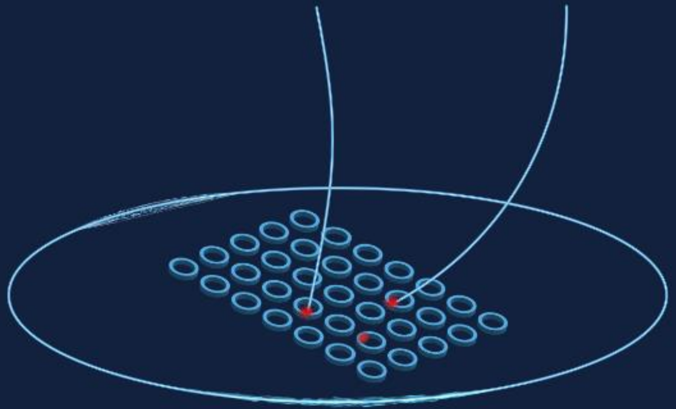
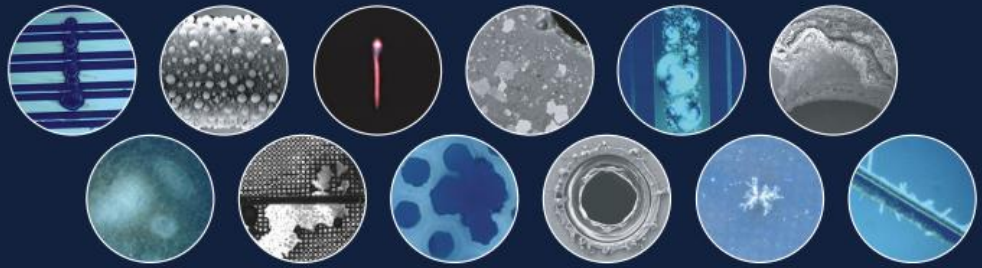


3rd International Conference on

DETECTOR STABILITY AND AGING PHENOMENA IN GASEOUS DETECTORS

CERN, Geneva
6-10 November, 2023



Conference Summary

Roberto Guida
for the Local Organizing Committee

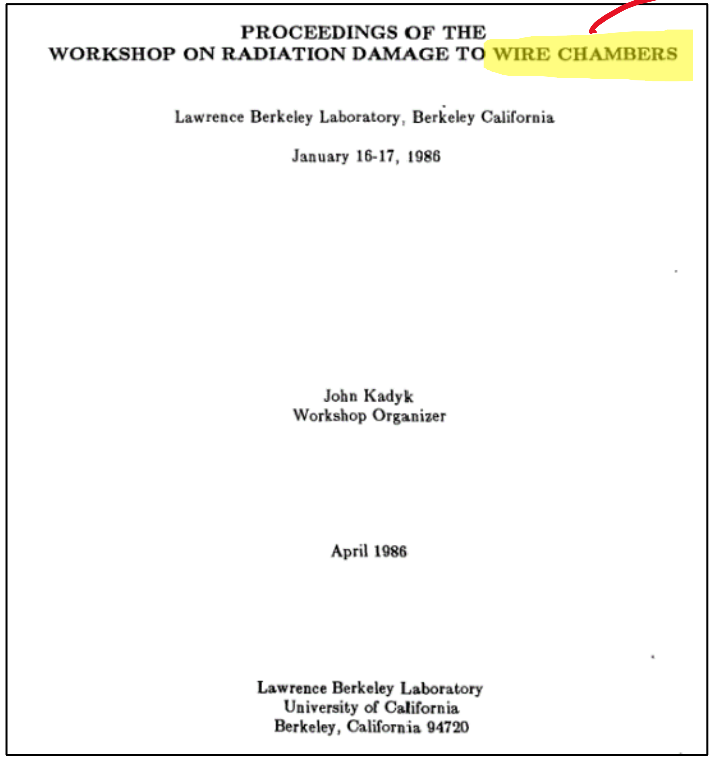
Outline

- Conference program
- Introduction to ageing phenomena
- Past, Present and future requirements
- Experience from current experiments
- Longevity studies
- Gas monitoring and material validation
- New materials
- New eco-friendly gases
- Conclusions

Introduction

3rd International Conference on Detector Stability and Aging Phenomena in Gaseous Detectors: November 2023, CERN

1st workshop, LBL 1986


PROCEEDINGS OF THE
WORKSHOP ON RADIATION DAMAGE TO WIRE CHAMBERS

Lawrence Berkeley Laboratory, Berkeley California

January 16-17, 1986

John Kadyk
Workshop Organizer

April 1986

Lawrence Berkeley Laboratory
University of California
Berkeley, California 94720

24 proceeding

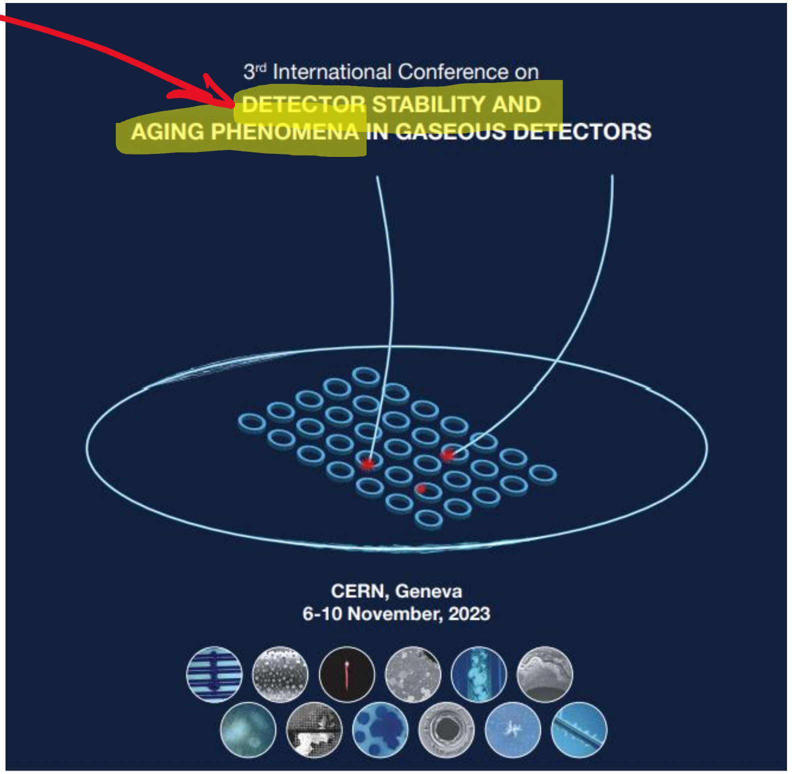
2nd workshop, DESY 2001

50 presentations

~90 participants for each

- 1st only on wire chambers
- 2nd ageing in gaseous detectors
- 3rd focus on ageing and stability: experience ageing observation and from stable detector operation

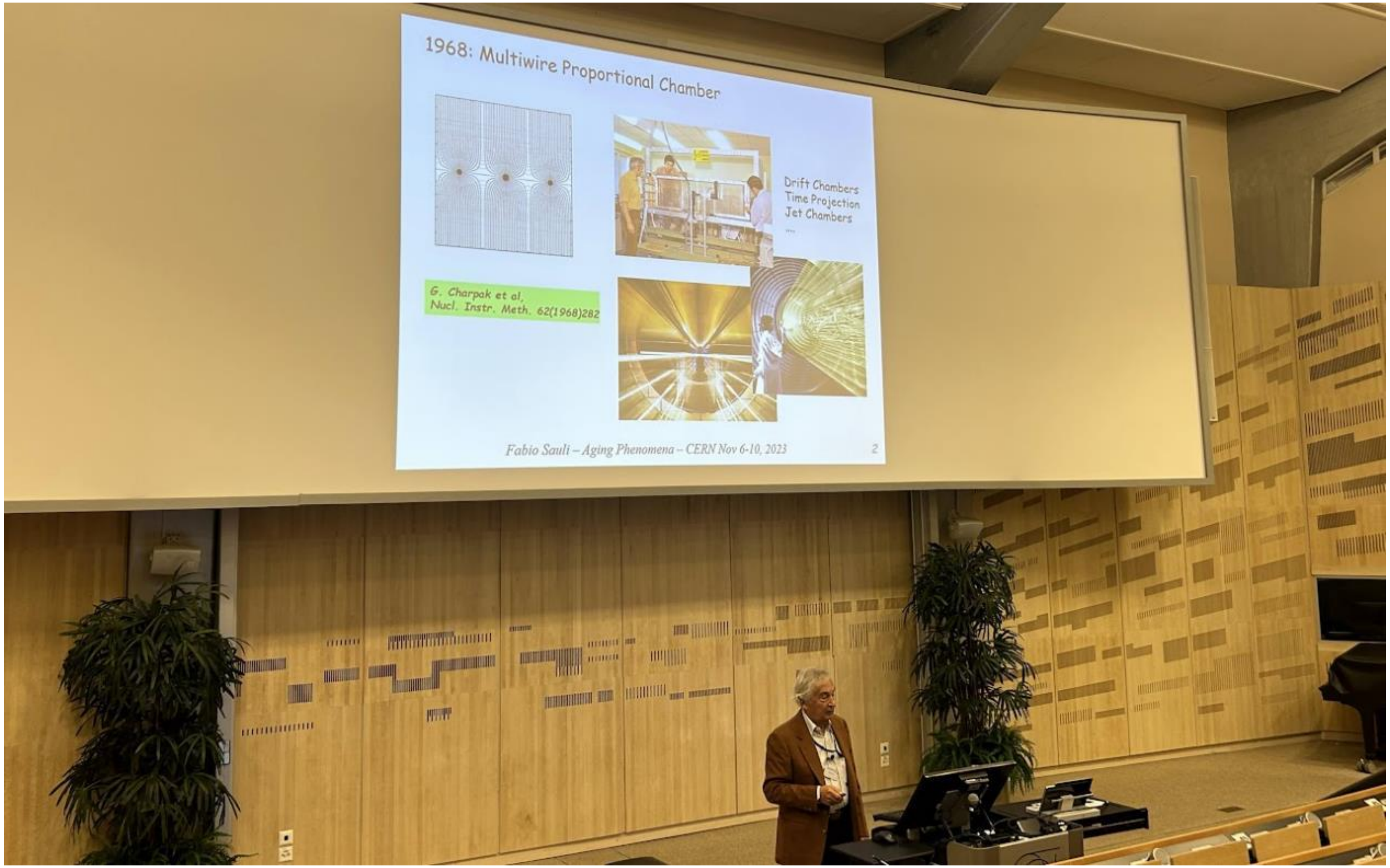
3rd conference, CERN 2023



62 presentations

Introduction

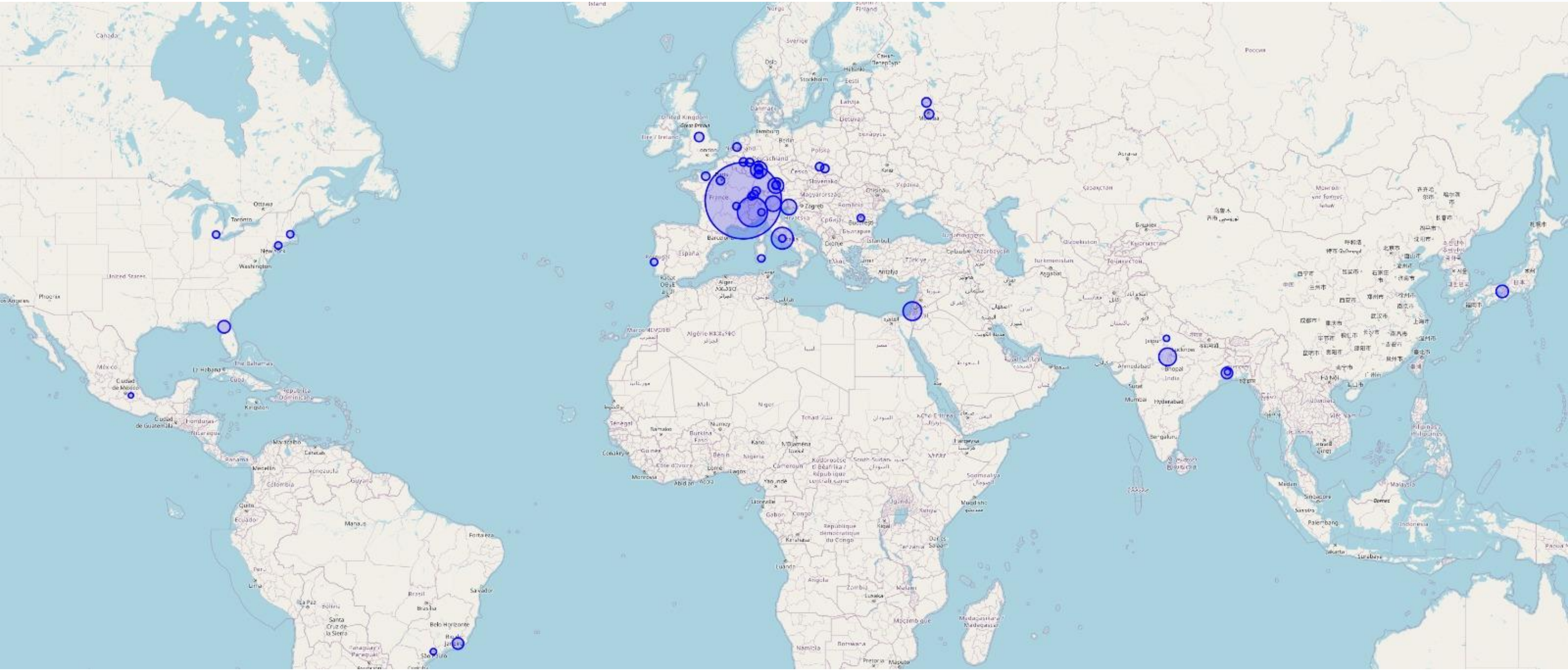
Only one person attended all the three conferences:



Picture from Cecilia Uribe Estrada

AGING PHENOMENA IN GASEOUS DETECTORS

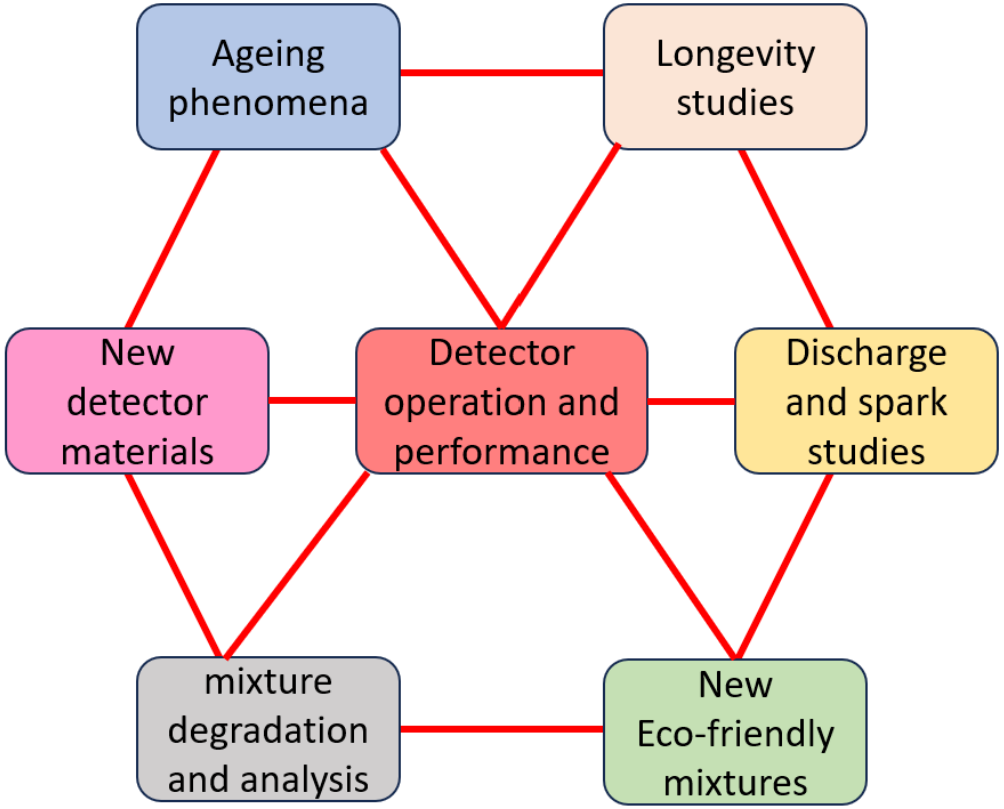
Participants from around the world



G. Rigoletti with ChatGPT

The conference program

6 sessions (+ Poster session):



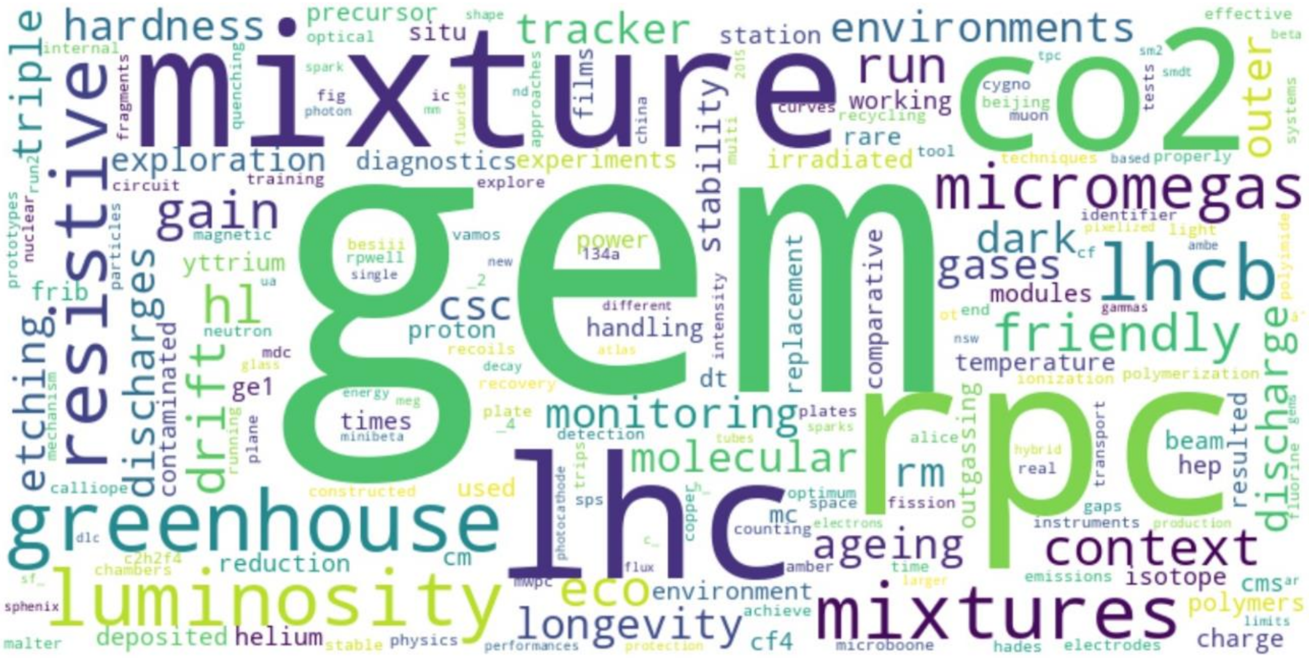
and now…I need to map 1 week in 1 hour:

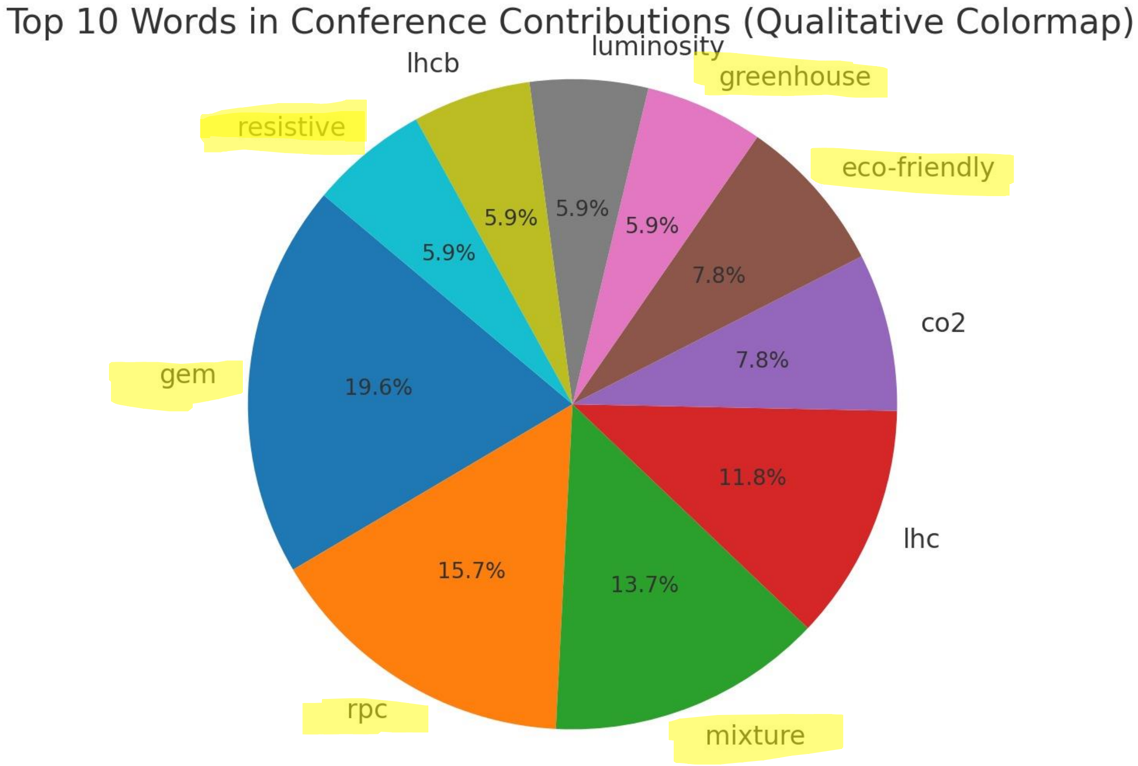
- *In the following I rearranged some talks/sessions to group topics*
- *I apologize for the conciseness*
- *All details available on the conference website: https://indico.cern.ch/e/agade23*
- *Proceedings will be published on NIMA VSI*

The conference program

AGING PHENOMENA IN GASEOUS DETECTORS

Analysing abstracts book with LLM

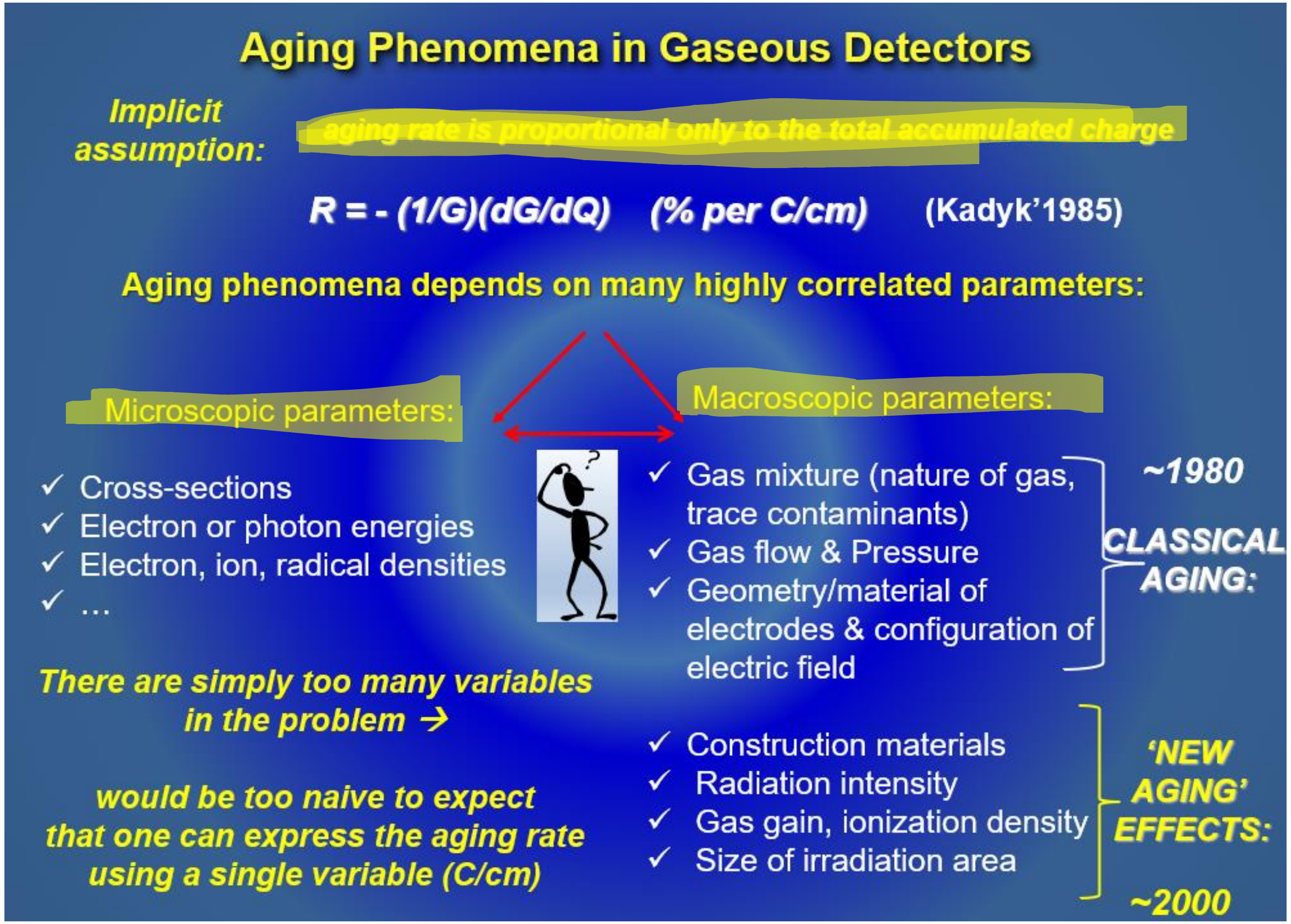




G. Rigoletti with ChatGPT

Introduction: complexity of ageing phenomena

Introduction: complexity of ageing phenomena

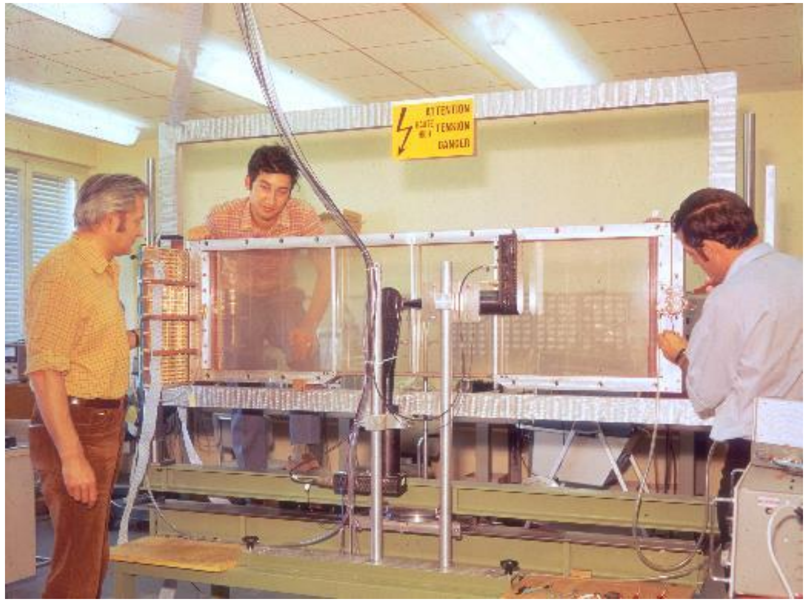


Radiation Levels not even thought in '1980: from mC/cm → C/cm

https://indico.cern.ch/event/1237829/contributions/5637200/

The beginning

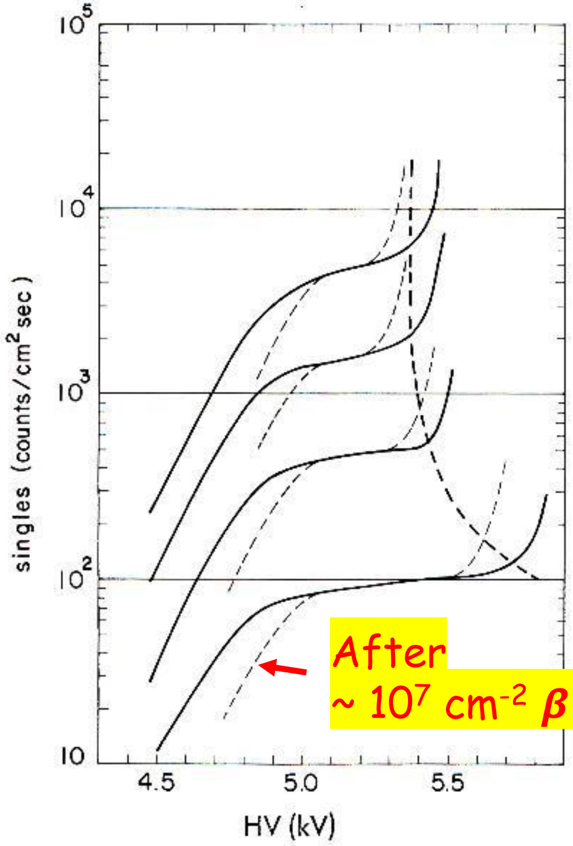
1968: Multiwire Proportional Chamber

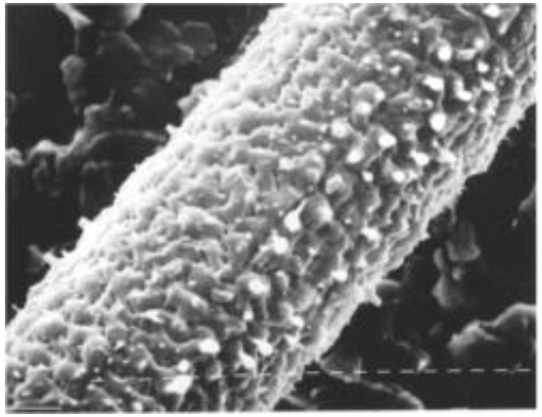


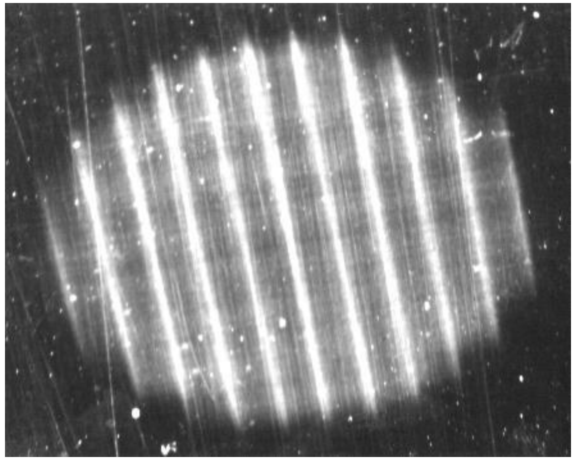
G. Charpak et al,
Nucl. Instr. Meth. 62(1968)282

Deterioration of Performances under Irradiation:

- Rate Dependence of Gain
- Higher Noise







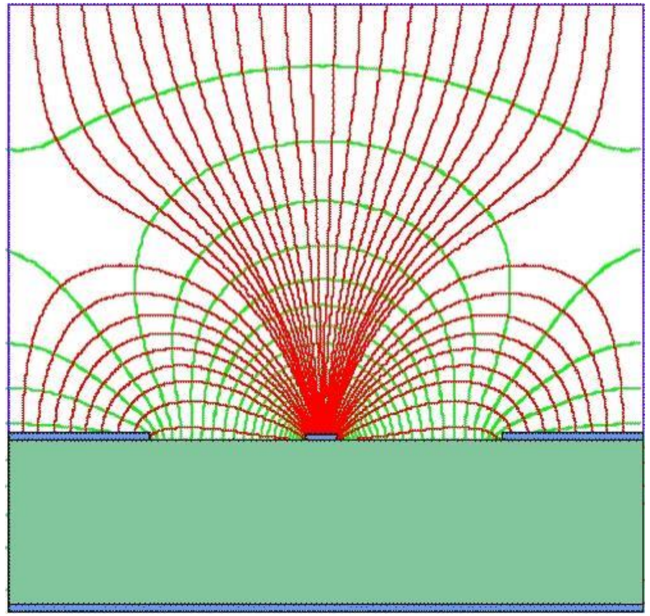
G. Charpak et al, Nucl. Instr. Meth. 99(1972)269

https://indico.cern.ch/event/1237829/contributions/5637193/

The beginning

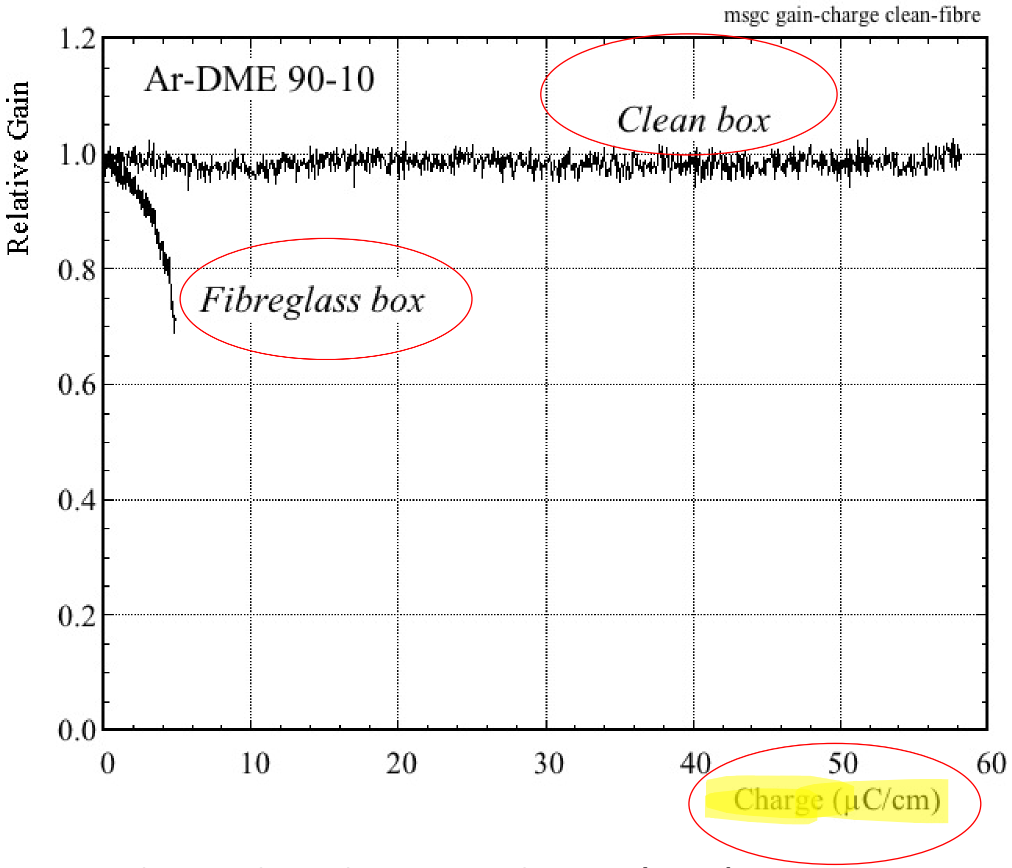
AGING PHENOMENA IN GASEOUS DETECTORS

1988: Micro-Strip Gas Counter (MSGC)

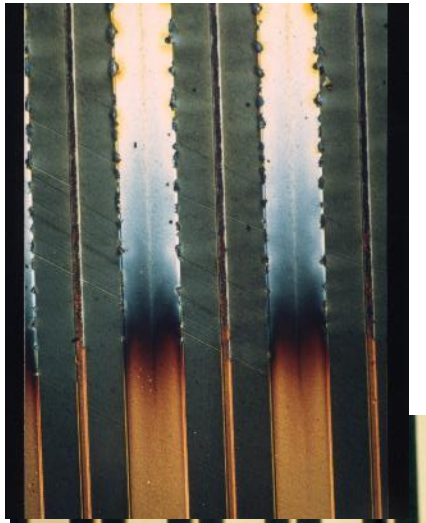


A. Oed,
Nucl. Instr. Meth. 263(1988)351

Extreme Dependence on Gas Purity



R. Bouclier et al, Nucl. Instr. Meth. A348(1994)109

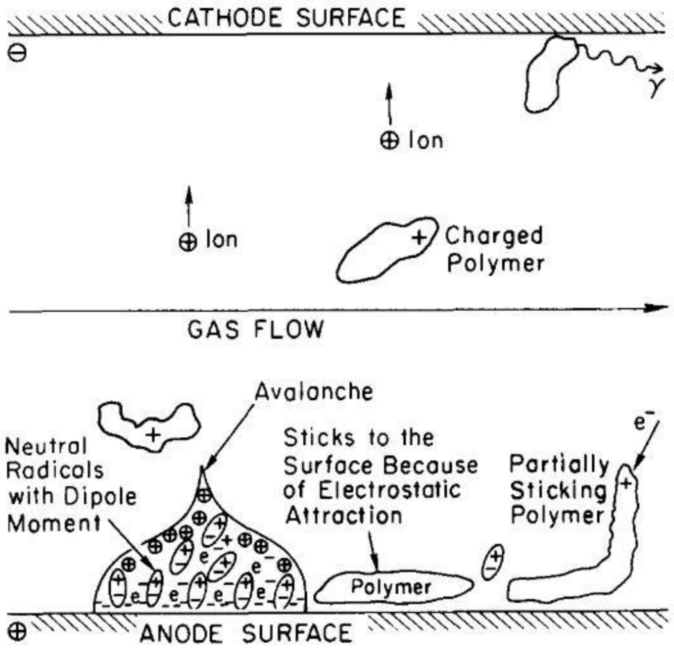


Polymer Formation and Plasma Chemistry

AGING PHENOMENA IN GASEOUS DETECTORS

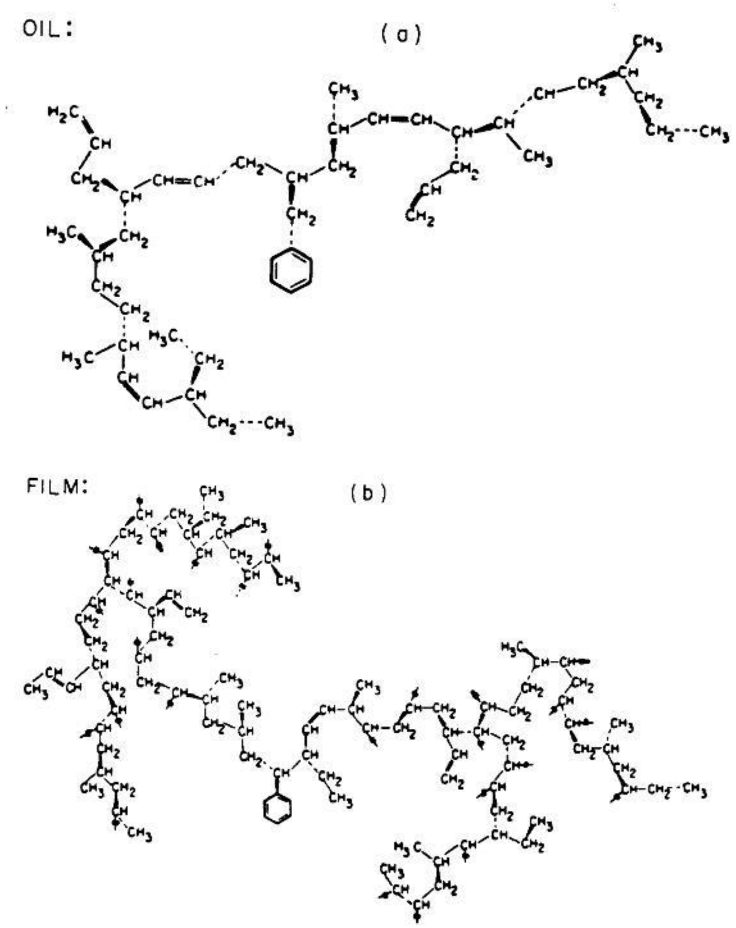
$e + CH_4 \rightarrow CH_2{:} + H_2 + e$

Production of CH_2: radicals
(precursors of Polyethylene)



J. Va'vra,
Nucl. Instr. Meth. A252(1986)547

Polyethylene Compounds

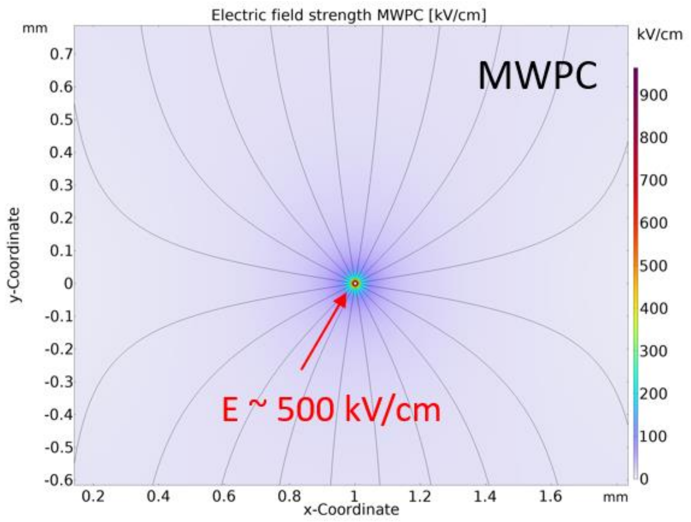


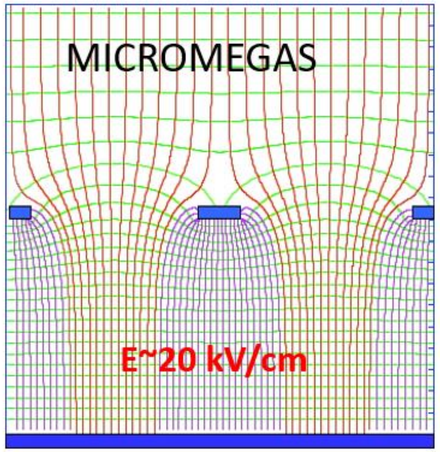
AVOID:
Plasticizers (Phthalates)
Sealant: RTV
Vacuum Grease
Oil Bubblers with Silicone
Silicone oil (Dow 704)
Duo-Seal
Epoxies: G10
…. and many others

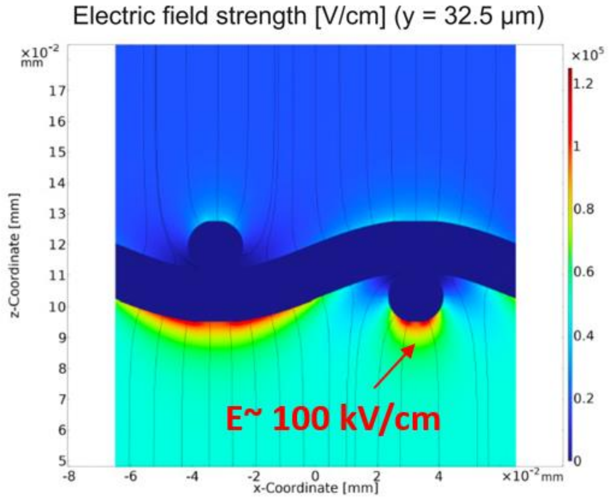
and
ageing test validation
for each component

Electric Field Strength

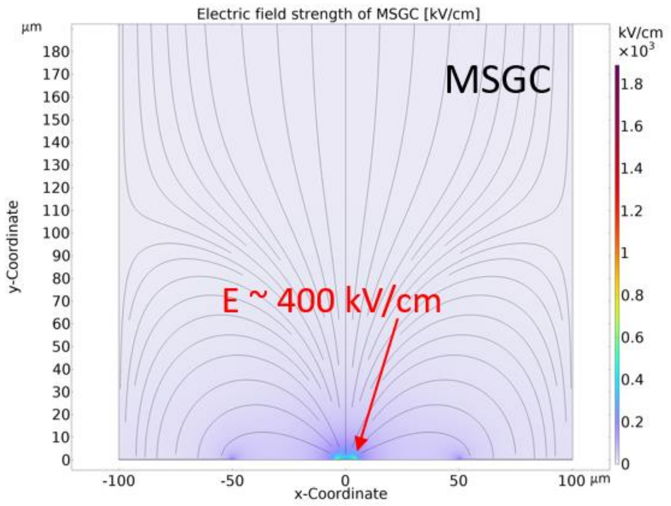
The higher is the electric field, the higher is the probability to enhance plasma chemistry effects

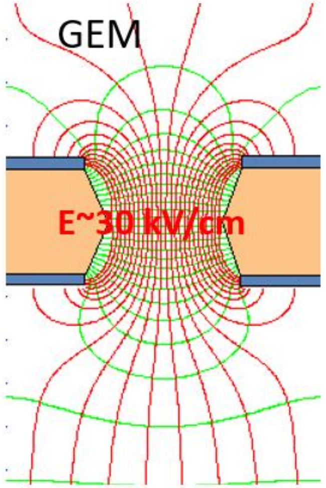


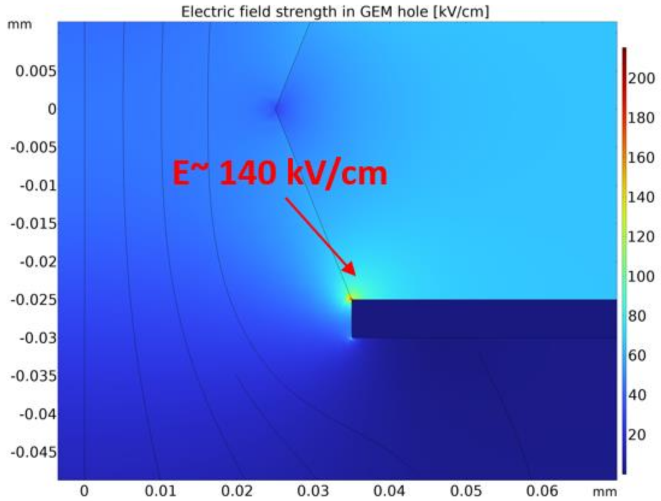




Interwoven Micromesh





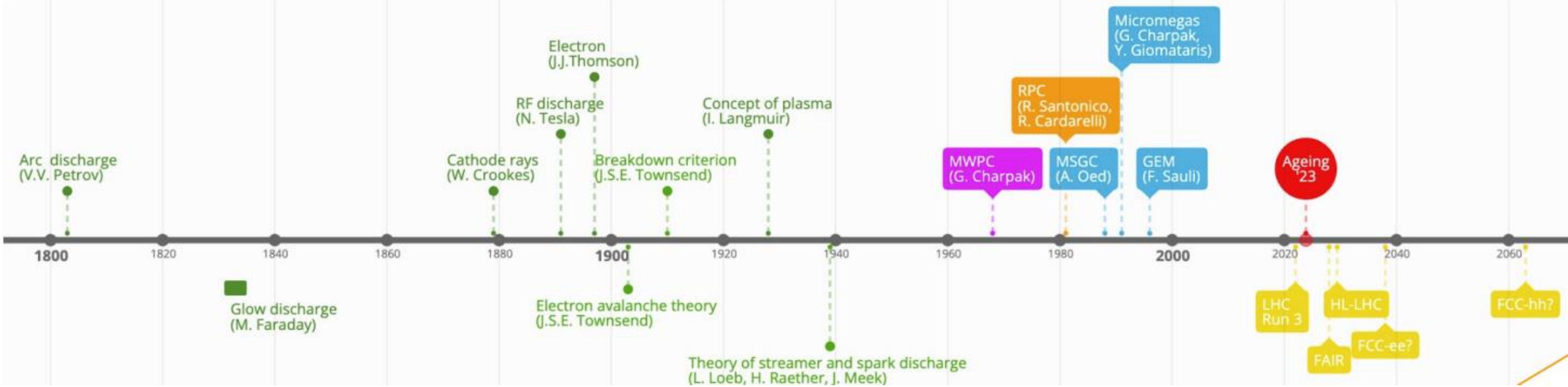


Lower GEM Hole Edge

Discharge phenomena

More than 200 years of gas discharge physics

- Many decades of experience with operating gaseous detectors, but now the challenge is getting more and more extreme! High particle rate, high radiation background, …



- Sparking limits
– When the critical charge (~10^8 or less?) is reached
– Enhanced by secondary emission from the high field regions in the cathode plane or Malter effect
– **Depending on the stored energy: can be destructive**

https://indico.cern.ch/event/1237829/contributions/5637227/

Discharge phenomena

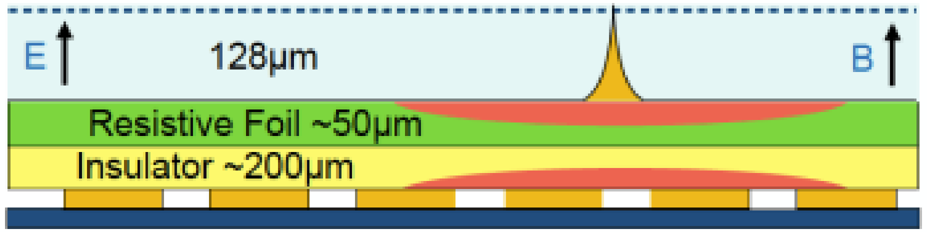
OVERCOMING THE LIMITS (AVOIDING QCRIT)

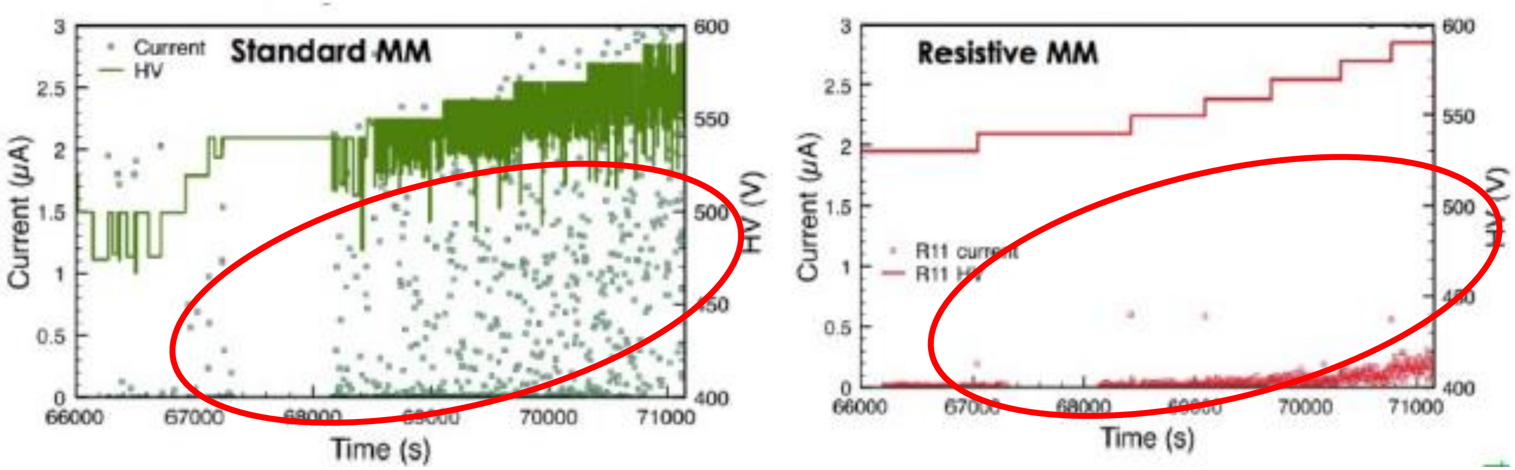
- GEMs are easy to stack
- GEM + MMG hybrids and multi-MMG stacks
- Optimized HV settings (lower amplification towards bottom of a stack)
- Resistive layers – running horse of (multi-gap) RPC technology

➞ drop of the electric field around the initial avalanche ➞ remaining counter area remains sensitive to particles

Resistive MPGDs

- Allow for charge sharing and create self-quenching mechanism
- Delay the charge evacuation and force local field reduction ➞ rate capabilities

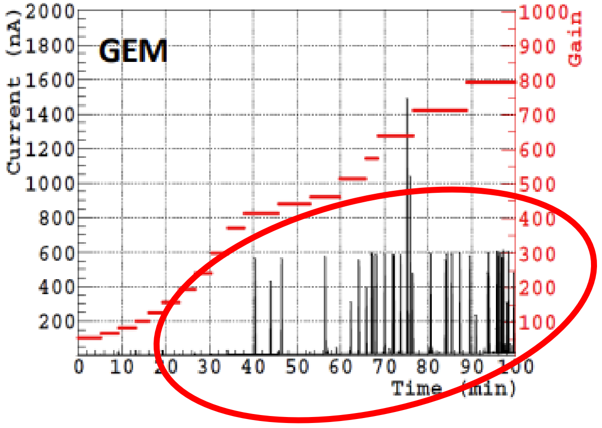


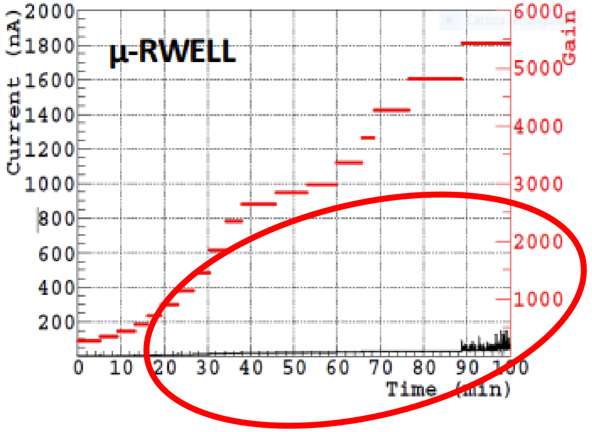


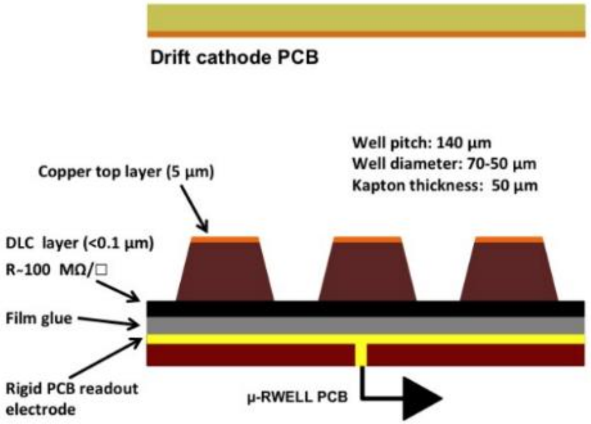
Discharge phenomena

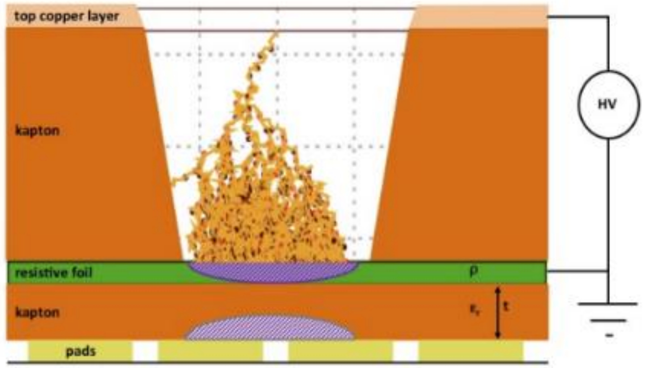
New structures: micro-RWELL

- Single-sided Gaseous Electron Multiplier (GEM) coupled to the readout anode through the material of high surface resistivity
- Single amplification stage ➞ material budget, simplicity, industrialization, costs!
- Resistive layer ➞ suppression of the transition from streamer to spark, with a consequent reduction of the spark amplitude.
- Drawback ➞ the capability to stand high particle fluxes is reduced, still 10 MHz/cm^2 demonstrated.



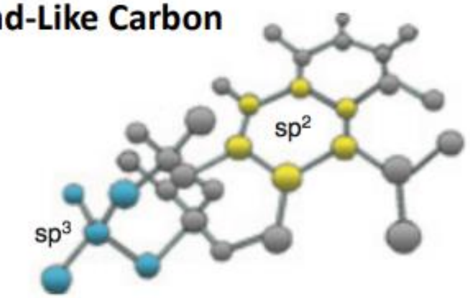






New concepts (DLC (TH)GEM, MM, sRPC) with DLC layers

Diamond-Like Carbon



GOLDEN RULES OF AGING PREVENTION

- Ultra-Pure gases
- Non-Organic Quenchers (CO_2)
- Choice of non-Outgassing Building Materials
- Non-Polymerizing Additives: Methylal, Propylic Alcohol
- Improved Cleaning Protocols
- Avoid Silicone-Containing Materials: Tubing, Sealings, ….
- Zapping: Burning Deposits with High Current on Anodes
- Addition of Compounds with Etching Properties (O_2, CF_4)
- The creation of reactive species is enhanced at high values of the electric field

But sometime tiny details escape, and an ageing effect appears

New requirements for even more difficult future conditions

@ LHC in 2008

Hz/cm^2 - 100 kHz/cm^2

2008: Original Gaseous Detectors in LHC Experiments

	Vertex	*Inner Tracker*	*PID/ photo-detecto r*	*EM CALO*	*HAD CALO*	*MUON Track*	*MUON Trigger*
ATLAS	-	***TRD (straws)***	-	-	-	***MDT (drift tubes), CSC***	***RPC, TGC (thin gap chambers)***
CMS ----- ***TOTEM***	-	- --------- ***GEM***	- **Max.rate**:20 kHz/cm^2	-	-	***Drift tubes, CSC*** **Barrel**: ~ 500 Hz/cm^2 **Endcap**: ~ 50 kHz/cm^2	***RPC, CSC***
LHCb	-	***Straw Tubes***	-	-	-	***MWPC***	***MWPC, GEM*** **Max.rate**:500 kHz/cm^2
ALICE	-	***TPC (MWPC)***	***TOF (MRPC), HPMID (RICH-pad chamber), TRD (MWPC)***	-	-	***Muon pad chambers***	***RPC***

https://indico.cern.ch/event/1237829/contributions/5637200/

New requirements for even more difficult future conditions

@ HL-LHC

10 kHz/cm^2 - MHz/cm^2

ATLAS Muon System Upgrade @ HL-LHC

Experiment / Timescale	Application Domain	Gas Detector Technology	Total detector size / Single module size	Operation Characteristics / Performance	Special Requirements / Remarks
ATLAS MUON UPGRADE CERN LS2 / LS3	Hadron Collider (Tracking/Triggering)	Endcap: Res. Micromegas & sTGC	Endcap area: 1200 m^2 Single unit detect: (2.2x1.4m^2) ~ 2-3 m^2	**Max. rate**:20 kHz/cm^2 **Spatial res.**: <100 μm **Time res.**: ~ 10 ns **Rad. Hard.**: ~ 0.5 C/cm^2	Redundant tracking and triggering; Challenging constr. in mechanical precision
ATLAS MUON UPGRADE (BIS78 PILOT) CERN LS2	Hadron Collider (Tracking/Triggering)	Part of Inner Barrel: RPC + sMDT	Barrel area (3 layers): 140 m^2 Single unit det.: ~ m^2	**Max. rate**:1 kHz/cm^2 **Spatial res.**: ~ 7 mm **Time res.**: ~ 1 ns **Rad. Hard.**: 300 fb	Redundant tracking and triggering; 9 layers with 2D hit position + time
ATLAS MUON UPGRADE (BI PROJECT) CERN LS3	Hadron Collider (Tracking/Triggering	Inner Barrel: RPC	Barrel area: 1400 m^2 Single unit det.: ~ m^2	**Max. rate**:10 kHz/cm^2 **Spatial res.**: ~ (0.1 x 1) cm in (η , φ) **Time res.**: ~ 0.5 ns **Rad. Hard.**: 3000 fb	Redundant tracking and triggering; 9 layers with 2D hit position + time
ATLAS MUON UPGRADE (early proposal; not approved) CERN AFTER LS3	Hadron Collider (Tracking/Triggering) (2.7 ≤|h| ≤ 4.0)	Forward region: Res MM, μWELL, μPIC	Total area: ~ 5 layers x1 m^2 Single unit detect: 0.1 m^2	**Max. rate**: 10 MHz/cm^2 **Spatial res.**: ~200 μm **Time res.**: ~ 5 ns **Rad. Hard.**: ~ 10 C/cm^2	Hit rates falls rapidly with the distance from the beam axis. Given parameters are for extreme conditions at 25 cm from the beam. Miniaturization of readout elements needed there to keep occupancy low

CMS and LHCb Muon System Upgrades @ HL-LHC

Experiment / Timescale	Application Domain	Gas Detector Technology	Total detector size / Single module size	Operation Characteristics / Performance	Special Requirements / Remarks
CMS MUON UPGRADE GE11 CERN LS2	Hadron Collider (Tracking/Triggering)	3-GEM	Total area: ~ 50 m^2 Single unit detect: 0.3-0.4m^2	**Max. rate**: 5 kHz/cm^2 **Spatial res.**: 0.6 – 1.2mm **Time res.**: ~ 7 ns **Rad. Hard.**: ~ 0.18 C/cm^2	Redundant tracking and triggering, improved pt resolution in trigger
CMS MUON UPGRADE GE21 CERN L3	Hadron Collider (Tracking/Triggering)	3-GEM	Total area: ~ 105 m^2 Single unit detect: 0.3-0.4m^2	**Max. rate**: 1.5 kHz/cm^2 **Spatial res.**: 1.4 – 3.0mm **Time res.**: ~ 7 ns **Rad. Hard.**: ~ 0.09 C/cm^2	Redundant tracking and triggering, displaced muon triggering
CMS MUON UPGRADE ME0 CERN L3	Hadron Collider (Tracking/Triggering)	3-GEM	Total area: ~ 65 m^2 Single unit detect: 0.3m^2	**Max. rate**:150 kHz/cm^2 **Spatial res.**: 0.6 – 1.3mm **Time res.**: ~ 7 ns **Rad. Hard.**: ~ 7.9 C/cm^2	Extension of the Muon System in pseudorapidity, installation behind HGCAL
CMS MUON UPGRADE RE3.1, RE 4.1 2023-24 (CERN L3)	Hadron Collider (Tracking/Triggering)	iRPC	Total area: ~ 140 m^2 Single unit detect: 2m^2	**Max.rate**: 2kHz/cm^2 **Spatial res.**: ~1-2cm **Time res.**: ~ 1 ns **Rad. Hard.**: 1 C/cm^2	Redundant tracking and triggering
LHCb MUON UPGRADE CERN LS4	Hadron Collider (triggering)	μ-RWELL	Total area: ~ 90 m^2 Single unit detector: From 0,4x0,3 m^2 To 0,8x0,3 m^2	**Max.rate**:900 kHz/cm^2 **Spatial res.**: ~ cm **Time res.**: ~ 3 ns **Rad. Hard.**: ~ 2 C/cm^2	About 600 detectors

new requirements for even more difficult future conditions

AGING PHENOMENA IN GASEOUS DETECTORS

@ beyond LHC

10 kHz/cm^2 - > MHz/cm^2

Gaseous MPGD Tracking @ Nuclear Physics and EiC

Experiment/ Timescale	Application Domain	MPGD Technology	Total detector size / Single module size	Operation Characteristics/ Performance	Special Requirements/ Remarks
CLAS12 @ JLAB Start: > 2017	Nuclear Physics/ Nucleon structure (tracking)	Planar (forward) & Cylindrical (barrel) Micromegas	Total area: Forward ~ 0.6 m^2 Barrel ~ 3.7 m^2 2 cylindrical layers R ~ 20 cm	**Max. rate:** ~ 30 MHz **Spatial res.:** < 200μm **Time res.:** ~ 20 ns	- Low material budget : 0.4 % X0 - Remote electronics
SBS in Hall A @ JLAB Start: > 2017	Nuclear Physics (Tracking) nucleon form factors / struct.	GEM	Total area: 14 m^2 Single unit detect. 0.6x0.5m^2	**Max. rate:**400 kHz/cm^2 **Spatial res.:** ~70μm **Time res.:** ~ 15 ns **Rad. Hard.:** 0.1-1 kGy/y.	
pRad in Hall B @ JLAB Start: 2017	Nuclear Physics (Tracking) precision meas. of proton radius	GEM	Total area: 1.5m^2 Single unit detect. 1.2x0.6 m2	**Max. rate:**5 kHz/cm^2 **Spatial res.:** ~70μm **Time res.:** ~ 15 ns **Rad. Hard.:** 10 kGy/y.	
SoLID in Hall A@ JLAB Start: ~ > 2020	Nuclear Physics (Tracking)	GEM	Total area: 40m^2 Single unit detect. 1.2x0.6 m2	**Max. rate:**600 kHz/cm^2 **Spatial res.:** ~100μm **Time res.:** ~ 15 ns **Rad. Hard.:** 0.8-1 kGy/y.	
E42 and E45 @ JPARC Start: >2020	Hadron Physics (Tracking)	TPC w/ GEM, gating grid	Total area: 0.26m^2 0.52m(diameter) x0.5m(drift length)	**Max. rate:**10^6 kHz/cm^2 **Spatial res.:** 0.2-0.4 mm	Gating grid operation ~ 1kHz
Electron-Ion Collider (EIC) Start: > 2030	Hadron Physics (tracking, RICH)	TPC w/GEM; GEM, MM, Gridpix, μ-PWELL planar & cylindrical detectors	Total area: ~ 3 m^2 Total area: ~ 25 m^2	**Spatial res.:** ~ 100 um (rϕ) Luminosity (e-p): 10^{33} **Spatial res.:** ~ 50- 100 um **Max. rate:** ~ MHz/cm^2	Low material budget Low material budget

Muon Systems at Future Colliders (FCC, LHeC, Muon)

Experiment / Timescale	Application Domain	Gas Detector Technology	Total detector size / Single module size	Operation Characteristics / Performance	Special Requirements / Remarks
LHeC COLLIDER MUON SYSTEM at HL-LHC	Electron – Proton Collider Tracking/Triggering	RPC / MDT	Total area ~ 400 m^2 Single unit detect: 2-5 m^2	**Max.rate**: 3 kHz/cm^2 **Time res.:** ~0.4 ns **Rad. Hard.:** 0.3 C/cm^2 **Spatial res.:** 1mm (RPC) 80 μm (MDT single tube)	
FCC-ee and/or CEPC IDEA PRESHOWER DETECTOR START: >2030	Lepton Collider Tracking	μ-RWELL	Total area: 225 m^2 Single unit detect: (0.5x0.5 m^2) ~0.25 m^2	**Max. rate:** 10 kHz/cm^2 **Spatial res.:** ~60-80 μm **Time res.:** 5-7 ns **Rad. Hard.:** <100 mC/cm^2	
FCC-ee and/or CEPC IDEA MUON SYSTEM START: >2030	Lepton Collider Tracking/Triggering	μ-RWELL RPC	Total area: 3000 m^2 Single unit detect: ~0.25 m^2	**Max. rate:** <1 kHz/cm^2 **Spatial res.:** ~150 μm **Time res.:** 5-7 ns **Rad. Hard.:** <10 mC/cm^2	
FCC-hh COLLIDER MUON SYSTEM START: > 2050	Hadron Collider Tracking/Triggering	All HL-LHC technologies (MDT, RPC, MPGD, CSC)	Total area: 3000 m^2	**Max. rate:** < 500 kHz/cm^2 **Spatial res.:** <100 μm **Time res.:** ~ 3 ns **Rad. Hard.:** ~ C/cm^2	Redundant tracking and triggering;
MUON COLLIDER MUON SYSTEM START: > 2050	Muon Collider	RPC or new generation fast Timing MPGD	Total area: ~ 3500m^2 Single unit detect: 0.3-0.4m^2	**Max.rate**: <100 kHz/cm^2 **Spatial res.:** ~100μm **Time res.:** <10 ns **Rad. Hard.:** < C/cm^2	Redundant tracking and triggering

- ✓ **Muon System at ILC:** no challenges, same technology as for HCAL (RPC, MPGD)
- ✓ **Muon System at LHeC:** CDR update uses design similar to Phase 2 in ATLAS, and in particular, **Barrel Muon - second generation RPC and small Monitored Drift Tubes:** 1 layer composed of a triplet of RPC 1mm gas-gaps and ~8 layers of MDT tubes assembled in station of ~ 2 m^2

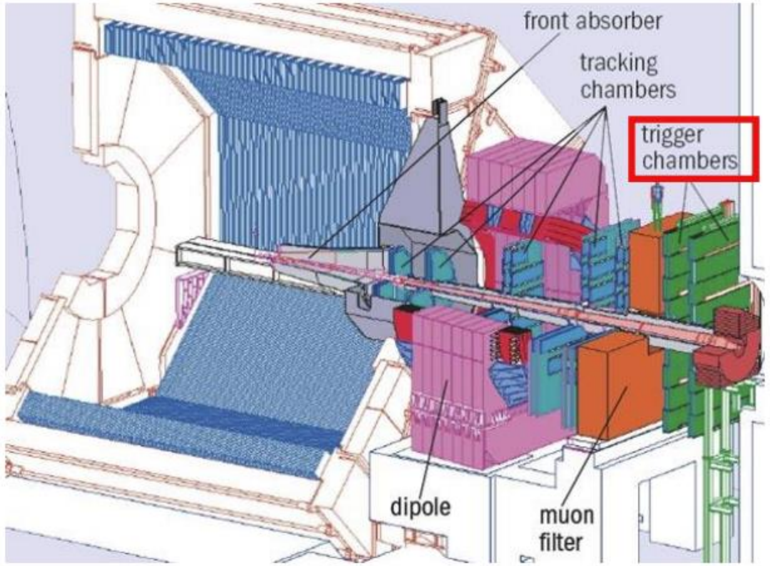
Experience for detector operation

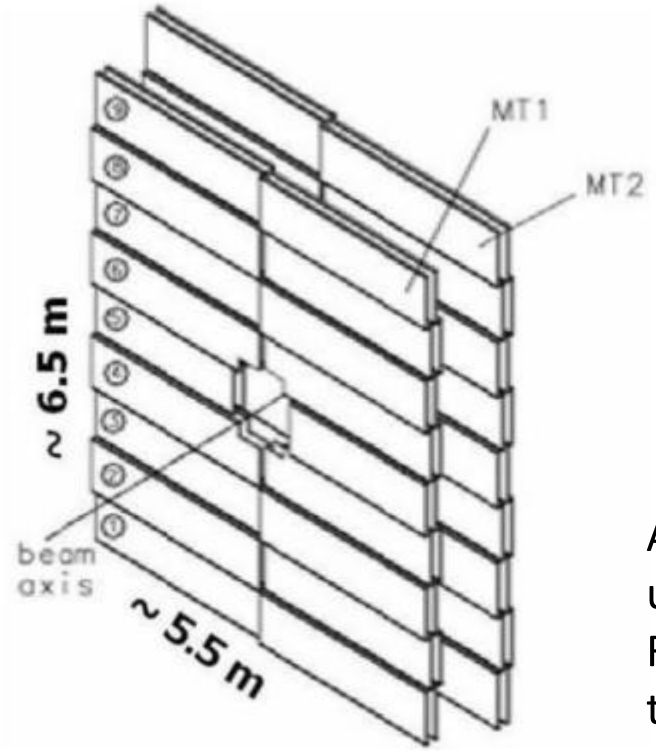
Ageing phenomena

AGING PHENOMENA
IN GASEOUS DETECTORS

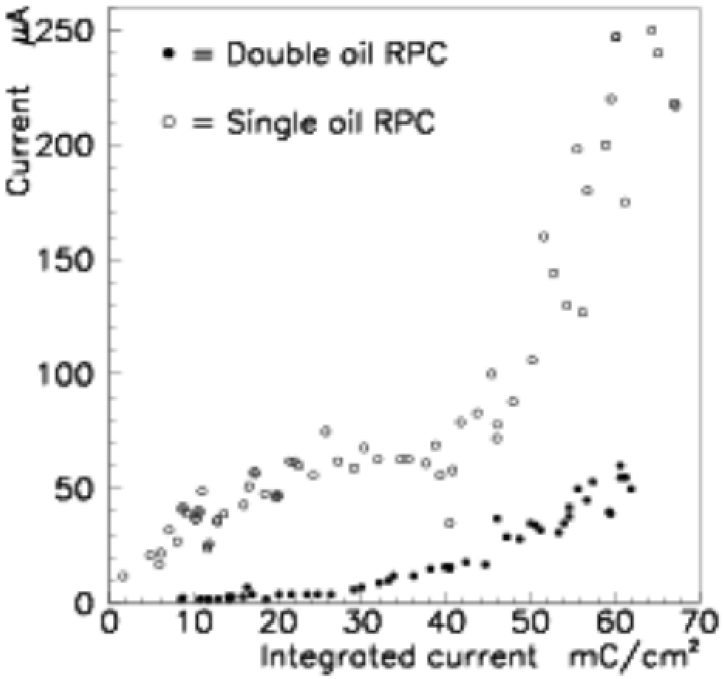
ALICE – MID

72 RPC arranged in 2 planes





Dark current – 1% SF_6



A thicker oil coating helps to keep dark current under control.

RPCs with triple oil coating were realized and tested in 2002-2003, but no sizeable difference with double coating

«Re-oiled» RPCs start with zero dark current but show rapid degradation

https://indico.cern.ch/event/1237829/contributions/5609624/

Ageing phenomena

The dark current is triggered by noise electrons emitted from localized areas of the cathode at a high rate (i.e. higher than the rate capability of the detector).

@GIF

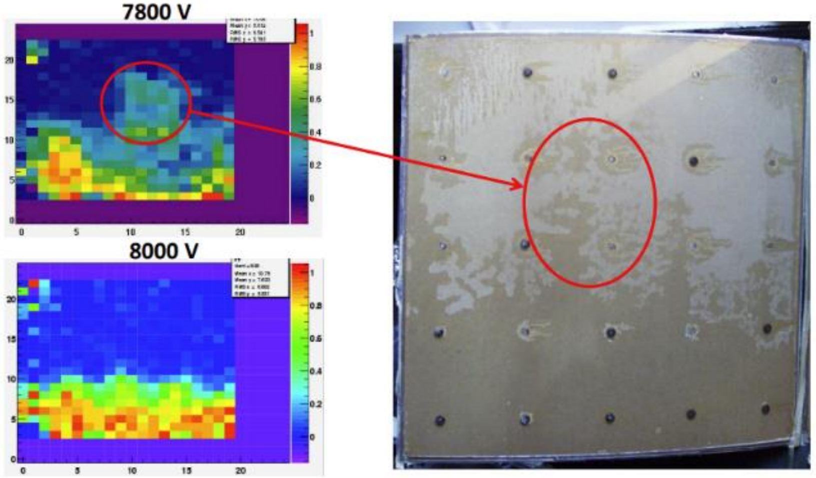
This could explain some observed facts, such as:

- The dark current increases above the electric field threshold where electron multiplication starts.
- Increasing the voltage ends up in dark current increase
- The chamber becomes inefficient in the zones interested by the phenomenon.
- The current causes a reduction of the effective voltage applied to the gas gap

Why are the noisy electron emitted? Two candidates:

- Malter effect, due to a polymerized insulator film.
- Roughness of the surface, due to loss of linseed oil coating

To answer to the dilemma, we finally open the chamber…

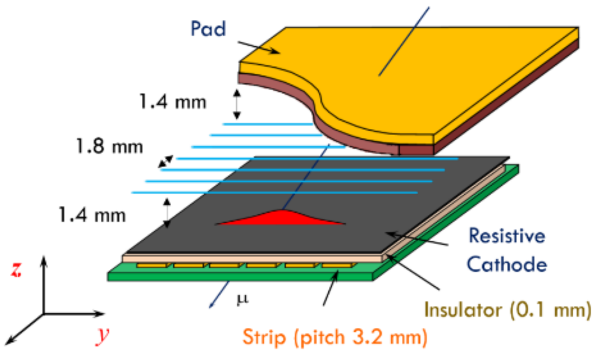


In the inefficient zone the linseed oil coating disappeared! Chemical corrosion?

Also with Ar/CO2 → HF is not the only ageing cause

Ageing phenomena

AGING PHENOMENA
IN GASEOUS DETECTORS



ATLAS - TGC

Gas gap as small as possible to avoid low energy particles stopping in the gas (Bragg peak)
Have a high field close to the wire, to avoid sensitivity to the gap spacing.
Resistive uniform cathode to avoid sparks due to non-uniformities.
Gas with high ionization for many ionization clusters for MIP's CO_2 (55%) n-C_5H_{12} (45%)

Detector validation:
10 small chambers (10X10cm²) were irradiated
A small chamber has accumulated 6 Coulomb/cm (20 HL-LHC years),no aging

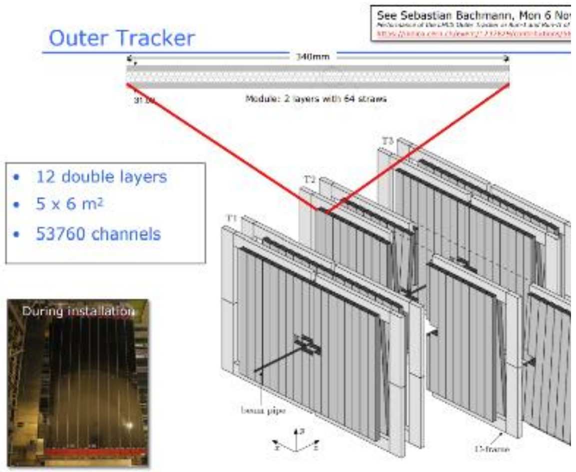
The deposits on wires are very small
→ n-pentane is a very strong cleaning agent, but the problem is that this cleaning effect will also affect cathode graphite repairs that were not properly done, in the long-term.

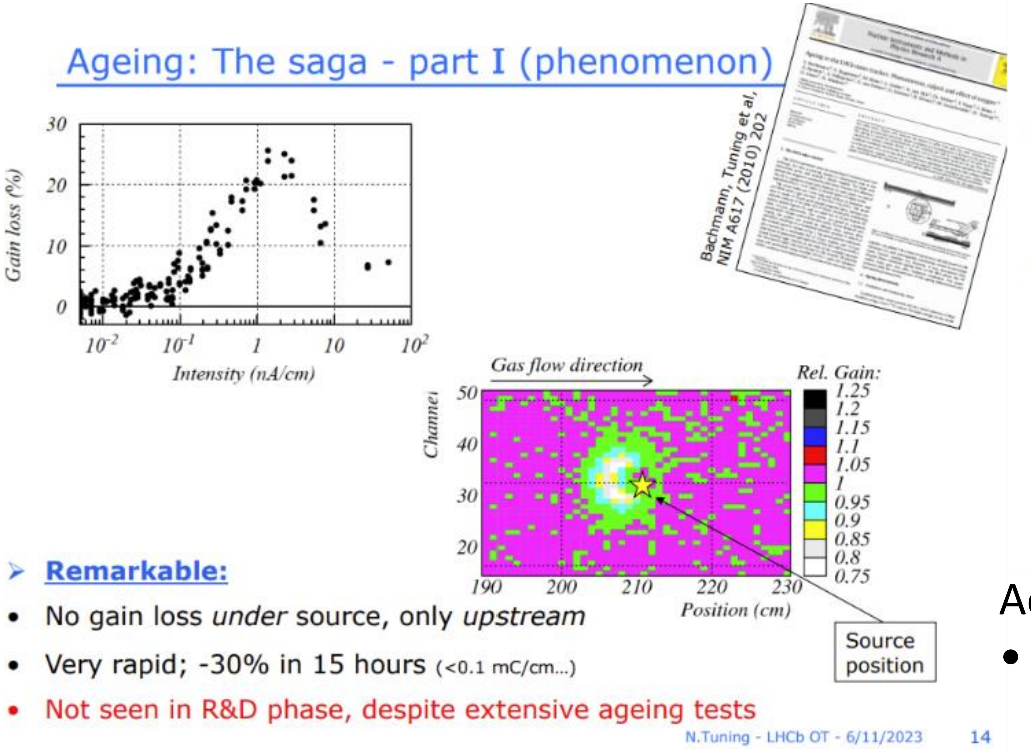
Small decrease in the MIP charge was accompanied by HV tripping chambers.
Problem was traced to a different n-C_5H_{12} supplier that was using different stainless-steel containers →
The n-C_5H_{12} is a very good cleaning agent, but it also cleans the rests of the welding materials.

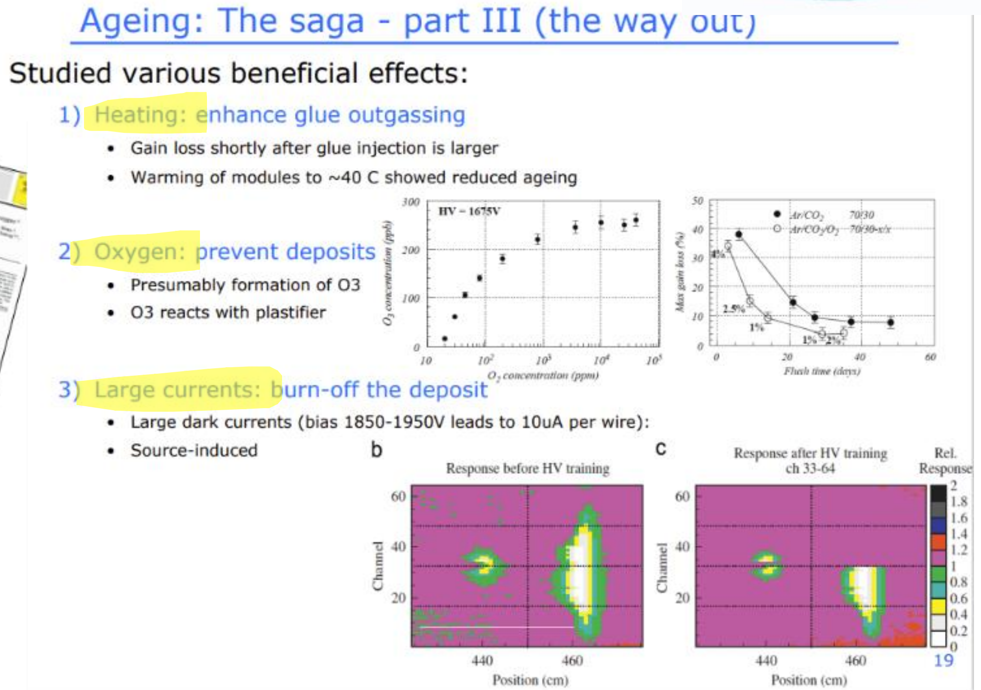
https://indico.cern.ch/event/1237829/contributions/5609567/

Ageing phenomena

Radiation Tolerance of the LHCb Outer Tracker (Straw tube)

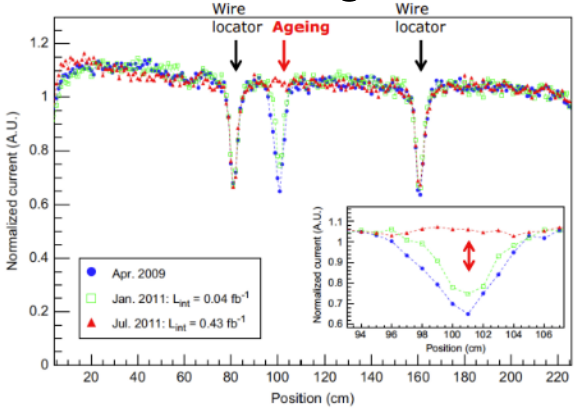






Accumulated up to 0.4 C/cm in hottest region

- The LHC even had curing effect:



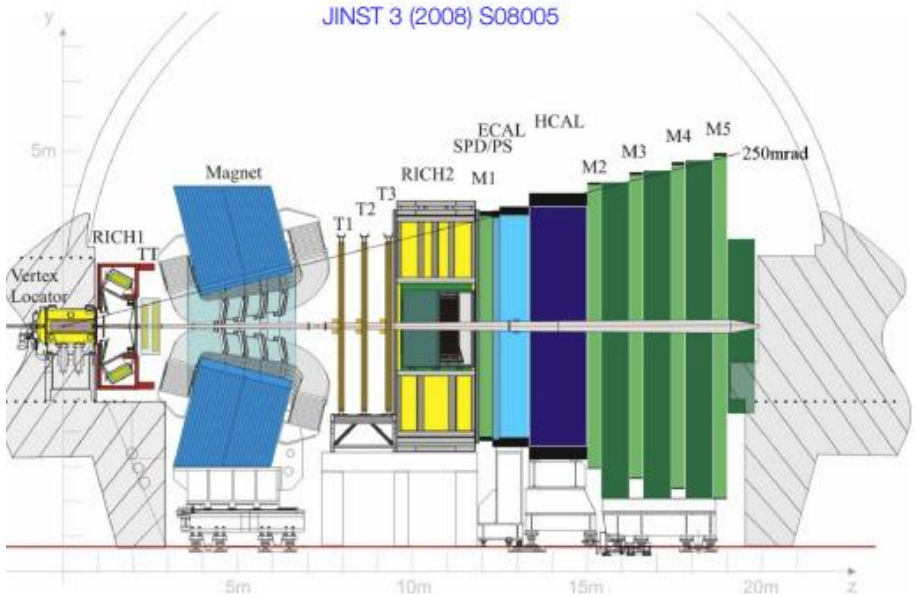
→ Cause:

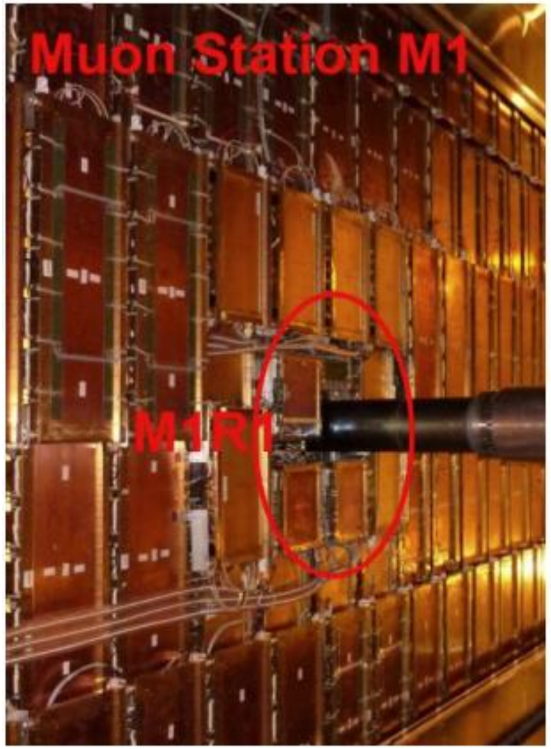
- Manufacturer changed plastifier: AY103 → AY103-1
- Culprit: di-isopropyl-naphthalene

https://indico.cern.ch/event/1237829/contributions/5609614/

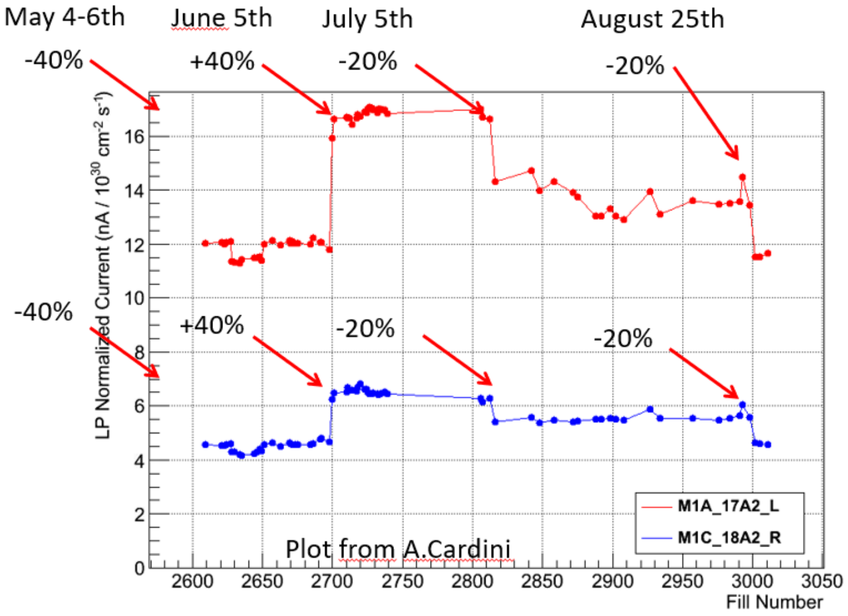
Ageing phenomena

LHCb - GEM





Run1
Gas gain fluctuations



M1 central region (M1R1):
0.6 m^2, 12 chambers (2 gaps of triple-GEM each) of 20x24 cm2
Gas mixture: $Ar/CO_2/CF_4$ at 45/15/40 %

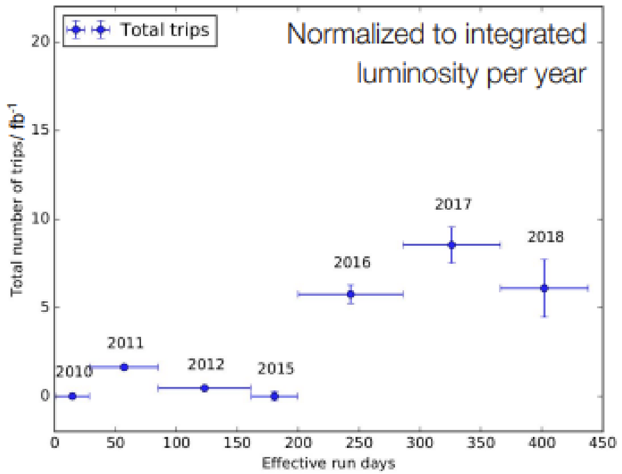
https://indico.cern.ch/event/1237829/contributions/5609606/
https://indico.cern.ch/event/1237829/contributions/5609602/

Possible causes:
-gas mixture
-gas supply
-detector properties
-enviromental conditions
-LHC luminosity
-...

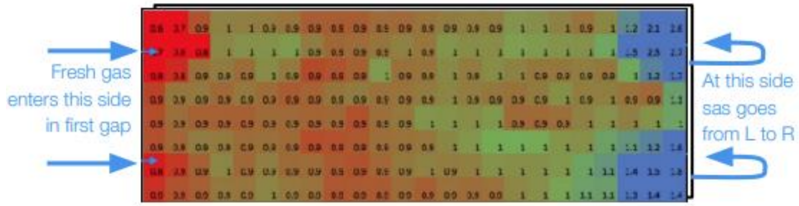
Ageing phenomena

LHCb-GEM

Run2: a lot of high currents (soft/hard shorts)

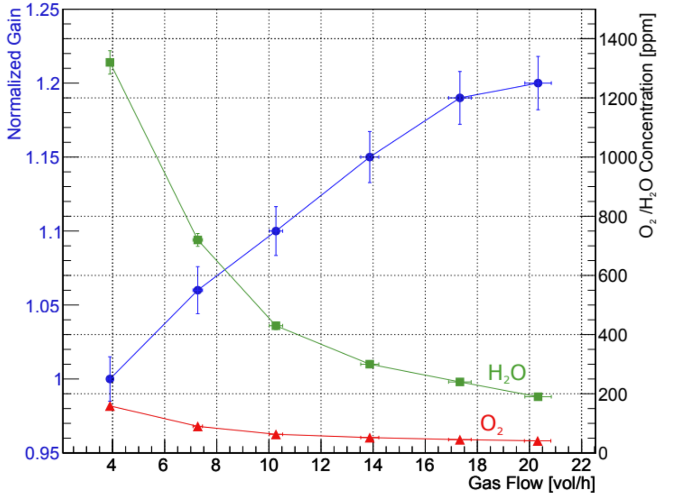


efficiency variation inside the chambers, as the ratio between rates of left and right gaps



No clear explanation so far.
Sulphur from ARALDITE 2012 hardener?

Run2: operation with gas recirculation



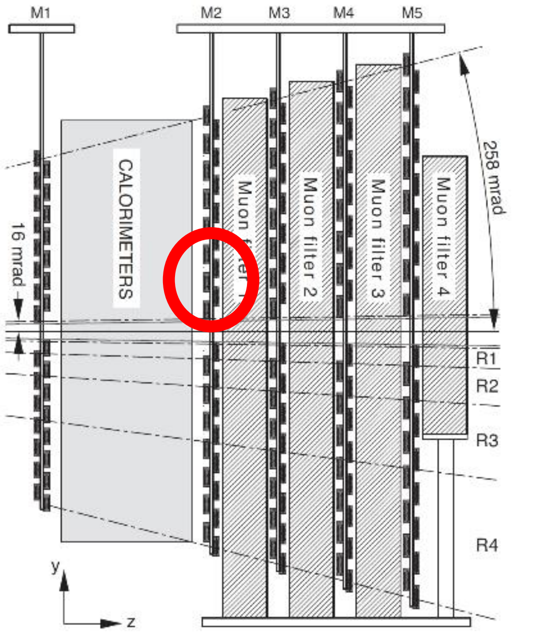
Some good effect from O2/H2O while in open mode?

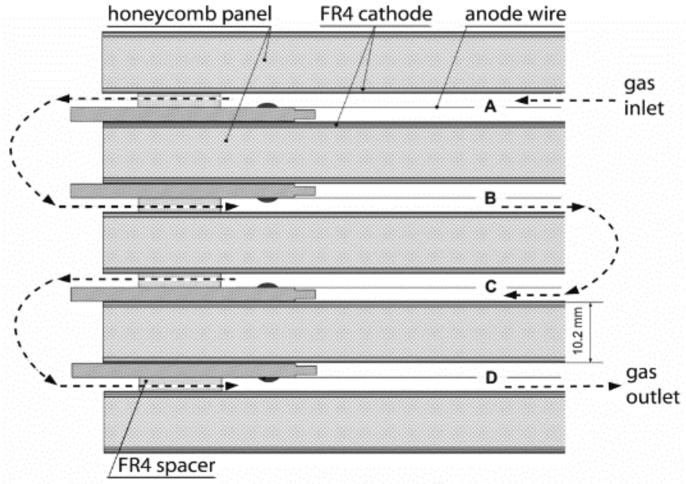
https://indico.cern.ch/event/1237829/contributions/5609781/

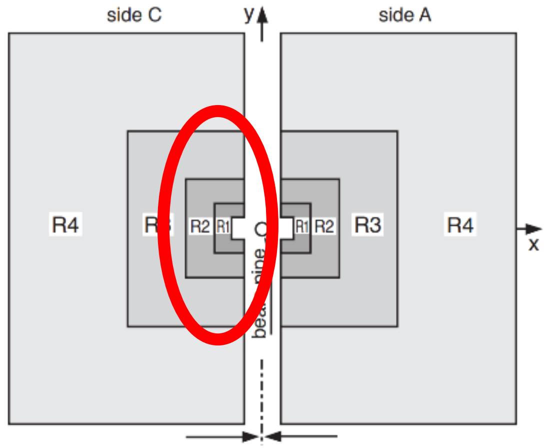
Ageing phenomena

LHCb - MWPC

- 5 stations M1-M5 (Run 1)
- reduced to 4 M2-M5 (Run 2 and Run 3);
- 4 regions R1-R4;
- 20 chamber types;
- 1368 MWPCs cover 435 m^2
- 40% Ar + 55% CO_2 + 5% CF_4 gas mixture;

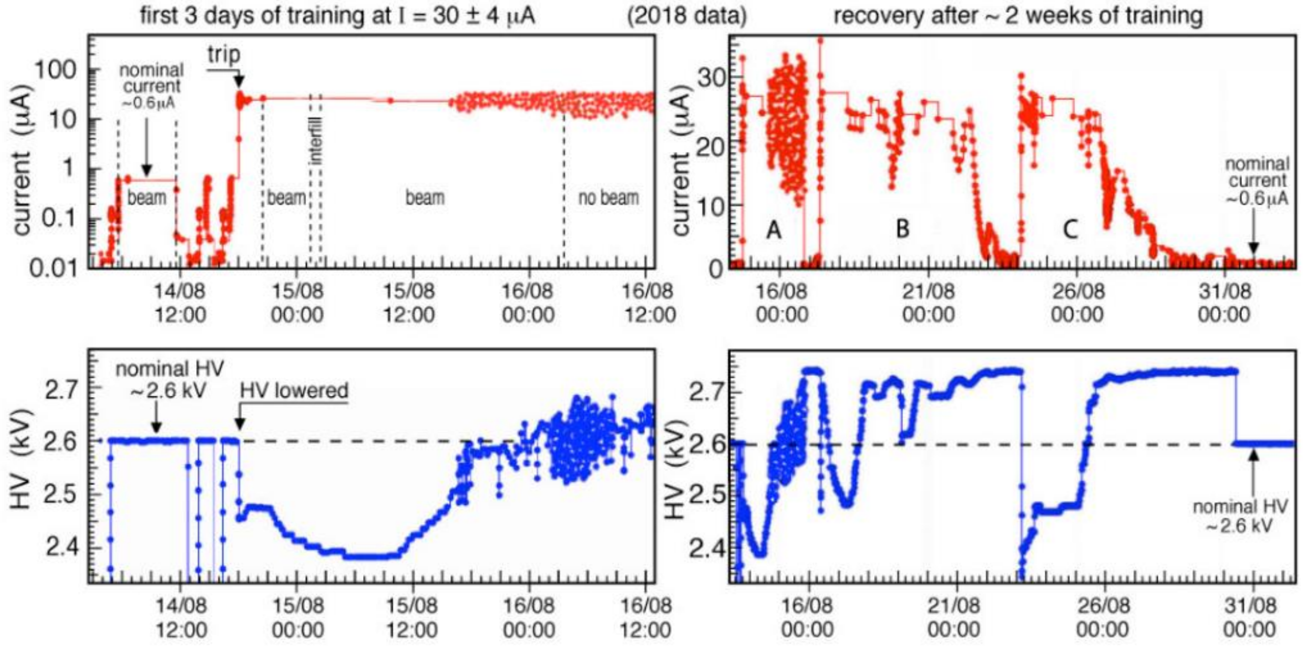




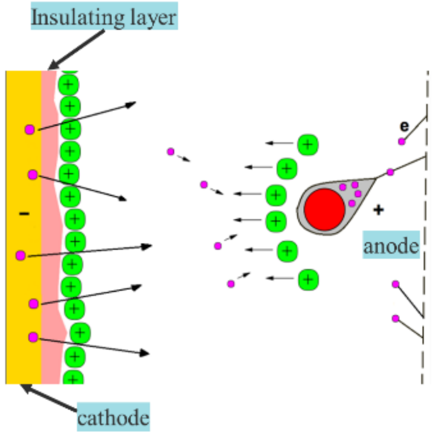


Ageing phenomena

- The effect of high self-substained currents has been detected in ~100 MWPCs gaps per each year;
- A higher current increases the concentration of fluorine radicals, produced by CF_4, which react with deposits (silicone, polymers), leading to surface etching by means of the creation of volatile products in the plasma;
- The procedure of training provides to restore the functionality of MWPC gap affected by Malter-like currents.



Manifestation of Malter Current Effect:
- self-sustained discharge ignited by high intensity irradiation and micro sparks;
- sustained uA current independent from external irradiation.



https://indico.cern.ch/event/1237829/contributions/5609611/

Ageing phenomena

Polyurethane foam is injected between two mold planes forming the cathode surface at the stage of MWPC production;
A mold release agent (ACMOIL36-4600) contains 5-10% silicone;

Curing Malter-like effects in MWPC

$$e^- + CF_4 \rightarrow CF_3^+ + F\bullet + 2e^-$$
$$e^- + CF_4 \rightarrow \bullet CF_3 + F\bullet + e^-$$
$$e^- + CF_4 \rightarrow \bullet CF_2 + 2F\bullet + e^-$$

$$4F\bullet + Si \rightarrow SiF_4\uparrow$$
$$4F\bullet + SiO_2 \rightarrow SiF_4\uparrow + O_2\uparrow$$

$$Si + \bullet CF_3 + F\bullet + 2O \rightarrow SiF_4\uparrow + CO_2\uparrow$$

The formation process is ongoing around anode wires. The concentration of free radicals is low around the cathode!
The training process requires a lot of time → days

Etching rate in a CF4/O2 mixture is significantly higher in comparison to the one in a pure CF4 plasma → hours;

$$O\bullet + \bullet CF_3 \rightarrow \bullet COF_2 + F\bullet$$
$$O\bullet + \bullet CF_2 \rightarrow \bullet COF + F\bullet$$
$$e^- + COF_2 \rightarrow \bullet COF + F\bullet + e^-$$
$$O\bullet + \bullet COF \rightarrow CO_2\uparrow + F\bullet$$

$$e^- + O_2 \rightarrow O^- + O^{\bullet\bullet}$$
$$e^- + O_2 \rightarrow {}^*O_2 + e^-$$

•COFx quickly dissociates with electrons and atoms and indirectly increases the number of fluorine radicals in the gas discharge plasma;
Both oxygen molecules O• • and *O2 are chemically aggressive and may be used for the etching processes;
[O2] optimized with Garfield

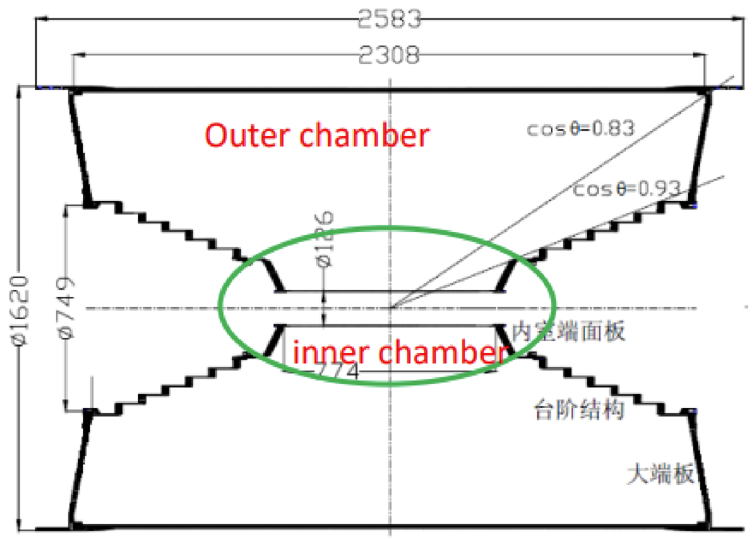
MWPC successfully in operation during data taking

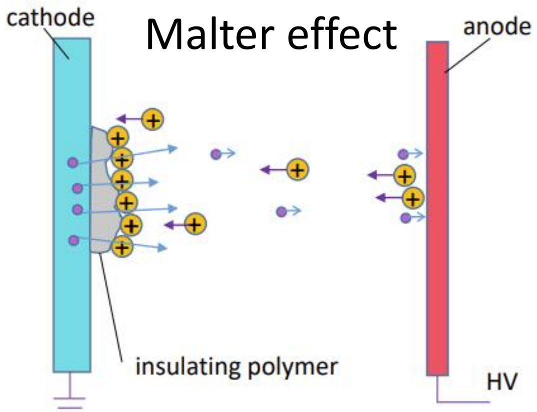
Ageing phenomena

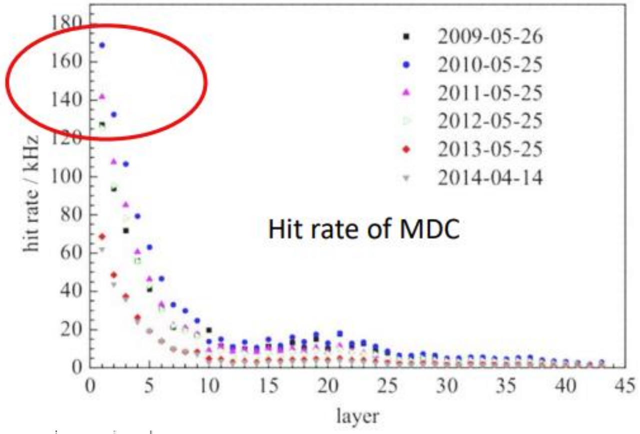
Beijing Spectrometer(BESIII): drift chamber

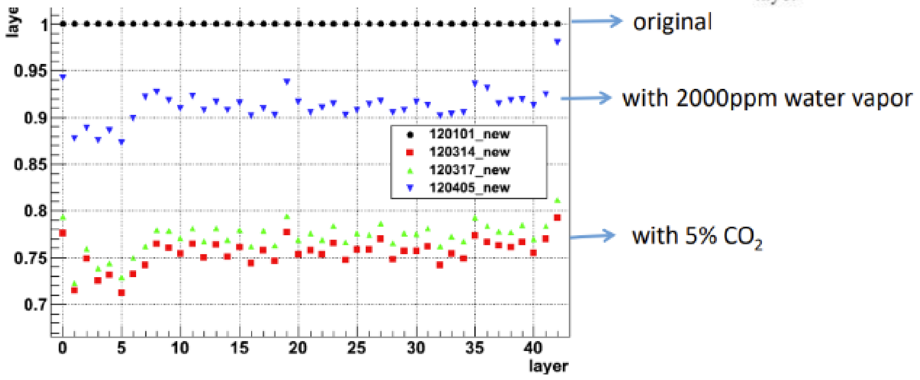
- He based gas mixture , He : C_3H_8 = 60% : 40%
- low material budget to reduce multiple scattering
- X0: 500 m, ve=3.8 cm/μs

- BESIII is a general purpose detector at Beijing electron-positron Collider (BEPCII), Ecm ≈ 2-5 GeV, Lpeak ≈ 1033/cm2/s
- Versatile researches in τ-charm physics









- The gain decreases about 23% with 5% CO_2 additive to the gas
- The gain decreases about 9% with 2000ppm water vapor additive to the gas

https://indico.cern.ch/event/1237829/contributions/5609619/

Ageing phenomena

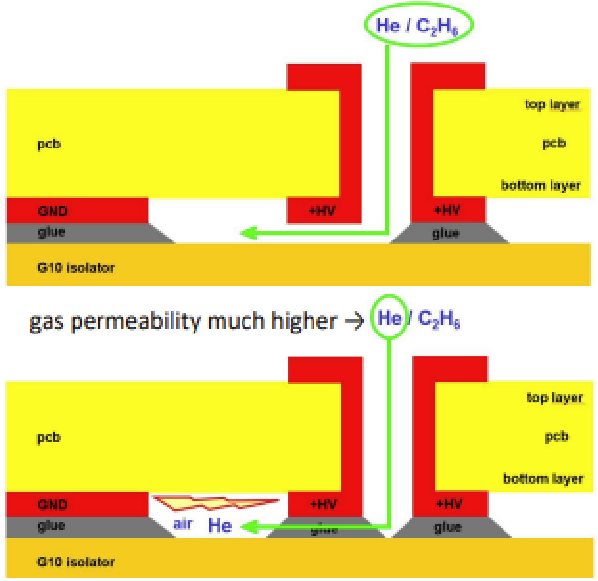
MEG experiment:
drift chamber system

- Initial HV instabilities due to "helium pocket" fixed with new design of wire pcb.

- individual timescales of performance degradation
  - within few weeks
  - within few months
  - never

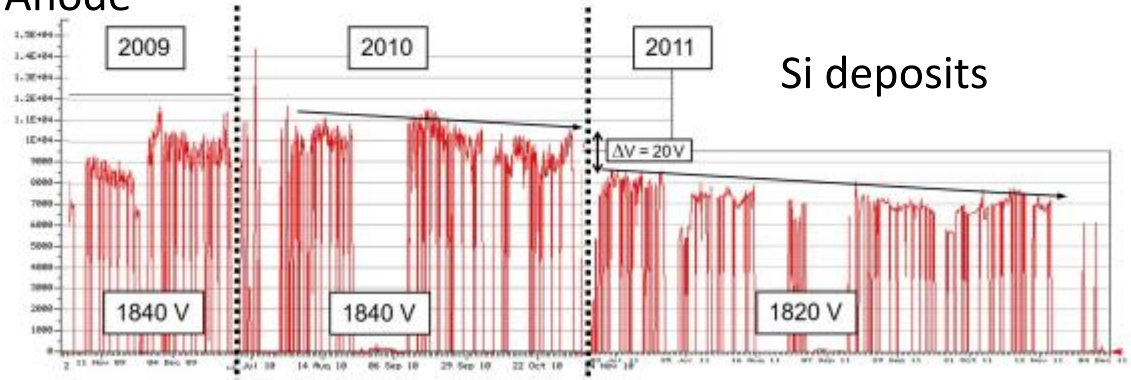
  → depending on thickness of glue that needs to be penetrated by Helium

Cathode



- Long-term operation showed 'classical' and 'textbook-like' anode wire and cathode aging

Anode



Si deposits

potential insulating thin film on cathode
- remaining photoresist
- traces of glue
- fingerprints
- avalanche-produces polymers from filling gas (C_2H_6)
- gas pollutants
- insulating deposits left from sparks

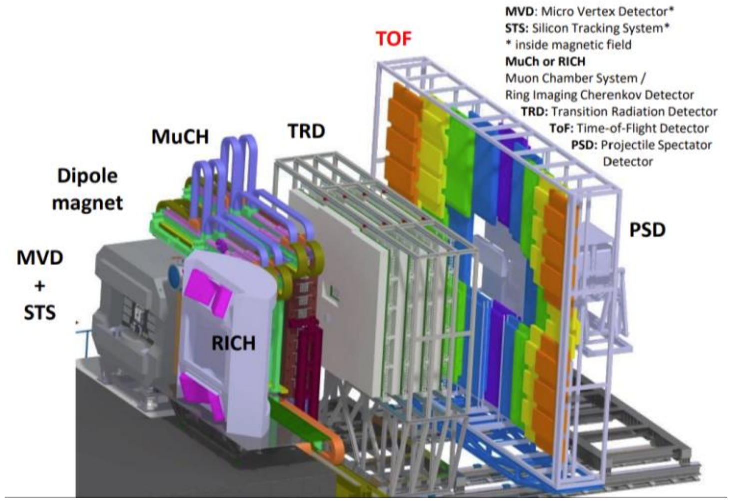
→ improved cleaning procedure by manufacturer improved operation of newly build dc modules

https://indico.cern.ch/event/1237829/contributions/5609643/

AGING PHENOMENA IN GASEOUS DETECTORS

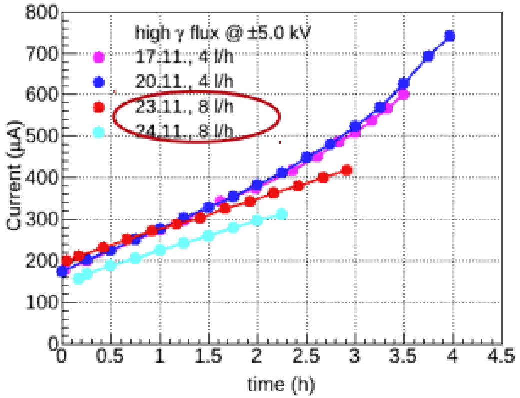
Ageing phenomena

Compressed Baryonic Matter (CBM)

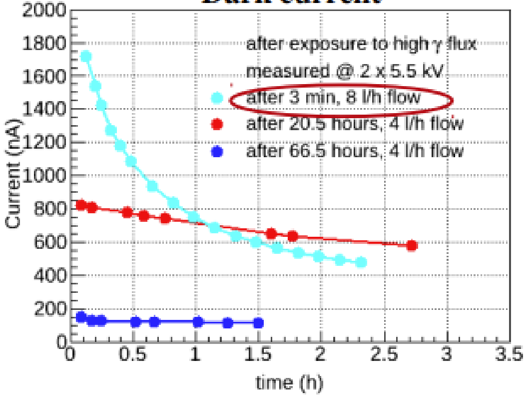


Rate capability required ~50 kHz/cm2

MSMGRPC under high γ flux

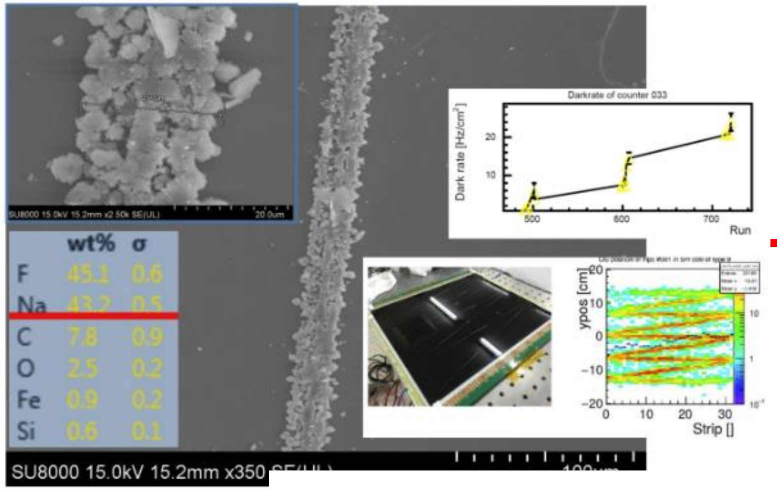


MSMGRPC short term recovery
Dark current



Gas distribution inside detectors

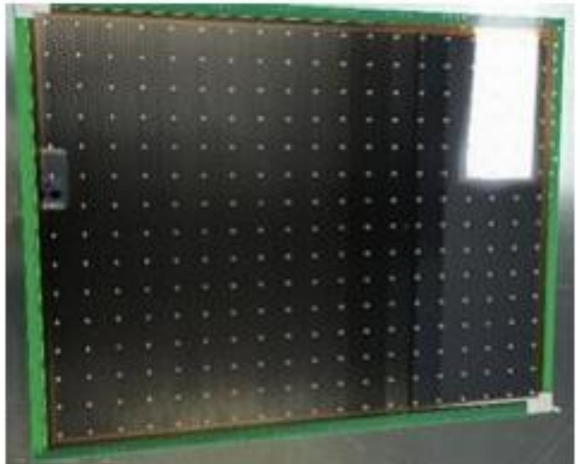
G05: fishline, side B

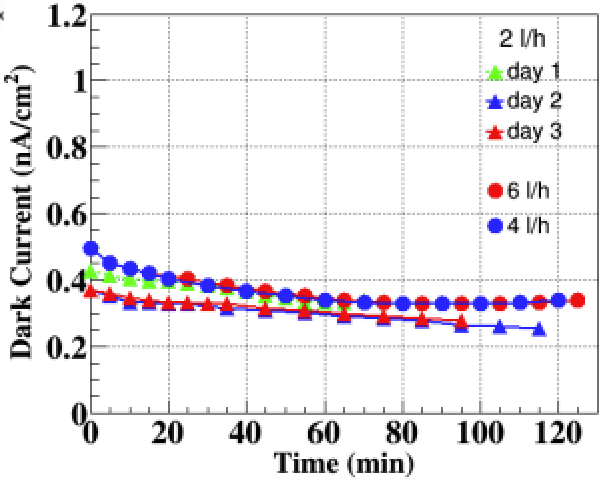


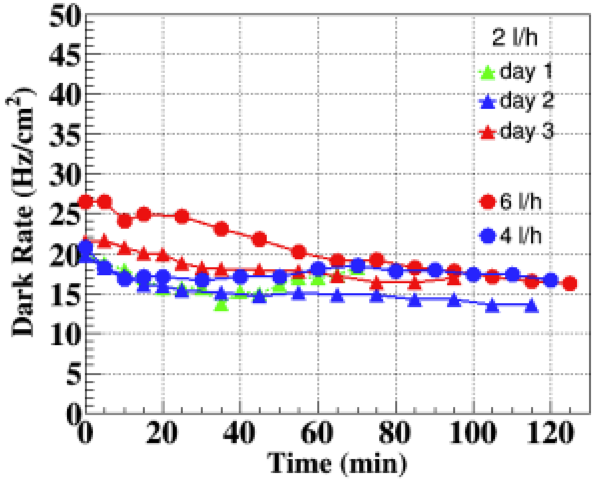
hua U)

Gas mix

“standard” spacers



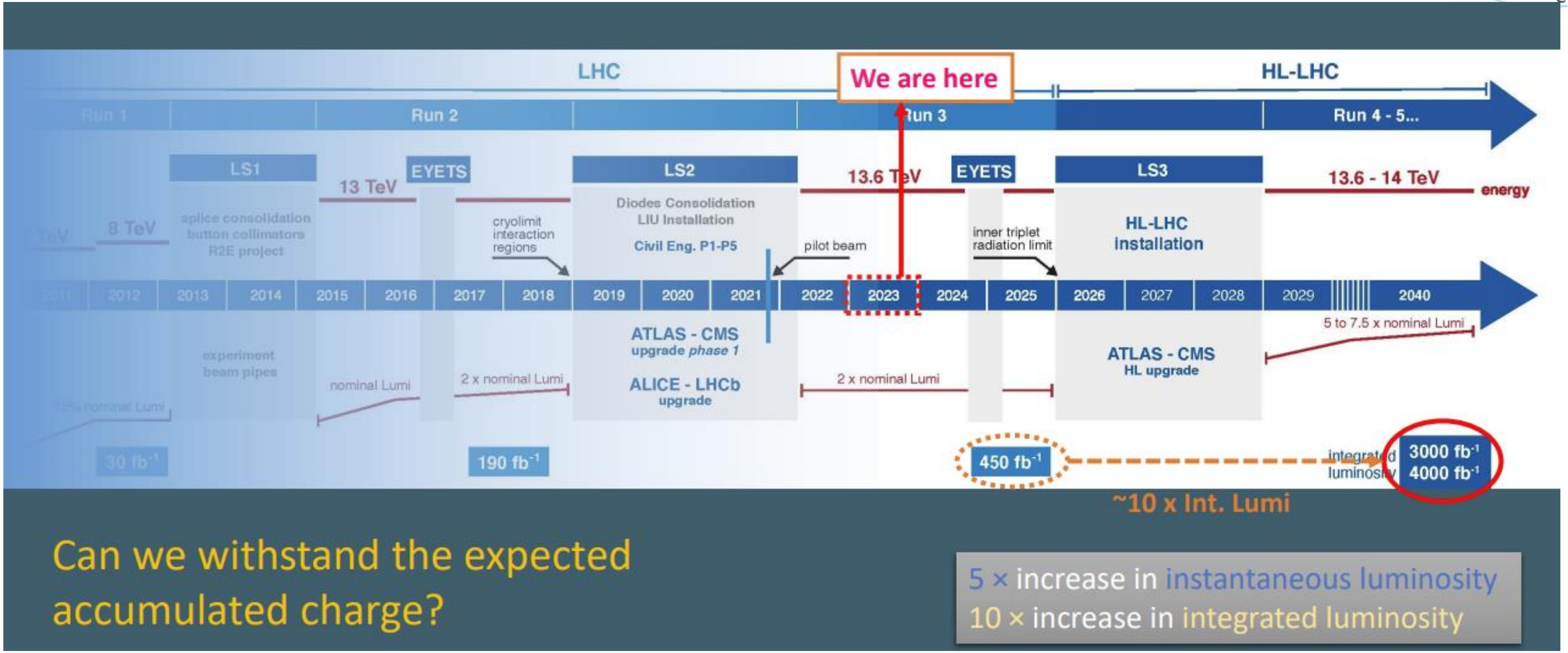




https://indico.cern.ch/event/1237829/contributions/5609600/

https://indico.cern.ch/event/1237829/contributions/5609568/

Longevity



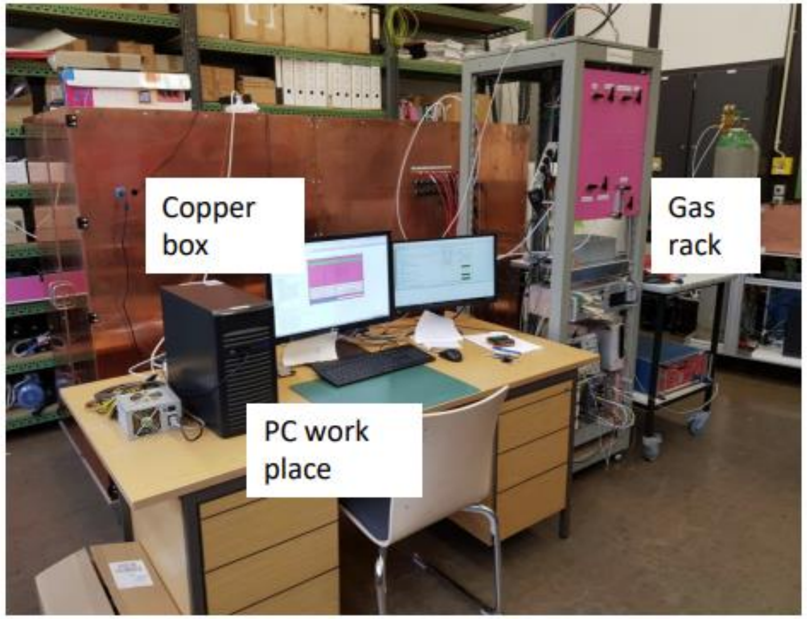
Validation of detectors to ensure good performance all along the expected data taking period: facilities with intense radiation source + beam

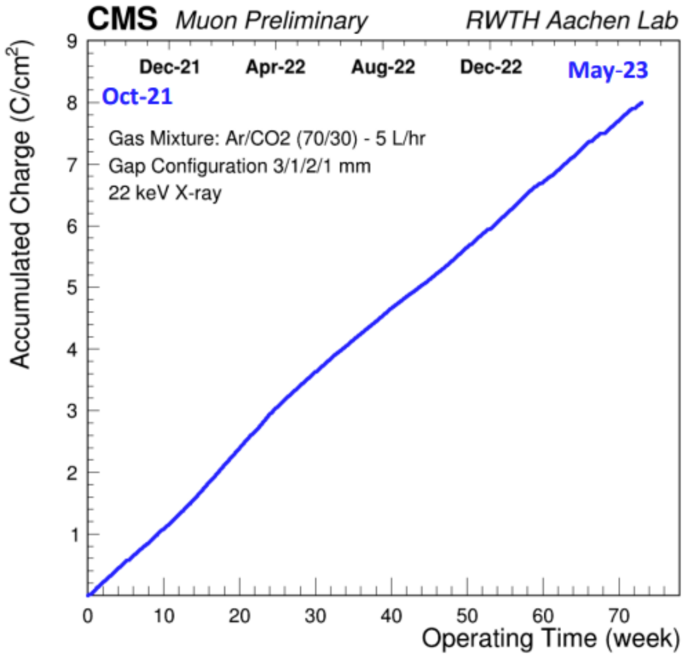
https://indico.cern.ch/event/1237829/contributions/5611095/

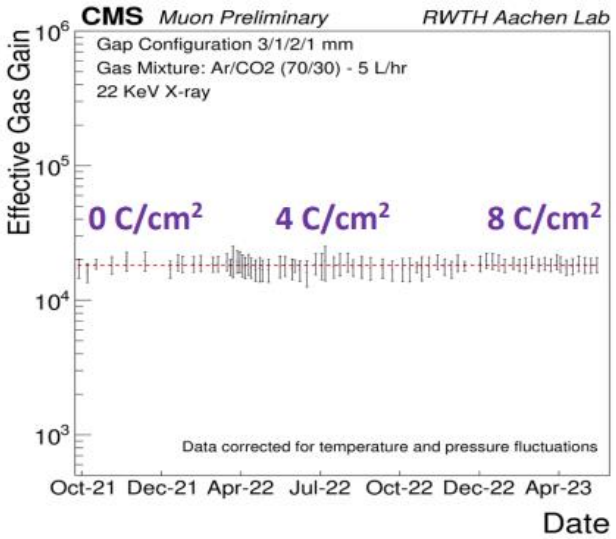
Longevity

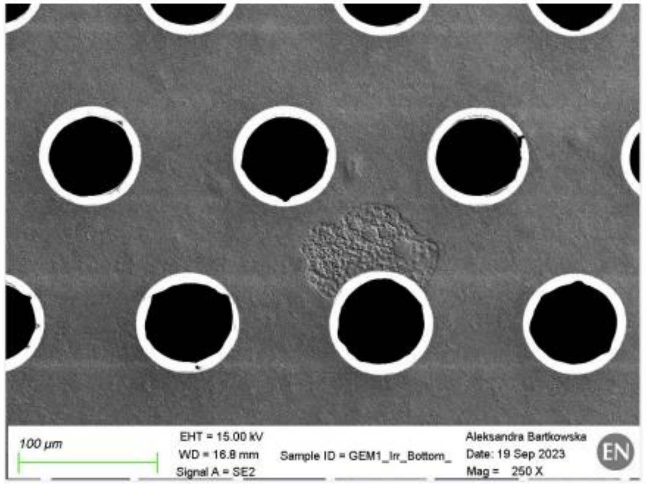
CMS – GEM for HL-LHC

Aging test Target value 8 C/cm2 → about 1.5 years of continuous irradiation
150 kHz/cm2 at the hottest point of most forward muon chambers in CMS Phase-2 geometry. From Fluka simulation.









https://indico.cern.ch/event/1237829/contributions/5611094/

✓ all fine

Longevity

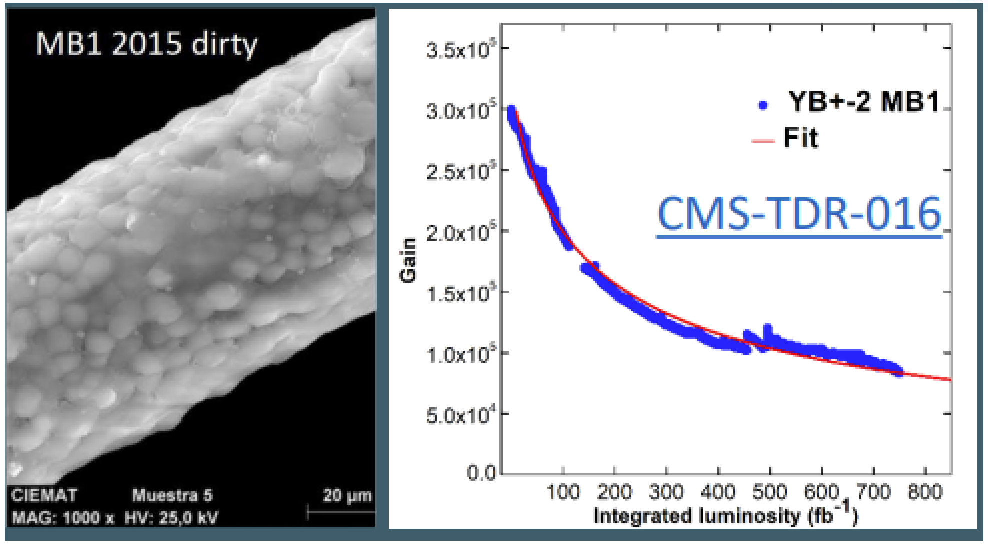
CMS-DT

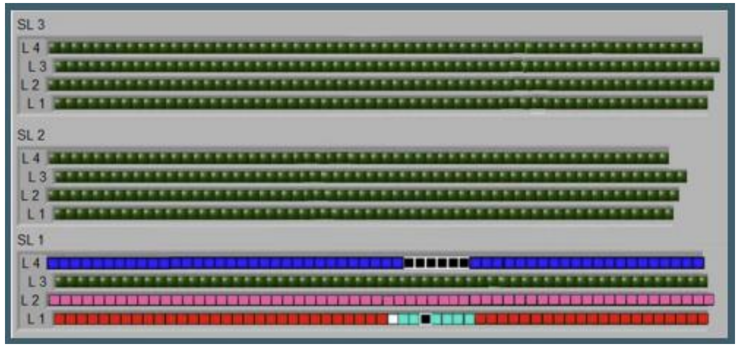
@GIF++

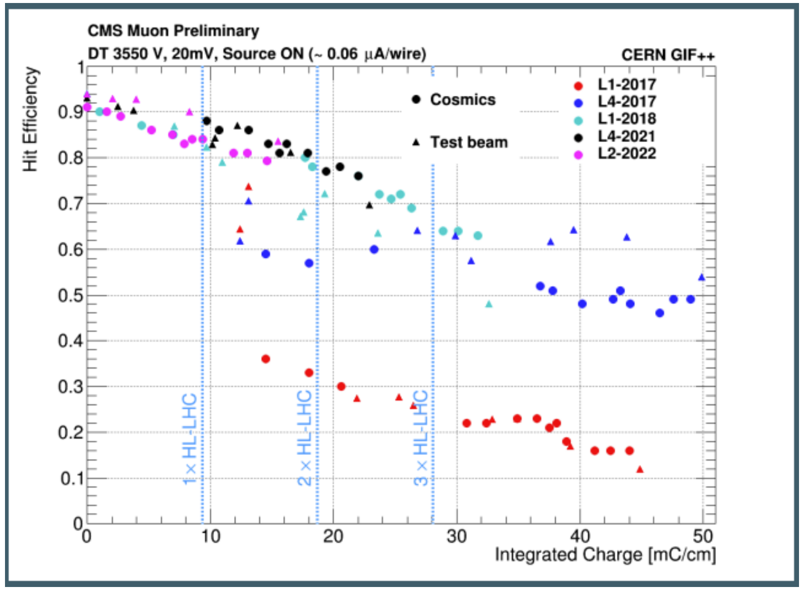
Irradiation of a spare (MB1) chamber at high rate (× 100 HL-LHC):

- Results at CMS TDR: The Phase-2 Upgrade Muon Detectors
- First hints that exposure to radiation change the detector performance
- Fast gain drop observed. Presence of Si an C coating with high resistivity

- Superlayer SL1 used for irradiation studies, while
    - Layers L1 & L4 in SL1 were always irradiated while HV was on
    - L2 in the same SL1 was included at the end (2022)
    - L3 in SL1 was kept off to be used as a reference
- SL2 & SL3 were used for internal trigger with HV in standby (1900 V) to be used as reference







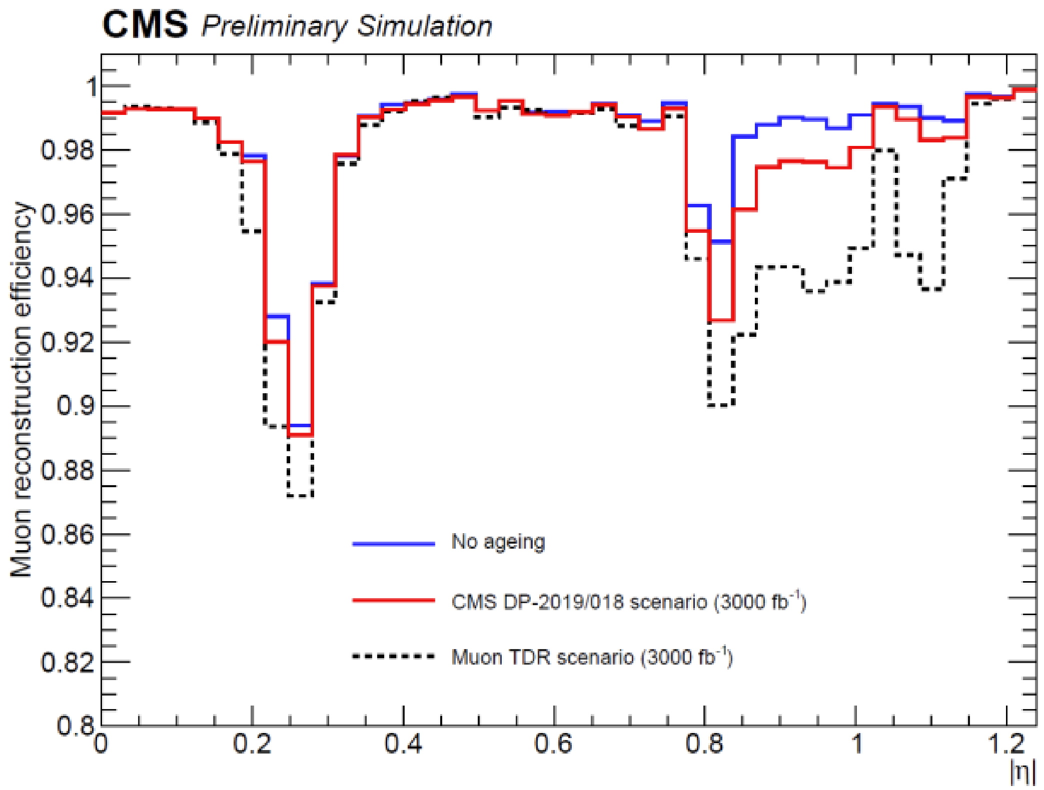
https://indico.cern.ch/event/1237829/contributions/5611095/

Longevity

CMS-DT physics performance

- The standalone muon reconstruction efficiency shows a minor impact on most of the region covered by the DTs

- The most aged DT region is also covered by 3 CSC stations and 4-5 RPC layers along a prompt muon trajectory



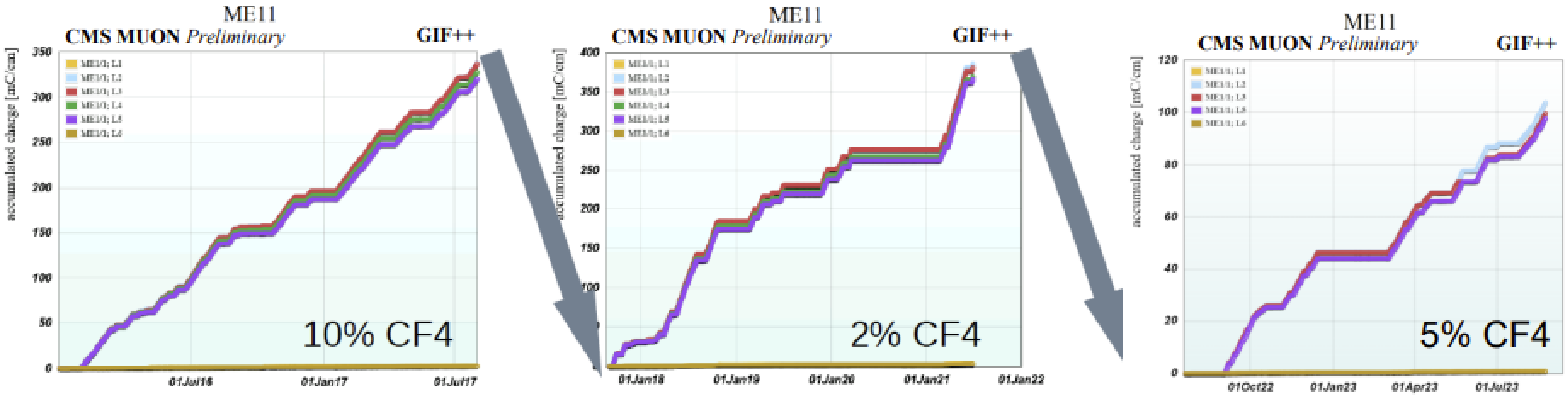
Mitigation strategies:

- Shielding (3 cm layer of Borated Polyethylene + 1 cm layer of lead for gamma absorption)
- Operational parameters (HV and threshold optimization)
- Open mode gas system to exclude accumulation of impurities
- New readout is foreseen (already under test in a couple of
- sectors at P5).
- New L1 trigger algorithms under study and development
- should mitigate the aging effects

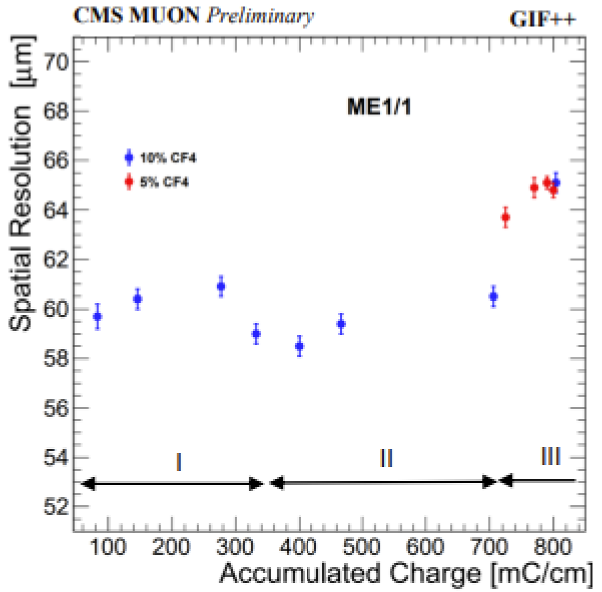
Longevity

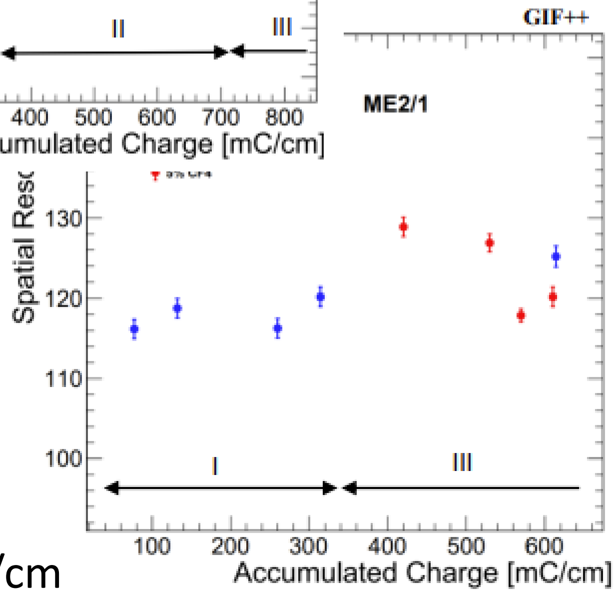
CMS-CSC @GIF++

Mainly to optimize [CF4] → decreasing as much as possible from 10% to ???



CSC	HL-LHC Expected * (3000 fb-1)	Accumulated charge Q (mC/cm)					
		before 2018	Nov.-2021	Oct.-2022	May-2023	19.07.23	25.08.23
ME1/1	200 mC/cm	330 (10% CF4)	700 (2% CF4)	725 (5% CF4)	770	790	800
ME2/1, S1	130 mC/cm	340 (10% CF4)		460 (5% CF4)	575	625	670
ME2/1, S2, S3		300 (10% CF4)		400 (5% CF4)	510	550	600
<ME2/1>		310 (10% CF4)		420 (5% CF4)	530	570	610





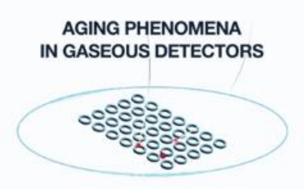
no significant degradation of the spatial resolution was observed for ME2/1 and ME1/1 < 700 mC/cm

Slight degradation of the ME1/1 resolution over 700 mC/cm is to be understood

https://indico.cern.ch/event/1237829/contributions/5611093/

Mixture monitoring and material validation

Monitoring the gas mixture



CMS - CSC

Data/software tools

• Systematic procedure to study in-situ aging

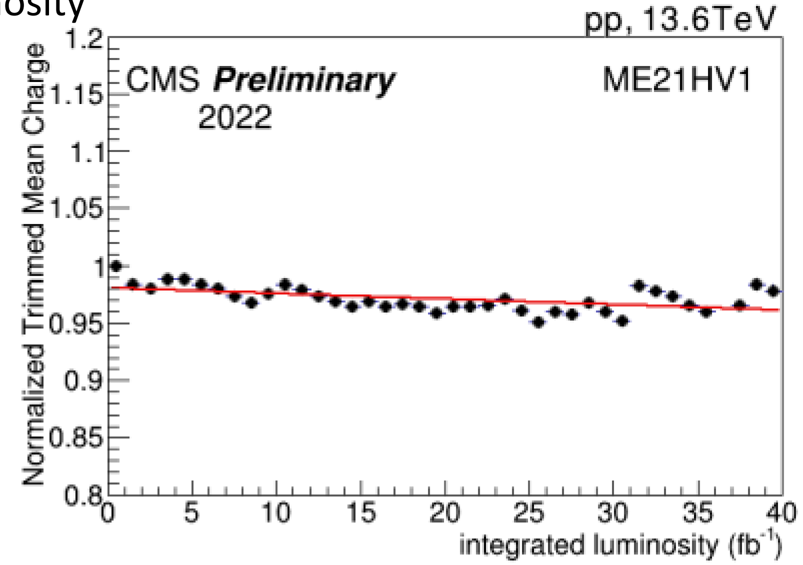
1) Z->μμ events and use the CSC hit charge as a proxy of gas gain

2) Atmospheric corrections

3) Normalisation to the lowest irradiation channels

• Results show no relevant degradation of CSC performance, if extrapolated to the integrated luminosity expected by the end of Run3 (300 fb-1)

• Analysis of the full Run 2 + Run 3 will give 10 times larger integrated luminosity



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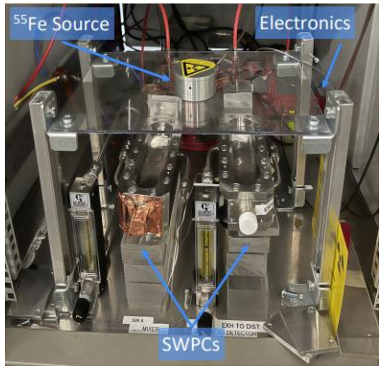
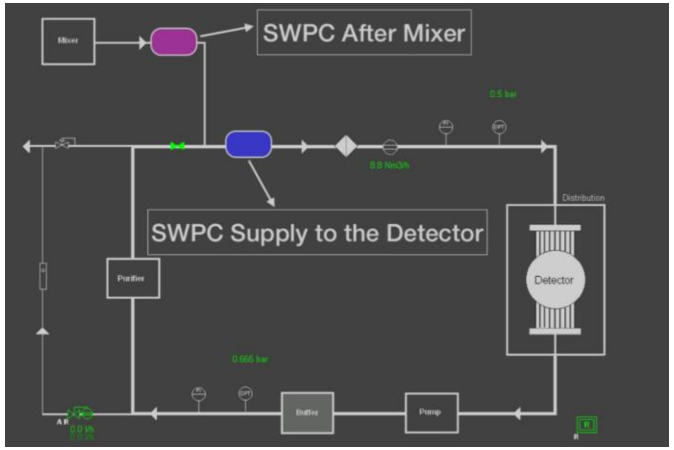
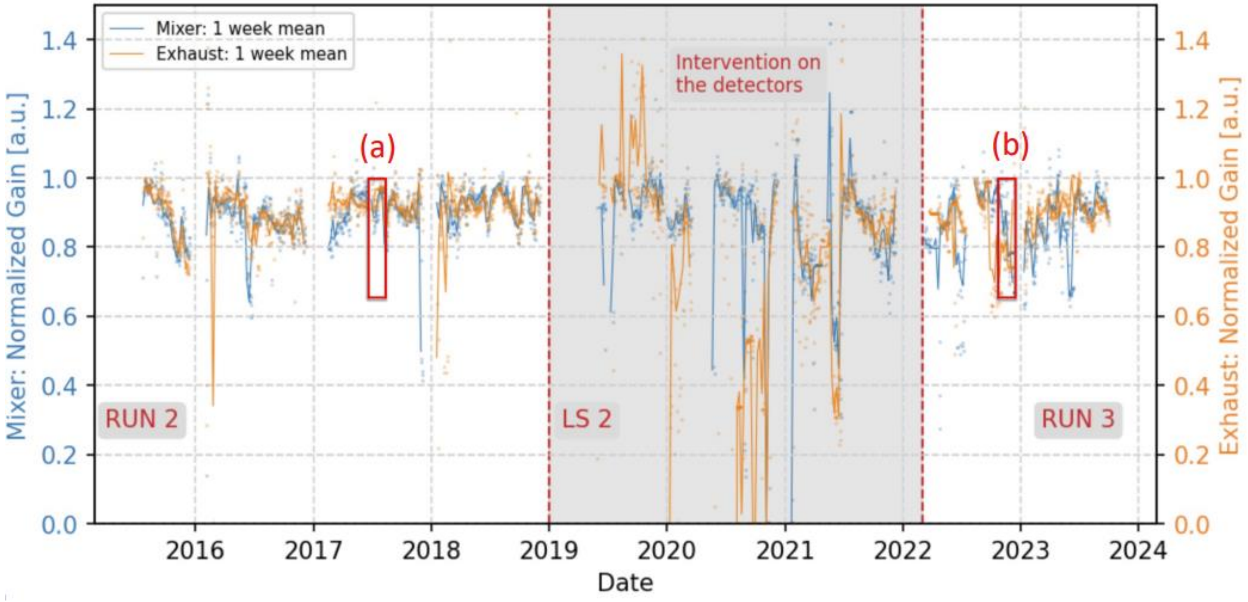
Dedicated two single wire chambers







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Chemical analysis

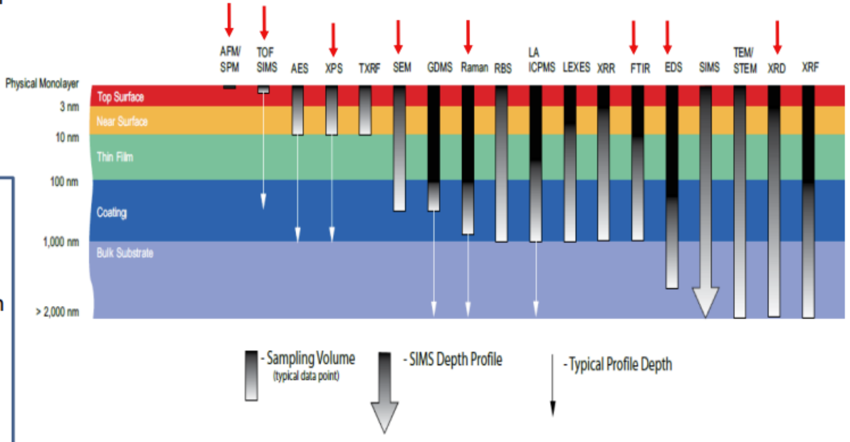
Chemical analysis of materials

Physical and chemical techniques in electrode aging studies

- We present a set of complementary analytical techniques which give a detailed characterization of deposits accumulated on MWPC electrodes
- **Multi-layered nature** of deposit demands combination of analytical techniques with **different penetration depths:**

- Atomic Force Microscopy **(AFM)**: No penetration
- Time of Flight Secondary Ion Spectroscopy **(ToF-SIMS)**: 1-2 nm, depth profiling up to several hundred nm
- X-ray Photoelectron spectroscopy **(XPS)**: ~ 5 nm, depth profiling up to 1 µm
- Scanning Electron Microscopy **(SEM/EDXS)**: < 2 µm
- Fourier Transform Infrared **(FTIR)** and Raman Spectroscopy: < 2-3 µm
- X-ray Diffraction **(XRD)**: < 15 µm

Typical analyses depths of characterization techniques



Cathode investigation techniques	**OM, AFM, SEM, EDS, FTIR, Raman, XRD, XPS, ToF-SIMS**
Anode wire investigation techniques	**OM, SEM, EDS, Raman, XPS, ToF-SIMS (limitations: round shape, small diameter)**

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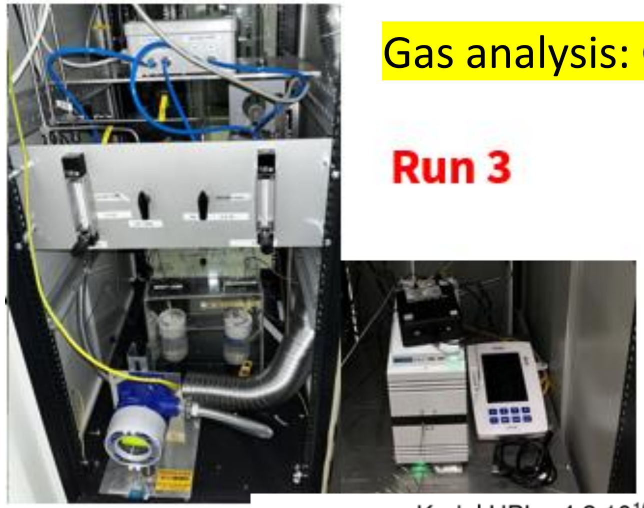
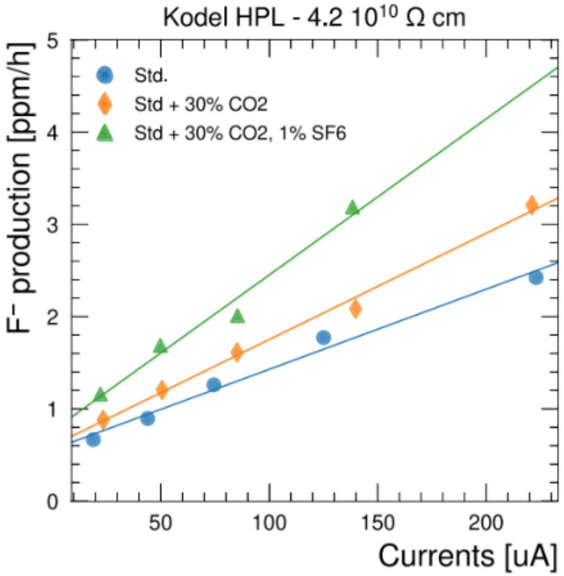
Gas analysis: GC and more



Run 3



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Validation of detector components: outgassing setups

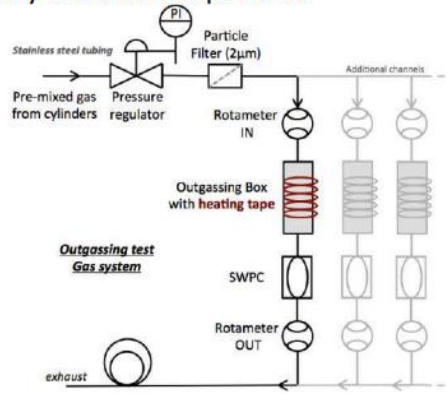
AGING PHENOMENA IN GASEOUS DETECTORS

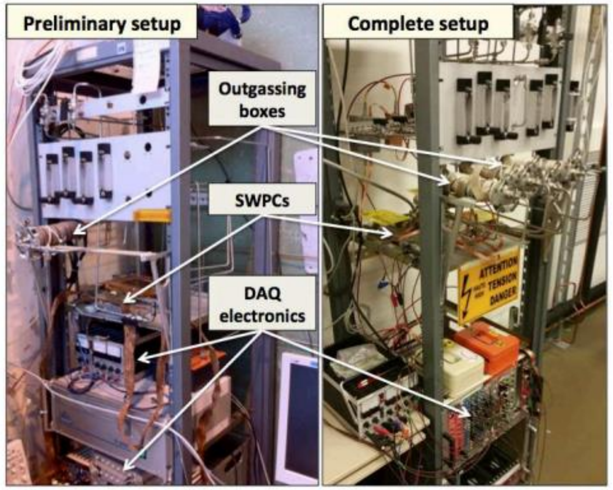
HL-LHC CMS

Test Setup Overview

Final setup configuration:

- 4 parallel test lines
- Each line is composed of an outgassing box with heating tape and a SWPC
- Individual control of gas flow and gas temperature
- Additional gas line to inject sample gas to a Gas Chromatograph
- Only metallic components

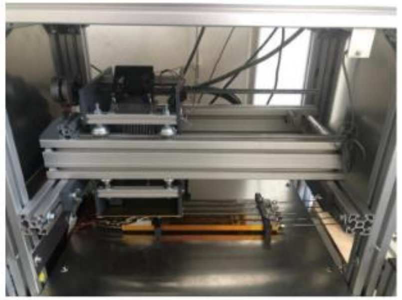


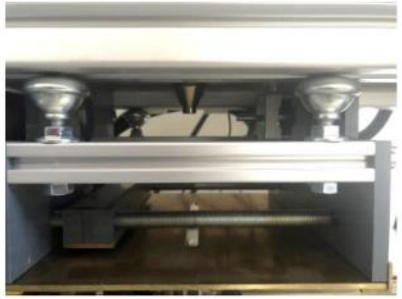


- Each SWPC is irradiated with a ^{55}Fe source @ 1 kHz
- Gas flow is set if 5 L/hr ($Ar/CO_2/CF_4$ – 45/15/40%)

Note: additional 10x10 triple-GEM detector was used for the most suspicious material for additional confirmation (downstream the SWPC)

TRT automated ageing setup (3rd generation of the setup)





- Setup consists of 5 prototypes with three straw tube in each. It means we have 5 channels to test.
- Gas mixture: bottle -> pressure regulator -> flowmeter -> tested component -> straw prototype
- High Voltage CAEN, remote control via USB
- Movement system & Collimator controlled by microcontroller
- Mini-X X-ray tube
- Signal via amplification and MUX send to multichannel analyser CAEN
- Software and user interface to control the setup

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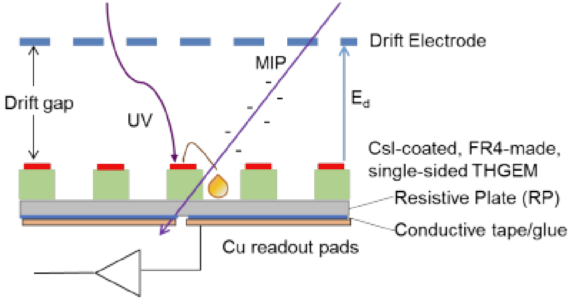
https://indico.cern.ch/event/1237829/contributions/5609630/

https://indico.cern.ch/event/1237829/contributions/5611076/

New materials and new eco-gases

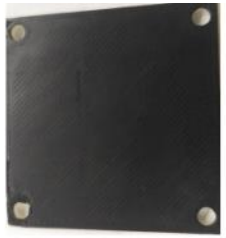
New materials

RPWELL performance
with tunable 3D printed resistive plates

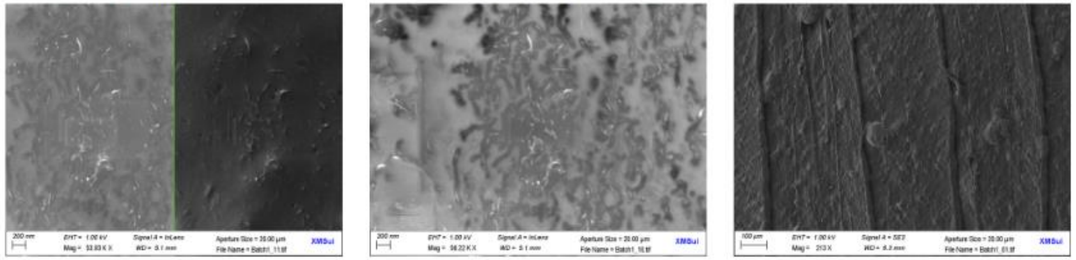


3D printed resistive plates

with tunable resistivity



- 3DXSTAT™ ESD ABS (Acrylonitrile Butadiene Styrene)
- Conductive additive: embedded multi-wall carbon nano-tubes (CNT)
- Printed with standard FDM 3D printer.
  Hot base and extruder nozzle temperature are inversely proportional to sample resistivity (min ~$10^5\ \Omega$ cm)
- Samples of different thickness and resistivity were produced by 3D & functional printing center @HUJI

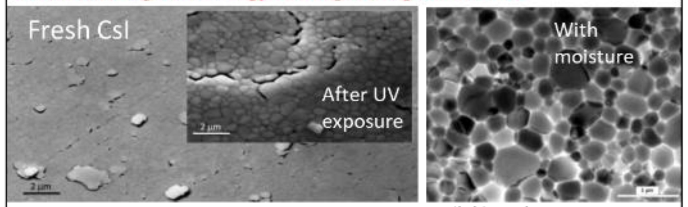


SEM images by Xiaomeng Sui @WIS. Directionality of filament deposition and of CNT distribution are clearly visible.

Photocathodes and aging causes

- Environmental Contaminations: e.g. O2, H2O, heat etc.
- Exposure of the PC to radiation due to particle flux.
- Ion back Flow (IBF) to the PC: mainly important for Gas avalanche detectors.

CsI is highly reactive with moisture: it took many years to develop appropriate substrate preparation, deposition method, and handling technology for high QE gaseous PDs



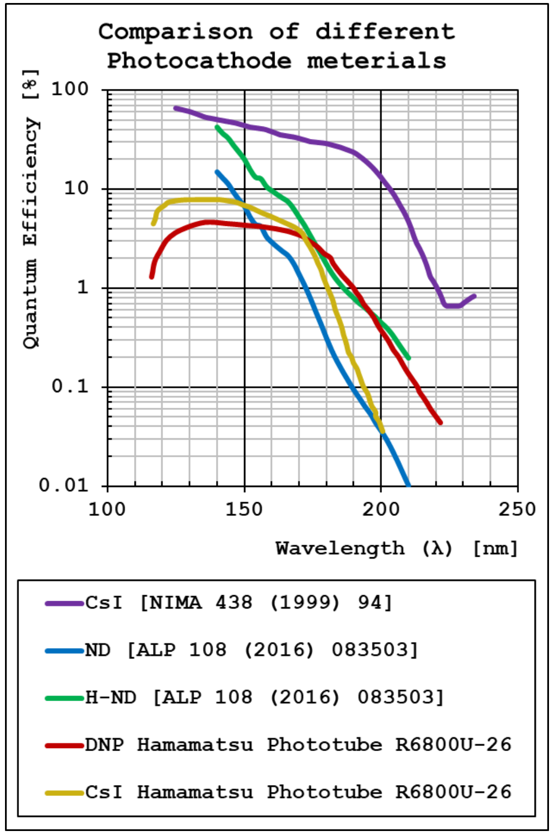
B.K. Singh et al. NIMA 610 (2009) 350 | Triloki et al. NIMA 695 (2012) 279–282

Quest for new PC materials:

Nano Diamond

Nano Diamond powder shows ~ 8 – 10% QE values @ 140 nm.

Hydrogenation of the ND powder shows even higher values of QE for the same wavelength.



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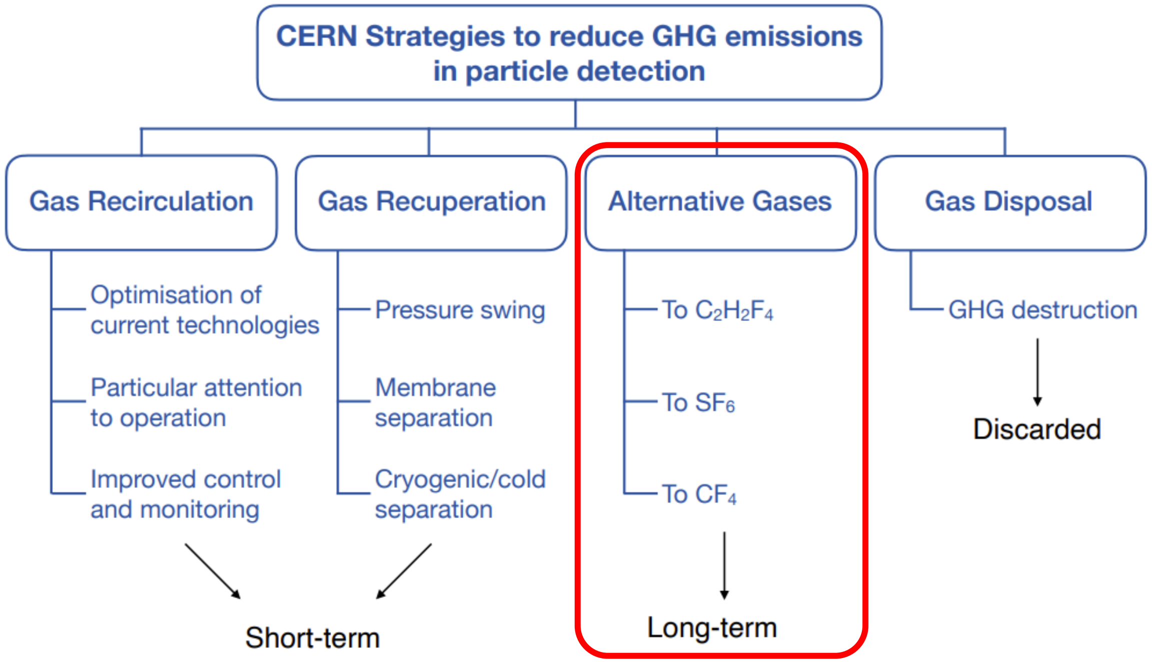
https://indico.cern.ch/event/1237829/contributions/5637225/

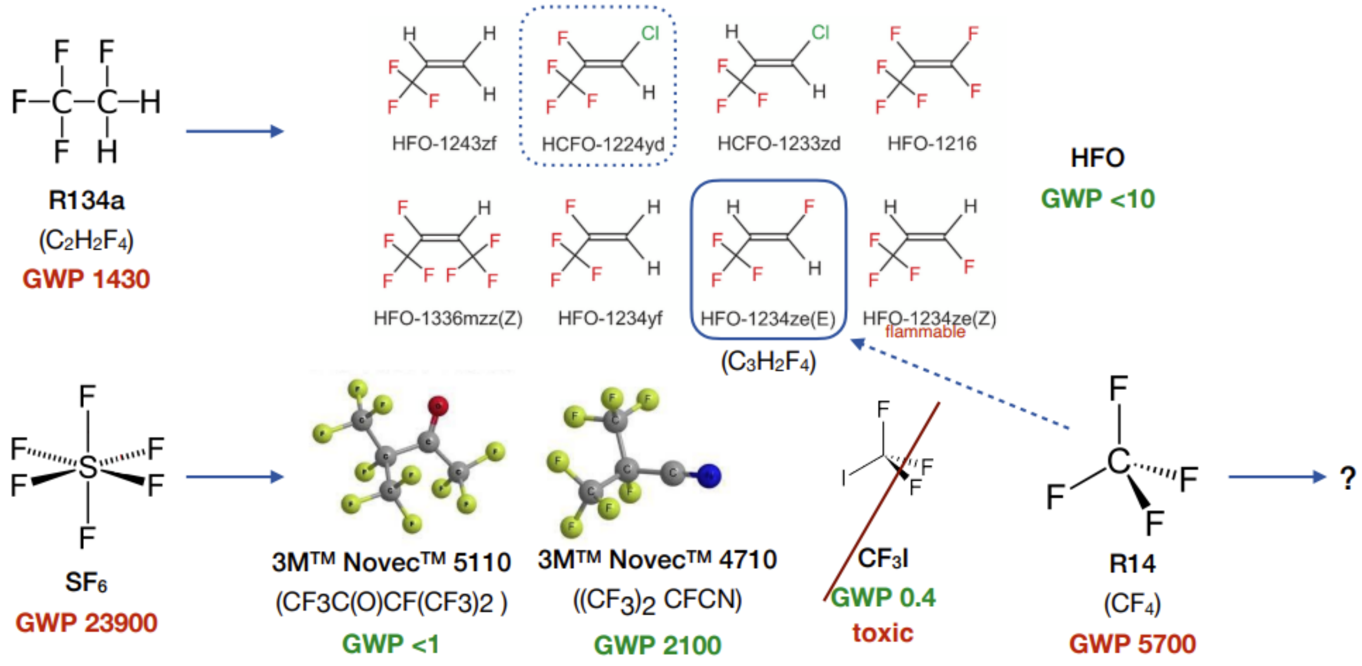
https://indico.cern.ch/event/1237829/contributions/5611057/

New eco-friendly gases

GHGs started to be affected by regulation aiming in reducing their use
Even more critical: PFAS (Per- and polyfluoroalkyl substances) are nowadays under close monitoring – regulations “started”



Alternative gases:



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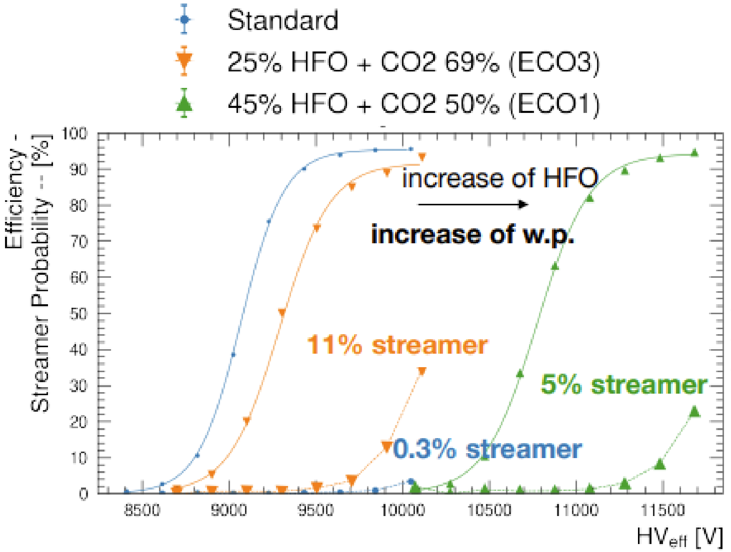
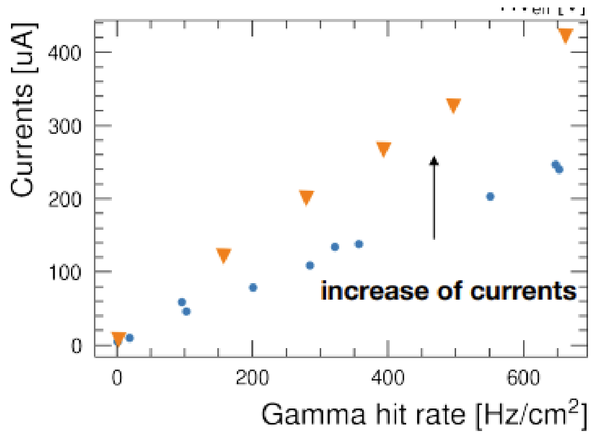
New eco-friendly gases

HFO based mixtures

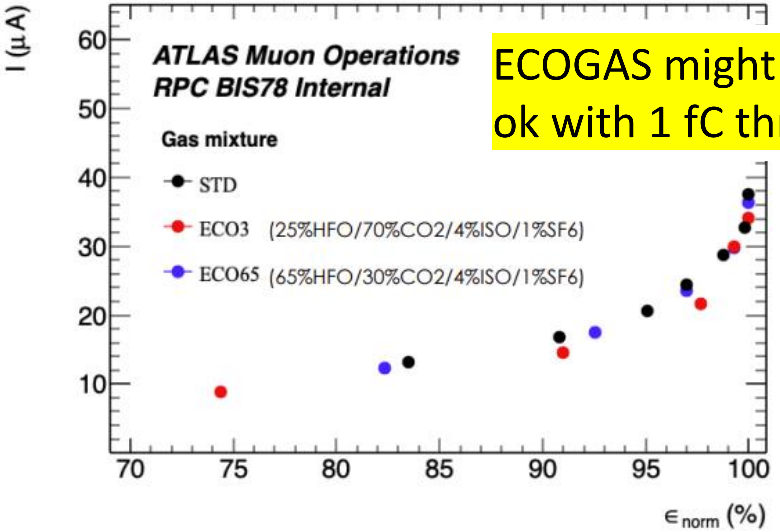
Eco-friendly gas mixtures have higher charge with respect to standard gas mixture
- Higher streamer fraction
- Higher currents
- Higher production of fluoride



Concerns about possible aging effects

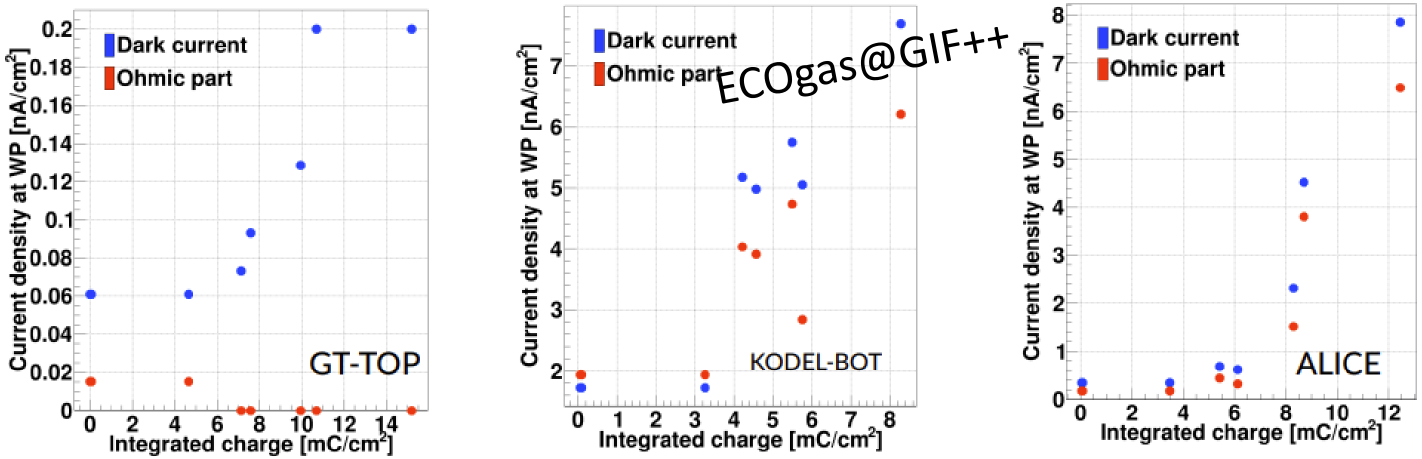


But with new FEB – ATLAS BIS upgrade



ECOGAS might might be ok with 1 fC threshold

ECO1 (50% CO2 and 45% HFO) → Increase of dark current (total and Ohmic)



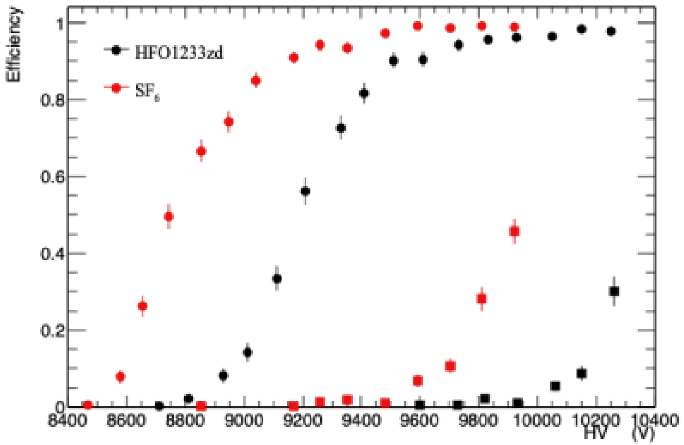
https://indico.cern.ch/event/1237829/contributions/5609576/

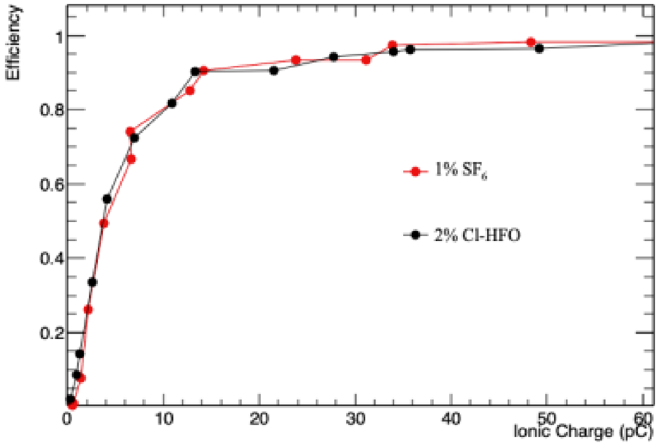
https://indico.cern.ch/event/1237829/contributions/5609610/

New eco-friendly gases

Replacing SF_6

Mixture under study : HFO1234ze(FHFO)/CO_2/iC_4H_{10}/SF_6 and HFO1234ze/CO_2/iC_4H_{10}/HFO1233zd(Cl-HFO)





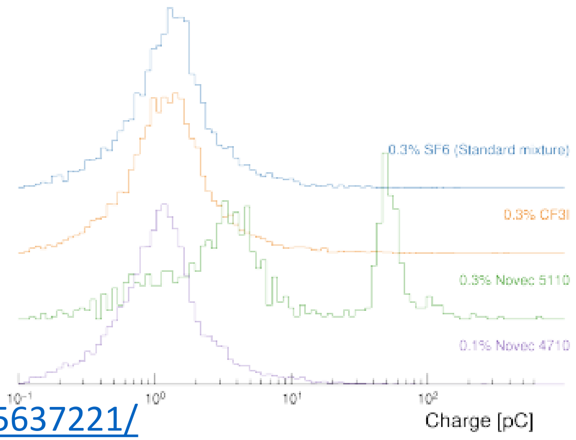
The Cl-HFO is a potential substitute of SF_6 in RPC eco-friendly mixtures

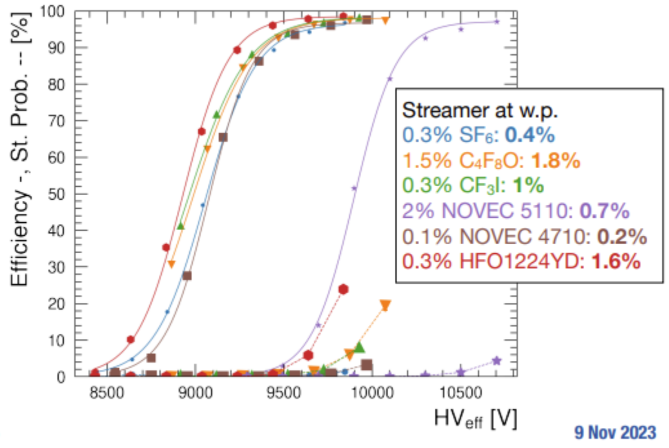
https://indico.cern.ch/event/1237829/contributions/5609576/

Novec

- Excellent performance for NOVEC 4710 in RPC but reactivity under study
- Reactions with H_2O and UV light

→ But they are PFAS





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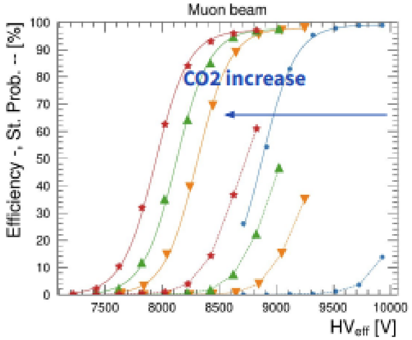
New eco-friendly gases

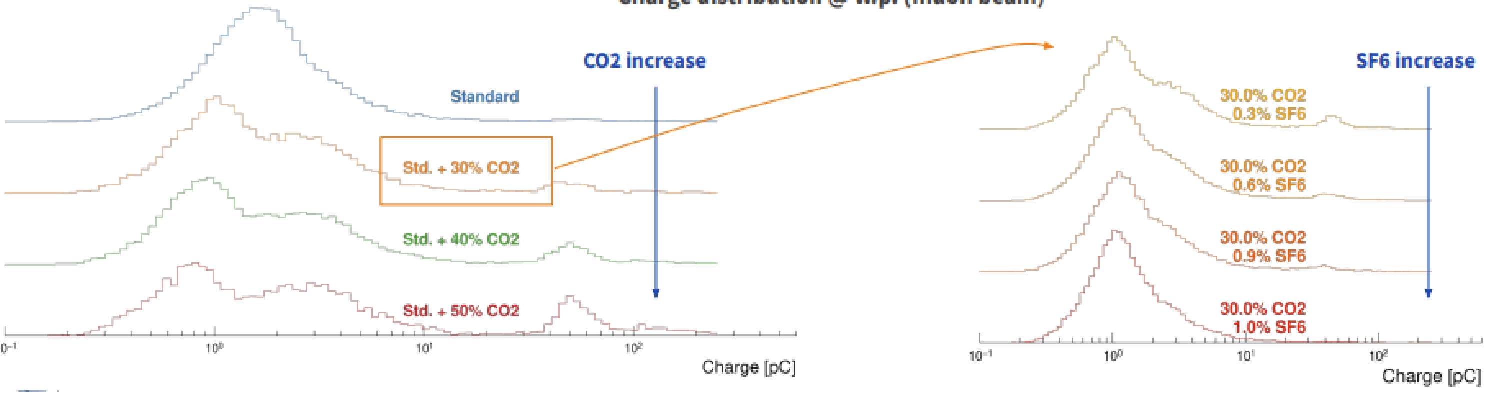
Transition mixtures:
RPC: diluting standard mixture with CO_2

Studies on CO2 impact when added to the standard gas mixture: 30%, 40%, 50%

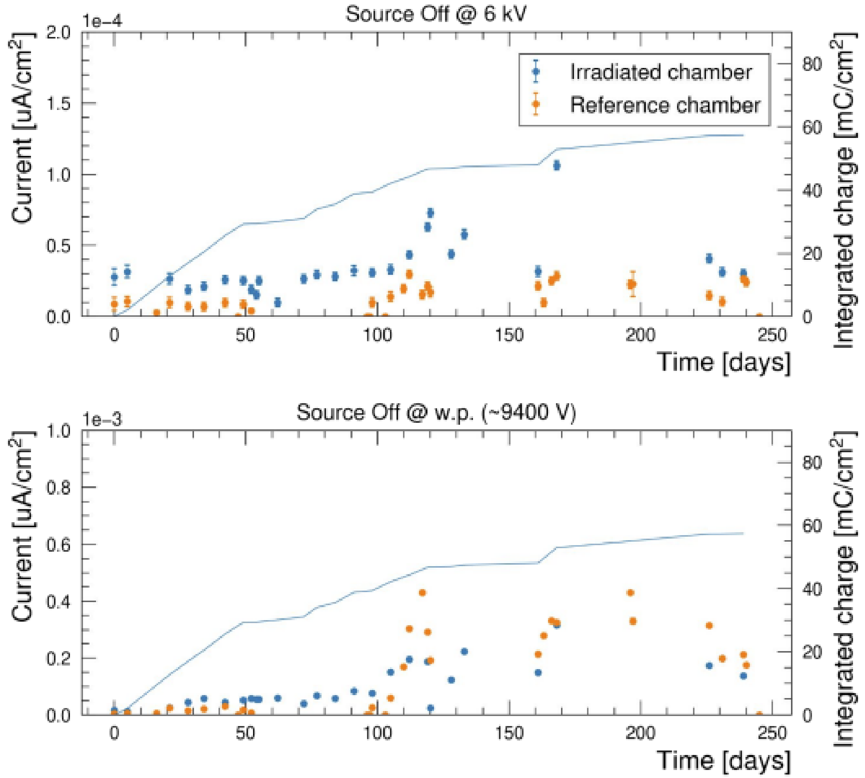
- Tests performed with **muon beam** and **gamma background**
- w.p. decreases of **~ 190 V / 10% CO2**
- **Streamer** fraction **increases** ⇒ SF6 concentration need to be adjusted



Charge distribution @ w.p. (muon beam)



longevity



- Currents, muon detection performance and resistivity monitored over time
- About 60 mC/cm^2 integrated (2 x ATLAS RPC Run 3 charge)
- Need to integrate ~850 mC/cm^2 (with safety factor 3) for HL-LHC
- No significant change in muon beam efficiency
- Overall stable rate capability/detector resistivity

https://indico.cern.ch/event/1237829/contributions/5611078/

New eco-friendly gases

For RPC:
HFO cannot directly replace $C_2H_2F_4$
- Higher applied voltage necessary (>14 kV)
- In std gas mix ~9.5 kV

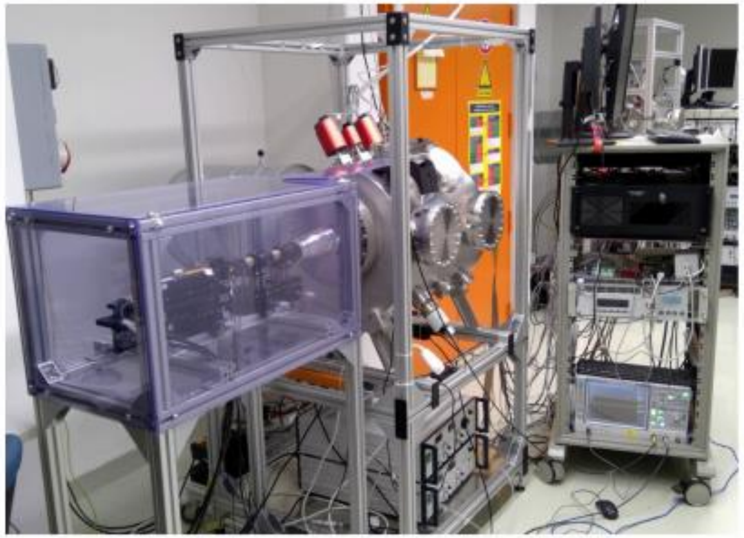
Addition of an "inert" gas to lower the w.p.
- Helium and CO_2 help in reducing the w.p
- + 10% CO_2 —> ~1 kV

For CSC:
CF_4 protect against anode ageing
- CF_3I and HFO1234ze not best candidates for stability and aging
- Look for other alternatives to CF_4 on-going

For LHCb RICH:
CF_4 or C_4F_{10} Necessary for good refractive index
- Replace C_4F_{10} with C_4H_{10} Refractive index matches very well but is flammable
- Replace CF_4 with CO_2 under investigation

For GEM:
CF_4 Necessary to enhance time resolution
- Replace CF_4 with ??? HFO? but study for time resolution are also needed

New gases are still not fully characterized
- The cross sections reproduce the transport properties via two distinct methods
- Boltzmann equation
- Monte Carlo simulation
- Measurements of electron transport coefficients
- Several gases and gas mixtures can be tested



Pulsed Townsend experiment at the High Voltage Laboratory (ETH Zurich)

Conclusions

The causes of the aging effects are quite well known: materials, glues, Si, …

Nevertheless, during industrial production of detectors for large experiments it is difficult to control everything

sometimes suppliers change tiny but important things, and we are neither aware

It is the devil's cunningness → and a new ageing effect appears

Nowadays the challenge is even/at least double:

- Industrial production for large experiments
- Unprecedent background conditions

From here the importance of:

- Sharing and keeping experience
- Validation of all components
- Database with characteristics
- Enlarge collaboration to include new skills (chemist, …)
- DRD1 framework

Thanks to all speakers, conveners, participants for the fruitful discussion and to the organizers (local and program committees)
Special thanks to our secretary Veronique

People and collaborations

Keep experience and expertise and transfer to young researchers working in large collaborations.

Examples:

Best Oral Contributions presented by young researchers:

- N. Rawal
  "In-situ monitoring of the CSC longevity at CMS"
- J. Merlin
  "Comparative Aging Studies of GEM Detectors in contaminated Environments"
- G. Rigoletti
  "Towards Sustainable RPC Detectors: Exploring CO2-Based Gas Mixtures for CERN LHC Experiments"

Best poster presented by young researchers:

- M. Verzeroli
  "Long-Term Stability of SWPCs in Monitoring CF4-Based Gas Mixture in CMS CSC Detectors"

Congratulations!

People and collaborations

Congratulations!

Picture from Cecilia Uribe Estrada

More pictures at https://photos.app.goo.gl/i4qksiuJV4EstVkr6 thanks to Cecilia Uribe Estrada

Picture from CERN Photo Service