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About aging of gas detectors: a compilation of some validation studies carried out for LHC

Input to RD51 WG2 meeting, Basic Detector R&D
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1. Introduction

Aging phenomena of gaseous detectors is a controversial field of study. While the degradation of gas detectors exposed to radiation is often observed and reported, the causes of such process are varied, and sometimes not fully understood. Studies in laboratory conditions have often revealed irreproducible outcomes, most likely because the contributions to the aging process are numerous and relate to both detector design and their operating gas mixture. There are mixtures more or less prone to aging; however, any 'good' gas mixture can make a detector fail because the gas becomes polluted by reactive products created in the avalanche process, by outgassing of materials used in the detector assembly or in the gas system. Fig. 1 shows schematically the influence of several aspects related to gas and materials that can shape the aging process.

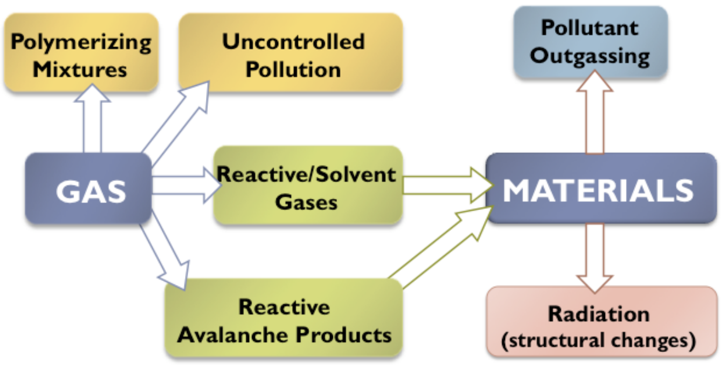

Fig. 1 Possible contributions of the gas mixture and assembly materials to gas detectors' aging.

Having acknowledged the difficulty of the topic, this note is not more than a short compilation of some facts made available during the R&D and construction phases of the gaseous detectors for LHC. It focuses on the long-term validation strategy of gas detector systems and the validation of components used for their assembly and their associated gas systems. The ultimate goal is to discuss a possible strategy for the development of radiation hardness micro-pattern gas detectors in the framework of the RD51 collaboration, *Development of Micro-Pattern Gas Detectors Technologies* [1].

Figure 2 shows the expected amount of accumulated charge (C/cm) in the hottest regions of some gas detectors systems in one year of LHC running (10^7 s), with the detectors operating at nominal conditions and at the LHC nominal luminosity. The total amount of accumulated charge shown for the different systems has been calculated applying different safety factors to account for uncertainties in the simulations and design changes of the radiation shielding; typically, factors between 5 and 10 have been considered. Parts of the ATLAS Transition Radiation Tracker (TRT), the largest straw-tube based system ever built, will collect charges exceeding 1 C/cm of wire per year, making this detector the most vulnerable to aging. The TRT community has therefore devoted a very considerable effort to understanding this process and to finding the optimal conditions to operate the detector as long as possible in conditions as safe as possible. Part of that work is presented in this note.

[1] http://indico.cern.ch/event/46019

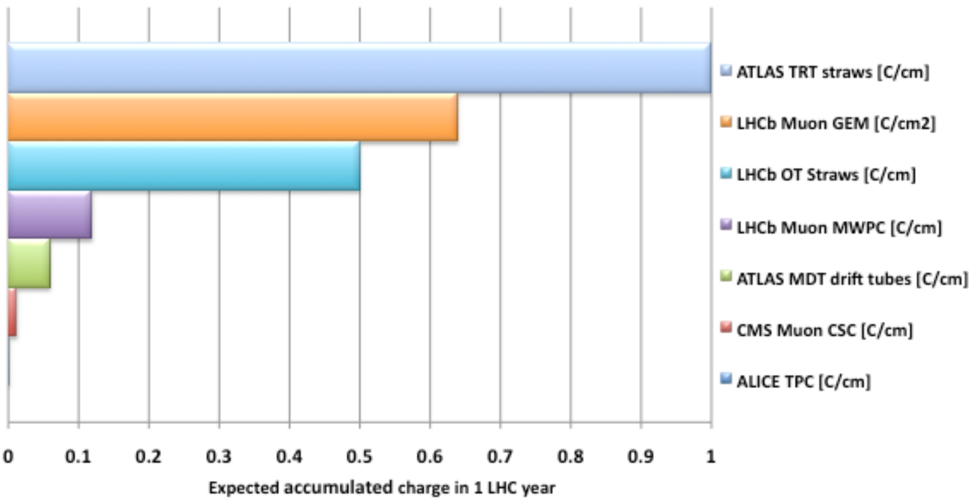

Fig. 2 Estimates of the accumulated charge per LHC year in the hottest regions of some LHC gas detector systems.

2. Accelerated Aging Tests

An important amount of accelerated aging tests have been carried out to ascertain the long-term performance of gaseous detectors. The parameters used during the tests can vary considerably when compared to the nominal operation conditions in the experiments, thus potentially affecting the result of the test. Yet several decades of research on the aging processes have led to some understating that improve the radiation tolerance of detectors; the gas detectors community seems to agree on a number of a parameters that are proven to affect the outcome of accelerated aging tests:

- **Gas mixture**: it has been systematically recognized that hydrocarbon-based mixtures tend to polymerize and produce deposit layers on the surface of wires. Often they do not permit accumulating charges above the 10-50 mC/cm scale. Additives to those mixtures, such as alcohol or water vapor, can improve significantly the detector's lifetime though. Mixtures of noble gases with CO_2 are more resistant to aging, safely a factor 10 more; if they do not get polluted, very long detector lifetimes are easily achieved. Even longer lifetimes are reported for CF_4-containing mixtures, but they are critical with the choice of assembly materials and components used in the gas systems. DME mixtures have also been tried and do not cause aging effects if materials are properly chosen and the gas is of very high purity. However, these mixtures show rather low drift velocities, are flammable and are not used at the LHC.
- **Gas flow**: it has always been considered a factor to bear in mind when performing aging tests. Traditionally, larger aging rates have been reported for lower gas flows, in agreement with the reasonable assumptions that, i) for low gas flows the reactive/polymerizing radicals created in the avalanche spend more time in the region of ionization and, ii) high flows can remove pollutants away from the avalanche region. With the widely spread use of non-polymerizing mixtures in LHC (such as Ar-CO_2, and mixtures containing CF_4), the aging rate seems to be defined by the amount of pollution that the gas brings in and/or by the fine balance between polymerization and CF_4-induced etching. Therefore, larger gas flows result in larger aging rates, either because more polymerizing pollution enters the ionization region, or the etching CF_4 radicals leave too early the ionization region, thus decreasing the etching power.
- **Ionization current density**: it defines the acceleration factor of the test. Fig. 3 shows the rate of aging (somewhat final gas gain drop in the test) for series of systematic aging studies of wire counters in Ar-CH_4 [90-10]. The plot compiles data obtained by several groups between the years 1992 and 2004 [2-4]. The measurements indicate consistently that aging tests carried out with very large detector currents deliver optimistic results. A possible explanation could be that at high rates space-charge saturation weakens the electrical field and the avalanche can extend over larger regions, possibly decreasing the polymerization efficiency; the rate of polymerization, closely related to the density of radicals, would decrease, and in turn, so would the concentration of deposits on the electrodes. Similar arguments would apply to the effect of discharges; they may also play a significant role in the aging rate and this needs to

be understood. A particle rate inverse dependence on the production of some polymerizing avalanche compounds has also been measured in tests carried out in controlled laboratory conditions [5].

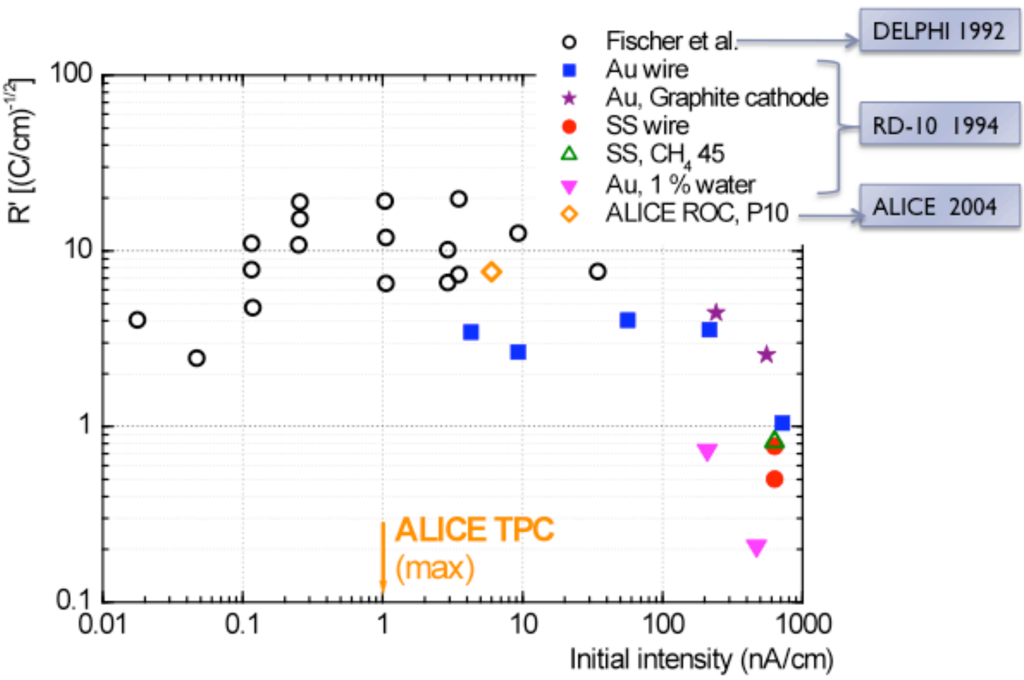

Fig. 3 Rate of aging as a function of the current in nA/cm of wire drawn at which the aging test is performed for several sets of systematic measurements with wire counters in P10 and slightly modified conditions (addition of water, different chamber geometries, anode and cathode materials, gas purity).

- **Irradiation area and type**: given the dose rate, it has been observed that larger irradiation areas can increase the aging rate, suggesting that laboratory tests with small beams do not represent real aging rates [6]. Some aging effects seem to be reproducible only in certain conditions. The Hera-B outer tracker reported major aging problems (Malter currents) systematically appearing only when the chambers were irradiated in a hadronic beam above a certain energy and possibly, only for an irradiated detector area above a certain size [7].
  A reasonable compromise needs to be found to define an acceleration factor (the maximal safe factor) that would permit carrying out validation tests in a reasonable amount of time and permitting a safe extrapolation of the results to the real operating conditions. As an example, the ATLAS TRT detector performs aging tests with an accelerator factor of 10, while the LHCb outer tracker, also a straw-based detector, has performed most tests with an acceleration factor close to 20. As there are evidences of non-linear dependences on the local radiation load and size of the irradiated area, ultimately, final conclusions should be drawn after having normalized the results of accelerated aging tests with a low intensity test. It seems that the results of low intensity tests can be scaled better.

- **Chamber geometry**: the large amount of existing data would suggest that the design of the detectors play a fundamental role in the aging rate. It is reasonable to think that, among many others, the aging of gas detectors will depend on anode to cathode distance, wire versus continuous cathode, anode and cathode materials, anode wire diameter, etc. For micro pattern gas detectors, it has been pointed out that the separation of gas amplification and the readout stages and a possible smaller effect of polymerization deposits on the electric field would explain their resistance to aging, as compared to traditional wire chambers. Therefore the outcome of generic aging studies may not be universal for all set-ups and detector types. The existing knowledge on aging results obtained with other detector geometries can be used only as starting point to design a gas detector and cannot to be taken for granted.

Successfully building a radiation tolerant gas detector needs series of systematic aging studies, with a fixed and carefully selected set of parameters, with prototypes containing well defined and carefully selected materials and construction techniques, tested in an environment resembling as much as possible the expected running conditions in the experiments. The minimal parameters that should be thoroughly chosen and controlled are the radiation load (test acceleration factor), type and area; and the gas mixture composition, purity and exchange rate. In addition, the detector's performance parameters monitored after/before the test should be well defined and agreed for a given detector technology, such as how to measure and represent pulse height distributions inside and outside irradiation areas, drawn currents, etc. Environmental parameters should also be recorded.

3. An Efficient Material Validation Strategy

The selection of adequate materials for the construction of gas detectors and their services has became a key issue in the LHC era. The systematic studies on aging carried out in the last decades have shown that pollution of gas mixtures can make the best-designed detector fail. An unambiguous case is silicone contamination. Since decades, silicone polymers have been systematically found coating aged chambers. However, the origin of the pollutant has often not been identified. The ATLAS TRT community, in a series of systematic tests, has firmly established that silicone pollution is the major danger for the operation of the TRT detector at the LHC. Minutes amount of this contaminant cause significant gain losses in a matter of days [8]. Having identified silicone as the major danger for the lifetime of the detector, a strategy was developed to minimize such pollution in the TRT gas mixture. An important effort was made to validate all components in contact with the gas, in the detector and associated gas systems, paying in addition special attention to accumulation effects in the final closed-loop gas system. Bearing in mind the large amount of different materials and components in contact with the gas and all parts used in the final gas system, the effort was concentrated in finding the conditions of operation in which an aging test would reveal rapidly any amplitude degradation. This strategy opposes to the time-consuming tests mentioned in Section 2, that usually last several months, as their goal is the long-term validation of a detector at a reasonable pace whilst still making possible a reasonable extrapolation to the real operating conditions.

The TRT community has found that the sealant Dow Corning RTV 3145 can be used as source of silicon delivering a controlled, constant rate of contaminated gas inside the straws [9]. This permits, possibly for the first time, to measure the equivalence between the gain drop in an irradiated straw and the amount of silicon pollution in the gas stream. It was found out that few ppb (!) of silicon in the gas induce 10% gain drop in about 100 hours of irradiation. It seems very difficult to construct a large-scale detector and associated gas system with those cleanliness requirements. For that reason, a major effort was carried out to find out a reliable test that could deliver a fast *Go/No-Go* response for the validation of materials in contact with the gas and thus, minimizing the possibility of polluting the TRT gas mixture with silicone. The following observations were found out in a series of systematic tests carried out irradiating with 6 keV X-rays several straw prototypes operated at the nominal gas gain of 2 x 10^4 in a controlled Silicon-contaminated gas mixture:

- **Gas Mixture**: the aging rate of the TRT straw tubes does not depend on the gas mixture for Ar-CO_2 [70-30], Ar-CO_2-O_2 [69-28-3], and the final LHC mixture, Xe-CO_2-O_2 [70-27-3], as shown in Fig 4. This implies that the cheaper gas mixture can be used to carry out the validation tests of materials.

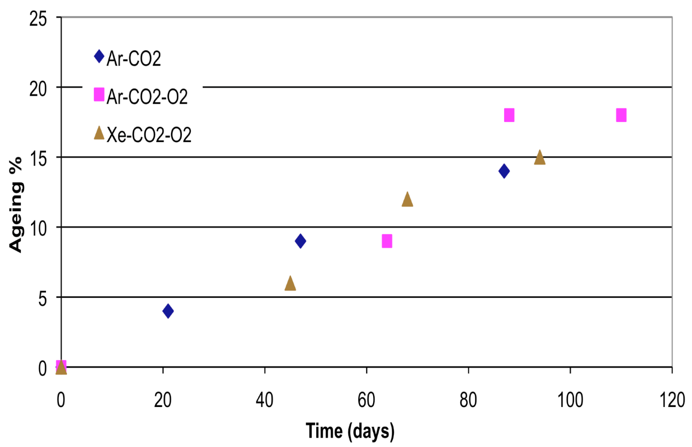

Fig. 4 Aging rate in TRT straws for Ar-CO_2, Ar-CO_2-O_2 and the final LHC mixture, Xe-CO_2-O_2.

- **Gas Flow**: TRT straws operating in the Si-contaminated mixture age faster for gas flows significantly higher than the nominal one of 1 volume exchange per hour. A liner dependence seems to apply up to 2.5 times the nominal flow and maximum damage seems to appear at about 10 volume exchanges per hour, as shown in Fig. 5. As the ageing rate flow dependence is not linear in all the flow ranges, 100 hours of the irradiation at 10 times the nominal gas flow is equivalent to 400 hours of the irradiation at the nominal gas flow.

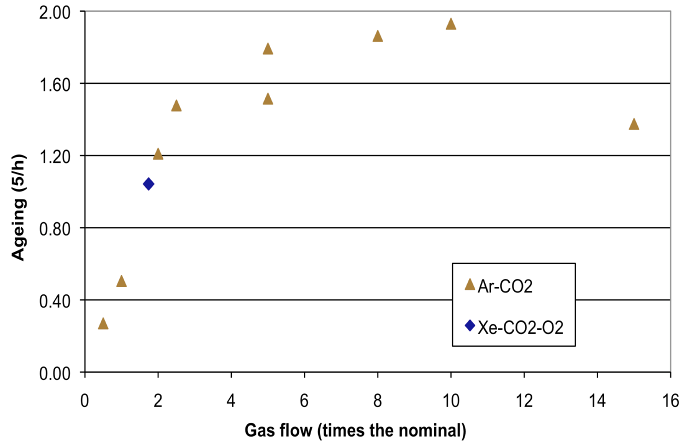

Fig. 5 Aging rate in the TRT straws as function of gas flow, expressed as times the nominal LHC flow of one volume exchange per hour.

- **Current density:** in agreement with the discussion presented in Section 2, large current densities appear to enhance the aging process in the TRT straw tubes (Fig. 6). The tests carried out at an ionization current of about 0.1 μA/cm show the larger gain losses. Unfortunately, this current is almost equivalent to the expected 0.15 μA/cm current drawn by the straws located in the hottest regions of the TRT. Further studies would be needed to verify whether this tendency is universal for all set-ups and detector types, and all types of gas mixtures and pollution.

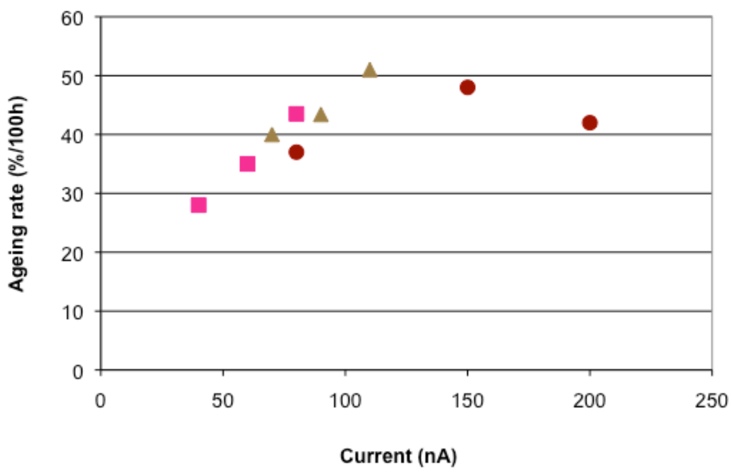

Fig. 6 Aging rate in the TRT straws as a function of the current density (nA in 1 cm of irradiated wire).

- **Irradiation area**: the maximum gas gain drop due to silicone deposits on the wire is observed at the very beginning (in terms of gas flow) of the irradiated area. Fig. 7 shows the relative gain measured along a straw irradiated 10 mm along the wire. The largest drop of the signal, i.e. maximum amount of deposits confirmed by the optical inspection of the wire, is found at the first edge of the irradiated wire area. This would imply that smaller irradiated spots, 1-2 mm in diameter, could be used to detect promptly gain drops due to accumulation of Si-induced deposits.

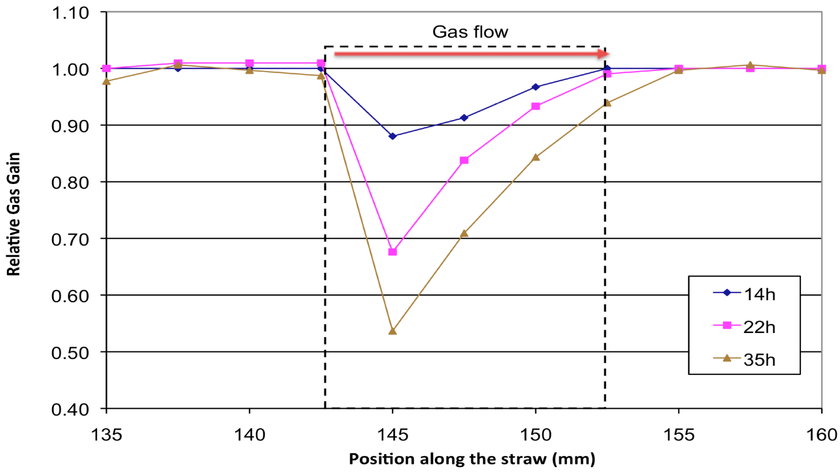

Fig. 7 Relative gain drop measured along a straw wire irradiated over 10 mm (area in between shaded lines). The wire was scan was repeated after 14, 22 and 39 hours of irradiation.

Taking into account all these observations, a typical validation run to certify the cleanliness of assembly materials, gas system components or fully assembled gas racks can be performed in about 2 weeks. The aging tests are carried out inserting the component under test as close as possible to the irradiated straws (~10 cm upstream the straw) in a clean-certified gas system. Then, the straws are flushed with Ar-CO_2 [70-30] at 1.5 cm^3/min/straw, which corresponds to 10 times the LHC nominal flow. The straw is irradiated 1-2 mm along the wire, inducing a current of about 0.15 μA/cm of wire for about 250 h. The gas gain is monitored and the test is considered successful if the final gas gain does not drop more than 1.5% (gain measurement accuracy is about 1%). Aging effects, if any, are usually observed in less than 100 hours for contaminated components. The conditions in these tests are compared with the TRT operating conditions at the LHC in Table 1. Taking into account all the parameters changed in the tests and reconverting the test conditions to the nominal TRT operating conditions, this type of validation test certifies the correct operation of the straws for about 1000 hours. This systematic approach it allowed an effective and in-depth characterization of components; in some cases, a minute amount of lubricant or a single material used in a given component could be identified as producing the large ageing rate. More than 10% of all the components claimed to be pure (according to the TRT cleanliness specification, i.e. silicone-free) by producers or suppliers required a special cleaning work or change of materials used inside the component. More than 100 components for gas systems have been certified clean in such manner in several hundreds of tests, including different production batches, silicone-filters and eventually the whole final gas system and pipe network at the experimental cavern [10, 11].

TRT operating conditions	LHC	Component Validation Tests
Gas Gain	~ 2 x 10^4	~ 2 x 10^4
Current Density	Up to 0.15 μA/cm	0.15 μA/cm
Gas Mixture	Xe-CO_2-O_2 [70-27-3]	Ar-CO_2 [70-30]
Gas Flow	0.15 cm^3/min/straw	1.5 cm^3/min/straw
Irradiation area		1-2 mm 6 or 8 keV X-rays

Table 1 ATLAS TRT straws operating conditions at the LHC and in material validation tests.

4. Discussion

4.1. Radiation-tolerant MPGD open issues

Among all gaseous detectors, the Micro-Pattern Gas Detectors have emerged as the most robust, radiation-hard technology. Lifetimes in excess of tenths of mC/mm^2 have been repeatedly reported with a variety of gases and obtained under different test conditions [12]. It should be noted that aging tests of MPGD have, up to date, been obtained irradiating ~cm^2 areas and mostly with X-rays.

Yet the variety of parameters as far as aging is concerned (gas mixture, detector geometry, electric field, dose rate, assembly materials, etc.) combined with the complexity of the processes that lead to diverse aging phenomena call for a continuation of systematic studies on aging, focusing on the specifics needs of MPGDs. This effort is particularly critical in a moment where very large size detectors are being developed and new applications emerge. We would like to stress the following issues:

- **Gas mixture:** future very large inner trackers and muon systems based on MPGDs are being considered for the upgrade of the LHC experiments. They will be exposed to an unprecedented high radiation environment. Are hydrocarbons trustable in MPGDs in high-rate experiments? New applications also demand finding new gas mixtures that will allow effective operation of MPGDs at very high gas gains.
- **Gas mixture purity:** understanding the effect of gas pollution on detector's performance is a key issue to be able to build large size MPGD and full detector systems. Reasonable and affordable cleanliness requirements for detector assembly materials and gas systems components must be defined and adopted.
- **Safe, accelerated aging tests:** the MPGD community needs to find and establish the most appropriate test conditions (radiation type and dose, gas flow, electric field, etc.) that would permit to accelerate tests in laboratory and at the same time make a correct extrapolation of results to the real experimental conditions. Appropriate aging set-ups are needed to validate detector modules of final design and sizes exposed to irradiation conditions as similar as possible to the final ones.
- **Material studies:** specific tests are needed to find clean, commercially available materials that can withstand up to Mrad doses without degradation of their fundamental and most representative properties.
- **Aging mitigation:** an important pending issue is finding mitigation and/or working remedies for failing detectors.

4.2. Tests set-ups and infrastructures

In order to ensure sufficient resources and coherence of test procedures and results within RD51, a set of test facilities shall be made widely available.

Aging set-up(s) at the RD51 participating institutes should be unified and, in a agreed manner, used to:
- Find suitable rad-hard gas mixtures for high-rate MPGDs.
- Find out the correlation between aging rate and current density and as a result, to establish a safe acceleration factor for aging tests.
- Carry out long-term aging tests of given MPGDs technologies with safe acceleration factors.

A unique, dedicated set-up shall be used to carry out fast ***Go-No Go*** **tests of components** and materials in contact with the gas. The set-up at CERN that has been used by the TRT to validate materials could be adapted and used for these studies. This set-up will permit:
- To define the cleanliness level required for MPGD: do they age in mixtures contaminated at the ppb, ppm, or percentage level?
- To identify the *killer* contaminants for MPGDs and establish the relationship between pollution amount and MPGD's aging rate.
- To find the optimal strategy (test protocols) to carry out very fast validation tests of MPGDs prototypes, detector's assembly materials and procedures, and gas systems components in contact with the gas.
- To carry out outgassing tests of rad-hard materials (Mrad scale): the construction of large area MPGDs and large systems demand, in particular, an exhaustive and systematic search for new yet commercially available materials, with attractive properties in terms of density, expansion coefficient, elasticity module, radiation hardness, electrical properties, etc. In particular there is an urgent need to find insulator materials that minimize charging-up and polarization effects of MPGDs. The use of materials complying with the previous requirements is conditioned by their outgassing properties when in contact with a given gas mixture.

Coordinated access to **irradiation facilities** for the selection of rad-hard materials, electronics and final validation of large detector assemblies. Two facilities at CERN are adequate for these tests:
- The CERN gamma irradiation facility GIF++ is expected to be operational towards the end of 2010 [13]. It is being designed to be able to uniformly irradiate large detectors, areas of few square meters, with a large flux of 660 keV γ rays (~10 TBq). The dose close to the source will be 100-200 rad/h. The uniqueness of this set-up is the possibility to simultaneously characterize the detector's

performance with a well focused 100 GeV muon beam high-energy particles from a SPS beam line and the photon background. The purpose of the tests is typically to measure whether the detection efficiency, rate capability and the resolution of the detectors are affected by the continuous exposure to background radiation over very large areas.

- The CERN PS-T7 proton and neutron irradiation facilities [14] are widely used for the characterization of materials, detectors and electronics. These facilities provide a number of advantages, such as exposure to high particle flux in reasonable time (~1-5×10^{13} 24 GeV/c protons/cm^2×h in a beam spot 2×2 cm^2), fast turnaround, the possibility to move samples into beam without entrance into irradiation area, and a well run infrastructure that minimizes administrative and setting up procedures. Scanning over surfaces up 20×20 cm^2 is possible, with the according reduction in flux/cm^2. An increase dose up 5 MGy (~2×10^{16} protons/cm^2) is being studied, to cope with the increasing requests linked to detector developments for the LHC upgrade.

Very high-rate MPGDs, such as the proposed Gossip development for the upgrade of the ATLAS tracker [15], will be exposed to doses about 3.4×10^{16} mips/cm^2 (~159 C/cm^2 at gas gain 2000). MPGD aging studies should therefore aim for accumulated charges well above 100 C/cm^2. This would need very long continuous irradiation period (~months) at the rates achievable in the facilities mentioned above. Dedicated set-ups should be used for these studies; a 5 GBq ^{90}Sr source has been proposed [16].

5. References

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