The high pseudorapidity region of the CMS muon system is covered by Cathode Strip Chambers (CSC) only and lacks redundant coverage despite the fact that it is a challenging region for muons in terms of backgrounds and momentum resolution. During the second long shutdown of LHC 2019-2020, two new RPC layers will be added, RE3 and RE4, which will completely cover the region of $|\eta|<1.4$ in the Endcap (as shown in Fig. 1). Thus, the additional new chambers will lead to an increased efficiency for both trigger and offline reconstruction in a region where the background is the highest and the magnetic field is the lowest within the muon system. The extended RPC system will improve the performance and the robustness of the muon trigger.

 Including RPC hits into the trigger primitive stub finding algorithm helps eliminate dips caused by the presence of high-voltage spacers inside the CSC chambers. The overall impact of the inclusion of RPC hits into the single muon trigger can be seen in Fig. 2, showing the single muon trigger efficiency with and without the usage of the RPC information. A clear improvement at the level of 15% can be seen between Figs. 1 and 2. In case of any CSC trigger problems in ME3/ME4/1, additional improvement would be expected [1].

3. The technology choice for RPC RE3 and RE4 chambers

- Design of the new chambers will be quite similar to the other existing RPC detector pads, each spanning 20 cm in width and radially oriented readout strips (as in Fig. 3).
- 18 new chambers per muon disk will be installed, 72 chambers in total for the RE3 and RE4 stations in both endcaps. Each station will provide one single hit for muon reconstruction with precise time information (~1.5 ns) and spatial resolution at the level of ~1 cm (perpendicularly to stripes) and ~2 cm (along stripes) [5].

4. Gamma Irradiation Facility (GIF++) at CERN

The Gamma Irradiation Facility (GIF++) was designed in collaboration of the CERN Engineering and Physics Department to test the future detectors of the LHC High-precision RPC (HPRC). The goal of the CMS experiment is actively using the GIF++ to investigate parameters of improved detectors [7].

5. RPC performance tests

5.1. Experimental setup

A large size transverse RPC prototype with thickness of 1.4 mm double-gap and with 20 mm wide strips has been installed and tested at GIF++ with a gun beam to evaluate the performances under different background conditions. The KODEN front-end electronics threshold has been fixed at 300 µV.

5.2. Efficiency and Cluster size

The efficiency and the average cluster size are plotted as a function of the applied effective voltage, in absence of background. As visible in Fig. 4, the gamma background rate of 1.91 Hz/μA-MeV (for the right side of the working voltage) is confirmed to be less than 0.3% while the efficiency remains slightly above 95% also under the maximum background rate [1].

The increase of the luminescence during the LHC running phase up to $5 \times 10^{12}$-cm$^{-2}$ is a concern of mass-energy of $s = 14$ TeV will be a challenge for the RPC system which does not affect the muon identification and reconstruction in the following ways:

- Performance: Increase of background rate which can lead to partial detector saturation and degradation of the performance.
- Aging: Continuous radiation will induce non-recoverable aging effects inside the RPC gap material which can alter the material properties (e.g., bandgap neutrality).

Both effects can lead to a degradation of the performance with a lower muon detection efficiency. Therefore it is necessary to estimate the impact of these effects under the LHC conditions up to an integrated luminosity of 300 fb$^{-1}$. The 2nd and 4th working data chambers will be subjected to a total expected irradiation rate of $5 \times 10^{12}$-cm$^{-2}$ during the lifetime of the detectors assuming a mean charge deposition up to $2 \times 10^{12}$-cm$^{-2}$ at 10% and a safety factor of 6.

Thus, the RPC longevity test are to certify this new detector technologies to scale up with respect the present RPC technology with both $\mu=0.6-0.4$ and $\epsilon=0.5-0.3%.\) The RPC prototype will be operated at 10% duty cycle and will be exposed to a total charge density of $1.5 \times 10^{12}$-cm$^{-2}$ during the lifetime of the detectors assuming a mean charge deposition up to $2 \times 10^{12}$-cm$^{-2}$ at 10% and a safety factor of 6.

The efficiency at working point is consistent for both RPC with a shift of 1.3 kV. Although we measured an increase of the cluster size in the order of one str [1].

The efficiency and the cluster size vs. effective voltage for the CMS RPC gas mixture and an ecological RPC gas mixture have been performed with 20 cm/20 cm size RPCs at GIF++ [5].

5.3. Eco-friendly gas mixtures for RPC

The European Community has prohibited the production and use of gas mixtures with Global Warming Potential (GWP) $>100$ and SF$\infty$ parameter to the RPCs for example present a GWP = 2600 and 2300 respectively and hence have to be replaced with alternatives with lower GWP. The R&D program of gas mixtures has been started inside the CMS Collaboration in order to find the right eco-friendly candidate.

The following gas mixtures have been used in the RPC prototypes at GIF++:

- 65% C2F4 + 10% Bi + 12% C4F8 + 13% mixture.
- 65% C2F4 + 20% Bi + 15% C2F6 + 13% mixture.
- 65% C2F4 + 20% Bi + 15% C2F6 + 13% mixture.
- 65% C2F4 + 20% Bi + 15% C2F6 + 13% mixture.
- 65% C2F4 + 20% Bi + 15% C2F6 + 13% mixture.
- 65% C2F4 + 20% Bi + 15% C2F6 + 13% mixture.
- 65% C2F4 + 20% Bi + 15% C2F6 + 13% mixture.
- 65% C2F4 + 20% Bi + 15% C2F6 + 13% mixture.
- 65% C2F4 + 20% Bi + 15% C2F6 + 13% mixture.

6. RPC aging studies at GIF++

The efficiency at working point is consistent for both RPC with a shift of 1.3 kV. Although we measured an increase of the cluster size in the order of one str [1].

7. Conclusion

Current State of the R&D on new iRPC for the CMS Muon System Upgrade is as follows:

1. The radiation environment in the CMS for the Phase-2 upgrade (L=510^{12}cm^{-2}) was studied using FLUKA simulations. The maximum hit rate of background particles on the improved RPC chambers is expected to be 750 MHz. Thus, the requirement for the new chambers is to withstand 2 Hz/cm$^{2}$ with a safety factor of three.

2. The better-performing RPC design with optimised electrodes (1.4 mm) and gas gap thickness (1.4 mm) were chosen. Work continues on the developing of new fast and low noise electronics for the RPC chambers.

3. The large size iRPCs prototype was successfully tested in an environments and high radiation at the GIF++. The chamber was tested by the CMS experiment and it was proven to be a very effective technology for CMS HL-LHC operating conditions.

4. Tests comparing standard size RPC performance with the standard CMS gas mixture and ecological gas mixture was tested with cosmic rays and muon beam at the GIF++. In both cases the working point was shifted of 1.3 kV. Further tests are ongoing.

5. The RPC longevity studies are started at GIF++ in October 2017. At the moment the RPC prototype chambers has accumulated 31% (of the total charge expected) to be collected by the chamber in the 10 years in the high LHC in high energy Endcap. Tests are ongoing.

References