Aging Effects in Gas Detectors

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Abstract

Degradation of performance of gas detectors under irradiation has been observed since the start of their use in particle physics experiments. In general the observed damage depends on the amount of radiation seen by the detector but in addition many other parameters like e.g. gas composition, gas quality, particle rate and particle type play an extremely important role. The dramatically increased demands in terms of radiation hardness at experiments like HERA-B or those at the LHC have triggered intensive and systematic studies of aging properties of materials, gases and components resulting in a compilation of a long list of materials, which are unusable for high rate experiments, and a selection of materials with acceptable aging properties. Comparisons with results obtained in plasma chemistry have led to an improved understanding of aging phenomena, but due to the large complexity of the processes involved it has until now not been possible to derive recipes which can be generally applied to all high rate applications.

Key words: aging, radiation damage, gas detectors, wire chamber, drift chamber
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1 Introduction

Degradation of performance of wire chambers under irradiation is a phenomenon which has been observed for a long time [1]. As the use of wire chambers in particle physics experiments became more and more common it was realised that a systematic study of the origin of wire chamber aging was required [2,3]. Investigations have shown that aging usually is related to the formation of deposits on the wires or other electrodes in the detector. In most

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cases polymerisation of hydro-carbon molecules in the avalanche in conditions resembling those known from plasma chemistry was identified as the main cause. The need for a concerted effort to understand the exact conditions which favour polymerisation led to the first “*Workshop on Radiation Damage to Wire Chambers*” held 1986 in Berkeley [4,5]. The many results presented at this workshop include a list of variables which affect aging adversely. A set of rules which should be followed was derived including a selection of materials and gases usable for chamber construction and operation. Experience has shown that the purity of the gases used is also of highest importance and that it must be maintained over the whole lifetime of the experiment: examples have been reported where temporary use of polluted components led to degradation of detector performance which persisted even after the pollution was removed from the system again (see Section 4). However, since many complex chemical processes are expected to occur simultaneously in the gaseous discharges surrounding the wire it is not surprising that a quantitative description of aging effects is still not available.

Dramatically increased radiation doses are expected for detectors which are presently under construction for the LHC. Fig. 1 compares typical particle rates as a function of the radial distance to the beam axis for experiments at LEP, HERA and the B-factories with those at the LHC. In the region where gas detectors are foreseen the expected particle rates increase by roughly four orders of magnitude. Therefore a significant increase in radiation hardness is required when going from experiments in the “pre LHC” era to those at the LHC. While in the past it was sufficient to consider detector lifetimes, expressed in terms of integrated charge per wire length, of $O(1 \text{ mC/cm})$ in the new regime values of up to $O(1\text{-}10 \text{ C/cm})$ have to be anticipated for 10 years of operation at the LHC. These tremendously increased demands on radiation hardness triggered a dedicated R&D effort to explore to what extent materials and gases can be found which allow operation under such harsh conditions. As it turned out not only an extremely careful selection of materials is required but also strict adherence to well defined procedures in chamber assembly and operation. Operation of new types of detectors like Resistive Plate Chambers (RPC) or detectors specifically designed for high rate applications like Micro Pattern Gas Detectors (MPGD) [6] has shown that under certain conditions new problems arise which go beyond the effects known from “classical aging” discussed here. The knowledge accumulated since the first workshop was summarised at the second international workshop on “*Aging Phenomena in Gaseous detectors*” held at DESY in the year 2001 [7]. The present article is largely based on results reported at this workshop and on several excellent comprehensive reviews of this subject [8–11].

Fig. 1. Measured and expected particle rates as a function of radial distance to the beam axis for various experimental conditions. A significant increase of radiation hardness is required for detectors in the LHC era.

2 Classical Aging Effects

By classical aging we mean the formation of deposits, conductive or insulating, on the electrode surfaces which may lead to a number of different operational problems, such as gain loss, worsening of energy resolution, excessive chamber currents, self-sustained discharges, sparking, high voltage instability, wire corrosion, wire swelling or wire rupture. These deposits generally are the products of chemical reactions that occur in the avalanche plasma close to the anodes of the detector, schematically illustrated in Fig. 2. During gas amplification many molecules break up in collisions with electrons, due to de-excitations of atoms, and UV photon absorption processes. Whereas most ionization processes require electron energies greater than 10 eV, the breaking of covalent molecular bonds and formation of free radicals requires only 3-4 eV, and can lead to a higher concentration of free radicals than that of ions in the gaseous discharges. Consequently, free-radical polymerization is regarded as the dominating mechanism of wire chamber aging. Since free radicals are chemically very active they will either recombine to form the original molecules or other volatile species, or may start to form new cross-linked molecular structures of increasing molecular weight. When the polymerized chain becomes large enough for condensation to occur, it can diffuse to an electrode surface. This has far-reaching consequences for chamber operation since these polymers exhibit excellent adhesion properties to surfaces, are resistant to most chemicals and insoluble in most solvents.

Impurities in the gas, which are transported with the gas flow may also directly

Fig. 2. Schematic of processes leading to formation of polymers and build up of whiskers in a wire chamber [12].

deposit on the surface of electrodes and insulators due to electrostatic forces. Organic materials can out-gas or some reactive gases (such as dimethyl ether, DME) can attack chamber materials and plumbing. Another possibility is that materials might undergo structural changes induced by the effect of ionizing radiation liberating new out-gassed pollutants that can promote polymerization. Furthermore, initially neutral gases sometimes become reactive because of the species created in the avalanche process close to the wire. The created species are reactive enough to remove layers of some materials, mechanically damaging the detectors and polluting the chamber gas. For example, tetra fluoride radicals can remove thin layers of material on coated wires. While this capability might help to remove deposits from polymerization it on the other hand may turn into a serious problem when the reactive species attack assembly materials. The probability of all these mechanisms to occur depends on a large number of factors: gas flow, gas gain, geometry and electric field configuration as well as the presence of additives have, amongst others been demonstrated to play an important role.

An example of a particularly disastrous effect is the so-called Malter effect [13] which can occur if the conducting cathode is covered with a thin insulating layer by polymerisation. The resistivity of the insulating layer defines the maximum rate capability of the detector before the onset of field-emission of electrons from the cathode. Field-emission starts if the rate of ionic charge neutralisation across the dielectric film is smaller than the rate of ion charge build-up (see Fig. 3). A positive feedback between electron emission at the cathode and amplification at the anode can thus develop and will cause high ionization densities in the chamber which can eventually lead to the classical self-sustained Malter discharge. Several factors may facilitate its ignition, such as insufficient conductivity of the cathode, highly ionizing particles, sparks, sharp points on electrodes causing corona discharges, or thin anode wires. It is easy to ignite Malter currents in a detector by operating with hydrocarbon gases at elevated high voltages or by forcing the chamber to breakdown. Observing single electron pulses can provide insight into the starting mechanism of this process. Recently it has been shown that a model based on the

Fig. 3. Schematic of the mechanism leading to the Malter effect (left). Example of a spontaneous increase of chamber current which persists even after the incident radiation has been switched off (right). The current only goes back to zero once the high voltage has been switched off [11].

Fowler-Nordheim equation is very well able to describe this process [14]. If the Malter effect remains undetected for a sufficiently long period of operation it can spread over a large area, thus causing irreparable damage to the chamber.

3 Insights from Plasma Chemistry

Some of the observed phenomena connected to aging can be qualitatively explained by plasma chemistry, although the conditions under which these processes occur generally differ for the two cases. While electric field, gas pressure, electron density and power density are typically very different between the two regimes, the electron energies are quite similar. In both cases the free radicals are most likely the active species involved in polymer formation. A complication arises from the fact that both polymer-forming species and species that cause ablation of materials by physical or chemical etching are created in the plasma of the original gas. In plasma chemistry this has led to the introduction of the ‘Competitive Ablation and Polymerization Principle’ [15]. For example the observation from several experiments that both polymerization and etching phenomena can occur in CF_4 -based gases can be well reproduced in plasma chemistry: the addition of oxygenated species shifts the chemistry of CF_4 plasmas towards etching, while the addition of hydrogenated species rather shifts it towards polymerization.

Another example is the result that most organic compounds with oxygen-containing groups usually are reluctant to form polymers. Many experiments have reported that adding small amounts (a few hundred to a few thousand *ppm*) of O_2 , H_2O or different kinds of alcohol (methanol, ethanol, iso-propanol) effectively suppresses polymerization and can in some cases even restore the original operation of an aged detector (for a recent example see e.g. [16]). This can be attributed to the fact that these molecules react with polymer

precursors to form volatile species which can be removed from the chamber with the gas flow. The large dipole moment of these molecules helps because the molecules tend to accumulate close to the electrode surfaces, where the polymer-forming species are created. An additional advantage in the case of H_2O is that it may increase the conductivity of electrodes and thus prevent the occurrence of Malter effect.

It has been observed in many experiments that the presence of even minute traces of silicon anywhere in the gas system of a chamber readily leads to formation of deposits, which can destroy the entire detector. This is corroborated by findings in plasma chemistry that the characteristic polymerization rate of silicon by far exceeds that of carbon, despite their identical valence shell structure. Silicon can polymerize both with hydrocarbons and oxygen to form rather heavy polymers, which can not be easily removed by the gas flow. The problem is aggravated by the fact that silicon-compounds are almost ubiquitous. They are found in many lubricants, adhesives and rubber, encapsulation compounds, silicon-based grease, various oils, G-10, RTV, O-rings, fine dust, polluted gas cylinders, diffusion pumps, standard flow regulators, molecular sieves etc.. Nevertheless, the source of the pollution could in some cases still not be clearly identified.

Despite the qualitative agreement between observations in plasma chemistry and experience from wire chamber operation it is difficult to derive quantitative conclusions, which would permit to predict aging properties of gases, mainly due the lack of systematic plasma chemical studies for conditions close enough to those occurring in the gas amplification process.

4 Laboratory Tests and Choice of Materials

For the reasons outlined in the previous section extensive laboratory tests of gases and assembly materials are required before constructing radiation hard gas detectors. The aging rate of a detector is usually expressed as the relative change of gain, G , per integrated charge per wire length, Q

$$R = -\frac{1}{G_0} \frac{dG}{dQ} \left[\frac{\%}{\text{C/cm}} \right]. \quad (1)$$

This choice is motivated by a rather simplistic model, which assumes that the number of radicals produced in the avalanche is proportional to the number of electrons. However, one of the important results of the extensive aging studies of the last decades is, that the aging rate in fact depends on many more factors than only the integrated charge. More specifically, it has been shown that aging depends on:

- size of the irradiated area,
- rate of irradiation,
- ionization density,
- particle type and energy,
- high voltage (gas gain),
- gas components (purity and amount of trace components),
- gas exchange rate and pressure,
- gas flow pattern,
- construction material.

A classical example of the importance of the proper use of materials over the entire lifetime of an experiment is shown in Fig. 4 (left), which illustrates that even the temporary use of ‘bad’ materials in the gas system can cause irreversible damage, even if they are later replaced by proper materials again [3]. An example of a reversible drop in performance is illustrated in Fig. 4 (right), which shows that the original gain of the detector can be restored as soon as the gas flow is sufficiently increased [17].

Laboratory tests therefore have to include out-gassing tests of materials, accelerated tests under irradiation and tests with prototype detectors under as realistic conditions as possible. In particular the last step has been shown to be very important. Several groups reported that gas detectors suffered in the real application of the experiment although careful tests that had been performed on individual system components before had not revealed any problems. Extensive and systematic out-gassing tests under controlled condi-

Fig. 4. Example of a permanent damage by wrong choice of material (left). Example of a reversible reduction of gain due to insufficient gas flow (right).

tions have been performed in the framework of the CERN RD-10 and RD-28 projects led by Fabio Sauli [18]. A good starting point for the selection of assembly materials, before even starting time-consuming laboratory tests, is the database of materials classified by NASA as low out-gassing [19] and therefore suitable for spacecraft usage. Although in many cases there is a good correlation between the out-gassing properties quoted by NASA and the results based on gas chromatography and the observed aging rate in the CERN tests,

significant differences have been observed for some specific materials. Tables of a number of ‘good’ and ‘bad’ materials resulting from these comparisons are given in [20] for different groups of materials such as epoxy compounds, conductive epoxies, adhesive tapes, sealants, rigid materials, O-rings or plastic pipes.

Accelerated aging tests sometimes can not be avoided in order to assess in a limited amount of time the expected lifetime of a detector under irradiation. Acceleration factors used in such tests range between typically 10 and 100. As stated above, aging critically depends on many parameters such as exact conditions of the avalanche dynamics, type and energy spectrum of incident particles, charge density and its spatial distribution. Hence there is some uncertainty as to how far the result of such tests can be transferred to the real situation in the experiment. For example, a too high space charge may decrease the polymerization efficiency thus underestimating the aging rate in the real detector, while a too low gas flow which has not been scaled appropriately with the radiation load may result in a too pessimistic removal efficiency of reaction products. Consequently, the outcome of such tests has only indicative character and cannot fully replace a test of a prototype system using all final components (including gas system, gas pipes etc.) under realistic conditions.

5 Choice of Gas

Mixtures of a noble gas and hydrocarbons are not trustable for long-term high rate applications. Hydrocarbons tend to polymerize, even in the absence of pollution. It is only a question of time when polymers will deposit on the electrodes with enough thickness to affect detection efficiency. It is generally accepted that oxygen-containing additives can improve the detector lifetime in such mixtures. DME has proven to give long lifetimes. However, a careful material selection for detector assembly and gas system components is required due to the high reactivity of this gas. Halogen contamination at the *ppb* level in combination with the use of DME has been shown to shorten detector lifetimes considerably. Such low pollution levels are clearly very difficult to monitor and to keep under control. CO₂ appears to be the conventional alternative as an easy-to-use component. CF₄-containing mixtures are very attractive in terms of aging due to the fine polymerization-deposition balance phenomenon (see Section 3). It is expected that radicals and ions created in the avalanche process are chemically reactive, competing with any polymerization process which is promoted by impurities in the gas. The competition between these two processes might slow down conventional aging effects. Unfortunately, contradictory effects have been observed with CF₄ mixtures. While CF₄ is a promising component for radiation hard mixtures, detailed studies are still necessary to find the conditions under which a particular detector might work satisfac-

torily. These mixtures need strict control of pollutants (especially water and possibly oxygen) to avoid shifting the delicate etching-deposition balance in an unwanted direction. F-radicals are very reactive and hence can clean up aged wires, but they are also able to attack certain materials used in the assembly. They are capable, for instance, of etching away Si compounds, which are then spread out in the entire system and may thus promote strong polymerization processes.

6 Summary

Aging of gaseous detectors still represents one of the limiting factors for their use in particle physics experiments. During the intensive research and development of gas detectors for high rate applications in the last decade an impressive amount of experimental information has been collected from laboratory test and detectors installed in running experiments. Some similarity with results from plasma chemistry has been observed, but the presence of many contradictory findings indicates that a detailed understanding of the complex processes taking place in the plasma of the avalanche is still lacking. However, it has become clear that for a successful construction and long-term operation of gas detectors for high rate applications an extraordinary radiation hardness of the construction materials and gas mixtures, as well as strict adherence to appropriate assembly procedures and quality checks is mandatory. Therefore, before starting construction of any new gas detector for high-rate applications thorough tests should be performed which should include an extended study of ‘large scale’ prototype chambers, exposed over their full area to irradiation with particles of proper type and energy distribution, realistic ionization density and rate. In order to explore the sensitivity to changes of operating conditions the tests in addition should include a systematic variation of all relevant system parameters. However, despite all precautionary measures the final answer on the radiation hardness of a detector will always have to come from the real experiment.

References

- [1] G. Charpak, H. Fischer, G.R. Gruhn, A. Minten, F. Sauli, G. Pich, G. Flugge, “Time degeneracy of multiwire proportional chambers”, Nucl. Instr. Meth., vol. A99, pp. 279-284, (1972).
- [2] M. Atac, “Wire chamber aging”, Proceedings of Workshop on Radiation Damage to Wire Chambers, LBL-21170, pp. 55-66, (1986).

- [3] J. Vavra, "Review of wire chamber aging", Nucl. Instr. Meth., vol. A252, pp. 547-563, (1986).
- [4] Proceedings of the Workshop on Radiation Damage to Wire Chambers, LBL-21170, (1986).
- [5] J. A. Kadyk, "Wire chamber aging", Nucl. Instr. Meth., vol. A300, pp. 436-479, (1991).
- [6] L. Ropelewski, "Micropattern Gas Detectors for Tracking," *These proceedings*.
- [7] Proceedings of the International workshop on Aging Phenomena in Gaseous Detectors, Nucl. Instr. and Methods A515, (2003).
- [8] M. Titov, M. Hohlmann, C. Padilla and N. Tesch, "Summary and outlook of the International Workshop on Aging Phenomena in Gaseous Detectors (DESY, Hamburg, October, 2001)," ICFA Instrum. Bull. **24**, 22 (2002)
- [9] M. Hohlmann, C. Padilla, N. Tesch and M. Titov, "Aging phenomena in gaseous detectors: Perspectives from the 2001 workshop," Nucl. Instrum. Meth. A **494**, 179 (2002).
- [10] M. Capeans, "Aging of gaseous detectors: Assembly materials and procedures," ICFA Instrum. Bull. **24**, 85 (2002).
- [11] M. Titov, "Radiation damage and long-term aging in gas detectors," ICFA Instrum. Bull. **26**, 002 (2004)
- [12] J. Va'vra, "Physics and chemistry of aging: Early developments," ICFA Instrum. Bull. **24**, 1 (2002) [Nucl. Instrum. Meth. A **515**, 1 (2003)].
- [13] L. Malter, "Thin film field emission", Phys. Rev., vol. 50, pp. 48-58, (1936).
- [14] A. M. Boyarski, "Model of high current breakdown from cathode field emission in aged wire chambers," Nucl. Instrum. Meth. A **535**, 632 (2004) [ICFA Instrum. Bull. **26**, 001 (2004)].
- [15] H. Yasuda, "New insights into aging phenomena from plasma chemistry," Nucl. Instrum. Meth. A **515**, 15 (2003).
- [16] D. Allspach *et al.* "Aging in the large CDF axial drift chamber," FERMILAB-CONF-04-449-E
R.S. Lu, "Performance and Operation Aspect of CDF Tracking/Vertexing Detectors," *These proceedings*.
- [17] M. Titov *et al.* "Aging studies for the muon detector of HERA-B," Nucl. Instrum. Meth. A **515**, 202 (2003).
- [18] R. Bouclier, M. Capeans, C. Garabatos, F. Sauli and K. Silander, "Effects of outgassing from some materials on gas chamber aging," Nucl. Instrum. Meth. A **350**, 464 (1994).
- [19] <http://outgassing.nasa.gov>
- [20] M. Capeans, "Aging and materials: Lessons for detectors and gas systems," Nucl. Instrum. Meth. A **515**, 73 (2003).