PH-DT
Detector Technologies

Overview of Radiation Hardness of Gaseous Detectors

Instrumentation Days on Gaseous Detectors

IPNO, Orsay, June 25-26, 2014

Mar Capeans
CERN

Outline

- Radiation Damage of Gas Detectors: Ageing Phenomena
- Rate of Ageing
- Factors Affecting the Ageing Rate
- Strategies to Build Radiation-Hard Gas Detectors
- Outliers
- Concluding remarks

Radiation Damage of Gas Detectors

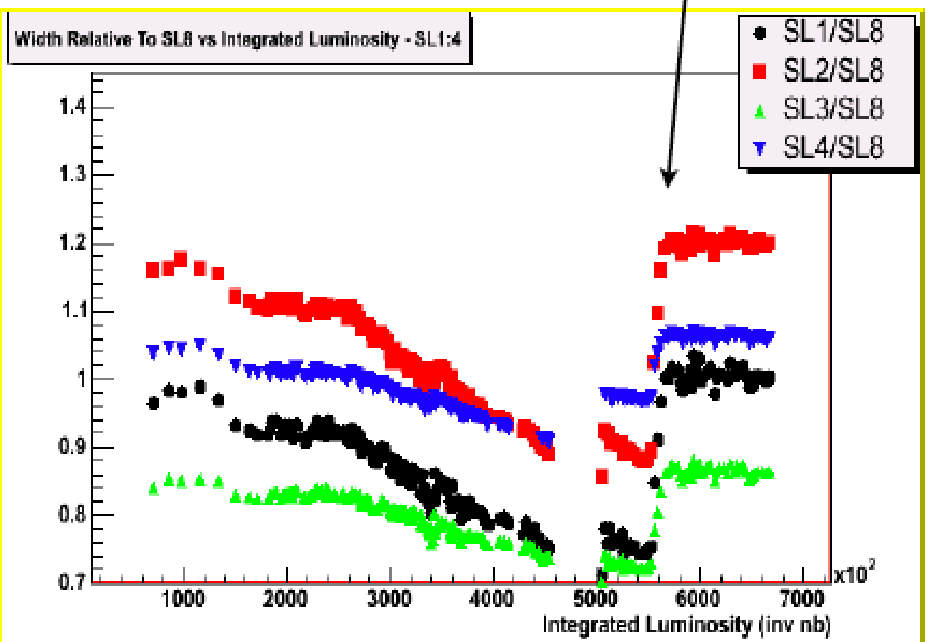
- **Deterioration of performance under irradiation** has been observed since development of Geiger and proportional counters (~100 years) and yet it remains one of the main limitations of Gas Detectors in high rate experiments.
- Deterioration in Performance: loss of gas gain, loss of efficiency, worsening of energy resolution, excessive currents, self-sustained discharges, sparks, loss of wires, changes of surface quality…
- In the Gas Detectors community, Radiation Damage is referred to as **ageing**

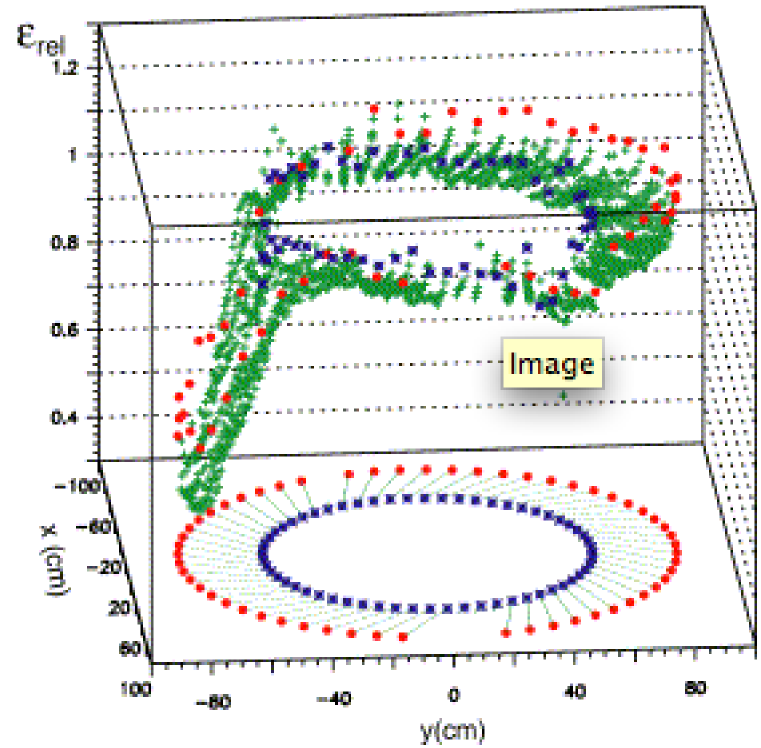
Radiation Damage → Gas Detectors ageing

Gray (Gy) → C/cm (or /cm^2)

Ageing of Gas Detectors in Experiments

Accidental addition of O_2 in the gas





Ageing in the Central Outer Tracker of CDF Fermilab (D.Allspach et al.)

Drift chamber

$Ar-C_2H_6$ [50-50] + 1.7% isopropanol

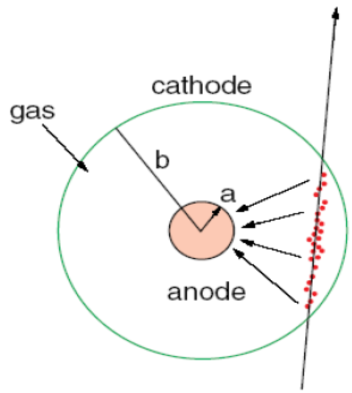
Ageing in the Central Jet Chamber of H1 DESY (C.Niebuhr)

Radial Wire Chamber

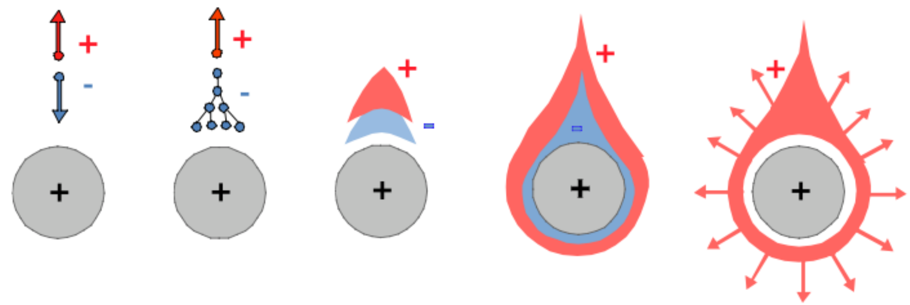
$Ar-C_2H_6$ [50-50] + water

Gaseous Detectors - Principle

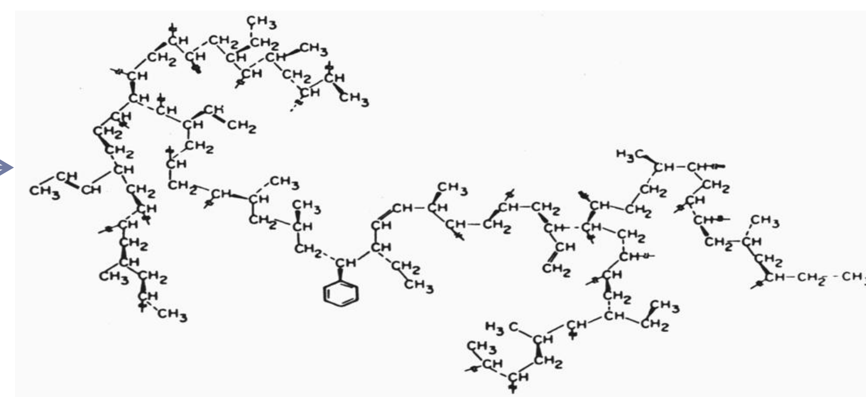
$$E(r) = \frac{CV_0}{2\pi\varepsilon_0}\frac{1}{r}$$



Principle of Gas Multiplication ~ Signal development



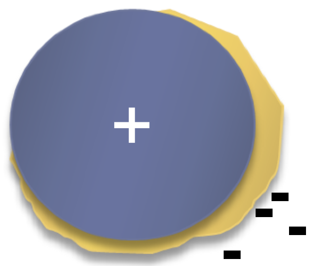
1. Gas mixture ⟶ Ar + CH_4
2. Initial Reaction ⟶ $e^- + CH_4 \Rightarrow CH_2{:} + H_2 + e^-$
3. Creation of radicals ⟶ $CH_2{:}$
4. Polymer Formations ⟶

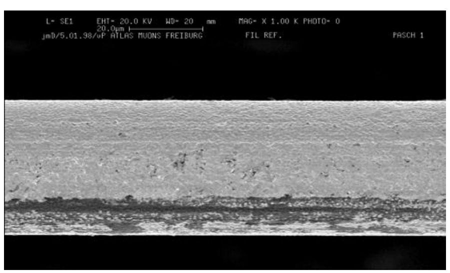


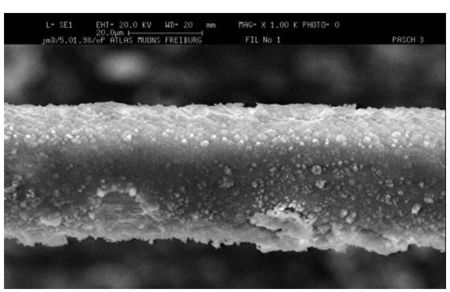
- Solid, highly branched, cross linked
- Excellent adhesion to surfaces
- Resistant to most chemicals
- Insoluble in most solvents

Ageing Phenomena

- Anode ageing: deposits on wire







Effect of Deposits

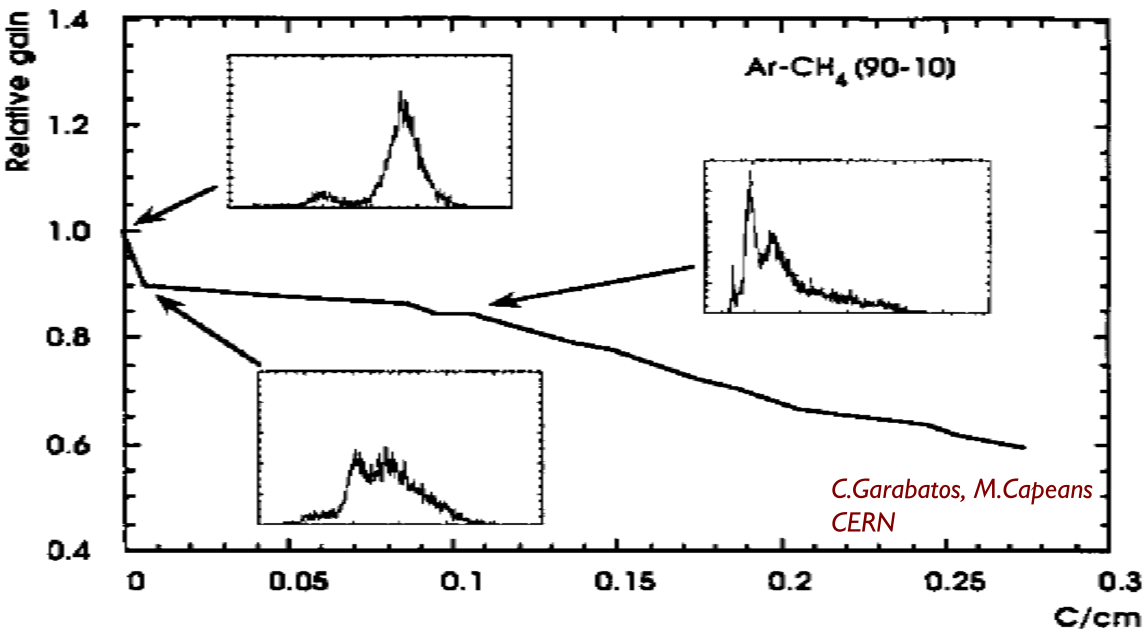
- If deposit is **conductive**, there is a direct effect: the electric field weakens (~thicker wire)
- If deposit is **insulating**, there is indirect effect due to dipole charging up: the field close to the anode will be screened as new avalanches accumulate negative charges on the layer

Consequences on the detector

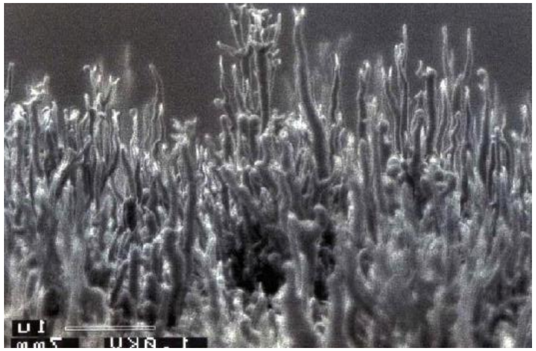
- Decrease of gain
- Lack of gain uniformity along wires
- Loss of energy resolution

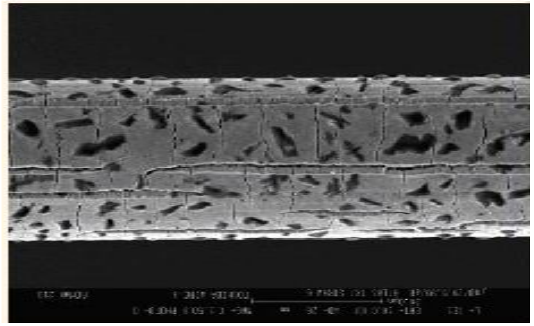
Anode Ageing

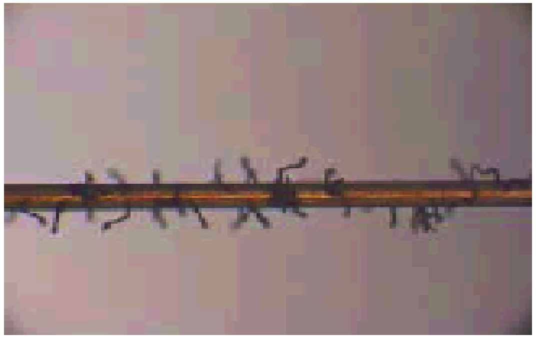
SWPC
Controlled Ageing Test in Laboratory



C.Garabatos, M.Capeans
CERN

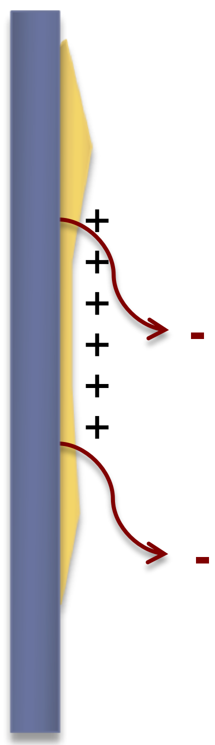






Ageing Phenomena

- Cathode ageing: layers on surfaces



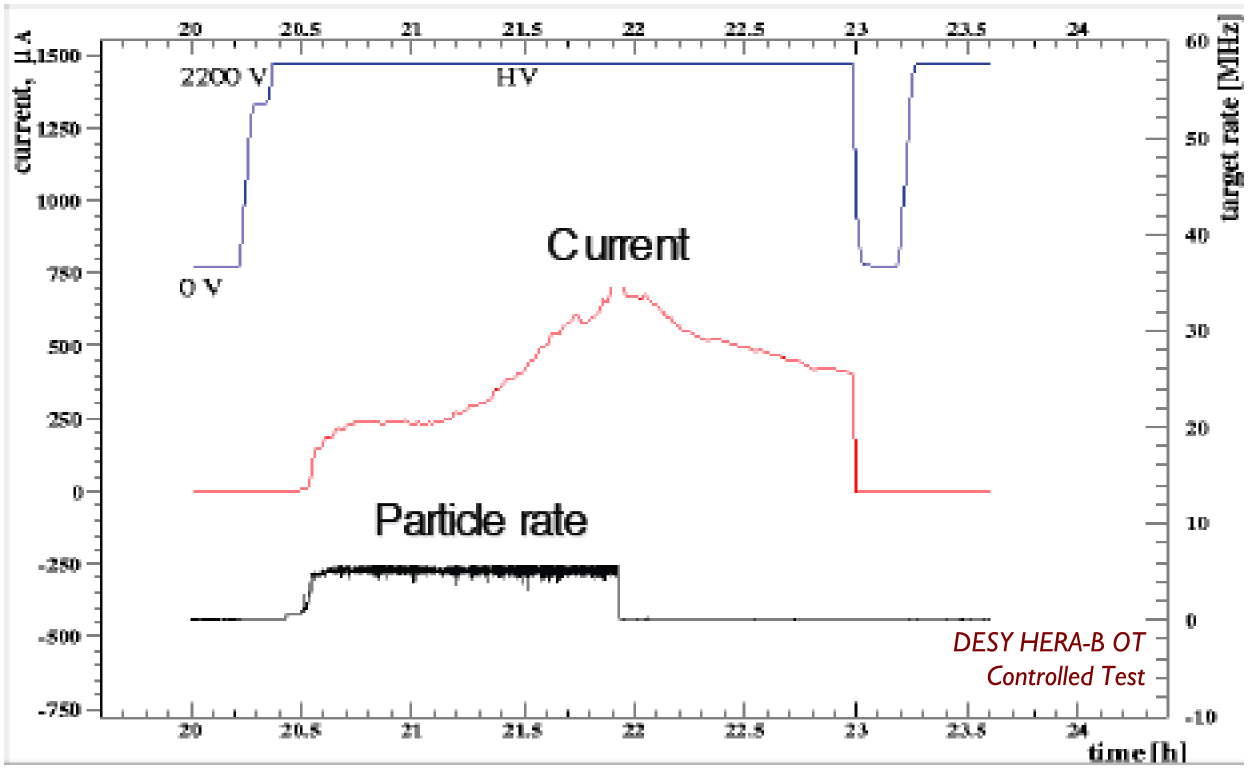
Effect of Layers

- Charges do not reach the cathode and layer becomes positively charged. This produces a large dipole electric field which can exceed the threshold for field emission and e^- are ejected from the cathode producing new avalanches
- Malter effect (self-sustained currents, electrical breakdown)

Consequences on the detector

- Noise, dark currents
- Discharges

Cathode Ageing



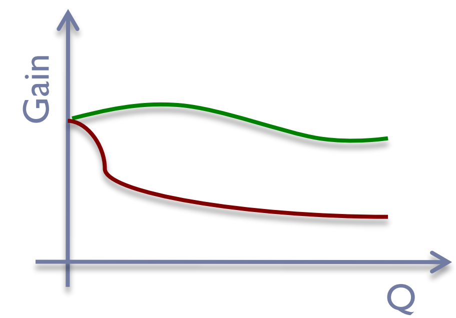
Malter effect

Rate of Ageing

- **Ageing depends on the total collected charge Q:**

Q [C] = Gain x Rate x Time x Primaries

  - Rate of ageing: R(%) ~ slope of **Gain vs. Q**
  - Ageing Unit depends on detector geometry: wires [C/cm], strips or continuous electrodes [C/cm^2]



- **Accumulated charge (C/cm) per LHC year** (diff. safety factors)**:**

Accelerated Ageing Tests

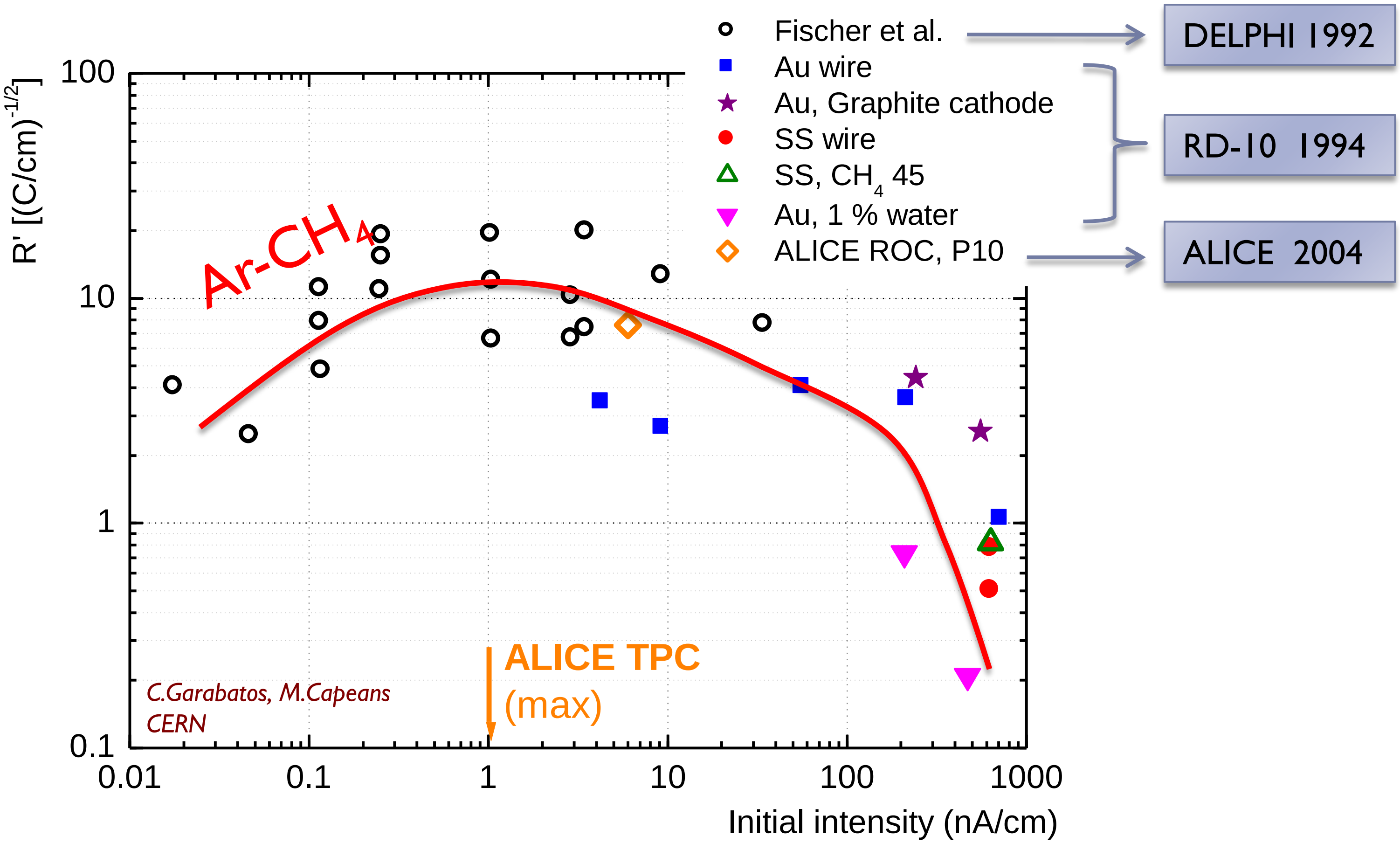
- Needed in order to asses lifetime of a detector under irradiation in a limited amount of time
- How much can we **accelerate** the tests in the lab with respect to the real conditions?
- …ageing depends on:

$$Q\,[C] = \text{Gain} \times \text{Primaries} \times \text{Rate} \times \text{Time}$$

- HV
- Gas mixture
- Pressure
- Gas exchange rate
- Electrical field strength
- Detector geometry
- …

- Dose rate
- Ionization density
- Particle type
- …

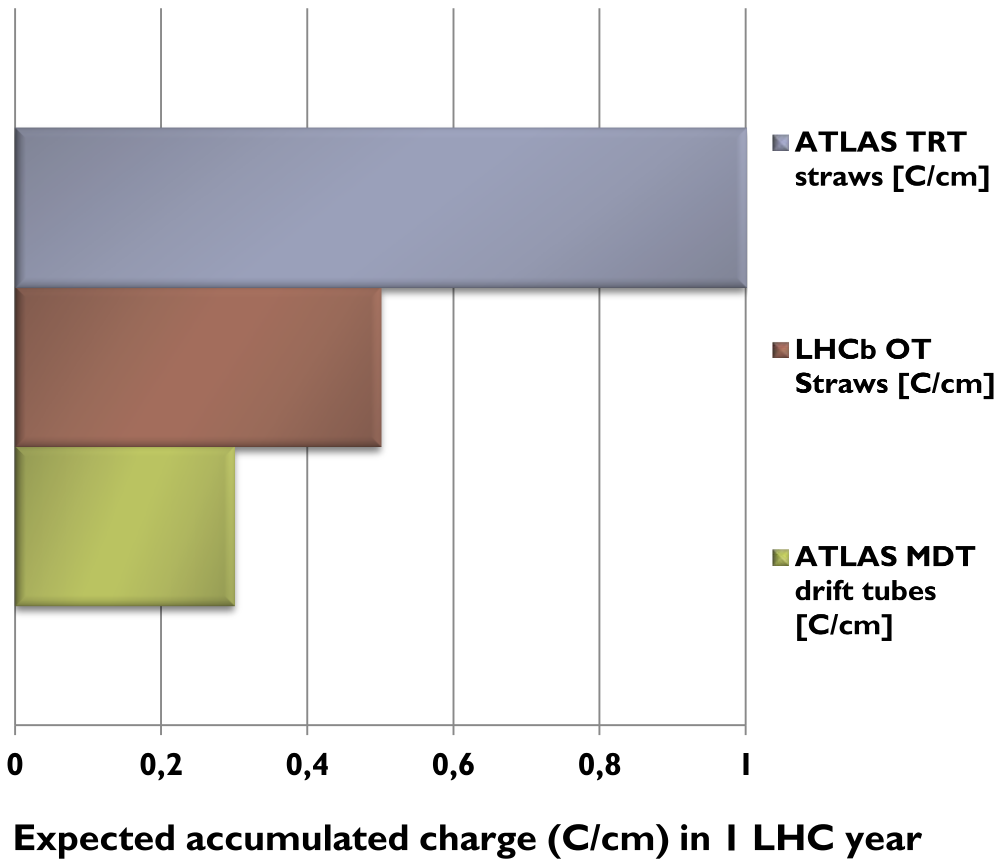
Rate of Ageing



- *Space charge gain saturation <u>can</u> decrease the polymerization efficiency*
- *Gas flow <u>can</u> be insufficient to remove reaction products created at high rate*

Acceleration Factors in Ageing Tests

Accumulated charge in 1 year at LHC

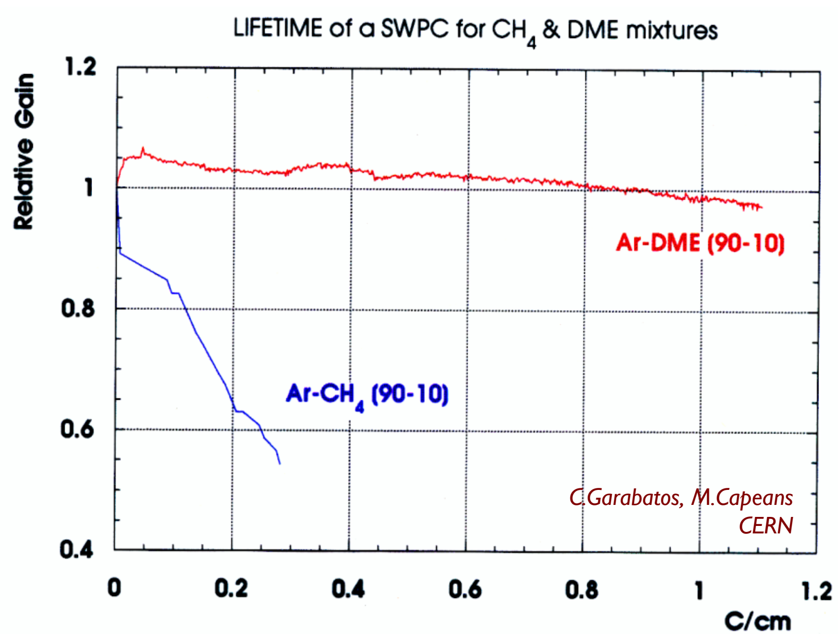


Acceleration Factor in Lab Tests

Atlas TRT	x 10
LHCb OT (Straws)	x 20
CMS RPC	x 30 (and much larger)

Influence of the Gas Mixture on Ageing

- Hydrocarbons: polymerization (so, ageing) guaranteed.
  - Polymer formation directly in the avalanche process.
  - Effect is more pronounced under spark/discharges



DME

- Flammable >3%
- Solvant
- Vulnerable to gas pollution

CO_2

- Increased HV
- More energetic discharges

CF_4

Deposition

In hydrogenated environments – CH_4

Deposits on wires

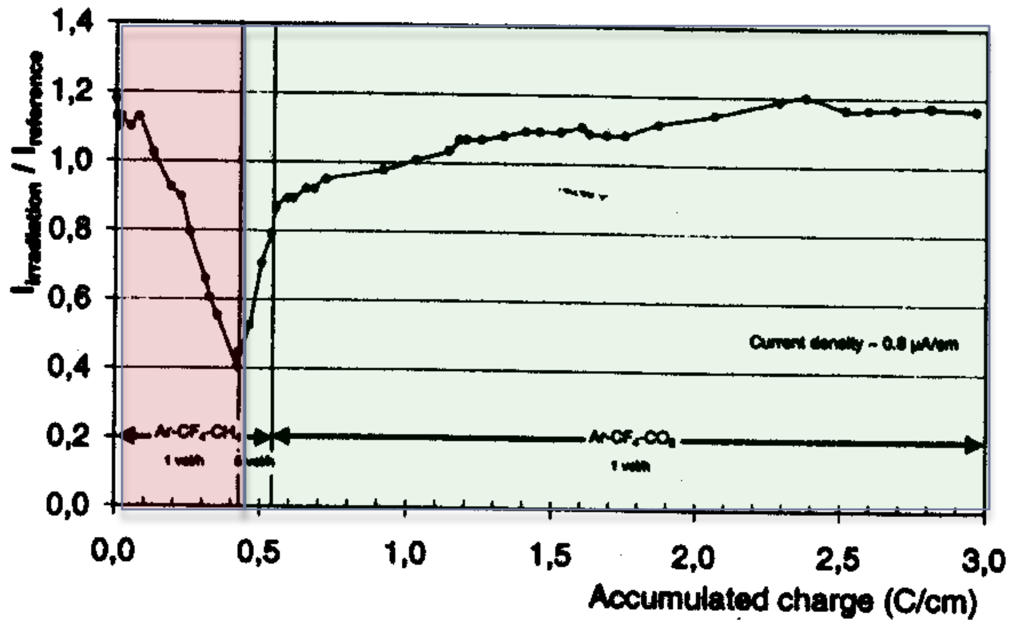
Etching

If oxygenated species are added – CO_2

Wire cleaning

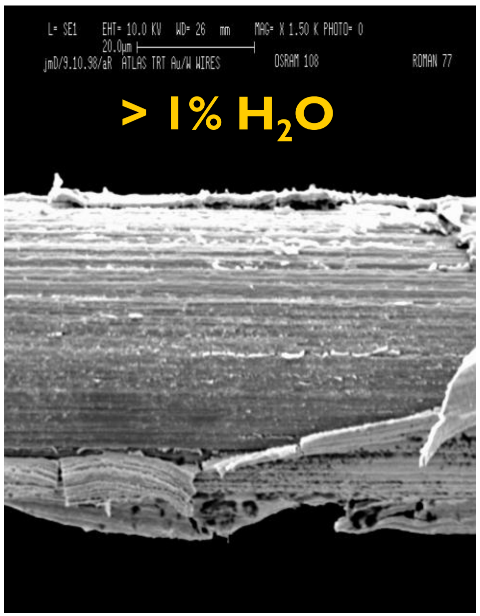
Can also be aggressive to some detector assembly materials, can accumulate

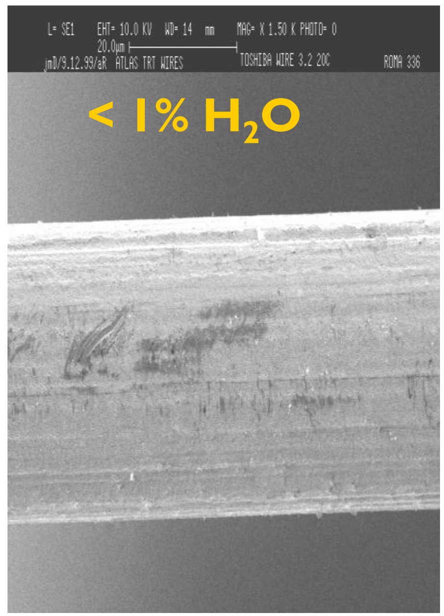
Ar-CH_4-CF_4 Ar-CO_2-CF_4



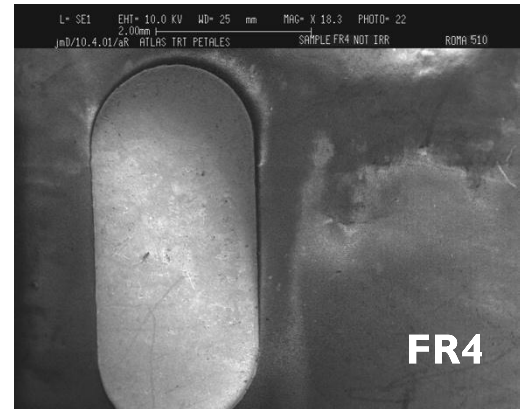
CF_4 Etching

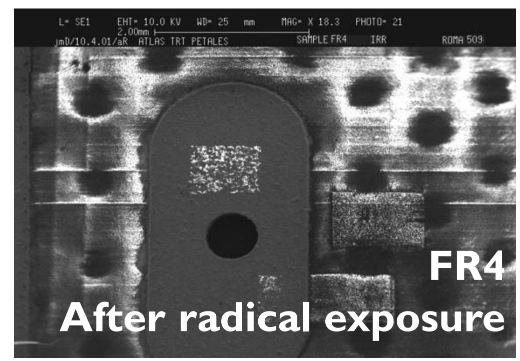
ATLAS TRT Straws, WIRE Au/W, Ar-CO_2-CF_4





ATLAS TRT PCB





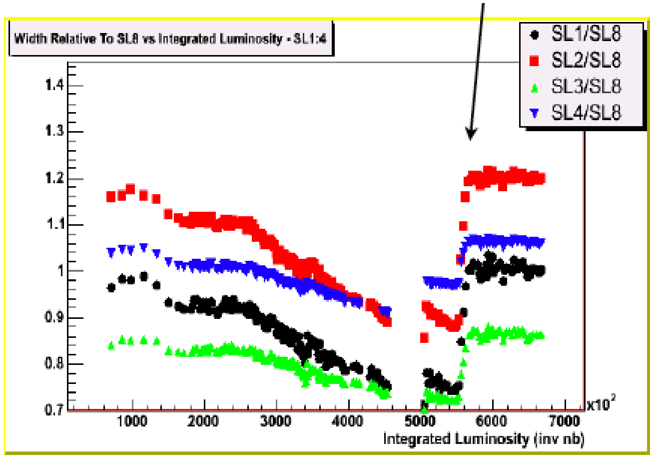
- Active species react with some metals (Al, Tin) and some insulator materials (Fiberglass)
- F species react with Si, which is distributed all around (polymerization trigger)

Additives, Emergencies

- Small concentrations of O_2 or H_2O or C_2H_6O can restore aged chambers or prevent effectively the ageing process to significant accumulated charges

- **O_2**
  - Etching of HC-deposits
  - Reacts with HC, and end products are stable and volatile
- **H_2O**
  - Reduces the polymerization rate in plasma discharges
  - Makes all surfaces slightly more conductive, thus preventing the accumulation of ions on thin layers responsible for the gain degradation and Malter effect
  - But, modification of the electron drift parameters or change in rate of discharges are not always acceptable
- **Alcohols**
  - Reduction of polymerization rate
  - Large cross section for absorption of UV photons

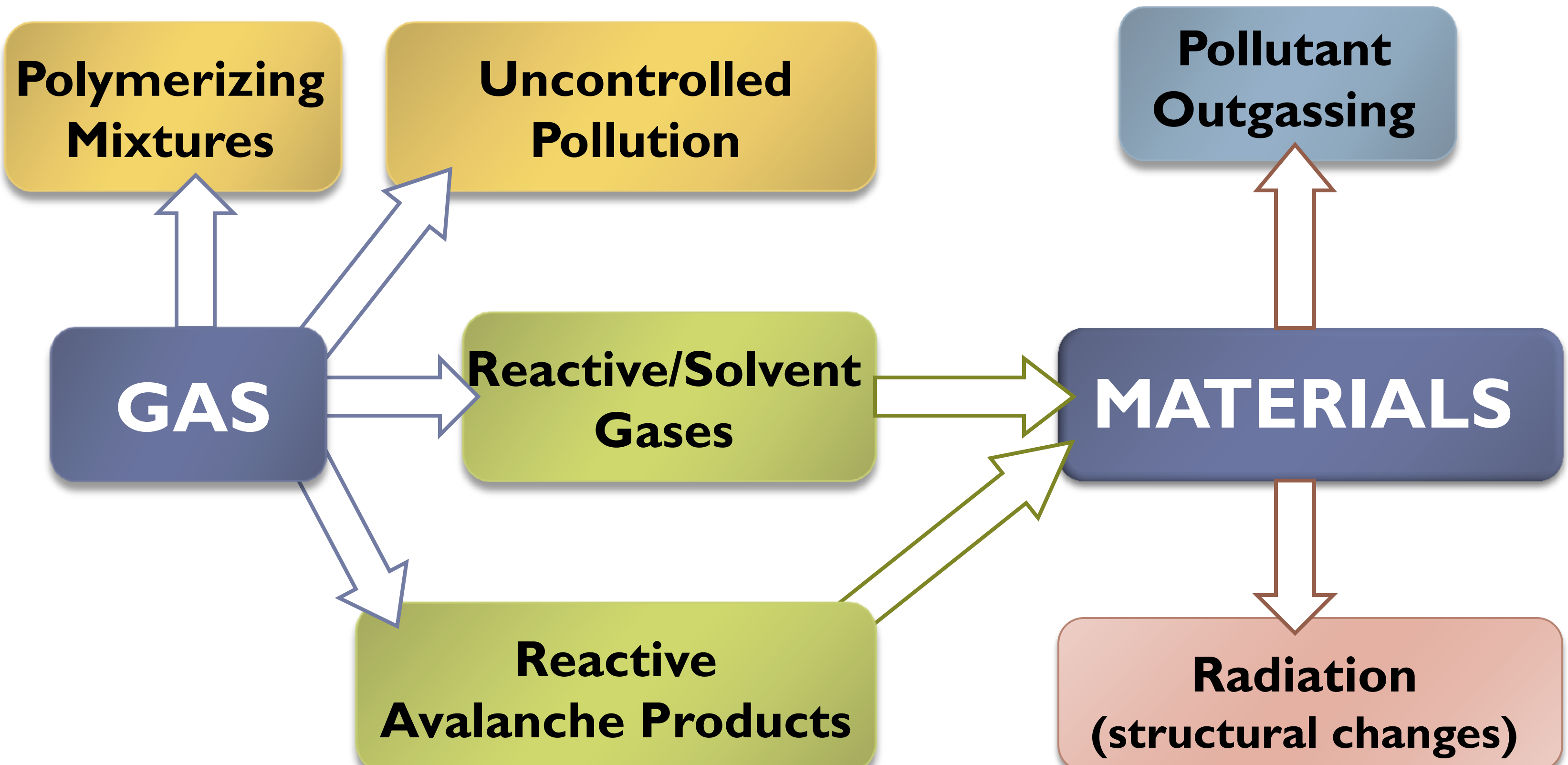
Addition of **O_2** in the gas mixture Ar-C_2H_6 [50-50]



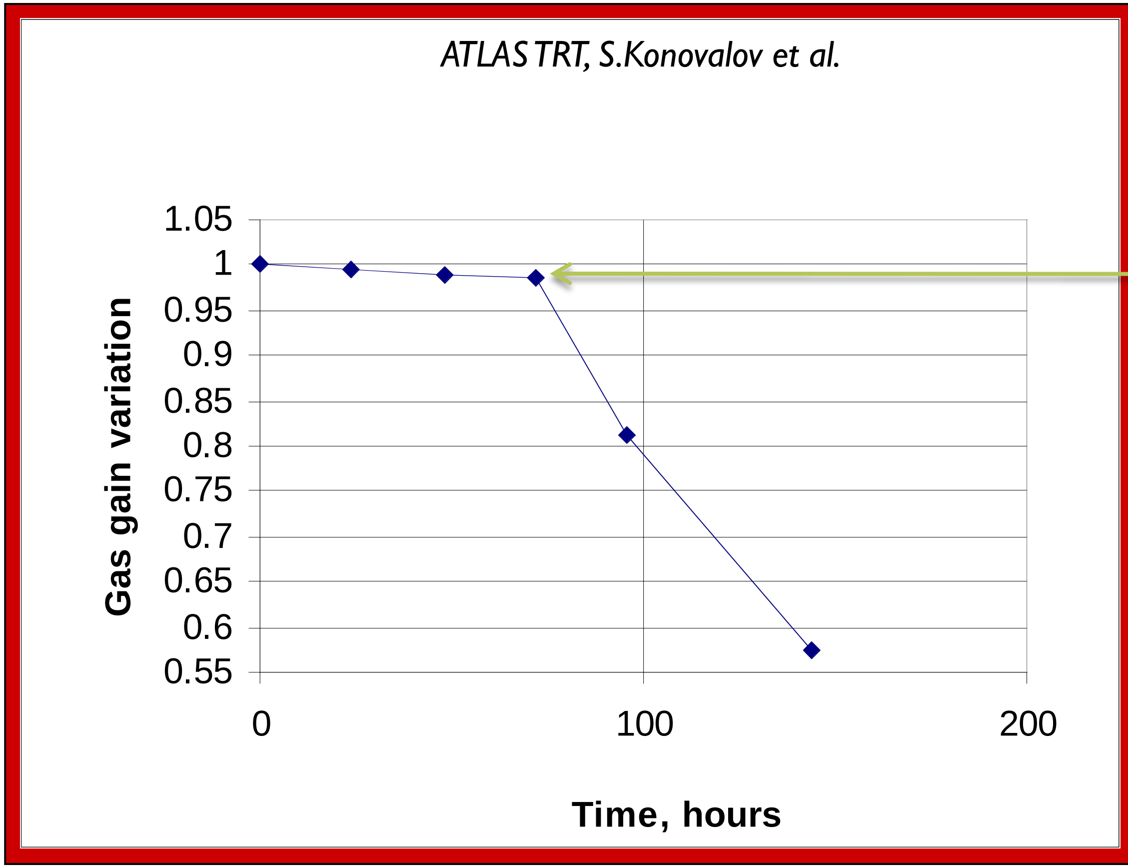
Gas Mixtures in LHC detectors

Experiment	Sub- Detector	Gas Mixture
ALICE	TPC, TRD, PMD	Noble Gas (Ar, Ne, Xe) + CO_2 Additive: O_2
ATLAS	CSC, MDT, TRT	
CMS	DT	
LHCb	OT straws	
TOTEM	GEM, CSC	
LHCb	MWPC, GEM	Ar - CF_4 - CO_2
CMS	CSC	
	RPC TGC RICH	$C_2H_2F_4$ - iC_4H_{10} - SF_6 CO_2 – n-pentane CF_4 or C_4F_{10}

Other Contributions to the Ageing Process

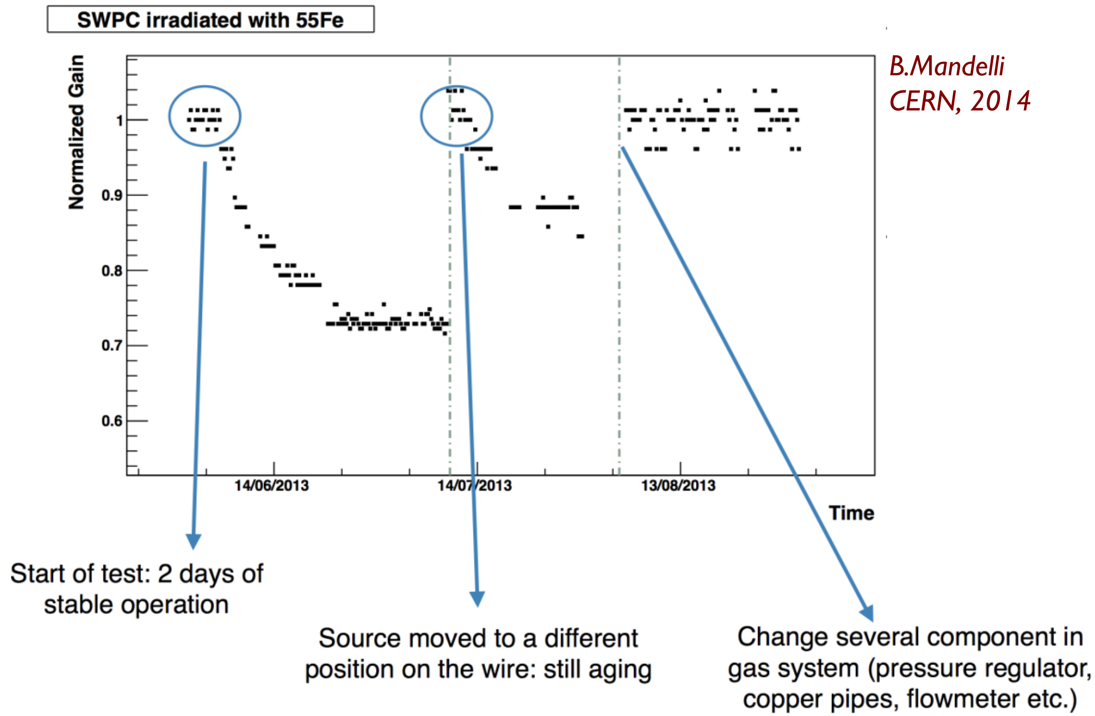


Pollution of the Gas Mixture



Inserted a new flowmeter (Voetglin V100) in the gas system, and gas gets polluted by minute amounts of Silicone-based lubricant

Pollution of Gas Mixture
- Targeting Super Clean System for Lab Tests



Gas system components

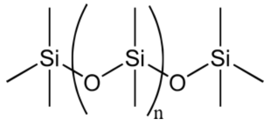
- Flowmeter Gilmont: OK, but flow/pressure not stable
- Flowmeter Voglin: OK if degreased
- ROTAREX (O_2-degreased) pressure regulator and valves: OK
- Std Pressure Regulator: depends on needed purity level…
- Bronkhorst MFC: OK if full metal + Kalrez-6375 joints
- SS Pipes & connectors: OK if cleaned (Ultrasonic bath)
- VITON joint: BAD
- O_2 (chemical cell) and H_2O (capacitive) sensors; after detector
- Pressure sensor "Sensortechnics": OK

Detector Assembly Materials, Full SS SWPC

- AY103+HY991: BAD
- Soldering paste without flux: BAD for a short period

http://detector-gas-systems.web.cern.ch/detector-gas-systems/Equipment/componentValidation.htm

Silicone Pollution

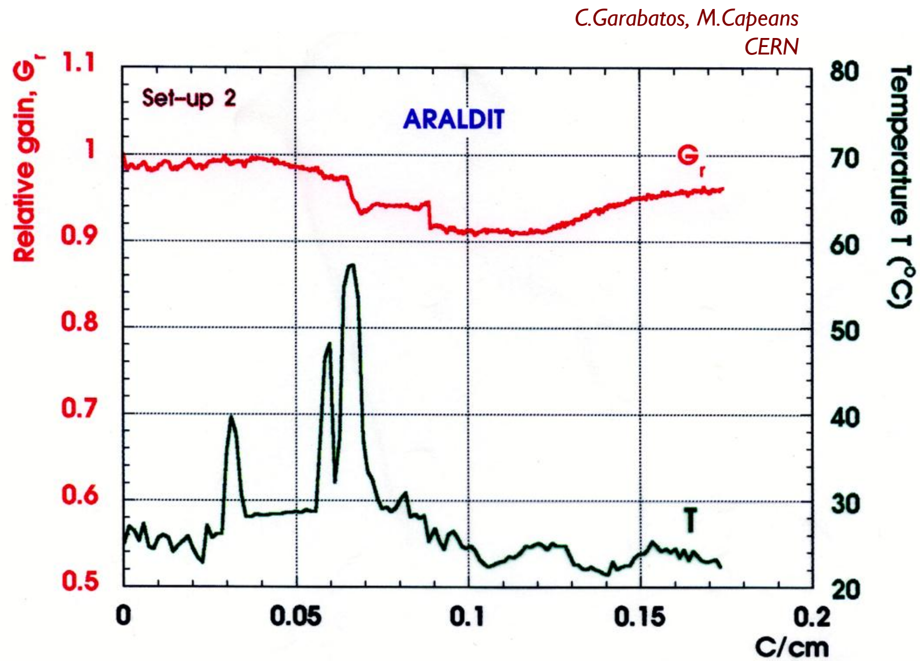


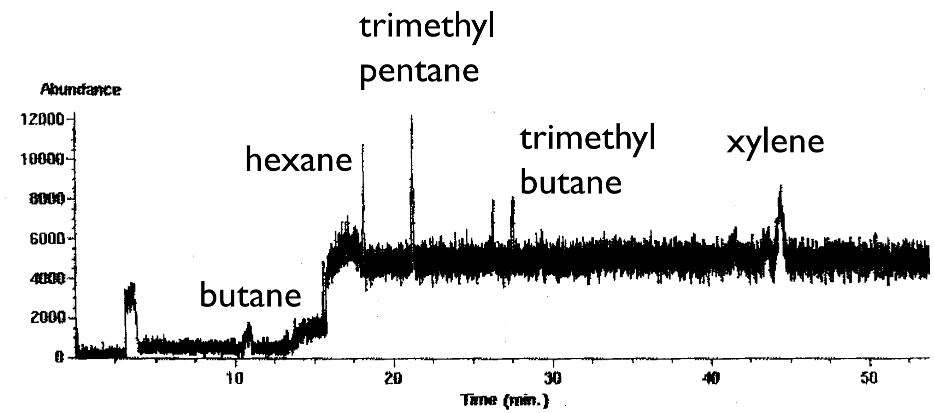
- Silicone has been systematically found coating aged chambers
- Silicone has a high natural affinity for most materials
- Silicone has the tendency to migrate
- Silicone is relatively inert chemically and unaffected by most solvents, therefore among the most difficult surface contaminants to remove
- Resistance to oxygen, ozone, and ultraviolet (UV) light
- Silicone is etched away by F-species

Possible Sources

- Silicone rubber sealants
- Silicone potting and encapsulation compounds
- Silicone adhesives
- Silicone Vacuum Grease (O-rings, mould-release agents)
- Silicone oil (bubblers, diffusion pumps)
- Polluted gas cylinders
- Detergent residues (sodium metasilicate)
- Glass and related products (glass fibres used for reinforcing resins)

Effect of Materials



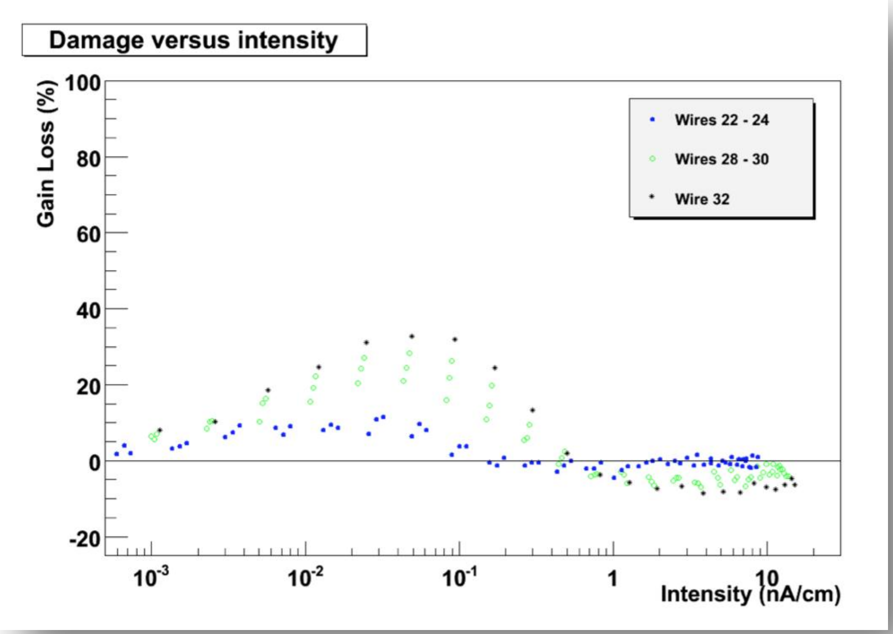


Ageing test of a SWPC counter
Epoxy **Araldit 106** inserted in gas stream

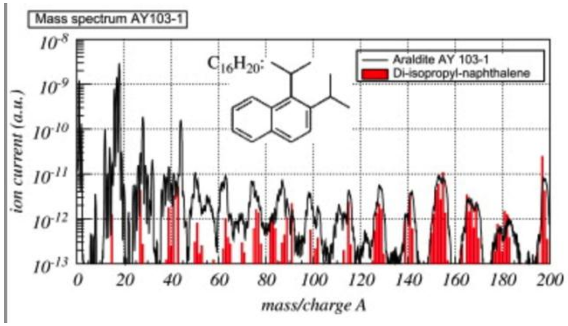
GC/MS analysis of the gas mixture
Outgassed components of Araldit 106

LHCb Straws Tubes

- LHCb Outer Tracker
  - Straw tubes Ø 4.9mm, 25µm W/Au wire, Ar-CO_2, 30 m^2
- Detected ageing (gain loss) at moderate intensities (and after chamber mass production was completed)
- Identified Culprit: plasticizer di-isopropyl-naphthalene in Araldit AY103-1



E.L.Visser, Preventing, monitoring and curing the ageing in the LHCb Outer Tracker, CERN Thesis-2010-094



LHCb OT

Ar-CO_2 70-30, 20 L/h, 1600 V

- *Ageing upstream the source*
- *Depends on radiation intensity*

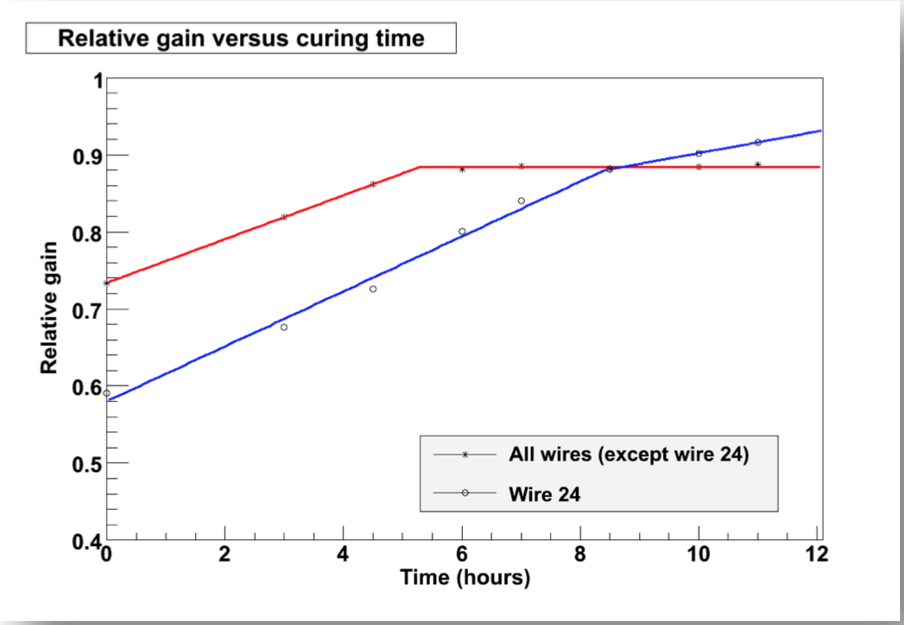
LHCb OT Ageing Remedies

Reduce risk of aging

- Adding 1.5% O_2 to Ar-CO_2 (increasing ozone concentration)
- Lowering gas flow (increasing ozone creation area)

Recover damaged wires

- Enter in discharge mode and generate dark currents (10 μA/wire)
- Increase HV (from 1600 to 1900V)… or increase Ar concentration, and optimize procedure using ionizing radiation 'to focus' the cleaning effect



Curing of damaged wires by applying 1850 V

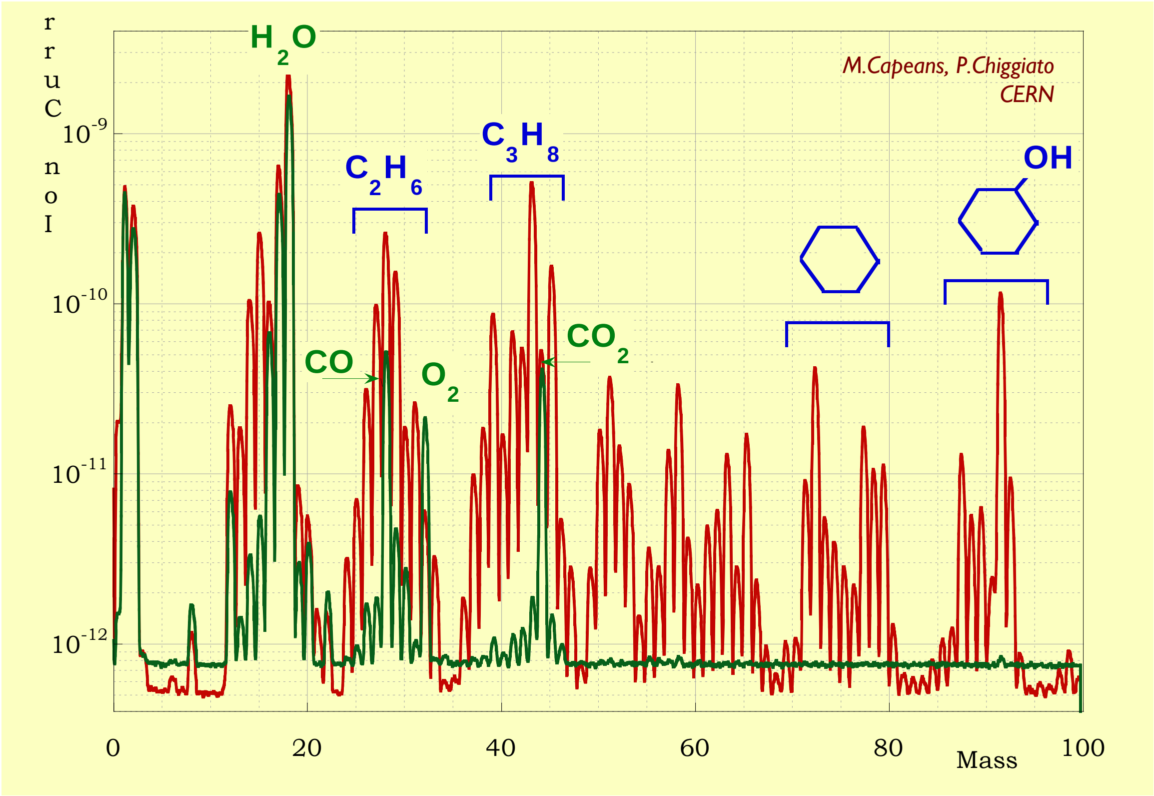
E.L.Visser, Preventing, monitoring and curing the ageing in the LHCb Outer Tracker, CERN Thesis-2010-094

CVCM, Gas Chromatography, Ageing Test 'à la CERN'

SAMPLE	NASA data (CVCM)	CERN data (GC/MS)	CERN Ageing test (Detector response)
Stycast 1266	BAD	OK	OK
Araldite 103	BAD	OK	OK
Araldite 106	BAD	BAD	BAD
Eccobond 285	OK	OK	OK
Nuvovern LW PUR	OK	OK	OK
ULTEM	OK	OK	OK
VECTRA 150	OK	OK	OK
Kalrez	OK	OK	OK
Epotek 905	BAD	BAD	
Dow Corning RTV	BAD	BAD	

- **Consult NASA database** to pre-select materials: thousands of entries for adhesives, rubbers and elastomers, potting compounds, etc…
- **http://outgassing.nasa.gov**

Materials



Analysis of outgassed components of a 2-component Polyurethane

1. Green: sample treated correctly
2. Red: one component expired

Materials

- Minor changes, big impact
- Difficult to control all parameters in large systems, at all stages
- Need validation of materials (detector assembly materials and gas systems' components), with an efficient strategy
- http://detector-gas-systems.web.cern.ch/detector-gas-systems/Equipment/outgassing.htm

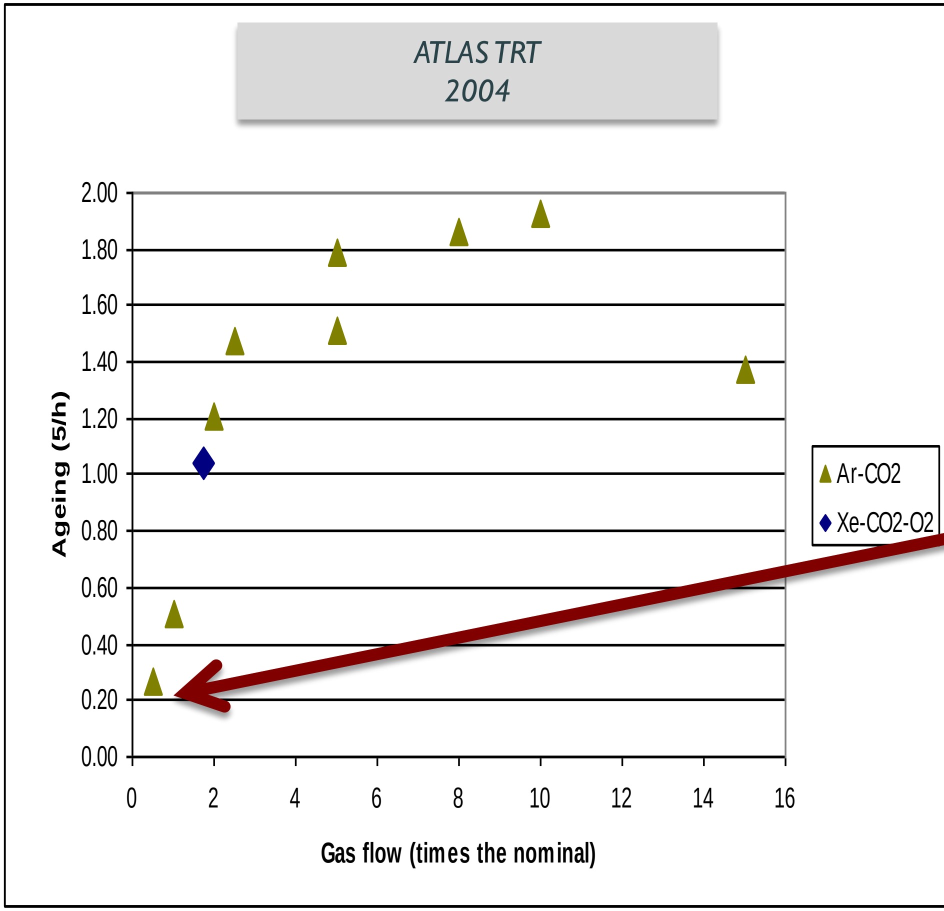
Rigid Materials

Source	Name	Type	Outgas	Effect in G.D.	Result
CERN/GDD	STESALIT 4411W	Fiberglass	YES	NO	OK
CERN/GDD	VECTRA 150	Liquid Crystal Polymer	YES	NO	OK
CERN/GDD	PEEK Crystalline	Polyeteherether ketone	NO	NO	OK
ATLAS/TRT	ULTEM	Polyetherimide	NO	-	OK
ATLAS/TRT	C-Fiber	C-fiber	NO	-	OK
ATLAS/TRT	POLYCARBONATE	C-fiber	NO	-	OK
HERA-B/ITR	FIBROLUX G10	Fiberglass	YES	-	BAD
HERA-B/ITR	HGW 2372 EP-GF	Fiberglass	YES	YES	BAD
CERN/GDD	RYTON	Polysulphur phenylene	YES	YES	BAD
CERN/GDD	PEEK Amorphous	Polyetherether ketone	YES	-	BAD

Epoxies *(C.Garabatos, M.Capeans)*

Source	Product	Curing T (ºC)	Outgas	Effect in G.D.	Result
CERN/GDD	EPOTECNY E505 SIT	50	YES	NO	OK
HERA-B/ITR	EPOTEK H72	65	YES*	NO	OK*
CERN/GDD	AMICON 125	85	NO	-	OK
CERN/GDD	POLYIMIDE DUPONT 2545	65	NO	-	OK
ATLAS/TRT	RUTAPOX L20	60	NO	-	OK
CERN/GDD	ARALDITE AW 106	70	YES		BAD
CERN/GDD	LOCTITE 330		YES	YES	BAD
CERN/GDD	EPOTECNY 503	65	YES (Silicone)		BAD
CERN/GDD	NORLAND UVS 91	50	YES	-	BAD

Ageing Rate for different Gas Flows



Lab test to measure rate of ageing in the TRT straws when the mixture is contaminated intentionally

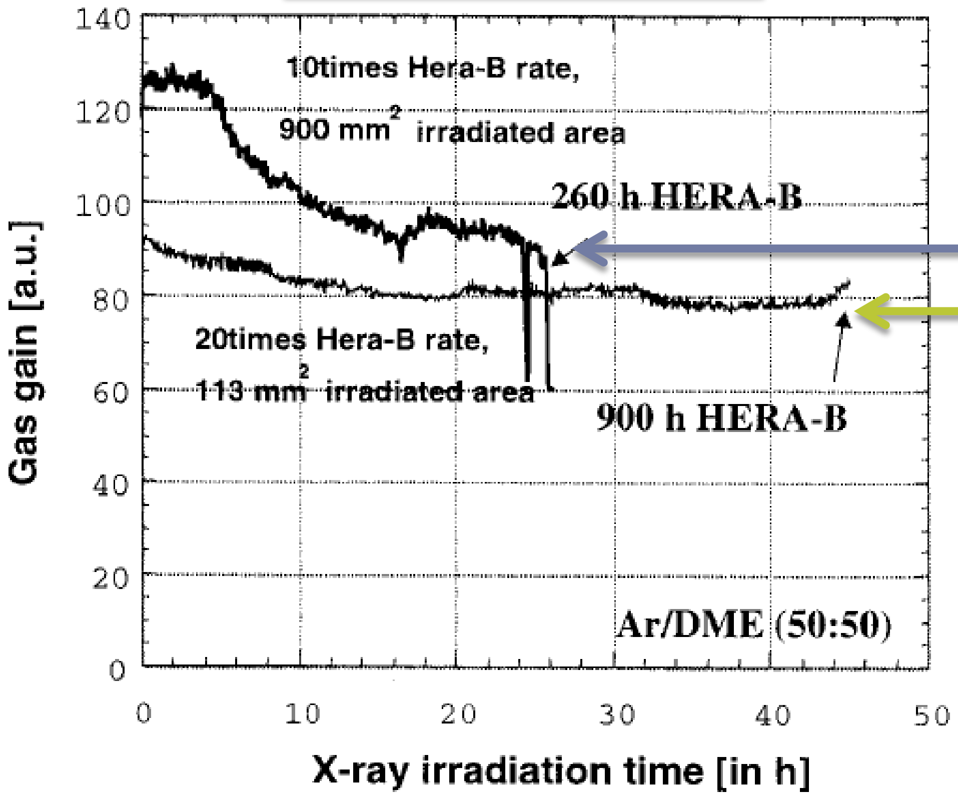
ATLAS TRT Validation Tests

LHC Nominal Gas Flow:

< 0.15 cm^3/min/straw

Ageing Rate for different Beam Size

Hera-B Inner Tracker (MSGC)
C.Richter et al.

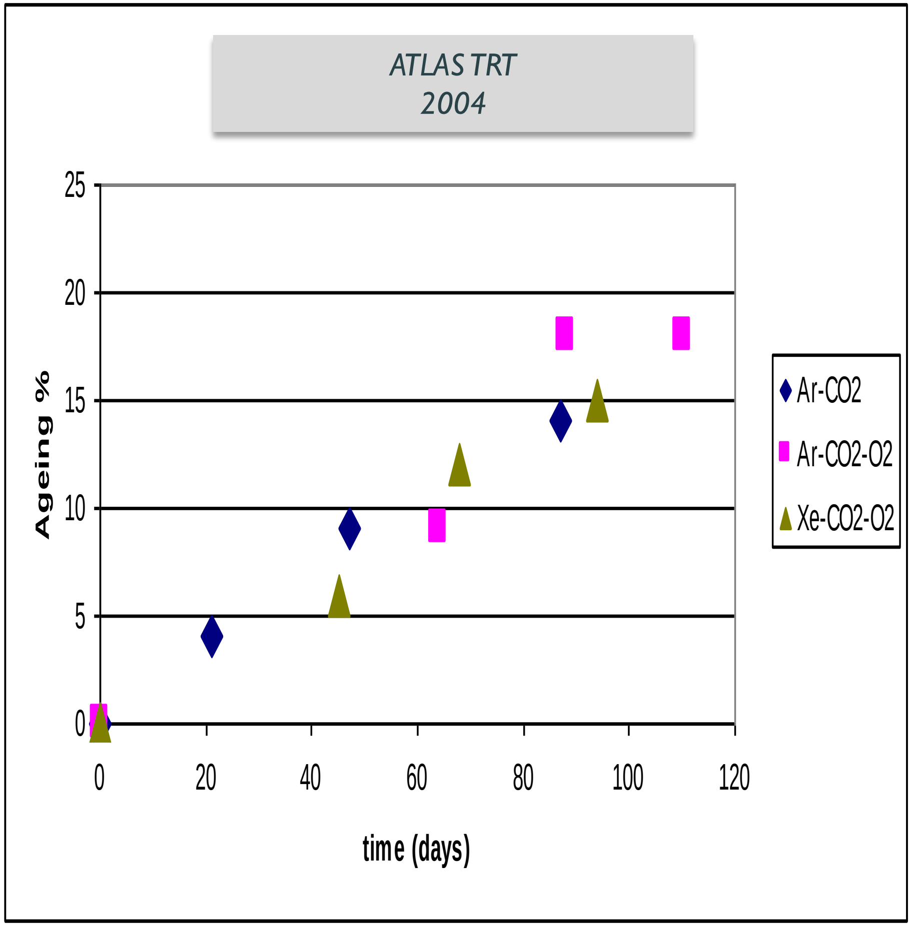


Lab test to measure rate of ageing in the Hera-B MSGCs with X-rays beams of different areas

Irradiated area: 900 mm^2
Acceleration factor x 10
ageing Rate: 28%

Irradiated area: 100 mm^2
Acceleration factor x 20
ageing Rate: 11%

Ageing Rate for different Gas Mixtures



Lab test to measure rate of ageing in ATLAS TRT straws when the gas mixture is contaminated intentionally

ATLAS TRT Validation Tests

LHC Gas Mixture: Xe-CO_2-O_2

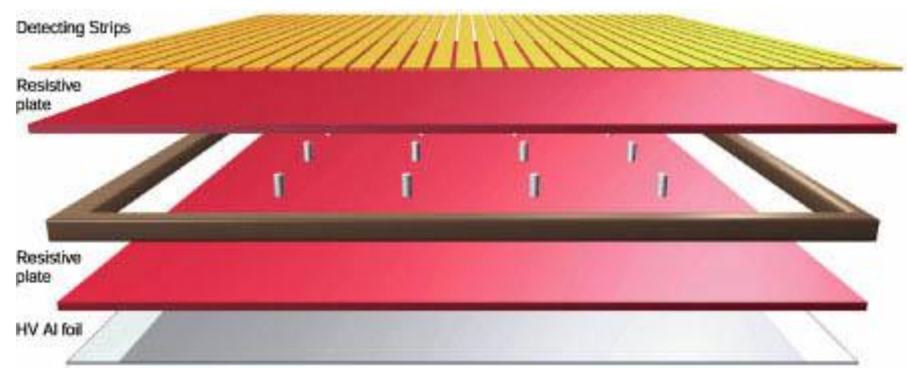
Lab tests: Ar-CO_2

Cheaper mixture, simpler set-ups

Non Classical ageing, Ex: RPC systems

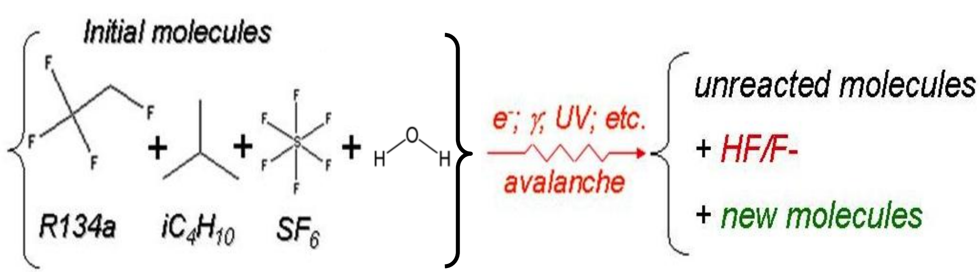
Resistive Plate Chambers (RPCs) at LHC:

- Large areas at low production cost
- High time resolution (~1 ns)
- Suitable spatial resolution (~1 cm)



Gas mixture:

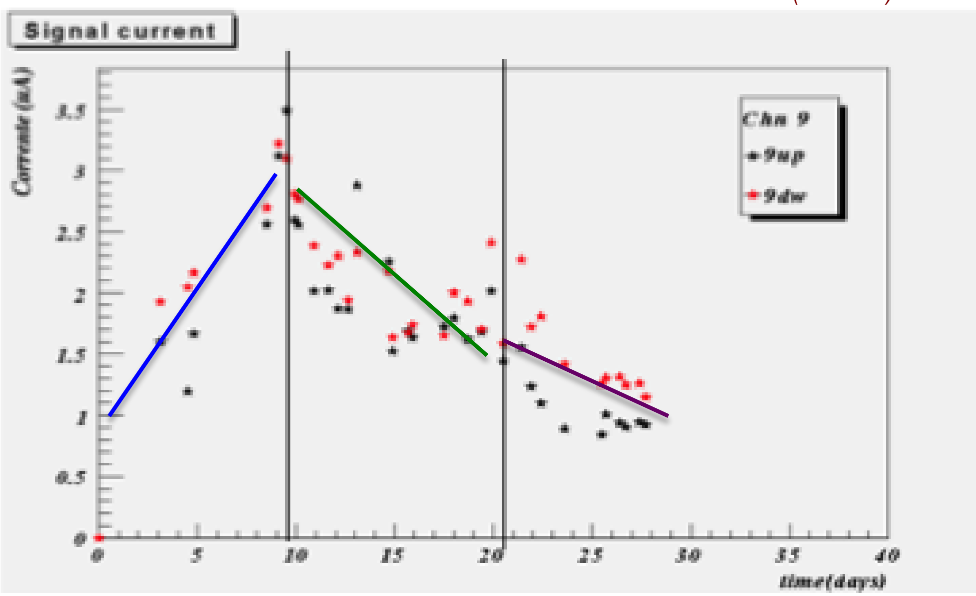
- **$C_2H_2F_4$ - iC_4H_{10} - SF_6 [95-5-0.3 %] +0.1% water vapour**
- The large detector volume (~16 m^3 in ATLAS and CMS) and the use of a relatively expensive gas mixture make a closed-loop circulation system unavoidable.



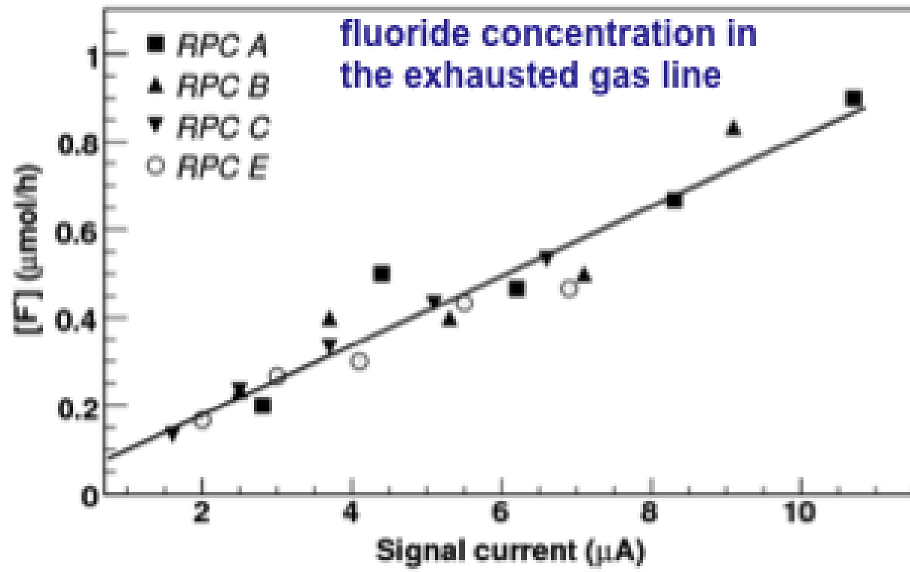
Non Classical ageing, Ex: RPC systems

RPCs under irradiation at GIF, effect of impurities on chamber currents

(R.Guida)



(R.Guida)



Closed-loop gas system

Open-loop gas system

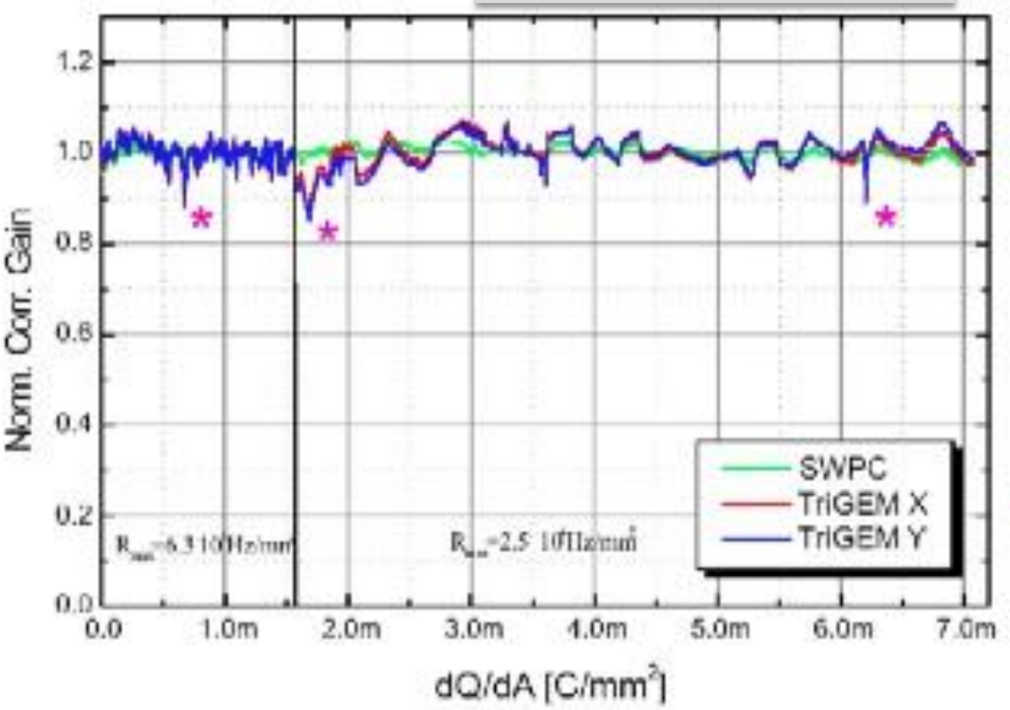
Closed-loop gas system with PURIFIERS

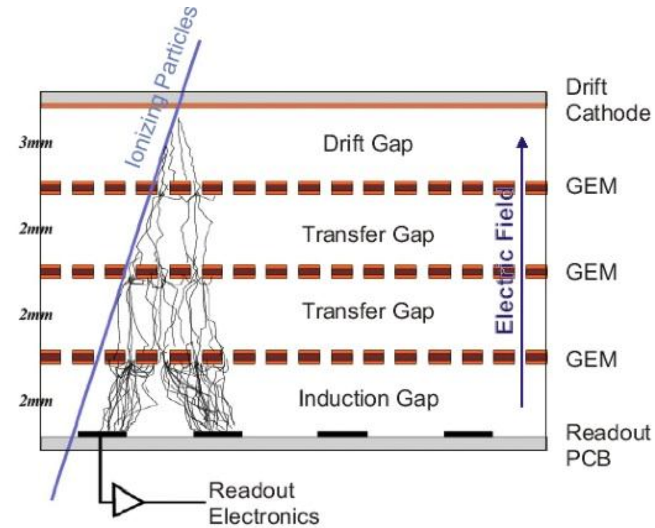
Ageing tests

Parameter	Proven Influence on the result of test	
Gas Mixture	Yes	There are polymerizing mixtures (CH_x), non polymerizing mixtures (CO_2), and cleaning mixtures (CF_4, O_2, H_2O…)! Polluted Mixtures 'pollute' all results
Gas Flow	Yes	Effect depends on: • if pollutant comes with gas flow • if pollutant is inside the detector (assembly material) • if gas etches away the pollutant
Ionization Current Density	Yes	Less ageing is usually measured at very large current densities
Irradiation Area	Yes	Small areas do not show the whole picture.
Irradiation Time (acceleration factor)	Yes	A reasonable compromise can be found…
Irradiation type	Yes	Specially for Malter currents
Chamber geometry	Yes	Can generic studies be applicable to all gas detectors types?

Radiation Hard Detectors, Ex. GEM

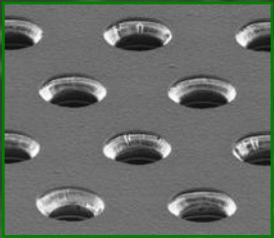
Tripple GEM, S.Kappler et al., 2001





Planar wireless devices where multiplication is obtained over extended regions in relatively moderate field appear to age at much slower pace

- ‘Good’ gas mixture: Ar-CO_2 70-30
- Absence of thin anodes
- Gas amplification inside holes, rather far from signal electrodes and walls
- Field shape and strength possibly not affected by polymerization deposits, if any



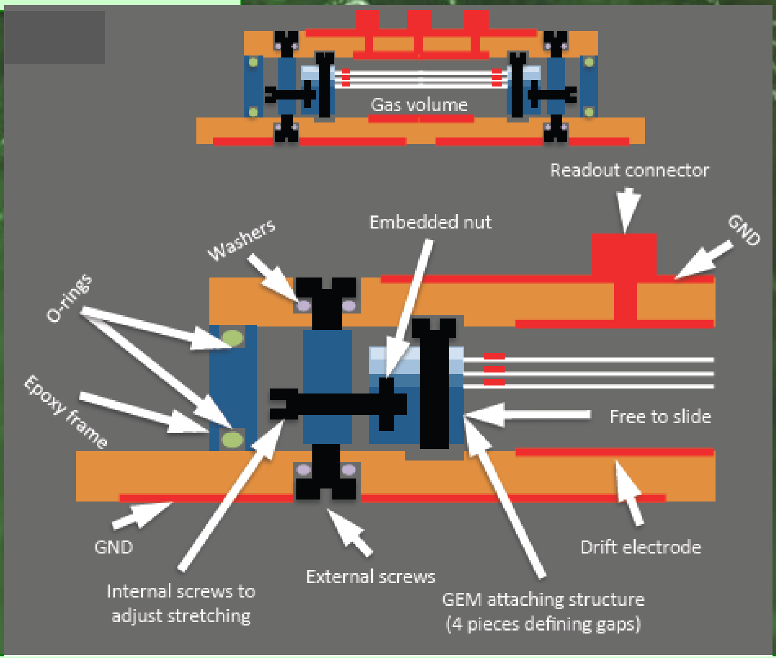
Std GEM :

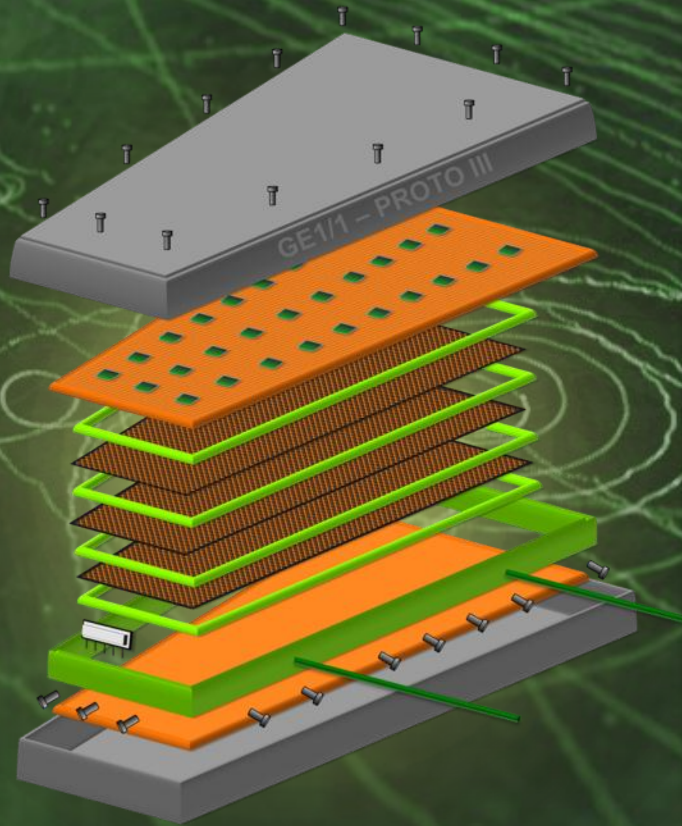
Kapton 50µm

Copper 5µm

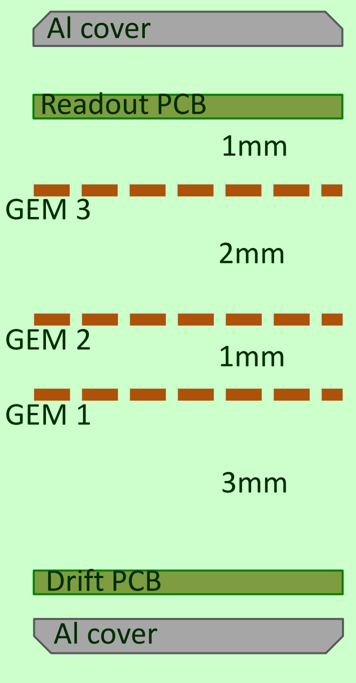
Holes 70µm (dia)

Pitch 140µm

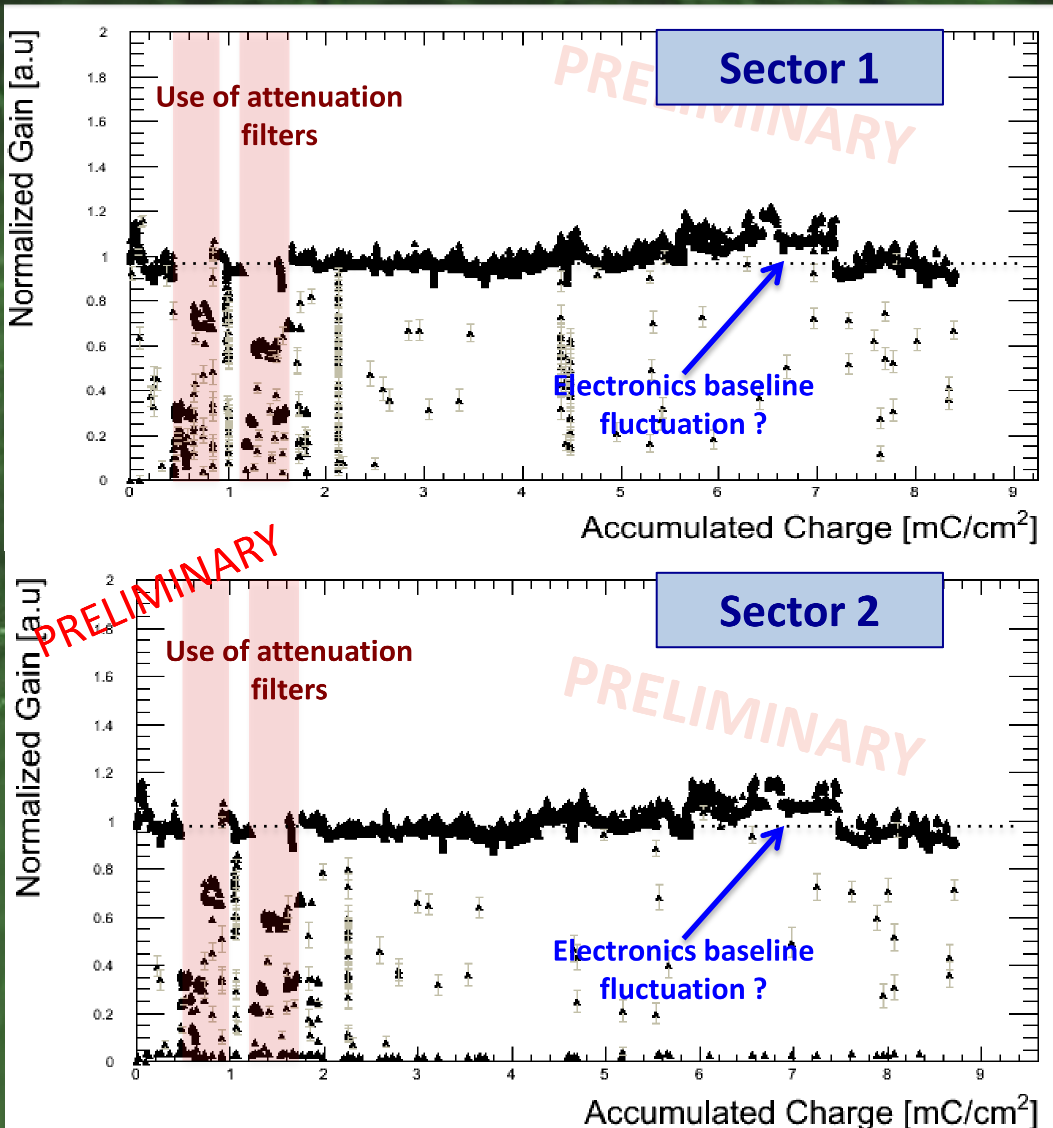




CMS GEM config. :



Classical Aging Test @ GIF (GE1/1-IV)



-> GE1/1-IV :

- Gas gain : $2x10^4$
- $Ar/CO_2/CF_4$:45/15/40
- Gas flow rate : 0.5L/h
- Max interaction rate : kHz/cm^2

-> Acceleration factor ~ x3

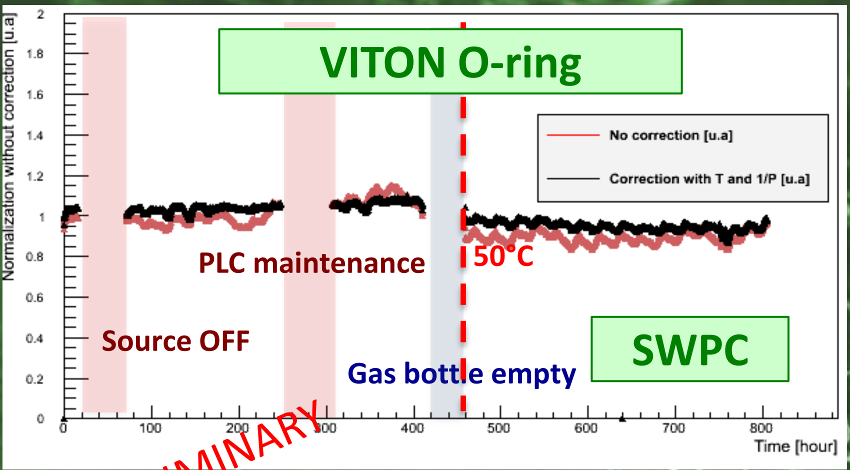
-> First observations :

- interaction rate similar to CMS
- accumulated charge : 9 mC/cm^2

→ ***No aging effect observed in the GE1/1 detector up to 9mC/cm^2 in realistic conditions***

CMS GEM Long term stability

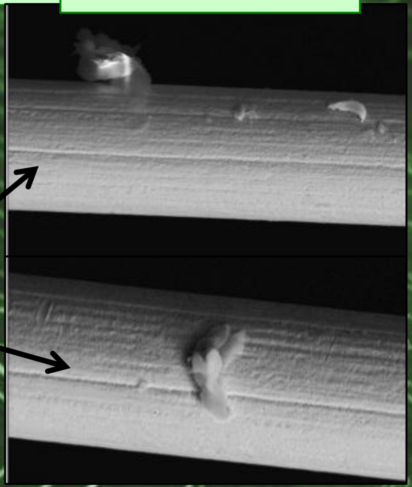
Outgassing studies

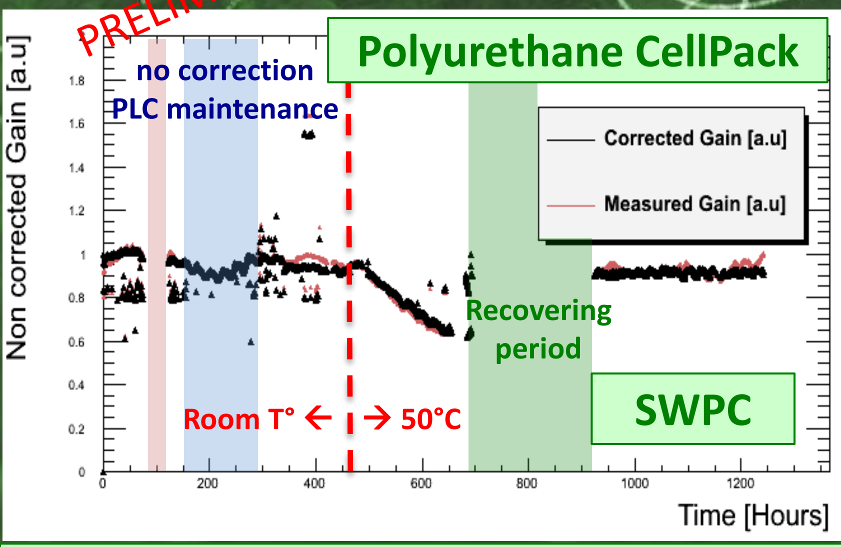


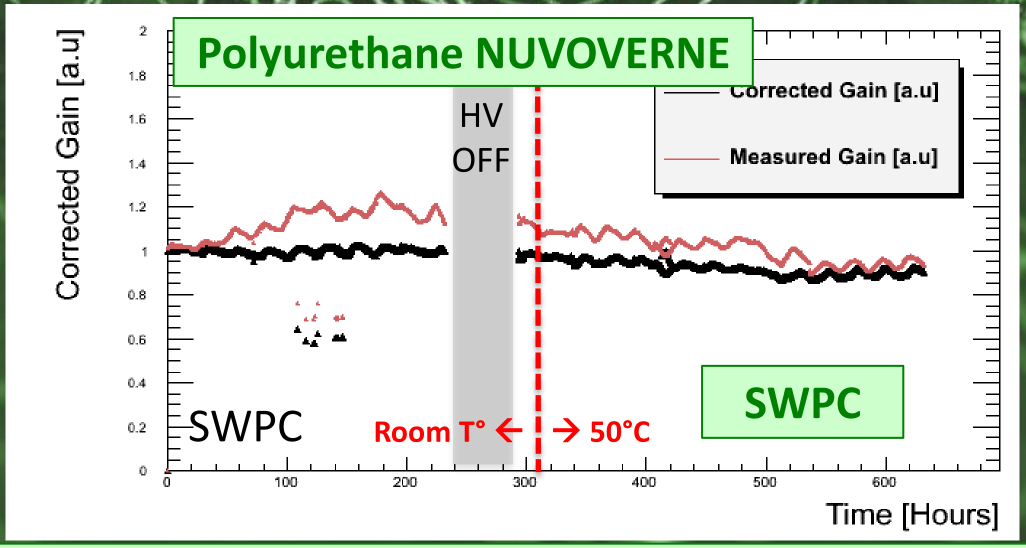
SWPC

- → No effect with VITON O-ring
- → No significant effect with NUVOVERN (extension of the test)
- → Strong gain drop with CellPack

SEM (CellPack)



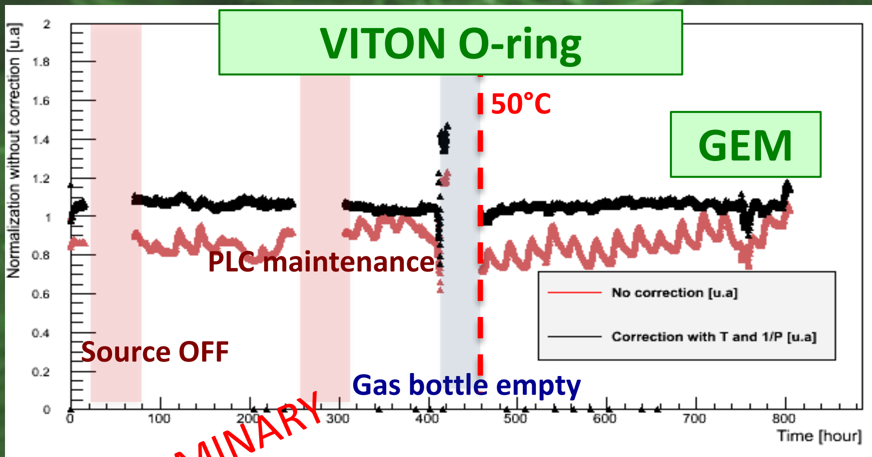




Aging study of large triple-GEM detectors for the high rate environment in CMS

CMS GEM Long term stability

Outgassing studies



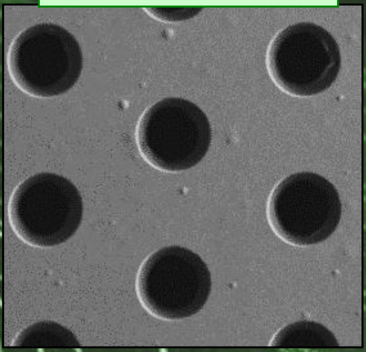
GEM 10x10

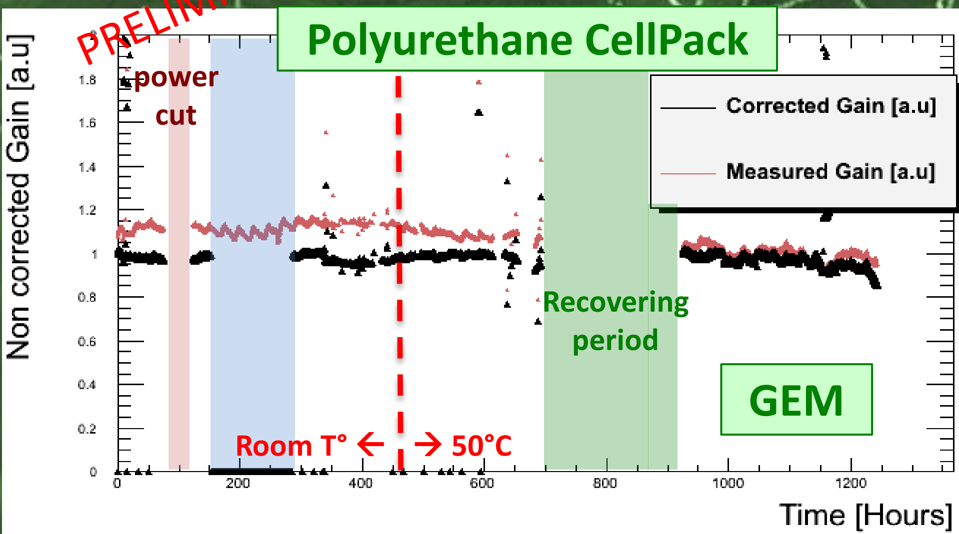
→ No effects on gain for all samples

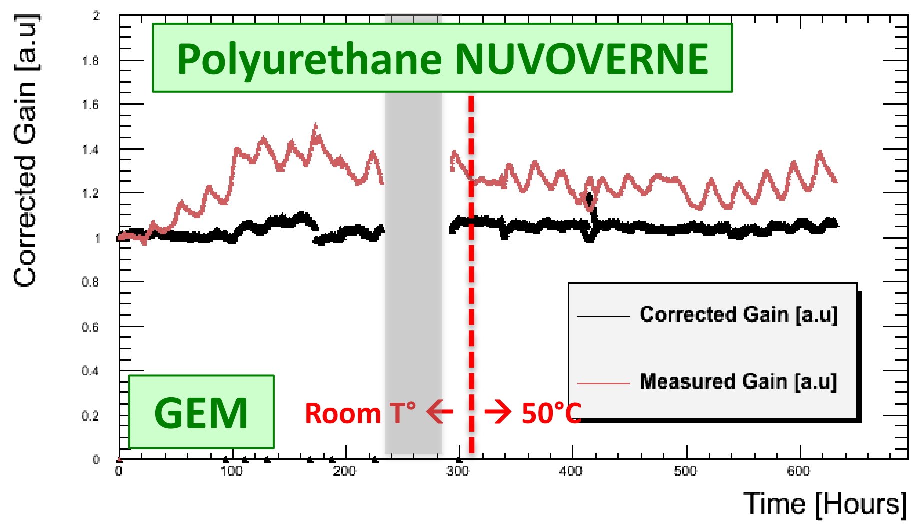
(event if outgassing material)

→ Does the polymers affect other properties of the GEM foils ?

SEM (CellPack)







Concluding remarks

- Gaseous detectors are still the first choice whenever large area particle detection and medium space resolution is required
- New gas detector developments (the MPGD family) extend the capability of gas detectors to applications where very high rate capabilities are required
- Long-term operation in the high-intensity experiments of the LHC- and HL-LHC-era not only demands extraordinary radiation hardness of construction materials and gas mixtures but also very specific and appropriate assembly procedures and quality checks during detector construction and testing
- Intensive research in this field has demonstrated that **when properly designed, constructed and operated, gaseous detectors are robust and stable**
  - ***Use good gases***: *noble gas with CO_2 and maybe a small concentration of CF_4 or small amounts of additives like water, O_2…*
  - ***Avoid contaminating the gas***:
    - *Use outgassing-free detector assembly materials*
    - *Control all components in contact with the gas (gas system, piping, etc).*
    - *Do careful quality assurance during detector production*
    - *Review existing knowledge!*
  - ***Test well:*** *select carefully the operating conditions in the lab (gas mix, gas flow, gain, rate, beam size, etc.)*
  - ***Monitor anomalous behaviour of detectors***. *If ageing is detected soon enough, detector can probably be recovered (using additives in the gas, varying the gas mixture, reversing HV for some time, flushing with large amounts of clean gas…)*

Compilations

- Ageing:
  - **Wire chamber ageing**, J.A. Kadyk (LBL, Berkeley)

    Nucl. Instrum. Meth. A300:436-479 (1991)
  - **Proceedings of the International Workshop on ageing Phenomena in Gaseous Detectors**, M.Holhman et al. (DESY)

    Nucl. Instrum. Meth. 515, Issues 1-2, (2003)

    - Fundamental understanding of aging processes: review of the workshop results, F.Sauli (CERN)
    - Ageing and materials: lessons for detectors and gas systems, M.Capeans (CERN)
- Materials Properties for Gas Detectors and Gas systems:
  - http://cern.ch/detector-gas-systems/Equipment/componentValidation.htm

BACK UP SLIDES

Radiation Hardness of Particle Detectors

For **silicon**, bulk radiation damage results from non-ionizing energy loss (NIEL) displacements, so total neutral and charged particle fluence is normalized to flux of particles of fixed type and energy needed to produce the same amount of displacement damage, conventionally 1 MeV neutrons (1 MeV $n/cm^2/year$)

For **gas detectors**, we consider amount of charge deposited on electrodes due to avalanches (C/cm per unit time) as the relevant magnitude

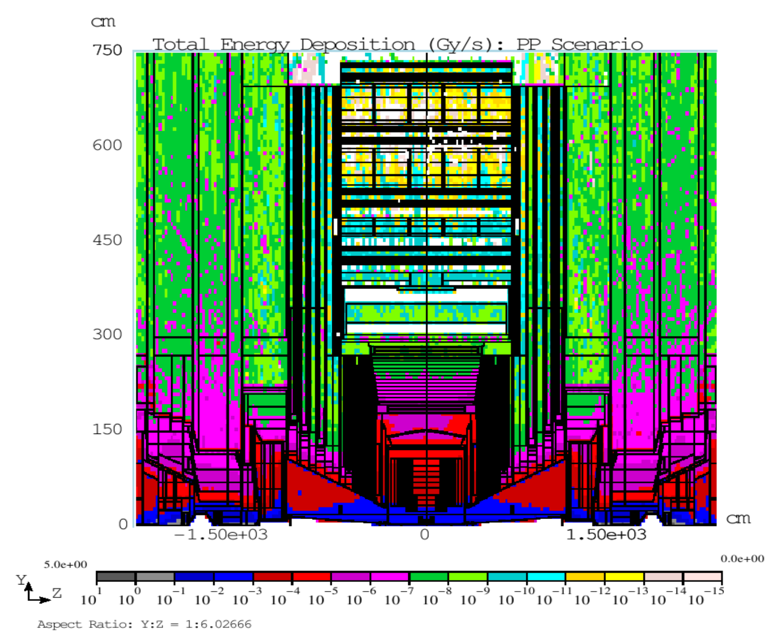
- Add Safety factors (x2, x5…)
- Radiation Hardness Tests
  - Expose detectors and components to very large particle rates to attain large doses in a very accelerated manner
  - Typical test lasts between days and weeks (time needed to achieve target dose)
  - Detector is powered and monitored; performance is tested before/after irradiation

- Add Safety factors (x2, x5…)
- Radiation Hardness Tests
  - Expose detectors and components to very large particle rates to attain large doses in a accelerated manner
  - Good tests are done as slow as possible (months) and irradiating areas as large as possible
  - Detector performance is monitored during irradiation

Radiation levels and Safety Factors

- Estimates:
  - Simulation of number and momentum spectra of particles arriving to detectors at LHC reference luminosities (and machine-induced backgrounds).
  - Get radiation dose maps, particle fluxes and energy spectra (photons, neutrons, charged particles).
- With magnets on:
  - They affect the low momentum particles which may loop and hit some of the detectors many times.
- With detector materials (location and quantity) as close as possible to reality.

Simulated radiation dose (Gy/s) map in CMS
P.Bhat, A.Singh, N.Mokhov

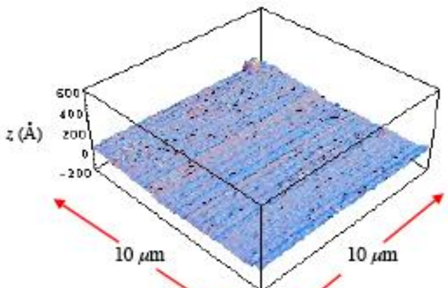


Note that radiation simulation may be wrong by some factors and long-term effects may not be fully predictable.
SAFETY FACTORS ARE ADDED TO ALL ESTIMATES

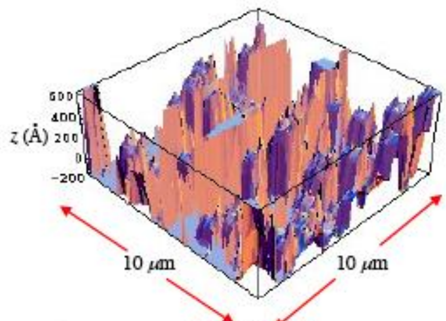
Non Classical ageing Processes

Non classical aging problems have been observed in

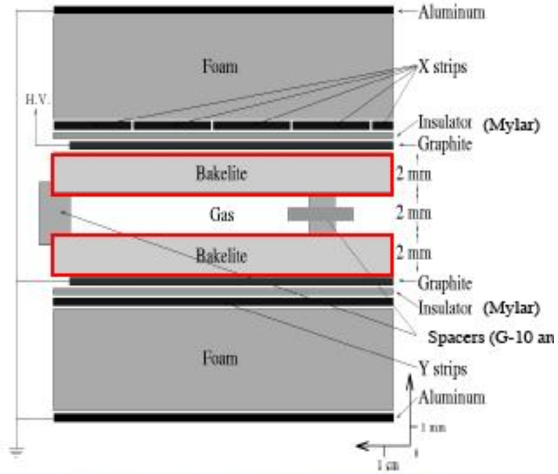
- Belle
  - 2000 ppm H_20 due to use of plastic tubing permeating too much water into the chamber
  - => HF acid etching of glass surface



Virgin Glass Surface



Bad Anode



- Babar
  - high temperature + uncured linseed oil => reduced resistivity of linseed oil
  - formation of droplets => shorts
  - growth of whiskers