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 the 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) and third layer (ME0) of GEM chambers that will complete the upgrade of the endcap muon system. The GE2/1 chamber production as started in 2021 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.), and its still ongoing with the goal to end it at

the end of the 2024. in the meanwhile it is also started the ME0 pre-production process with the assembly and the test of some first prototypes of the new chambers

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)
- Muon electronics coordination (2023-now)

In parallel the group is 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.

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 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) started 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. Starting from spring 2023 the mass production of GE21/ chamber started and 26 assembly kits have been shipped to Frascati and here assembled and fully validated.

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 and ARDUINO. 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 environmental 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.

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 [?] [?] [?] to replace the tetrafluorethane $C_2H_2F_4$ (commonly called r134a) used for the Resistive Plate Chambers: Tetrafluoropropane ($C_3H_2F_4$) and Trifluoroiodometano (CF_3I). Both of them are very electronegative and cannot be used alone to replace the r134a because the working voltage is moved at 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 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. The activities related to these aging studies at GIF++ proceeded smoothly during 2023. In summer 2023 we performed a third test beam to evaluate the performance of the RPC with a muon beam and under several gamma irradiation doses. The test beam of 2023 is a very important test because it comes after one year of irradiation for the chambers and permits to compare the performance after a long RPC aging period. Integrated charge between 100 and 250 mC/cm^2 according to the chamber position have been collected at the end of 2023 and preliminary comparison of RPC performance in 2022 and 2023 test beam have been obtained. All these activities are also covered under the AIDAInnova European program that has been launched in 2020. The task 7.2.3 covers the ecogas studies for RPCs under the responsibility of one of the member of Frascati group. Results of the activities at GIF++ have been collected in the following papers [12] and [13]. The studies are also included in the new DRD1 Collaboration that is going to be defined at CERN with a member of CMS Frascati group as conveners of the working group related to gas an material studies.

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 the so-called 2.3. 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/cm^2). 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 0.35μm 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 FEBs version 2.1 are used in two RE4.1 chambers and four FEBs version 2.2 are used in two RE3.1 chambers.

The final FEB production requires also the definition of a Quality Control protocol in order to have fully qualified boards to be installed on the chambers, with the first boards to be installed in January 2024 during the '23-'24 Year Extended Technical Stop (YETS 23-24).

In October 2023, the 2023 Annual review of the Phase-II Muon upgrade was held and the committee approved the installation of up to 4 chambers During YETS 23-24 with 'final' chambers (hence not to be replaced): having the final front end and be able exercise the readout during real data taking will be invaluable experience for the actual operation of the final detector.

In addition, in February 2024 the RPC back-end hardware has been successfully reviewed in an Electronics System Review (ESR) of the CMS Phase-2 hardware, with the goal of endorse the procurement of the full quantity of the different back-end boards required for CMS Phase-2 installation, commissioning, and operation, including:

- Manufacturing the custom hardware
- Procurement of optical engines and accessories
- Spares management and supply

The RPC back-end system consists of three ATCA shelves, with the iRPC back-end implemented in

one ATCA shelf with 8 Serenity modules, the RPC back-end implemented in one ATCA shelf with four Serenity modules and the RECF implemented in one ATCA shelf with 8 Serenity modules. The ESR committee noted that only one rack has been assigned which is insufficient, thus one more rack was requested. The Serenity community is committed to provide first Serenity modules before June 2024, not to be held back due to lack of back-end hardware, and a significant fraction of the total modules one year later.

2.5 Muon Electronics Office

The Frascati Group is involved in the coordination of the Muon Electronics Office (MEO) since September 2023. Since then, the group contributed to the organization of the following official reviews:

- October 2023, Annual review of the Phase-II Muon upgrade
- February 2024, Electronics System Review of the CMS Phase-2 back-end electronics

The MEO works as a common interface for all Muon sub-detectors electronics offices toward the CMS upper management and is responsible for coordinating and supervising the Muon sub-detectors activity, promoting the exchange of knowledge among the Muon community and following the policies agreed by the Muon Insitution board and the CMS Collaboration Board.

3 Activity planned for 2024

The Frascati group will participate in the upgrade and installation activities for both the GEM and the RPC detectors.

The year 2024 plans are the end of the GE2/1 chambers productions and the beginning of the ME0 mass production.

Although the production and installation plans for the GE2/1 has been affected by the 2020 pandemic and all the side effects it introduced in terms of material delivery, at moment the production of the GEM chambers is ongoing and the aim for the GE2/1 completion by 2024 is maintained. Frascati has the goal to produce and fully validate up to 48 GE2/1 chambers.

The Gas Gain Monitoring system will be commissioned in view of the start-up of the experiment expected in May 2023.

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.

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 and the installation during YETS 23-24 of up to 4 chambers equipped with the new electronics was authorized in October by the 2023 Annual review of the Phase-II Muon upgrade committee. In February 2024 the RPC back-end hardware has been successfully reviewed in an Electronics System Review (ESR) of the CMS Phase-2 hardware. During this year, the activity will be focused in further advancing the tests on FEBs integration with the improved-RPC chambers, integration with the Back-End boards and Link-boards as well as the preparation for the FEBs mass production and definition of a suitable quality control protocol for FEBs validation.

4 Conference talks and papers by Frascati Authors

For the complete listing of CMS papers 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.* CMS Upgrade and Future
   Plenary given at BSM2023: Beyond Standard Model: From Theory to Experiment, 6-9 Nov 2023, Hurghada (Egypt)".

5. 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)

6. 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)

7. D. Piccolo *et al.*, "High-rate tests on Resistive Plate Chambers filled with eco-friendly gas mixtures" accepted for publication on European Physical Journal

8. D. Piccolo *et al.*, "Preliminary results on the long term operation of RPCs with eco-friendly gas mixtures under irradiation at the CERN Gamma Irradiation Facility" Submitted to EPJplus focus point on the green transition of particle detectors

9. R. Campagnola *et al.*, "Status of the production of GEM chambers for the CMS experiment at Large Hadron Collider", accepted for publication on Nuovo Cimento - Colloquia on Physics

10. R. Campagnola *et al.*, "Status della produzione delle camere GEM per l'esperimento CMS al Large Hadron Collider", parallel session given at 109th National Congress of Italian Physical Society, 11-15 September 2023, Salerno (Italy)

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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. D. Piccolo *et al.*, "High-rate tests on Resistive Plate Chambers filled with eco-friendly gas mixtures" accepted for publication on European Physical Journal C

13. D. Piccolo *et al.*, "Preliminary results on the long term operation of RPCs with eco-friendly gas mixtures under irradiation at the CERN Gamma Irradiation Facility" Submitted to EPJplus focus point on the green transition of particle detectors