Aging problems of the Inner Tracker of HERA-B – an example for new detectors and new effects

Thomas Hott* for the HERA-B Inner Tracker Collaboration**

1) Introduction

The new generation of high-rate experiments for high-energy physics demands gaseous detector technologies closing the gap between the capabilities of silicon strip detectors and conventional gaseous detectors like Multi-Wire-Proportional-Chambers (MWPCs). Most new designs are based on micro pattern structures, i.e. regular arrangements of very tiny electrode structures to generate gas amplification and for readout.

Aging due to gas polymerisation is a permanent risk for any gaseous detector operated under high rates. Additionally, in the case of modern micro pattern detectors material outgasing becomes a much more dangerous source for pollutants and therefore for gas aging because the surface to volume ratio is increased tremendously compared to typical MWPCs.

Very often surfaces carrying electrodes are involved in the detector operation. Their electrical, chemical and mechanical surface and bulk properties determine the short-term and long-term performance.

The Micro-Strip-Gas-Chambers (MSGCs) and GEM-MSGCs (GEM = Gas-Electron-Multiplier) developed for the Inner Tracker of HERA-B are typical examples for such new detector types as well as their requirements: particle rates up to $2 \cdot 10^4$ mm^{-2} s^{-1}, radiation doses of more than 1 mrad y^{-1} during five years of operation, spatial resolution of about 100 μm and signal collection within 100 ns. The active detector surface of 25 cm · 25 cm and the chamber volume of 500 cm^3 are comparable large but still typical dimensions.

On the way towards a working technology, the Inner Tracker Collaboration was forced to carry out extended basic research in electronically conductive surface coatings for the MSGC wafers and in the GEM technology. Not all problems could be solved. The chambers are very sensitive to gas pollutants and electrical discharges are a permanent risk.

Nevertheless, the successful operation of more than 130 GEM-MSGCs for more than 9 month in HERA-B has proven the suitability of these new detectors for high-rate experiments.

*   Thomas.Hott@cern.ch
** University of Heidelberg, University of Siegen, University of Zuerich

2) Aging Tests and Experimental Settings

Bulk Effects

Slight surface conductivity is mandatory for any MSGC designed for high-rate experiments to avoid surface charging-up between anodes and cathodes in order to provide the required rate capability.

The first type of MSGCs developed for HERA-B was based on a bare, ionic conductive DESAG D-263 glass wafers carrying the electrode structures (Figure-1) providing bulk conductivity as well.

High-rate, long-term measurements with soft X-rays (mainly Cu-K_α) revealed an effect named ´sudden death´: the sudden and total breakdown of the chamber performance after a charge collection equivalent to less than 1 year of operation in HERA-B (Figure-2). This effect can be explained as electrical field distortions caused by ion migration inside the bulk. Of course, the energy deposition in the glass due to absorbed photons influences the ion migration as well as the applied electrical fields. Taking into account the different energy deposition when operating such MSGCs in an environment of Minimum-Ionising-Particles (MIPs) a different aging behaviour can be expected. Nevertheless, MSGCs built on ionic conductive glass were regarded as unusable for HERA-B [1].

A way to overcome the ´sudden death´ problem while keeping the material budget acceptable in terms of the radiation length X_0 is the use of ´diamond coated´ MSGCs (Figure-3). The ´diamond coating´ is a thin (≈ 80 nm) electronically conductive layer of amorphous C, Si, N and H between wafer glass and anode-cathode structure [2].

During the studies of the ´sudden death ´effect with X-rays it turned out that the strength of this effect does not depend only on the accumulated charge but also on the experimental settings. For the same charge accumulation rate it was found aging occurs much faster when operating a chamber in the mode of ´right gas gain´ compared to chamber operation in the ´right avalanche size´ mode. ´Right gas gain´ means applying potentials as foreseen for MIP detection to all electrodes and therefore generating about 10 times larger avalanches and much more intense plasma in each gas amplification. This is due to the release of about 10 times more charge in the counting gas by an absorbed Cu-K_α photon with respect to a passing MIP. The ´right avalanche size´ mode requires reduced potentials and does therefore also not represent the operation conditions in high-energy physics experiments.

Comparable aging tests carried out by the group of F. Sauli [**3**] operating similar MSGCs always at equal gas gains but varying the charge accumulation rates showed rather little aging for charge accumulation rates being about 30 – 40 times higher than expected for LHC experiments or HERA-B and rather fast aging when operating at charge accumulation rates of approximately only 10 times higher.

For the development of the HERA-B Inner Tracker it was concluded that aging tests with soft X-rays must be performed in both modes: ´right gas gain´ and ´right avalanche size´ and should not exceed charge accumulation rates of more than 10 – 20 times as expected for HERA-B to be regarded as representative.

Gas Aging

Classical gas aging, observed as deposits coating the anodes with polymers or pure carbon (Figure-4), occurred the first time when carrying out high-rate X-ray tests with GEM-MSGCs of final design and size [4]. Only radiation-hard, non-outgasing materials had been selected after passing extensive tests proving their suitability.

As long as irradiated surfaces have been in the order of 10 – 20 mm^2 no gas aging was observed in both, MSCGs and GEM-MSGCs. Once the irradiated surfaces were enlarged to at least several cm^2 gas aging occurred in presence of Ar-DME mixtures. Similar to the ´sudden death ´phenomenon gas aging occurred always stronger for moderate charge accumulation rates (Figure-5).

No gas aging was found with Ar-CO_2 mixtures. Ar-CO_2 70-30 was chosen finally for the operation in HERA-B. Compared to Ar-DME 50–50 this choice implied several drawbacks to be accepted: lower primary ionisation, larger strip multiplicity (due to larger diffusion of the drifting electron cloud), higher gas gain, i.e. increased potential differences for compensation and intrinsic lower discharge stability (causing higher operation risks) [4].

3) Spark Problem

Detectors operated in an intense, high-energetic hadron beam must tolerate a considerable amount of Heavily Ionising Particles (HIPs) releasing about 10 – 100 times more charge than a passing MIP. The main operation risk for gaseous detectors is induced discharges caused by those HIPs. They are endangering MSGCs in particular when traversing the chamber very close to the wafer surface generating discharges between anodes and cathodes (Figure-6a, b).

Several factors are influencing the discharge probability and the destructive potential [5]. The discharge probability depends mainly on the potential difference between anodes and cathodes (Figure-7) but also substantially on the counting gas mixture. The gas gain will be different for same potential differences in different gas mixtures but discharge probabilities were expected to be more or less similar at similar gas gains. Obviously this is not the case, e.g. AR-DME 50-50 offers more discharge and operation stability than AR-CO_2 60-40 (Figure-8).

Several beam tests and X-ray measurements have confirmed that a standard ´diamond coated´ MSGC operated at a gas gain of about 6000, as required by the HELIX-128 ASIC front-end electronics, and with reasonable long strips, as required by HERA-B, will not survive in the HERA-B environment for more than few hours.

4) Multiple Electrode Sparks (MES)

The combination of a GEM [6] with a ´diamond coated´ MSGC (Figure-9) is a way to overcome the spark problem as long as both gas amplifying stages, i.e. GEM and MSGC, are operated at undercritical potentials with respect to HIP induced discharges.

During the operation of GEM-MSGCs, using AR-CO_2 70-30 counting gas, at HERA-B, it turned out the required total gain of at least 6000 demands potential differences in the GEM and between anodes and cathodes still allowing sporadic induced discharges in both stages. Usually they were not fatal but in rare cases consecutive discharging of all electrodes was induced causing severe large-scale destructions in the anode-cathode structure. This special type of combined discharges, named Multiple-Electrode-Sparks (MESs), start always with a discharge between both sides of the GEM through one of the GEM holes. Due to the potential drop in the GEM and the sudden potential difference rise between lower GEM electrode and the anode-cathode structure the next discharge occur, destroying several anodes and cathodes due the large capacity of the GEM. This is followed by a second discharge in the GEM and a discharge between GEM and drift electrode. Sometimes even a second discharge between GEM and anodes-cathode structure may happen. It was found that the probability for MESs to occur can be reduced significantly by reducing the drift field, i.e. the electrical field between drift electrode and GEM and between GEM and anode-cathode structure [4]. Reducing this field implies unfortunately a gas gain reduction in both amplifying stages and must be compensated by increasing the potential difference inside the GEM and between anodes and cathodes causing again a much higher risk for ´normal´, fatal HIP induced discharges.

5) Diamond Aging

A very particular aging effect is related to the ´diamond coating´ of the MSGC wafer. The effect was found when carrying out high-rate, long-term X-ray tests with GEM-MSGCs of final design and size, irradiating ´large´ surface areas. The applied electrical potentials have been as foreseen for the operation in HERA-B. Three periods of different detector performance were observed: i) normal behaviour (charge collection correspond to $t < 1$ year of operation in HERA-B), ii) continuous worsening of energy resolution combined with a general shift towards higher gas gains while all potentials were kept constant (charge collection correspond to $1 < t < 1.5$ years of operation in HERA-B), and iii) almost fully recovered energy resolution while the gas gain remains significantly increased (charge collection correspond to $t > 1.5$ years of operation in HERA-B) (Figure-10).

This change of detector performance can be explained as follows: during each gas amplification process some ´diamond coating´ is etched or sputtered away next to the anode edges. In phase i) the effect is too small to influent the detector performance. In phase ii) enough coating is removed in-homogenously causing local variations of surface conductivity, non-linear potential drops between anodes and cathodes and gas gain variations worsening the energy resolution. Once the coating is removed almost completely and uniformly next to the anodes, phase iii) starts. The potential drop remains non-linear but is now uniform along the anodes as well as the gas gain. The gas gain stays increased compared to phase i) because the potential drop takes now mainly place in the very small region of removed coating [4]. The MSGC works almost like a Micro-Gap-Chamber.

Most probably reducing the drift field for MES suppression leads to stronger diamond aging. In order to keep the gas gain constant the potential difference between anodes and cathodes must be increased and the shape of the gas amplification avalanches changes. The plasma becomes much more intense above the coating next to the anode edges.

So far diamond aging has not been observed in beam tests. This might be due to the much smaller accumulated charge but could be as well the result of the smaller avalanche sizes generated by MIPs. Therefore it has not been clarified yet if diamond aging will become a visible effect in HERA-B. ´Diamond aging´ has no relevance when only hit information is required, as in HERA-B, but detectors designed to deliver dE/dx information might seriously suffer.

6) Conclusions

Developing new detector technologies for high-energy physics experiments requires carefully selected experimental settings for any test measurement. Charge accumulation rate, gas gain, particle/photon rate and composition, exchange rate of counting gas etc. have strong influence on the aging behaviour. Their individual and correlated influence must be also understood to allow reliable predictions about the long-term detector performance under final operation conditions. Any far extrapolation of results implies high error risks and must be avoided. Complementary measurements allow better predictions.

Detector modules of final design and size should be tested as soon as possible - large fractions of the chambers, better complete chambers should be irradiated. Risking complete chambers might deterrent but facing problems early is fundamental. It will finally reduce costs and time.

Any change of detector design or operation settings can/will cause additional operation problems and should be avoided if possible. In the case of the HERA-B Inner Tracker development the introduction of additional ´active´ components like the ´diamond coating´ and the GEM, as well as each change of the electrical field configuration, created severe new operation problems.

Induced electrical discharges are a main operation risk for micro pattern detectors with their tiny electrode structures. Their appearance depends strongly on the beam composition. Intense hadron beams generate the most harsh operation environments. Discharge problems scale with the applied potential but depend also significantly on the counting gas, surface conductivities, installed capacitances, strip materials and conditioning of chambers.

Many problems are connected, and due to overall detector requirements some ´bad´ compromises are unavoidable.

Eventually, final electronics determining the required gas gain, signal shape, noise and pick-up, should be used for all test measurements as soon as possible.

References

[1] T. Hott, Entwicklung und Test großflächiger Mikro-Streifen-Gas-Kammern fuer das innere Spurkammersystem von HERA-B, Ph.D. thesis; Univ. of Heidelberg, Germany (1997).

[2] F. Sauli, et al., PPE-GDD, CERN, Geneva, Switzerland (1995).

[3] M. Capeans, Study of the Aging of Gaseous Detectors and Solutions for the use of MSGCs in High-Rate Experiments; Ph.D. thesis, Univ. of Santiago de Compostela, Spain (1995).

[4] C. Richter; Development of Micro-Pattern-Gas-Detectors for High-Rate Experiments; Ph.D. thesis, Univ. of Heidelberg, Germany (2000).

[5] S. Visbeck, Untersuchungen von Prototypen der Mikro-Sterifen-Gas-Kammern des inneren Spurkammersystems des HERA-B Experiments; Diploma thesis, Univ. of Heidelberg, Germany (1996).

[6] F. Sauli, et al., The Gas-Electron-Multiplier (GEM); CERN PPE/96-177, CERN, Geneva, Switzerland (1996).

Figure-1: Schematic view of a MSGC built on ionic conductive DESAG D-263 glass.

Figure-2: Long-term behaviour of an uncoated MSGC operated at different gas gains.

Figure-3: Schematic view of a ´diamond coated´ MSGC built on alkali free DESAG AL-45 glass.

Figure-4: Severe gas aging was observed during a hadron beam test at PSI in 1998. Deposits of pure carbon and polymers were found on the anodes after charge accumulation of ≈ 0.2 mC/cm (≈ 0.4 HERA-B years).

Figure-5: Gas gain as function of irradiation time. In case of large irradiated surface and two times lower charge accumulation rate, the aging process is significantly increased.

Figure-6a: Slightly damaged MSGC anode and cathodes due to operation in an intense p/π beam (PSI 1996).

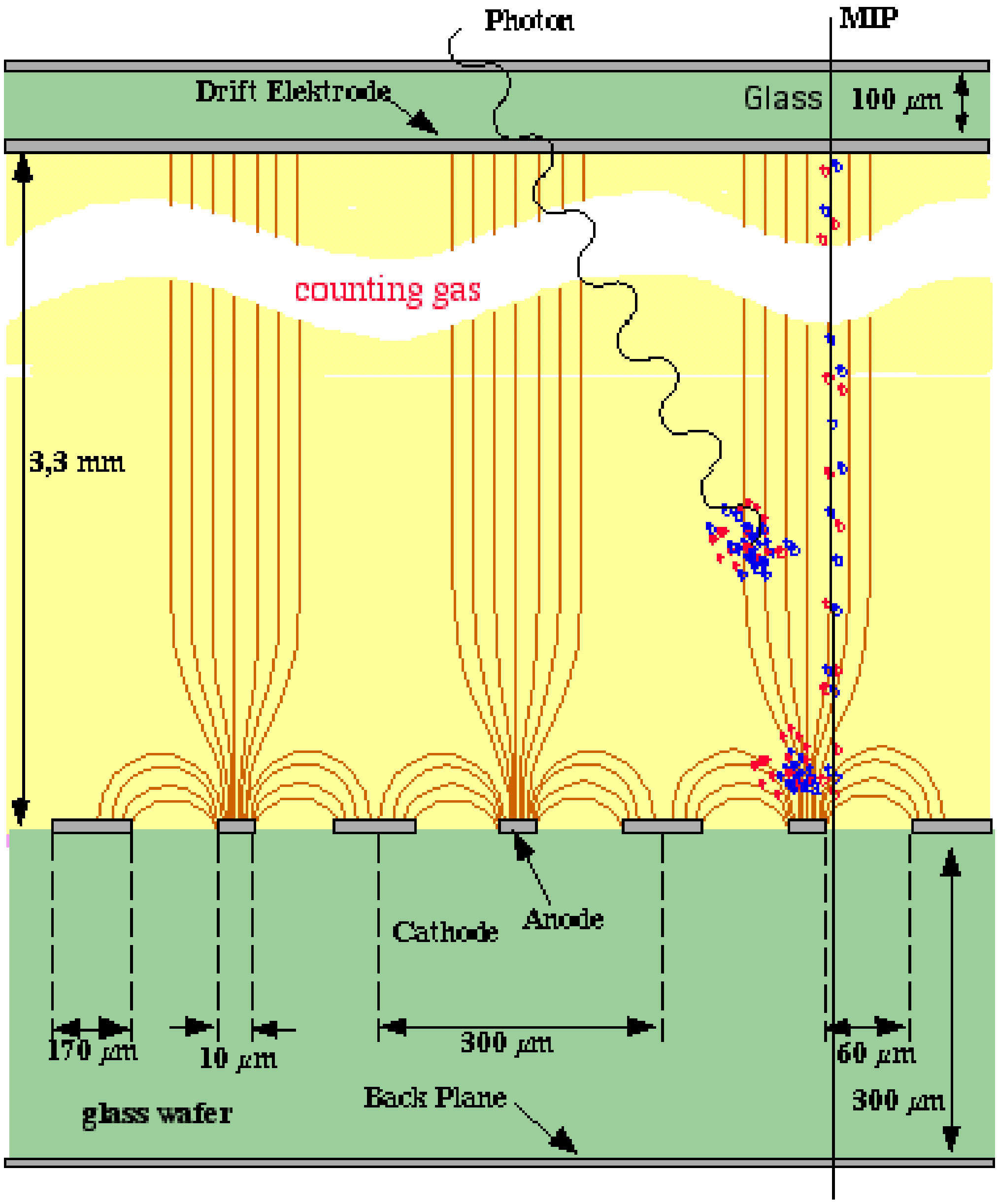
Figure-6b: Destroyed MSGC anode due to operation in an intense p/π beam (PSI 1996).

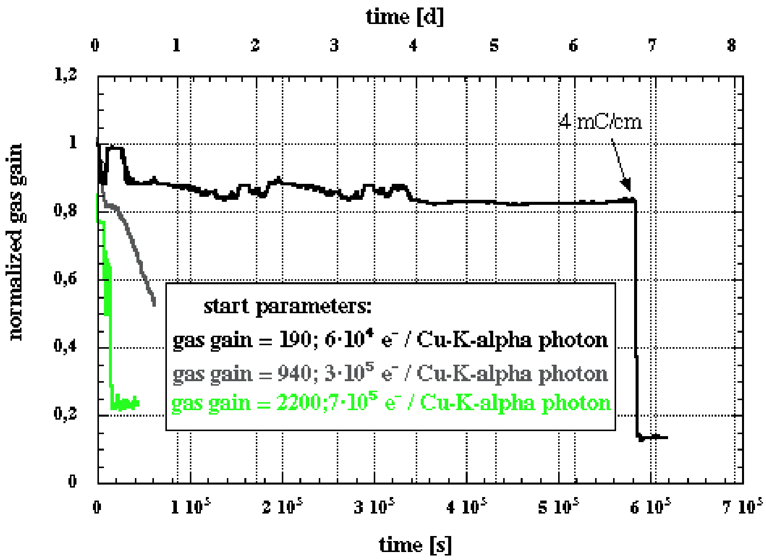
Figure-7: Probability of HIP induced discharges (arbitrary units) as function of the MSGC anode-cathode potential difference (anode = ground potential).

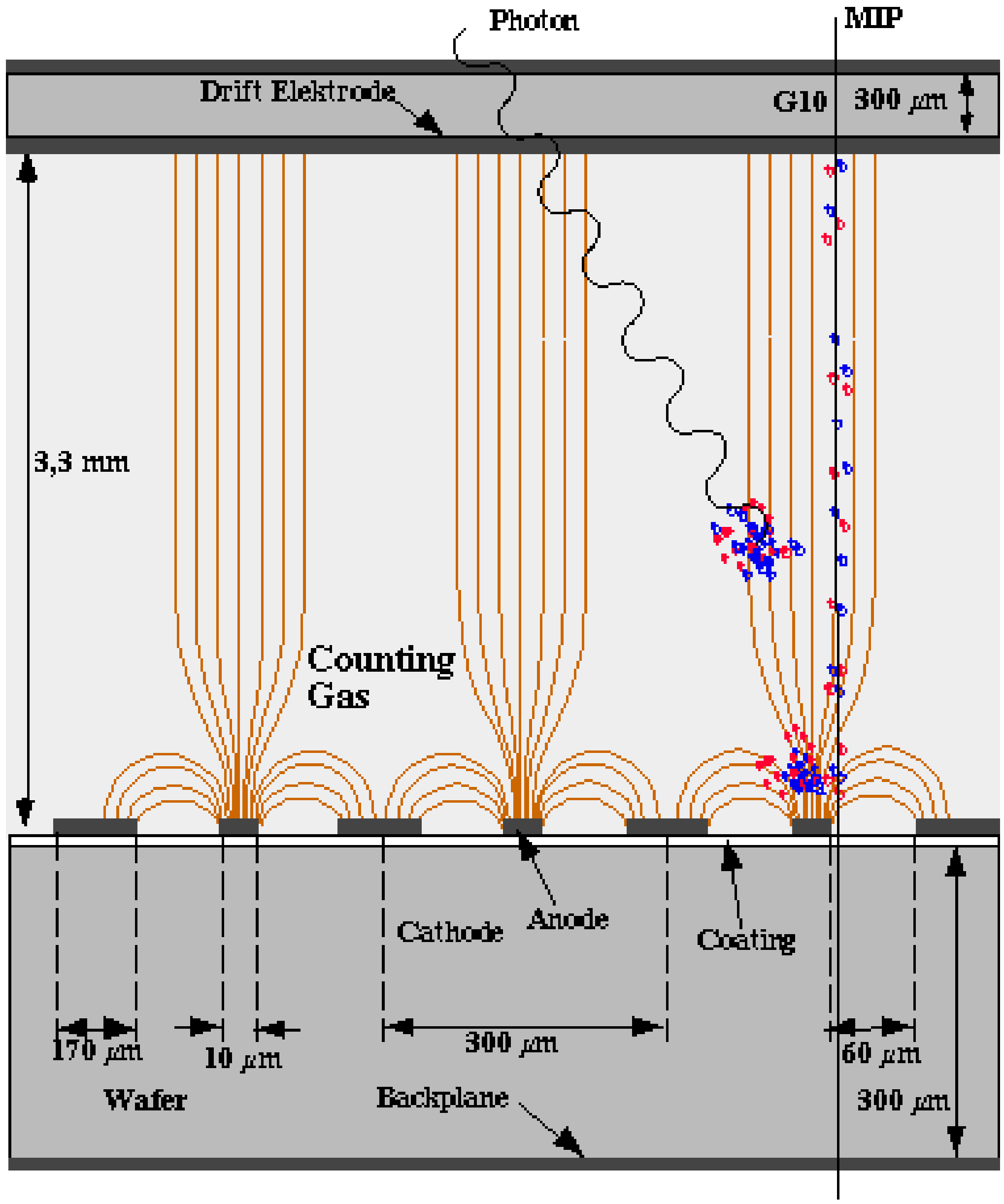
Figure-8: Probability of HIP induced discharges (arbitrary units) at small gas gains for AR-DME 50-50 and AR-CO_2 60-40.

Figure-9: Schematic view of a GEM-MSGC as used in HERA-B. The MSGC wafer is ´diamond coated´.

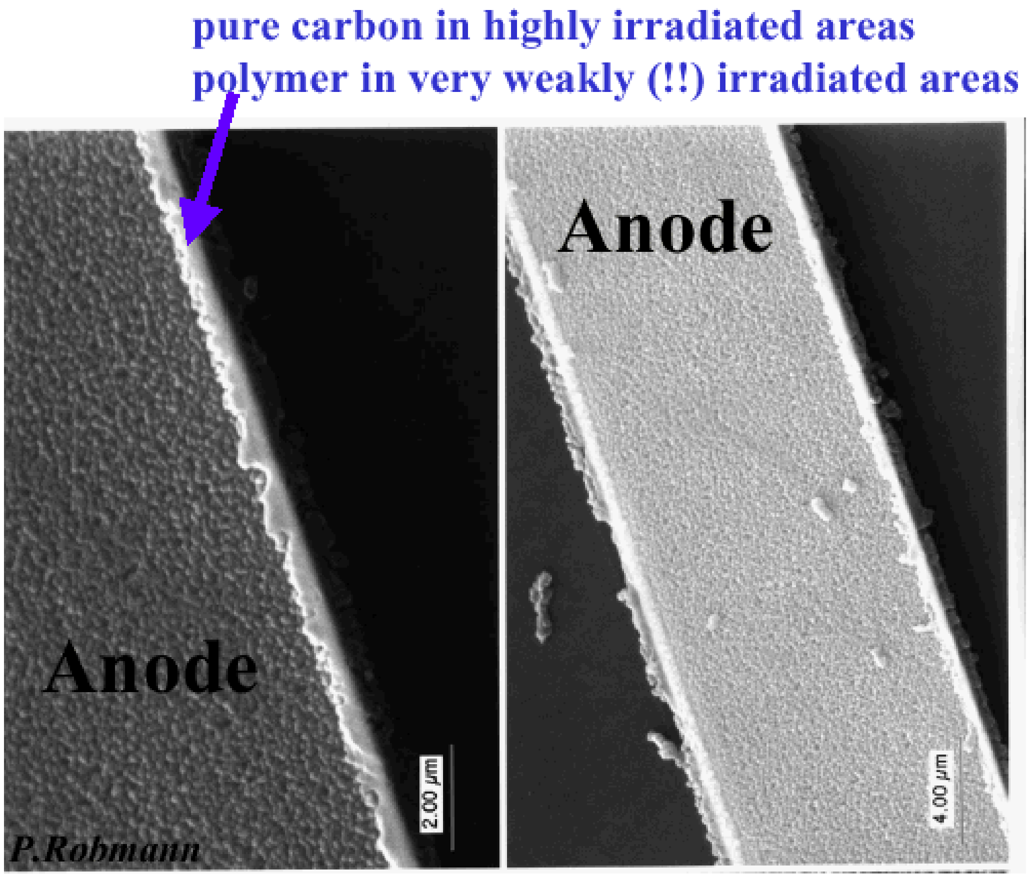
Figure-10: The three phases of diamond aging.

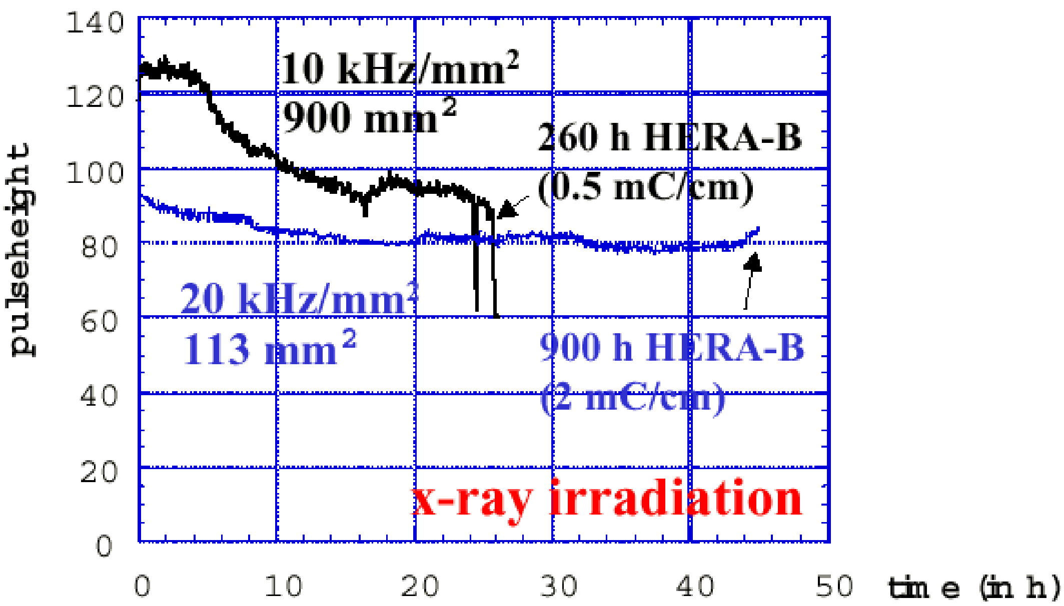

Photon
MIP
Drift Elektrode
Glass
100 µm
counting gas
3,3 mm
Cathode
Anode
170 µm
10 µm
300 µm
60 µm
300 µm
glass wafer
Back Plane

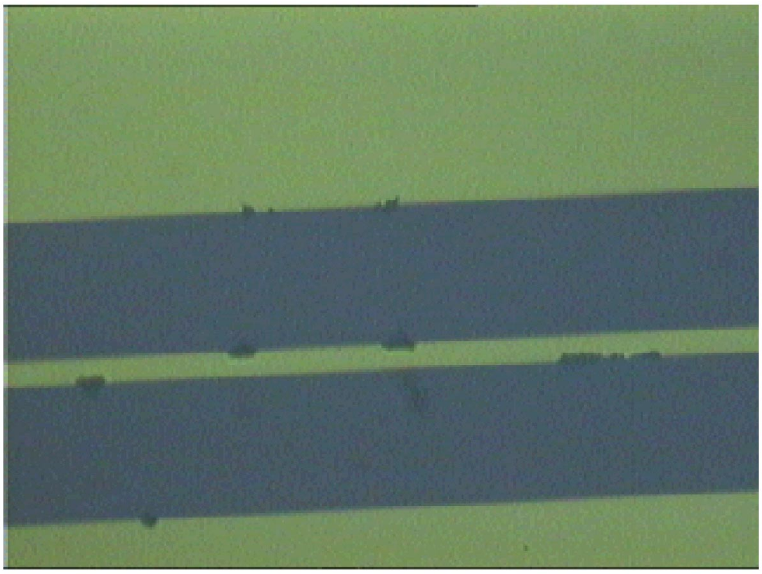

time [d]
0
1
2
3
4
5
6
7
8
1,2
1
0,8
0,6
0,4
0,2
0
normalized gas gain
4 mC/cm
start parameters:
gas gain = 190; 6·10⁴ e⁻ / Cu-K-alpha photon
gas gain = 940; 3·10⁵ e⁻ / Cu-K-alpha photon
gas gain = 2200;7·10⁵ e⁻ / Cu-K-alpha photon
0
1 10⁵
2 10⁵
3 10⁵
4 10⁵
5 10⁵
6 10⁵
7 10⁵
time [s]

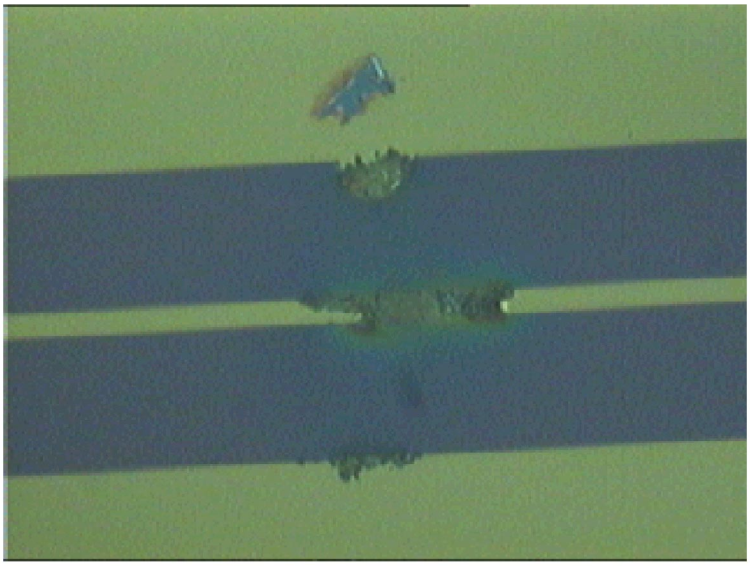


Photon
MIP
Drift Elektrode
G10
300 μm
3,3 mm
Counting
Gas
Cathode
Anode
Coating
170 μm
10 μm
300 μm
60 μm
300 μm
Wafer
Backplane

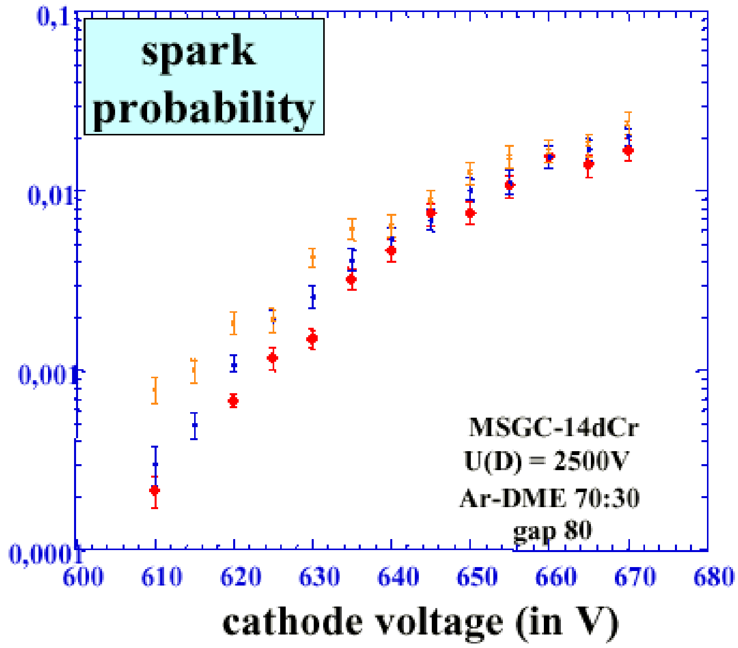

pure carbon in highly irradiated areas
polymer in very weakly (!!) irradiated areas
Anode
Anode
2.00 µm
4.00 µm
P.Rohmann


pulseheight
time (in h)
0
10
20
30
40
50
0
20
40
60
80
100
120
140
10 kHz/mm²
900 mm²
260 h HERA-B
(0.5 mC/cm)
20 kHz/mm²
113 mm²
900 h HERA-B
(2 mC/cm)
x-ray irradiation



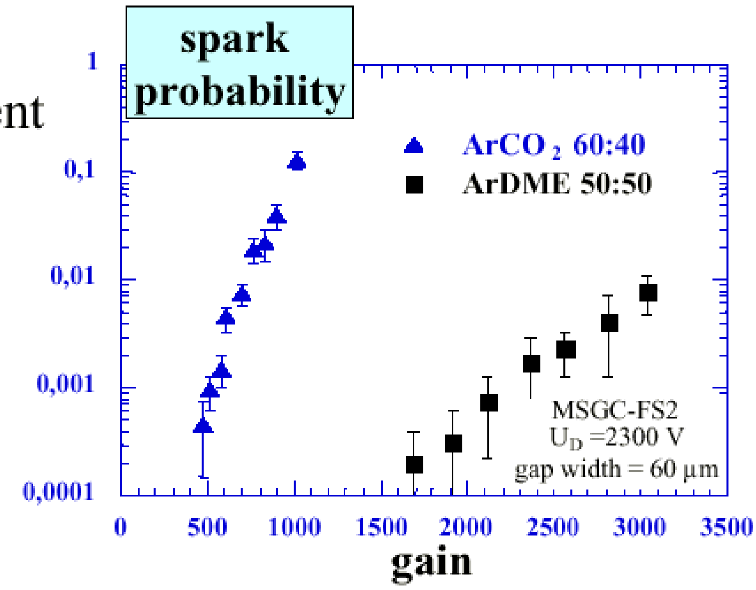


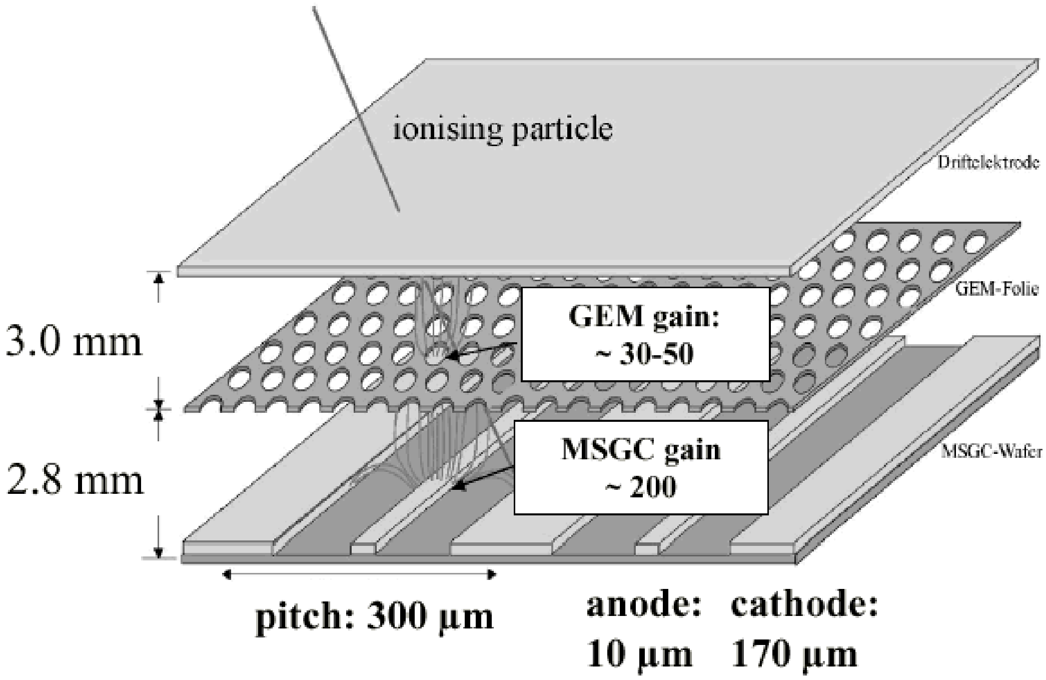
• strong dependence on cathode voltage



• gas dependent

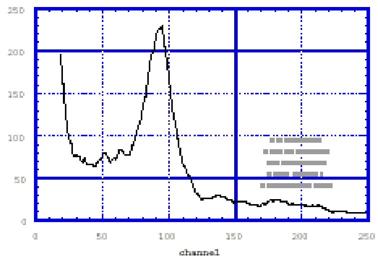
(ArDME much better than e.g. $ArCO_2$)





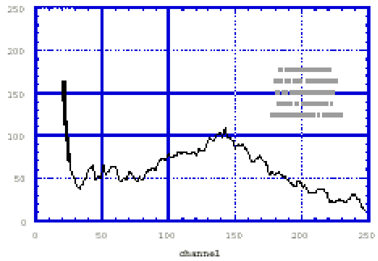
Cu-K$_\alpha$–spectra:

U_K =485 V



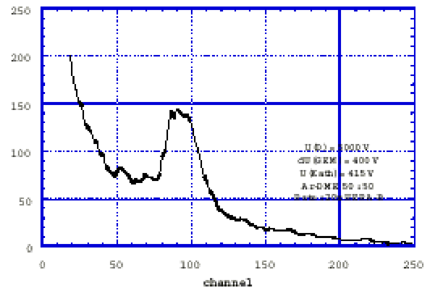
phase 1:
0 < x < 1 Hera-B year

U_K =485 V



phase 2:
1 < x < 1.5 Hera-B years

U_K =415 V !



phase 3:
x > 1.5 Hera-B years
stable operation for
at least 4 years