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Resistive plate chambers for the LS1 muon upgrade in CMS experiment at LHC

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In the view of the high luminosity run of LHC from 2015 onwards, during the last two years (2013/2014 – Long Shutdown LS1) one of the major upgrades of the CMS experiment is completing and improving the muon system performances by installing a fourth layer of RPC detectors in the forward region. The fourth trigger station (on two new endcap disks) consists of 144 double-gap RPC chambers, which are assembled and tested at three different production sites – CERN (Switzerland/France), Ghent (Belgium) and BARC (India). The complete chamber construction, quality control procedures and preliminary results are detailed here.

Key words: resistive-plate chambers; muon spectrometers

INTRODUCTION

The Compact Muon Solenoid (CMS) experiment [1] has been collecting data successfully, since the start of the first Large Hadron Collider (LHC) physics run in 2009. Phase 1 of the LHC will continue until about 2022 and during that period, the instantaneous luminosity delivered to the experiments is foreseen to increase gradually up to more than twice its nominal value of 10^{34} $cm^{-2}s^{-1}$. There are two shutdown periods [2] scheduled to give the machine and the experiments the necessary time to anticipate these luminosity increases - Long Shutdown 1 (LS1) in 2013/2014 prepares the accelerator to run at its nominal luminosity and Long Shutdown 2 (LS2) in 2018/2019 should take it to 2.2 times this value. In particular the muon system during LS1 is upgraded with the installation of a new layer of Resistive Plate Chambers (RPC) [3] detectors on the endcap regions. Before this upgrade only three RPC layers were installed. Adding the fourth RPC station, called RE4, is going to increase the overall robustness of the CMS muon spectrometer while improving the trigger efficiency by adopting a three-out-of-four stations majority trigger logic, covering the region up to $|\eta| = 1.6$.

The RE4 project [4] is multi-national and is carried out by several institutions. The gas gaps for the RPC detectors are produced in Korea, while Pakistan, Italy and Finland are working on the front-end electronics, DAQ and power system. 200 cooling sets are produced and tested in India, while Bulgaria, Georgia, Mexico and Pakistan are responsible for detector assembly and testing. The chamber services (gas, cooling and cabling) are built in Italy, India and Pakistan, while China provides the readout strips and mechanical frame boxes. All countries provide participants in the chamber construction and testing.

The RE4 project consists of 72 super-modules, each of which is made by two RPC chambers, so the total is 144 double-gap RPCs. The new RE4 detectors are going to instrument two disks, called RE+ and RE-, located on the opposite endcaps of the detector. Each disk is made out of two rings - the inner one is called RE4/2, while the outer ring is called RE4/3. As shown in Fig. 1, there are 36 trapezoidal shaped detectors in each of the two rings, which are built in three different assembly sites: India (BARC), Belgium (Ghent University) and Switzerland/France (CERN). BARC and Ghent are in charge of 25% of the production each, respectively RE4/2 and RE4/3, while the remaining 50% of the production is carried out by CERN which work on both chamber types RE4/2 and RE4/3.

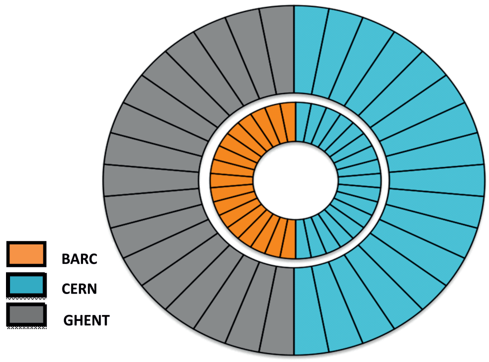

Fig. 1. Schematic layout of one of the two new endcap disks.

CHAMBER DESIGN, PRODUCTION AND QUALITY CONTROLS

The present RPC trigger logic requires hits in at least three layers and since in the system before the upgrade there are only three RPC detector stations in the endcaps, this causes the observed drop in the efficiency shown in Fig. 2. As the figure shows, adding the 4^{th} 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 the barrel system (up to $|\eta| = 1.6$).

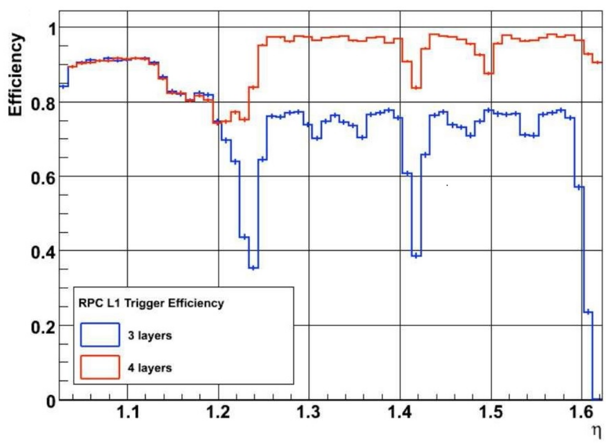

Fig. 2. Simulated RPC Level-1 trigger efficiency for the present system with three endcap layers compared to the system after the upgrade with four endcap layers.

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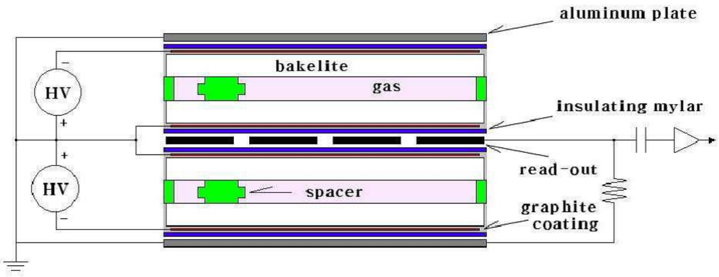
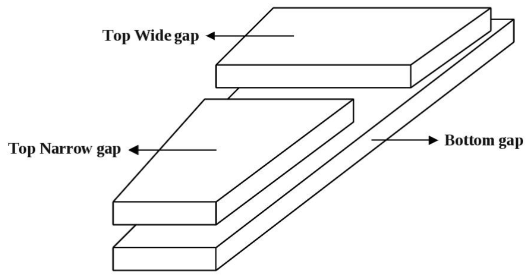


(a)



(b)

Fig. 3. Schematic representation of the double-layer layout of the endcap chambers (a). Configuration of the gas gaps of the endcap chambers (b).

The RE4 project is inheriting the chamber design from the already existing RPC Endcap chambers, shown in Fig. 3. The detector relies on 2 mm trapezoidal shaped HPL gas gaps, that are organized in a double-layer configuration with a copper strip readout panel placed in between. The resistivity of the HPL sheets is of the order of 2 - 5 $\times$ 10^{10} Ωcm. A chamber is made of three kinds of different gap geometries - the bottom layer uses one large gas gap, while the top layer is segmented into two parts. This is done to simplify the signal cable routing.

The readout strips are segmented in three η-partitions with increasing strip pitch from 1.5 cm to 4 cm. Each partition has 32 strips, yielding a total of 96 strips per chamber. Coaxial cables are used to connect strips to Adapter Boards which are linked to 3 Front-End Boards (FEBs) per chamber. Every chamber has 1 Distribution Board (DB) for the electronics control. Link Boards (LBs) are the main components of the off-detector electronics. They receive signals in LVDS (Low-Voltage Differential Signaling) standard from the FEBs. The LBs perform the synchronization with the LHC clock and transmit the signals to Trigger Electronics in the control room. In each LB crate there is a Control Board (CB) that drives the crate, provides inter-crate communication and takes care of the connection to the readout and trigger systems.

The HPL sheets ($\approx$ 3500 m^2) are the first step in producing RPC gas gaps. The raw material comes from Italy, where the HPL panels are produced by the Puricelli firm (Milan), validated by INFN (Pavia), cut by RIVA firm (Milan) and finally the surface is cleaned by General-Tecnica (Frosinone). Then they are sent to Korea where the HPL panels are used for assembling RPC gaps. The Korean gap manufacturing site – KOrea DEtector Laboratory (KODEL) performs several measurements on the HPL panels in order to ensure the correct resistivity, color, roughness and thickness. Next step is graphite coating for the HPLs, which is protected with a polyethylene terephthalate (PET) film [5]. The assembled gaps are treated with linseed oil mixed with heptane. Once fabricated, the new RPC gaps go through series of tests to ensure the quality during the construction process. First are gas leak and spacer tests. Then gaps are subjected to high voltage (HV) scan to measure the dark current and to current monitoring at the expected operating voltage (9.7 kV) over one week. This first gaps validation is called Quality Control 1 (QC1). Once it is over, a box containing a number of gaps between 30 and 40 is dispatched from Korea to chamber assembly sites.

The chamber mechanics (honeycomb boxes, screen boxes, readout strip panels, etc.) are produced by two Chinese companies – Beijing Axicomb Technology Co., Ltd. and Beijing Gaonengkedi SGT Co., Ltd, while the detector electronics are produced in Pakistan. The new off-detector electronics are produced by the INFN (Italy), while the CMS Warsaw group (Poland) takes the responsibility to integrate the new electronics in the trigger system.

The final assembly of the RPC detectors is shared by three institutions – BARC (Mumbai, India), Ghent University (Ghent, Belgium) and CERN (Switzerland). Each of these assembly sites has built up special RPC labs with setups for detailed quality control of both RPC gas gaps and completed chambers.

In the second phase of the quality control (QC2) the RPC gaps performance is validated by repeating some of the tests performed in Korea. Once taken out of the boxes in the assembly sites, gaps are subjected to visual inspection, gas tightness, spacer test and electrical dark current measurement. While inspected visually, each gap is characterized with a detailed checklist which ensures that there are no visual damages present and the gap is eligible to be used. The gas gap spacer and leak tests check that there are no detached gap spacers and the leak rate is within specifications (0.4 mbar/10 min). The last test in QC2 is the high voltage scan which main aim is measuring the dark current and its stability over a period of 3 days. There has been found an overall rejection factor of 10% at QC2.

When a site fully validates a set of three gaps, these are used to start the chamber construction. The quality control at this stage of detector production (QC3) goes through chamber visual inspection, gas tightness, electrical and dark current measurement, as well as cosmic muon commissioning by means of a dedicated cosmic ray stand (telescope). While under visual inspection, each chamber needs to pass through a detailed checklist in order to validate the manufacturing process of the chamber. After that comes the leak test, which measures the chamber gas leak. This is done in order to check whether, during chamber manufacturing, the gap gas inlets are correctly connected to chamber service panel. The electric test is done by powering and checking the front-end boards while the gaps are subjected to a high voltage scan in order to ensure that the RPC gaps operate without problems. The final procedure in the QC3 protocol is the chamber by chamber performed high voltage scan that aims at characterizing detector response while measuring main detector performance parameters such as efficiency, cluster size and noise. Each detector is subjected to three independent efficiency scans using three different configurations - double-gap, top single-gap and bottom single-gap. This is done because the RE4 chambers are based on double-gap RPCs. During each efficiency scan there are 7 runs taken at different effective HV, from 8.5 to 10 kV. In each run there are 10k events collected in approximately 2 hours. In order to maintain each RPC chamber gain constant against environmental changes, the scan is performed using the effective high voltage to correct the applied one on the chamber. The applied HV is corrected in response to the changes in environmental pressure according to Eq. (1) [6]:

$$HV_{\mathrm{eff}} = HV \frac{p_0}{p} \frac{T}{T_0} \quad (1)$$

where $p_0 = 990$ mbar.

The cosmic stand in each assembly site is equipped with two scintillator layers (top and bottom) that form the trigger. The front-end boards of the chambers are connected via flat cables to TDCs to tag and record all hits. Three reference chambers installed in the stand are used by the analysis routine to perform a tracking algorithm in order to reconstruct cosmic muon tracks.

After passing successfully the cosmic test, every chamber is powered on and monitored for about three weeks in order to check its stability over time. This is the next step (QC4) in quality control protocols for RPC detectors. If there are no problems with the dark current and it is stable, a pair of chambers, one RE4/2 and one RE4/3 type, is assembled into a Super Module. This assembly task is done in order to reduce the amount of time needed to install all RE4 detectors at CMS. Since RE4/2 and RE4/3 share the same cooling circuit and gas pipes, and are attached mechanically to the same structure, this allows for several commissioning protocols to be performed before the real detector installation at CMS. The first disk (RE4 positive) was installed in December 2013 while the installation of the second one (RE4 negative) finished in May 2014.

The full history of each chamber and every component is stored in an Oracle based Construction Database, which includes all measurements performed before, during and after the detector assembly. This enables CMS to follow the evolution of each chamber in time.

The RPC detector performance [7] starts with evaluating the gap performance during QC2 at assembly sites. First is the leak rate test, shown in Fig. 4(a), which is performed measuring the leak drop in time of each gap. The gaps are initially pressurized to 20 mbar over ambient pressure. Also at the end of this test, all gap spacers are checked in order to spot any detached one. Once the leak and the spacer tests are successfully ended, the gaps are subjected to a high voltage scan in order to measure the dark current response. During this test, the high voltage is ramped from 1 kV to 10 kV. There are two different steps of ramping - a step of 1 kV up to high voltage of 8 kV and a step of 100 V between 8 kV and 10 kV. Moreover, after the high voltage scan, all gaps are kept at 9.7 kV for 3 days for monitoring possible dark current drift in connection with pressure and temperature. Fig. 4(b) shows the dark current distribution for all gaps at the 10 kV.

After the gap performance evaluation is the turn of QC3, where the assembly sites have to fully commission each detector. The full evaluation of the

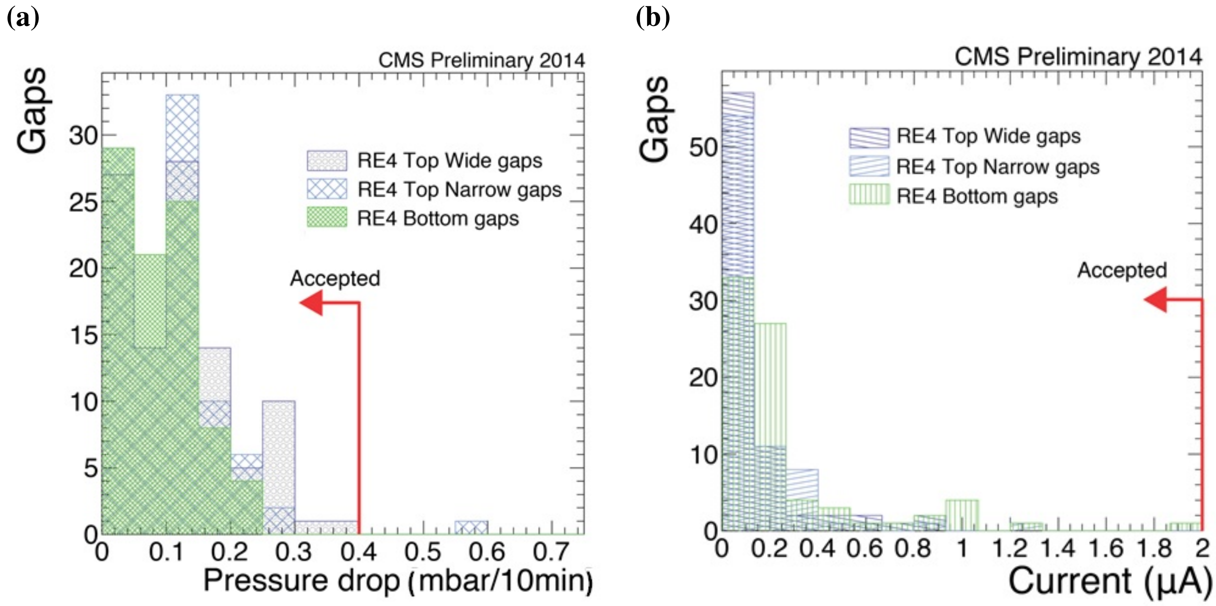


Fig. 4. Leak rate (a) and dark current (b) distributions of gaps adopted for the RE4 detector construction.

performance of RPC detectors under test and the full characterizing of each chamber is done using the tracking telescope. The average cluster size distribution, evaluated in three different η segments at the expected working point is shown in Fig. 5(a). The distribution of the expected working point is shown in Fig. 5(b).

The expected working point is defined by adding 150 V to the measured efficiency at 95%. The efficiency along the high voltage scan and the fitting of the data-points are described by Eq. (2) [8]:

$$\eta = \frac{\varepsilon_{\max}}{1 + \exp^{-\lambda(HV_{\text{eff}} - HV_{50\%})}} \qquad (2)$$

The high voltage at 50% efficiency (HV50%) is shown in Fig. 6. The overall average maximum

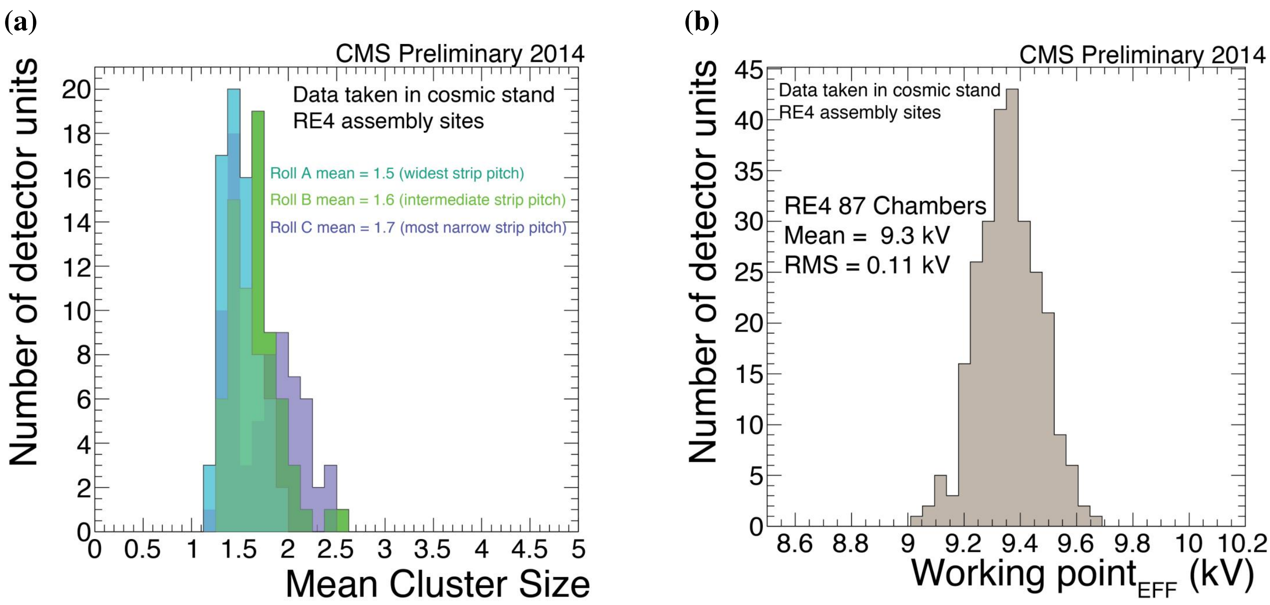


Fig. 5. Mean cluster size at the expected nominal HV working point of commissioned RE4 detectors.

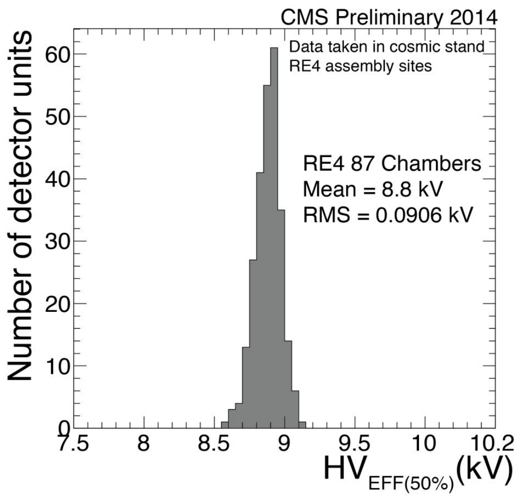


Fig. 6. High voltage distribution at 50% efficiency, as defined in Eq. (2).

efficiency in double gap mode ($\varepsilon_{\max}$) for the endcap chambers before the upgrade (only three layers) is shown in Fig. 7(a), while the one for the new RE4 layer of detectors is shown in Fig. 7(b).

CONCLUSIONS

During LS1 the RPC collaboration built and commissioned more than 144 RPC chambers. The RE4 project finished on schedule and in the budget, thanks to the good organization of every Institution and the professional work of all of the participants. At the present moment both disks have been instrumented and commissioned successfully. The new detector performance is in agreement with expectations and previous results.

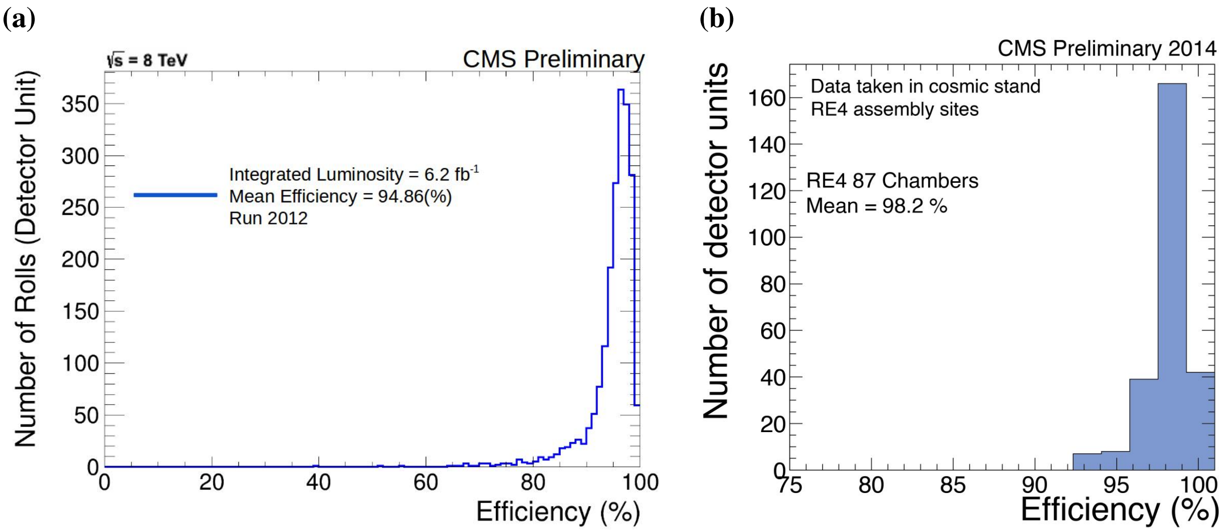


Fig. 7. The average maximum chamber efficiency of the endcap chambers before the upgrade (a) and the average maximum chamber efficiency of the RE4 chambers (b), extrapolated from the plateau curve, see Eq. (2).

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ИЗРАБОТКА И ТЕСТВАНЕ НА КАМЕРИ СЪС СЪПРОТИВИТЕЛНА ПЛОСКОСТ ЗА ОБНОВЯВАНЕ НА МЮОННАТА СИСТЕМА НА ЕКСПЕРИМЕНТА CMS

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(Резюме)

При подготовка за периода на работа с по-висока светимост от 2015 г., през последните 2 години една от основните задачи за експериметна CMS на ускорителя LHC в CERN е довършване и обновяване на мюонната система чрез поставяне на четвърти слой (RE4) камери със съпротивителна плоскост (Resistive Plate Chambers - RPC) в предната част на детектора. Четвъртата мюонна станция (два нови диска за затварящите части) се състои от 144 RPC камери, които са произведени и тествани в три производствени лаборатории – CERN (Швейцария), GHENT (Белгия) и BARC (Индия). Целта на този доклад е запознаване с процесите на конструиране и качествен контрол при производство на камерите, както и представяне на предварителни резултати получени при работата им.