Resistive Plate Chambers for the upgrade of the CMS experiment

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Abstract

The muon trigger for the Compact Muon Solenoid (CMS) experiment at the Large Hadron Collider (LHC) facility, is designed to have four layers of Resistive Plate Chambers (RPCs) in the forward region ($1.2 < \eta < 1.6$). In the present phase, the experiment runs with three layers of RPCs in the end-caps on either side. It is proposed to install the fourth endcap (± RE4) consisting of Resistive Plate Chambers (RPCs) for the CMS muon endcap system, in order to improve its Level-1 trigger efficiency and thereby completing the full implementation of the TDR, after which LHC will run with its full designed luminosity. This station will be installed in the first long shutdown of LHC during 2013-2014. With lessons learnt from the earlier installation of the RPCs, several modifications in the new construction and test procedures have been recommended for this upgrade. The prototypes for the upgrade were assembled in 2011, thereby giving the green signal for mass production for bakelite and gas gaps. In this presentation, we will discuss about the entire procedure of fabrication of bakelite gas gaps, standardisation of leak and spacer tests for the gas-gaps, the new design for the Cu cooling system, data base alongwith assembly, testing and characterization of RPCs which would be executed in a synchronised way at the three assembly sites at CERN, BARC-Mumbai and University of Ghent, Belgium.

1. Introduction

Resistive Plate Chambers (RPCs), developed by R. Santonico [1] in the early 80's, are parallel plate gas detectors, made of highly resistive plates such as glass or bakelite (ρ_{bulk} ~ 10^{10} to 10^{12} Ωcm), coated with graphite ($\rho_{surface}$ ~ 1 MΩ/ , thickness ~ 100 µm) to provide the anode and cathode and are operated either in avalanche or streamer mode with a typical combination of gas mixture consisting of R134a ($C_2H_2F_4$) as the main component (~ 95%), alongwith other gases such as Iso-butane and SF_6. RPCs are not a proportional counter. They are designed to create an avalanche and then also configured to arrest the avalanche from spreading out. They have found wide appplications in collider and neutrino based experiments [2,3], as trigger and/or tracking detectors, becasuse of following features :

a. low cost in fabricating large surface areas units (1 sq. m to 4 sq. m), wireless detectors, instead use strips
b. excellent count rate capabilities (~ 10s kHz/cm^2),
c. timing resolution (σ ~ 2 - 3 ns)
d. efficiency > 95%
e. no degradation in performance parameters in hostile radiation environment and
f. stable performance over extended period

Fig. 1 shows a schematic of an RPC. The resisitive plates determine the count rate capability whereas the gap between the plates determines the timing characteristics. Time resolutions of the order of picoseconds have been achieved with multigap timing RPCs (mRPCs) having gas-gaps of the order of 100s of microns, used basically for particle identification via time of flight method.

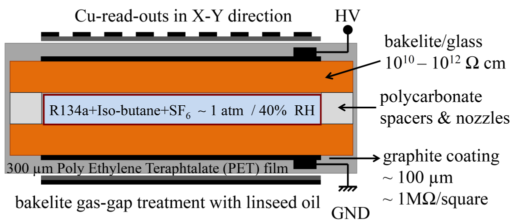

Fig. 1, Schematic of an RPC with anode, cathode and read out planes in X and Y

2. The CMS muon system

The CMS detector consists of Drift Tubes (DTs) in barrel region, Cathode Strip Chambers (CSCs) in the end-cap (forward) region and Resistive Plate Chambers (RPCs) in both the regions. RPCs have very good timing but not a good position resolution, DTs which are slower, have a good position resolution and not a good timing, whereas CSCs have a good position resolution and acceptable timing [4]. As such, the CMS has two independent muon triggering systems, complementary to each other, thereby providing :

a. trigger at high luminosity
b. good muon ID over wide range of momenta and angles
c. improved tracking momentum resolution above 200 GeV/c

The TDR for the muon trigger for the CMS experiment at the LHC facility, envisages to have four layers of Resistive Plate Chambers (RPCs) in the forward region (1.2 < η < 1.6). The present CMS experiment has three layers of RPCs in the end-caps and the RPC trigger logic requires hits in at least three layers, which causes the observed drop in efficiency for the endcaps with only three stations. Adding the 4th layer in the endcaps, enabling a 3-out-of-4 trigger logic in those regions, will bring the RPC endcap performance to a similar level as in the barrel region, Fig.2, [5].

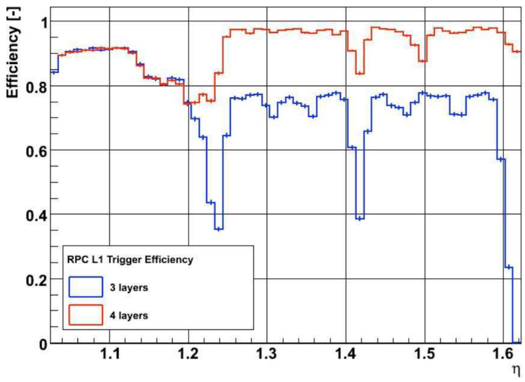

Fig. 2, Comparison of simulated RPC Level-1 trigger efficiency for the upgraded version with the present system with three end caps

The end-caps consist of three trapezoidal bakelite gas-gaps configured as a double gap RPC (Fig. 3), [6]. The present forward region (end caps) consists of 432 chambers mounted in a staggered way in two concentric rings on the end cap disks to cover its surface (~ 150 m^2 per disk). The double gap geometry, improves the efficiency, allows safer operation at higher threshold and also improves the time resolution. In order to increase the L1 trigger efficiency, it is proposed to install the fourth end-cap layer during the long shutdown (2013-2014), after which LHC will run with its full designed luminosity (more than 10^{34} $cm^{-2}s^{-1}$ at 14 TeV). The CMS-RPCs work in the avalanche mode satisfying the following criteria :

a. efficiency, $\varepsilon > 95\%$
b. streamer fraction, $f < 10\%$ &
c. cluster size, $N_S < 2$

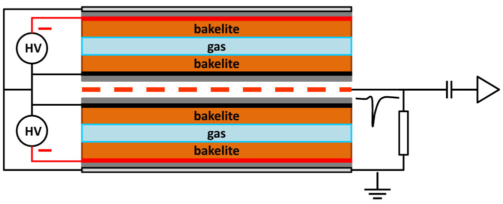

Fig. 3, Schematic of a double gap RPC

The construction procedures of RPCs, with the experience gained during the operation of RPCs in the present set-up, has been improved, keeping backward compatibility with the presently installed RPCs. As in the past, the fourth layer will consist of 2 rings denominated as RE4/2 and RE4/3, each having 36 chambers. Both end-caps will be instrumented for a total of 144 chambers with another 56 chambers as spares, adding to 200 chambers for the RPC upgrade project, which then fully restores the TDR version of CMS with RE4 RPCs.

3. Prototype assembly for RE4

A pre-production run, prior to the actual mass production of gas-gaps for the RPC upgrade was planned in March/April 2011 and about 18 gas-gaps for the two rings (RE4/2 and RE4/3) were sent to CERN for their evaluation. The prototype asembly for RE4 was thus launched with the arrival of fresh set of gas-gaps from Korean DEtector Lab, KODEL, South Korea, mechanics from China and the improved Cu cooling system from India. Two prototypes, one for each ring were assembled. Figure 4, shows a fully assembled RPC for the RE4/2 ring under test in a dedicated laboratory at CERN and its corresponding efficiency plot for one of the η partitions (A1), at different threshold settings. The above quality test validated the entire construction chain and the compatibility of various components used to build the chamber, like the bakelite in terms of surface smoothness and its bulk resistivity.

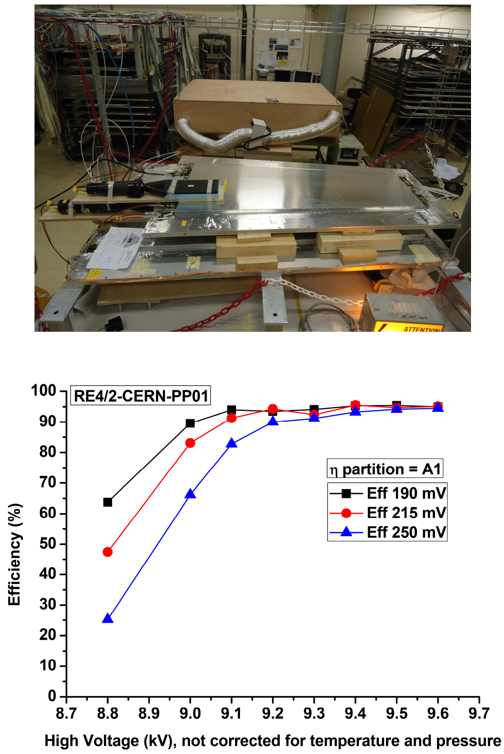

Fig. 4, RE4/2 prototype under tests (top) with efficiency plot (bottom) for different threshold settings

It also validated the gas-gap fabrication procedures in terms of its mechanical and electrical properties, gluing of gas-gaps, bonding of spacers. Finally the measured cosmic efficiencies did certify the behaviour of gas-gaps coupled to the front end electronics, matching the specifications set by CMS. During the pre-production run all the necessary mechanical components were revalidated and the technical specifications and quality assurance and quality control, QA/QC protocols were formalized.

4. Fabrication of HPLs and gas-gap production

About 600 foils of 1620 mm × 3200 mm × 2 mm thick high pressure laminates (HPLs - bakelite sheets) are produced at Puricelli firm (Milano). The QC of the HPL sheets is done at INFN Pavia, where their resistivity is measured to ensure that they are within the specified range of ρ_{20} = 1 - 6 × 10^{10} Ω cm and σ/μ < 0.5. Next, the foils are cut at Riva (Milano) and finally surface cleaned by General Tecnica (Frosinone), before they are sent to Korean DEtector Lab. (KODEL), South Korea for production of gas-gaps. At KODEL, the gas-gaps are produced with linseed oil treatment on the inside surface of the bakelite sheets, graphite coating on the outer surfaces, mounting of 2 mm button spacers, side spacers and gas nozzles. For the RPC upgrade, 100 chambers each of type RE4/2 and RE4/3, are to be built, each requiring three different types of gas-gaps to be assembled which are detailed in Table 1, where N, W and B means Narrow, Wide and Bottom gas gaps respectively. Keeping a contingency of 10%, about 110 gas-gaps of each type shall be produced in KODEL in a phased manner. For the RPC upgrade project, 660 gas-gaps will be produced at KODEL, with a production rate of 3 gaps/day, thereby needing 11 months for the entire gap production.

Table 1

gas-gap type →	RE 4/3 Top N	RE 4/3 Top W	RE 4/3 B	RE 4/2 Top N	RE 4/2 Top W	RE 4/2 B
total gas-gaps →	110	110	110	110	110	110

5. Mechanical tests for the gas-gaps

Since the gas-gaps are transported through a large distance via air freight and then handled at airports before delivery to the respective assembly sites, their mechanical properties are evaluated through leak and spacer tests before they are assembled. Five tests are being performed for gaps - Visual Test, Leak Test, Resistivity Test and Dark Current Test (I) and Dark Current Test (II). The Dark Current Test I is the HV scan of gaps between 100 Volts and 10000 Volts while the Dark Current Test II is the Long Term Stability test which aims to monitor the stability of the current in time at a fixed voltage

The trapezoidal gas-gaps have nozzles in the four corners for gas flow. The 2 mm gap uniformity is maintained through a grid (10 cm x 10 cm) of button spacers (of height uniformity within 20 μm) between the bakelite sheets. The 20 μm precision ensure that the gap remains uniform over the entire area of the gas-gap providing a uniform electric field. These spacers could also get popped up because of insufficient bonding of the glue at the fabrication site, though sufficient care is taken to keep the spacers pressed, guaranteed by water column, for 14 hours during curing. The spacers can also get popped up because of mishandling of the gas-gap crates at the time of delivery. A gas-gap, even with a single popped spacer cannot be used and is to be rejected. In order to certify these gas-gaps, a new system has been designed where the gas-gaps on arrival from KODEL, undergo a leak and spacer test. The gas-gaps are pressurised at 20 mbar above atmospheric pressure with Argon gas and the pressure is recorded digitally through a transducer (Sensor Technics - CTE7000) with a 20 bit ADC.

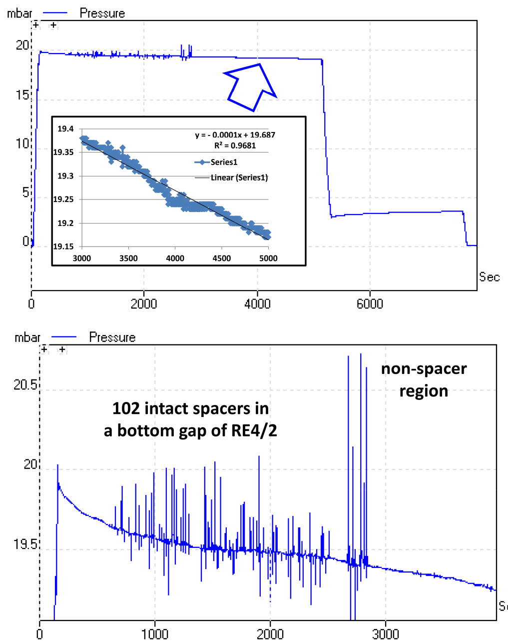

Fig. 5, Gas-gaps pressurised to 20 mbar and 3 mbar of overpressure to calculate the leak rate (top panel) and spacer test for gas-gaps showing acceptable pressure fluctuations (± 0.5 mbar) for intact spacers (bottom panel)

The QA/QC "as prescribed by the CMS experiment for the leak test" needs the gap to remain pressurised at 20 mbar for 10 minutes and the dP/dt for each gas-gap is measured. Then, the overpressure is reduced to 3 mbar, which emulates the situation in the CMS cavern, for the next 10 minutes. The dP/dt is measured again at 3 mbar and then the overpressure is released to zero. A plot of the measured dP/dt is shown in the top panel of Fig. 5 for the RE4/2-bottom gas-gap with 102 spacers. The inset in the top panel corresponds to the acceptable leak rate (-2.3×10^{-4} mbar×litre/s) from the particular gas-gap. At 3 mbar of overpressure, initially, we do find a positive slope, i.e rise in pressure with time, but then it stabilizes. Probably we have to allow more time for pressure etc. to stabilize, rather than taking the measurements in quick successions and should also have the environmental pressure outside recorded simultaneously. Table 2 shows the maximum allowed pressure drop for different gas-gaps, normalized to 2 litres of gas volume.

Table 2

gas-gap type →	RE 4/3 Top N	RE 4/3 Top W	RE 4/3 B	RE 4/2 Top N	RE 4/2 Top W	RE 4/2 B
$[dp/dt]_{max}$ (mbar/600s) →	0.3 mbar	0.1 mbar	0.4 mbar	0.1 mbar	0.1 mbar	0.2 mbar

For spacer test, a template with known spacer position is placed over the gap and each spacer position is pressed to record the fluctuations in the pressure. For intact spacers, the fluctuations in the pressure are in the range of ± 0.5 mbar, whereas for the same pressure applied in the non-spacer region, resembling a popped up spacer, corresponds to large fluctuations (± 1 mbar and beyond), as shown in the bottom panel of Fig. 4. The gas gap is qualified when no spacer causes an overpressure peak larger than ± 0.5 mbar.

6. Electrical tests for the gas-gaps

QA/QCs for electrical tests of the gas-gaps have been formulated to be uploaded on the data base, prior to assembly and dispatch to CERN. Each gas-gaps will be purged with RPC gas mixture (R134a : Iso-butane : SF_6 :: 95.2 : 4.5 : 0.3) with 40 % RH in the gas mixture at a flow rate of 5 litres per hour for 48 hours, with P_0 = 1010 mbar and T_0 = 293°K, before undergoing the dark current tests. The gas-gaps will be ramped upto 10 kV of applied HV (E ≈ 50 kV/cm) and the maximum acceptable dark currents are shown in Table 3.

Table 3

gas gap type →	RE 4/3 Top N	RE 4/3 Top W	RE 4/3 B	RE 4/2 Top N	RE 4/2 Top W	RE 4/2 B
I_{max} (μA) →	3.5	2.0	5.1	2.0	2.0	3.5

The gas-gaps are then subjected to stability test for three days at the sites with HV at 9.7 kV. The acceptance criteria for the gas-gaps is that during the stability tests the increase in dark current should be less than 50% and $I < I_{max}$, as mentioned in Table 3. The HV working point depends on temperature and pressure of the environment, where the measurement is being done. Therefore, together with atmospheric pressure [mbar], the values for environmental temperature [°C], environmental relative humidity [%], gas temperature [°C] and gas relative humidity [%] are also to be stored in the data base. The HV values should be in volts while the I_{mon} values should be in microamperes. The formula used for the effective high voltage value is the following :

$$HV_{effective} = HV_{applied}[(P_o / P) \times (T / T_o)]$$

where P_o = 1010 mbar, is the reference atmospheric pressure and T_o = 293 K, is the reference ambient temperature. Once, the gas-gaps pass the acceptable criteria of mechanical and electrical tests, they are ready for assembly into an RPC.

7. Read out strips and electronics

Each RPC in the end-cap has a trapezoidal segmented readout strip divided in 3 η partitions, with 32 strips each, yielding a total of 96 strips per chamber. Each strip is soldered with coaxial cables (50 Ω) to a 16 channel adaptor board which get linked to three Front End Boards (FEBs) for each chamber, which are electronically controlled through a Distribution Board (DB). The FEBs generate an LVDS (Low Voltage Differential Signal) which are transmitted to the off-detector electronics consisting of Link Boards (LBs), which perform the synchronization with the LHC clock and the transmission to the Trigger Electronics in the control room.

8. Granularity in η & ϕ and the momentum resolution

The RPCs provide a fast and highly segmented trigger with a sharp transverse momentum threshold over a large portion of rapidity range $|\eta| < 1.6$. Muon detection is quite central to the CMS detector and the solenoidal field bends muon in the ϕ direction. The bending power of CMS magnet is uniform in the barrel region and is equal to 17 Tm. In the end cap it reduces to 8 Tm at $|\eta| = 2.0$ and to 6 Tm at $|\eta| = 2.4$. Therefore particles of a given p_t bend differently at different $|\eta|$. One has thus to know $|\eta|$ in order to determine p_t from $\Delta\phi$ measurements. The ten degrees RPCs in the end-cap region provide a granularity of $\Delta\eta \times \Delta\phi$: 0.1×0.3^{O}. The precision of 0.1 in η, therefore determines the maximal length of the strips. The high field of the solenoid is the key to excellent momentum resolution of the detector. Drift Tubes (DTs) in the barrel and Cathode Strip Chambers (CSCs) in the end caps provide track segments in each muon station with a spacial and angular precision of 1-2 mm and 10-60 mrad respectively. Muons are reconstructed as objects that have track in the muon spectrometer and a corresponding matched track in the inner tracker. The muon system stand alone resolution, $\Delta(p_T)/p_T$ (%) is about 20 – 40 % at 1 TeV, which when matched with the central tracker, improves to 6 – 17 % at 1 TeV. The CMS detector has been optimized in such a way so as to provide an excellent muon signature for several interesting/exciting events such as :

a. $H \to Z\,Z \to \mu\,\mu\,\mu\,\mu$ (Fig.6),
b. $H \to \mu\,\mu\,\mu\,\mu$,
c. $Z \to \mu\,\mu$,
d. $W \to \mu\,\nu$

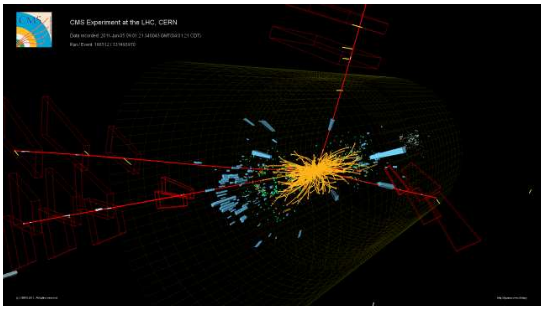

Fig. 6, A typical event of $H \to Z\,Z \to \mu\,\mu\,\mu\,\mu$, for the 8 TeV data in CMS

9. Redesigned Cu cooling system for the RE4-RPCs

With the experience gained with the installed RPCs in the existing end-caps, the Cu cooling system for the RPCs was redesigned. In the new design, the area of Cu plates has been increased optimally with water flowing through Cu pipes, in a closed circuit. The earlier installed, 8 mm ϕ brass unions with a single ferrule, have been replaced with SS double ferrules to ensure that there is no water leakage at the coupling junctions. Improvement in the cooling system had to be introduced for RE4, due to its particular position facing the electronics of the other muon system based on Cathode Strip Chambers. The new cooling system is envisaged also for RPC that will replace malfunctioning chambers in the other layers, so the design includes backward compatibility.

A prototype of the Cu cooling system was fabricated in BARC, Mumbai, meeting the required specifications and was dispatched to CERN during the pre-production run. The Cu cooling system was fabricated with Deoxidized High Residual Phosphorus (DHP) semi hard Cu pipes (8 mm OD and 6 mm ID) and Cu sheets with 1 mm thickness. The DHP Copper is a commercially available material of pure copper, which has been deoxidized with phosphorus, leaving relatively high residual phosphorus content. This copper has a lower electrical conductivity and is used where there is need for heat transfer and electrical properties are not important. The Cu cooling system will have chilled water at 19°C running at a pressure of 2 bar, in order to cool the electronics and the body of RPCs through the aluminum honey comb panels on to which it is mounted. A typical Cu cooling system for RE4/3 type RPC is shown in Fig. 7. The Cu pipes were soldered (~ 200°C) to the Cu plates with soldering material having a composition of Sn : Ag : Pb :: 62 : 2 : 36. After complete assembly, the Cu cooling systems are tested for any possible leakage with Argon gas at 20 bar of pressure. Special jigs were made to ensure that the Cu pipes do not bend and maintain their straightness, while soldering them to the Cu plates. The fabricated Cu assembly was further subjected to leak tests with 20 bar of Argon gas for 30 minutes. The leak test is performed three times for each set by loosening the brass couplings to the Cu pipes (Sagana connectors) and again tightening them, as these couplings will have to be loosened again, for the Super Module assembly (described in section 11).

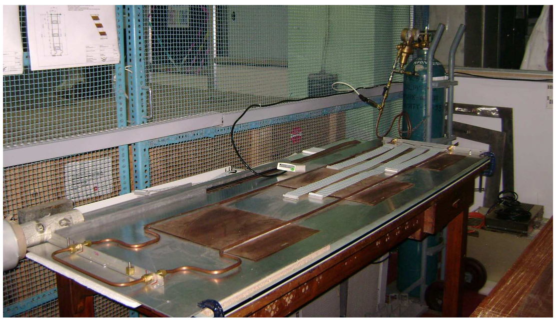

Fig. 7, Cu cooling assembly for a typical RE4/3 RPC, under leak test after fabrication at NPD-BARC

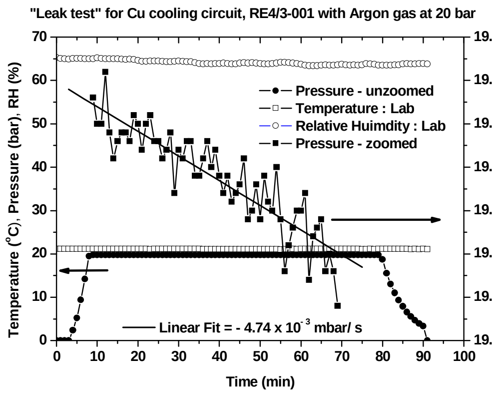

Fig. 8, Leak test for Cu cooling assembly with Argon gas at 20 bar of pressure and 21° C

As shown in Fig. 8, the pressure remain stable (closed circles) at 20 bar with surrounding temperature in the lab also remaining constant at 21°C (open squares), thereby ensuring that there were no leaks developed in the system while fabricating the assembly, subjected to high temperatures while soldering the Cu pipes to the Cu plates. The zoomed part (solid squares) shows a pressure drop of - 4.74×10^{-3} mbar/s, which translates to an acceptable leak rate of 5.36×10^{-4} mbar.litre/s. The Cu cooling systems for all the chambers are being fabricated and tested at BARC, Mumbai and shall be dispatched to the other assembly sites in a phased manner synchronising with the delivery of gas gaps from KODEL.

10. The Construction Database

Each of the QA/QCs procedures mentioned above, for each chamber, shall be stored in an Oracle based Construction Database. The database will include all measurements at the gas-gap level, HV scans, characterization of RPCs in terms of efficiency, cluster size and strip profile, performed during the detector assembly and the Super Module assembly. This will enable CMS to follow the evolution of each chamber in time, in case problems related to chamber performance should appear during operation later on [7].

11. Delivery schedules of RPCs from the assembly sites

For the start up it is proposed to build 50 chambers each in India (RE4/2), and University of Ghent, Belgium (RE4/3) and the remaining (50 chambers of RE4/2 and 50 chambers of RE4/3) at CERN. In India, two institutes are collaborating jointly for the project, namely – Nuclear Physics Division-BARC, Mumbai and Panjab University, Chandigarh. CERN site will coordinate the logistics & setting up protocols for QA/QC. Construction data base has been implemented for QC from chamber components (bakelite, gaps, electronic etc.) to final chamber Super Module assembly. The chamber mechanics, which includes honey comb panels, screen covers, Cu read out strips and Cu-mylar sheets to be used as a Faraday cage, have been produced by two Chinese companies: Beijing Axicomb Technology Co., Ltd and Beijing Gaonengkedi SGT Co., Ltd., which have also produced the similar components for the existing end cap systems. At the time of writing this paper, all the relevant components of the chamber mechanics have been delivered at the respective assembly sites for all the 200 chambers and the RPC assembly work is expected to begin soon after the arrival of first batch of gas-gaps at the assembly sites. Gas-gaps will be produced at a rate of approximately 60 gaps per month at KODEL, and will then be dispatched to the three sites. The first set of gas-gaps is expected to be dispatched to the three sites in Sep/Oct 2012. The chamber production rate is foreseen as three RPCs per month in Mumbai, five RPCs per month at Ghent and ten RPCs per month at CERN, given the available logistics and infrastructure in these sites. Figure 9, shows the three assembly sites respectively at Mumbai, CERN and Ghent, with their cosmic hodoscopes. All the assembly sites are ready with their respective hodoscopes, VME based DAQs and QA/QC procedures for the launch of production of the first ten chambers, each, from Oct/Nov 2012 onwards. Instrumentation for monitoring of the environmental pressure, temperature, and relative humidity to run the HV scripts and for ramping of gas-gaps for dark current measurements have been implemented in all the three sites. The development of software tools for offline analysis and characterization of RPCs is being fine tuned at the moment. All operations are performed via webpages click-by-click and all the actions are logged in the e-log system to easily/simply manage the sites.

Fig. 9, Cosmic hodoscopes at RPC labs., at NPD-BARC, Mumbai (left), CERN-904 site (middle) and Ghent site (right)

One RE4/3 chamber coupled to a RE4/2 chamber forms a ten degree Super Module (SM) assembly as shown in Fig. 10 (left panel). The Super Module assembly integration will take place at CERN and will be coupled in such a way so that the gas flow in the bottom chambers is in a reverse direction to that in the top chambers. All the SM assemblies will later be installed at P5 to have the fourth layer of end cap, similar to that shown in Fig. 10 (right panel).

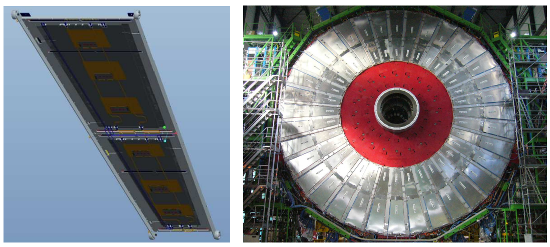

Fig. 10, A Super Module Assembly, where an RE4/3 chamber is coupled to an RE4/2 chamber (right panel) and one of the existing end cap (left panel)

It is proposed to have the installation and commissioning of the SM assembly and the end-caps, tentatively, as shown in the Table 4.

Table 4

S N	Installation & Commissioning	Proposed schedule
1	36 SM for Endcap 1 ready for P5	Mar. 2013
2	36 SM for Endcap 2 ready for P5	Sep. 2013
3	First endcap (+ Z side)	Dec. 2013
4	Second endcap (– Z side)	July 2014

12. Acknowledgements

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