Large Scale Test and Performances of the RPC Trigger Chambers for the Atlas experiment at LHC

G. Aielli\textsuperscript{a}, M. Alviggi\textsuperscript{b,c}, V. Ammosov\textsuperscript{d}, M. Bianco\textsuperscript{e, f}, P. Camarri\textsuperscript{g}, V. Canale\textsuperscript{b,c}, M. Caprio\textsuperscript{b,c}, R. Cardarelli\textsuperscript{a}, G. Carlino\textsuperscript{b}, G. Chiodini\textsuperscript{e}, M. R. Coluccia\textsuperscript{e}, R. de Asmundis\textsuperscript{b}, M. Della Pietra\textsuperscript{b,c}, D. della Volpe\textsuperscript{b,c}, A. Di Ciaccio\textsuperscript{a,g}, A. Di Simone\textsuperscript{a,g}, E. Gorini\textsuperscript{f, i}, F. Grancagno\textsuperscript{e}, P. Iengo\textsuperscript{b}, B. Liberti\textsuperscript{e}, S. Patricelli\textsuperscript{b,c}, R. Perrino\textsuperscript{e}, M. Primavera\textsuperscript{e}, R. Santonico\textsuperscript{a,g}, G. Sekhniaidze\textsuperscript{b}, S. Spagnolo\textsuperscript{e, f, g}, F. Tassielli\textsuperscript{e, f}, Yu. Svidorov\textsuperscript{d}, V. Zaets\textsuperscript{d}.

\textsuperscript{a}INFN sez. Rome2, Roma, Italy
\textsuperscript{b}INFN sez. Naples, Napoli, Italy
\textsuperscript{c}University “Federico II”, Napoli, Italy
\textsuperscript{d}IHEP, Protvino, Russia
\textsuperscript{e}INFN sez. Lecce, Lecce, Italy
\textsuperscript{f}University of Lecce, Lecce, Italy
\textsuperscript{g}University “Tor Vergata” Roma, Italy

Abstract—Resistive Plate Chambers will be used as trigger detectors in the barrel region of the Muon Spectrometer of the ATLAS experiment at the LHC. The total number of RPC units to be installed is greater than 1000, covering a total surface of about 3650 m\textsuperscript{2}. Three cosmic rays test stands have been designed and built in Naples, Lecce and Rome “Tor Vergata” INFN laboratories in order to carry out the Quality Assurance tests of the ATLAS RPCs. Although, the three test stands use different techniques to trigger and reconstruct cosmic rays, the same tests are performed and quality criteria applied. Since August 2002 more than 600 units have been tested, mainly in the Naples site. The large number of RPC units tested allows a statistical evaluation of the uniformity and stability of the main RPC characteristics over a large scale production. Most of the tested RPCs satisfied the required specifications and only a small fraction of them had to be rejected.

Index Terms—RPC, ATLAS, Quality Assurance, Cosmic Rays Test.

I. RPCs FOR THE ATLAS EXPERIMENT AT LHC

The ATLAS experiment uses bakelite RPCs as trigger detectors [1] in the barrel region of the Muon Spectrometer to fulfill the following requirements: high efficiency (> 97%), good time resolution (∼ 2 ns), high rate capability (up to ∼ 100 Hz/cm\textsuperscript{2}), and measurement of the second space coordinate in the spectrometer non-bending plane (space resolution of 5-10 mm). An RPC unit contains two (BMS unit type) or four (BML, BOS, and BOL unit types) active gas volumes which are disposed on two parallel layers. Each gas volume is made of two bakelite plates having a bulk resistivity in the range of (1-4)×10\textsuperscript{10} Ωcm and a thickness of 2 mm. The external surfaces are varnished with graphite paint, while the internal surfaces are coated with linseed oil. The bakelite electrodes are kept 2 mm apart by polycarbonate spacers and frame (see Fig. 1). The gas mixture is C\textsubscript{2}H\textsubscript{2}F\textsubscript{4}/C\textsubscript{4}H\textsubscript{10}/SF\textsubscript{6} in the fractions of 94.7%/5%/0.3% and the gas working mode is the saturated avalanche regime. The pick-up electrodes are strip-shaped copper panels, with a pitch ranging between 26.4 mm and 33.9 mm. Two read-out panels are respectively positioned on the top and on the bottom of the gas volumes, with the strips oriented orthogonally (η and φ coordinates) and insulated from the gas volume with a 190 μm thick PET layer.

More than 1000 RPC units will be installed in ATLAS covering a total surface of about 3650 m\textsuperscript{2}. The extreme difficulty in accessing the ATLAS sub-detectors, after installation is complete, imposes a high standard Quality Assurance for these units.

Corresponding author: M. Della Pietra.
Tel.: +39 081676125. E-mail: massimo.dellapietra@na.infn.it
II. COSMIC RAYS TEST STANDS

In order to perform the Quality Assurance test of the ATLAS RPCs three cosmic rays test stands have been designed and built: one in Naples INFN and University of Naples “Federico II”, one in Lecce INFN and University of Lecce, and one in Rome2 INFN and University of Rome “Tor Vergata”. The Naples test stand is operative since August 2002 and more than 500 units have been already successfully tested. The Lecce test stand is fully operational since July 2004 and about 100 units have been successfully tested up to now. Finally, The Rome2 test stand has been built in order to test the biggest RPC units (BOL unit type) which are expected to be produced at the end of 2004.

Even though, the three test stands use different setups and techniques, the Quality Assurance of the ATLAS RPCs is guaranteed at the same level. To ensure this 32 RPC units have been tested both in Naples and Lecce sites. The cross check of the results showed the compatibility of the two independent outcomes, particularly, in terms of accepted or rejected chambers.

A. The Naples cosmic rays test stand

The mechanical structure of the Naples test stand [3], [4] consists of 4.5 m long, 2 m wide, and 3.2 m high iron made support frame (see Fig. 2). It hosts (on the top and on the bottom) two carriages where the trigger and tracking systems are placed. Each one is composed by a 1 m² scintillator plane and a multilayer drift chamber. The drift cells are 27 mm high, 92 mm wide, and 1200 mm long, with a maximum drift path of 46 mm. Two adjacent drift planes are shifted by half of the cell size to reduce the left-right ambiguity. A cosmic ray crossing the apparatus can be detected in the drift chambers with a maximum of 4 points in the x-z view and 4 points in the y-z view, which are then available for off-line track reconstruction. The space-time drift relation is determined for each run with an autocalibration procedure based on a likelihood method. The off-line reconstruction efficiency is about 96%, however tight selection criteria are applied on the candidate tracks to improve the space resolution of the projected tracks, reducing the sample to about 50% of the triggered cosmic rays. In Fig 4(a) the distribution of the single wire drift chamber residual, defined as the difference between the coordinate of the projected track and the measured coordinate, shows that a space resolution of about 40μm is achievable.

The RPC detector under test are positioned by a manually mobile carriage between the two trigger and tracking systems. The two systems can be synchronously moved by two remotely controlled motors, in order to scan the whole active surface of the RPC detectors. The mobile carriage can accommodate up to 8 RPC units, which can be simultaneously tested.

The scintillators, the drift chambers, and the RPC detectors are readout by three different hardware systems. The trigger scintillator signals are acquired by Time Digital Converter (TDC) modules having a sampling time of 25 ps and hosted in a CAMAC crate. Instead, the arrival time of the electrical pulses, sent by the drift chamber read-out channels, are acquired by 1.04 ns sampling time TDC modules based on VME standard. Finally, electrical pulses from RPC read-out channels are first converted from ECL signal standard to TTL signal standard, with a pulse width of 30 nsec, by Receiver modules (custom made at INFN Roma2), then acquired by 25 ns sampling time TDC based on VME standard (Latch modules custom made at INFN Lecce). A total number of more than 3300 RPC front-end electronic channels are readout.

The data acquisition is performed by a computer connected through MXI-PCI bus interface to VME crates, resulting in an acquisition rate of 8 Hz. In addition, a dedicated detector control system, based on National Instruments® hardware and software (Labview®) solutions, was developed in order to set and control all the detector working parameters (gas flow and
mixture composition, gas volumes applied high voltage and dark current, front-end channels voltage threshold and current absorption) as well as the environmental parameters (atmospheric temperature, pressure, and relative humidity). All the values are continuously stored in a dedicated database allowing to get their historical trends and correlations. The measured values of the atmospheric pressure \( p \) and gas temperature \( T \) are used to correct in real time the RPC operating voltage by scaling the gas volume applied high voltage \( V_o \) according to the relationship:

\[
V = V_o \frac{p_T}{pT_0}
\]

where \( T_0 = 293.15 \, ^\circ\text{K} \) and \( p_0 = 1013 \, \text{hPa} \) are the arbitrarily chosen pressure and temperature reference values \([5]\). A particular task of the slow control system is to take care of the RPC gas distribution and allow an automatic leak test of the RPC gas volumes.

Automatic analysis software procedures have been developed to carry out the RPC Quality Assurance tests and the results are published on the web and stored in a local database.

### B. The Lecce cosmic rays test stand

The mechanical structure of the Lecce test stand is similar to the Naples one. It is 4.3 m long, 2.2 m wide, and 3.4 m high. Moreover, as the above Naples setup, the apparatus consists of several subsystems: gas distribution, high voltage distribution, low voltage distribution, trigger logic, RPC detectors VME readout standard, and data acquisition and detector control system based on National Instruments® hardware and software solutions.

The most relevant difference of Lecce test stand \([6]\), with respect to the previous one, is the use of a standalone cosmic ray trigger and tracking system built with 4 pre-tested ATLAS RPC units of BOSB type (covering a surface of about 4.3 m²). The trigger signal is obtained by logic unit modules, based on NIM standard, which realize the time coincidence between the fast logical OR signals of different Trigger RPC read-out panels (see fig. 3). The fast logical OR signal of each read-out panels is provided by the Latch modules itself.

The advantages of this setup are a complete coverage of the chambers under test, avoiding time consuming position scans, the use of one readout system (Receiver modules and Latch VME modules) and one output data format, and the possibility to monitor RPC detector behaviors in the long term for the trigger chambers. In addition, a large number of independent gas lines (one for each gas volume layer), high voltage and low voltage channels (one for each read-out panel) are present, in order to easily isolate defective detectors.

The cosmic rays are selected with a loose trigger request and further refined on-line, requiring a minimum and a maximum number of hits in the trigger RPC. This strategy allows to consider events with well reconstructed tracks and reject noisy and multi-tracks events. Moreover, the resulting acquisition rate is of about 50 Hz.

Events are then analyzed off-line looking for straight tracks (85% of the events contain good track candidates). Those tracks are then used for efficiency computation of the RPCs under test and for monitoring purposes.

The monitor, control, and readout software is based on Labview®. In addition, configurations, runs and results are managed by MySQL databases and presented via web interface.

The gas volume high voltage correction (described in section II-A) is done off-line and not in real time by the detector control system such as in the Naples setup.

In Fig 4(b) the distribution of a single strip RPC residual shows a space resolution compatible with a strip pitch of about 28 mm \( (\sigma_x = \frac{\text{strip pitch}}{\sqrt{2}}) \). The projected track space resolution, reached by the RPC trigger chamber, is enough accurate to perform a tomography of the chambers under test (see section III).

### C. The Rome2 cosmic rays test stand

The mechanical structure of the Rome test stand is also similar to the previous two, but larger. It is 8 m long, 1.5 m wide, and 4 m high. Moreover, the trigger and tracking techniques are the same as implemented at the Lecce site, this is based on 4 pre-tested ATLAS RPC of BOL type. The peculiarity of this test stand with respect to the Lecce one, is the large size of the RPC chambers that must be tested. In fact, the active area covered by these detectors is about 5.6 m² and a total number of 5376 RPC front-end electronic channels must be readout.
III. QUALITY ASSURANCE TEST

The ATLAS RPC Cosmic Rays Quality Assurance is a detailed procedure composed by several tests, performed at each site, in order to verify that all the requirements on the RPC performance are fulfilled. The tests are the following:

**I-V Curves** - The gas volume RPC dark currents are continuously monitored in order to verify that no anomalous increase of the dark current during the test period occurs. In Fig. 5 the dark current versus the applied high voltage is shown for gas volume belonging to the same chamber. The current-voltage characteristics show a linear increase of the current at low voltage, followed by an exponential grow at higher voltage. The current versus voltage curves are interpolated by the following formula:

\[ I = V/R_{Bulk} + I_0 e^{V/V_0} \]

where \( R_{Bulk} \) is the ohmic contribution, \( I_0 \) is the average primary cluster charge per unit time, and \( V_0 \) depends on the effective Townsend's coefficient of the gas mixture.

Gas volumes with high dark currents (greater than about 10 \( \mu \text{A/m}^2 \) at the RPC working point) are rejected and substituted.

**Single Rates** - Two different measurements are performed in order to measure the uncorrelated activity of the detector. In the first one an external 20 Hz trigger open a time window of 500 ns and the counting rate due to the dark current of all read-out channel is measured. This measurement allows the identification of the noisy read-out strips.

In the second method the RPC hits of each read-out strip panel are counted all together by a scaler for different high voltages and front-end voltage thresholds. In particularly, at low values of the gas volume voltage, when the RPC detector activity is negligible, the noise only due to the front-end electronics can be measured and pathological cases of read-out panels identified.

**Efficiency Curves** - In this test the detector efficiency is measured as a function of the applied high voltage and for different front-end voltage thresholds, allowing to determine the detector working point. The efficiency curve for \( \phi \) and \( \eta \) read-out strip panels is measured separately for each RPC gas volume. For each high voltage value and voltage threshold value 10 thousand events are collected. This allows to measure the efficiency with a statistical error less than 0.3%. A read-out panel is considered efficient if, in correspondence to the track impact point, obtained by projecting the cosmic ray track reconstructed by the tracking chambers, a hit from a read-out strip is detected inside a fiducial region. The size of the fiducial
region is chosen according to the reconstruction resolution and geometrical misalignment between RPC detectors and tracking detectors. The width of the fiducial region, of about ±20 mm, is slightly different between Naples and Lecce site, being optimized separately, to lead to a systematic error on the efficiency of about 0.5%. The efficiency curves (see Fig. 6) can be interpolated by a Fermi function:

\[
\varepsilon = \frac{\varepsilon_0}{1 + e^{B(V - V_{50\%})}}
\]

in order to evaluate the efficiency value at plateau \(\varepsilon_0\), the high voltage value \(V_{50\%}\) at which the efficiency is 50% of \(\varepsilon_0\), and the high voltage drop \(\Delta V_{10\%-50\%}\) between the 10% and the 90% of the efficiency with respect to \(\varepsilon_0\), which is related to the fit parameter \(B\). The distribution of the number of adjacent hits associated to a track (cluster size) and the distribution of the number of clusters per event (cluster multiplicity) are also measured during the efficiency curves test. In fact, they are crucial figures of merit to understand the detector performances. The tests show that, at the detector working point, the average cluster size is typically 1.5 and the cluster multiplicity is basically one, proving that the read-out strip cross-talk and correlated noise are small.

**Space Efficiency Uniformity (Tomography)** - The space uniformity of the gas volumes efficiency (tomography) is measured in two dimensions, in order to identifying any small region of inefficiency. This is done considering efficient a local gas volume region when, in correspondence to the track impact point, at least a hit is detected on the \(\eta\) or \(\phi\) read-out panels. In fact, when an electronic avalanche develops in the gas volume, it could be safely assumed that the probability of no hits on the two read-out panels is negligible. In addition, when tracks leave hits only in one read-out panels, it is evidence of electronic inefficiency of the not-responding panel.

In Fig.7 two RPC tomographies of an active layer (constituted by two adjacent gas volume) are shown. In both examples it is possible to notice regularly localized inactive spot, due to the 1 cm polycarbonate spacers, and a narrow region of inefficiency near the gas volume borders, due to the polycarbonate frame. In case of real gas volume defects, due for example at construction errors, regions or spots of inefficiency are clearly visible and than detected by the test. To perform the two dimension tomography a high statistic set of reconstructed muon tracks is needed (at least 20 tracks/cm²).

**Gas Tightness** - During the Quality Assurance procedure each gas volume undergoes a leak test to ensure its gas tightness. The differential pressure, between the gas volume of the RPC under test and a reference gas volume, is monitored for three hours, after imposing about 3 mbar of over-pressure and closing the gas inlet and outlet. An RPC unit is accepted only if it passes all the described tests. In 2004 spring 32 units have been tested in both Naples and Lecce sites in order to check if the different hardware and software solutions, chosen in building the test stands, could introduce some systematic effect in the Quality Assurance tests. No significant differences between Naples and Lecce results have been observed and the same decisions were taken about accepting or rejecting a detector unit or their components.

### IV. TEST STATUS AND RESULTS

Up to October, 2004 about 550 RPC units have been approved by Quality Assurance test in Naples and Lecce, representing more than 52% of the total number of RPC units foreseen in ATLAS. Fig. 9 shows the test rate of both Naples and Lecce sites. A summary of the test status for each RPC type is shown in table I, where the numbers in parenthesis represent the fraction of detectors with respect to the total number of units needed for ATLAS.

![Fig. 6. Example of plateau curves for both \(\eta\) and \(\phi\) read-out panels related to the same gas volume. The corresponding value of the parameters \(\Delta V_{10\%-50\%}\) and \(V_{50\%}\) are shown. The high voltage HV is normalized as explained in section II-A.](image-url)
Fig. 7. On the left: RPC tomography done in Naples with high space resolution. On the right: RPC tomography done in Lecce with the RPC tracking. Inactive regions due to the gas gap spacers and frame are clearly visible.

Fig. 8. On the left: gas volume efficiency distribution at working point. On the right: distribution of the fit parameter $V_{60\%}$ obtained by fitting the gas volume efficiency curve.

shown in Fig. 8(b). A clear peak in this distribution indicates a good homogeneity in the working parameters for chambers constructed and tested in different times and conditions.

In table II are reported the RPC single component rejection factors obtained from the ATLAS RPC Quality Assurance. You can see that the RPC chamber rejection factor due to the presence of one defective gas volume is only 5%. The table also shows the gas volume failure fraction due to wide inefficient regions, to high dark current, to a gas leak, and for other causes. The rejection factor is even lower for read-out panels. In fact, only 2.5% of the read-out panels has been repaired because they presented more than two inefficient channels or they were too much noisy (see table II).

V. CONCLUSIONS

THREE cosmic rays test stands have been built and designed, in different sites in Italy, to carry out the Quality Assurance of the RPCs for the ATLAS experiment at LHC. One of them is fully operative in Naples since August 2002 and another one started its routinely operation in Lecce on July 2004. Each site has a tested chamber rate of about 8 RPC units per week and, up to now, 552 units have been certified as goog, corresponding to about 52% of the ATLAS Muon Spectrometer. The third cosmic rays test stand, located in Rome, is ready to start its program at the beginning of 2005. The statistical distribution of the RPC characteristics, accumulated with the tests, proves that the RPCs performances are stable and uniform, satisfying the experiment requirements. Up to now 95% of the approved gas volumes has an efficiency greater than
Fig. 9. Total number of ATLAS RPC units certified by Quality Assurance Test Since August 2002. Left axes reports the total number of RPC certified, the right one the corresponding fraction respect to the total.

<table>
<thead>
<tr>
<th>Gas Volumes</th>
<th>Read-out Panels</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tested</td>
<td>2114</td>
</tr>
<tr>
<td>Approved</td>
<td>94.7%</td>
</tr>
<tr>
<td>Rejected</td>
<td>5.3%</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Failure reasons</th>
<th>Gas Volumes</th>
<th>Read-out Panels</th>
</tr>
</thead>
<tbody>
<tr>
<td>High current</td>
<td>2.3%</td>
<td>Dead</td>
</tr>
<tr>
<td>Local inefficiency</td>
<td>1.6%</td>
<td>Noisy</td>
</tr>
<tr>
<td>Gas leak</td>
<td>0.5%</td>
<td>Inefficient</td>
</tr>
<tr>
<td>Other reasons</td>
<td>0.9%</td>
<td>Other reasons</td>
</tr>
</tbody>
</table>

97%, as expected by the evaluation of the detector active area. Moreover, the average efficiency of the read-out panels is about 98% as required by the project design. The studies also show that the failure rate of the single RPC components, mainly gas volume and read-out panels is acceptable. In fact, we found an average rejection rate of 5% for the gas volumes, which are discarded, and 2.5% for the read-out panels, which are repaired. The end of the Quality Assurance test is foreseen on July 2005.

REFERENCES