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Operation and performance of the CMS Resistive Plate Chambers during LHC run II

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The Resistive Plate Chambers (RPC) at the Compact Muon Solenoid (CMS) experiment at the CERN Large Hadron Collider (LHC) provide redundancy to the Drift Tubes in the barrel and Cathode Strip Chambers in the endcap regions. Consisting of 1056 double gap RPC chambers, the main detector parameters and environmental conditions are carefully monitored during the data taking period. At a center of mass energy of 13 TeV, the luminosity reached record levels which were challenging from the operational and performance point of view. In this work, the main operational parameters are discussed and the overall performance of the RPC system is reported for the LHC run II data taking period. With a low amount of inactive chambers, a good and stable detector performance was achieved with high efficiency.

1. Resistive Plate Chambers at CMS

The Resitive Plate Chambers (RPC) at the Compact Muon Solenoid (CMS) experiment[1] at the CERN Large Hadron Collider (LHC) provide redundancy to the muon trigger system which consists of Drift Tubes (DT) in the barrel and Cathode Strip Chambers (CSC) in the endcap regions. Besides trigger redundancy it also contributes to the muon reconstruction and identification. The CMS RPCs consist of 5 barrel stations having 480 chambers whereas the endcaps consist of 576 chambers distributed over 4 stations on each side. Currently, the RPC pseudorapidity η coverage is 1.9 but an extension up to 2.4 is foreseen near 2020.

A CMS RPC chamber consists of two gaps operated in avalanche mode to ensure reliable operation at high rates. Each gap consists of two 2 mm thick high resistive High-Pressure Laminates (HPL) separated by a 2 mm gas gap. A graphite coating at the outer surface of the HPL plates guaranties a uniform distribution of the charges to achieve a uniform electric field over the entire gap area. A non-flammable 3-component gas mixture of 95.2% freon (C2H2F4, known as R134a), 4.5% isobutane (i-C4H10), and 0.3% sulphur hexafluoride (SF6) is used with a relative humidity of 40-50%. The readout plane is located between both gaps and consists of strips aligned in the $|\eta|$ direction with a pitch width between 2.28 and 4.10 cm in the barrel and between 1.74 and 3.63 cm in the encaps. In total, the entire system contains 137,000 of such copper strips covering an area of about 4000 m^2. The strip signals are asynchronously sent to the Front End Boards (FEBs) which shapes the signal before being sent to the RPC linkboard system and the CMS data acquisition system. The FEBs are electronically controllable by means of the signal threshold to handle the noise of the detector.

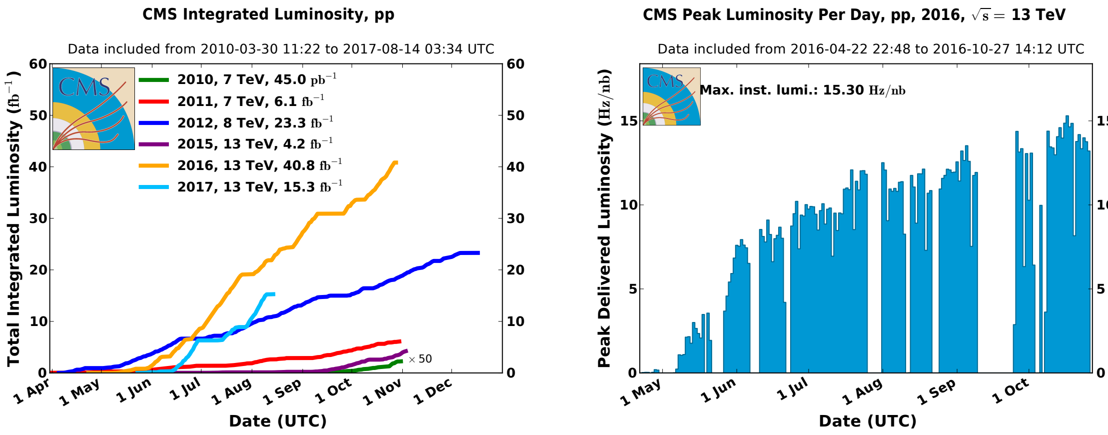

Figure 1. Delivered integrated luminosity over the years by the LHC (left) and instantaneous luminosity evolution during 2016 data taking (right)[2].

2. Run II in some numbers

After the Higgs boson discovery in 2012 during run I of the LHC data taking period, the accelerator and the experiments had their first Long Shutdown (LS1) of two years in 2013-2014. From the RPCs point of view, the fourth endcap station chambers were installed covering the full four disks in both endcaps as was initially foreseen. Besides this, a general maintenance was performed with the aim of recovering broken chambers and reparation of gas leaks.

After the LS1 in 2015, the LHC was again operational to deliver proton-proton collisions at an increased center-of-mass energy of $\sqrt{s}$ = 13 TeV. Besides the energy increase, also the instantaneous luminosity was expected to increase throughout the years. 2015 was a warm up year delivering an integrated luminosity of 4.2 fb^{-1} (see Fig. 1) with a maximum luminosity achieved around 0.5×10^{34} cm^{-2}s^{-1}. During that year the newly installed RE4 stations were successfully commissioned providing good data to the CMS Muon system. In 2016, the LHC geared up rapidly, providing stable beam collisions with a record peak instantaneous luminosity of 1.53×10^{34} cm^{-2}s^{-1}. As a result, also the data collection reached a record level up to an integrated luminosity of 40.85 fb^{-1}.

During 2016, CMS collected 37.87 fb^{-1}, yielding a luminosity loss of 2.98 fb^{-1} which was assigned due to temporary failures of different subsystems. The RPC system experienced only very few hardware problems in 2016 which was due to channel readout problems and the partial failure of the high voltage power supply system. Besides these incidents, the RPC operation for both 2015 and 2016 was stable, with 98% active chambers.

3. Background rate

Besides detection of muons directly emerging from the proton-proton collissions, other particles such as gammas, alpha particles, electrons and neutrons are present due to nuclear interactions with the detector materials. The cumulative effect of these interacting particles is called the background rate and it can leave hits in the detector with a similar characteristic as muons. At high rates, this can obviously affect the muon reconstruction and therefore the behavior of the background rate versus instantaneous luminosity needs to be understood. In Fig. 2, the current through the RPC and hit rate are plotted versus instantaneous luminosity. In both cases, a natural linear relationship is observed, which was already known from run I, but in a lower instantaneous luminosity regime. Extrapolations towards higher luminosities up to 5×10^{34} cm^{-2}s^{-1} results in a good estimation of the currents and background rate expected for the High-Luminosity LHC (HL-LHC).

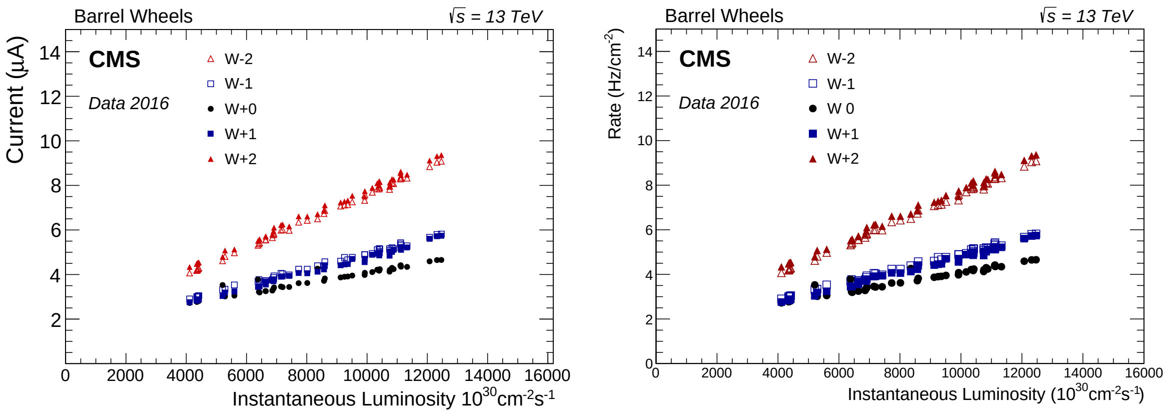

Figure 2. Current (left) and hit background rate (right) dependency of the instantaneous luminosity in the barrel region[3].

4. RPC Performance

The RPC system needs to fulfill several requirements in order to have a good performance and deliver qualitative physics to the CMS muon system. Several performance parameters are continuously monitored and the detector operational parameters needs to be adapted in order to fulfill these requirements and to optimize the physics performance. Furthermore, as the system gets older and aging effects might appear both in time or as a consequence of radiation, the hardware performance monitoring is also necessary and crucial. An overview of the three most important performance indicators are explained below and the results are given for the 2016 data taking period.

4.1. Working point calibration and efficiency

A high muon detection efficiency is the most basic and important requirement for the RPC system. A minimum of 95% is required over the entire system. The efficiency is directly related to the voltage applied and the threshold set on the electronics: the avalanches inside the gas gap have a higher probability to induce a detectable signal when the voltage is increased and the electronic threshold decreased. However, the range of both parameters are limited due to the detector noise and cluster size (see next sections respectively). The avalanche size also depends on the environmental conditions, in particular the pressure. Therefore, the working point HV_{WP} is corrected online as function of the pressure P according to:

$$HV_{corr} = HV_{WP}\left((1-\alpha) + \alpha\frac{P}{P_0}\right),$$

with $\alpha = 0.8$ and a reference pressure of $P_0 = 965$ mbar. The temperature variation is not (yet) taken into account.

The working point voltages of the RPCs are obtained by performing a high voltage scan during calibration runs: the efficiency is measured as function of the high voltage applied. The efficiency for each high voltage point can be obtained from two methods[4][5]:

- Segment extrapolation method: the muon tracks are extrapolated from the other muon detectors (DTs in the barrel and CSCs in the endcaps), and the corresponding muon hits are counted in the RPCs;
- Tag and Probe method: a new method using muon candidates from the tracker only.

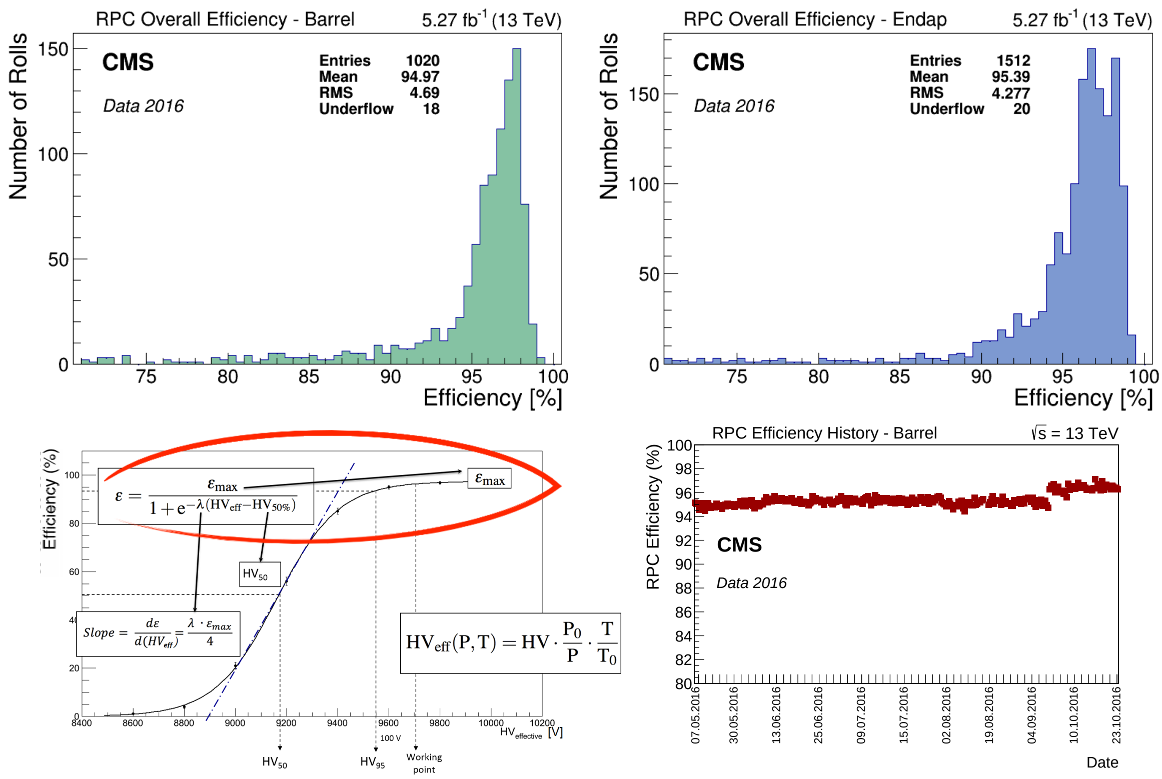

Figure 3. Top row: efficiency in barrel (left) and endcap (right) for the first period of 2016 data taking period. Bottom left: procedure to extract the working point from the high voltage scan. Bottom right: efficiency over time for the entire 2016 data taking period[3].

When plotting the efficiency versus high voltage, a sigmoid-like curve is obtained and the working point parameters are extracted from the fit, as shown in Fig. 3 (bottom-left). For the first data taking period in 2016, the results are shown in Fig. 3 (top row). An average of 95% is obtained for both barrel and endcap. Some RPCs with very low efficiency experience gas leaks or threshold control problems.

The efficiency at working point is continuously measured during data taking and is a good indicator of the stability of the RPC system. As shown in Fig. 3 (bottom right), the efficiency is very stable during the entire 2016 data taking period, resulting in a good performance. Also no detector degradation is observed as a direct effect of the high instantaneous luminosity or in-time aging. The efficiency increase at the end of the data taking period was after the recalibration of the working points and thresholds.

4.2. Intrinsic noise rate

The intrinsic noise rate is defined as the rate seen by the RPC chamber during cosmic data taking. In these circumstances, RPC high voltage is at its working point and only cosmic muons are detected. However, other contributions to the rate intrinsic to the detector can be detected due to noise coming from the high voltage system, tensions in wires, etc. Therefore it is crucial to keep this noise as low as possible, with a maximum of 5 Hz/cm^2 which is required by CMS.

The noise is measured between the LHC fills when the RPCs are at their working point or during calibration at the beginning of the year. The remote threshold control enables to control the noise per 8 strips in a chamber. Monitoring and adjusting during the data taking period is necessary to remove noisy channels which can affect the physics performance.

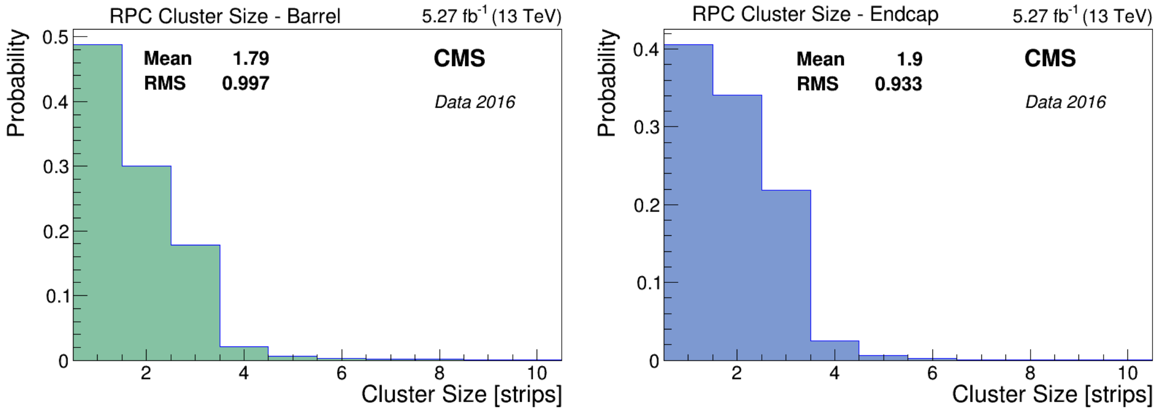

Figure 4. Cluster size distribution for barrel (left) and endcap (right) RPC chambers[3].

The intrinsic noise levels in 2015 and 2016 are continuously measured in both barrel and endcap and their values are not exceeding 0.15 Hz/cm^2, which is far below the limit. A slight dependency on the luminosity is observed which is the consequence of residual radiation after the beam dump.

4.3. Cluster Size

In ideal circumstances, only one strip is fired when a charged particle passes through both gas gaps, yielding the maximum power in position resolution of the muon reconstruction. However, fluctuations in the gas gain, high voltage, local environment and the bi-gap effect can alter the avalanche sizes, and therefore it is possible multiple strips are fired for the same muon. The cluster size is defined, on average basis, as the amount of strips fired per muon and can be maximal around 2-3 by CMS requirements.

In particular, the applied high voltage mainly determines the avalanche size and applying too high voltages can cause streamers with a large charge density in the gap covering several strips and hence the increase of the cluster size. On the other hand, the threshold applied is also sensitive to the cluster size. During operation, the cluster size is monitored by detailed analysis and the thresholds can be adapted accordingly if needed. In Fig. 4, the mean cluster size for barrel and endcap are shown for the 2016 data. The mean value of cluster size is lower than 2 and is stable during the data taking period.

5. Conclusions

During run II the CMS RPC system performed very well with a good and stable hardware operation. No major degradation has been observed concerning the hardware. Continuous and periodic detector calibrations assured good detector performance resulting in a high efficiency, low noise rate and low mean value of cluster size.

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