# PSI-beam-test results (March 26th - April 14th 1999)
# GEM-MSGCs for the HERA-B experiment

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## The GEM-MSGC detector

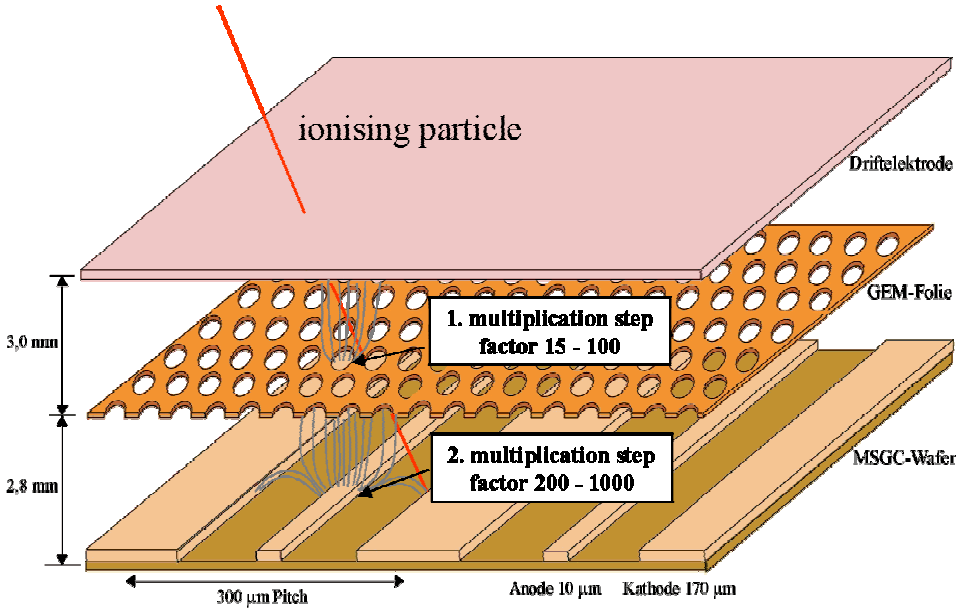


**Figure 1 : Schematic cross section of a GEM-MSGC as used for the HERA-B experiment**

The GEM-MSGC detector (figure 1) has an active size of 25 cm x 25 cm. The cover of the chamber consists of a 0.3 mm G10 plate and a 125 µm thick kapton foil covered with 18 µm copper, which serves as the drift cathode. The drift gap is 3 mm wide, the transfer gap 2.7 mm. Both, the drift and the transfer field are about 5kV/cm.

The GEM foil is made of a 50 µm thick Kapton foil, covered with 7 µm copper on each side. The Kapton holes have a diameter of about 55 µm, the corresponding hole diameter in copper is 95 µm. The holes are staggered with a pitch of 140 µm.

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The MSGC-plate is made of 0.4 mm AF45 glass, coated by a plasma CVD method ('diamond like coating')[1]. The coating has a thickness of about 0.08 µm and a typical surface resistivity of $10^{14}$ Ohm/square.

The electrode structure, consisting of vaporated gold layer of 0.5 µm thickness, is produced by a lift-off technique. This structure consists of 10 µm wide anodes and 170 µm wide cathode strips with a gap of 60 µm in between, resulting in a pitch of 300 µm.

The backside of the wafer is covered by colloidal graphite to provide a well-defined electrical boundary plane both for the signal propagation and for the electrostatic field configuration.

# The experimental goals

This beam test in hadronic environment was foreseen as the final test before the start of the mass production of GEM-MSGCs for the inner-tracker system of the HERA-B-experiment. In the focus of interest for this test were three points:

## 1. Gas ageing under intense irradiation

This problem occurred on several pre- and main-series chambers, both, in hadronic environment (e.g. PSI beam test in 1998) and with X-rays. There was a severe gain loss within hours with Ar-DME 50:50 as standard counting gas, as it is demonstrated in figure 2.

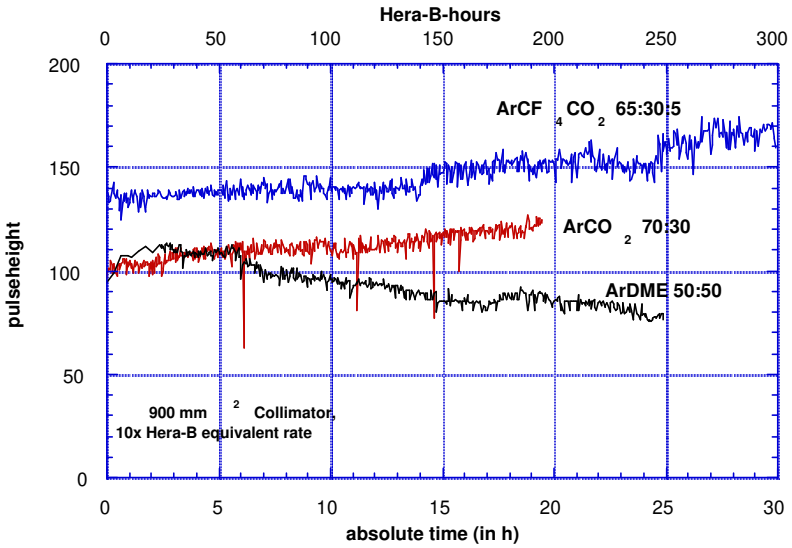



**Figure 2: comparison of the development of gain under X-ray irradiation with 3 different gases: ArDME 50:50, $ArCO_2$ 70:30 and $ArCF_4CO_2$ 65:30:5**

A surface analysis[2] revealed, that all anodes (but not the cathodes) were covered by a thin additional surface layer. On the anodes a 300 nm thick carbon layer was found in the irradiated area. In the non

[1] Manufactured by the Fraunhofer Institut für Schicht- und Oberflächenphysik in Braunschweig

irradiated regions there was a deposit of typically 30 nm of carbon (70 at%) and hydrogen (20 at%), which is most likely an insulating hydrocarbon. It could be demonstrated in various X-rays tests, that this problem does not occur when $ArCO_2$ is used under identical conditions. The final proof for a long detector lifetime had to be done in the PSI beam with high rates and high hadronic radiation doses.

## 2. Safe operational conditions in hadronic environment

Especially in hadronic environment, MSGCs turned out to be very delicate in view of their operational safety:

- There are anode-cathode discharges (sparks) which can easily destroy the MSGC structure within hours. The spark rate could be reduced by orders of magnitude by using GEMs as a pre-amplifying structure. The reason for this effect is the separation of amplification process into two locally independent steps. As a result, the cathode voltages can be drastically reduced without loss of total gain.
  It is known from various measurements in the laboratory, that the regime of safe operation is drastically reduced for Ar-$CO_2$ compared to Ar-DME, due to a much worse quenching behaviour of $CO_2$. Figure 3 shows the spark rates of both gas mixtures, the sparks were induced by a gaseous alpha source.

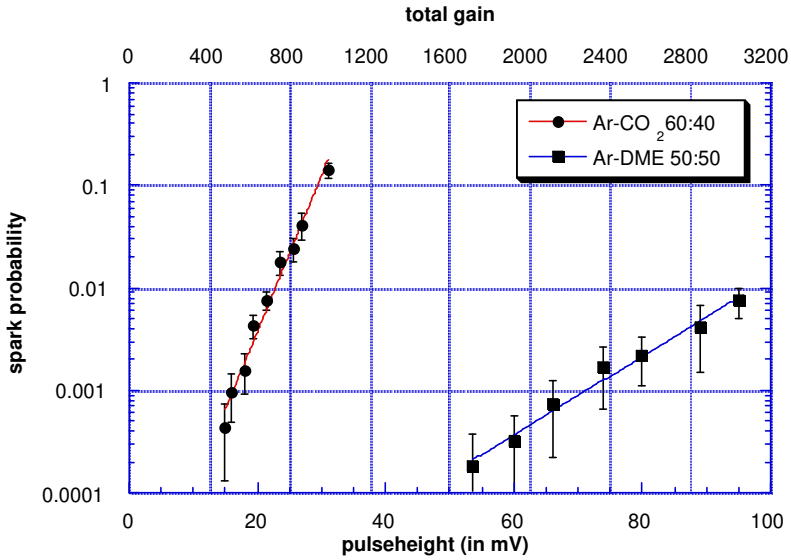



**Figure 3: comparison of the spark probability in MSGCs without GEM**

- Besides from anode-cathode-discharges, there is another type of discharge, the multiple-electrode-sparks (MES). They are known to produce even more severe damages in the MSGC-structure than conventional anode-cathode sparks. MES usually lead to shorts between anodes and cathodes in a macroscopically region. The process usually starts with a GEM discharge, which then can induce - with a certain probability - a MES discharge. In this phase all electrodes

[2] Fraunhofer Institut für Schicht- und Oberflächenphysik in Braunschweig

(drift, GEM, cathodes and anodes) are involved in the discharge process. There are two factors determining the MES-rate in hadronic beams:

1. The probability of GEM-sparks, which is usually much higher in hadronic beams compared to X-ray beams.
2. The probability of the following discharge process. This parameter is basically determined by the strength of the transfer-field (field between GEM and MSGC-structure).

As a result of the PSI test in 1998 it was found, that there are operation conditions with low transfer fields (< 5 kV/cm), where the MES rate is negligible. The optimum between low sparking probability (where low transfer fields are required) and an acceptable electron drift velocity (where high drift- and transfer fields are necessary), was found to be 5 kV/cm in Ar DME 50:50 (figure 4). This test had now to be repeated for Ar-$CO_2$ 70:30, which became the standard counting gas because of the ageing problems with Ar-DME.

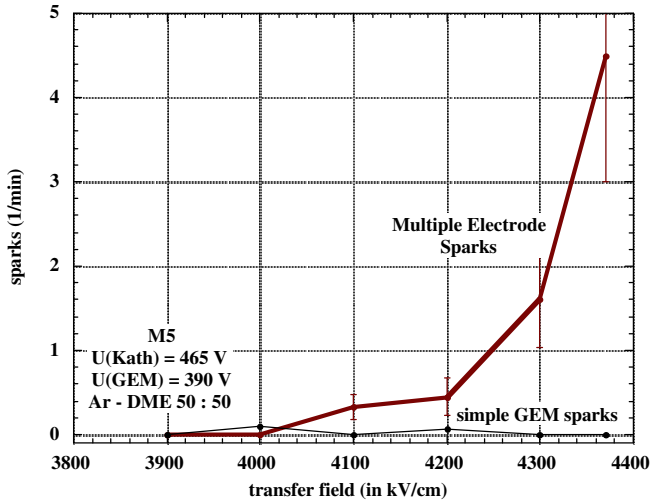


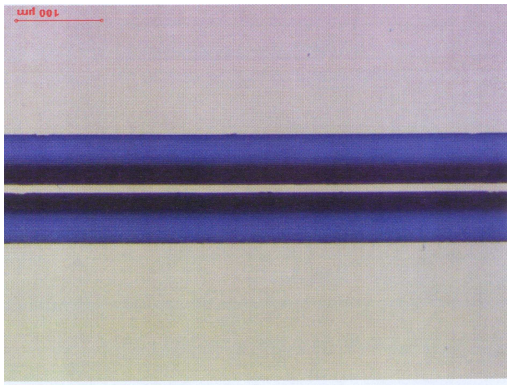

**Figure 4: MES probability vs.transfer field (result from PSI beam test in Oct 1998)**

# 3. Irradiation damage to coating structure, changes in conductivity

To reduce the surface resistivity, the HERA-B MSGCs-substrates are coated as described before. This layer, consisting of amorphous hydrogenated carbon film, is used to avoid charging-up effects between anodes and cathodes.

Unfortunately that thin layer is affected by operating the chamber in intense radiation fields. As a result, the layer thickness is drastically reduced[3], especially next to the anodes, as it is demonstrated in figure 5.

[3] Analysis by the Fraunhofer Institut für Schicht und Oberflächenphysik in Braunschweig



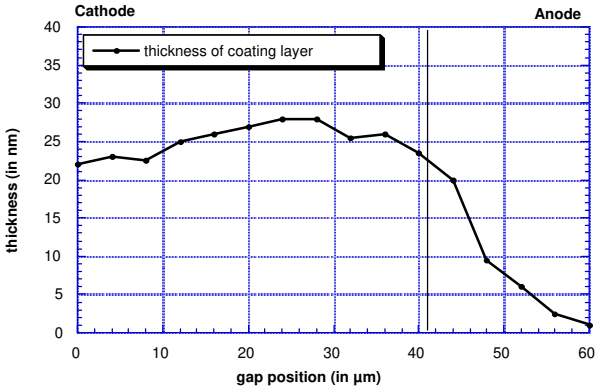



**Figure 5:**

**a) Irradiation damage after intense X-ray irradiation next to anodes**

**b) Thickness of counting layer**

We observed three phases, which strongly influence the detector gain:

In the beginning, there are good pulseheight spectra with a sharp Cu-$K_\alpha$ peak and the chamber operation is normal (figure 6). This phase lasts about 1 year of HERA-B operation on equivalent charge deposition.

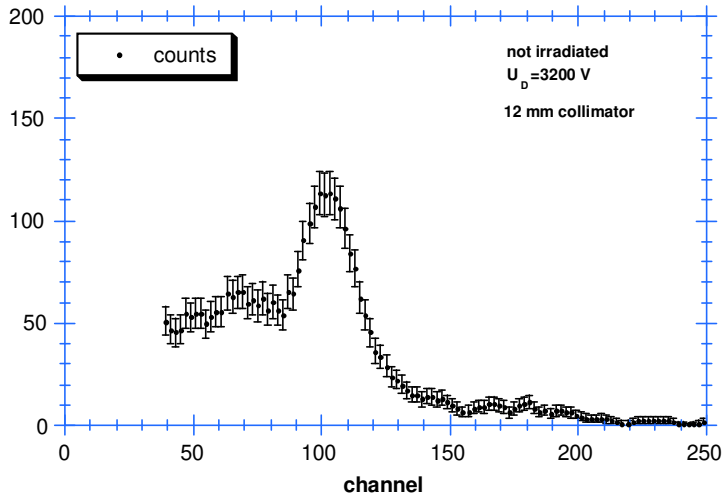



**Figure 6: X-ray pulseheight spectrum in phase I of the irradiation period**

After this initial phase the average gain is steadily rising. At the same time the spectra become very broad (figure 7a) and after some time the energy resolution is completely lost (figure 7b). This phase of high gain but no energy resolution we call phase II of the DLC ageing.

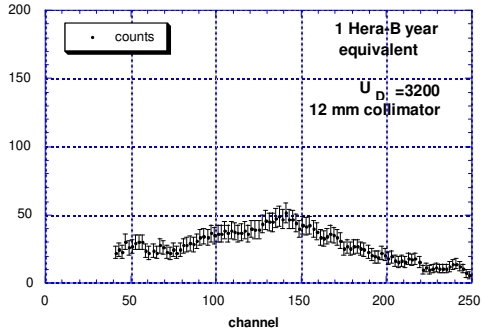
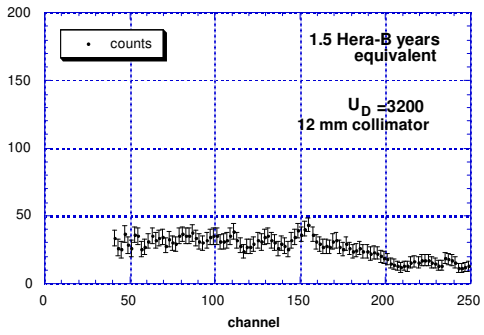



**Figure 7: a) Spectrum broader, gain raising (phase II)**




**b) Energy resolution completely lost (phase II)**

After a time corresponding to typically 2 years of year of HERA-B operation, a new maximum in the pulseheight spectrum was found. The MSGC gain is now much higher than the original gain (at the same voltages) by up to a factor of 4. This factor is now strongly rate dependent as demonstrated in figure11, for a rate of 20 times Hera-B equivalent charge (typical `Inner Tracker Hera-B Rate´ is $10^4$ MIPs / $mm^2$s) the factor decreases to only 1.5 – 2. This last phase (phase III) is astonishingly stable over another 2 Hera-B-years of X-ray irradiation, no more changes were observed. The chamber is still fully operational. Figure 9 shows the full development in time of the gain as described before with a mean rate of 20 times Hera-B equivalent charge.

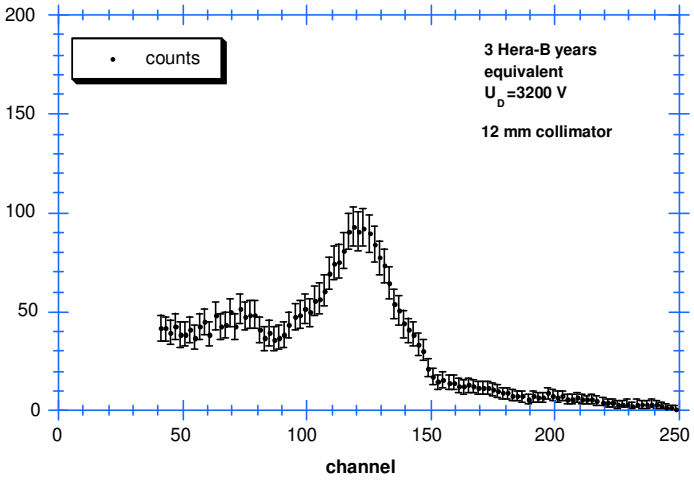



**Figure 8: Pulseheight spectrum after reduction of cathode voltages (phase III)**

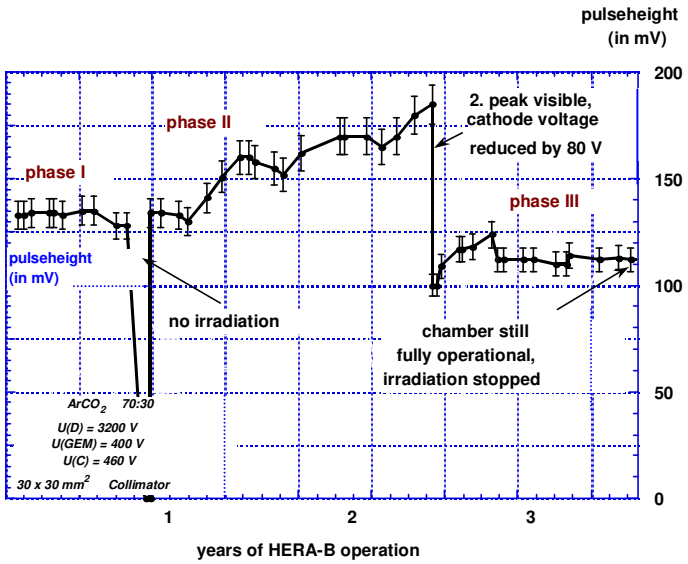



**Figure 9: Typical development of the gas gain under X-ray irradiation**

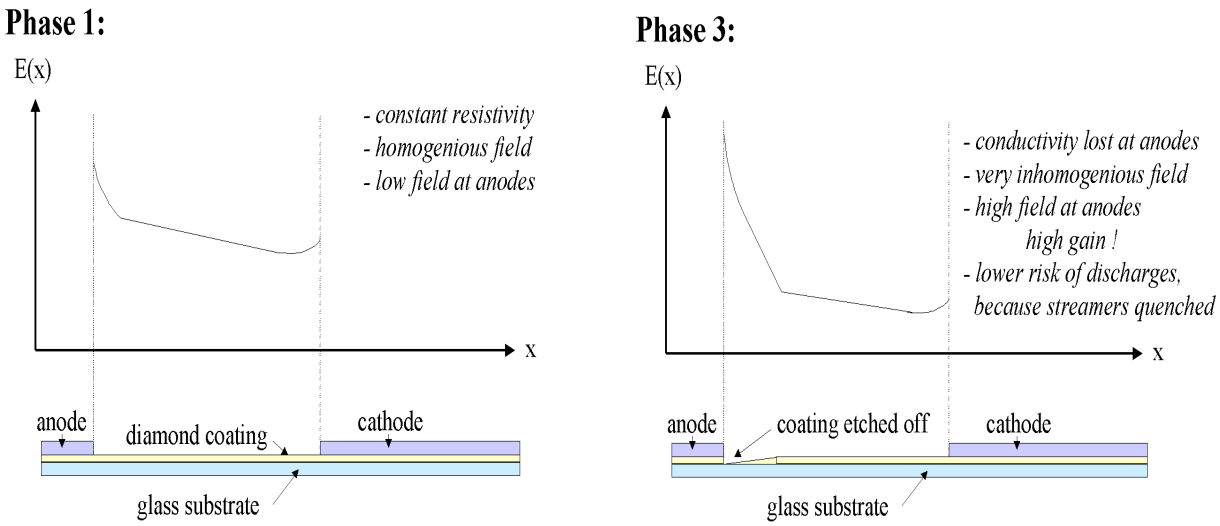
As a consequence of the decreasing thickness of the DLC layer, the coating resistivity is dramatically increased near the anodes (figure . The electric fields in the gap and especially next to the anode edges are strongly influenced and as a result of the increased fields next to the anodes the gas gain goes up.

In the transition from phase I (figure 10 a) to phase II the gain along the anode strips becomes very inhomogeneous, because the etching process is microscopically inhomogeneous. Those minimal fluctuations in resistivity next to the anodes cause great changes in gain and as a consequence the energy resolution is completely lost. After continuation of irradiation, more and more material of the coating layer is etched off (even in the middle of the gap) the coating free gap becomes wider and wider and thus the field less dependent from small variations of the gap width. A good stability in phase III is reached (figure 10 b), when the innermost coating layer is completely etched off.

## Operation of MSGCs after DLC etching (phase III):

### Spark tendency:

The anode-cathode discharge probability in phase III is expected to be even lower than in the beginning (phase I). The discharge process needs a high field strength over all of the gap between anodes and cathodes. In phase III there are extremely high fields next to the electrode edges, but very low fields in the middle of the gap, which is an effective region to quench the streamer, which could slightly turn into a discharge. Due to the lower fields in the middle of the gap, the spark tendency is effectively reduced as seen with internal alpha particles in the counting gas.




**a) Phase I (homogenious coating)**

**b) Phase III (coating etched off next to anodes)**

**Figure 10: Electric fields in the gap between anodes and cathodes and consequences in chamber operation**

**Correlation between rate and gas gain:**

In phase III there is a strong relation between irradiation rate and gas gain, as shown in figure 11. A new MSGC detector with diamond-like coating doesn't show any rate dependence, but has lower gains for all rates.

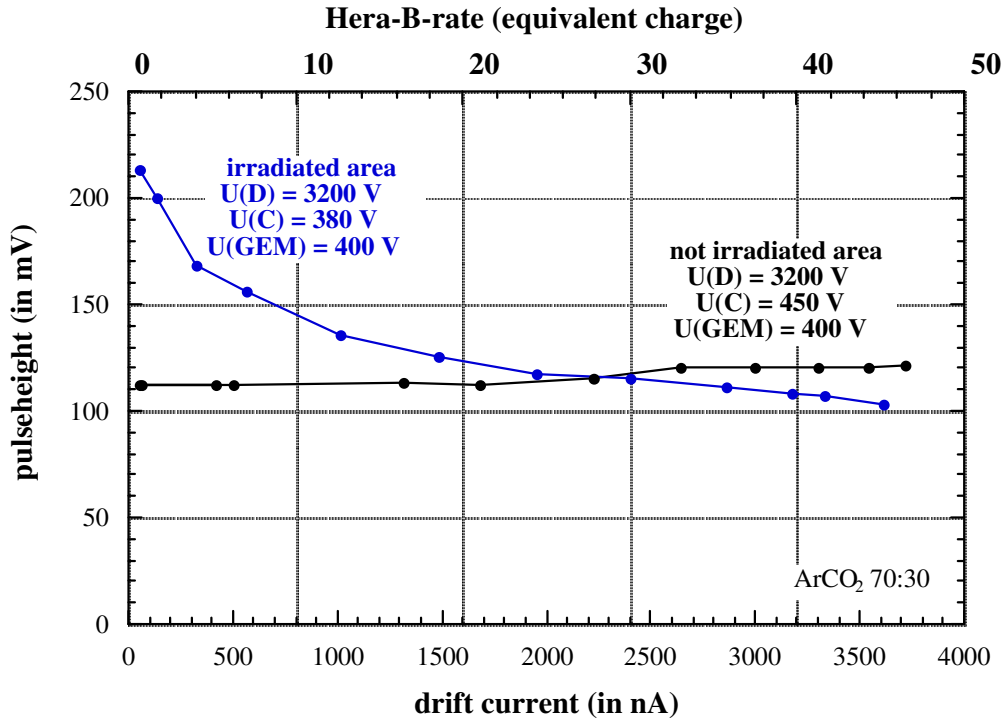



**figure 11: rate dependence of gain in phase 3 compared to stable gain in phase 1**

**Efficiency:**

The detector efficiency is expected to be not negatively influenced by this process, since the electron amplification does not decrease but the signals do even increase and the efficiency is also going up. Detailed efficiency measurements with MIPs in phase III are presently in preparation.

If the total chamber has reached phase III, there is the possibility to lower the cathode voltage for 80-100 volts, to bring the amplification factor to standard values like 4000. Nevertheless, it will not be possible to lower the cathode voltages after some time of use in the Hera-B experiment, since it cannot be expected, that all parts of the chamber will go to phase III at the same time, due to great variations of the irradiation rate along one chamber. Another problem is the rate dependency of the gain, which also causes great variations in gain along the different regions of one chamber and it is not possible to adjust voltages for every single cathode group.

At the PSI test beam, it was a good opportunity to test, if the coating is also damaged in a hadron beam and if the velocity of this process is comparable to the X-ray results.

# test set-up at PSI:

The beam was used by four different LHCb inner tracker groups and by the Hera-B inner tracker group together (see figure 12) with two different beam setting were used:

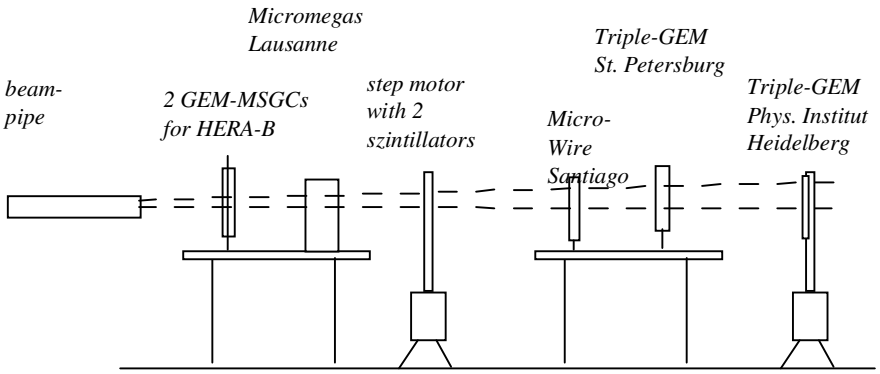



**Figure 12: experimental setup at PSI (April 1999)**

**Day-time:** pi+ with low rates (up to 100 Hz/mm$^2$) for signal and efficiency studies for the LHCb detectors

**Night-time:** 80 % protons and 20 % $\pi^+$ with high rates (up to 60 kHz/mm$^2$) for ageing studies and optimisation of chamber parameters for the HERA-B detector.

All detectors were in one line. In the front there were the two GEM-MSGCs from the HERA-B experiment, followed by the Lausanne Micromegas and in third position there were two finger szintillators on a two dimensional step-motor to monitor the beam profile. Next, there was the Micro-Wire chamber from Santiago, and in the end the two Triple-GEM-detectors, one from St. Petersburg and the other one from the Heidelberg Institute (which was also mounted on a step motor).

# Beam profile:

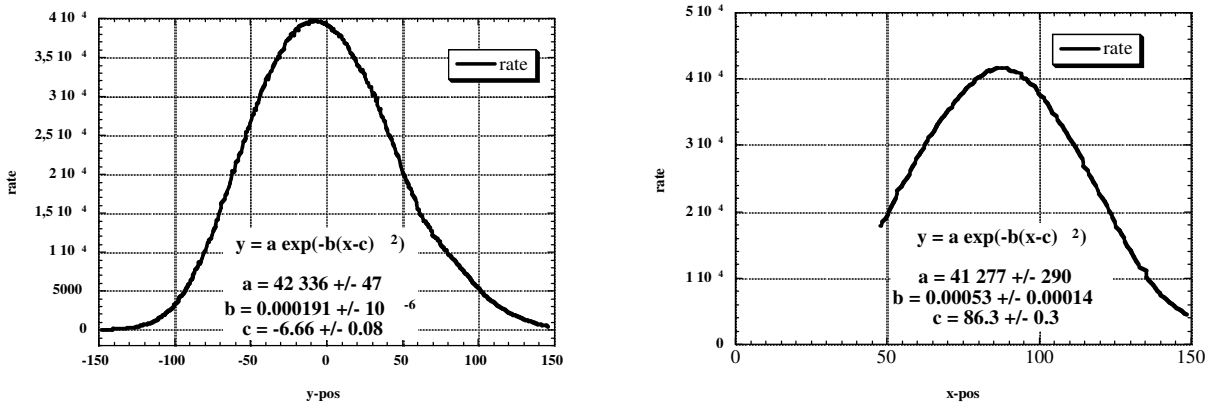



**Figure 13: PSI beam profile in x- and y direction, 80% protons and 20 % pions**

Figure 13 shows the beam scans in both directions. The beam shape is nearly gaussian, but the sigma in y-direction (along the strips) is about 50% bigger than in x-direction. Both scans were done with the proton settings (p=350 MeV/c) for the night measurements.

# Irradiation time:

In table 1 all irradiation periods for the HERA-B chambers are listed up. To calculate the equivalent HERA-B radiation dose, we included the fact that Protons have a 5 times higher number primary ionisation compared to MIPs. (In the daytime, the HERA-B detectors were not switched off, but the accumulated radiation dose is negligible compared to the Proton irradiation due to the much lower number of primary electrons of Pions.)

| **date** | **irradiation time,** | **duration** | **rate** | **HERA-B-hours (accumulated charge)** | | | |
|---|---|---|---|---|---|---|---|
| | **only protons** | **(in h)** | **(in kHz)** | **pos 1** | **pos2** | **pos 3** | **pos 4** |
| 2.-3.4 | 1-5 h | 4 | 5.5 | 10 | | | |
| 3.-4.4. | 0.30-10.30 h | 10 | 16 | 80 | | | |
| 4.-5.4. | 23-10 h | 10 | 26 | 125 | | | |
| 5.-6.4. | 1.30-9.40 h | 8 | 16 | 60 | | | |
| 6.-7.4. | 2-10 h | 8 | 16 | | | 60 | |
| 7.-8.4. | 2-11 h | 9 | 20 | | | 90 | |
| 8.-9.4. | 1-7 h | 6 | 20 | | | 60 | |
| 9.-10.4 | 0.40-10.40 h | 8.40 | 40 | 160 | | | |
| 10.-11.4 | 0-9 h | 10 | 55 | | 250 | | |
| 11.-12.4. | 0-9 h | 9.40 | 40 | 180 | | | |
| 12.4. day | 9-19 h | 10 | 28 | | | | 90 |
| 13.-14.4. | 23-7 h | 8 | 60 | 240 | | | |
| **sum:** | | 101,2 | | 855 | 250 | 210 | 90 |

**Table 1: Irradiation periods for the HERA-B detector, irradiation dose for all positions**

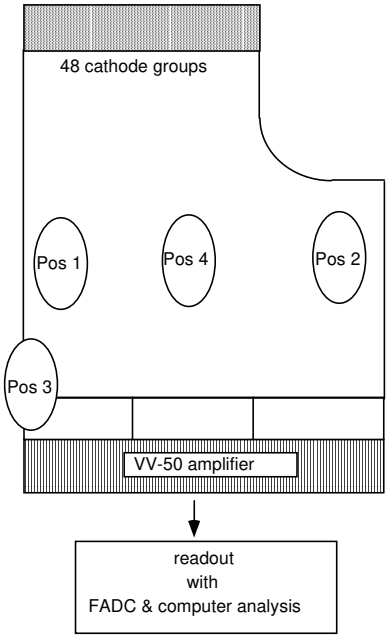



**Figure 14: Irradiation positions on chamber 1**

The different irradiation positions are visualised in figure 14. On position 1 we achieved a charge accumulation comparable to 1/3 HERA-B year, which is still to less to extrapolate the situation to 3 full Hera-B years, but it could give a first impression of long-term operation conditions and rapid ageing processes.

# Results

## Parameters for the measurements

The chambers were irradiated with constant proton rates. The detector currents (cathode, GEM_upper, drift) were monitored and logged to file. Gas ageing, which was observed in the MSGC currents at the last PSI-test within one night, can be easily detected from observing changes in the currents at constant irradiation rate. Also a steadily rising gain, as it is expected when the coating resistivity changes, has an effect on the chamber currents.

Anode-cathode sparks can be detected as peaks in the cathode currents. It is unfortunately not possible to do quantitative measurements with this method, because sparks may be lost between the read out times of the current meters.
Also MES, which produce peaks in all currents and which are often followed by anode-cathode shorts at the MSGC structure, can be detected by the slow control.

It was planned to have quantitative measurements of the spark rates with pick-up electrodes, but due to an excessive number of pick-up signals from other set-ups (especially Micromegas), we couldn't make use of our spark.

The easiest way to detect changes of the coating layer is an observation of the pulseheight spectra. We used $^{55}$Fe with an energy of 5.9 keV to create pulse height spectra on various positions on both chambers. Broadening spectra as well as increasing gains are a clear evidence for a transition from phase I to phase II. Following each Proton irradiation period at night, there was a control measurement in the morning using the $^{55}$Fe-source (no beam).

## 1. Gas ageing with $ArCO_2$ 70:30

After an accumulated dose of 1/3 HERA-B year equivalent, there was no hint for gas ageing with $ArCO_2$. No loss in gain was observed ($^{55}$Fe-measurements) and the currents while proton irradiation were very stable except for the first few minutes, where polarisation effects in the GEM foil result in higher gains. In contrast to these measurements, in October 1998 rapid ageing was observed with Ar-DME using the same type of `main series chambers'.

## 2. Operation stability

1. To be sure to have enough gain reserve for HERA-B operation, we chose a visible gas gain of at least 4000 (which means an absolute gain of about 8000) for all irradiation periods. Concerning the probability for sparking it turned out to be much more favourable to operate the chambers at a relatively high gas gain at the GEM and reduced gas gain at the cathodes than vice versa. With the following voltage settings (U(d) = 3600 V, U(GEM) = 430 V, U(c) = 530 V) (figure 15) several anode-cathode sparks were observed, while no sparks (at the same gain) but lowered cathode voltages (U(d) = 3600 V, U(GEM) = 450 V, U(c) = 520 V) (see figure 16) could be detected.

   In general the safety margin for anode-cathode discharges is significantly reduced in $ArCO_2$ compared to ArDME, but a set of operational conditions can still be found with safe operation conditions.

   (The short-term variations in gain of about 5% are induced by the controlling mechanism of the `GEM-Verteiler-Box´, which is the device that creates the GEM-voltages by an (active) resistive voltage divider, and adjusts them independently of the chamber currents to the nominal voltages.)

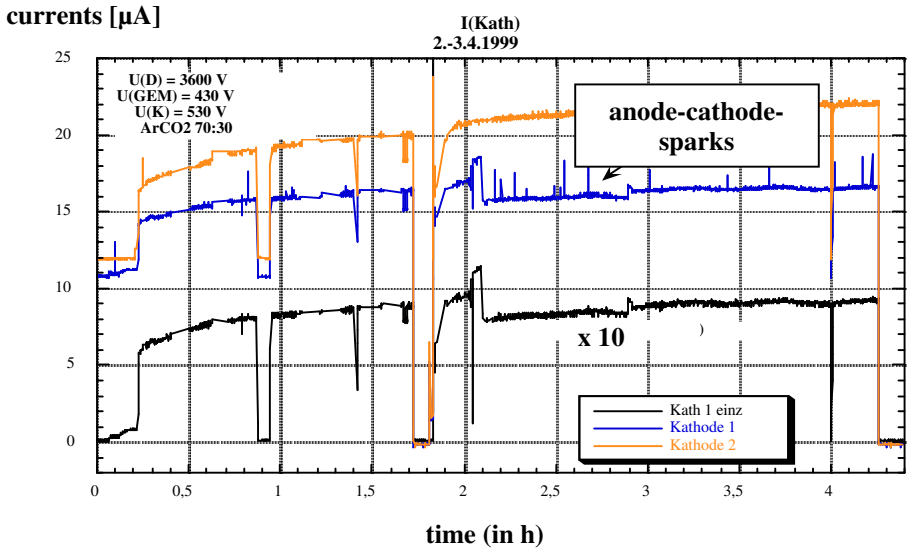



**figure 15: Cathode currents for both chambers, anode-cathode sparks in chamber 1, operation conditions:U(d) = 3600 V, U(GEM) = 430 V, U(c) = 530 V, $ArCO_2$ 70:30**

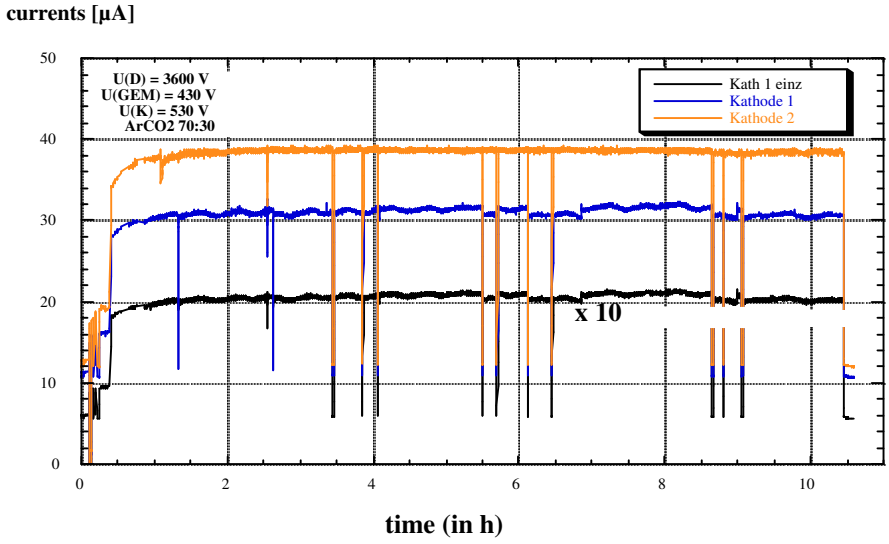



**figure 16: Cathode currents for both chambers, stable operation, no sparks operation conditions: U(d) = 3600 V, U(GEM) = 450 V, U(c) = 520 V, $ArCO_2$ 70:30**

2. In total we saw 2 multiple-electrode-sparks (MES) which both led to shorts at the MSGC structure. Both MES occurred at comparatively high transfer fields (5.2 kV/cm). After we reduced the transfer fields by 10 % to 4.8 kV (after about half of the irradiation does was already accumulated) we had stable operation without any sparks. The long term tests at PSI show again, that the regime of safe operation is reduced compared to Ar-DME. But as there are even higher drift velocities in Ar-$CO_2$ than in Ar-DME, it is acceptable to lower the transfer fields without increasing the ballistic deficit.

3. We also tested the operation stability of outer segments of the MSGCs next to the frames (position 3), which are known to be very critical in point GEM discharges in intense irradiation fields. The gain was also set to 8000 with the same voltage conditions as used for the positions in the MSGC center. The spark tendency was found to be absolutely comparable to the results of the other positions.

## 4. Changes in coating

It was very important to find out, if the time scale for the changes in the DLC layer in hadron beams is comparable to those we measured with X-rays. The first hints for a transition from phase I to phase II are rising gains and a loss of energy resolution. A comparison from spectra in the very beginning (figure 18) to those from the end (1/3 HERA-B year, figure 19) demonstrate that the energy resolution has not changed (The voltage settings are not comparable !).

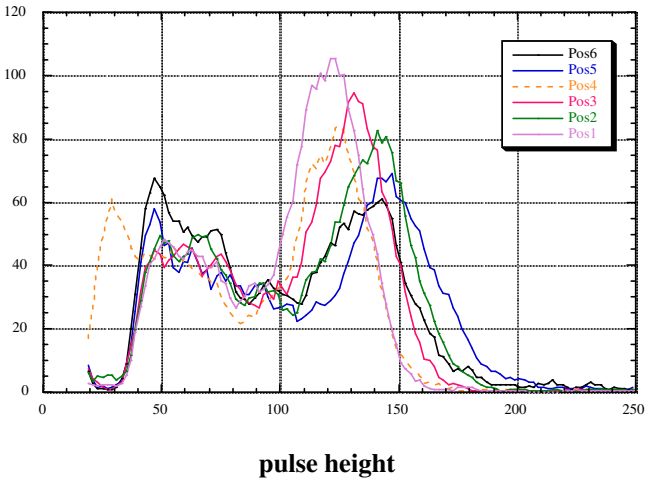



**Figure 17: $Fe^{55}$ spectra on 6 different positions along strip (MSGC 1, left position)**

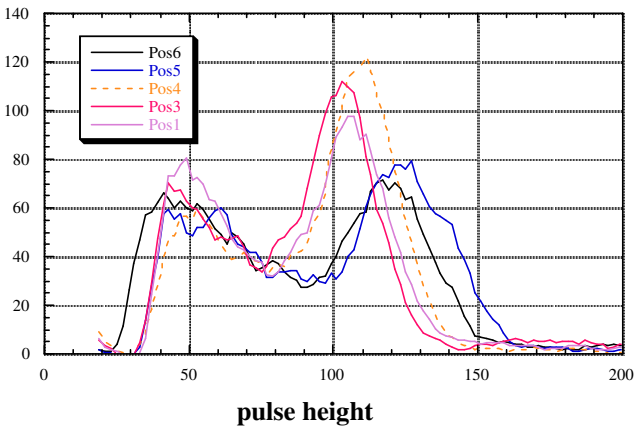


**Figure 18: $Fe^{55}$ spectra after irradiation (MSGC1, left position)**

The optical inspection of the chamber proved, that there are only almost invisible shadows next to the anode strips. In the beginning the changes in the diamond coating turned out not to be faster in hadron beams.

# Final results

In this test it could be corroborated, that the gas ageing problem previously observed with Ar-DME is not existing for an $ArCO_2$ mixture. The safety margin for discharges is reduced compared to Ar-DME but it is still possible to have safe and stable operation in intense hadron beams even at high gains of about 8000. It is recommendable to use low cathode voltages and transfer fields, but high GEM voltages to reach high gains.

The irradiation time was to low to check the long time scale of the changes in diamond coating, but it could be proved, that there are still good spectra after 1/3 HERA-B year of operation.