Radiation Hardness of Gaseous Detectors

1st EIROforum School on Instrumentation

Mar Capeans

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Outline

- Radiation Damage of Gas Detectors: AGING
- Aging Phenomena
- Particle Rates at LHC
- Factors Affecting the Aging Rate
- Strategies to Build Radiation-Hard Gas Detectors

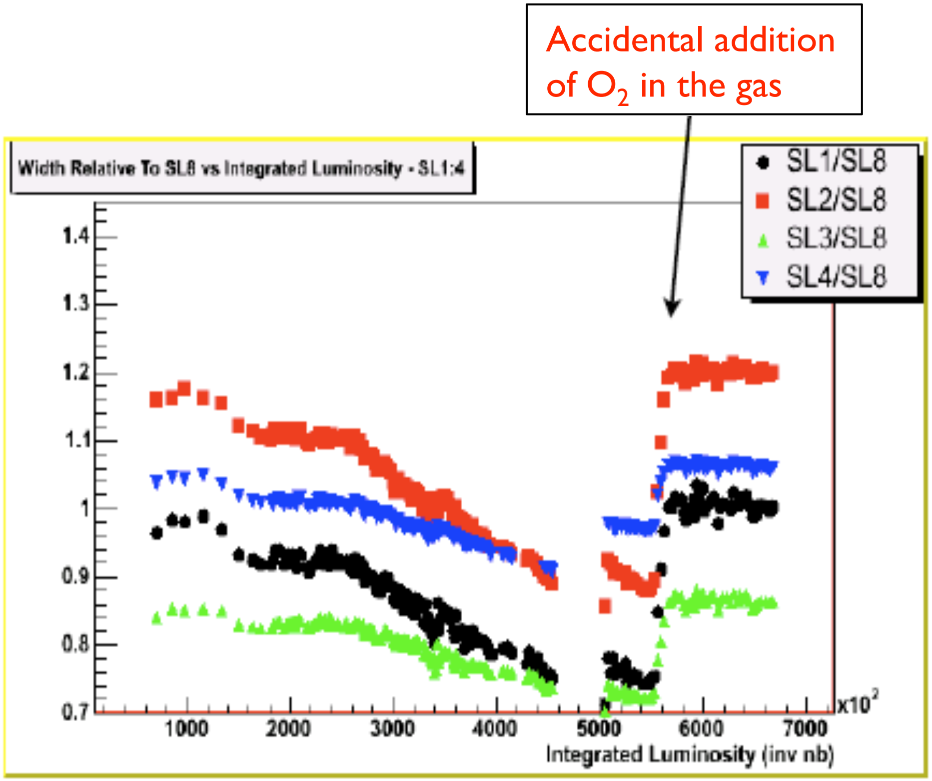
Radiation Damage of Gas Detectors

- **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 to use 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 **AGING**

Radiation Damage → Gas Detectors Aging

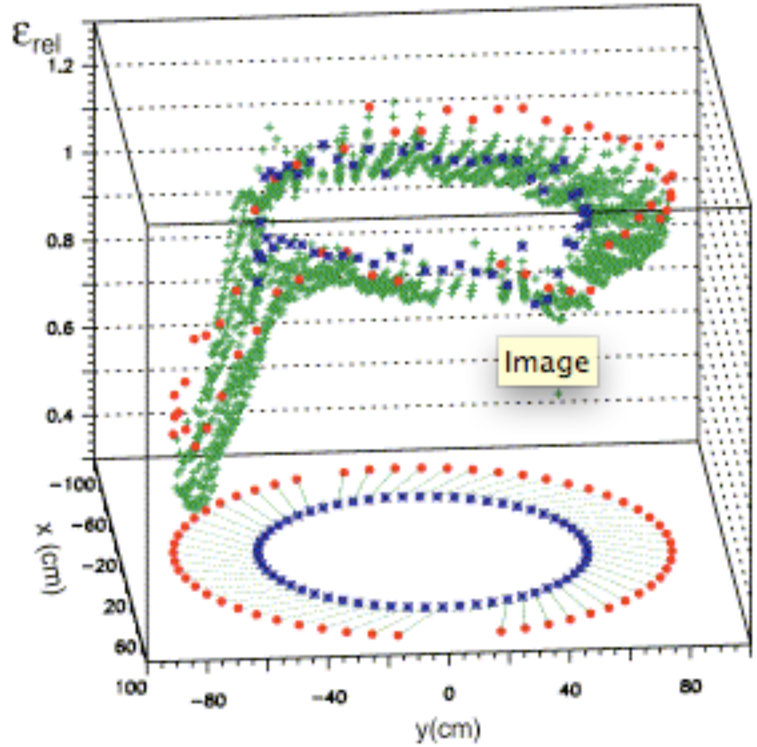
Gray (Gy) → C/cm (or /cm^2)

Aging of Gas Detectors in Experiments



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

Drift chamber
Ar-C_2H_6 [50-50] + 1.7% isopropanol

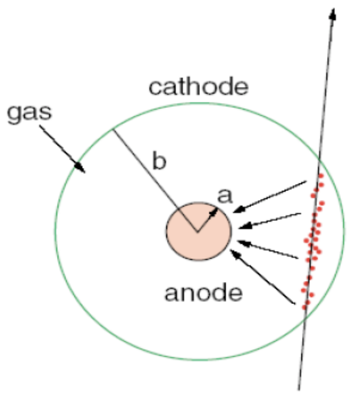


Aging in the Central Jet Chamber of H1
DESY (C.Niebuhr)

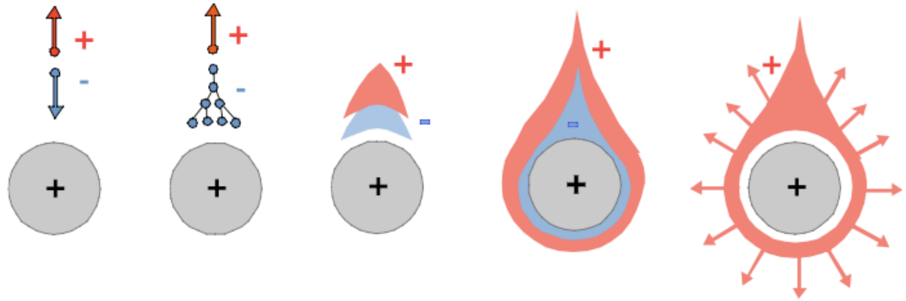
Radial Wire Chamber
Ar-C_2H_6 [50-50] + water

Gaseous Detectors - Principle

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



Principle of Gas Multiplication ~ Signal development

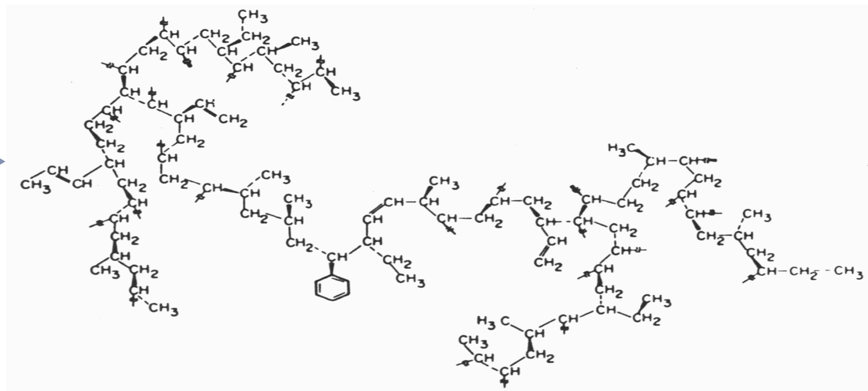


1. Gas mixture → $Ar + CH_4$

2. Initial Reaction → $e^- + CH_4 \Rightarrow CH_2: + H_2 + e^-$

3. Creation of radicals → $CH_2:$

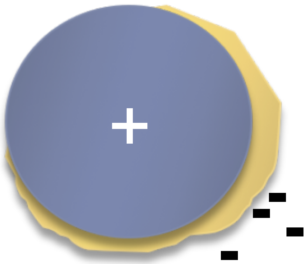
4. Polymer Formations →

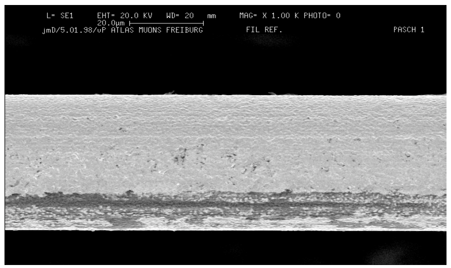


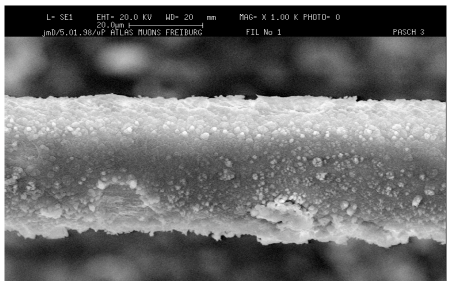
- Solid, highly branched, cross linked
- Excellent adhesion to surfaces
- Resistant to most chemicals
- Insoluble in most solvents

Aging Phenomena

- Anode Aging: deposits on wire







Effect of Deposits

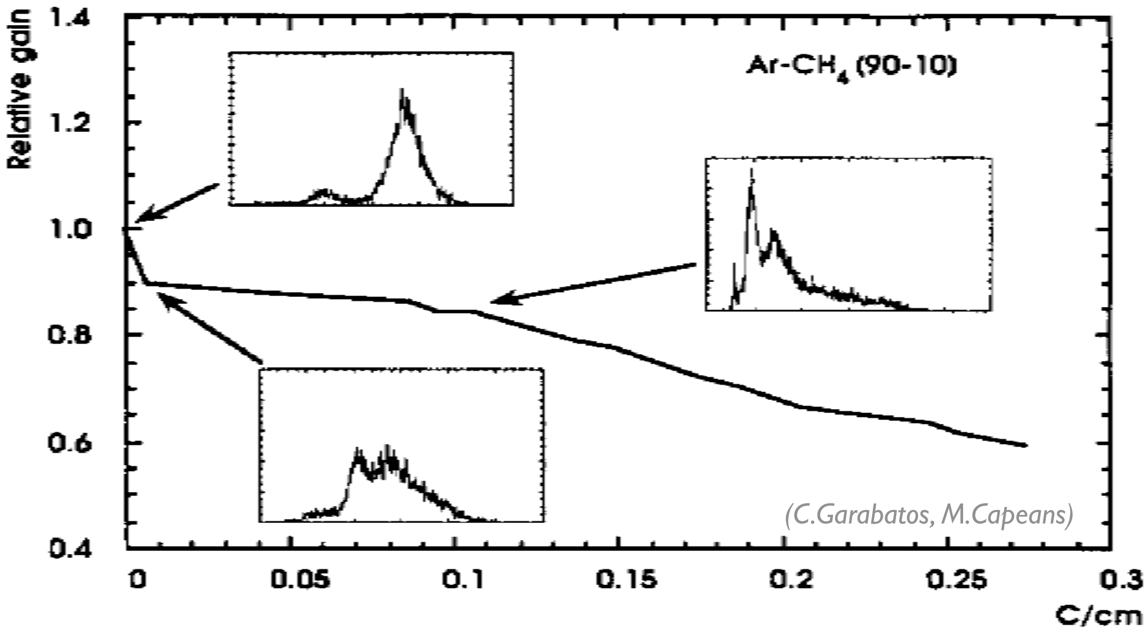
- If deposit is **conductive**, there is a direct effect: the electric field weakens (~thicker wire)
- If deposit is **insulating**, there is indirect effect due to dipole charging up: the field close to the anode will be screened as new avalanches accumulate negative charges on the layer

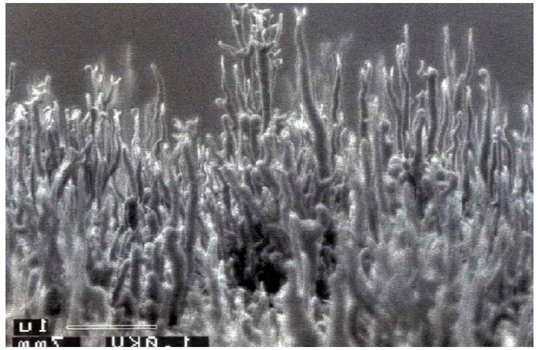
Consequences on the detector

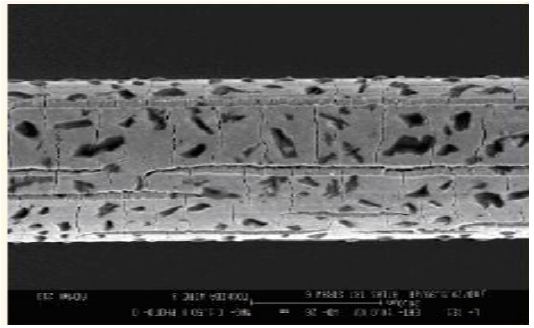
- Decrease of gain
- Lack of gain uniformity along wires
- Loss of energy resolution

Anode Aging

SWPC
Aging Test in Laboratory

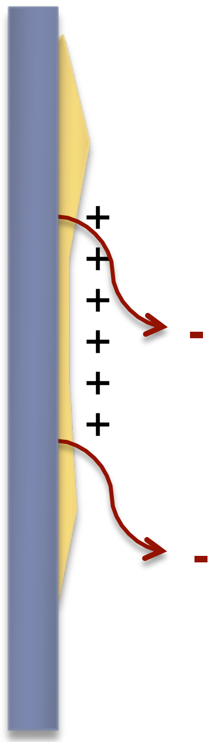






Aging Phenomena

- Cathode Aging: layers on surfaces



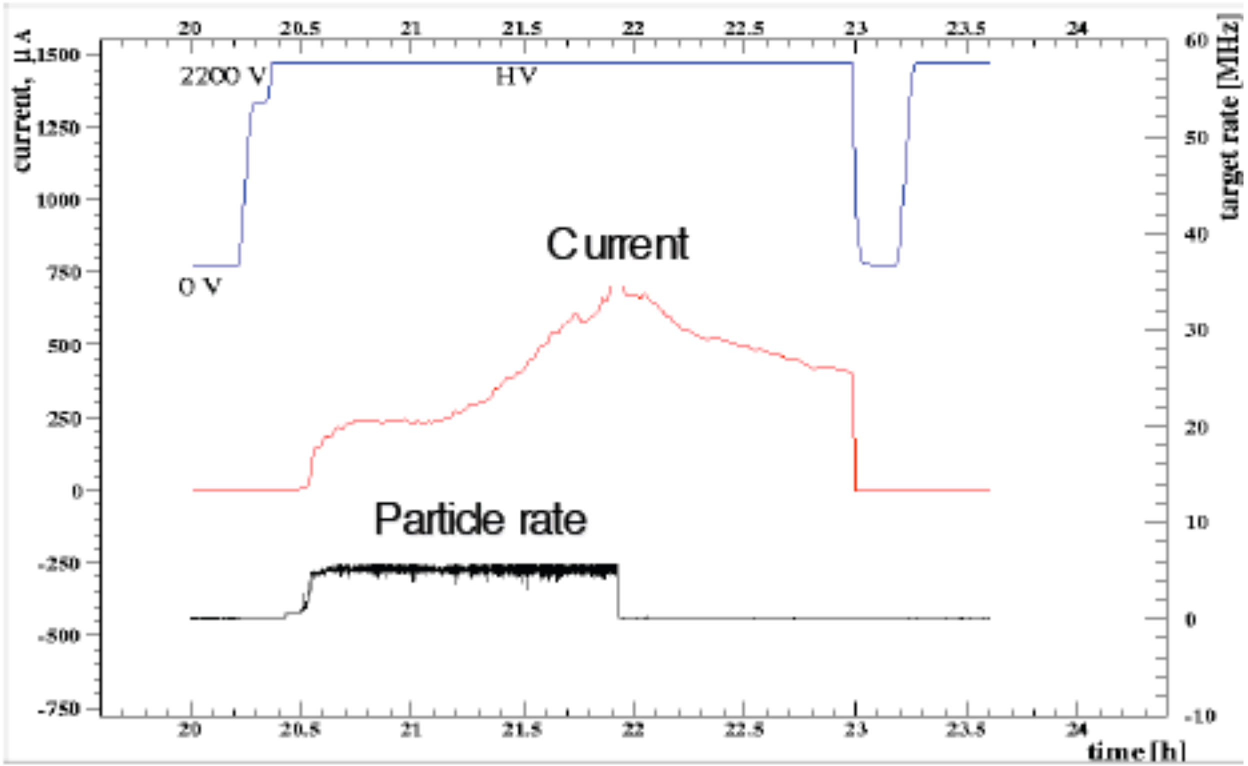
Effect of Layers

- 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 Aging



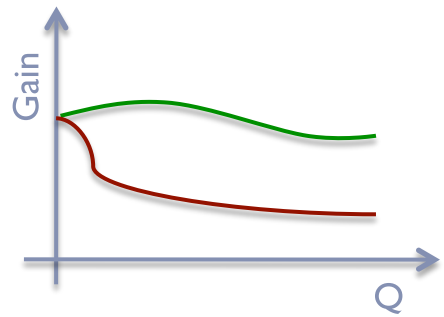
Malter effect

Rate of Aging

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

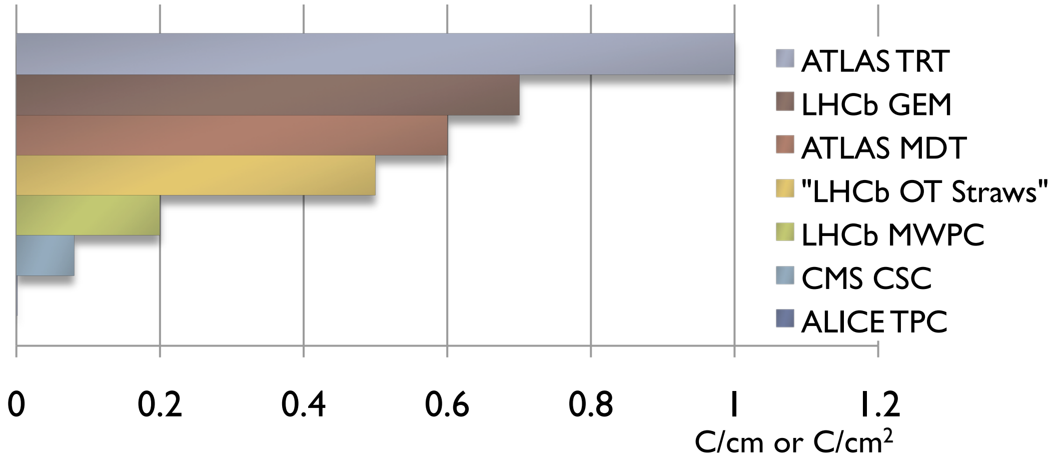
  Q [C] = Gain x Rate x Time x Primaries

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



- **Accumulated charge per LHC year:**

  - 1 LHC year = 10^7 s
  - Different safety factors
  - Detectors operating at nominal conditions



Accelerated Aging Tests

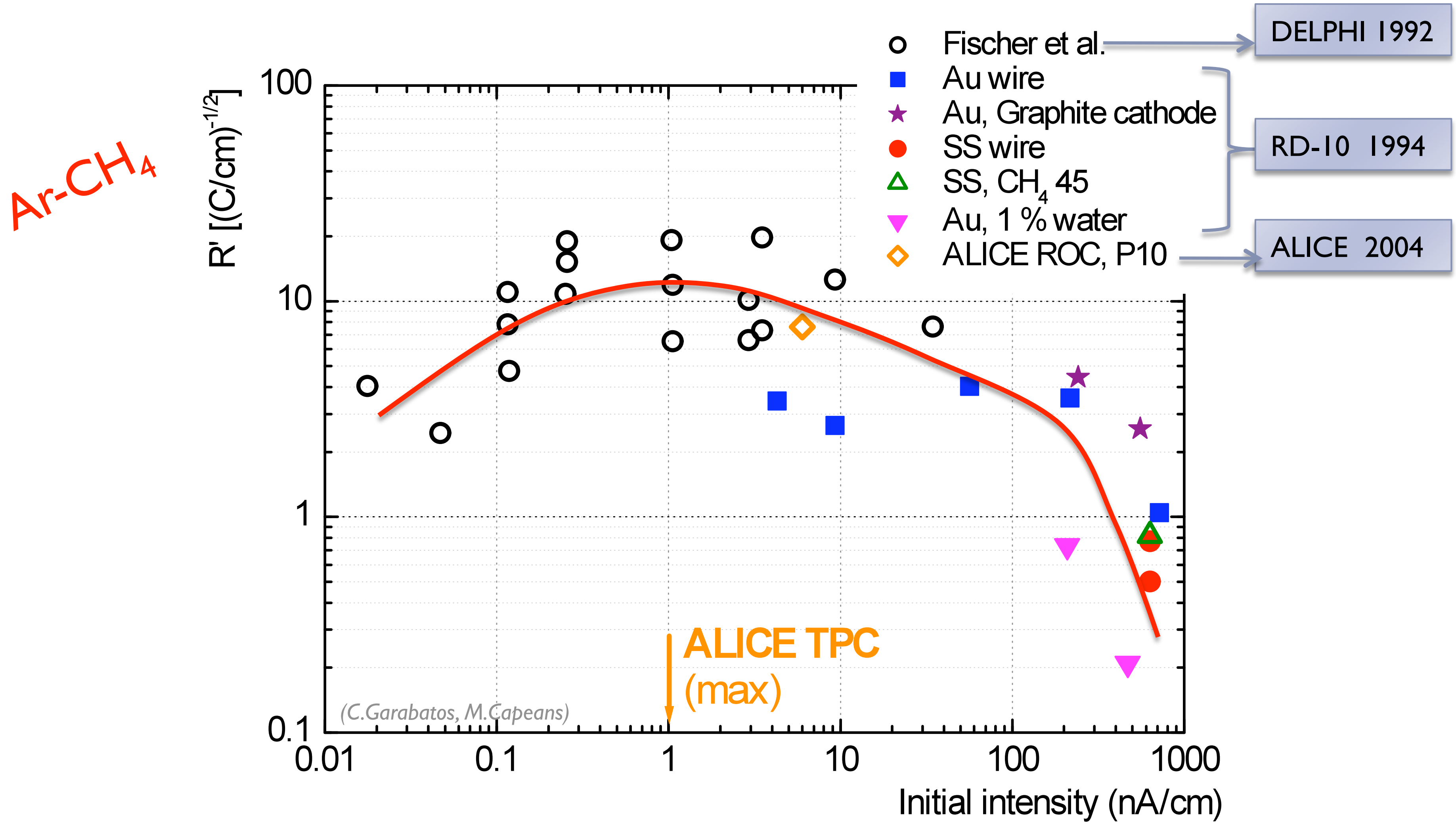
- Needed in order to asses lifetime of a detector under irradiation in a limited amount of time
- How much can we **accelerate** the tests in the lab with respect to the real conditions?
- …Aging depends on:

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

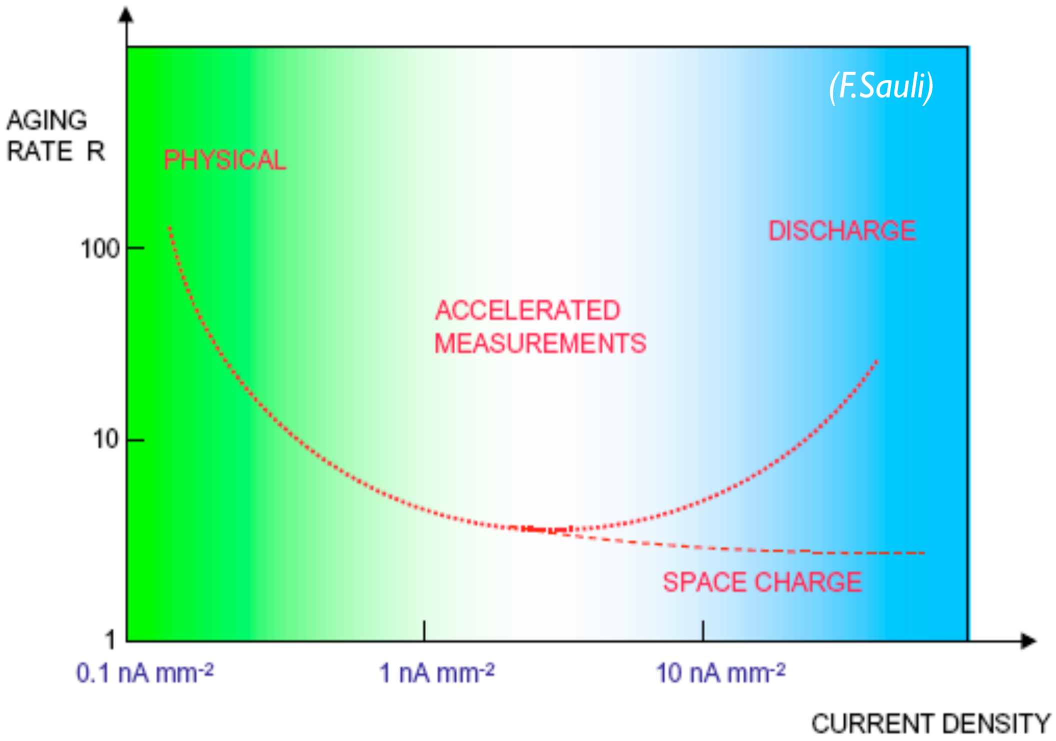
Gain:
- HV
- Gas mixture
- Pressure
- Gas exchange rate
- Electrical field strength
- Detector geometry
- …

Primaries:
- Dose rate
- Ionization density
- Particle type
- …

Rate of Aging



Extrapolation of Results



Examples:

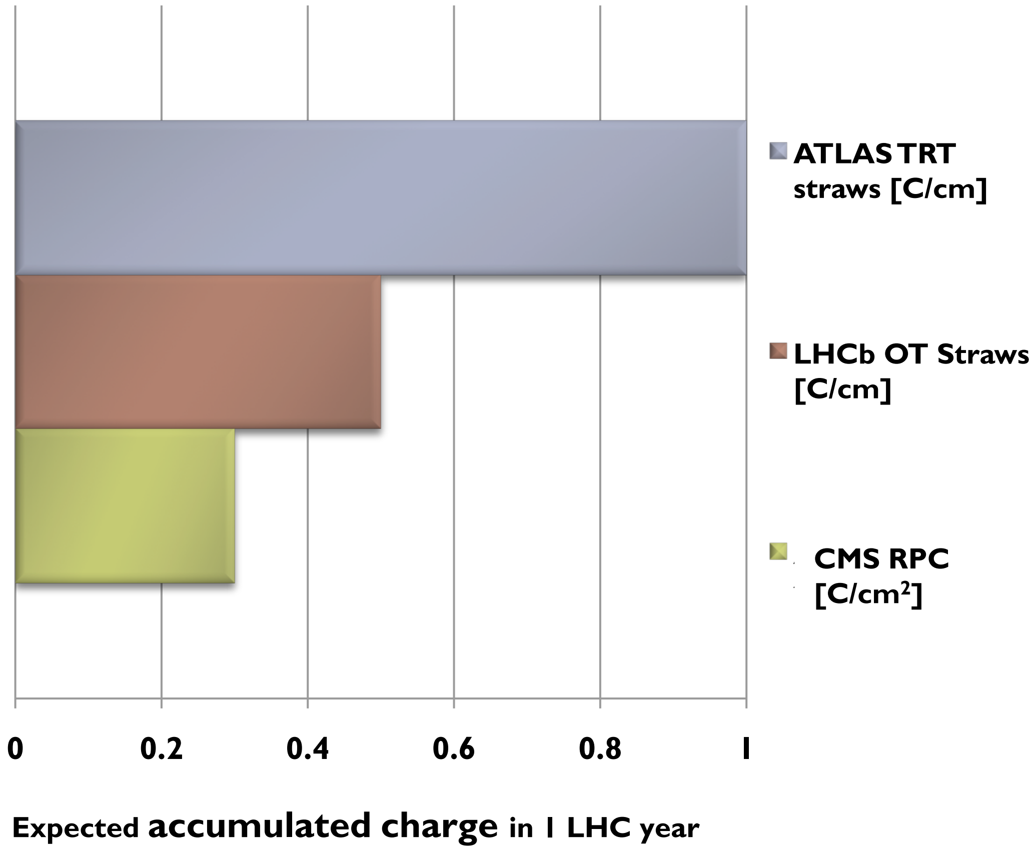
- Space charge gain saturation can decrease the polymerization efficiency
- Gas flow insufficient to remove reaction products created at high rate

Acceleration Factors in Aging Tests of LHC Detectors

Acceleration Factor in Lab Tests

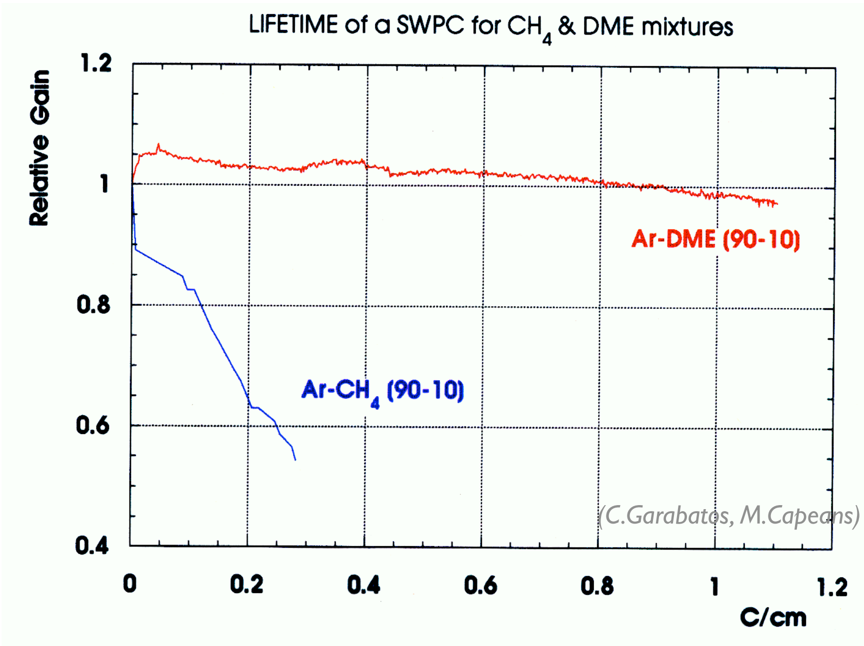
Atlas TRT	x 10
LHCb OT (Straws)	x 20
CMS RPC	x 30 (and much larger)

Accumulated charge in 1 year at LHC



Influence of the Gas Mixture on Aging

- Hydrocarbons: polymerization (so, aging) 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

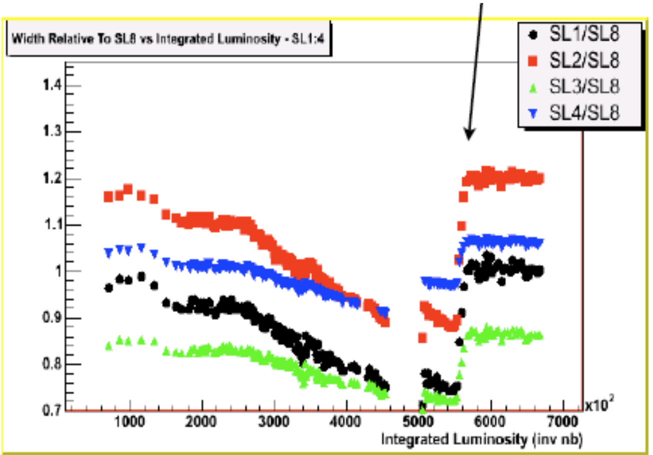
- Increased HV
- More energetic discharges

Additives, Emergencies

- Small concentrations of O_2 or H_2O or C_2H_6O can restore aged chambers or prevent effectively the aging 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]



CF_4

Deposition

In hydrogenated environments – CH_4

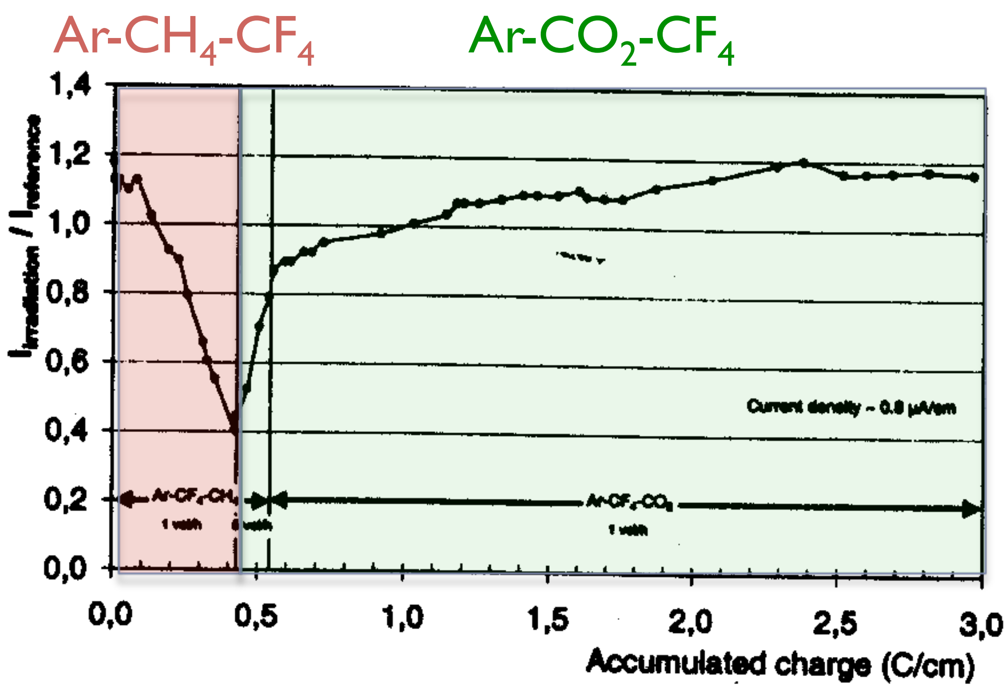
Deposits on wires

Etching

If oxygenated species are added – CO_2

Wire cleaning

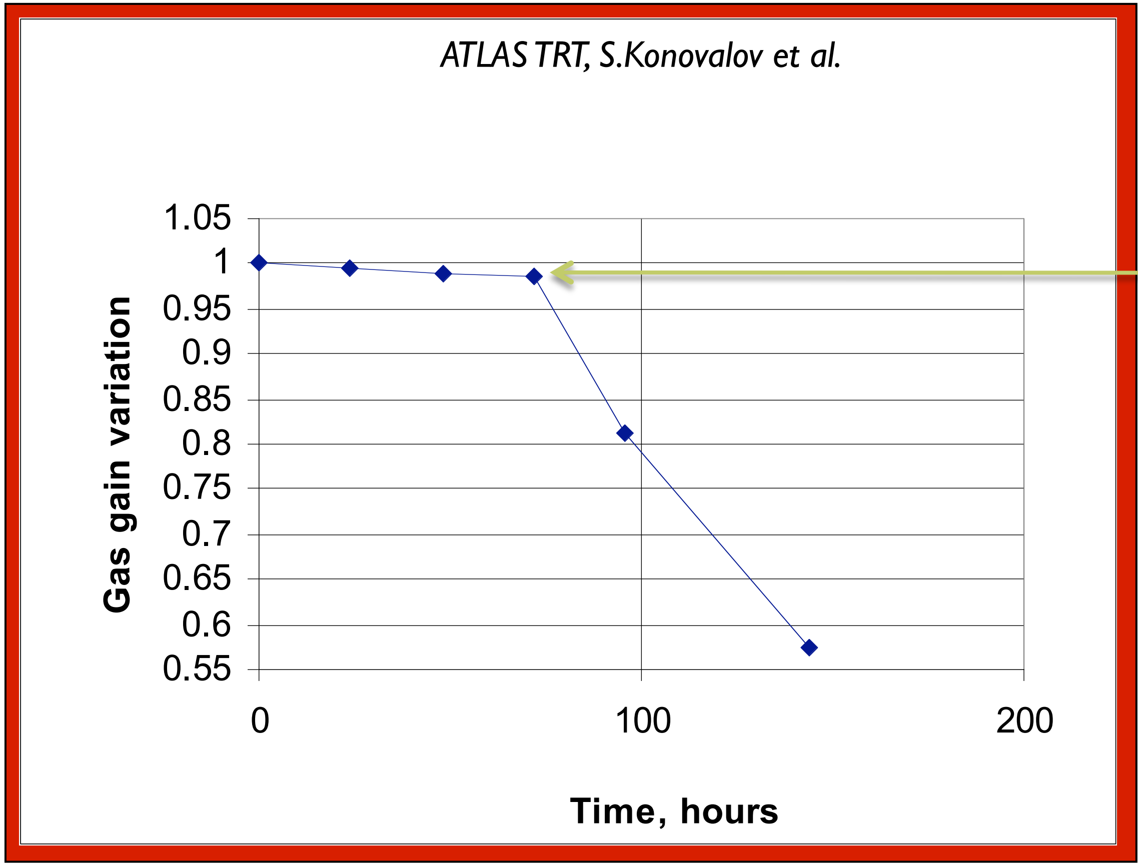
Can also be aggressive to some detector assembly materials, can accumulate



Gas Mixtures in LHC detectors

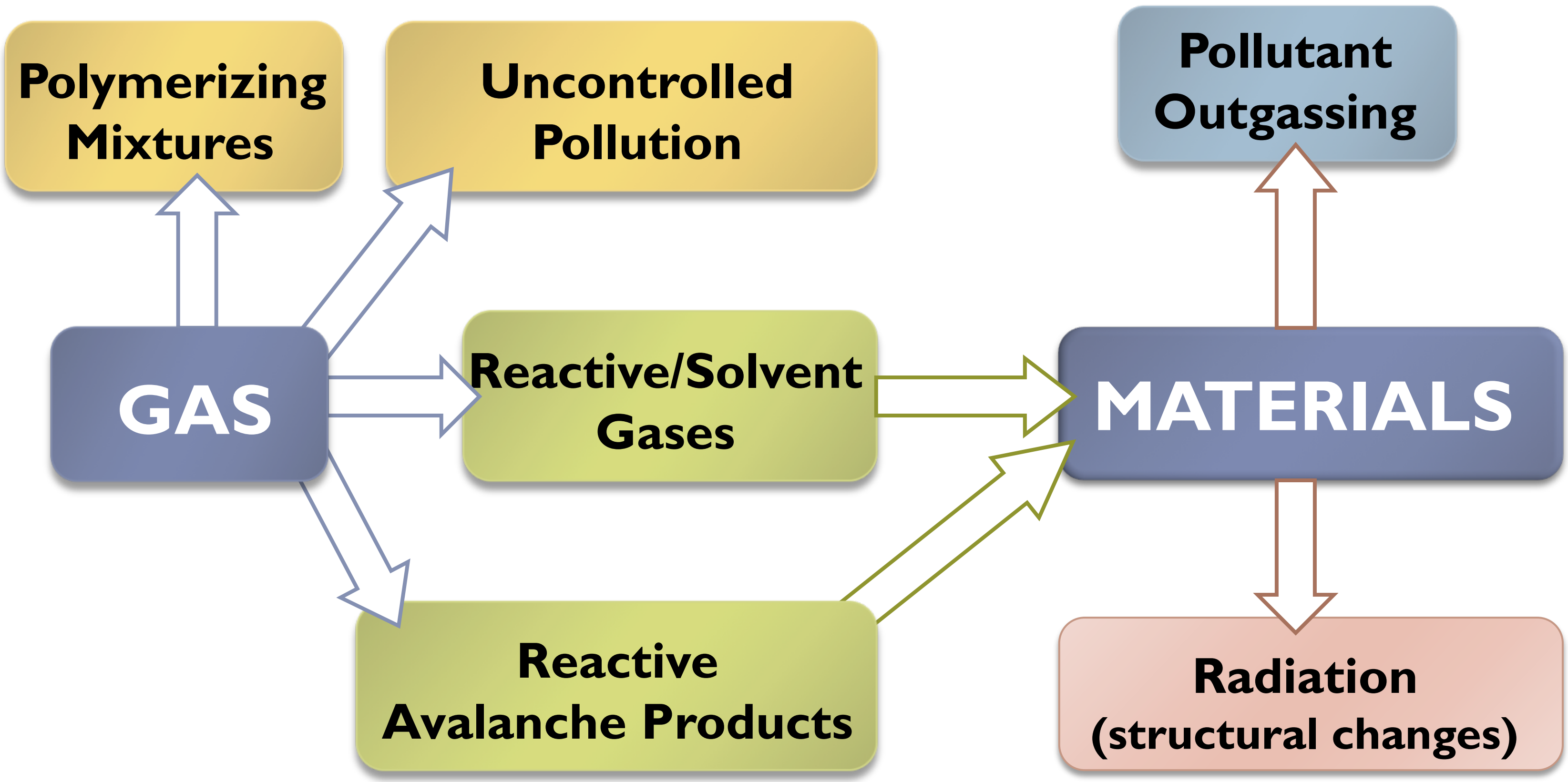
Experiment	Sub- Detector	Gas Mixture
ALICE	TPC, TRD, PMD	Noble Gas (Ar, Ne, Xe) + CO_2
ATLAS	CSC, MDT, TRT	
CMS	DT	
LHCb	OT straws	
TOTEM	GEM, CSC	
LHCb	MWPC, GEM	Ar - CF_4 - CO_2
CMS	CSC	
	RPC TGC RICH	$C_2H_2F_4$ - iC_4H_{10} - SF_6 CO_2 – n-pentane CF_4 or C_4F_{10}

Pollution of the Gas Mixture



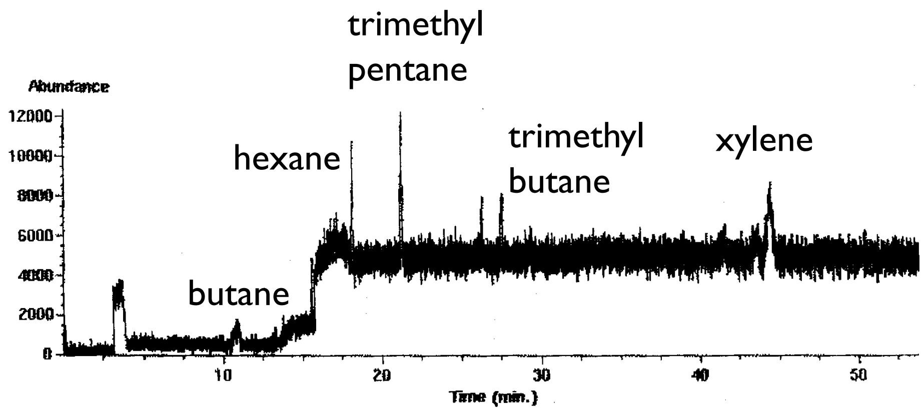
Inserted a new flowmeter in the gas system, and gas gets polluted by minute amounts of Silicone-based lubricant

Other Contributions to the Aging Process



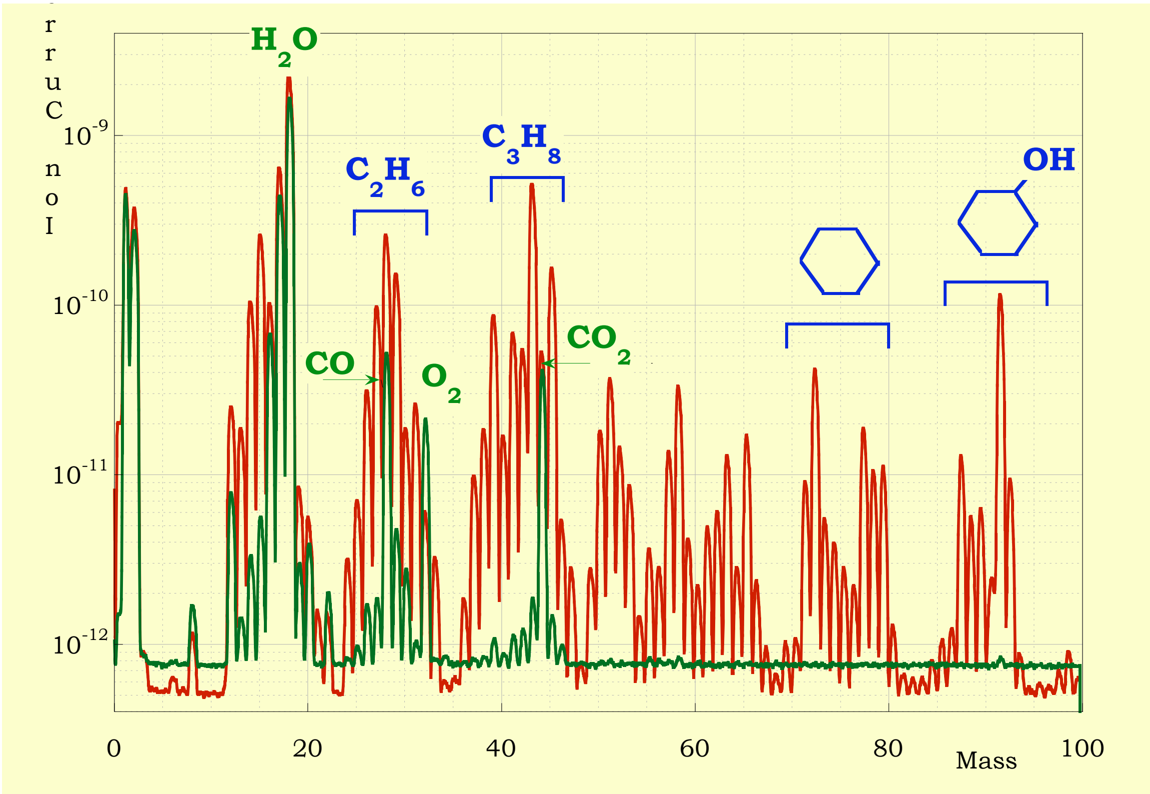
Effect of Materials

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



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

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

Rigid Materials

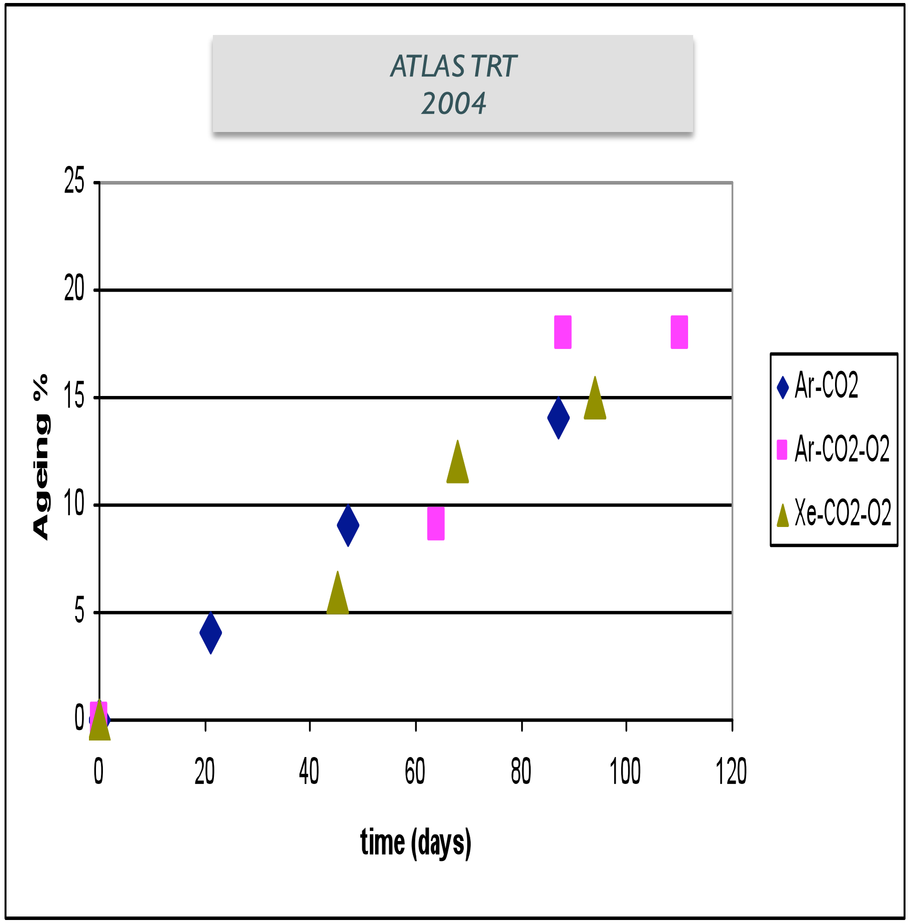
Source	Name	Type	Outgas	Effect in G.D.	Result
CERN/GDD	STESALIT 4411W	Fiberglass	YES	NO	**OK**
CERN/GDD	VECTRA 150	Liquid Crystal Polymer	YES	NO	**OK**
CERN/GDD	PEEK Crystalline	Polyeteherether ketone	NO	NO	**OK**
ATLAS/TRT	ULTEM	Polyetherimide	NO	-	**OK**
ATLAS/TRT	C-Fiber	C-fiber	NO	-	**OK**
ATLAS/TRT	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

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**

(C.Garabatos, M.Capeans)

Aging Rate, for different Gas Mixtures



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

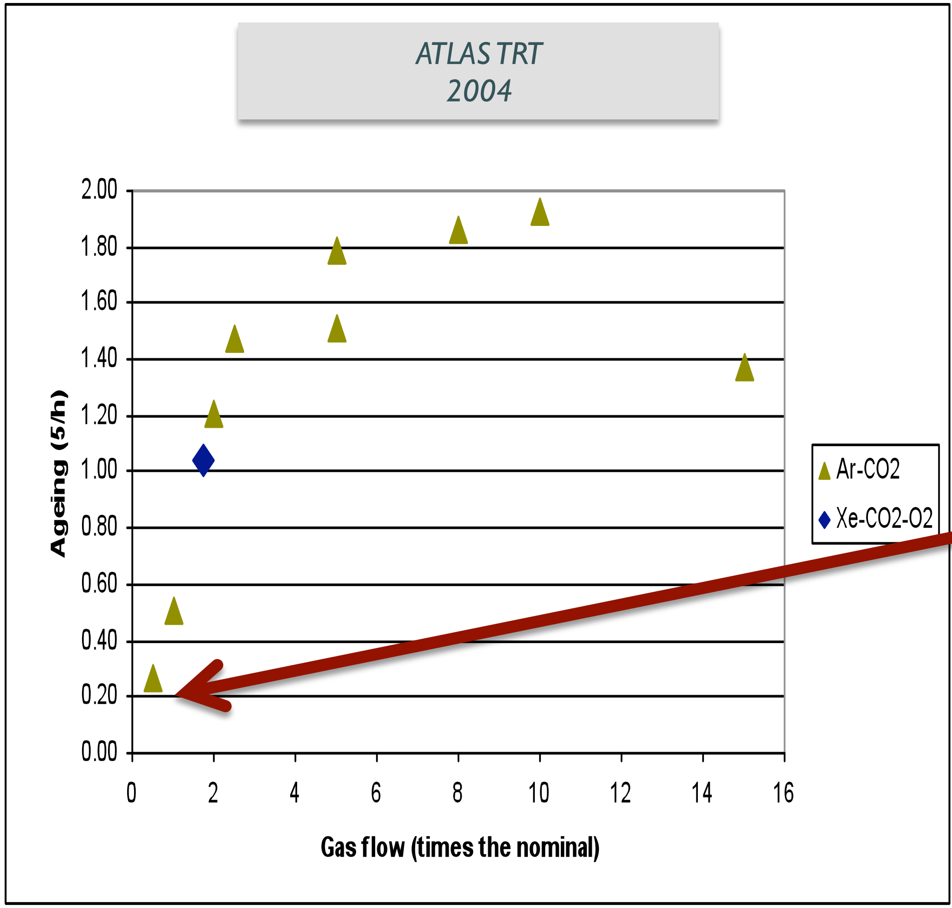
ATLAS TRT Validation Tests

LHC Gas Mixture: $Xe\text{-}CO_2\text{-}O_2$

Lab tests: $Ar\text{-}CO_2$

Cheaper mixture, simpler set-ups

Aging Rate, for different Gas Flows



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

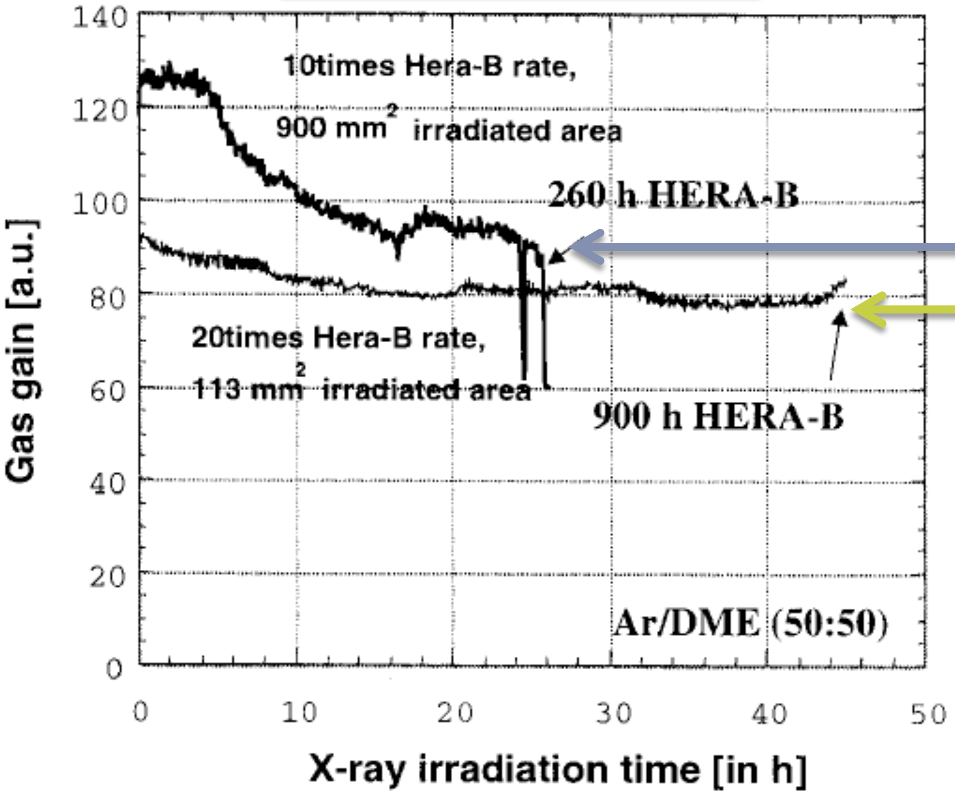
ATLAS TRT Validation Tests

LHC Nominal Gas Flow:

< 0.15 cm^3/min/straw

Aging Rate, for different sizes of the beam

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



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

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

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

Aging 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 screw up all results.
Gas Flow	Yes	Effect depends on: if pollutant comes with gas flow, if it's already inside the detector, if gas etches away the pollutant!
Ionization Current Density	Yes	Less aging observed at very large current densities.
Irradiation Area	Yes	Small spots 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?

Key Messages

- **Testing the effect of radiation** on detector systems is fundamental for their correct design and operation, and specially for evaluating their lifetime in the experiments. This is a field of activities on its own.
- **Different processes are responsible of radiation damage** of different detector technologies (Silicon, Gas detectors, etc) and on- and off-detector electronics.
- Radiation dose maps are simulated. Accelerated Lab Tests may not be fully extrapolable to real conditions. We need to add to same **safety factors**.
- A dramatic increase of the radiation intensity encountered by gaseous detectors (collected charge ~ C/cm/wire per year) at the high-rate experiments of the LHC era has demanded a concerted effort **to fight against aging.**

Rad-Hard Gaseous Detectors

- **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 aging 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

- Aging:
  - Wire chamber aging, J.A. Kadyk (LBL, Berkeley)
    Nucl. Instrum. Meth. A300:436-479 (1991)
  - Proceedings of the International Workshop on Aging Phenomena in Gaseous Detectors, M.Holhman et al. (DESY)
    Nucl. Instrum. Meth. 515, Issues 1-2, (2003)
  - Aging and materials: lessons for detectors and gas systems, M.Capeans (CERN)
    Nucl. Instrum.. and Meth. A515:77-88 (2003)
- Materials Properties for Gas Detectors and Gas systems:
  - http://cern.ch/detector-gas-systems/Equipment/componentValidation.htm
  - http://cern.ch/materials *(DB under construction)*

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

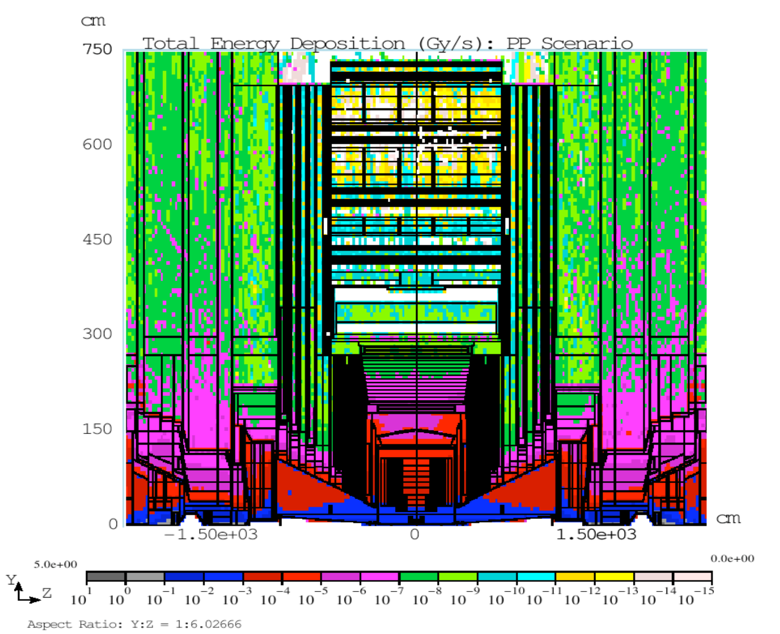
- Add Safety factors (x2, x5…)
- Radiation Hardness Tests
  - Expose detectors and components to very large particle rates to attain large doses in a very accelerated manner
  - Typical test lasts between days and weeks (time needed to achieve target dose)
  - Detector is powered and monitored; performance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

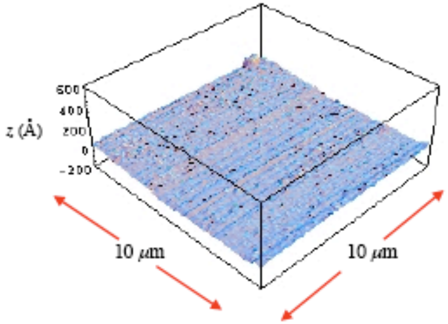


Note that radiation simulation may be wrong by some factors and long-term effects may not be fully predictable.
SAFETY FACTORS ARE ADDED TO ALL ESTIMATES

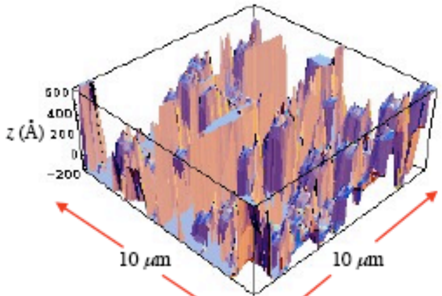
Non Classical Aging Processes

Non classical aging problems have been observed in

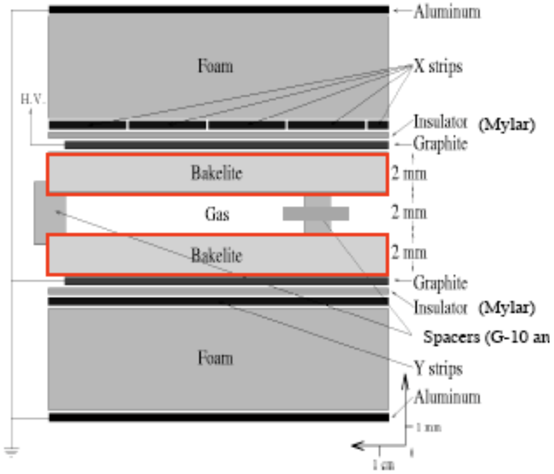
- Belle
  - 2000 ppm H_20 due to use of plastic tubing permeating too much water into the chamber
  - => HF acid etching of glass surface



Virgin Glass Surface



Bad Anode



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