CMS CSC longevity study

E. Kuznetsova, V. Palichik and V. Perelygin

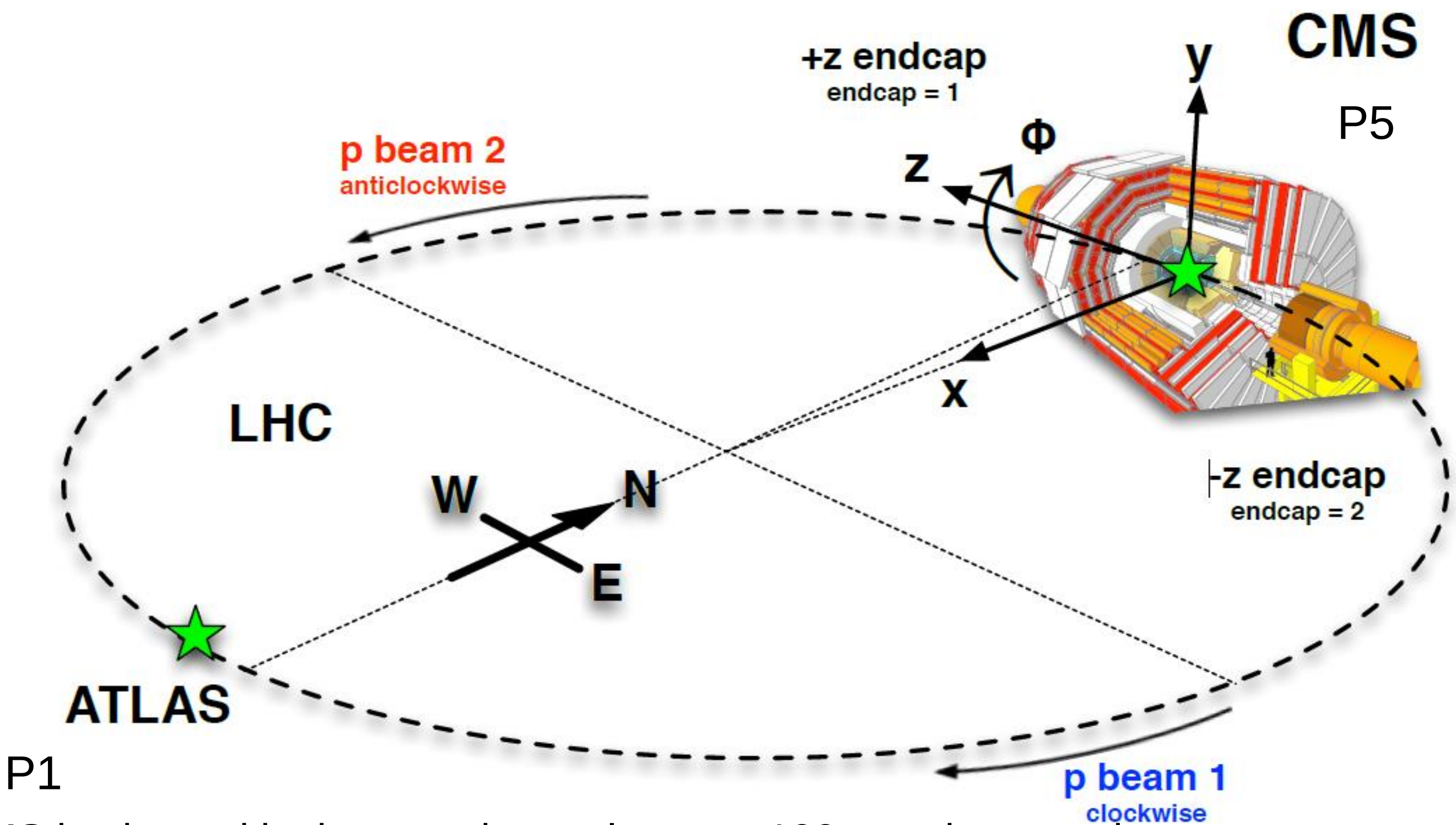
On behalf of the CMS Muon group

VII International Conference on Particle Physics and Astrophysics (ICPPA 2024)
October 22-25, 2024
Moscow, Russia

Outline

- CMS experiment at CERN and Endcap muon system
- CSC operation in pp collisions
- Gas detectors – Longevity problem
- Greenhouse gases usage problem
- Mini CSCs longevity study
- Results of CMS CSCs longevity study at GIF++ setup
- Conclusions

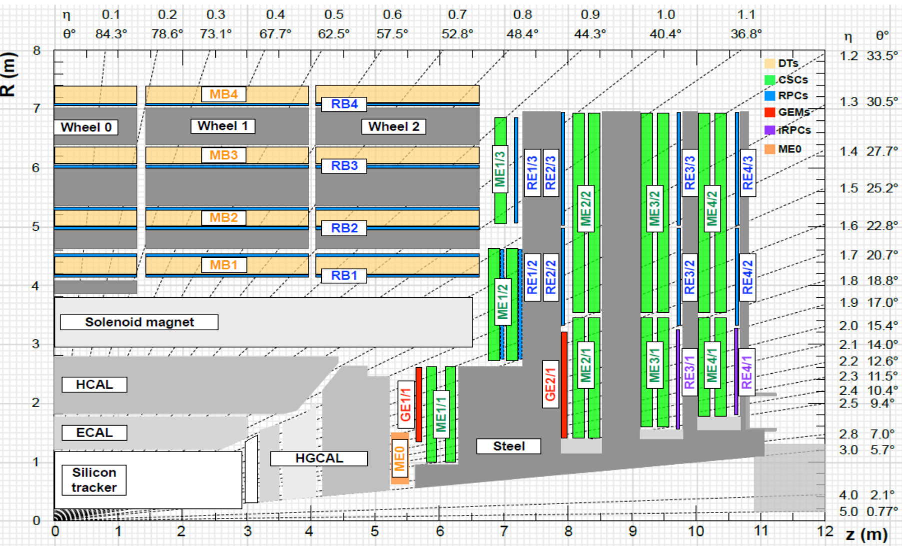
CMS – one of two general purpose detectors at LHC



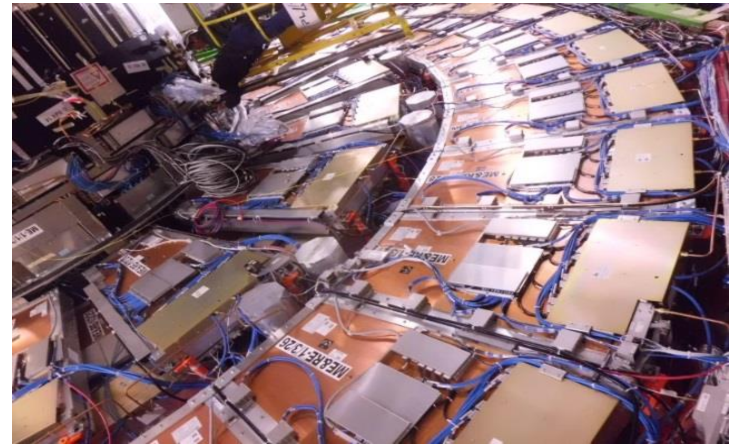
- CMS in situated in the experimental cavern 100m underground.
- Total weight around 14000 tons (the heaviest in LHC).
- 15m in diameter and 21.5m long.
- Composed of the **inner Si tracker, Magnet, ECAL, HCAL and Muon system**.
- CMS Solenoid is 13m long and 6m in diameter,

operates at 4.5 K with I= 20 kA, B= 3.8 T - the most powerful of its kind ever built.

CMS Muon system. General description

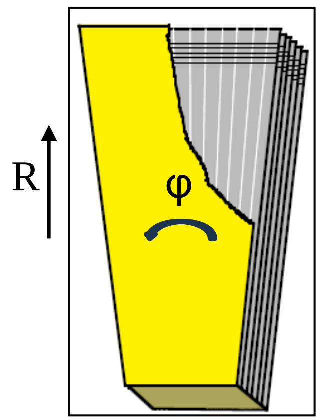


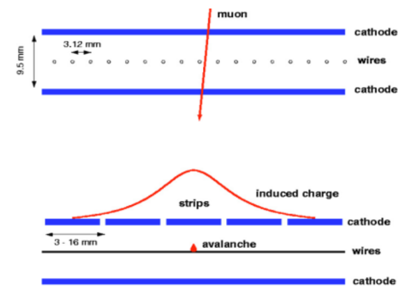
CMS quarter view (upgraded)



Muon system provides:

- **Muon identification and momentum measurement**
- **Muon trigger**
- **Rejection of background and pileup by matching of muon tracks with inner Tracker**
- **H → ZZ* → 4μ ("golden mode")**





A CSC consists of 6 layers and operates as a standard multi-wire proportional chamber (MWPC) with cathode strip readout.

Cathode Strip Chambers (CSC) are part of the CMS Endcap Muon system covering the pseudorapidity range $0.9 < |\eta| < 2.4$ and form 4 muon stations in each Endcap with **540 CSCs** (marked green). The stations, in turn, consist of rings of 36 or 18 trapezoidal CSCs named **MEx/y,** where *x* stands for station number and *y* for ring number. The chambers operate with the gas mixture **40%Ar+50%CO_2+10%CF_4.**

Sensitive area: 6,300 m2. No. of channels: 477K

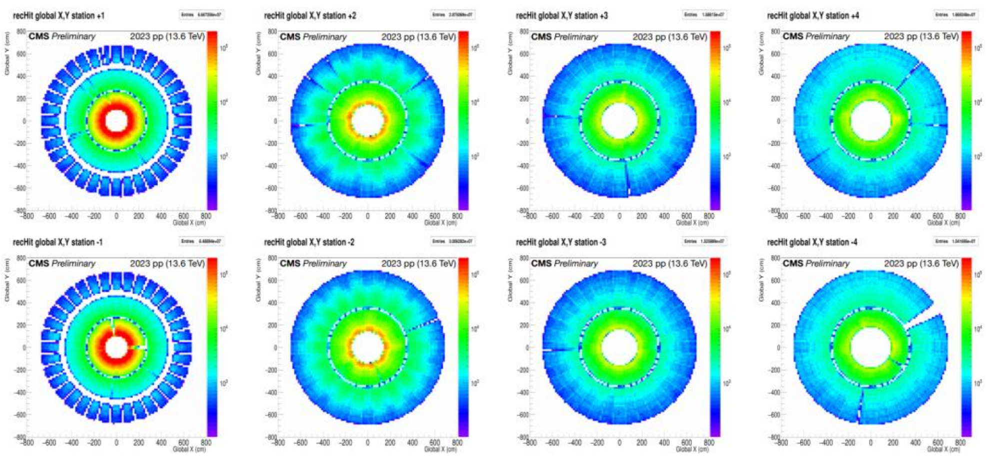
In addition to CSCs there are the following muon detectors in the Endcap part – GEx/y (GEMs), REx/y (RPCs).

G.L. Bayatian et al. [CMS collaboration] "The Muon Project", Technical Design Report, CERN/LHCC 97-32, CMS TDR 3, 15 December 1997.

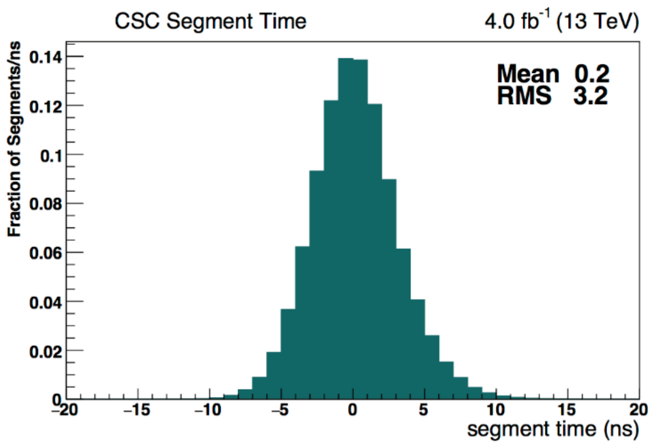
S. Chatrchyan et al. [CMS Collaboration], "The CMS experiment at the CERN LHC", JINST 3 (2008) S08004.

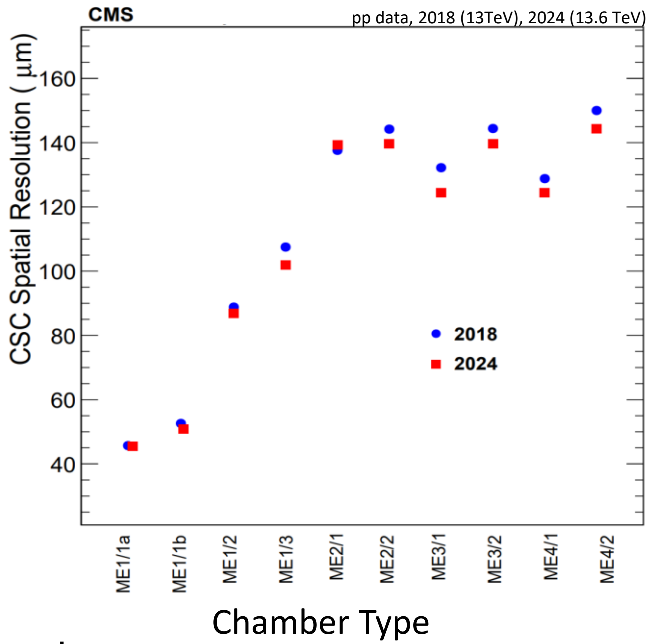
CSC muon system performance in pp collisions

CSC reconstructed hit positions from one run of a muon-triggered dataset



The global x and y position of reconstructed CSC hits in the four stations of the +z and -z endcaps of the CMS endcap muon system from one run (166 pb^{-1}) of a muon-triggered dataset





CSC muon system operation:

Timing resolution ~ 3 ns

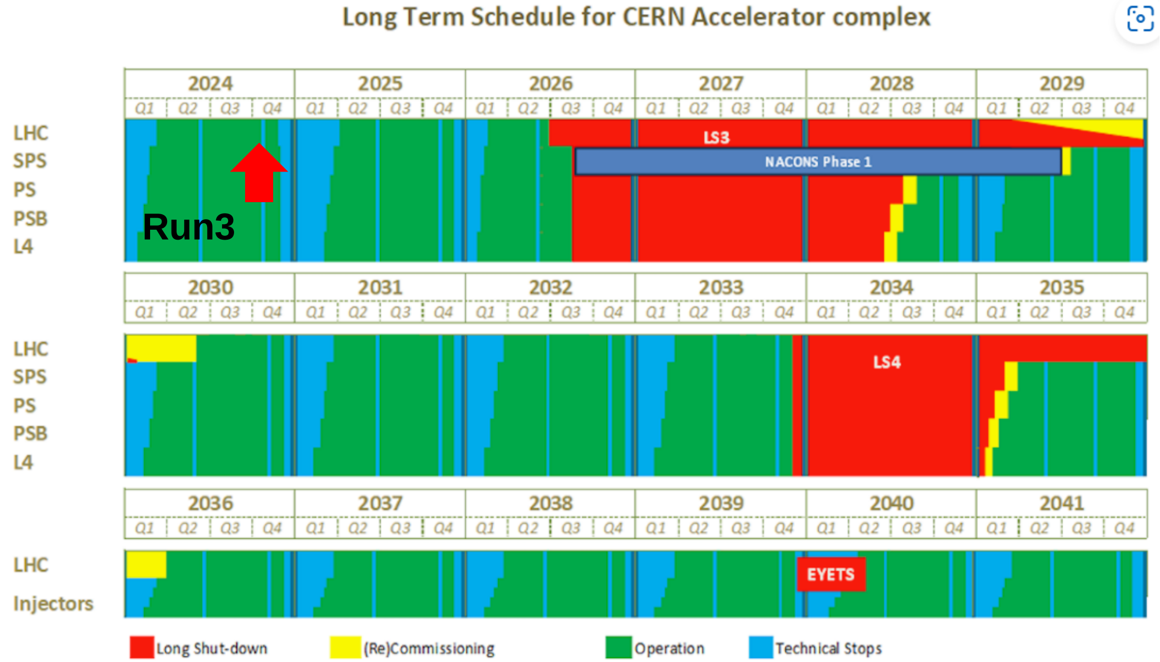
Spatial resolution 45 - 150 µm

S. Chatrchyan et al., The performance of the CMS muon detector in proton-proton collisions at √s = 7 TeV at the LHC, CMS-MUO-11-001, CERN-PH-EP-2013-072, JINST 8 (2013) P11002. DOI: 10.1088/1748-0221/8/11/P11002.

S. Chatrchyan et al., Performance of the CMS muon detector and muon reconstruction with proton-proton collisions at √s = 13 TeV, JINST 13 (2018) P06015.

LHC - HL LHC schedule and Longevity problem

The investigation into the longevity of gaseous detectors is important: particularly in anticipation of the
1. **forthcoming upgrade of the Large Hadron Collider (LHC) to the High-Luminosity LHC (HL-LHC)**
2. **the planned upgrade of the CMS forward endcap zone during LS3.**



HL-LHC Operational scenarios for:

Total integrated luminosity of **$3000fb^{-1}$ to $4000fb^{-1}$** in around 10-12 years [ca. 10x LHC]

An integrated luminosity of **~250 fb^{-1} per year**

Nominal: levelled inst. luminosity of 5×10^{34} $cm^{-2}s^{-1}$ (events/crossing ~130)

Ultimate: levelled inst. luminosity of 7.5×10^{34} $cm^{-2}s^{-1}$ (events/crossing ~200)

Background rate and Accumulated charge increase.

Therefore, the study of possible ageing effects of detector materials and gases is of great importance.

Greenhouse F-gases usage limitation, Global warming potential

The regulations

*In 2014, the European Commission adopted a new regulation limiting the total amount of important **fluorinated greenhouse gases (F-gases)** that can be sold in the EU from 2015 onward and phasing them down in steps to **one-fifth of 2014 sales in 2030.***

- Means that the availability of the product on the market will be unstable.

- Increasing price.

CSC F-gas footprints:

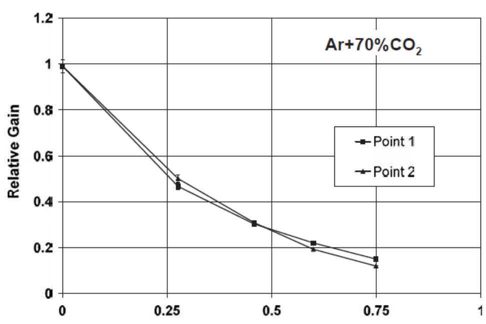
- CSCs use the working gas mixture ***40%Ar+50%CO_2+10%CF_4***

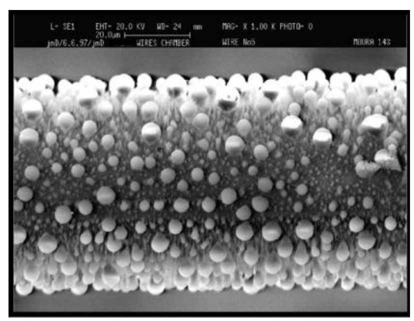
CF_4 is used to prevent aging and ensure reliable operation but has very high GWP ~ 7000

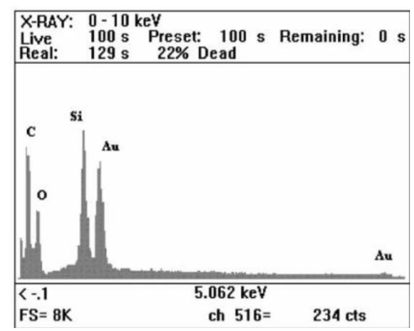
Early studies with first small CSC prototypes irradiation with ^{90}Sr source.

With 30%Ar+70%CO_2 gas mixture observed relative **2^x gas gain drop at 0.25 C/cm** accumulated charge. The reason was Si deposits on wires.

This effect was not observed in tests with 40%Ar+50%CO_2+10%CF_4 up to the charge of 13 C/cm







CF_4 in the mixture prevents deposition of Si on the anode wires by forming gaseous SiF_4

$$4F\bullet + Si = SiF_4 \uparrow$$

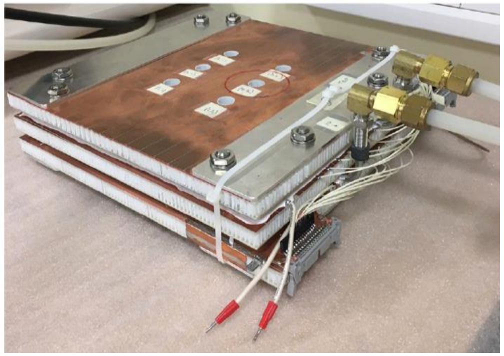
For CSC prototypes designed later, the Si sealant was no used in the contact with the sensitive area.

T. Ferguson et al. Aging studies of CMS muon chamber prototypes. NIMA 488 (2002) pp. 240–257.

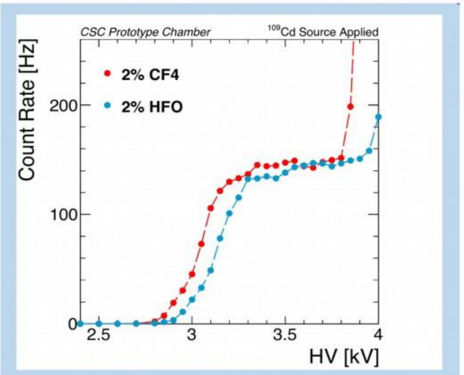
Greenhouse F-gases usage limitation. Solutions

Solution 1 (under study): new eco-friendlier gas options → HFO-1234ze for CSC

HFO-1234ze
($C_3H_2F_4$, GWP < 1 for 100 year)



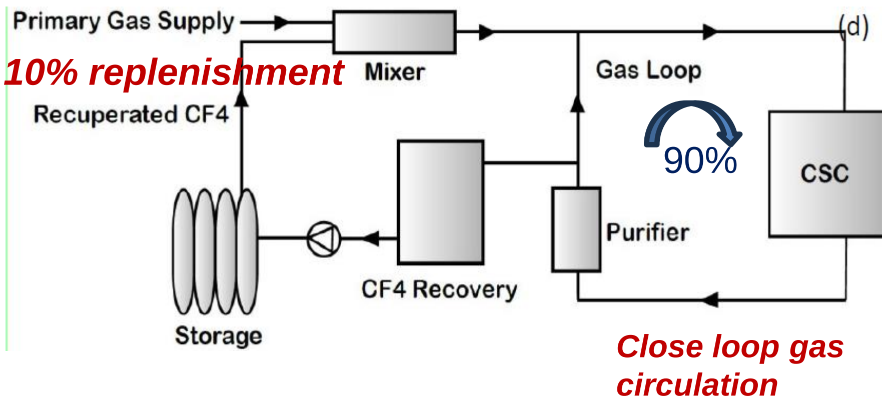
Mini- CSC (30x30 cm^2)
(ME2/1 geometry, two Layers)



Magnitude and length of efficiency plateau for 2% HFO mixture is the same as for 2% CF_4

Performance of the CSC operation with HFO in the working gas mixture looks promising, **but its longevity properties are still under study.**

Solution2: CF_4 recuperation factory (done)



A new CF_4 recuperation plant was designed, built and successfully implemented @ P5 by the CERN Gas Group. As of 2024, the CF_4 recuperation efficiency is ~ 70%. Now CSCs operate with:
40%Ar+50%CO_2+4%CF_4(fresh)+6%CF_4(rec.)

CSC Fresh CF_4 consumption:
540 CSCs, φ_{total}= 6.8 m^3/h;
$\varphi_{repl.}$= 0.68 m^3/h;
φ_{CF4}= 0.068 m^3/h;
$\varphi_{CF4\ fresh}$= 0.027 m^3/h = **27 l/h**
(by 60% less than in 2018)

Solution 3: F-gas consumption reduction

Longevity studies with mini-CSC prototypes with reduced CF_4 fractions

The aging effect study on mini-CSC prototypes under irradiation with a laboratory ^{90}Sr source using different gas mixtures based on Ar+CO_2 **with 5%, 2%, and 0% CF_4** fractions was investigated. The accumulated charge was about **300 mC/cm.**

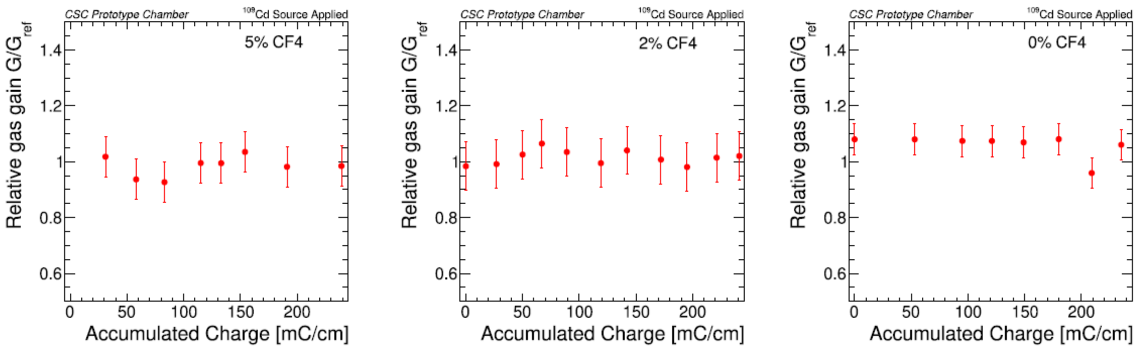
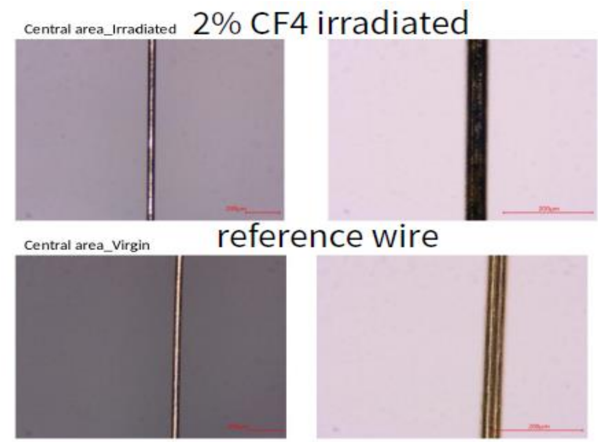
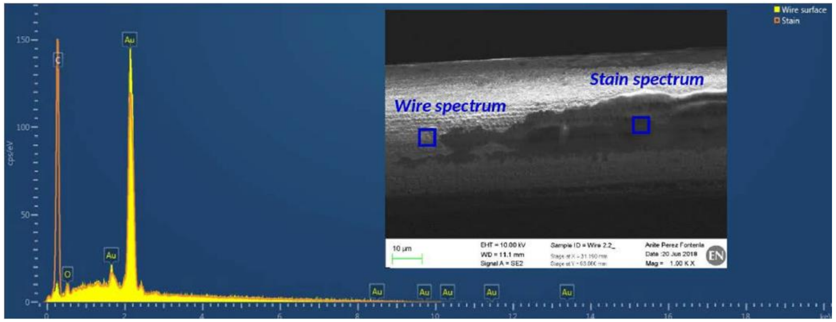


Fig. 3 Relative gas gain as the peak position of a ^{109}Cd X-ray spectrum measured in the irradiated area and normalized to that of non-irradiated reference zones for gas mixtures with 5, 2, and 0% CF_4 (left, center, right)



In tests with 2% and 0% CF_4 mixtures, wire **darkening** was observed, and **spectrometric analysis confirmed** the presence of carbon on the wires, while **no color change was seen for the 5% CF_4 mixture**.

*At the same time, no deterioration of chamber characteristics (**dark current, strip-strip resistance and gas amplification**) was observed.*

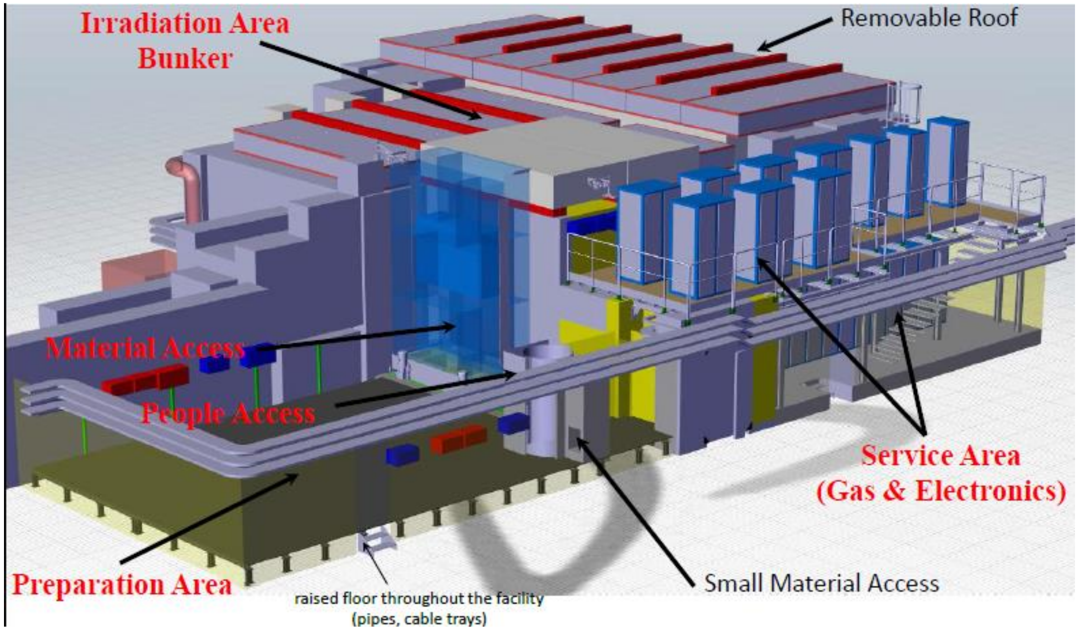


Gas mixtures containing less than 5% CF_4 are potentially hazardous to long-term CSC operation due to carbon deposition on the anode wires.

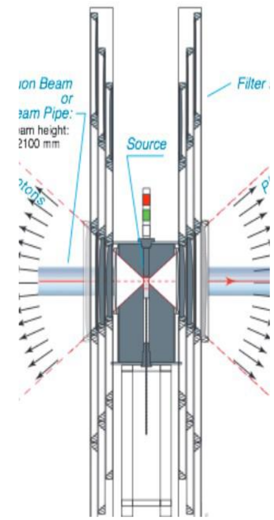
E. Barberis et al. Longevity studies of CSC prototypes operating with Ar+CO2 gas mixture and different fractions of CF4 Eur. Phys. J. Plus 139, 166, (2024).

The Gamma Irradiation Facility (GIF++) at CERN

- **The Gamma Irradiation Facility (GIF++)** was designed and built at the CERN SPS North Area (EHN1) in 2015.
- With this facility, the detectors could simultaneously be exposed to the photons from a ^{137}Cs source and to a high-energy **H4 SPS beam**.



GIF++ Source with filters



- **14 TBq (2015) ^{137}Cs source (Eγ = 662 keV)**
- **H4 SPS beam line**
- **A set of filters: Attenuation Factor: (1 ÷ 46000)**
- **Upstream + Downstream ± 37° irradiation cone**

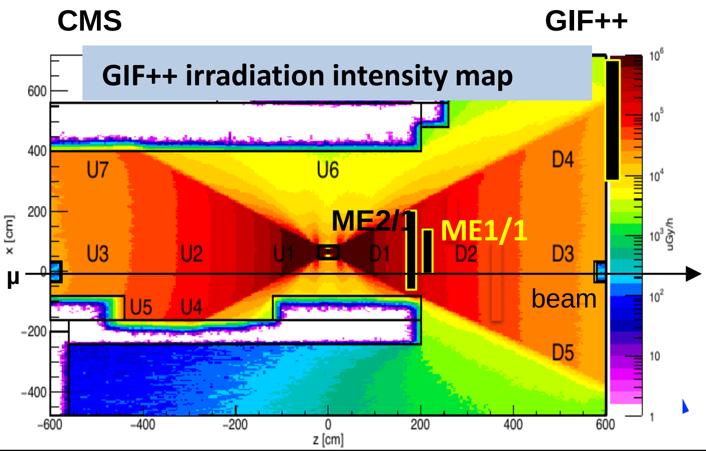
Att.Fact. 1÷46.4k

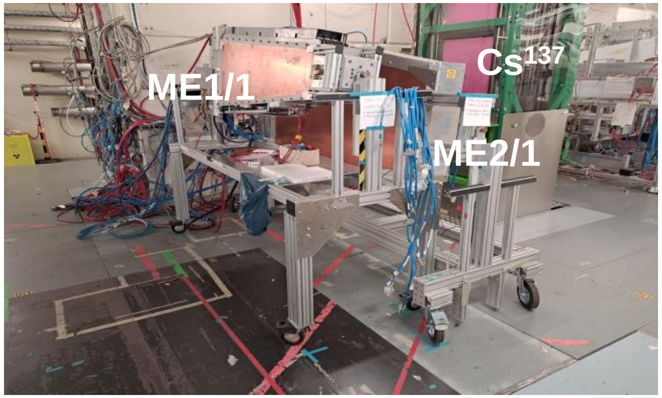
Plane :	A	B	C
Pos. 1	1	1	1
Pos. 2	10	1.47	2.15
Pos. 3	100	100	4.64

M.R. Jäkel et al.CERN GIF++ : A new irradiation facility to test large-area particle detectors for the high-luminosity LHC program. PoS (TIPP2014) 102.
D. Pfeiffer et al. "The radiation field in the Gamma Irradiation Facility GIF++ at CERN", Nucl. Instr. Meth. A 866 (2017) 91–103

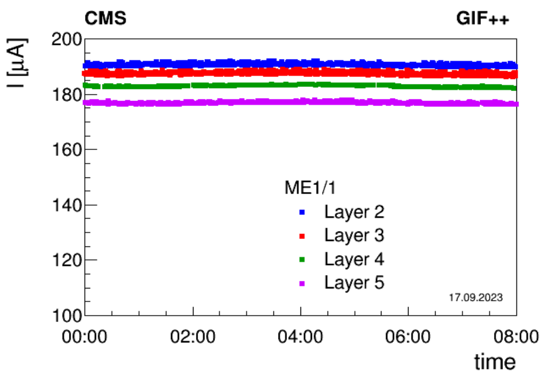
CSCs Longevity study: irradiation position at GIF++ and Layer currents

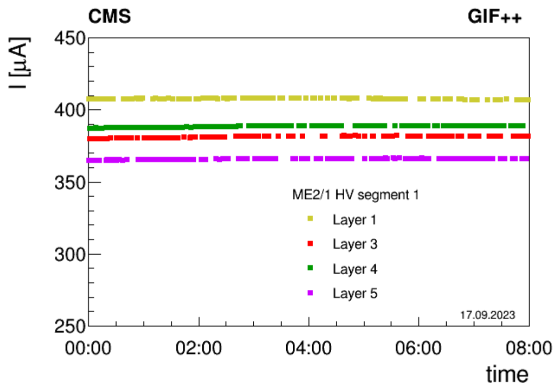
Aging effects are studied at the Gamma Irradiation Facility (GIF++) at CERN, with two CSCs: ME1/1 and ME2/1. These chambers, designed differently, are situated in the forward region, where they operate under high background rates.





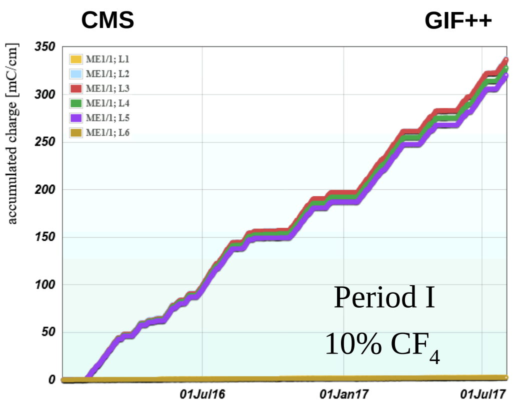
D. Pfeiffer et al., *The radiation field in the Gamma Irradiation Facility GIF++ at CERN.* Nucl. Instrum. and Meth. **A 866** (2017) pp. 91–103.

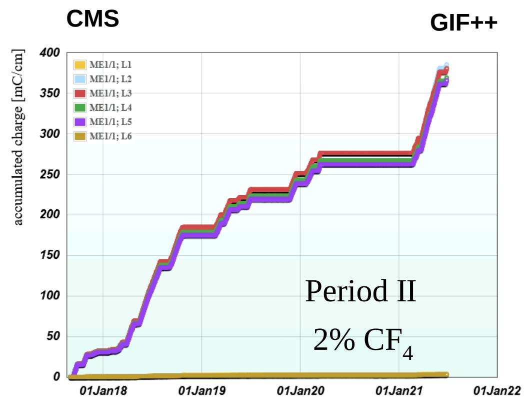


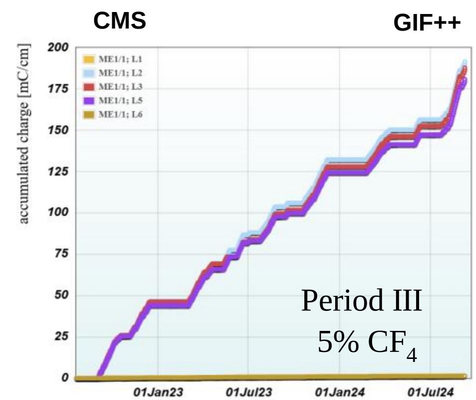


ME2/1 and ME1/1 are composed of 6 identical trapezoidal proportional chambers (layers) with cathode strip readout (CSCs). During the irradiation high voltage has been applied to 4 layers (**irradiated layers**) while 2 others were off (**reference layers** with HV= 0V).
In the irradiation position ME2/1 is in front of ME1/1 and ~1.8m from the ^{137}Cs.
Each layer of ME2/1 active area is divided by 3 independent high voltage zones – **HV segments**.
The current of ME1/1 irradiated layers is ~ 190 μA, while for ME2/1 segment 1 it is ~ 390μA.

CSCs Irradiation at GIF++ - accumulated charge



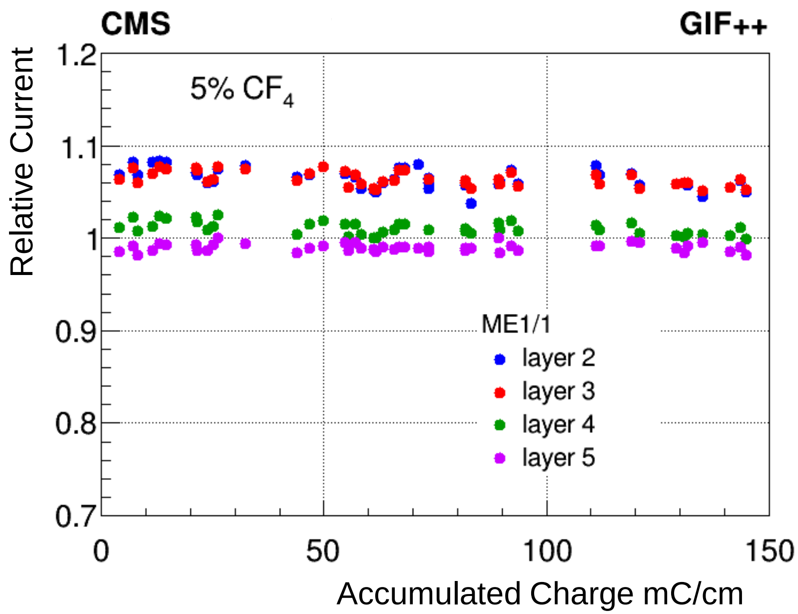


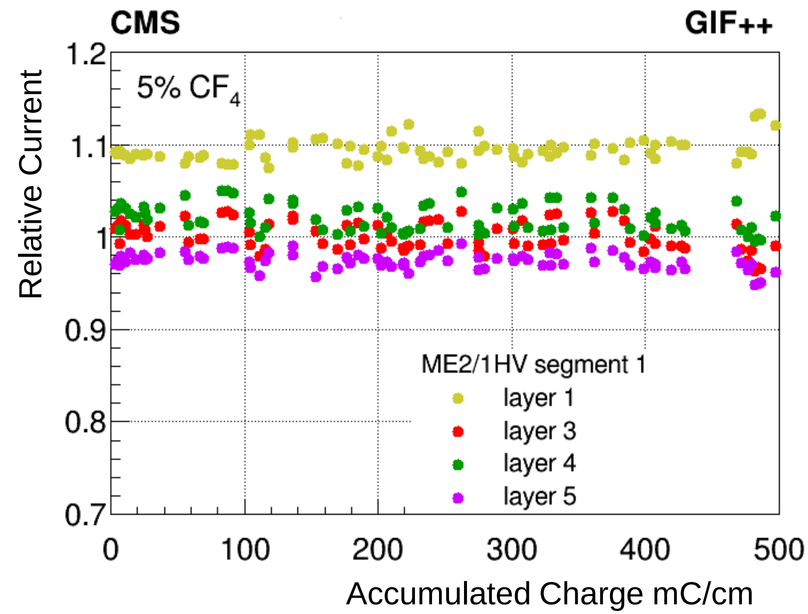


CSC	Accumulated charge Q (mC/cm)			
	before 2018 **($10\%\ CF_4$)**	November 2021 **($2\%\ CF_4$)**	20.09.24 **(5% CF4)**	Total
ME1/1	**330**	**370**	**190**	**890**
<ME2/1>	**310**	**Not irradiated**	**495**	**805**
	Period I	*Period II*	*Period III (ongoing)*	

- ME1/1 plots showing accumulated charge per 1cm of anode wire length vs time during CSC irradiation at GIF++ (^{137}Cs) with different gas mixtures: ($40\%Ar+50\%CO_2+10\%CF_4$ – period I, $40\%Ar+58\%CO_2+2\%CF_4$ – period II and $40\%Ar+55\%CO_2+5\%CF_4$ – period III). Layer 1 and Layer 6 are the reference layers and so have negligible accumulated charge.
- The table shows the accumulated charge for ME1/1 and ME2/1 (average value for the three HV segments) for different periods of irradiation.
- Accumulated charge estimated at the end of HL-LHC running assuming Run 3 currents and background occupancies (preliminary results), corrected using FLUKA simulation for HGCAL presence is for ME1/1 ~ 400 mC/cm, while for ME2/1 ~ 220 mC/cm.

Relative currents in irradiated layers vs accumulated charge

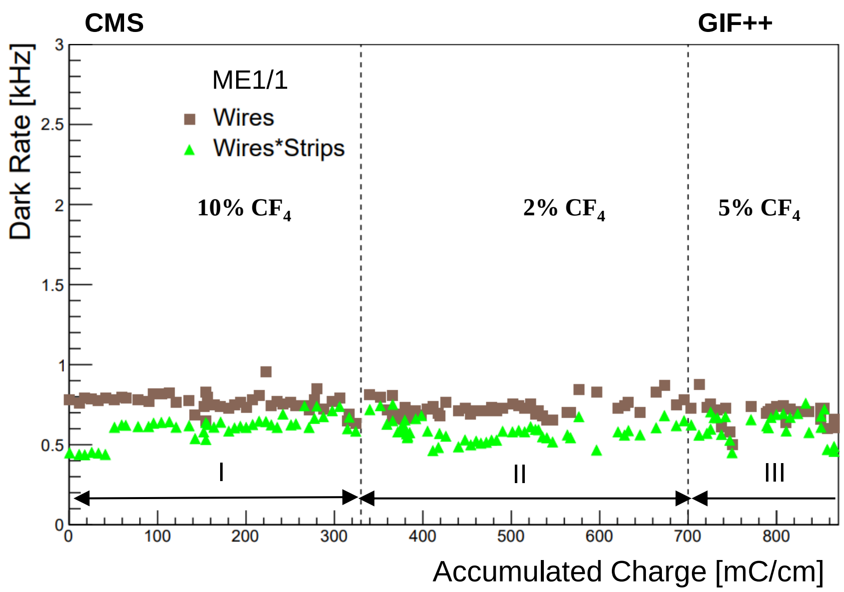


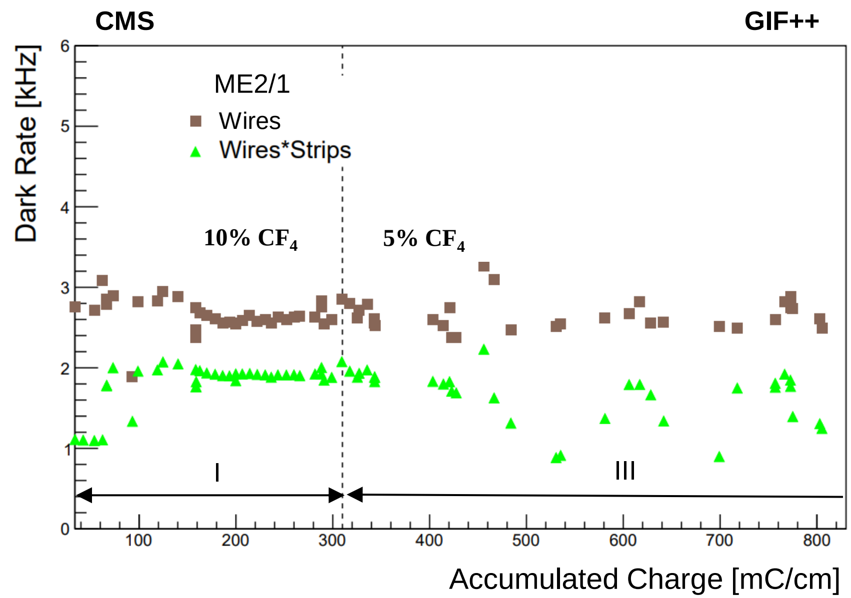


ME1/1 (left) and ME2/1 (right) plots of the relative currents in irradiated layers vs the accumulated charge. The relative current is a ratio of a value of the current in **irradiated** layer and an averaged current value of the two **reference** layers. During irradiation, the reference layers have HV=0. The closer the layer is to the Source, the higher current it has.

The data refers to the period of irradiation with 40%Ar+55%CO_2+5%CF_4 gas mixture. Each layer of the ME2/1 active area is divided into three independent high voltage zones – HV segments. Right plot is for ME2/1 segment 1.

Dark rate measurements





Measurements of the CSC dark rates with single layer mode trigger as a function of the accumulated charge.

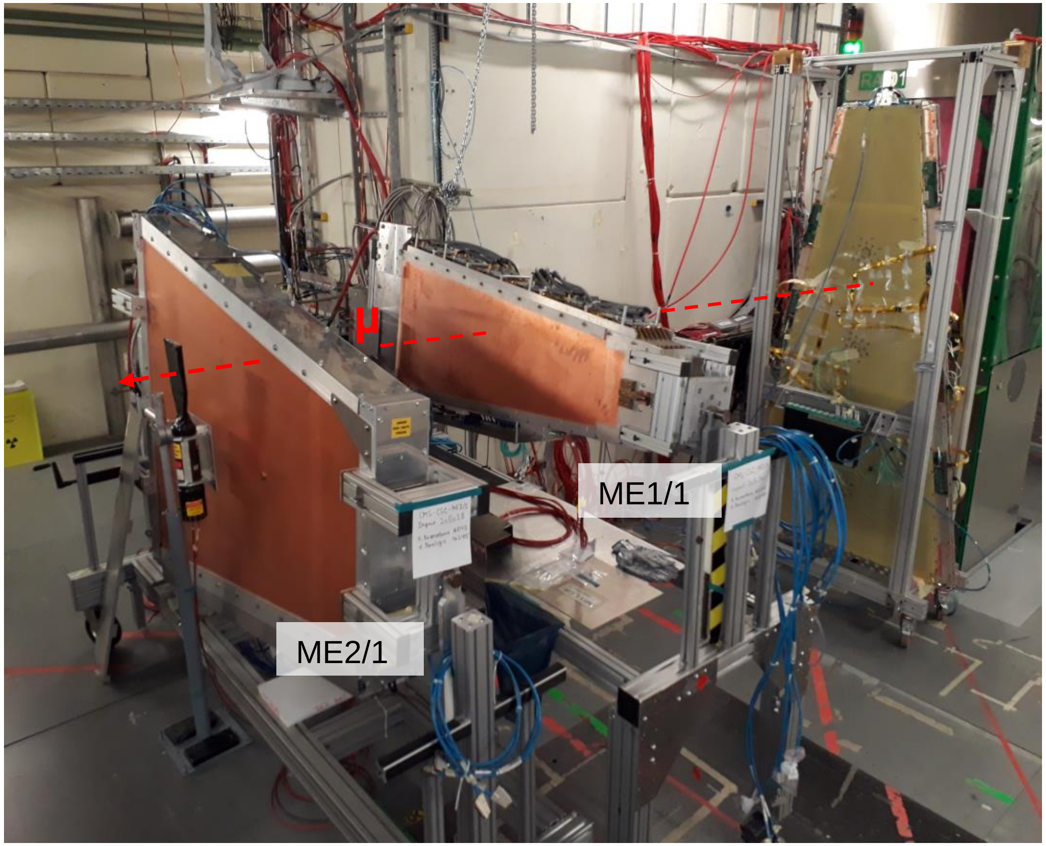
1. The ME1/1 dark rate (left) is measured during irradiation with the nominal 40%Ar+50%CO_2+10%CF_4 gas mixture (up to 330 mC/cm), then with 40%Ar+58%CO_2+2%CF_4 gas mixture up to 700 mC/cm (period II) and then the gas mixture was changed to 40%Ar+55%CO_2+5%CF_4 (period III). The dark rates measured with anode readout electronics only (Wires) and as **a coincidence** of the anode and cathode signals (Wires * Strips) are shown.

2. The ME2/1 dark rate (right) is measured during irradiation with the 40%Ar+50%CO_2+10%CF_4 gas mixture up to 310 mC/cm (period I), then the gas mixture was changed to 40% Ar+55%CO_2+5%CF_4 (period III) .

The difference between dark rate measured with Wires only and measured with matched Wire and Strip signals arises because the cathode readout is installed only for 80% of the CSC active area.

The periodic deviation in the Wires*Strips rate in period III of irradiation is caused by the cathode electronics instabilities.

CSCs measurements with muon test beams



Measurements with the muon test beam:

1. External scintillator trigger, S_{CSC} * S_{GIF} separating 15x15cm^2 area.

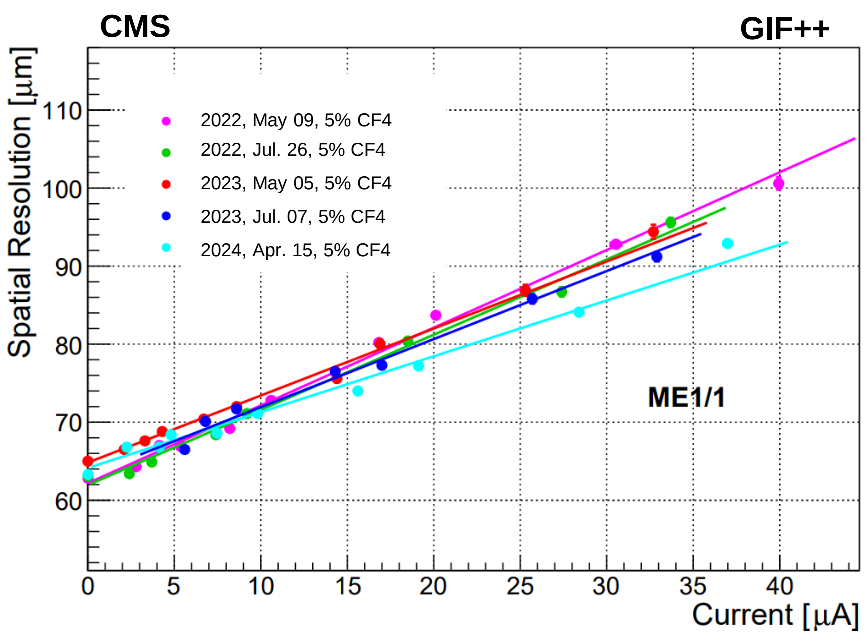
a). Spatial resolution vs Source intensity

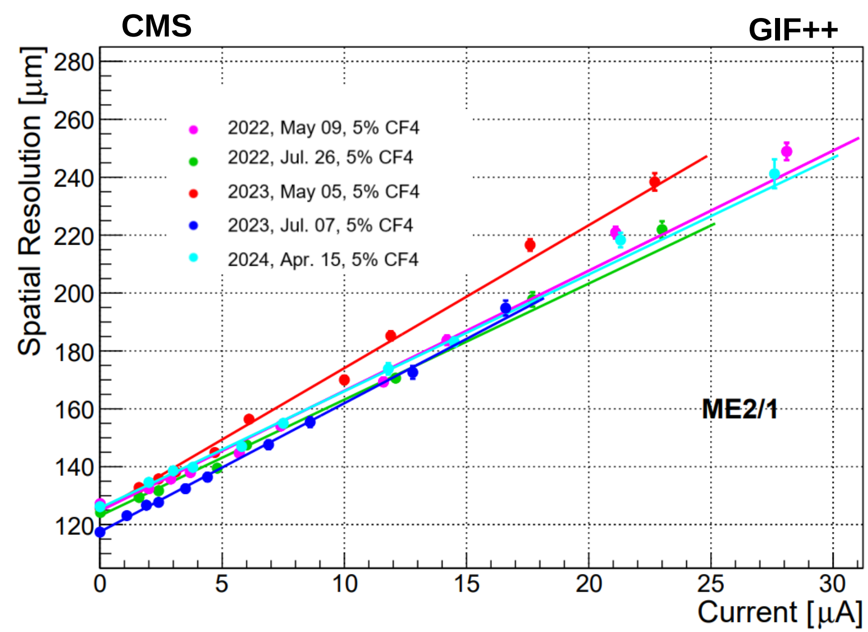
b). Efficiency vs HV (work in progress)

2. Large statistics CSC in self-trigger mode, Source off.

ME2/1 and ME1/1 in Test Beam position.
Irradiation position differs from the Test Beam one.

CSCs spatial resolution: GIF++ μ beam with Filter scan





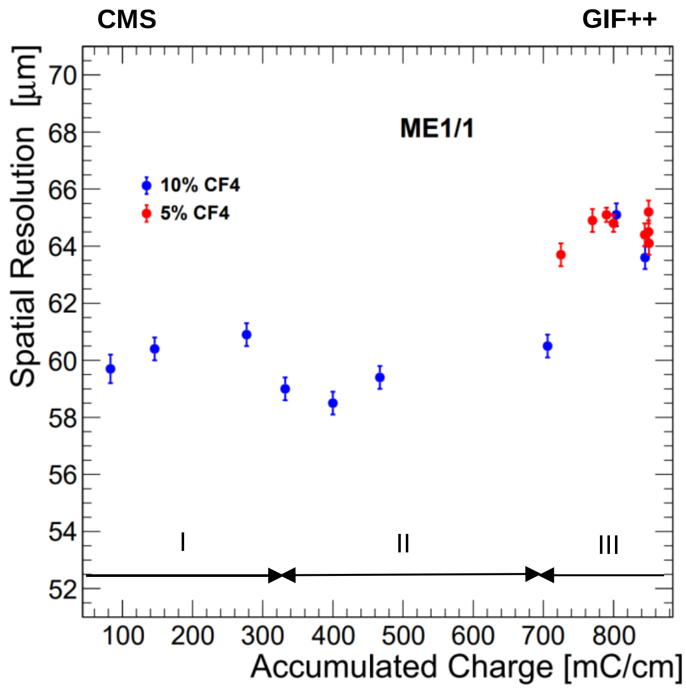
Spatial resolution of ME1/1 (left) and ME2/1 (right) vs mean CSC layer current with 5% CF_4 (40%Ar+55%CO_2+5%CF_4) gas mixture.

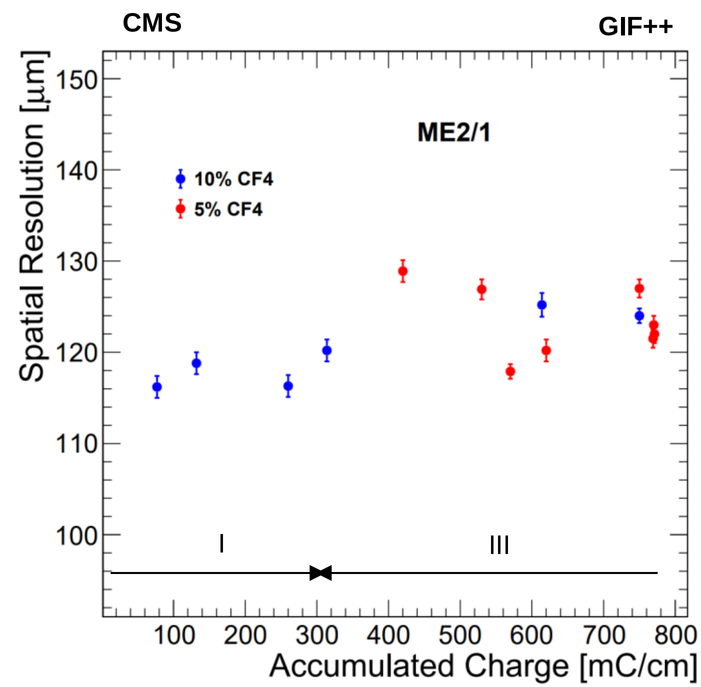
The measurements are performed with a muon beam and varying ^{137}Cs source background.

The results are corrected for atmospheric pressure variation.

The spatial resolution degrades linearly with the background intensity.

CSCs spatial resolution vs accumulated charge





Spatial resolution of the ME1/1 (left) and ME2/1 (right) chambers measured with a muon beam as a function of the accumulated charge.
The first 330 mC/cm of charge (period I) was accumulated with the nominal 40%Ar+50%CO_2+10%CF_4 gas mixture, then irradiation was continued for ME1/1 only with the reduced CF_4 content (40%Ar+58%CO_2+2%CF_4 – period II) and finally the irradiation continued for both CSCs with 40%Ar+55%CO_2+5%CF_4 mixture (period III). Blue points represent measurements with 10% CF_4 gas mixture flow, while the red points represent the measurements with 5% CF_4 gas mixture.
No significant degradation of the spatial resolution was observed for the whole irradiation period up to the charge of 700 mC/cm for ME1/1. The slight degradation of the ME1/1 resolution in period III (2023-2024) is to be investigated.
The errors are statistical. We estimate the systematic errors as ± 2 μm for ME1/1 and ± 3-4 μm for ME2/1.

Conclusions

- The Cathode strip chambers (CSCs) are the part of the CMS Endcap muon system and operate well in collisions since 2008.
- The forthcoming upgrade of the Large Hadron Collider (LHC) to the High-Luminosity LHC (HL-LHC) and the planned upgrade of the CMS forward endcap zone increase the importance of longevity studies of the gas detectors.
- Greenhouse F-gases usage limitation induced additional studies towards the reduction of the CF_4 fraction in the gas mixture or it's replacement by more ecological gas.
- The longevity studies with different gas mixtures with mini-CSCs showed that the gas mixtures containing less than 5% CF_4 are potentially hazardous to long-term CSC operation.
- The tests with mini-CSCs will continue with new set of prototypes including the aging study with 100% recuperated CF_4.
- The longevity studies of the CMS CSCs ME1/1 and ME2/1 carried out at GIF++ (CERN) since 2016 show no signs of CSC ageing.
  - three gas mixtures were used: 40%Ar+50%CO_2+10%CF_4, 40%Ar+58%CO_2+2%CF_4 and 40%Ar+55%CO_2+5%CF_4;
  - the accumulated charge for ME1/1 is 890 mC/cm while for ME2/1 it is 805 mC/cm.

Thank you!