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Longevity studies for the CMS Muon System towards HL-LHC

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The High Luminosity LHC program will pose a great challenge for the different components of the CMS Muon Detector. Existing systems, which consist of Drift Tubes, Resistive Plate Chambers (RPC) and Cathode Strip Chambers (CSC), will have to operate at 5 times higher instantaneous luminosity than the designed for, and, consequently, will have to sustain about 10 times the expected LHC integrated luminosity. Additionally, to cope with the high rate environment maintaining a good performance, additional Gas Electron Multiplier and improved RPC detectors will be installed in the innermost region of the forward muon spectrometer of the CMS experiment. The design of these new detectors will have to assure their long-time operation in a hard environment. Finally, RPC and CSC use gases with a global warming potential and therefore a search for new eco-friendly gases is necessary, as part of the CERN-wide program. To address all of these challenges a series of accelerated irradiation studies have been performed for all the muons systems, mainly at the CERN Gamma Irradiation Facility, or with specific X-ray sources. In this summary the status of the studies on the longevity of the different systems of the CMS Muon Detector, after the large integrated charge in the last years, will be reported. Additionally, actions taken to reduce the actual detector aging and to minimize greenhouse gas consumption will be discussed.

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1. Introduction

The Compact Muon Solenoid (CMS) [1] is a multipurpose particle physics detector built at the CERN Large Hadron Collider (LHC). The CMS basic design element is a super-conducting solenoid that produces a 3.8 T magnetic field. The tracker, the electromagnetic and hadron calorimeters are within the field volume. The iron yoke is instrumented with a muon spectrometer for muon identification, momentum measurement, and bunch crossing assignment for triggering. The present muon spectrometer, designed in the 90's to deal with the initial LHC specifications (instantaneous luminosity of about 10^{34} cm^{-2}s^{-1}), is composed of 5 separate wheels in the barrel containing 4 concentric layers of detectors, and 4 independent disks both in the positive and negative endcaps. Three different gaseous detector technologies are employed: drift tube (DT) chambers, in the barrel region, to detect muons up to pseudo-rapidity $|\eta| < 1.2$; cathode strip chambers (CSC) to handle the higher rates and non-uniform magnetic field in the endcap region $0.9 < |\eta| < 2.4$; and resistive plate chambers (RPC) located in both barrel and endcap regions up to $|\eta| < 1.9$.
A major upgrade of the LHC is planned to fully exploit the physics potential of the accelerator (Phase2) [2]. This will imply to operate with an instantaneous luminosity increased by a factor 5-7, higher pile-up (PU, up to 200), collecting an integrated luminosity about 10 times larger than the LHC design value. High rate conditions will not only accelerate the aging process of the detectors and electronic components but also result in increased trigger rates which translate into more demanding requirements on the electronics. The CMS muon system upgrade program [3] will cover the substitution of the on-detector electronics of the existing detectors and the installation of new muon Gas Electron Multipliers (GEM) and improved RPC (iRPC) detectors to increase the number of the hit measurements along the muon path in the high η region. The locations of the additional detectors, specifically ME0, GE1/1, GE2/1, RE3/1, RE4/1 are indicated in Figure 1. The GE1/1 ring is already in place and has recently started to take data, while the GE2/1 and ME0 chambers will be installed in the next scheduled shut-down.
As part of the upgrade program, longevity studies of both existing and new muon systems are aimed to certify the detector performance for 10 years of operation under the harsher HL-LHC conditions. A further challenge during the Phase2 operations concerns the phase out of the fluorinated greenhouse gases planned by CERN according to the Europen Commission regulations[5]. Studies to find alternative gas mixtures to operate RPCs and CSCs are ongoing (DTs and GEMs use Ar/CO_2-based mixtures), as well as the improvement in the gas system technology aimed to reduce the gas consumption.

2. Long term irradiation studies

Assessing the longevity of the muon system represents one of the milestones of the upgrade program. Most of the aging program is carried out at the CERN Gamma Irradiation Facility (GIF++) [4] which is equipped with a 100 GeV/c muon beam and a γ-ray 13.5 TBq Cs-137 source. Full-size DT, RPC, CSC, and GEM chambers are exposed to high rate, where the accumulated charge per cm of wire, or per cm^2 area is used as a proxy of radiation exposure. The High Voltage (HV) currents measured at CMS are used to extrapolate the amount of integrated charge corresponding to HL-LHC adding a safety factor 3 to account for all the possible unknown effects. Due to the high

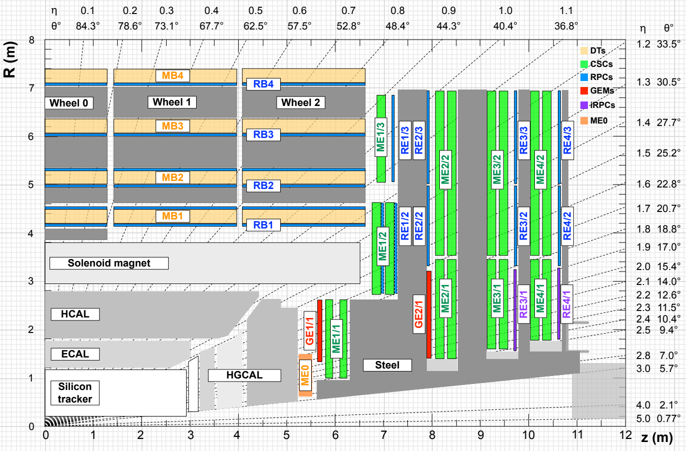


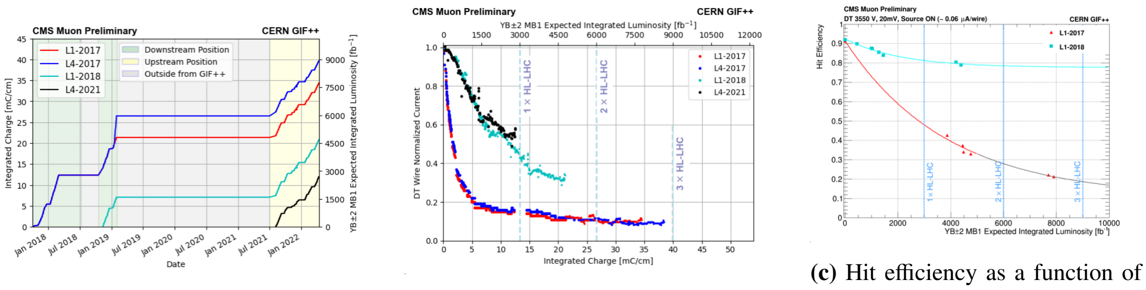
Figure 1: An R-z cross section of a quadrant of the CMS detector, including the Phase-2 upgrades (RE3/1, RE4/1, GE1/1, GE2/1, ME0). The interaction point is at the lower left corner. The locations of the various muon stations are shown in color (MB = DT = Drift Tubes, ME = CSC = Cathode Strip Chambers, RB and RE = RPC = Resistive Plate Chambers, GE and ME0 = GEM = Gas Electron Multiplier). M denotes Muon, B stands for Barrel and E for Endcap.

value of accumulated charge expected on ME0, irradiation tests on GEM chambers are ongoing also at the X-ray facilities in Aachen and Seoul, where the charge accumulation can be much faster. Irradiation tests are also fundamental to assess the performance of the RPCs and CSCs operating with alternative gas mixtures at the level of radiation expected at HL-LHC. The presence of these specific greenhouse gases is not accidental: CF_4 is an efficient non-flammable photon quencher, added to enhance the CSC longevity (Sec.2.3), and to make electron drift velocity fast; $C_2H_2F_4$ is used as an efficient photon quencher, while SF_6 is a strongly electronegative gas, and both components are needed to ensure a stable operation of RPCs.

2.1 DT

DT longevity studies have been ongoing since 2017 on a spare MB2 chamber, consisting of 12 layers (L) arranged in 3 super layers (SL), each one containing hundreds of cells. The drift-cell is the basic element nominally operating with anode wire at 3600 V. Fig.2a shows the evolving operations at GIF++: L1 and L4 of SL1 are the only ones kept on during the irradiation, while the L3 is kept off and used as the reference in the gain calculation. Performance of all the wires in L1 (L1-2017 in red) and L4 (L4-2017 in blue) measured in the first year of irradiation showed a deep decrease of the gain (Fig.2b). To understand the phenomena behind this effect, in 2018 some wires in L1 were extracted, analyzed, and replaced with new wires, represented in cyan in all the plots of Fig.2. Something similar was done again in 2019 replacing some wires in L4, and one of the replaced wires in the L1, represented in black in all the plots of Fig.2. Spectroscopy analysis showed the presence of a large peak of carbon (C) in the coating material deposited on the L1-2017 wires, almost absent in the extracted L1-2018 wire, whose gain decreases much slower (cyan curves in Fig.2). Despite this correlation, what caused the deep loss of gain in the L1-2017 wires is still unclear. Therefore a mitigation strategy has been adopted to slow down the aging effects: reducing the HV of 50 V allows to accumulate about 30% less charge; operating with the gas system in

open loop instead of closed loop minimizes the circulation of impurities; and installing a borated polyethylene shielding coupled to a layer of lead allows to halve the radiation from the neutron background.
The different loss of gain reflects into hit efficiency measurements shown in Fig.2c. For the L1-2017 wires the single hit efficiency drops to 20% around 3 HL-LHC, while the efficiency of the wires replaced in 2018 (L1-2018) is expected to be around the 80%.



(a) Integrated charge collected by MB2 chamber at GIF++, y-axis on the right shows the corresponding LHC integrated luminosity.

(b) Li/L3 relative current (gain) as a function of the integrated charge. Top x-axis shows the corresponding LHC integrated luminosity.

(c) Hit efficiency as a function of the integrated charge for the background rate expected on the most exposed DT chambers, the MB1 of the external wheels.

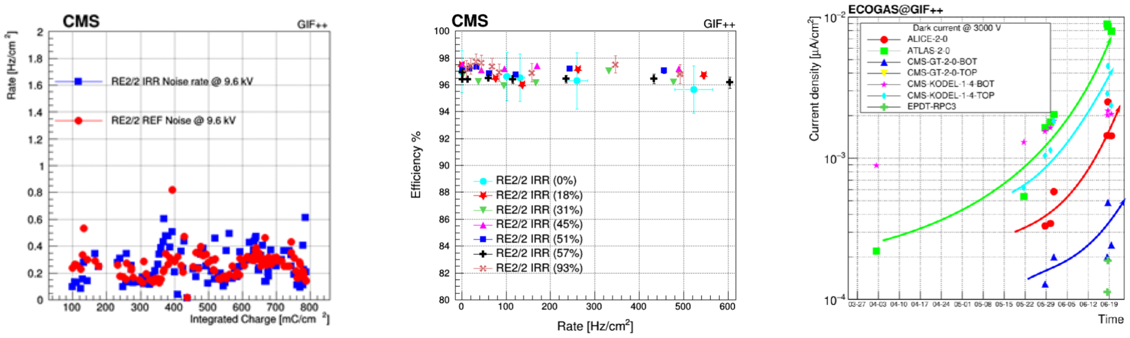
Figure 2: DT results of the irradiation tests

2.2 RPC

RPC double gap chambers nominally operate in avalanche mode above 9000 V with a mixture of $C_2H_2F_4$ (95.2%), iso-C_4H_{10} (4.5%), and SF_6 (0.3%). Longevity studies with the nominal gas mixture show stable performance evaluated in terms of noise rate (Fig.3a) and hit efficiency (Fig.3b) at the expected HL-LHC rates. Very challenging are instead the ecogas studies, handled by a joint collaboration between CMS and other CERN experiments[6]. Three potential mixtures, combining different amount of CO_2, HFO, iso-C_4H_{10}, and SF_6, are under study: 50/45/4/1, 60/35/4/1, and 69/25/5/1. The first one, giving high dark current (Fig.3c), has been discarded, while the other two, showing a good preliminary efficiency in test beam, are going to be studied in longer term.

2.3 CSC

CSC chambers at CMS nominally operate with a gas mixture composed of 40% Ar, 50% CO_2 and 10% of CF_4. The irradiation campaign started in 2016 reached about the amount of integrated charge requested for the longevity studies. Results show a stable performance in terms of gain and spatial resolution, both operating with the nominal gas mixture and operating with only 2% of CF_4, respectively shown in the plot of Fig.4a up to 250 mC/cm and above. Despite the optimistic prediction the microscope analysis highlighted the presence of a larger pollutant layer on the wires that operate with a reduced amount of CF_4. This further motivated the search for an alternative gas. At moment, the most promising one is the HFO-1234ze, preliminary tested only with a small 30x30 cm^2 CSC prototype. Results are rather stable in terms of gain (Fig.4b) despite a rapid increase of dark current is measured for very high values of instantaneous luminosity (6 HL-LHC) (Fig.4c). It could be caused by the use of a very small prototype, therefore studies on a regular CSC spare chamber are fundamental to have the final assessment.

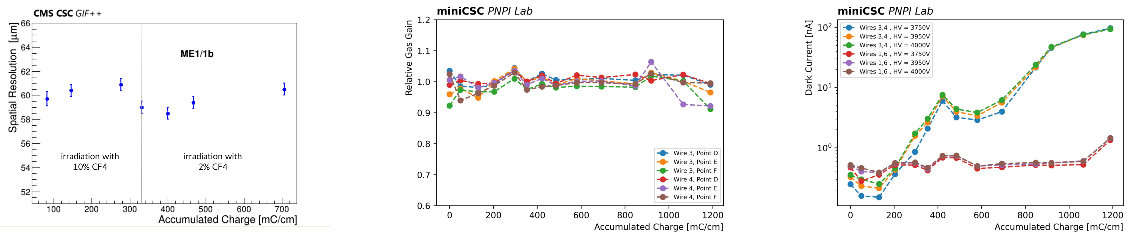


(a) RPC Noise rate as a function of the integrated charge measured with source off. Red and blue curves represent the reference and the aged chambers respectively.

(b) RPC hit efficiency as a function of the background rate. Each curve is relative to the percentage of integrated charge respect to the one expected at 3 HL-LHC.

(c) Dark current of the RPCs using the CO_2/HFO/iso-C_4H_{10}/SF_6 50/45/4/1, during the irradiation period [6]: high increase of dark currents after 30 days of irradiation.

Figure 3: RPC results of irradiation tests



(a) Spatial resolution as a function of the integrated charge: data up to 200 mC/cm have been collected using the nominal gas mixture with 10% of CF_4; data above 200 mC/cm have been collected using only 2% of CF_4.

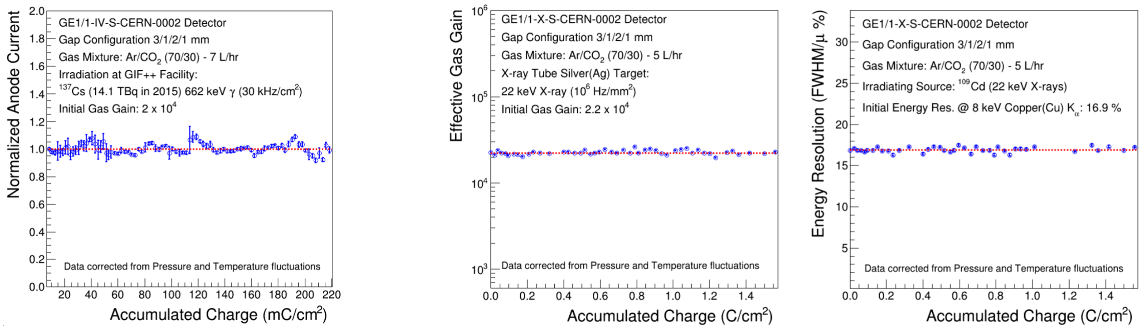
(b) Gain as a function of the integrated charge of a 30x30 cm^2 CSC prototype using the HFO-1234ze at different values of HV. Measurements have been done at high value of instantaneous luminosity (6 HL-LHC).

(c) Dark current as a function of the integrated charge of a 30x30 cm^2 CSC prototype using the HFO-1234ze at different values of HV. Measurements have been done at high value of instantaneous luminosity (6 HL-LHC).

Figure 4: CSC results of irradiation tests

2.4 GEM

Longevity studies done at GIF++ allowed to assess the performance of the GE1/1 and the GE2/1 chambers, which remained stable at HL-LHC expected rates (Fig.5a). For what regards ME0, which is going to instrument the extended η region up to 2.8, the accumulated charge is predicted to be about 2 order of magnitude higher than for the other GEMs, therefore their longevity assessment will come from an ongoing test with X-rays in specific facilities in Aachen and Seoul. Preliminary results, based on about the 15% of the expected charge, show a stable gain and a stable energy resolution (Fig.5b).



(a) Gain as a function of the integrated charge obtained at GIF++

(b) Gain (left) and energy resolution (right) as a function of the integrated charge measured during the test beams at X-ray facilities

Figure 5: GEM results of irradiation tests

3. Conclusions

Studies to assess the longevity of the CMS muon systems have been carried out since many years as part of the CMS muon upgrade program. Results obtained at the CERN GIF++ indicate that all the existing muon systems can efficiently continue to operate at HL-LHC. DT system is the one showing a degraded local hit efficiency, even though it would affect only the 10% of the chambers. Despite that, global muon trigger performance is predicted to remain stable in barrel, thanks to the redundancy of the muon system and to the new Phase2 back-end electronics that can efficiently compensate for the local hit loss. More time is needed to accumulate enough charge to validate ME0. Optimization of the gas system technology, aimed to reduce the consumption of the greenhouse gases, is already working for the CSCs while is being deployed for the RPCs. At the same time searches for alternative gas mixtures are continuing.

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