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Quality Assurance Tests of the CMS Endcap RPCs

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Abstract

In this note, we have described the quality assurance tests performed for endcap Resistive Plate Chambers (RPCs) at two different sites, Pakistan Atomic Energy Commission (PAEC) and National Centre for Physics (NCP), in Pakistan. This paper describes various quality assurance tests both at the level of gas gaps and the chambers. The data has been obtained at different time windows during the large scale production of CMS RPCs of RE2/2 and RE2/3 type. In the quality assurance tests, we have investigated parameters like dark current, strip occupancy, cluster size and efficiency of RPCs.

1 Introduction

Resistive Plate Chambers (RPC) are the dedicated detectors used for the first level muon trigger of CMS. Good performance of RPC is essential in assigning the muon to the right bunch crossing at the LHC. CMS uses double gap bakelite RPCs of 2 mm gas gap, operated in avalanche mode, whose design considerations have been proven successfulln in several tests [1].

The Pakistani group is responsible for the RPCs which are used in the CMS endcaps. For this purpose several prototypes were made from 1999-2003 and they were tested at European Centre for Nuclear Research (CERN) using the X5 beam [2]. A total number of 320 endcap RPCs were produced and tested. The shape of the RPC is trapezoidal and it covers 10° in ϕ. The endcap RPCs are double gap chambers with the readout strips running perpendicular to the beam line (in ϕ). Details of chamber construction are given in the next section.

2 Chamber Construction

A schematic diagram of a double gap resistive plate chamber is shown in Fig. 1. The bottom gap covers the entire chamber while the top gap was cut into two parts (narrow and wide). The gas gap consists of two bakelite plates each 2 mm thick and four polycarbonate edge profiles running along the four sides to seal the gas volume completely. Bulk resistivity of bakelite plates is of the order of 10^{10} Ω cm. Thickness of the gas gap is also 2 mm, which is kept uniform with the help of PVC spacers. Spacers are glued between the two bakelite plates, placed uniformly at a distance of 100 mm. The gas is allowed to pass through an inlet into the gas volume. The graphite is painted onto outer surfaces of the bakelite plates. The outermost layers of the bakelite sheet are connected with the high voltage while the inner sheet is grounded. The readout is performed by means of copper strips. The plane of readout strips is segmented on a 200 μm thick myler sheet with 1.5 mm inter strip spacing to pick up signals from both gas volumes. Top and bottom gaps are superimposed to sandwich the strips running between the two gaps. Charge is induced on the strips from both gaps to enhance the signal amplitude. An external aluminum frame encloses the chamber to ensure rigidity and protection. In addition, high voltage connectors and gas inlets and outlets are mounted on the outer aluminum frame.

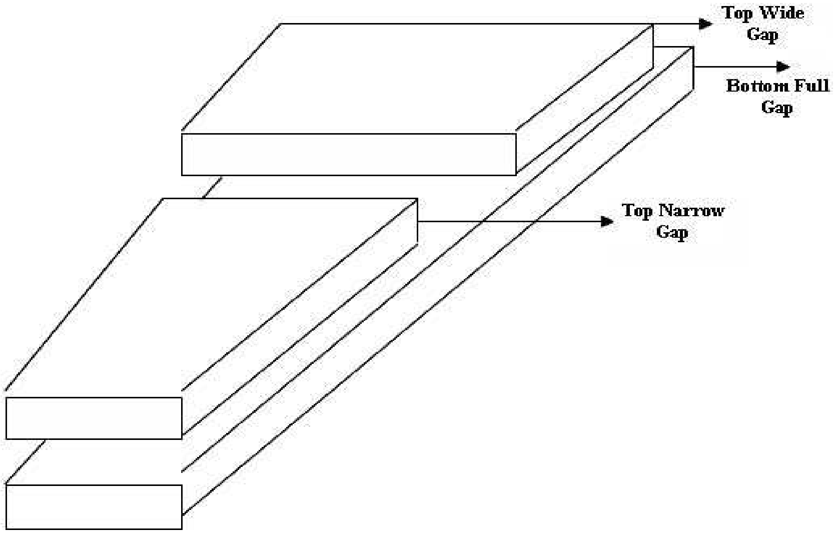


Figure 1: Gap segmentation of CMS endcap RPC.

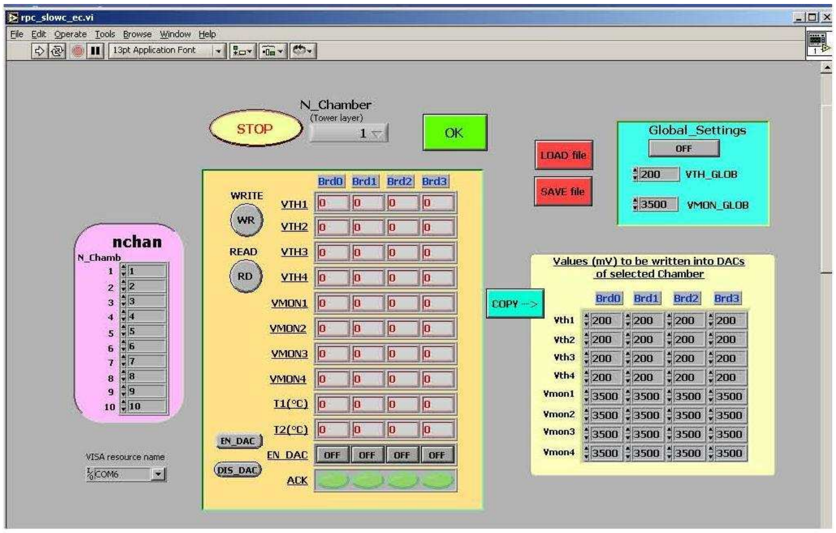
Quality assurance of the chambers consisted of the following steps.

- Pre-assembly testing or testing of components
- Gap testing
- Chamber testing

3 Pre-assembly testing and preparation

3.1 FEB Boards testing

Construction of FEB (Front End Board) for barrel RPC and endcap RPC is the same except that barrel FEB has 16 channels while endcap FEB has 32 channels. The setup used for FEB included a power supply, FEB test bench, RS232 cables and a computer with labView software. FEB was connected to com port of computer via RS232 serial cable. The LV power supply provided power to FEB. Input signals were generated with FEB test-bench setup. Verification of the existence of signals and their delay for each FEB channel was performed. The same procedure was followed for all Front-End Boards. All the data for each FEB board was stored in a database.



N_Chamber (Tower layer): 1

Global_Settings: OFF

VTH_GLOB: 200

VMON_GLOB: 3500

VISA resource name: COM6

nchan

N_Chamb	
1	1
2	2
3	3
4	4
5	5
6	6
7	7
8	8
9	9
10	10

	Brd0	Brd1	Brd2	Brd3
VTH1	0	0	0	0
VTH2	0	0	0	0
VTH3	0	0	0	0
VTH4	0	0	0	0
VMON1	0	0	0	0
VMON2	0	0	0	0
VMON3	0	0	0	0
VMON4	0	0	0	0
T1(°C)	0	0	0	0
T2(°C)	0	0	0	0
EN_DAC	OFF	OFF	OFF	OFF
ACK				

Values (mV) to be written into DACs of selected Chamber

	Brd0	Brd1	Brd2	Brd3
Vth1	200	200	200	200
Vth2	200	200	200	200
Vth3	200	200	200	200
Vth4	200	200	200	200
Vmon1	3500	3500	3500	3500
Vmon2	3500	3500	3500	3500
Vmon3	3500	3500	3500	3500
Vmon4	3500	3500	3500	3500

Figure 2: labView panel used to test FEBs.

Figure 3: Readout electronics and cooling system of chamber.

3.2 Coolant pipes

To extract heat from electronics, copper pipes were used for cooling system of the chambers. These pipes were bent with the help of jigs to follow the proper routing inside as well as outside the chamber. The pipes were heated with a controlled heating plate and then were put in the cold water. The time duration for heating of each shape varied and was monitored during the process. The pipes should not have any kinks after heating. Prepared pipes were then blown with dry air to remove moisture or any dust particles. For each pipe, one end was blocked and the other end was connected to the oxygen cylinder with a pressure regulator. Pressure was gradually increased upto 20 bar and was maintained for 5 minutes. Soap solution was used to check for any leaking at joints as well as brazing ends.

3.3 Coaxial cables and adapter boards preparation

Wire cutters and wire strippers were used for the preparation of coaxial cables. Each coaxial cable was cut with cable cutter, ruler and blocking jig attached to the table with proper length. The coaxial cables were prepared manually and then soldered to the adapter boards. The lengths of the conductor and braid ends were selected with the help of a jig screwed to the wire stripper. Each cable was tested for the insulation with the ground braid and central conductor.

3.4 Flat ribbon cables preparation

The flat cables were cut with the ribbon cable cutter and the length of each cable was measured before attaching connectors to the ends. The flat ribbon cables were prepared with the help of a vise. The connectors were carefully pressed in the vise. Each flat ribbon cable was tested before storage. The flat cable for the low voltage (LV) supply was also cut, prepared and tested in the same way.

3.5 Epoxy filling for high voltage connectors

HV connectors were soldered along with the four ground connections and proper care was taken that the top red insulation of HV cables stays on the cables. The correct order of HV connections was maintained for the cut gaps and full gap. An epoxy was used to insulate soldered connections inside the connector. The epoxy was filled with the help of a syringe when a set of twelve chambers was ready. The epoxy was left for 24 hours to dry. For preparation of epoxy, the CATALYST used was 18% of the STYCAST. The two portions were mixed gently for at least 5 minutes. A sample of used epoxy is retained for future reference.

4 Gap testing

4.1 Visual test

The dimensions of each gas gap were checked at random positions. The buckling of the gap was also noted and a gap bent more than 8 mm was rejected. The gas inlets, HV and ground connections were checked for any damage. Gas gaps that passed initial visual test were stored in a temperature and humidity controlled environment.

4.2 Leakage test

Two inlets of the gas gap were blocked and the other two inlets were connected to a gas system and a manometer respectively. Each gap was kept under 20 mbar pressure for 10 minutes and the pressure reading was observed on manometer. The gap was rejected if the pressure column on the manometer dropped by 4 mm after 10 minutes.

4.3 Spacer test

A template sheet marked with all spacer locations was placed on the gas gap. After 10 minutes of over pressure of 20 mbar in the 2 gas gap, the height of water column in the manometer was measured. Each spacer was pressed twice (5 N force at least) and the water column of the manometer was checked. If there was a sudden jump of about 1.5 - 3 cm then that spacer was considered as broken. This information was noted in the gas gap test check list and chambers with broken spacers were discarded.

4.4 High voltage scan and dark current

Gaps which passed the leakage and spacer tests were placed under high voltage with the gas mixture (Freon 95% and Iso-butane 4.5%) under 2 mbar pressures at 5 L/hr for 8 - 10 hours. The dark current was measured and the gaps with less than 5 - 6 μA current were accepted for assembly while others were rejected. SF_6 was not used while testing the gaps. The high voltage and dark current data was noted and graphs were plotted. The data and plots were saved in a database for future reference. All the tests were performed in a temperature and humidity controlled environment. The temperature and humidity readings were noted and stored in the database as well.

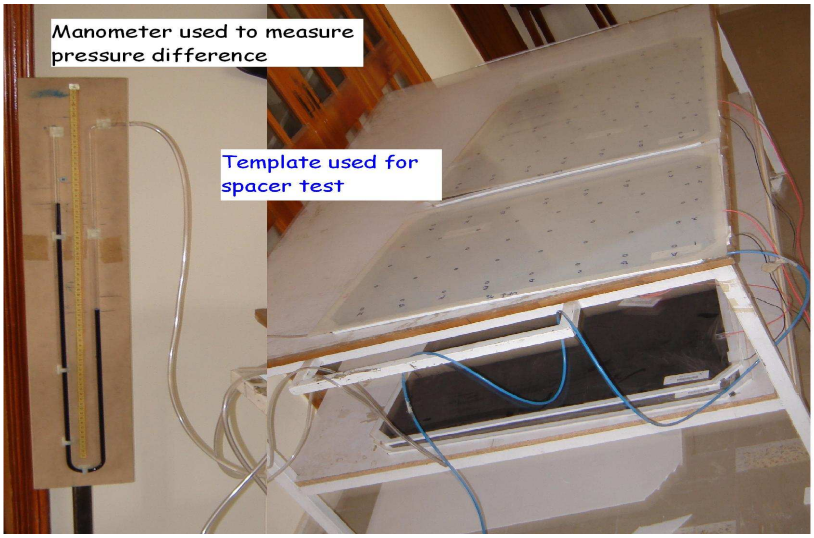


Figure 4: Setup used for spacer test.

5 Chamber Testing

5.1 Visual Inspection

For visual inspection of a chamber, its shielding cover was removed and all components including screws, connectors, signal cables and soldering were checked properly.

5.2 Conditioning (Gas Flow and High Voltage)

After visual inspection, chambers were placed horizontally in the cosmic ray stand. Each RPC was connected to the gas system, high voltage system and DAQ system. The gas system was based on a series of three BRONKHORST Hi-Tech EL-FLOW mass flow meter/controllers F-201C. The gas system is shown is Fig. 5. To test the chambers, the gas mixture composed of 96% $C_2H_2F_4$, 3.5% iso - C_4H_{10} and 0.5% SF_6 was distributed via parallel system to the chambers. The gas composition was monitored and recorded with a relative precision better than 1%. Gas flowing through the chambers was maintained at a rate of 5.6 L/hr for RE2/2 type chambers and 7.6 L/hr for RE2/3 type chambers. Gas was allowed to flow for 14 - 16 hours for 8 volume changes. Normally one volume change occurs in 2.0 - 2.5 hours. We did 8 volume changes, so that gas gaps were properly filled with gas, no air was left inside the gas gaps and gas was uniformly distributed in the gaps. After 8 volume changes of gas, high voltage of 8.4 kV was applied to the chambers for 6 - 8 hours so that the dark current of gaps becomes stable. Initially the fluctuations in the current were quite large, which clearly showed the presence of impurities (humidity, defects, etc...). These impurities needed to be burnt to keep the chambers at a constant HV for a long time to get the stability in the current. The behavior of dark current shown by the gaps was also monitored against high voltage. The value of dark current should be less than 5 μA at 9.6 kV. Chambers with current more than 5 μA were rejected. If the value of dark current remained stable and below 5 μA (which is required) then it was an indication that the chambers were ready for further testing.

5.3 Cosmic ray test

This section describes the setup used to study the general performance of the RPCs. The experimental area for the RPC testing was located in NCP laboratory. The cross-section of each RPC was exposed to cosmic ray muons as shown in Fig. 6. Apparatus used for cosmic test included high voltage power supplies, gas flow rate controller, gas mixture, trigger setup and data acquisition system. The hodoscope (cosmic ray muon stand) used in the test can house ten chambers at a time which can be tested simultaneously. The chambers were placed horizontally. Temperature of the laboratory was kept constant by air-conditioning systems, while humidity and temperature were monitored continuously with the help of proper devices.

The cosmic ray muon test stand for the RPC consisted of a muon trigger system that was generated by two layers of scintillators; one layer was located at the top while the other was at the bottom of the test stand. Each layer contained 8 scintillators and covered an area of 190 cm × 160 cm. Fig. 7 shows the scintillators locations, S1 on

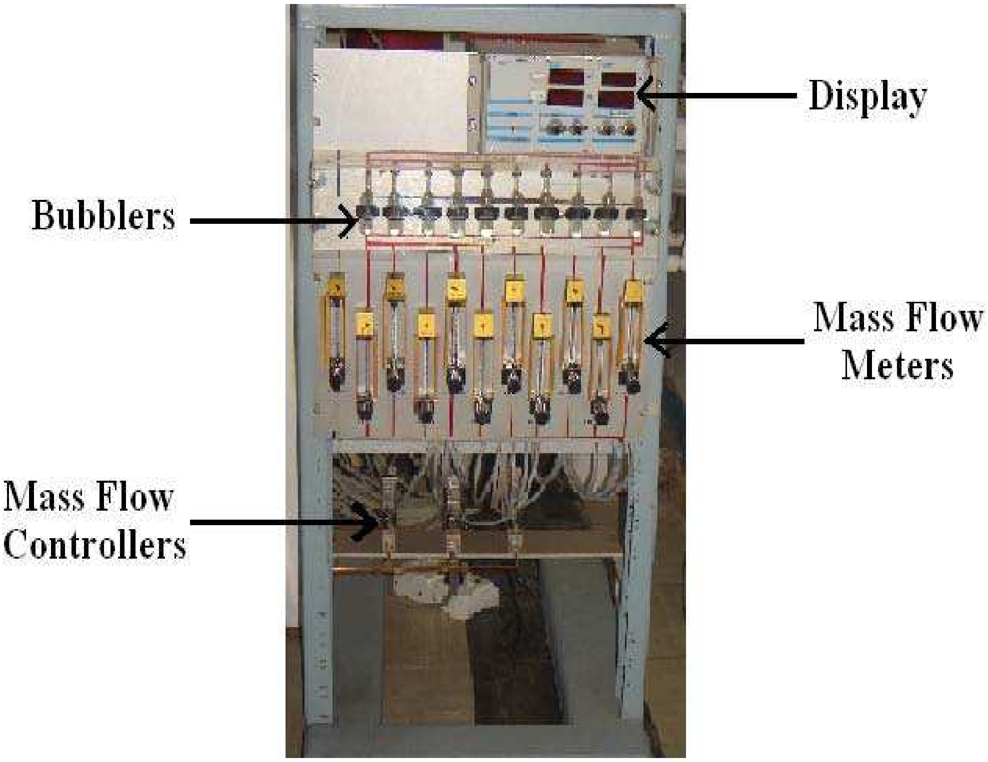


Figure 5: Gas system.

Figure 6: Cosmic ray stand for RPC testing.

top and S2 at the bottom of the test stand. Output of scintillator layers was connected to output of chambers in a logical “AND”. The gas system was based on mass flow meters and controllers. The gas mixture was composed of 96.5% $C_2H_2F_4$, 3.5% iso - C_4H_{10} and 0.5% SF_6 and was supplied in parallel to all ten chambers in the cosmic ray muon stand. The gas composition was monitored continuously. The high voltage power supply distribution was based on the Universal Multichannel CAEN/SY1527 unit which has the internal processor and internal network connections. The DAQ system consisted of two VME crates housing 15 TDC modules sampled by 40 MHz clock (which corresponds to 25 ns time sensitivity). Each TDC processes the LVDS signals after amplification and discrimination. The triggered signals were further processed by the data acquisition system. TDCs were operated in the common stop mode. When the trigger was generated the data was transmitted to a PC for storage and analysis. Different scripts and JAVA applets were used to display summary plots. A summary of the chamber performance was stored into the RPC Production Database, which was based on the MySQL database. Data for each chamber is also accessible through web interface.

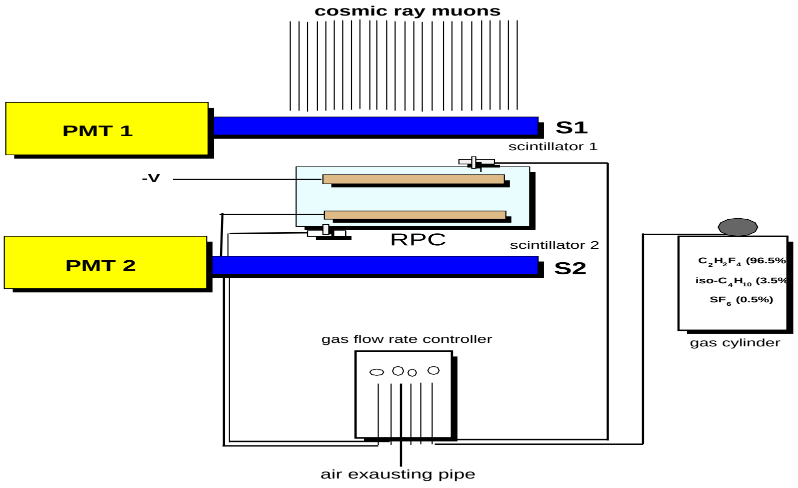


Figure 7: Schematic diagram of endcap RPC test setup.

In the cosmic ray test, chambers were characterized from the point of view of their efficiency, dark current, strip occupancy and cluster size. High voltage of RPCs was varied from 8.2 - 9.2 kV in steps of 0.2 kV and from 9.2 - 9.6 kV in steps of 0.1 kV. For each high voltage point, 20,000 events were collected. The data collection was performed by an online DAQ program based on VME standards. All the commands to any module in DAQ system were issued by a computer running a LINUX operating system. The commands must pass through the NIM crate controller. In the DAQ system crate controller acts as a master while all other modules (TDCs) are slaves to the crate controller. Looking from from front, crate controller always occupies the first two slots of the crate at the left hand side.

The behavior of the dark current, temperature and humidity was also monitored against each high voltage step. The suitable temperature and humidity for testing is found to be 20 - 22 °C and 35 - 40% respectively.

A schematic diagram of trigger logic is shown in Fig. 8. The induced pulses on the strips were observed on the oscilloscope. The signals from the scintillators were used to trigger the system and set a time reference for the measurements. The 8 PMT signals of each scintillator plane were connected via the discriminators to an “OR” unit. The output of the two “OR” units was then passed to an “AND” logical unit, whose output served as a trigger signal for the readout system.

5.4 Signal readout

When charged particles (mostly muons) ionize the gas of the RPC, an avalanche is formed by multiplication in the gas. The avalanche charge is collected by the anode and produces an induced charge on the external readout electrode, representing the prompt signal of the RPC. The signals are readout at a fixed frequency and were stored in a temporary memory. The RPC readout strips are connected to the FEBs by co-axial cables via the adapter boards.

The FEBs were connected with the TDCs through connectors which were placed in the VME crate. A TDC was

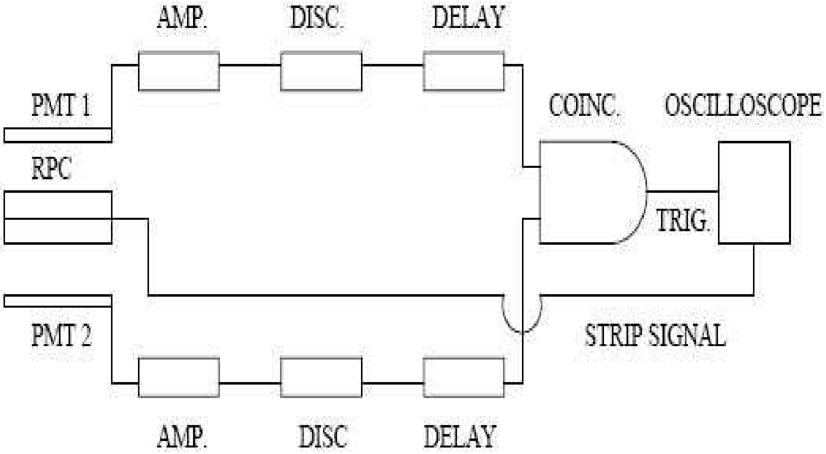


Figure 8: Trigger logic and coincidence of RPC.

used to read out the information from the FEBs and transfer the information to the computer. Signals from the RPC were amplified and digitized to LVDS in the FEB and then converted to ECL signals in the custom-made LVDS-ECL converter boards. The ECL signals were fed into the START inputs of the multihit TDC and the trigger signals from scintillator counters into the STOP inputs of the TDC. Signals from the chamber were also fed into the STOP inputs of the TDCs. When a trigger was detected the DAQ read the data from the TDC and stored it in a binary output file for further offline analysis. In parallel, the program continuously plotted a set of histograms which enabled the online monitoring of the data. After data acquisition, we started analysis which is explained in next section. We will see the experimental results of RPC parameters and compare them with the CMS requirements.

6 Results of Cosmic Test and Discussion

6.1 Data Analysis

To read and analyze the data, an off-line analysis software has been developed in C++. This off-line analysis program reads and processes the binary output of the DAQ to generate the plots/histograms. The results were analyzed using standard high-energy physics analysis tool ROOT [3]. The results are stored in the form of histograms.

6.2 RPC Parameters

Using the data and custom developed software the plots of the following RPC parameters are obtained:

- Dark Current
- Strip Occupancy
- Cluster Size
- Efficiency

6.2.1 Dark Current

The detector draws some amount of current even in the absence of any charged particle passing through it. This current is known as dark current. To determine dark current of a chamber, the chamber was connected to high voltage. Currents through each of the gas gaps were monitored. Given that current should be constant in time, any major deviations from this indicated a problem with the gas gaps or chamber electronics. For the efficient performance and acceptance of a chamber the value of dark current should be less than 5 μA. Temperature and humidity in the lab was also recorded because the performance of RPCs and resistivity of bakelite are functions of these parameters. We found the dark current to be around 3 μA. Plots of dark current for the chambers **CMS-RE-2/2-PK-032** and **CMS-RE-2/3-PK-015** are shown in Fig. 9 and Fig. 10 respectively.

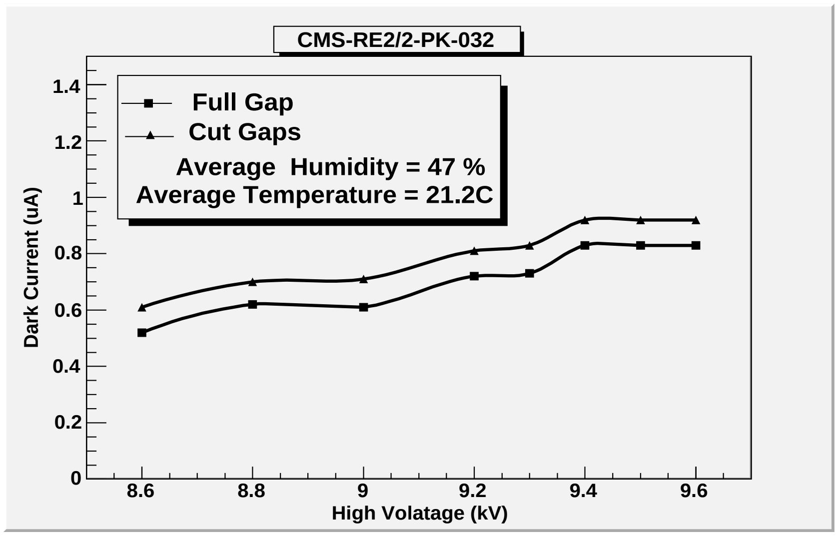


Figure 9: Plot of Dark Current for CMS-RE-2/2-PK-032.

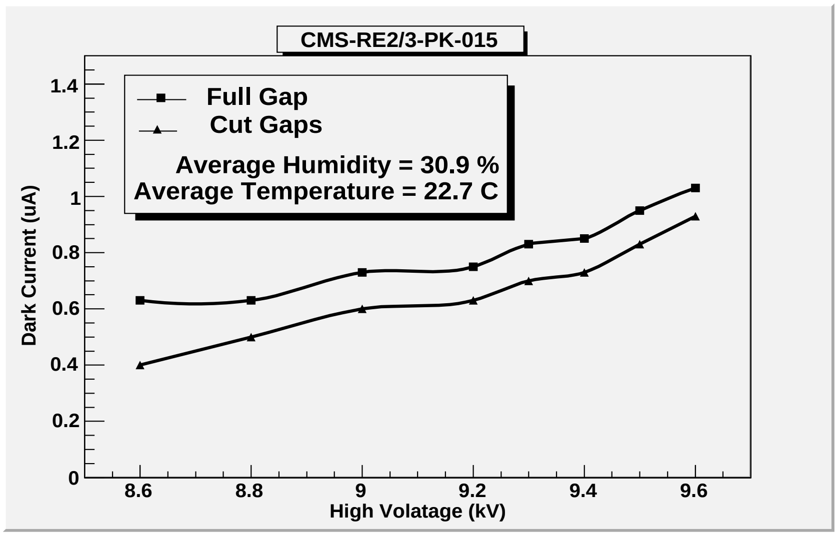


Figure 10: Plot of Dark Current for CMS-RE-2/3-PK-015.

6.2.2 Strip Occupancy

Strip response profiles are created and they serve two main purposes: first, to ensure that the chamber is connected properly to the DAQ system and second, to ensure all readout strips are active and working properly as they are supposed to.

Improper soldering of connections can lead to strips that appear to be dead in the strip response profile. Each RPC contains a total number of 96 readout strips and each of them is supposed to be in proper working condition. There can be some noisy strips, which show large number of hits and there can be some dead strips also, which show no signal or hit. A hit is defined as a signal recorded on a single readout strip within the 25 nsec time window. All the strips of RPC were checked and faulty strips were observed. If a chamber had more than 2 noisy or dead strips, then the chamber was rejected. A rejected chamber was reassembled to remove those noisy and/or dead strips so that it can fulfill the CMS requirement. All chambers were tested following the same method.

Number of cosmic muons passing a unit cross-sectional area is constant for a given altitude. Ideally we expect a flat distribution for strip occupancy. The number of hits decreases towards the edges of chambers corresponding to strips 1, 32, 33, 64, 65, 96. We get three humps in the distribution corresponding to three radial segments of strips.

The plots of strip occupancy for the chambers **CMS-RE-2/2-PK-032** and **CMS-RE-2/3-PK-015** at 9.4 kV are shown in Fig. 11 and Fig. 12 respectively. For chamber **CMS-RE-2/2-PK-032** strips 33-49 were swaped with 50-64. This problem was fixed afterwards. In these plots there is no dead strip one strip (strip number 32) is noisy i.e this strip has large number of hits. This noise is due to the high voltage cable which is passing by near this strip. Neglecting these two facts the strip occupancy distribution is according to expectation within small statistical fluctuations.

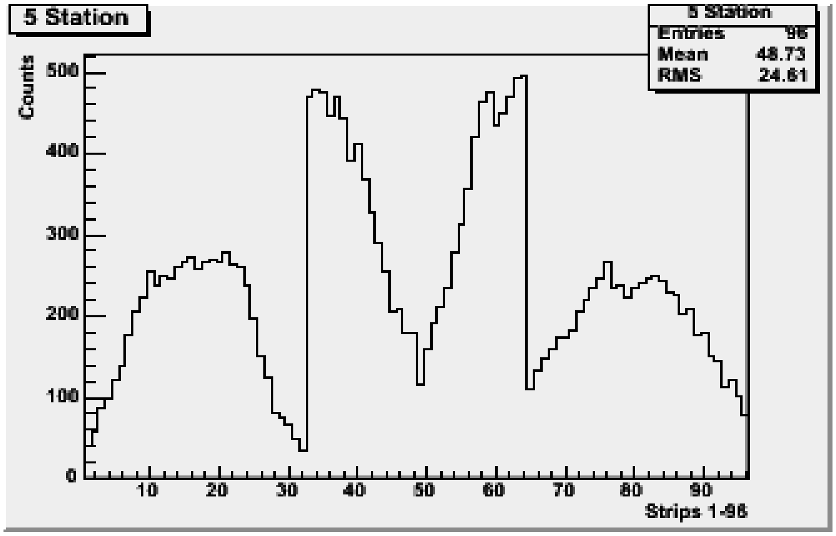


Figure 11: Plot of Strip Occupancy for CMS-RE-2/2-PK-032 at 9.4 kV.

6.2.3 Cluster Size

Another important parameter for chamber performance is the cluster size. This is measured for every chamber at several voltages. To define a cluster, we first ordered all the hits of a particular RPC in time and then searched for clusters. Within 25 nsec time window, all simultaneously fired adjacent strips form a cluster. The cluster size of a chamber is defined as “the average value of the cluster size distribution, sampled in the first 25 ns while the trigger window used is of 100 ns”. A cluster size should be small in order to achieve good momentum resolution. The number of strips in a cluster should be less than three for efficient performance of RPCs and this number corresponds to the CMS criteria regarding cluster size. The plots of the cluster size for the chambers **CMS-RE-2/2-PK-032** and **CMS-RE-2/3-PK-015** are shown in Fig. 13 and Fig. 14 respectively.

If we look at these plots the cluster size is less than three. So we can say that both the plots are in good agreement with the CMS criteria. The formation of clusters from 8.6 kV to 9.6 kV is not uniform, it grows with increasing high voltage.

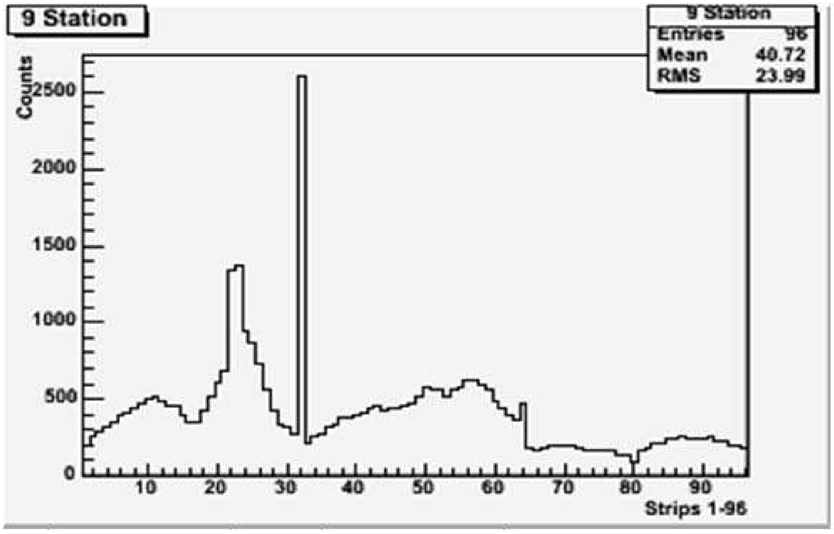


Figure 12: Plot of Strip Occupancy for CMS-RE-2/3-PK-015 at 9.4 kV.

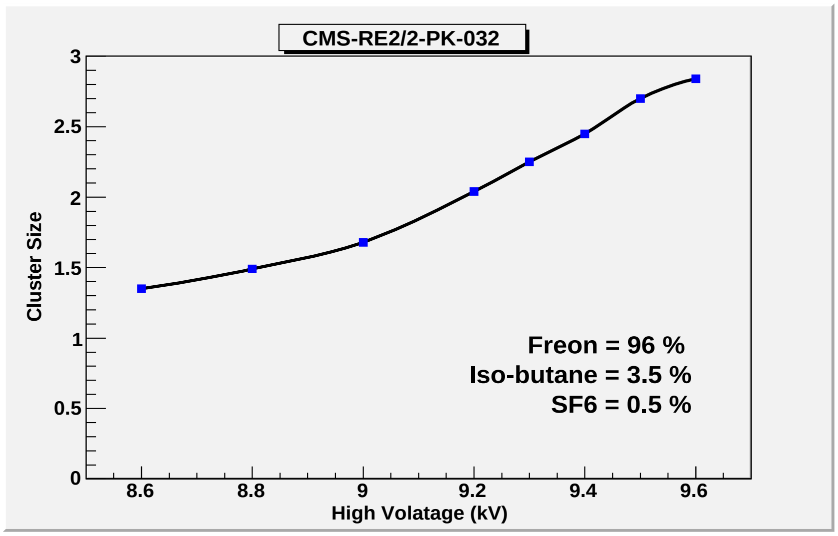


Figure 13: Plot of Cluster Size for CMS-RE-2/2-PK-032.

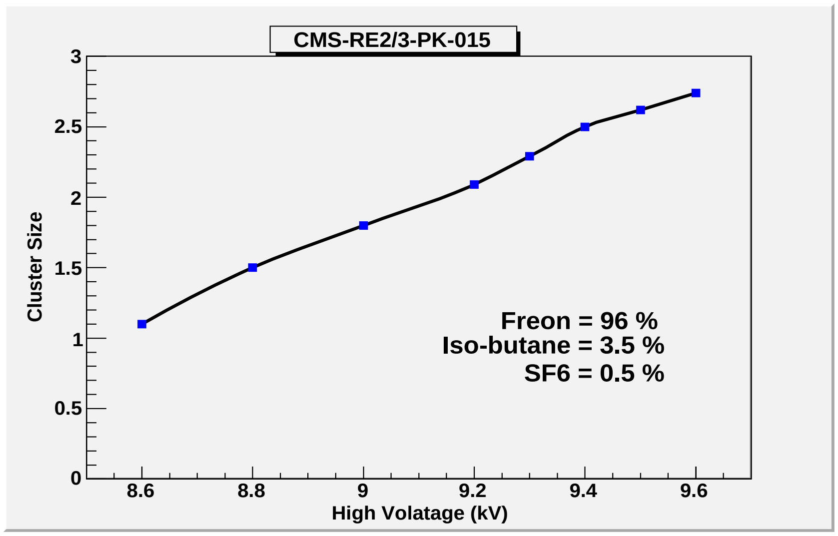


Figure 14: Plot of Cluster Size for CMS-RE-2/3-PK-015.

6.2.4 Efficiency

Chamber efficiency is obtained with the “coincidence” method by evaluating the ratio between the number of events in which RPC has at least one fired strip in the trigger window (100 ns) and the total number of recorded events, with correction for spurious hits [4].

The efficiency is defined as [5];

$$\varepsilon = \frac{[(N_{ob}/N_t) - P_s]}{1 - P_s}$$

where N_{ob} is the number of observed events, N_t is the number of total events and P_s is the probability of the spurious hits. The probability of the spurious hits is determined by counting the hits in a time window delayed 100 ns after the trigger. The value of the efficiency should be greater than 95% at operating voltages. For good performance of an RPC, its efficiency plateau should extend over 300 V. The maximum efficiency and length of plateau depends upon the gas mixture. The efficiency plots of the chambers **CMS-RE-2/2-PK-032** and **CMS-RE-2/3-PK-015** are shown in Fig. 15 and Fig. 16 respectively.

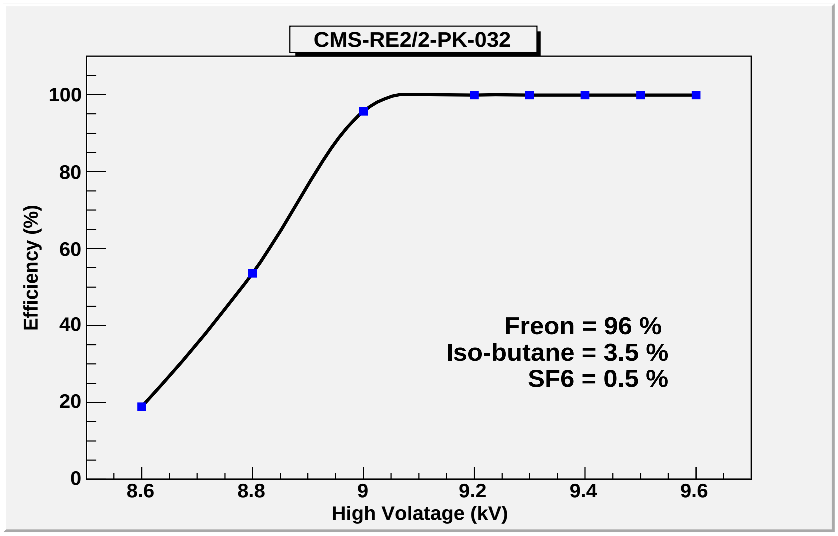


Figure 15: Plot of Efficiency for CMS-RE-2/2-PK-032.

When applied high voltage is small, ionization in the chamber is small which results in a small current in the gap.

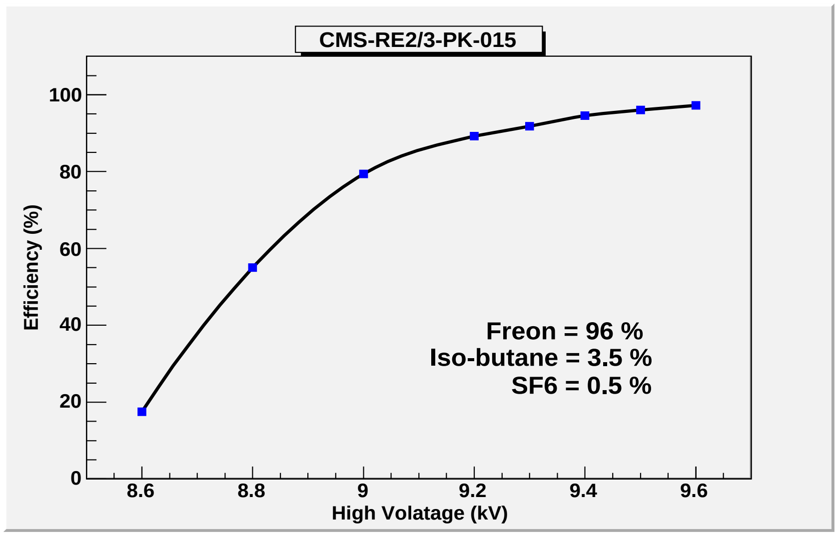


Figure 16: Plot of Efficiency for CMS-RE-2/3-PK-015.

Ionization increases linearly with applied voltage. Above 9.2 kV, behavior of the efficiency is constant. The plateau of operating high voltage starts at 9.2 kV to 9.6 kV. Length of plateau is greater than 300 volts for the gas mixture used. The value of efficiency is almost $>$ 95% at operating high voltage. The same chambers were later tested at CERN, and similar results were reproduced.

Finally all above parameters were analyzed, from which the overall behavior of the chamber was reflected. On this basis, chambers were accepted or rejected.

6.3 Conclusion

A complete cosmic ray muon test stand was built in the NCP laboratory to test the CMS endcap RPCs. The cosmic ray test setup has been put into operation since November 2005, when the first RPC (RE-2/2) was tested. Until now all chambers with 158 RE-2/2 and RE-3/2 $(\pm Z)$ and 160 RE-2/3 and RE-3/3 ($(\pm Z)$), have been tested in the lab and most of them have a good stability and performance.

With the cosmic test, some problematic RPCs were found and fixed immediately. The techniques of RPC assembly were thus improved with the passage of time and the cosmic ray test was proven to be most effective. Following the strict quality control procedure, the average RPC rejection rate was found to be around 3%. Chambers were mostly rejected due to fault or damage during transportation from PAEC site to NCP site. The results of the cosmic rays tests were very encouraging showing a good reproducibility of the RPC detectors. The average chamber efficiency was found to be more than 95% with an average dark current of less than 3 μA. Table 1 shows a comparison of test results with CMS requirements.

Table 1: A comparison of our test results with CMS requirements for different RPC parameters

Parameters	CMS Requirements	Test Results
Dark Current	< 5 μA	< 3 μA
Dead and/or Noisy Strips	< 3	< 3
Cluster Size	< 3	< 3
Efficiency(%)	$>$ 95%	$>$ 95%
Plateau Region	$>$ 300V	$>$ 400V

The test procedure allowed to certify chambers based on the values of their working parameters. A chamber was accepted only if it satisfied all the quality assurance criteria mentioned in this note. All test results are available on the web: $http://www.ncp.edu.pk/rpc\_test.htm$; with overall statistics.

Acknowledgements:

We would like to thank Pakistan Atomic Energy Commission, for providing man power to assemble the chambers.

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