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.

After the successful data taking in the 2024 the LHC and the CMS experiment are facing an extensive upgrade in preparation of the High-Luminosity operations of the phase-3 and the experiments are working on the consolidation of the present system and the installation of new devices that will improve the detector performances.

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 and the GEM system successfully participated in the 2024 data taking campaign.

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 finalization, started in 2021, has been postponed due to the High Granularity E-CAL installation schedule that force to move ahead with the ME0 chambers construction.

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)
- BRIL and TETRA-BALL coordination and commissioning (2024-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.

3 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 ME0 set of GEM chambers, that will be installed for the Phase-3 of CMS, was expected to start from the beginning of 2026 but has been anticipated to match the High Granularity E-CAL Upgrade. The first pre-production set of 5 ME0 assembly kits arrived in Frascati by the end of spring 2024 and the team proceeded with the assembly and the subsequent quality controls for the chambers validation.

4 BRIL (CMS, CSN 1)

4.1 Introduction

The Beam Radiation, Instrumentation, and Luminosity (BRIL) [14)] group operates a number of detectors for measuring the luminosity and monitoring beam conditions in CMS (Compact Muon Solenoid) at CERN. Having multiple detectors provides redundancy in case of problems with one, as well as a way to measure how their behaviour changes in different LHC beam conditions. These detectors are expected to play an important role in the upcoming Run 3 of the LHC. Within the BRIL collaboration, Frascati and Turin INFN sections are developing "Tetraball", a single moderator neutron spectrometer for the CMS cavern.
The main characteristics of this spectrometer are the following:

- It is sensitive to neutrons from thermal to GeV;
- Its response is nearly isotropic by combining radial positions;
- It is made up of a single polyethylene sphere containing pairs of radiation resistance SiC diode. One member of the pair is coated with ^{6}LiF to make the whole detector sensitive to neutrons while the other sensor is not coated, so is mainly sensitive to photons and charged particles;
- It is equipped with a lead shell to make the device sensitive to high-energy neutrons;
- It needs a single exposure and an unfolding process to get the spectrum while the traditional method of Bonner spheres requires multiple exposures.

4.2 Simulations

Tetra-Ball (T-Ball) is a new type of extended energy range single sphere neutron spectrometer suited for the long acquisition of neutron spectra in the High-Luminosity LHC period in the CMS Cavern. Compared to its predecessor, the SP2, it reduces the number of sensors from 31 to 21.

This is achieved with a tetrahedric disposition of the sensors.
The polyethylene spherical moderator is 28 cm in diameter and includes a lead insert for the detection of neutrons above 10 MeV. The work performed describes the T-Ball design and calculates the response matrix considering four different irradiation geometries. The impact of anisotropy effects on the T-Ball spectrometric performance is investigated by simulation. Although the performed work does not cover the totality of the possible energy distributions and conditions of use, the results suggest that T-Ball could offer adequate spectrometric performance and a good isotropy in most operating scenarios in the high-energy field.
The spatial distribution of thermal neutron sensors in T-Ball in comparison to SP2 is shown in Fig. 1.

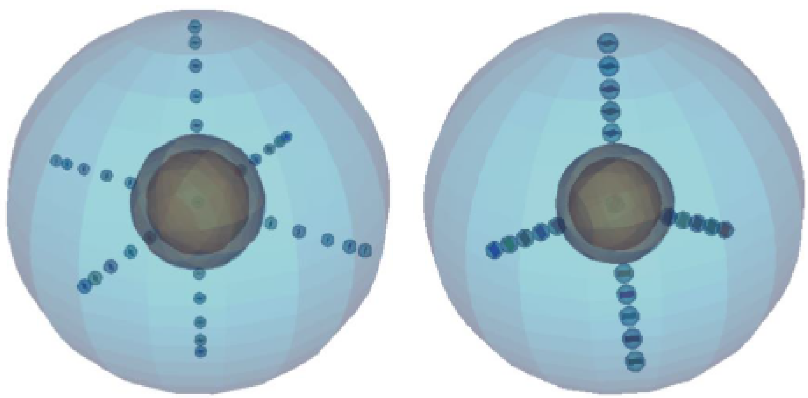

Figure 1: Disposition of the internal thermal neutron detectors in the SP2 (left) and T-Ball single moderator neutron spectrometers (right).

After having proved that the response of the device is isotropic through simulations, we can compute the set of response functions (for each radial position) when the neutron field is impinging the device isotropically. The set of response functions in this case are those shown in Fig.2 which are reminiscent of the classical response functions of standard Bonner Sphere Systems.

Fig. 3 shows an unfolded neutron spectrum in a MC-Unfolding test where the goodness of the isotropic response is under test. In that test, similar conditions of those found in CMS cavern are simulated. The neutron spectrum shown in Fig. 3 is therefore containing the same elements that will be find on the CMS cavern, that is to say, thermal, epithermal, fast and high energy neutrons.

4.3 Experimental tests

The electronic boards for the project were designed by DIGITECH srl (Peccioli, Pisa) and tested by LEMRAP.

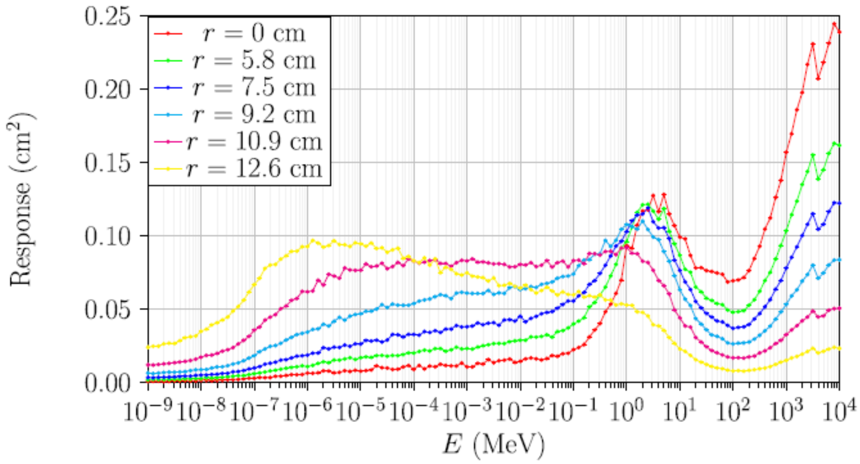

Figure 2: Response matrix of the T-Ball obtained under isotropic irradiation geometry. The response as a function of the radial position is obtained by averaging the readings of the detectors at the same radial position.

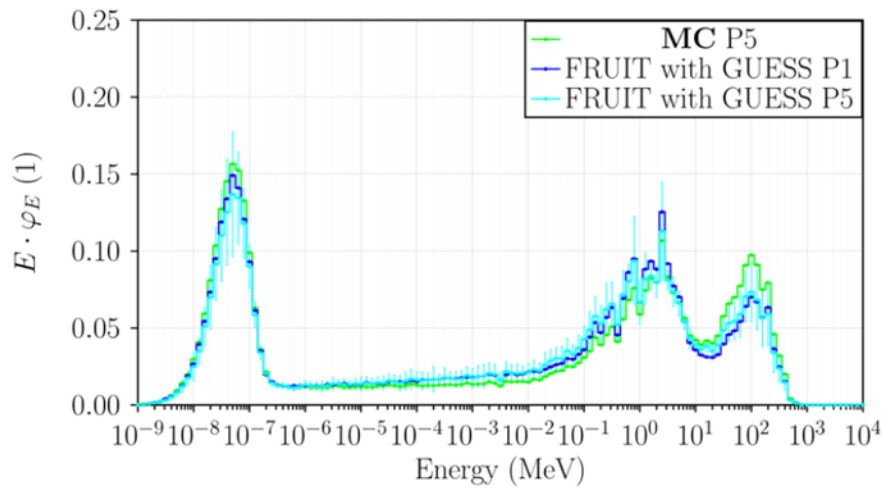

Figure 3: Unfolding test using the isotropic response matrix and changing the guess spectrum.

The electronic chain used for the experiment is made up of two different boards, shown in Fig. 4:

- a multi-channel analogue board, in order to correctly acquire the pulses produced in the interactions of the neutron field with the neutron spectrometer;
- a digital board and a microprocessor, in order to discriminate the pulses beyond a certain threshold (due to neutrons and not to photons or electronic noise) and to count them using

a dedicated software.

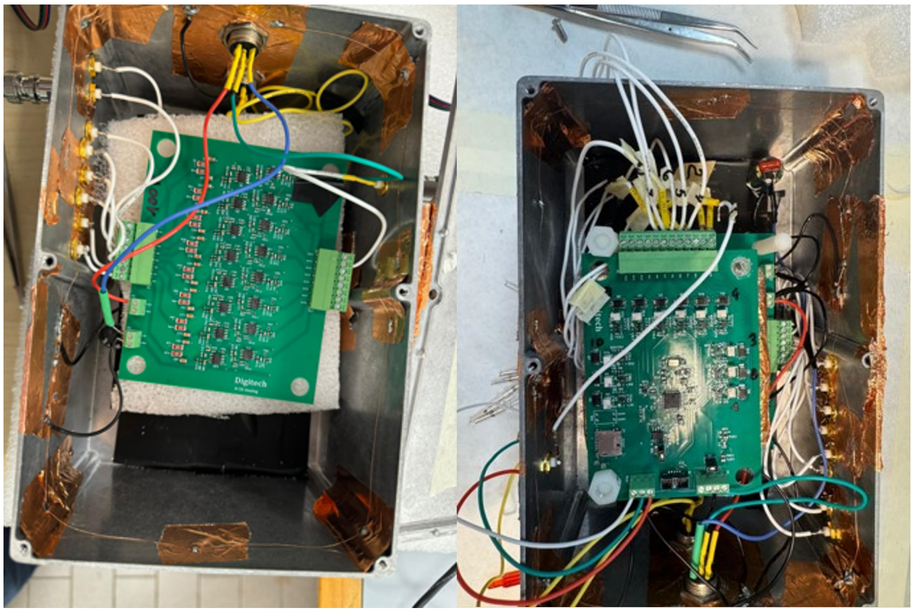

Figure 4: (Left) Analogue board equipped with pre-amplifier and amplifiers. (Right) Digital board with comparator and counting microprocessor.

The aim of this activity was to optimize the parameters of the analog board to extract a neutron pulse height distribution from the silicon carbide detector when exposed to neutrons.
In addition, a challenging work was performed in order to guarantee stability and efficiency for a 42-channels analog-digital system.

An example of Pulse Height Distribution (PHD) obtained with a Silicon Carbide detector covered with 6-Lithium Floride (see Fig.5) in the thermal neutron source HOTNES (Thermal Neutron Source in ENEA Frascati) is reported in Fig. 6.

During 2024, a set of experimental tests was performed in CMS cavern with different configurations in order to study the response of the system under variable experimental conditions (proton-proton, heavy ions collisions).
An example of experimental configurations (4 Bonner Spheres with 4 detector couples, one bare and one covered with 6-Lithium Floride) installed by our research team in CMS experimental cavern is shown in Fig. 7.

First experimental results show that the count rate of covered detectors is proportional to the instantaneous luminosity (see Fig. 8).

Figure 5: SiC placed inside HOTNES.

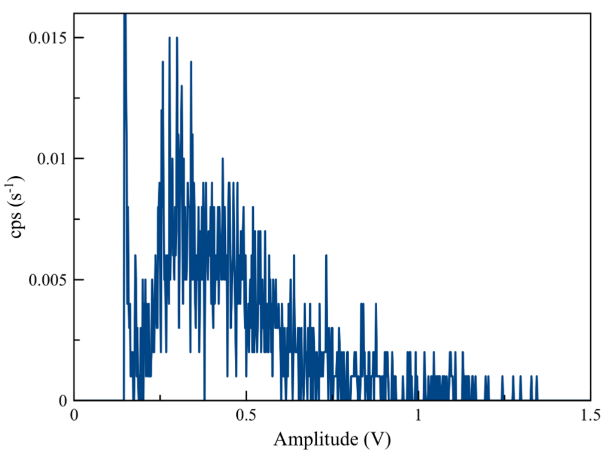

Figure 6: Spectrum of the 7.6 mm2 SiC obtained at HOTNES with the 3-channel DIGITECH board.

The program of year 2025 includes the development, the calibration and the installation of a first Tetraball inside the CMS cavern.

Figure 7: Experimental set-up in CMS cavern with 4 Bonner Spheres, each one containing a couple of SiCs (one bare and one covered with 6-Lithium Floride).

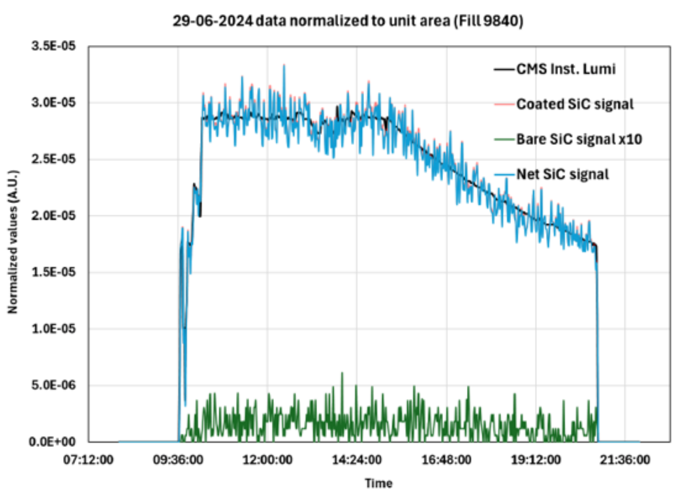

Figure 8: Neutron count rate of a covered silicon carbide as a function of instantaneous luminosity.

5 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 new GGM system with Arduino-based sensors was brought to operation in early 2023 as planned. At the end of 2024, the system experienced major gas leaks from the RPC gaps, supposedly caused by fatigue and glue/components failure. Refurbishing of RPC gaps started by means of use of spare gaps stored in Frascati since 2006. The system is expected to be fully operational again in mid 2025.

6 GEM Database

The CMS Frascati group contributed to the upgrade of the GEM Database. In particular, completion of the ME0 database has been finalized with validated electronic components, ME0 modules, and stacks. The quality control file format has been fine-tuned and finalized. An initial data upload of detector components and various quality control (QC) metrics demonstrated that the system is fully operational. Additionally, support for the GE21 database has been integrated, along with bug fixes and optimizations.

7 Heterogeneous Computing

A new line of research has been initiated during 2024 in the Computing task force researching on Heterogeneous Computing. Porting an existing CMSSW (Software) Producer class (JetCoreClusterSplitter) to the new Alpaka-GPU environment to enhance performance. Both the original and newly ported JetCoreClusterSplitter Producer employ a K-map algorithm to split reconstructed clusters, improving tracking efficiency in high pile-up environments. The new developed producer (available on CMSSW github) leverages a Structure of Arrays (SoA) and runs fully in parallel on the GPU, significantly boosting performance through GPU parallelism.

8 RPC gas mixture R&D and AidaInnova European program activities

The R&D activities related to studies of alternative ecological gas mixtures for RPC operations in the CMS experiment have been developed inside the AIdaInnova European program 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. All the studies are carried on in the context of the EcoGas@GIF++ Collaboration involving people coming from CMS, ATLAS, ALICE, LHCb/Ship experiments and CERN EPDT group, with the goal to verify the long term performance of RPC operated with ecological gas mixtures under LHC-like background conditions. The AidaInnova project will end in March 2025 after 4 years of operations testing several RPC chambers with ecological gas mixtures and under radiation. The most interesting gas mixtures tested are the so called ECO2 and ECO3 mixtures that have been compared to the standard gas mixture (STD), the one used for Atlas and CMS experiment:

- STD: $C_2H_2F_4$ - i-C_4H_{10} - SF_6 (95.2 % - 4.5 % - 0.3 %)
- ECO2: $C_3H_2F_4$ - CO_2 - i-C_4H_{10} - SF_6 (35 % - 69 % - 4 % - 1 %)
- ECO3: $C_3H_2F_4$ - CO_2 - i-C_4H_{10} - SF_6 (25 % - 69 % - 4 % - 1 %)

The chambers are operated under gamma irradiation at GIF++ facility at the operation voltage and the dark current of all the RPCs are monitored during the time. Every year several test beams are performed in order to compare RPC performance as a function of the time and of the integrated charge. The irradiation campaign started in 2022 and after three years of operation an integrated charge between 50 and 350 mC/cm^2 according to the chamber position and to the time of installation have been collected. The CMS chamber in particular already integrated a charge corresponding to the full LHC life without taking into account the factor 3 of safety factor.

The effect of the irradiation produces an increase of the dark current of the detectors, that could be a sign of deterioration of the electrode surfaces. At the same time the maximum efficiency of the chamber is almost stable as a function of the integrated charge, while the working point is shifted at higher values mainly due to the increased drop of voltage across the electrodes because of the current increase. Results of the activities at GIF++ have been collected in the following papers [12)] and [13)] and presented in several conferences. A complete report on the last four years activities has been submitted at the end of 2024 and will be published in the final report of the AidaInnova project.

9 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.

10 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 Institution board and the CMS Collaboration Board.

11 Activity planned for 2025

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

The year 2025 plans is the start of the ME0 chambers mass productions. Frascati has the duty to complete the assembly of 45 ME0 modules and to validate them with QC test concerning HV stability, gas tightness and gain uniformity.

The Gas Gain Monitoring is back in operation and ready for the next CMS data taking, providing the RPM gas mixture stability monitoring.

The studies of ecogas mixtures for RPC detectors will continue at the irradiation facilities GIF++ of CERN inside the new DRD1 Collaboration that is going to be defined at CERN.

The Chambers will be maintained under irradiation and more test beams will be performed in summer of 2025. An upgrade of the system is expected at GIF++ to improve the monitoring of the environment during data taking. There are plans to open some of the irradiated chambers to analyze the electrode surface and to start a new aging campaign replacing also the SF_6 with alternative ecological gases.

Concerning the RPC electronics, the final FEBs design was revised and approved by an Electronic System Review committee at Cern in February 2024 and the installation during YETS 24 of up to 4 chambers equipped with the new electronics was authorized in October by the 2024 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.

12 Conference talks and papers by Frascati Authors

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

- 9 - 13 december 2024 Geneva, Switzerland. CMS Upgrade Week held at CERN. A. I. Castro-Campoy et al., The first TB Carrot (arm) assembled and tested at LNF.
- 9 October 2024 Teddington (UK) Neutron Users Club NUC 2024 at the National Physics Laboratory NPL.
  A. I. Castro Campoy et al., A simple PGAA system for boron determination in the tens of milligram range. R, Bedogni et al., The evolution of Bonner Spheres into single moderator neutron spectrometers.
- 7-9 October 2024, Roma, Università La Sapienza, CMS Italia meeting. Roberto Bedogni et al., Invited talk "Tetraball".
- CMS Upgrade Week held on CERN From 16th to 20th September 2024. Poster. Caballero-Pacheco, M.A. on behalf of CMS-BRIL collaboration. Tetra-Ball: a novel neutron spectrometer for the BRIL upgrade project.
- 28 – 31 May 2024 SATIF-16 16th workshop on Shielding aspects of Accelerators, Targets and Irradiation Facilities - National Laboratories of Frascati, Italian National Institute for Nuclear Physics (INFN).
- R. Bedogni et al., From Bonner Spheres to real-time single-moderator neutron spectrometers.
- M. A. Caballero Pacheco et al., The Tetra-Ball single moderator neutron spectrometer.

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. 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

14. R. Bedogni, M. Costa, E. Durisi, E. Mafucci, V. Monti, M. A. Caballero Pacheco, A.I. Castro-Campoy, D. Dashdondog, L. Russo, A. Pietropaolo, G. Pasztor, O. Karacheban, A. Lokhovitskiy, S. Mallows. TetraBall: A single-moderator neutron spectrometer for HL-LHC.
    Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment Volume 1068, November 2024, 169805.
    https://doi.org/10.1016/j.nima.2024.169805