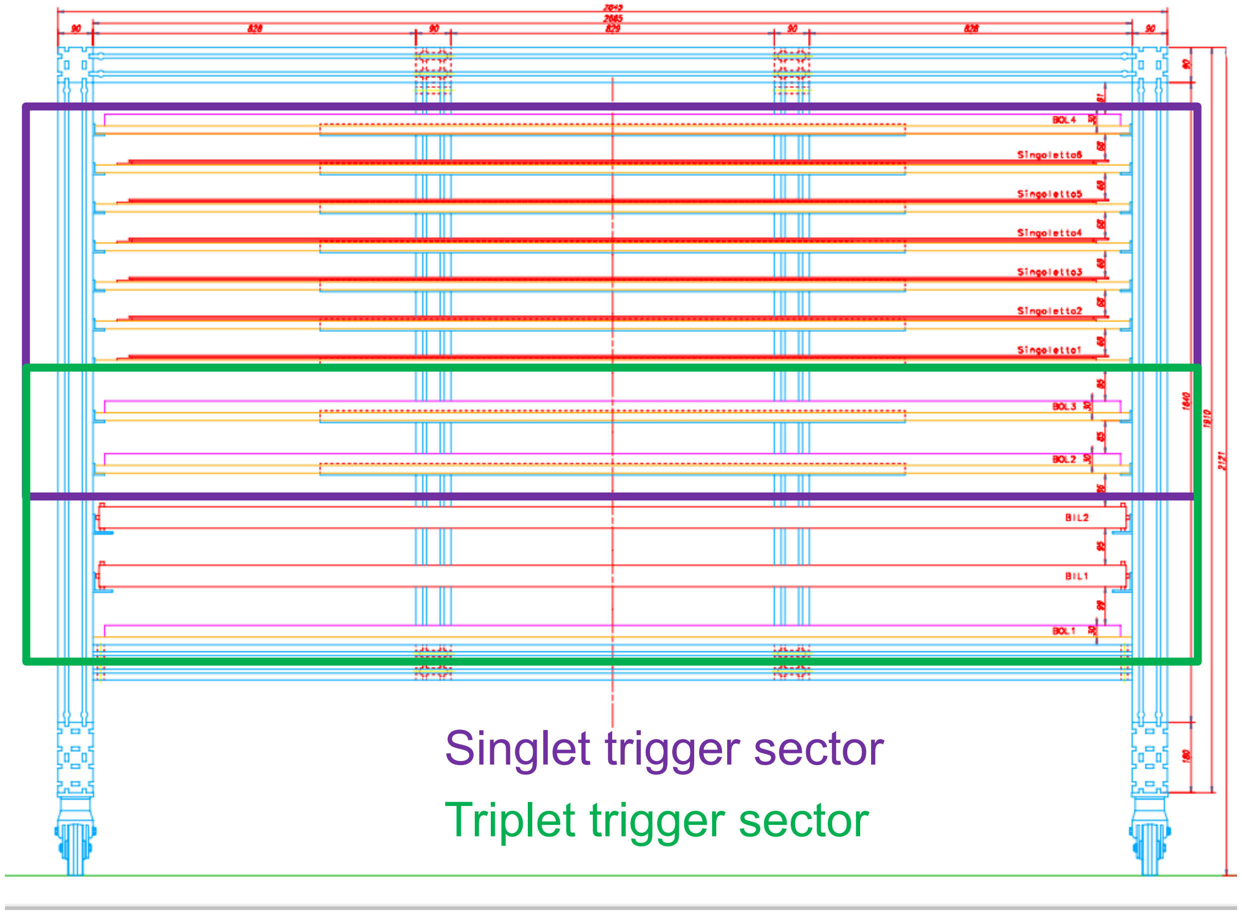
Two trigger sectors available for QA/QC tests:

- **Upper sector to certify up to 6 BIL singles**
- **Lower sector to certify up to 2 BIL chambers (triplets)**

Tower structure with 4 RPC Legacy detectors used as trigger:

- 1 on the top;
- 2 in the middle;
- 1 on the bottom.

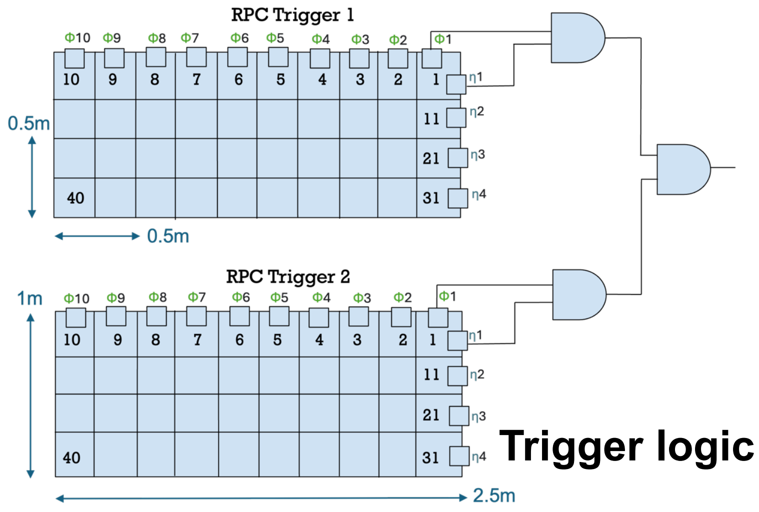
The height of the trigger detectors can be adjusted according to the number of detectors under test and to optimize certification under production.
All the 4 RPC gas volume and 8 read-out panels have been refurbished and the trigger detectors have been assembled at CERN and installed.



Trigger logic and performance

A measurement of the **trigger time resolution** for the cosmic ray test stand has been performed after the installation of 2 trigger detectors.
The trigger logic has been implemented on an open FPGA module with up to 196 input-output channels interface:

- Quadruple coincidence of 4 read-out planes (2 RPCs with η and φ coincidences);
- 40 Regions of Interest (RoIs) defined in the FPGA to perform an online trigger topology and tracking and acquired with a TDC to validate the system.

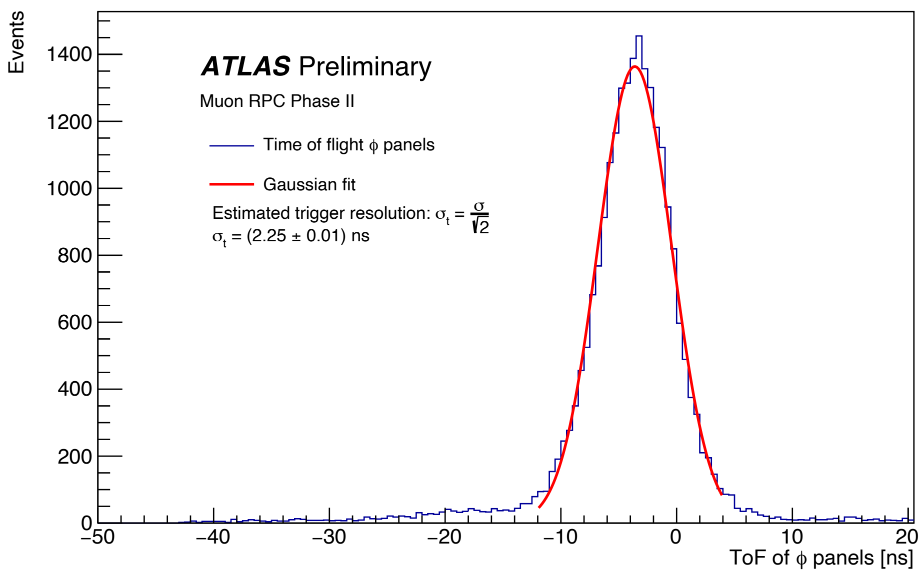


Trigger logic

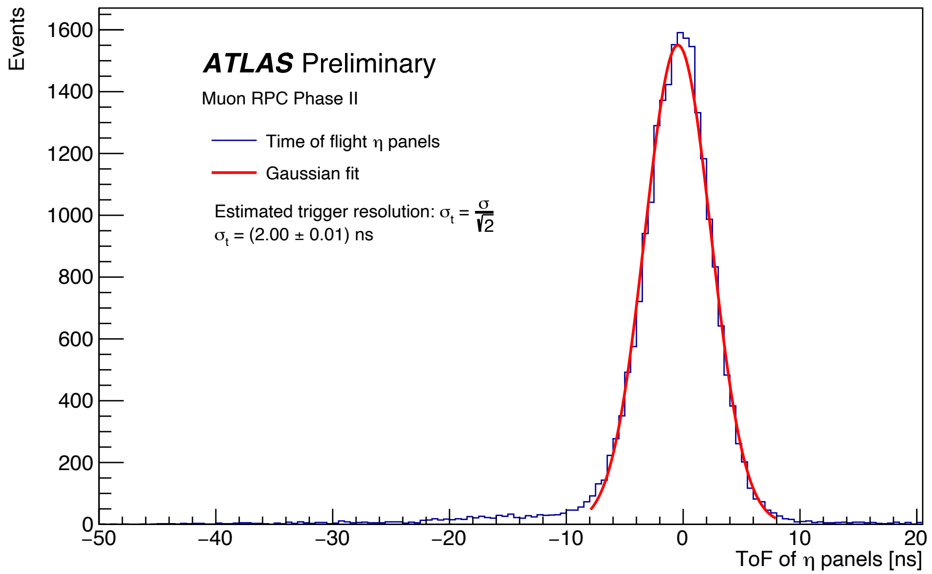
The time of flight is estimated by selecting tracks with hits in each of the 4 panels.
Time resolutions of 2.25 ns and 2.00 ns were measured for φ and η panels, respectively.

The rate produced by the FPGA trigger logic is also compared with an equivalent NIM one.

Time response of φ panels



Time response of η panels



Conclusions

New state-of-the-art RPC detectors have been developed:

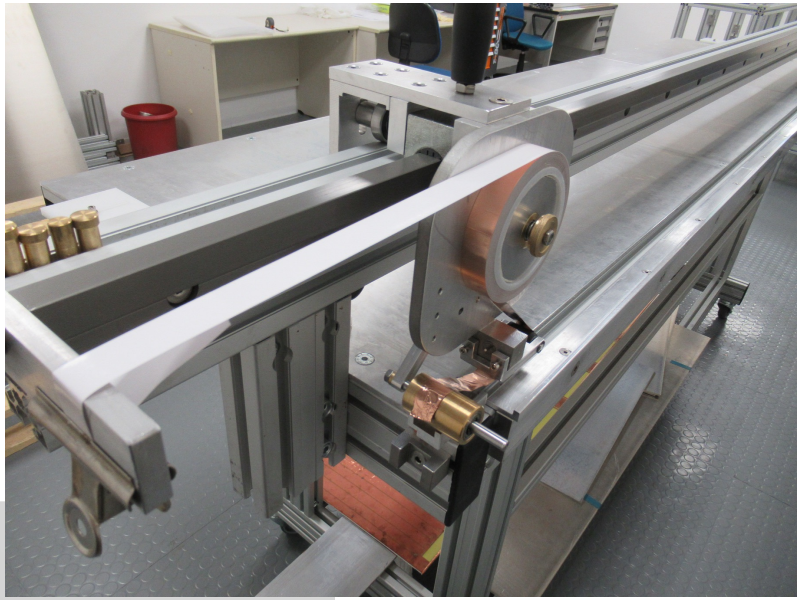
- New gas volume with 1 mm gas gap thickness with improvements on gas and high voltage distributions:
  - Improved time resolution from 1 ns to 0.4 ns;
  - Reduced singlet thickness (13 mm);
- New FE electronics consisting in Si technology preamplifier and SiGe-HPT ASIC with Discriminator and TDC embedded:
  - Sensitivity to signal of 1-2 fC;
  - TDC Time resolution around 100 ps;
- Second coordinate reconstruction capability through difference of signal propagation times along the strip;
- Improved rate capability up to 10 kHz/cm^2;
- New on-detector DCT developed with about 250 ps time resolution.

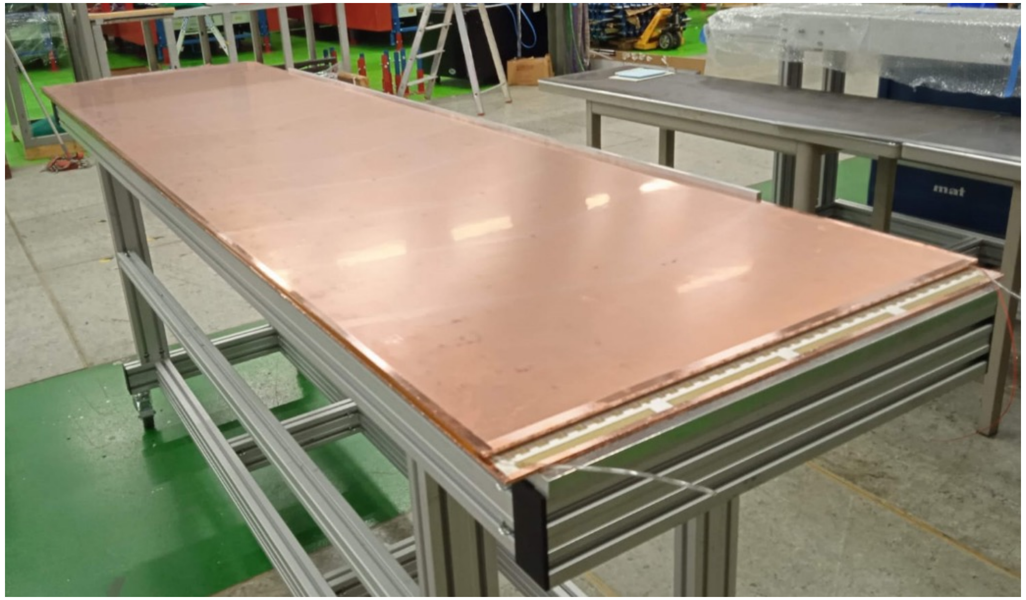
Detector components production started:

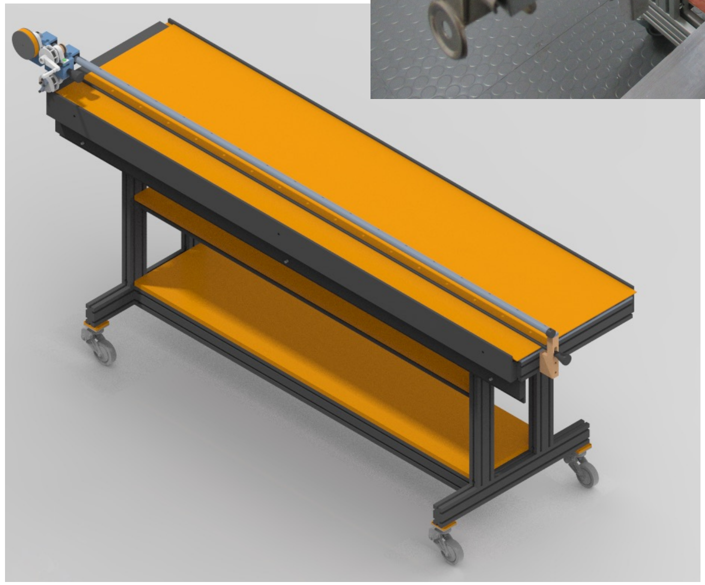
- Gas gaps production and test in Italy; two additional producers under qualification;
- Readout panels assembly and test in INFN Cosenza and Hefei China;
- FE electronics is close to complete the integration tests, ASICs already partially produced;
- BMBO-DCT second prototype under validation. BI-DCT first prototype close to production;
- Prototype of the chamber mechanics started after tender assignment.

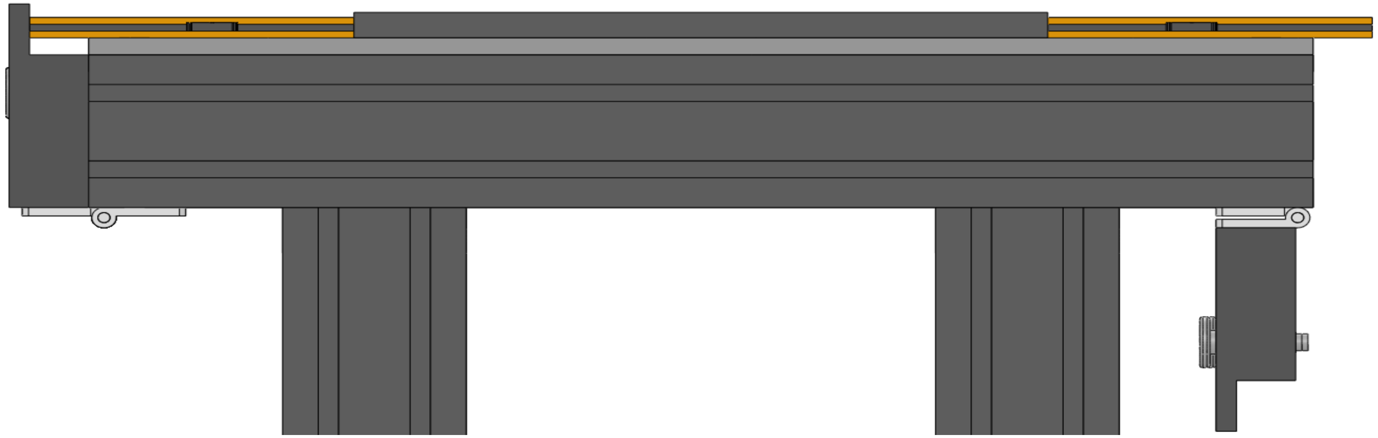
Back-up slides

Production at CERN

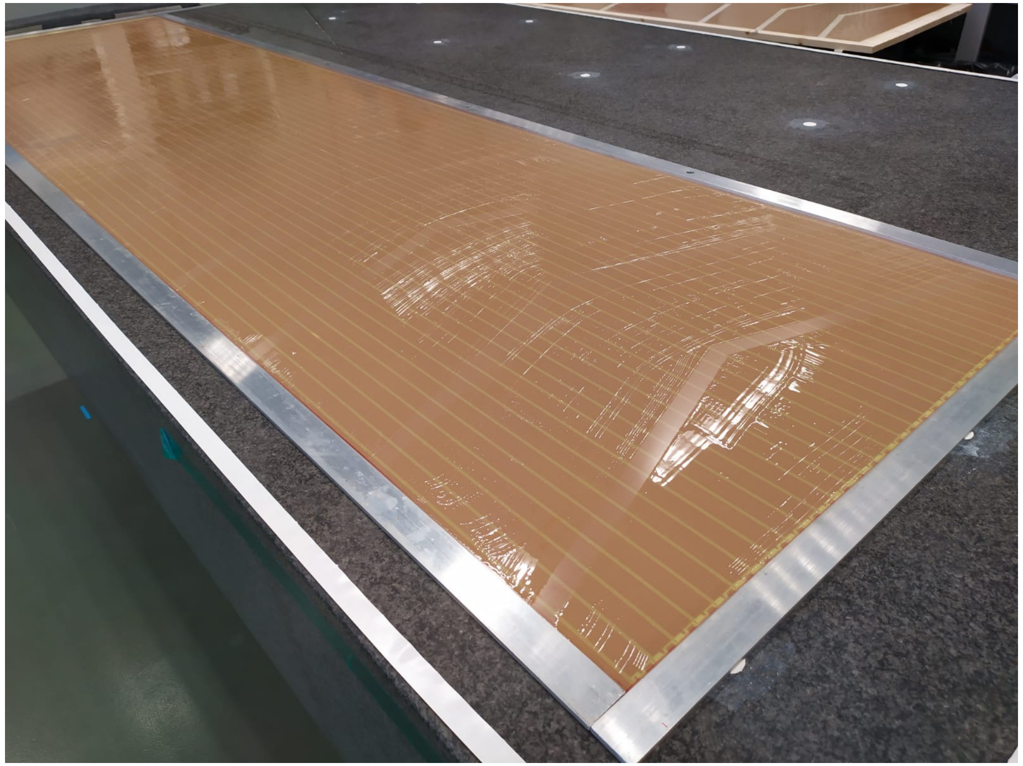








Read-out panels



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.

Power System

For Phase II, an upgrade of the current Muon Power System is expected. This consists in new modules for LV, HV and ADC for all the Muon detectors. Alongside new power modules, a new Branch Controller is introduced (CAEN R6060) which is responsible for the communication between the DCS and the remote crates.
The modules for the BI-RPCs currently have highest priority.

Radiation hardness tests being carried out at the CHARM facility.