CMS

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1 Introduction

The Compact Muon Solenoid (CMS) [1) 2)] is one of the four experiments around the interactions points of Large Hadron Collider at CERN. The experimental program of CMS is wide and general purpose, namely it is build to study all possible phenomena that could happen at the huge Energy produced in LHC. CMS is composed by several layers of detectors surrounding the LHC collision point and that works as a big and complex 3-dimensional camera with 140 Millions channels and able to shot 40 Million pictures per second (as many as the protons collisions in LHC). The scientific program of the CMS experiment is vast and cover the study of the characteristics of the Higgs Boson [3)], the search for dark matter particles and any possible sign of anomalies with respect to the present theoretical picture, the Standard Model. To face up this ambitious research program, the experimental apparatus is composed by several devices around the interaction point and immersed in a magnetic field of about 4 Tesla.

At moment the LHC and the CMS experiment are facing an extensive upgrade in preparation of the High-Luminosity operations of the phase-2 and the experiments are working on the consolidation of the present system and the installation of new devices that will improve the detector performances.

The 2021 as 2022 has been a hard year due to the covid restrictions and many activities have proceeded slowly.

One of the key element of the CMS detector is the highly performing and redundant muon system. Drift tubes and Resistive Plate Chambers (RPC) in the Barrel and Cathode Strip Chambers and RPCs in the endcap are used for both triggering and tracking of muon particles. New Gas Electron Mutlipliers [5)] (GEM) detectors will improve the muon trigger performance in the high pseudorapidity region. In 2020 the installation and commissioning of the innermost layer of GEMs (GE1/1) have been completed.

The next step is the production of the second layer (GE2/1) of GEM chambers that will complete the upgrade of the endcap muon system. The GE2/1 chamber production as started at CERN despite the heavy difficulties due to the pandemic restrictions, which slowed down the raw material procurement (GEM foils, PCB readot boards and drift PCB boards, inner and outer chamber frames, etc.)

The activity of the CMS Frascati group is focused on various activities involved in the Muon project. Many responsibilities are covered by Frascati members, and in view of the high luminosity LHC upgrades of phase-2, the group is also highly involved in the construction of GEM detectors. Maintenance of the Gas GainMonitoring of the CMS and studies of eco-friendly alternative gas mixture for the RPC operations are the other two core activities of the group.

2 Main responsibilities of the CMS Frascati group

The Frascati group is deeply involved in the muon project of the CMS experiment since 2005 and has been holding responsibilities since then. The group has been responsible for both construction and maintenance of the Gas Gain Monitor system of the RPC muon detector and is involved in all the activities related to the running of the detector and the reparations during shutdown periods. Moreover the Frascati group has the responsibility of the construction of part of the GEM chambers for the CMS upgrade program. Several official roles have been covered by members of the group during the last years.

- Detector Performance Group coordination (2010-11)
- RPC Run coordination (2011-12)
- GEM hardware coordination (2013-now)
- RPC National Representative (2013-14 and 2015-16)
- GEM Resource Manager (2015-17)
- GEM National Representative (2018-2020)
- RPC electronics coordination (2020-now)

In parallel the group is at moment responsible for the construction of the GEM chambers for the CMS muon upgrade, and for the R&D efforts to find an ecological gas mixture for the RPC operations, and to study its interactions with GEM and RPC materials.

2.1 GEM chamber assembling at Frascati

As part of the muon upgrade program for the CMS phase-2 [6], GEM detectors have been installed in the pseudo rapidity range of $1.6 < |\eta| < 2.2$ during the Second Long Shutdown (LS2) of the LHC (2019). The existing CMS muon system has been built with complementary trigger capability by using three detection technologies: Drift Tubes (DTs), Cathode Strip Chambers (CSCs) and Resistive Plate Chambers (RPCs). The detectors coverage at CMS of DTs, CSCs and RPCs in pseudo rapidity range is < 1.2, $1.0 < |\eta| < 2.4$ and $\eta > 1.6$ respectively. The RPCs are not implemented beyond pseudo rapidity 1.6 and to maintain existing performance of the CMS detector during High Luminosity LHC (HL-LHC), the empty region has to be instrumented. The GEM is the most suitable detector technology for this region thanks to good time resolution (4 to 6 ns) and high rate capability (100 MHz/cm^2). The addition of GEM to the CMS muon system will improve the muon momentum resolution, reduce the global muon trigger rate, assure a high muon reconstruction efficiency, and increase offline muon identification coverage.

The first stations installed are those in the innermost station of the muon system at the higher η position, the so called GE1/1. They have been built between the end of 2017 and May 2018. After construction each chamber has been tested and installed in CMS during the 2019.

The production of the second set of GEM chambers (called GE2/1), that will be installed for the Phase-2 of CMS, was expected to start from the beginning of 2020. the CMS Frascati group started the preparation of the assembly and test facility for the new GE2/1 detector in fall 2019 but due to the COVID pandemic, the construction of a larger number of chambers (about 53) will start in spring 2021. These chambers are larger than the GE1/1 and during the 2019 the local Frascati infrastructures have been improved to handle this new type of GEM detectors.

In Spring 2022 the first 6 assembly GE2/1 kits arrived in Frascati where the team proceeded with the assembly and the subsequent quality controls for the chamber validation. Due to some delays in the delivery at CERN of some the assembly components further assembly kits will be delivered in the production sites in spring 2023 so the the Frascati group participated at CERN to the assembly of 15 modules of the GE2/1 chambers, and to the realization of mechanical structures needed for the storing of the GE2/1 modules.

2.2 GGM maintenance and data analysis

The Gas Gain Monitoring (GGM) [7) 8) 9)] is part of the CMS RPC detector. Purpose of the GGM is to monitor the stability of gain for changes due to differences in gas mixture compositions. The GGM has been designed, built and operated under responsibility of the Frascati group since its proposal, in 2005. In year 2019 a radical rewriting of software was begun. The whole data acquisition system was ported to C++, the data analysis software was ported to ROOT and all operative systems aligned with the latest versions used by CMS. Two servers have been updated and tested. The system uses pressure, temperature, relative humidity sensors originally read out by a PICO system and LabView software. As a part of the upgrade, the readout of PICO system was moved to Linux OS. The upgraded system was scheduled to be implemented and tested over 2020. Because of the COVID-19 outbreak, the plan was swiftly changed. A clone of the GGM DAQ system was realised in Frascati and has been currently operating since then. The Frascati group implemented the upgrade with collaborators from Eastern Mennonite University, Harrisonburg, VA (USA) (S. Colafranceschi and collaborators) who remotely operated the system. The upgrade operations on the GGM was declared high priority task by the CMS management (CMS RPC GGM Maintenance IMPACT 157814). The GGM system went into major upgrade both for what concern the environmetal sensor system hardware (gas pressure, temperature and humidity and atmospheric parameters) and both the software needed to control the new sensor hardware based on Arduino system [?)]. The whole system has been debugged and is now operated. The new subsystem with Arduino-based sensors is planned to be operational in early 2023. Since year 2019, the GGM system is a Frascati institutional responsibility.

2.3 RPC gas mixture R&D

After a long R&D program developed in laboratory, starting from the end of 2019 the main activity in the ecogas studies has been to test the RPC performance with eco-frindly gas mixtures under irradiation at GIF++. R&D program has found two interesting candidates [12] [13] [14] to replace the tetrafluorethane $C_2H_2F_4$ (commonly called r134a) used for the Resistive Plate Chambers: Tetrafluoropropane ($C_3H_2F_4$) and Trifluoroiodomethane (CF_3I). Both of them are very electronegative and cannot be used alone to replace the r134a because the working voltage is moved to very high values not compatible with the present CMS RPC HV system. One of them ($C_3H_2F_4$) is at moment used to operate RPCs at GIF++ under irradiation. A Collaboration of people coming from CMS, ATLAS, ALICE and LHCb/Ship experiments and Cern gas group has been set up with the goal to study the operation stability of the RPCs with Tetrafluoropropane or any other interesting gas that will be found in laboratory tests. Starting from March 2021 this activity has been covered also under the AidaInnova European program.

After several test beam to characterize the RPC performances with a gas mixture based on $C_3H_2F_4$, CO_2, isobuthane and SF_6 in different percentage of CO_2 in August 2022 we started the long term aging of the detectors under irradiation. RPCs are operated under irradiation with a mixture of Tetrafluoropropane, CO_2, isobuthane and SF_6 with the following percentages: 35%, 60%, 4% and 1% respectively. Every week an HV scan is performed without irradiation to evaluate the currents at different voltages. By the end of 2022 between 30 and 100 mC/cm^2 have been collected, according to the chamber position.

2.4 RPC electronics

As part of the CMS experiment Phase-II upgrade program, new RPCs will be installed in the forward region. As high background conditions are expected in this region during the high-luminosity phase of the LHC, an improved RPC design has been proposed with a new Front-End electronics to sustain a higher rate capability and better time resolution.

The RPC rate capability is mainly limited by the current that can be driven by the high resistivity electrodes and can be improved by modifying the parameters that define the voltage drop on the electrodes. The possible ways to increase the detectable particle flux consist in decreasing the electrode resistivity; reducing the electrode thickness; reducing the average charge per count.

The average charge per count reduction is the only viable solution to increase the rate capability while operating the detector at fixed current. Consequently, a very sensitive Front-End (FE) electronics is required. An improved-RPC chamber has been designed by reducing the electrode and gas gap thickness. A full-size prototype of a double-gap improved-RPC chamber has been built for testing purposes under high irradiation.

A new Front-End Board (FEB) for the improved-RPCs has been developed at IP2I-Lyon and is presently under test at Cern. The FEBs development started in 2017. Several versions have been produced and the present version is 2.2. Early versions showed performance issues, essentially crosstalk, but along with refinement of the design these issues have been solved.

The new FEB aims to keep the improved-RPC efficiency as high as the current CMS RPC by using a sensitive and low-noise electronics, to increase the RPC spatial resolution thanks to high time resolution components and also to sustain a much higher rate (up to 2 KHz/cm2). The PETIROC, an ASIC that has all of these characteristics, is proposed to perform the readout, in association with a high-resolution delay-line Time Digital Converter (TDC), implemented on a Field-Programmable Gate Array (FPGA) to digitize the signal collected by the strips. The FEB design relies on the PetiROC2C pre-amplifier and discriminator ASIC that has been specifically developed for the CMS iRPC detector. The ASIC is implemented using the AMS 0.35um SiGe process. The new FEB is presently equipped with six PETRIOC 2C and three Altera Cyclone V FPGA, with the aim of reaching a threshold of 50 fC. The new FEB radiation hardness was tested with photons from 60Co at ENEA Calliope facility in July 2021 and more tests on Single Event Effect (SEE) have been performed with neutrons and protons in 2022, at the Frascati Neutron Generator and CHARM facility, respectively. Studies on cross-talk and efficiency have also being successfully carried out. Four demonstrator chambers were installed between 2021 and 2022 and are currently operated in CMS. Four FEB version 2.1 are used in two RE4.1 chambers and four FEB version 2.2 are used in two RE3.1 chambers.

3 Activity planned for 2023

The year 2021 will be crucial for the production of GE2/1 chambers. Although the production and installation plans will be affected by the pandemic situation, at moment the production of the GEM chambers should start at the middle of the year and all the laboratories involved are starting to prepare the setup for production an quality monitor. Frascati is one of the production sites with the goal to produce 48 chambers

the Frascati group will participate in the upgrade and installation activities for both the GEM and the RPC detectors. The Gas Gain Monitoring system will be commissioned in view of the start-up of the experiment expected in May 2022.

The production of the GE2 GEM chambers will proceed in the Frascati laboratories with the assembly of the further 37 chambers and is expected to involve the group for the full year.

Frascati indeed is one of the GEM production sites together with INFN Bari and others institute from India and China.

Studies of ecogas mixtures for RPC detectors will continue at irradiation facilities GIF++ at CERN, inside the new created collaboration that involves groups working on RPCs in all the LHC experiments and in activities beyond collider physics. A proposal has also been submitted in the AIDAnova framework with the goal to improve the infrastructures used to study on long time base the new ecofriendly gas mixtures under irradiation.

da aggiornare AIDAinnova ?

Activity planned for 2023 —ECOGAS —- DI SEGUITO NEL TESTO ?

Studies of ecogas mixtures for RPC detectors will continue at irradiation facilities GIF++ at CERN, inside the new created collaboration that involves groups working on RPCs in all the LHC experiments and in activities beyond collider physics. The irradiation campaign will continue for all the year in order to collect as mach integrated charge as possible. New test beams are foreseen by this summer and the plan is to check the performance of the chambers after a first period of irradiation. A campaign to measure the HF production under operation. With HFO based gas mixtures will also started in the Frascati laboratory in collaboration with the Atlas group of Tor Vergata. We will use the X ray gun to irradiate a small RPC and to measure the amount of HF produced under operation.

Concerning the RPC electronics, the final FEBs design was revised and approved by an Electronic System Review committee at Cern in February 2023. During this year, the activity will be focused on FEBs integration tests with the improved-RPC chambers, integration with the Back-End boards and Link-boards as well as the preparation for the FEBs mass productions.

4 Conference talks and papers by Frascati Authors

For the complete listing of CMS papers in 2021 see /www.slac.stanford.edu/spires/

1. A. Ferretti *et al.* [ALICE and ECOGAS], [arXiv:2112.08899 [physics.ins-det]].
2. A. Samalan *et al.* [CMS], JINST **17**, no.01, C01011 (2022) doi:10.1088/1748-0221/17/01/C01011 [arXiv:2109.14331 [physics.ins-det]].
3. M. Abbas, M. Abbrescia, H. Abdalla, A. Abdelalim, S. AbuZeid, A. Agapitos, A. Ahmad, A. Ahmed, W. Ahmed and C. Aimè, *et al.* JINST **16**, no.11, P11014 (2021) doi:10.1088/1748-0221/16/11/P11014 [arXiv:2107.09364 [physics.ins-det]].
4. S. Meola *et al.* Hints of BSM physics at CMS
   Plenary given at EDSU2022: 4th World Summit on Exploring the Dark Side of the Universe, 7-11 Nov 2022, La Reunion (France)
5. M. Gouzevitch, S. Meola *et al.* CMS iRPC FEB development and validation
   Plenary given at RPC2022: XVI Workshop of Resistive Plate Chamber and Related Detector at Cern in Sept. 2022 , 26-30 Sep 2022, CERN, Geneva (Switzerland)

References

1. CMS Collaboration home page is /cms.cern.ch/.

2. R. Adolphi *et al.*, “The CMS experiment at the CERN LHC,” JINST **3** (2008) S08004

3. S. Chatrchyan et al., “Observation of a new boson at a mass of 125 GeV with the CMS experiment at the LHC”, Phys. Lett. B 716 (2012) 30

4. M. Tytgat, *et al.*, “The Upgrade of the CMS RPC System during the First LHC Long Shutdown,” PoS RPC **2012** (2012) 063 [JINST **8** (2013) T02002] [arXiv:1209.1979 [physics.ins-det]].

5. D. Abbaneo, *et al.*, “A GEM Detector System for an Upgrade of the High-eta Muon Endcap Stations GE1/1 + ME1/1 in CMS,” arXiv:1211.1494

6. A. Colaleo, *et al.*, “CMS TECHNICAL DESIGN REPORT FOR THE MUON ENDCAP GEM UPGRADE,” CERN-LHCC-2015-012 ; CMS-TDR-013. - 2015. (Technical Design Report CMS ; 13)

7. S. Bianco [CMS RPC], “Gas Analysis and Monitoring Systems for the RPC Detector of CMS at LHC,” IEEE Nucl. Sci. Symp. Conf. Rec (2006), 891-894 doi:10.1109/NSSMIC.2006.355990

8. S. Colafranceschi *et al.*, ”Operational experience of the gas gain monitoring system of the CMS RPC muon detectors,” Nucl. Instrum. Meth. A **617** (2010) 146. doi:10.1016/j.nima.2009.06.095

9. L. Benussi *et al.*, “The CMS RPC gas gain monitoring system: An Overview and preliminary results,” Nucl. Instrum. Meth. A **602** (2009) 805 doi:10.1016/j.nima.2008.12.175 [arXiv:0812.1108 [physics.ins-det]].

10. https://docs.arduino.cc/hardware/nano

11. L. Benussi *et al.*, “Characterization of the GEM foil materials,” arXiv:1512.08621 [physics.ins-det].

12. L. Benussi *et al.*, “Candidate eco-friendly gas mixtures for MPGDs,” arXiv:1512.08542 [physics.ins-det].

13. L. Benussi, S. Bianco, M. Ferrini, L. Passamonti, D. Pierluigi, D. Piccolo, A. Russo and G. Saviano, “A study of HFO-1234ze (1,3,3,3-Tetrafluoropropene) as an eco-friendly replacement in RPC detectors,” arXiv:1505.01648 [physics.ins-det].

14. L. Benussi *et al.*, “Properties of potential eco-friendly gas replacements for particle detectors in high-energy physics,” arXiv:1505.00701 [physics.ins-det].