Computer Physics Communications

Recommendations for building and testing the next generation of gaseous detectors

Bernhard Schmidt*

DESY, Notkestr.85, 22607 Hamburg, Germany

Elsevier use only: Received date here; revised date here; accepted date here

This paper is the write-up of the very last talk of an interesting, exciting and exhausting workshop. It is not meant as another summary talk, but as the very personal view of the situation and recommendations for the future work.

1. Introduction

Giving general recommendations for building and testing of gaseous detectors is an almost impossible task. Especially in a framework where the most elaborated knowledge has been presented and multiply summarized by the world experts in the field. Making gaseous detectors radiation hard is a highly complex problem and no general solution for all kinds of applications exists. Nevertheless, some common rules and understandings have emerged in the past years and I will try to summarize a few of them here. Quite some of them sound trivial, unfortunately this does not mean that they are usually obeyed.

Since the last aging workshop in 1986 [1,2], a completely new class of gaseous detectors for high radiation levels has been developed. These are the detectors for the LHC experiments, for HERA-B and other high flux environments (e.g. synchrotron radiation detection) which are in the focus of detector development right now. These devices have to face radiation levels which were not even thought of in 1986, the scale we are talking about has been extended by almost three orders of magnitude from 'milli-Coulombs per centimeter' to 'many-Coulombs per centimeter' nowadays. In consequence, there are actually two rather distinct classes of gaseous detectors now. Those for 'standard radiation levels' like detectors at LEP, at HERA e-p or at the new e^+e^- colliders on one side and the above mentioned high flux detectors on the other side.

* Corresponding author. Tel.: +49-40-8998-4943; fax: +49-40-8998-4033; e-mail: bernhard.schmidt@desy.de.

2. Standard Detectors

For the standard applications, all basic rules how to build such a detector, how to test and operate it are well known. It has been demonstrated in various experiments and for all kinds of applications that these detectors are able to work and to survive their anticipated life time if some fundamental rules of construction and operation are followed.

Construction of these detectors profits from more than 40 years of experience. There are several well-known 'never do' rules [2], like avoiding silicon oil bubblers, certain glues, PVC tubing, wooden insulators and many others, whose observance will avoid running into major disasters (see e.g.[3]). Moderate care in building these detectors is recommended, but no exceedingly strict requirements in terms of clean rooms and/or materials and procedures. A huge variety of gases has been successfully used for the operation of gaseous detectors in moderate radiation environment, notably all kinds of hydrocarbons, alcohol, methylal, freons, DME, ammonia and others.

Operation of these 'standard detectors' is fine as long as any excessive radiation level is avoided. They are normally switched to 'safe' or even turned off under conditions, which are far from 'normal operation' at LHC!

If nevertheless a 'standard detector' gets sick and 'aging' is observed, the golden rule of applying additives to the gas has a fair chance to bring it back to operation. Some impressive examples have been shown at this workshop [20,21,22]. The main problem with curing detectors by additives is the observation of a certain individualism amongst them. They all need special treatment and invidiual recipes to be kept alive.

In summary, one can say that gaseous detectors for classical applications with medium or low radiation levels are now well understood devices based on an enormous amount of expertise.

3. Detectors for high radiation levels

The real challenge today are gaseous detectors for LHC like environments. This is especially true if new detector technologies are entering the game, normally introducing a new class of aging phenomena [e.g. 4, 5, 6]. A first step in the direction towards high rate experiments has been done by HERA-B at DESY, the final goal are the huge systems at ATLAS and CMS. For those detectors, recommendations of how to build and test them are much more complicated since the final proof of practicability has still to come! The initial goals of HERA-B in terms of radiation tolerance of the gaseous detectors for the inner (ITR) and outer (OTR) tracking systems were fully comparable to the corresponding systems at LHC experiments. The development of these devices has yielded a multitude of valuable findings and improvements [5-12] from which LHC experiments may benefit. In this sense, HERA-B is the first 'large scale test' going beyond laboratory dimensions for the new generation of gaseous detectors. Despite the positive demonstration that these detectors are able to handle and survive the envisaged radiation densities on a short time scale, HERA-B did not give much insight for the long term behavior and detector aging under real conditions since the so far accumulated dose corresponds to a fraction of a LHC year only. There is still room for interesting experiences and bad surprises!

3.1. Materials

A comprehensive search for and investigation of materials for high rate detectors has been carried out during the last decade. At CERN, the RD-10 (later RD-28) group was basically devoted to that issue and contributed substantially to present-day knowledge (see [14] and references therein). A detailed summary on material questions was given during this workshop by M. Capeans [13]. Not unexpected, the list of 'never use' is much longer now. As a guideline to start with, the NASA study on outgassing properties of materials for space science [15] is an excellent choice. Nevertheless, this can only be treated as a good recommendation for what to try out and does not excuse anybody from doing its own tests. Outgassing of materials and the resulting aging phenomena are not only a serious but also a complex field and the whole picture can be dominated by fine details of the set-up and experimental conditions. This implies, that outgassing and aging tests have to be done as close as possible to the final parameters of the envisaged application of the detector. For high radiation applications, new phenomena like radiation induced outgassing (due to disintegration of materials and radio-chemical reactions) might become important.

3.2. Gases

The situation with gases for high rate tracking is quite easy to survey now since almost all gases are excluded. Especially the full set of hydrocarbons, the real work horses in conventional detectors, are banned due to their pronounced tendency to cause aging by plasma polymerization. Similarly, the good old 'medicines' to cure chamber problems like alcohol, water or methylal are a poisonous breath in presence of strong irradiation. The puristic sample of gases left over for use in high radiation level detectors are noble gases, CO_2 and CF_4. Especially the last one has proven to be a quite a dangerous companion. It offers a lot, basically the only way to get a high drift velocity and thus fast read out, but it is hard to control and shows a significant agressiveness to wires and chamber construction materials [4,8,12,16,23]. Despite considerable R&D and a enormous progress in understanding the highly complex plasma chemical reactions in theses gases [17], the final prove that CF_4 containing mixtures can be kept under control (by adding or removing water for instance) and used in long term applications still has to come.

3.3. Construction

The construction of high rate detectors is mainly burdened and restricted by the allowed materials as discussed above. Obviously, any construction has to start from non-suspicious materials like metal, ceramics, glass and so on and add plastic material only with greatest care. One of the few general rules and advice which can be given is to carefully think about the electric field distribution in the detector. This question is less trivial than one might assume due to the fact that the counting gas becomes a fairly good conductor under irradiation, a much better conductor than typical solid insulators. In consequence, the field distribution is by no means determined by the capacity matrix, but currents have to be taken into account. This is especially true close to boundaries, a notoriously dangerous regime. A rather interesting rule to be learned from experts in high voltage insulation techniques is the strict avoiding of 'triple junctions' (especially on cathodes), singular points (or lines) in space where three different materials touch each other. A simple 'triple junction' is shown in figure 1, where a metal surface and an insulator touch inside the counting gas and are exposed to an otherwise homogeneous electric field produced by electrodes at top and bottom of the figure. Fig. 1a) shows the rather trivial case when the gas is a better insulator than the solid 'insulator' at the bottom. If such an arrangement is irradiated and the conductivity of the gas becomes higher than the one of the insulator, the field will change dramatically due to the currents (Fig. 1b). In this state, the 'triple junction' has developed as a hot spot with enormous field enhancement and is highly prone to be the origin of problems and the source of discharges. Fig. 1c shows the transition of the field strength at the surface, the time scale is a question of the capacity and conductivity of the specific case. As a general rule it follows, that in high radiation environments electric fields are determined by capacities AND currents. Triple junctions should be avoided and, if this is not possible, put into a field free or low field regime.

Another important detail to be taken into account during construction is the gas distribution inside the detector. In high rate detectors, it is not only the distribution of the 'main gas', but also the distribution of avalanche products, long lived radicals and other dangerous components, which play an important role. To understand their distribution as function of external parameters like gas flow, temperature or radiation load, is of vital interest for optimization of the robustness against aging of the device. Unfortunately, this is a quite complex problem (to some extent with the exception of straw detectors) since the transport of this species is affected by the forced flow (pressure gradients) as well as by diffusion and convection (partial pressure and temperature gradients). All these parameters usually are completely different in prototypes and test chambers from the final detector!

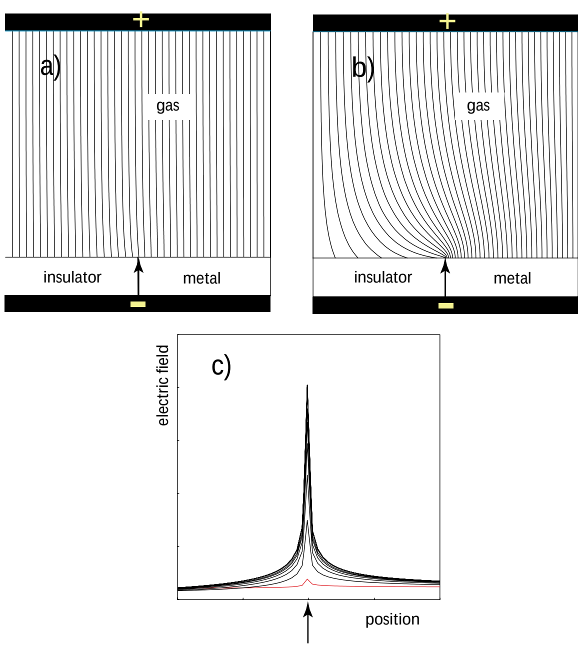

Figure 1: Electric field close to a junction of a metal and an insulator in counting gas.
a) Conductivity of the gas is 1/10 of the insulators'.
b) Conductivity of the gas is 10 times the insulators'.
c) Development in time of the electric field strength at the surface for case b). The triple junction is located at the position of the arrow. The various lines show the electric field strength for different points in time between the initial condition (purely capacitive) and the final condition with currents.

The classical method to study gas flow in chambers, by building a transparent prototype and smoking some cigars into it (Fig. 2) is not very appropriate to solve this problem. On the other hand, there exist several programs and (equally important) experts to use them which allow to model gas exchange in complex geometries since this is a common problem for various technical and industrial applications. It is strongly recommendable to invest some money for getting professional help here.

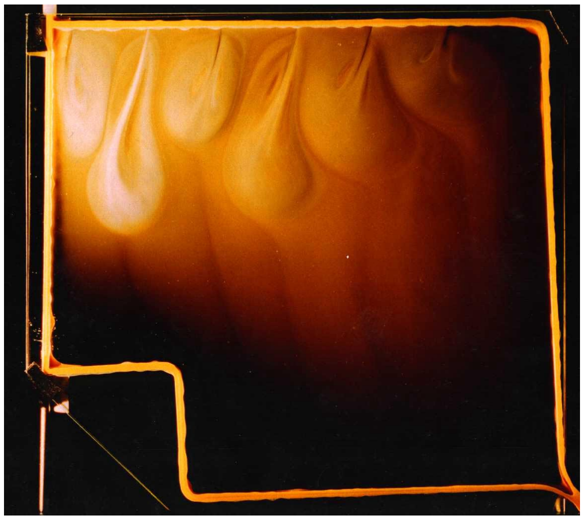

Figure 2: Testing the gas flow in a MSGC prototype by means of Cohiba Siglo IV [24].

3.4. Building the detector

It goes without saying that building the detector and its components has to be done under clean and, most important, under well controlled conditions. With 'clean' not only the absence of dust particles is described but also the way how parts and tools are handled. There is a considerable risk of introducing bad components in an otherwise properly constructed detector just by improper handling. Typical examples are unfiltered air, greasy fingers, polluted tools or improper storage places. Much more detailed discussions of the subject can be found in the contribution of M. Capeans to this workshop.

An essential ingredient for successful detector building is a quite rigorous documentation of what has been done by whom and when. This extra effort will pay off largely if you have to reconstruct and pin down problem paths. Part of this rigorousness is keeping samples of materials you have used, not just samples of 'the same kind'.

If you have made a proper documentation of all the rules for building the detector, you have to verify that the rules are not violated! Be especially aware of 'slip in' changes which are a natural outcome of routine work. A typical example are glueing techniques. It is most essential to stick to *proven* procedures of mixing, curing, outgassing, application and so on even if the people doing the work might not understand why this has to be done that way. Any detail changed might have fatal consequences. The same holds for soldering techniques, solder tin is *not* a unique product and has to be chosen with care.

As a little example of how soldering/glueing techniques can jeopardize the struggle for a reliable detector, a problem occurred with the HERA-B Outer Tracker (OTR) chambers should be looked at in a bit more detail. In its first year of operation, this detector suffered a lot from high voltage problems, resulting in finally as much as 15% of dead area. After opening the chambers and a critical inspection, the problem could be traced to a specific HV capacitor at the HV distribution boards of the modules. Two out of 18 capacitors per board had been surface mounted (glued and soldered) using a slightly different technique to simplify the production process of the boards. As a consequence, the capacitors had a fatal tendency to produce surface discharges across their insulator, sometimes resulting in a permanent short. From the measured statistics, it could be deduced that the average time to produce such a problem per capacitor was something like 50 years, much too short if you have to keep the failure rate per year at the permille level due to unavoidable grouping of the HV channels. This illustrates another point as well, namely that prototpyes of huge systems really have to be big to discover problems on a finite time scale. In this case, a few thousend capacitors would have to be used in tests to allow for a statistically significant result within months. It should be added here that all 16000 faulty mounted capacitors in the HERA-B OTR have been replaced meanwhile, increasing the HV stability of the system by about one order of magnitude.

A few more trivialities: mixing ‘identical’ material from different suppliers is not recommendable. It is already difficult enough to keep one supplier and his products under control.

Avoid any ‘ad hoc’ changes in procedures or materials! If a problem occurs: find and *verify* your remedies, otherwise you might introduce new hidden problems. This will take some time, and if your time schedule does not allow for it, the schedule is imperfect.

Another vital point in building the detector is quality control. It should be obvious, that not only the quality of the final product, but also intermediate steps have to be validate and closely followed. In case of a modular production, samples should be taken in regular intervals and tested rigorously. These tests have nothing to do with the final quality control every item has to pass! They are rigorous in the sense that they probe the limits of the product, and the tested modules should *not* be used for the final detector!

Do not save money on the wrong place, typically tools, man power, testing equipment, prototypes. It will pay off later. Finally: do not produce in a rush! A big and complex system which has to last for a long time needs *care* and can not be build in a crash effort.

4. Preparatory work: test, test, test ….[7]

As pointed out by many speakers at this workshop, testing is the most vital, the most beneficial and the most cumbersome work while constructing and building a gaseous detector. Besides verifying the basic functionality of the device, its ‘durability’ and ‘robustness’ are the parameters to check in view of the envisaged life time and environment. All phenomena, making the behavior of the detector different (usually worse) than its initial state, usually are called ‘aging’. Despite the fact that in almost all cases the observed degradations are due to wear and not a sign of temporal decline. The central goal of ‘aging tests’ therefore is to find a set of internal and external parameters for the detector element optimizing its robustness and stress tolerance, mainly in view of radiation load. The fundamental problem of aging tests is simple but far-reaching: real time tests are normally excluded as are tests of the full system. Thus aging tests are done on “small” but hopefully representative mockups or sub-elements of the final detector, and they are done on an accelerated time scale. The resulting necessity to extrapolate from the behavior of the test set up to the full system/full time performance is the most critical part of aging research. Together with the multitude of parameters, the somehow arbitrary extrapolation and acceleration factors are causal for the often contradictory and irreproducible results in aging research.

The problems of finding a representative 'test sample' of the final device are obvious, it should contain all (critical) components in the final composition and arrangement. Modular detector concepts have some advantages here. System effects coming in on 'large scale' only, are neglected and have to be evaluated separately. How to scale properly from accelerated tests is somehow less obvious since important (usually not well based) assumptions about aging mechanisms (aging models) have to be made to treat the various parameters properly.

4.1. Aging models and the scaling problem

Typical aging phenomena in gaseous detectors like polymerization, etching, corrosion, deposits, wire swelling and so on depend on many highly correlated *microscopic* parameters like the densities of electrons, ions, radicals, photons and neutral gas composites. What can be steered and influenced on the other hand are *macroscopic* parameters like the gas flow and temperature, the radiation density, radiation type, electric potentials and the *main* gas components. Due to the necessary acceleration of the test, NO test will reproduce exactly the microscopic parameters of the system under real operation! In consequence, model assumptions are needed to link the microscopic parameters with the external ones.

The most simple and commonly used model makes the following assumptions: gas avalanches are independent and the 'damage rate' is proportional to the local current. In this simple model, there is just one scaling variable, the accumulated charge, describing the integral stress and the expected damage at a certain detector area. This model has worked fine and thus proven its validity for low radiation intensities but it has NOT been validated for high intensity applications. In contrary, there are many hints if not evidences that it is not adequate:

- Evidence for non-linear dependence on *local* radiation load (rate effects) [7,16,18,19]
- Evidence for dependence on the *size* of the irradiated area (aging as non-local phenomenon) [5]
- Evidence for the participation of long lived, radiation produced species. [8,16]

The latter would automatically violate the simple scaling assumptions and create non-local and intensity dependent effects. In this case, scaling becomes especially complicated as should be illustrated on two examples: if 'creating' dangerous species in the avalanches dominates, aging should be enhanced downstream with the gas flow (not scaling with the local radiation load). If burning away dangerous species in the avalanches dominates, an upstream enhancement could be expected. In both cases, the aging rate would by no means scale with the radiation intensity. Reality will be a complex mixture of many processes and 'dominance' could well be different in the test set up and in the full system. Aging depends explicitly on the gas exchange rate, the recommendation to start with would be to scale the gas exchange rate with the irradiated volume.

4.2. How to plan and perform aging tests ?

First of all, choose the parameters of the set up carefully and make sure you have considered potential influences and dependences. Which parameter has to be extrapolated how? During tests, vary all parameters systematically to explore the parameter space with reasonable density. Check if your assumptions about dependences of observables are valid. It goes without saying, but reproduce your results! If you can't reproduce your findings, you have no basis to extrapolate to anywhere.

Which are the most fundamental parameters to be varied in any aging test for high rate detectors? For a LHC type device, the following list seems to be mandatory :

- The local radiation density
- The integral radiation load on the full detector
- The radiation type (photon, hadrons, …)
- The gas exchange rate

- The gas composition in view of 'small' components (O_2, H_2O,…)

Others might be important for special cases like photon or neutron detectors.

In any case, the large set of parameters which have to be controlled and explored demand for the most rigorous method of performing the tests. This implies that a clear strategy of 'what do we want to learn' exists. Parameters should be varied in a systematic way, strictly avoiding to change two or more parameter at once. All accessible parameters have to be documented, even if they seem to be obvious or trivial. Minimally have to be recorded :

- the gas parameters, including water and oxygen content, flow, temperature and pressure
- The radiation level as function of time and space
- All currents and voltages
- Who has done what and when

The status of the aging process should be checked by measuring the pulse height distribution (preferentially with X-rays) as function of position, inside and outside the irradiated area. Currents are integral quantities and might hide important facts.

If you observe unexpected things, do not ignore them or stop at the 'this might be due to ...' level. Verify and cross check your interpretations and do not continue until you have clarified the point. Be always aware of hidden parameters which might severely influence your results.

If finally a working point for the test setup could be established, you have to extrapolate to the full detector. At this point, my personal credo is, that NO parameter should be extrapolated by more than one order of magnitude. Recovery from a missing factor of 3 is likely, a missing factor of 100 is almost impossible to overcome.

4.3. Prototypes

The first verification of the established working point and its extrapolation comes from a 'full size prototype'. Full size here means, the smallest independent element of the final detector. For modular systems, this could be a quite handy device, but on the other hand, a large number of 'modules' gives more room for system cumulative effects which have to be investigated separately. The prototype has to be exposed to the real radiation profile (not just a small spot) of realistic radiation type to validate his performance. If this is not possible, go as close as possible and confirm the extrapolations.

Prototypes should be tested extensively, if possible exceeding the envisaged final stress. A surviving prototype has not been tested enough.

Finally it has to be mentioned, that testing devices and prototypes should not be dictated by financial limits. Testing has to be a substantial fraction of the total cost of the system if a certain level of reliability and durability is required. Saving money in the test phase is extremely hazardous and prone to jeopardize a lot of work.

5. Final remarks

Building gaseous detectors is a complex art. It needs a lot of communication, common efforts and sharing of know-how of all people in the business. This workshop was an outstanding example of how to improve on that. Thanks to all participants who made it a big success, and thanks to the organizers for their enormous, professional, responsible, and encouraging work.

Detectors are like us: aging is unavoidable, surviving in good shape the main issue.

References

[1] J. Kadyk, ed., Proc. Workshop on Radiation Damage to Wire Chambers, LBL-21170 (1986).
[2] J. Kadyk, Nucl. Instr. and Meth. A 300 (1986) 436.
[3] R. Henderson and R. Openshaw, these proceedings.
[4] T. Ferguson, et al., these proceedings.
[5] T. Hott, these proceedings.
[6] M. Hildebrandt, these proceedings.
[7] H. Albrecht, et al., these proceedings.
[8] A. Schreiner, these proceedings.
[9] M. Capeans, K. Dehmelt, M. Hohlmann, B. Schmidt, these proceedings.
[10] K. Berkhan, et al., these proceedings.

[11] M. Hohlmann, A large ultra-clean gas system with closed loop for the high-rate Outer Tracker at HERA-B, these proceedings.
[12] M. Titov, these proceedings.
[13] M. Capeans, these proceedings.
[14] R. Bouclier, et al., Nucl. Instr. and Meth. A 381 (1996) 289.
[15] W.A. Cambell, Jr. and J.F. Scialdone, NASA-RP-1124-Rev-3 (1993).
[16] T. Akesson, et al., these proceedings.
[17] H. Yasuda, these proceedings.
[18] M. Kollefrath, talk at this workshop.
[19] K. Kurvinen, et al., these proceedings.
[20] A. Boyarski, these proceedings.
[21] D. Bailey, these proceedings.
[22] C. Niebuhr, these proceedings.
[23] G. Gavrilov, Nucl. Instr. and Meth. A 488 (2002) 240, and talk at this workshop.
[24] H. Rieseberg, private communication (1996).