Longevity studies for the CMS Muon System towards HL-LHC

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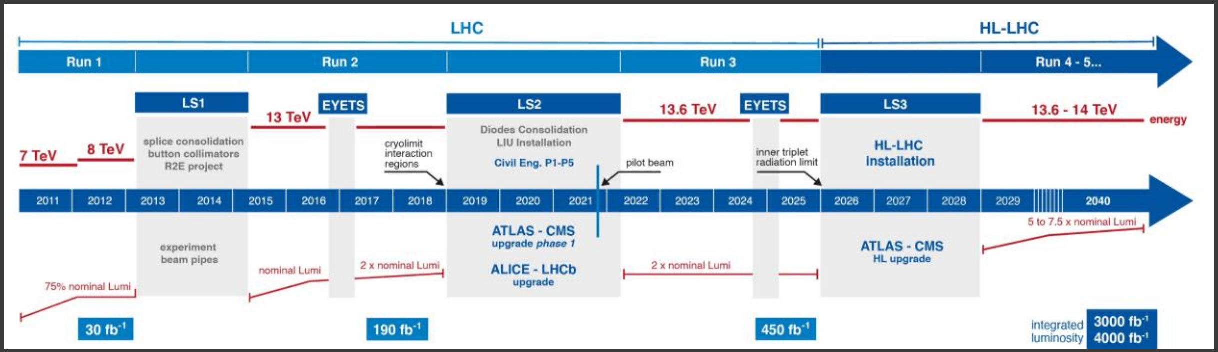
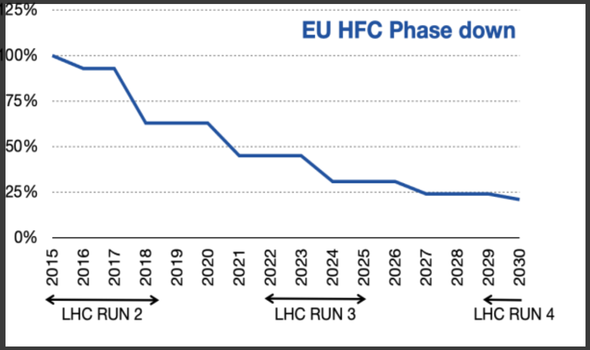
Introduction

The CMS Muon Spectrometer, composed by gaseous detectors, was designed to deal with the LHC conditions

- excellent performance either in terms of efficiency than in terms of resolution
- essential for trigger and reconstruction





A major upgrade of the LHC is planned to fully exploit the physics potential of the accelerator (Phase2)

- higher PU environment 140 (up to 200)
- expected instantaneous luminosity of ~5(7)x 10^{34} cm^{-2} sec^{-1} (5 x LHC)
- integrating about a 10 times larger LHC design luminosity (3000 fb^{-1})

CERN, according to the European strategy to phase down of greenhouse gases planned:

- the reduction of the consumption by mid Run3
- the use of alternative gases in longer terms

Worse background conditions will not only accelerate the aging process of the detectors and electronics component, but also result in increased trigger rates, which translate into more demanding requirements on the electronics

Muon system in Phase2

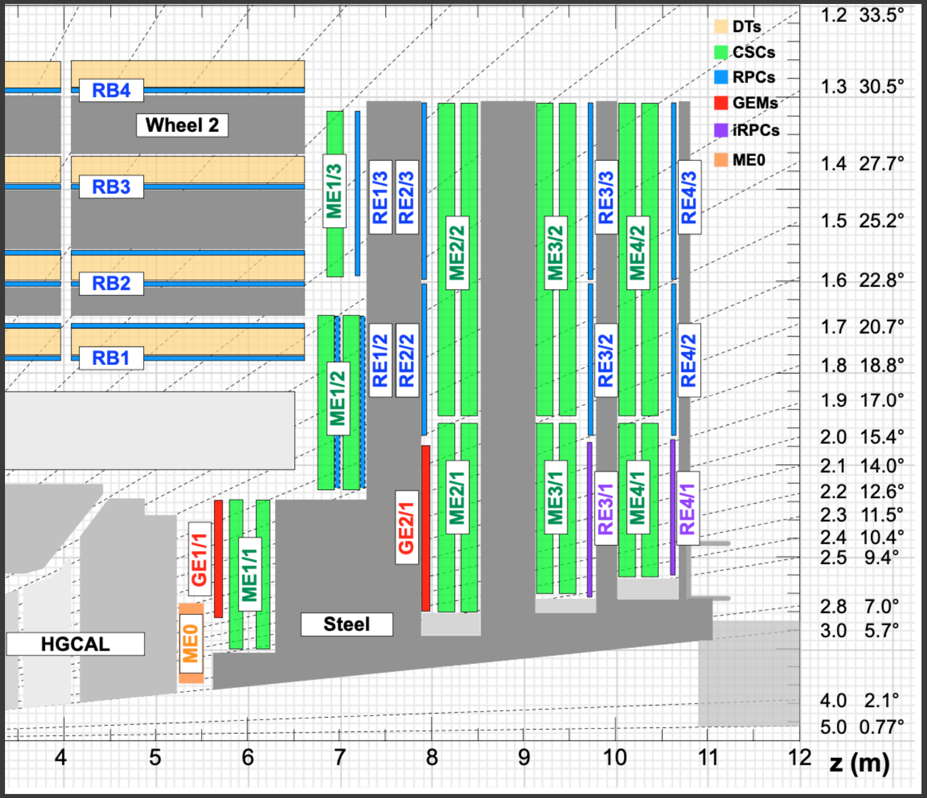
Challenge: cope with the higher rate, fully profiting from it and maintaining the present excellent performance along the 10 years

Strategy:

- **upgrade of the on-detector electronics** of the existing detectors mainly implemented during the Long Shutdown 3 (LS3):
  - Drift Tubes (DT)
  - Resistive Plate Chambers (RPC)
  - Cathode Strip Chambers (CSC)

- **installation of new muon stations,** already occurring during LS2, adding redundancy to the system, **providing more precise measurements of muon parameters in the forward region (higher background and a lower magnetic field):**
  - Gaseous Electron Multipliers (GEM):
    - GE1/1 (already installed)
    - GE2/1
    - ME/0
  - Improved RPC (iRPC)

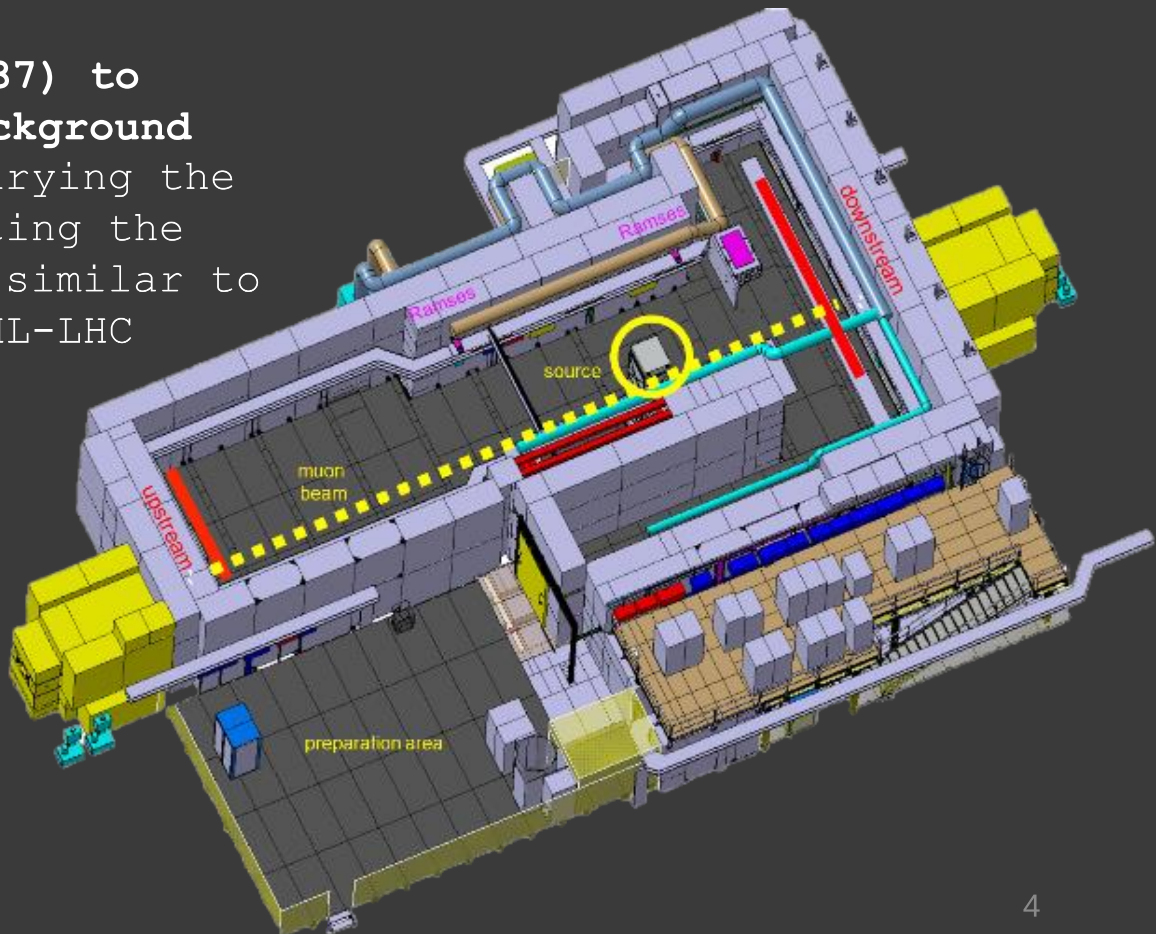
- **long-term irradiation tests** to evaluate the muon chambers performance at high value of integrated charge



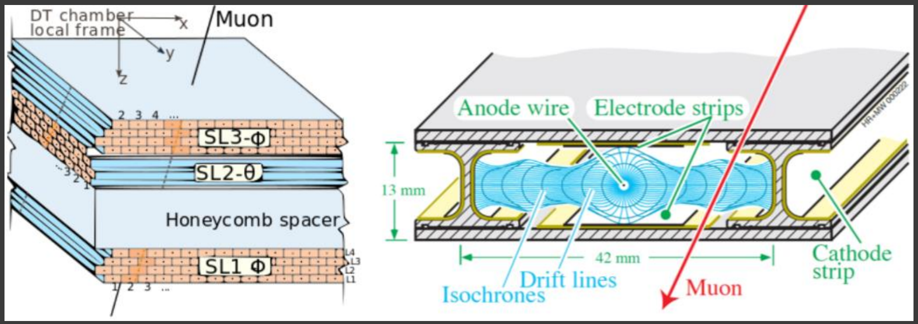
GIF++ irradiation setup

Most of the aging program is carried out at the CERN Gamma Irradiation Facility (GIF++) equipped with:

- **a 100 GeV/c muon beam**
- **gamma source (13 TBq Cs-137) to reproduce the expected background**
  - movable filters for varying the gamma flux and generating the background conditions similar to the ones expected at HL-LHC

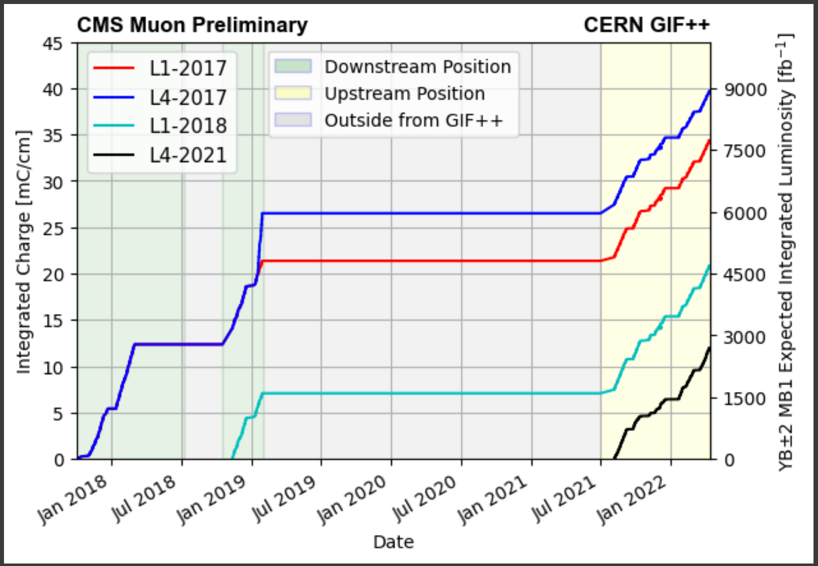


DT irradiation



A DT chamber, 2.5m x 2m (2.5m x 4m) consists of 12(8) layers (L) arranged in 3 (2) super layers (SL), each one containing up to hundreds of cells:

- the basic element is a rectangular 4cm **drift cell filled with Ar/CO2 (85/15%) gas mixture, nominal operating at 3600 V**
- electrons, from muon ionization, drift towards the anode wire, registering a time measurement (hit-position assuming v-drift 55μm/ns)
- **muon segment tracks are built with at least 3 hits in two independent SL**

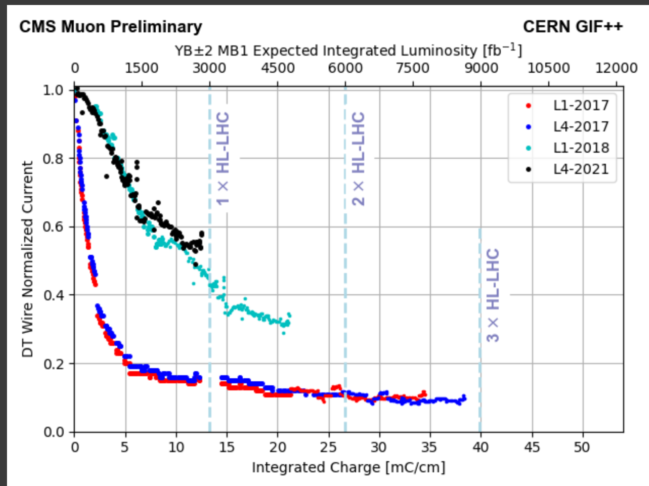


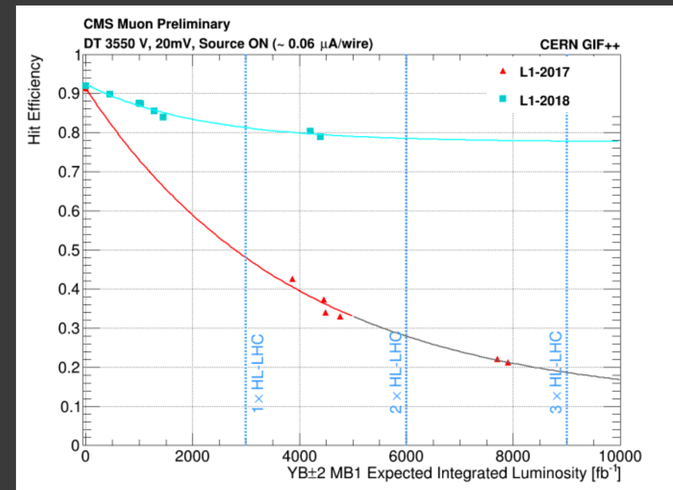
A spare MB2 chamber, with 3 SL, irradiated since the 2017:

- only L1 and L4 of SL1 are on during the irradiation, while L3 is kept off and used as reference
- SL2 and SL3 are used for internal trigger

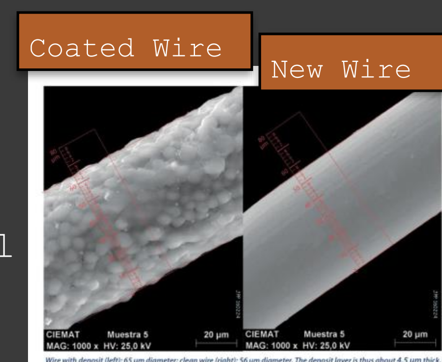
- in Summer 2018 8 wires in L1 were extracted, analysed, and replaced with new wires
  - among the new replaced, 1 has been extracted and analysed in the 2020
- the same happened in the 2021 for 5 wires in L4

DT aging studies





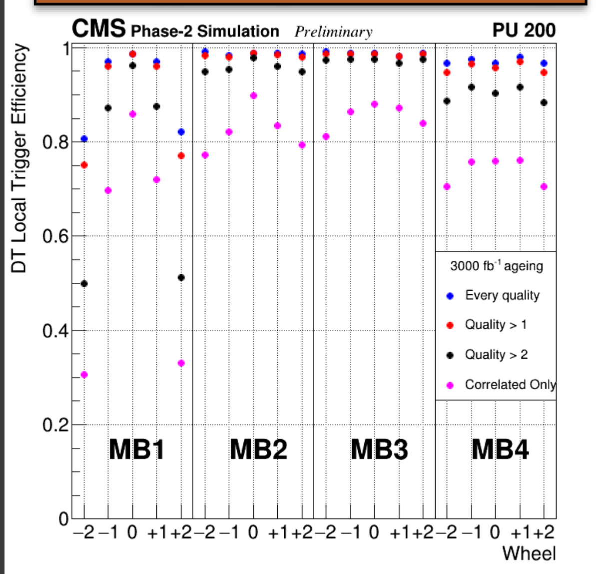
- Analysis of the currents monitored by the HV boards gives an estimation of the gain
- Using of cosmic muons (internal trigger) to estimate the hit efficiency is mainly to study the behaviour among the different irradiation periods, than to obtain the absolute expected efficiency:
  - background conditions expected in the MB1 of the external wheels
    - similar in the top sectors of the MB4
    - 10 times smaller in the MB2 and negligible in the MB3
- layers irradiated since the beginning show a fast degradation in the performance(red and blue markers)
- the more recent irradiation of the replaced virgin wires shows a slower reduction of gain and smaller loss of efficiency
- correlated to the presence of a carbon peak in the spettroscopy analysis(backup)



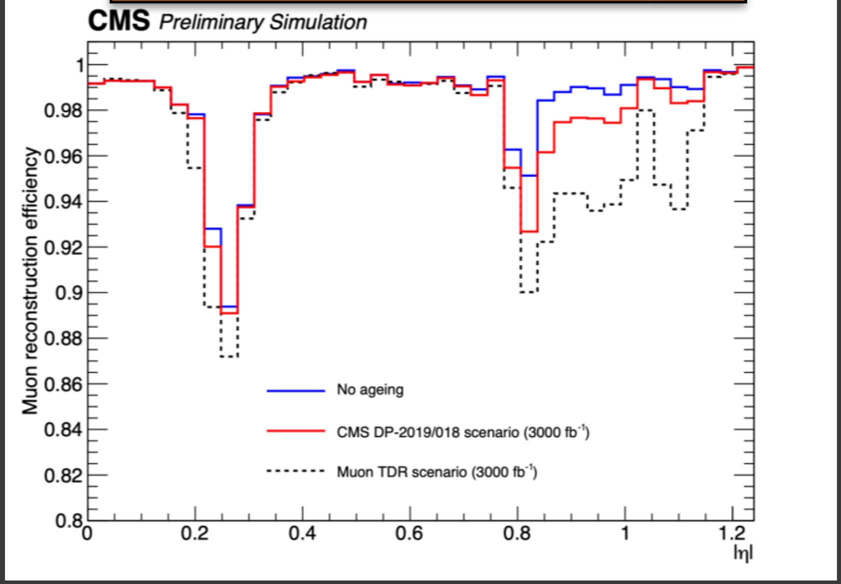
Electron avalanche enable chemical reactions of impurities creating a coating on the wires

DT aging on physics performance

DT trigger segment efficiency



Standalone muon reco efficiency

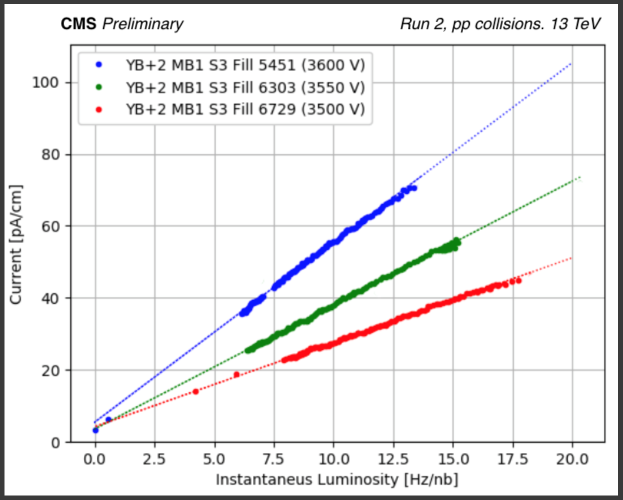


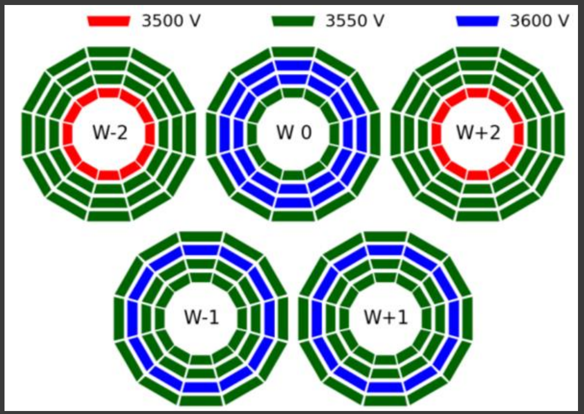
The expected hit efficiency (worst scenario) has been used to evaluate the final impact at HL-LHC with a safety factor 2:

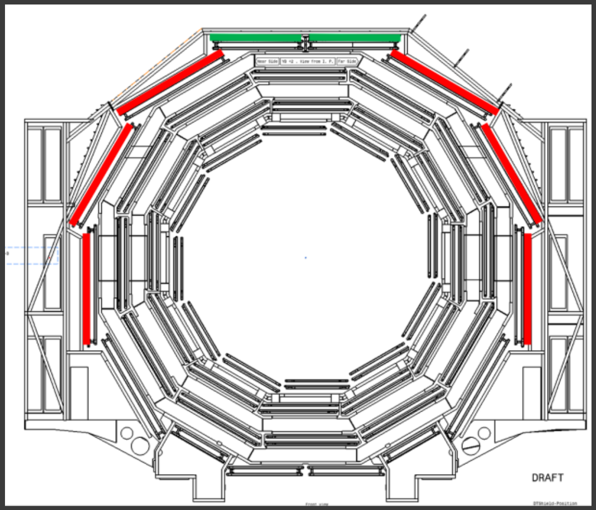
- the major effect seen in the **DT local trigger efficiency** of MB1 is effectively mitigated by:
  - multiple layers per chamber (3 out of 8 are needed)
  - handling of TDC hits in the backend in Phase2
  - redundancy of the CMS muon system
    - the most aged DT region is also covered by 3 CSC stations and 4-5 RPC layers along a prompt muon trajectory

- Minor impact on the overall reconstruction of the standalone muons

DT mitigation strategy







A strategy to mitigate the DT longevity has been adopted:

- reduced voltage of the wires in the most exposed chambers in the 2016:
  - each step of 50 V decreases the integrated charge of the 30%
  - reducing the readout thresholds from 30 to 20 mV

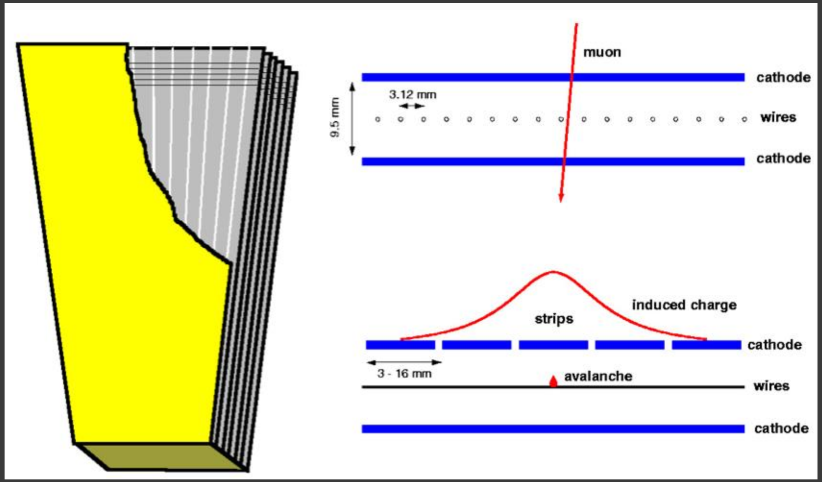
- gas system modified in the 2017 to operate in open loop
  - minimize the recirculation of the impurities

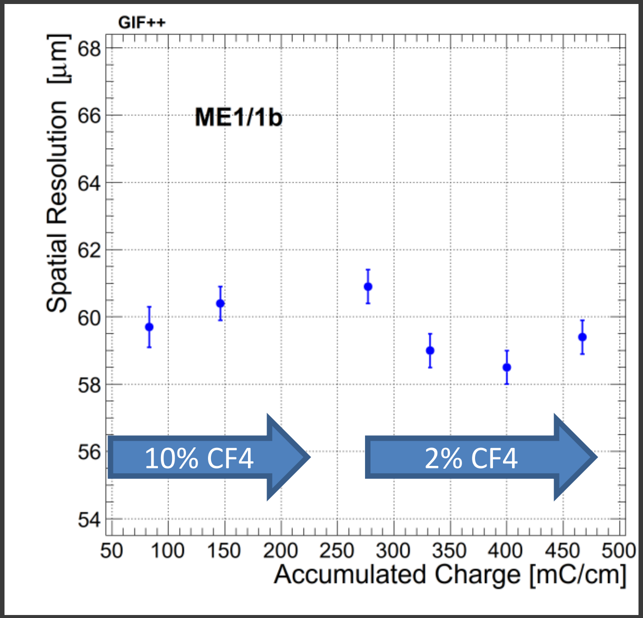
- shelding installed during LS2 for the neutron background reduction in the top sectors
  - 3 cm layer of Borated Polyethylene + 1 cm layer of lead for gamma absorbtion
  - expected 30-40% of reduction of dose from neutron

CSC Aging tests

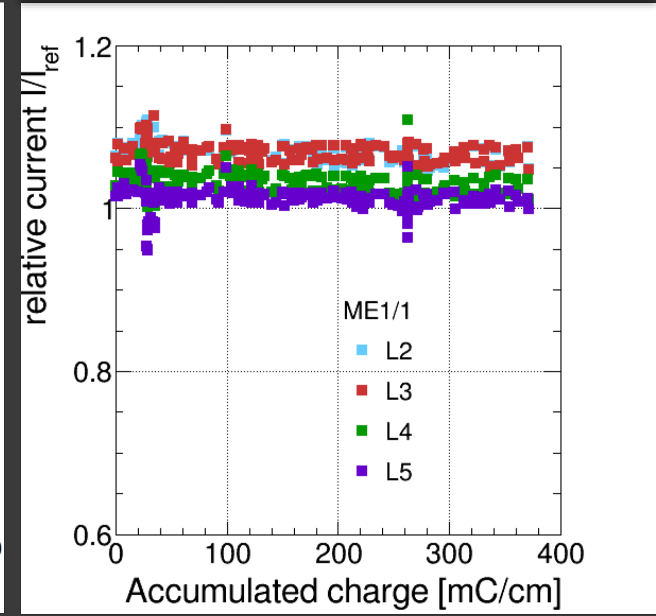
A CSC is a multi-wire proportional chamber with 6 gas gaps, each with radial cathode strips and perpendicular wire groups:

- using a 40% Ar, 50% CO_2, 10% CF_4 gas mixture
- CF_4 has a greenhouse warming potential (GWP) 6500
- both electrons and ions are respectively read giving two coordinates per each detected particle
- segment tracks are reconstructed in 3D





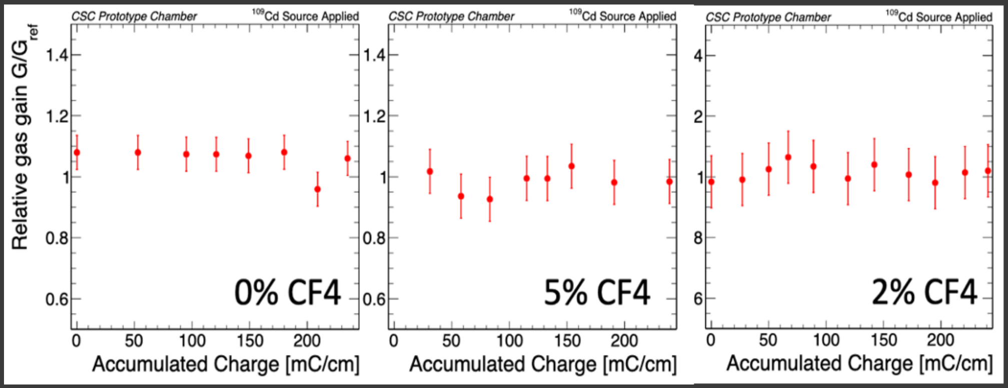
Relative gain with the 2% of CF4



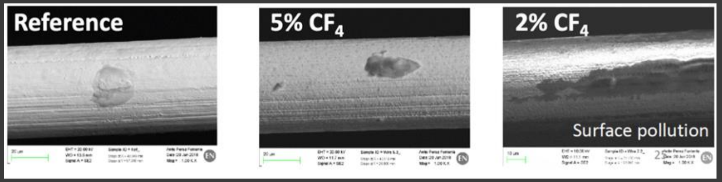
Accelerated (~25) irradiation campaign is ongoing at the GIF++:

- spare chamber: 4 aged layers and 2 kept as reference
- period 2016-2021: using 10% CF4
- after Fall 2021: using 2% CF4
- On the most exposed chambers ~190 mC/cm are expected after 1 HL-LHC
- No significant sign of aging

CSC eco-gas

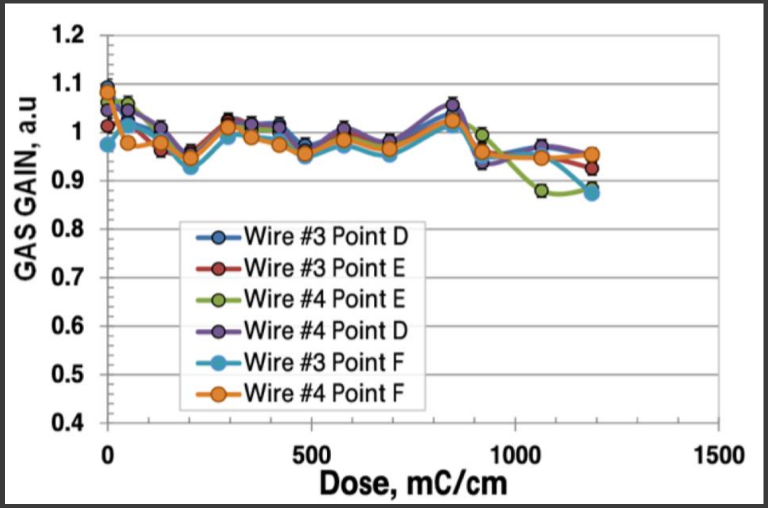


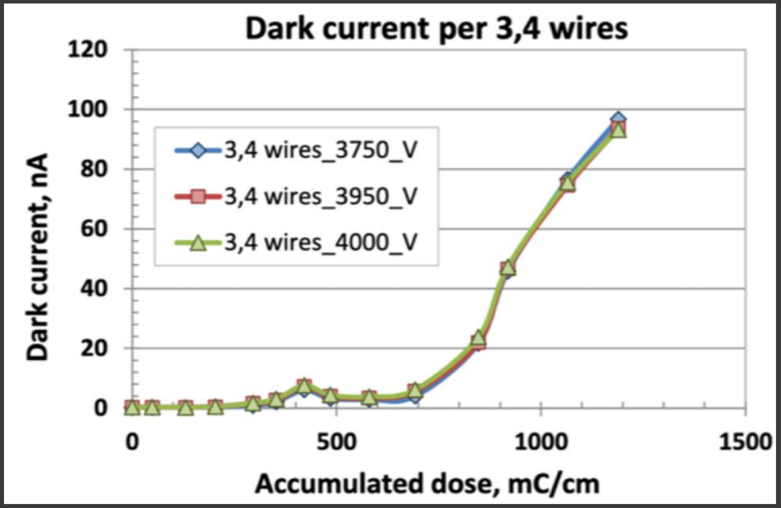
The reduction of CF_4 doesn't seem to affect the CSC gain, despite an increased pollution is visible on the wire: validated up to 2 HL-LHC



Preliminary study, performed on a 30x30 cm^2 CSC prototype, on the alternative HFO-1234ze (GWP 7) gas:

- constant gain up to 10 HL-LHC instantaneous luminosity
- high increases of dark current after 6 HL-LHC inst.lumi
  - probably due to a too much fast aging, to be repeated on a standard spare CSC

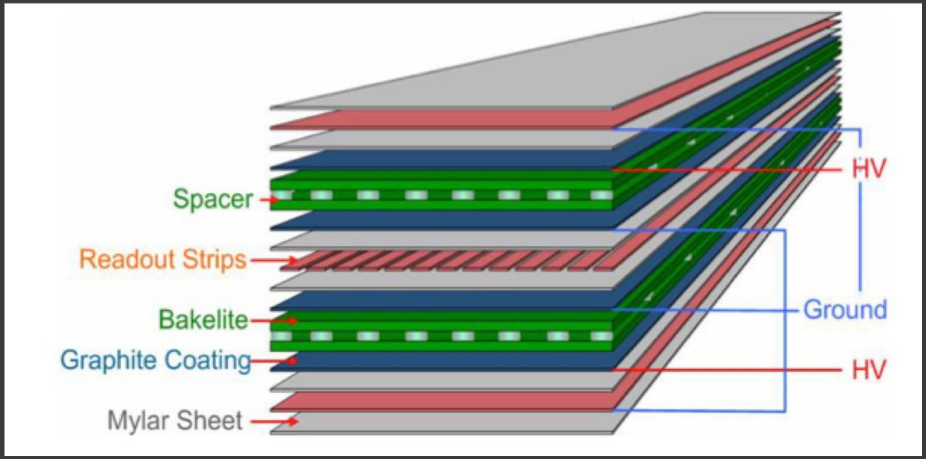




RPC

RPC double gap chambers:

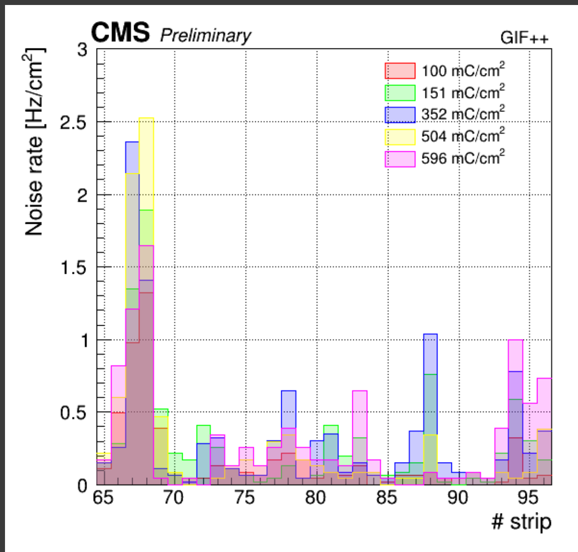
- 2mm gap width filled with the $C_2H_2F_4$(95.2%)+iso-C_4H_{10}(4.5%)+SF_6 (0.3%) gas mixture, nominal operating above 9000 V
- bakelite bulk resistivity ρ=1~6 x 10^{10} Ωcm
- operated in avalanche mode
- signal is read on strips of width 1-4 cm
- very fast, used for triggering

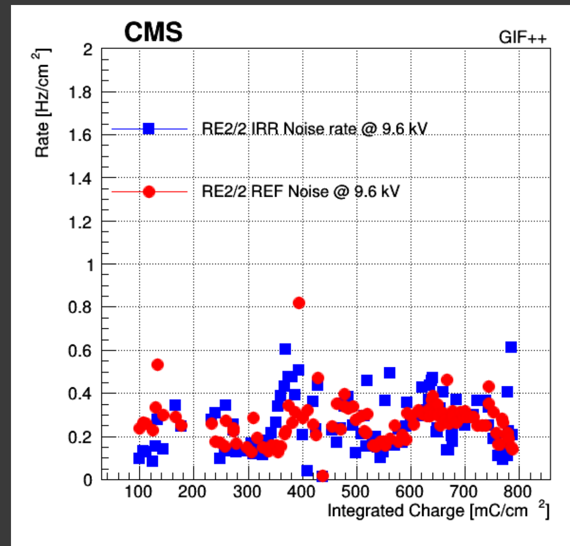


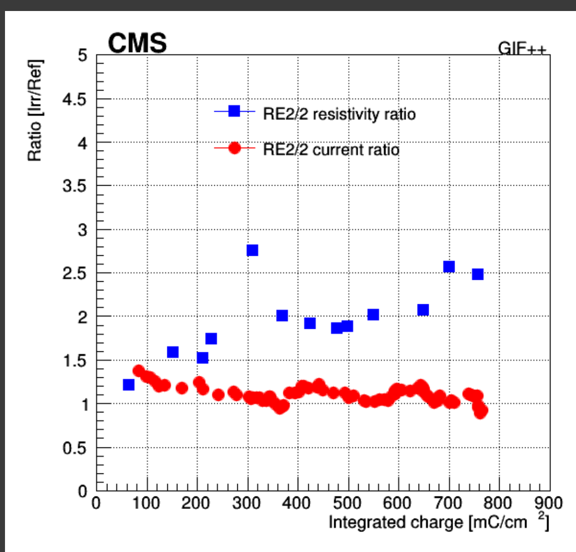
RPC longevity studies are currently ongoing since the 2016:

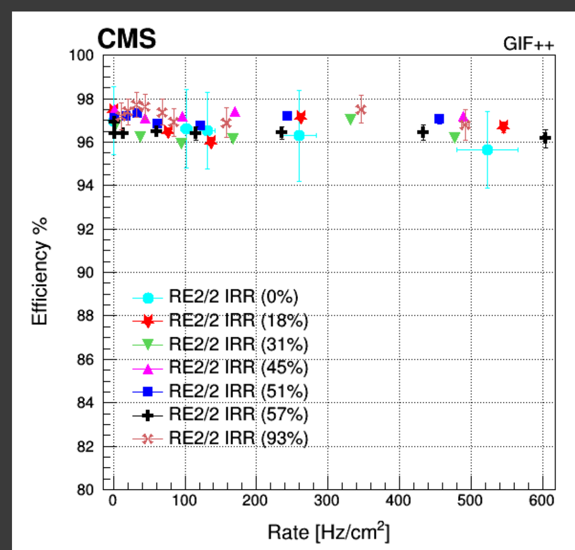
- 2 spare chambers are continuosly irradiated (RE2 and RE4)
- 2 spare chamber are used as a reference
- main detector parameters are monitored as a function of the integrated charge and of the backgroud rate

RPC Aging results









Source OFF results:

- Noise is stable even aging the detector

Source ON results:

- Small increase in resistivity operating in similar conditions as CMS (gas volume and humidity)
- Not optimal at GIF++ with an high rate of gamma background
- Moving to 60% of humidity and 3 x gas volume mitigates this effect also showing that can be recovered

- No significant sign of aging

RPC eco-gas

Studies done in the ECOGAS@GIF++ task force:

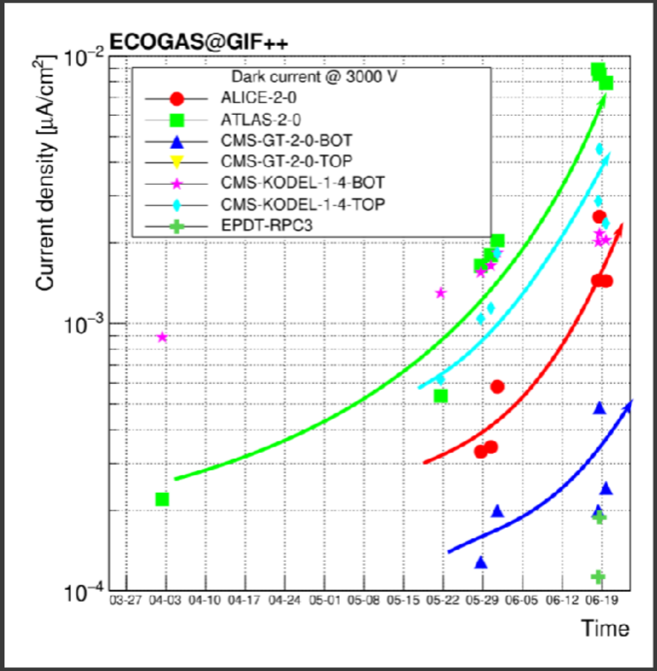
- joint collaboration (ATLAS, CMS, LHCb, CERN, SHIP) to find an alternative to $C_2H_2F_4$ (GWP 1430)

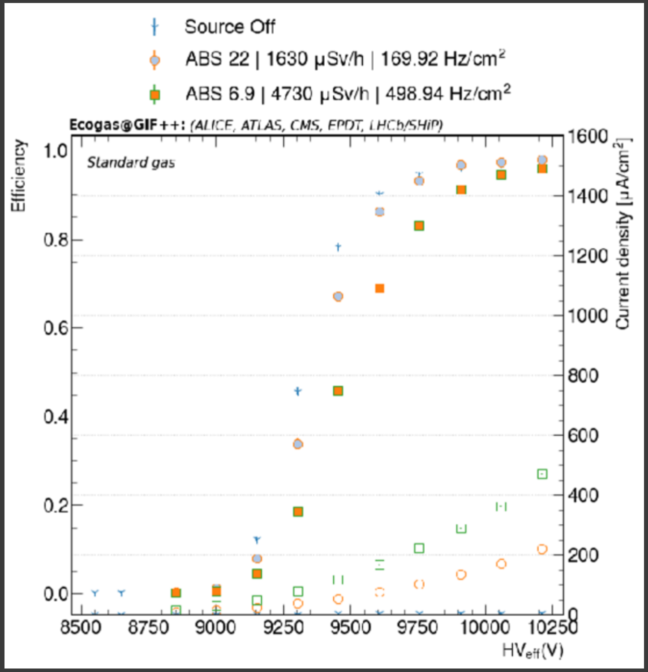
- Tested 3 different gas mixtures:

ECO1: CO_2 50%, HFO 45%, iC_4H_{10} 4%, SF_6 1%

ECO2: CO_2 60%, HFO 35%, iC_4H_{10} 4%, SF_6 1%

ECO3: CO_2 69%, HFO 25%, iC_4H_{10} 5%, SF_6 1%

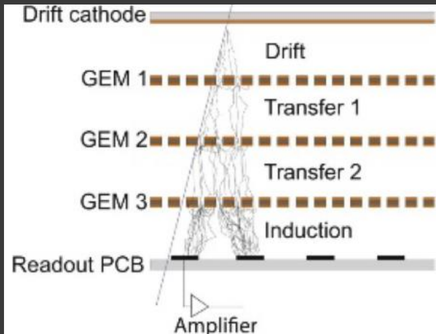




- Discarded ECO1 giving high dark curruent

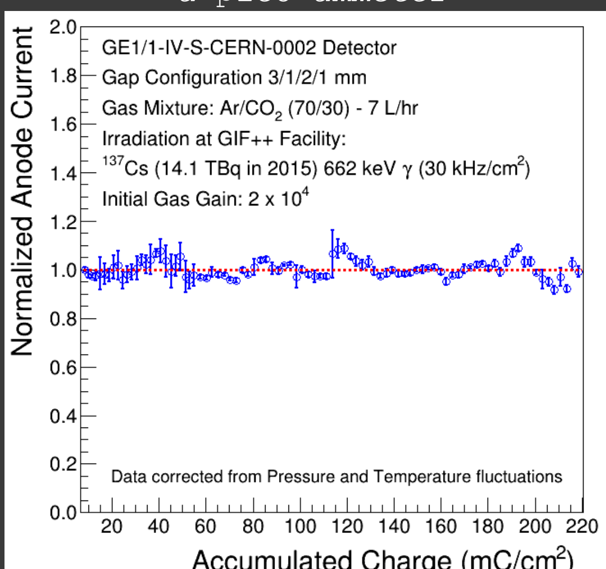
- ECO2 and ECO3 have characterized with test beam
- to be use in long term irradiation study

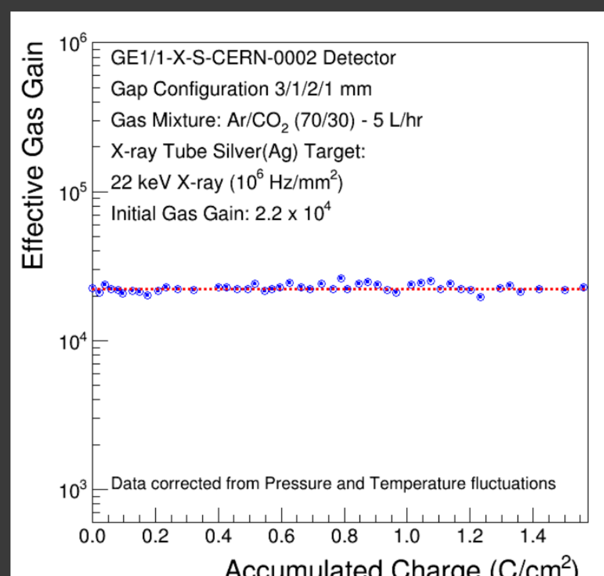
GEM Aging with X-ray

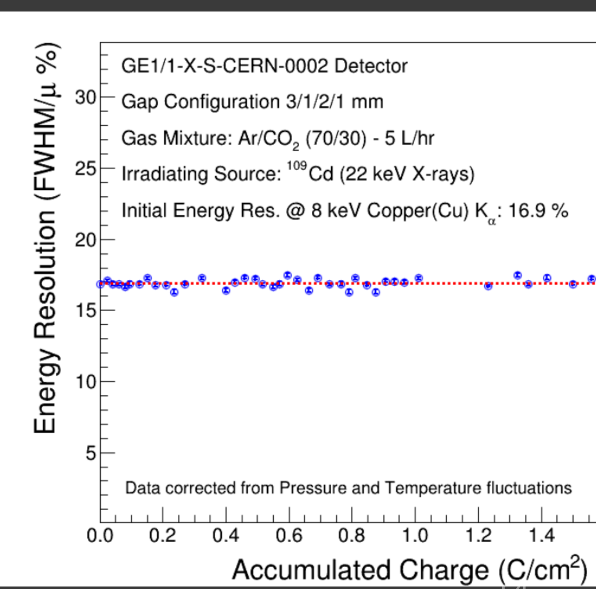


- Triple-GEM are micro-pattern gaseous detectors made of 3 GEM foils in cascade:
- operating with Ar/CO_2 70/30% gas mixture
- instrumenting region with high rate, expected int. charge:
  - 60 mC/cm2 GE1/1 → validated with a SF 3.6
  - 30 mC/cm2 GE2/1 → validated with a SF 7
  - 7900 mC/cm2 ME0 → not validated, reached only 1.5 C/cm2
    - accelerated irradiation (8 times more than GIF++) is ongoing in X-ray facilities in Aachen and Seoul

Current measured by a pico-ammeter







Summary

Efforts have been going since many years to estimate the performance of the Muon CMS detectors in the harsh HL-LHC conditions

Results obtained at CERN GIF++ show that the CMS muon system can continue to efficiently operate:

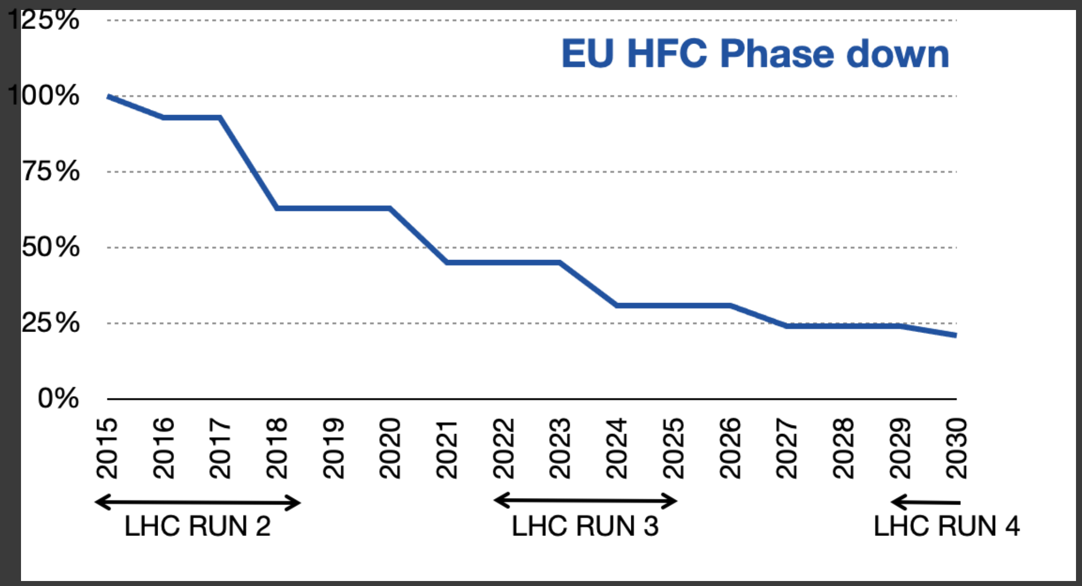
- mitigation strategy is already in place in view of the future operations to slow down the aging of the DTs
- optimization of the gas system technology is ongoing, it’s aimed to reduce the consumption of the GHG for RPCs and CSCs

Final assessment is expected by the end of the year

Back-up

Greenhous gasses (GHG)

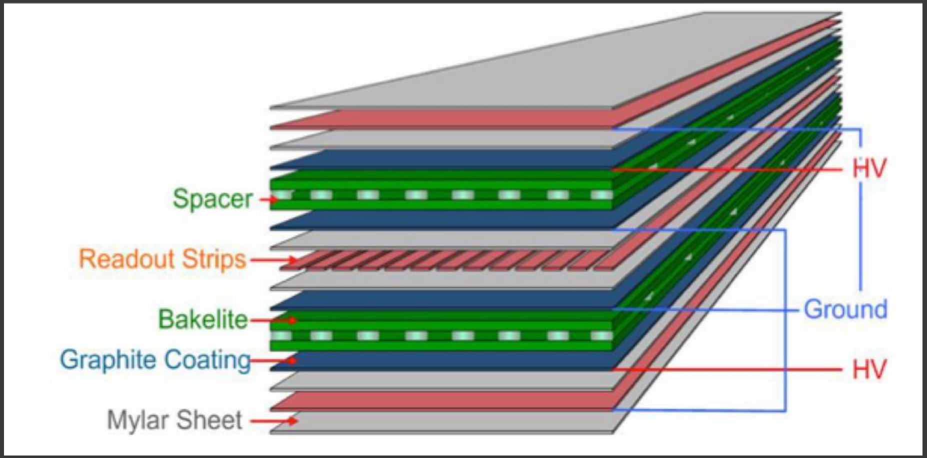
Despite almost no aging effect is seen, both CSCs and RPCs have to deal with the European/CERN strategy to reduce the use of GHG:



- reduction of the consumption up to mid-Run3:
  - Optimization of the current technologies to reuse the gas
    - Done since 2021 for CSCs
    - Onging R&D for the RPCs (prototype installed 2 years ago)
  - Campaign of gas leak repair for RPCs

- use of alternative gasses in the long term

iRPC



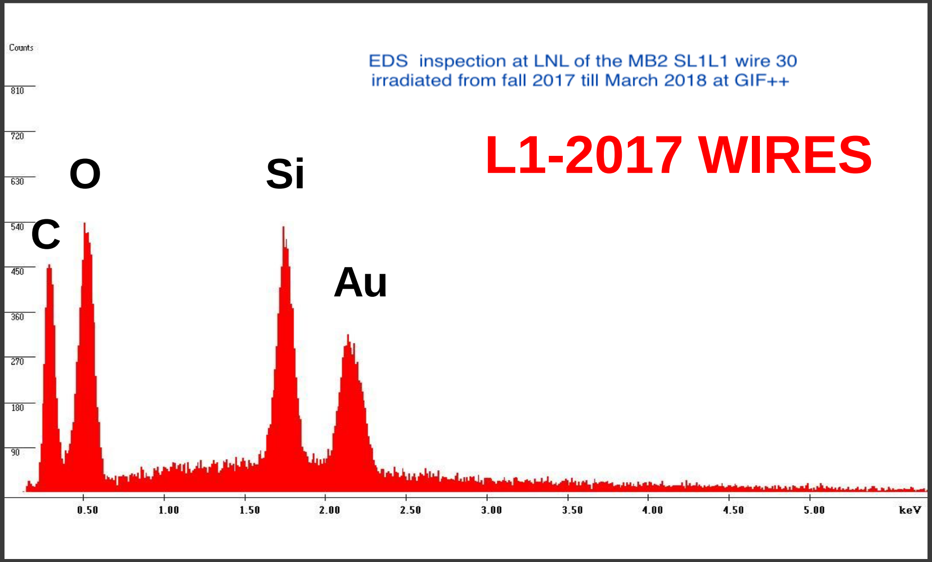
RPC double gap chambers:

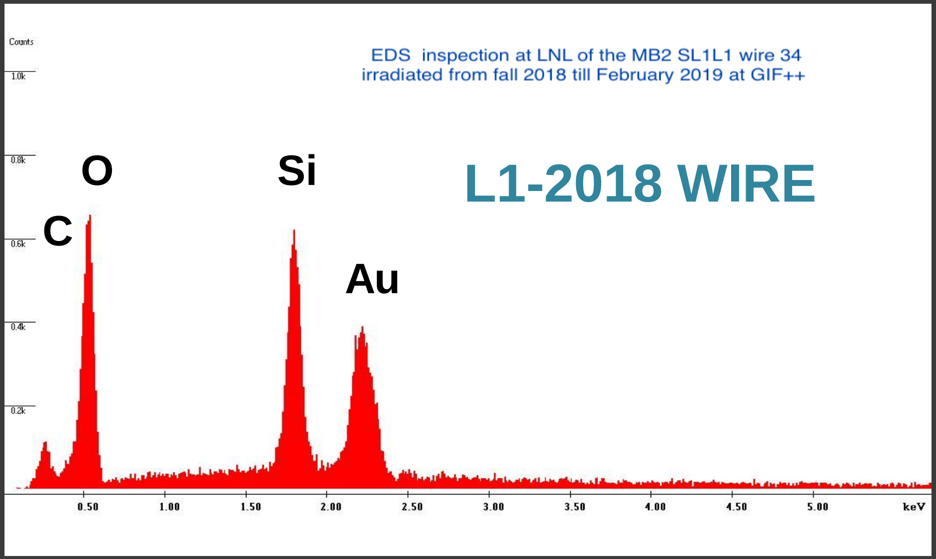
- 2mm gap width filled with the $C_2H_2F_4$(95.2%)+iso-C_4H_{10}(4.5%)+SF_6 (0.3%) gas mixture, nominal operating above 9000 V
- bakelite bulk resistivity: $\rho = 1\sim6 \times 10^{10}\ \Omega$cm
- operated in avalanche mode
- strips of width 1-4 cm

iRPC:

- 1.4mm gas gap
- resistivity: $\rho = 0.9\sim3 \times 10^{10}\ \Omega$cm operating at ~7000 V
- strips width 0.7-1.2cm

DT: spettroscopy analysis

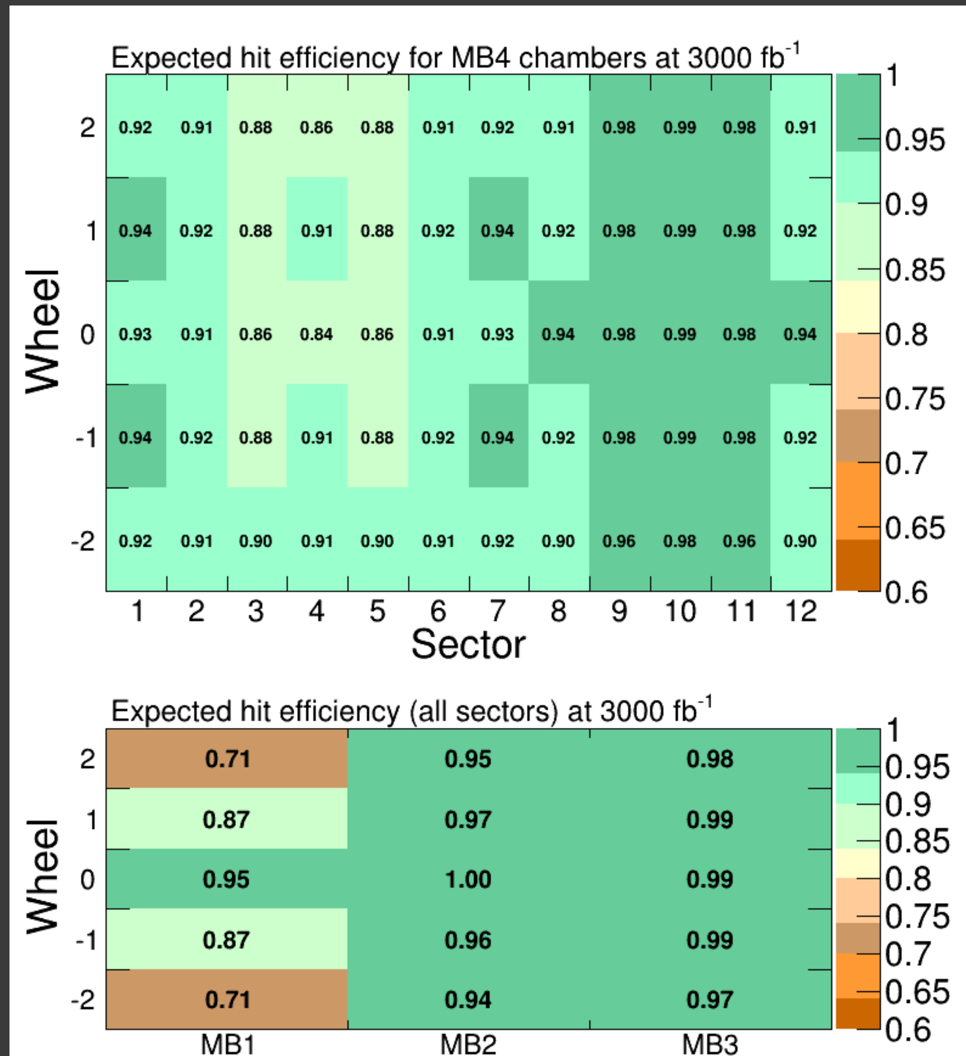




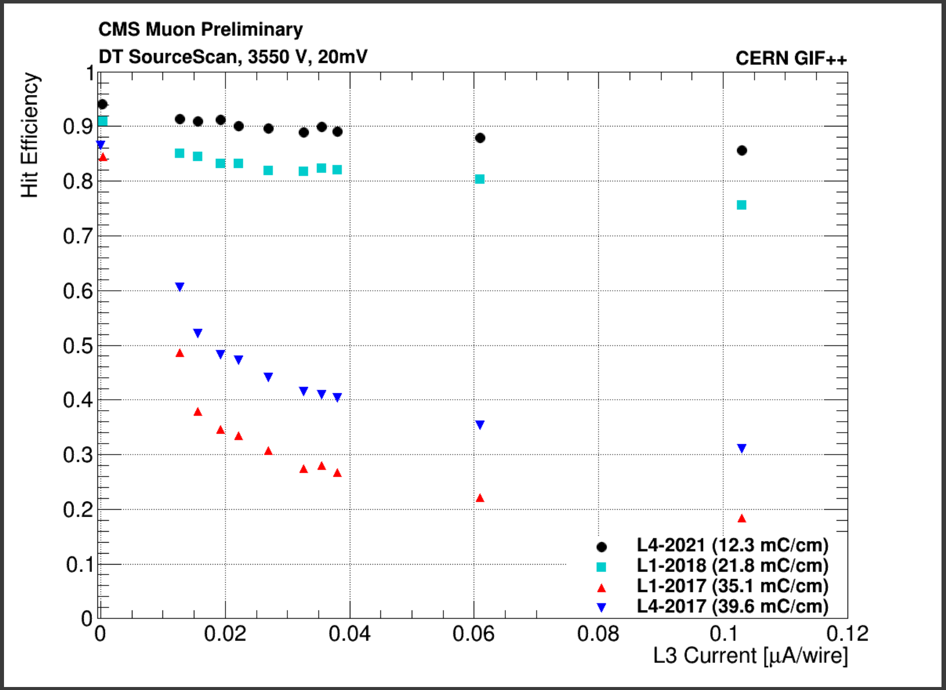
Energy dispersive X-ray spectroscopy (EDS) of a wire of SL1L1 of the MB2 chamber exposed at GIF++ on the first irradiation, 2017-2018 , and extracted after ~1 Hl-Lhc integrated charge (as expected on the most exposed DT chamber, MB1 of wheels +2 and -2).In the x axis the energy of the absorbed gammas of different material are reported. From the left the peaks correspond to carbon (C), oxigen (O), silicon (Si) and aurum (Au).

Energy dispersive X-ray spectroscopy (EDS) of a wire of SL1L1 of the MB1 chamber exposed at GIF++ on 2018-2019 after ~0.7 HL-LHC integrated charge (charge expected on the most exposed DT chamber, MB1 of wheels +2 and -2). In the x axis the energy of the absorbed gammas of different material are reported. From the left the peaks correspond to carbon (C), oxigen (O), silicon (Si) and aurum (Au).

DT local efficiency



DT hit efficiency



CSC aging in physics performance