MSGC Development for HERA-B

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The Inner Tracker System of the HERA-B experiment at DESY is built by groups at the Universities of Heidelberg, Siegen and Zürich. The system consists of 184 Microstrip-Gas-Chambers (MSGC) with a total number of 147 456 electronic channels. The detectors have to cope with particle fluxes up to 25 kHz mm$^{-2}$ and to tolerate radiation doses of 1 Mrad per year. During the development of these chambers it was found that conventional MSGC, operated in intense hadronic fluxes, are rapidly destroyed due to the phenomenon of induced discharges. The introduction of a Gas Electron Multiplier (GEM) as preamplification structure offers the possibility to build robust and reliable detectors allowing for ample gain reserve in the hostile environment of HERA-B.

1 Introduction

The goal of HERA-B is to establish CP violation in B-decays. As source of the B mesons, an internal wire target in the 800 MeV proton beam line of HERA is used. Thus HERA-B is a fixed target experiment of type forward spectrometer. The specific requirements of the detector elements are due to the enormous amount of $4 \times 10^{14}$ events which have to be recorded per year and from which about 1000 of the rare decays into $J/\Psi K_s$ have to be extracted.

This means that HERA-B has to run at a mean interaction rate of 40 MHz. Four overlayed events per bunch crossing every 96 nsec with a mean number of about 200 tracks have to be recorded and analyzed. The events are strongly boosted in the forward direction and about half of the tracks have to be followed in the Inner Tracker system, covering the area from 5-30 cm around the beam pipe. As solution for the inner tracker detector elements, Microstrip-Gas-Chambers (MSGC) were foreseen and are, in the new version as GEM-MSGC, the now approved and accepted technology.

2 The parameters of the HERA-B Inner Tracker

The task of the Inner Tracker detectors is twofold since they have to deliver tracking information and to provide fast signals for the first level trigger simultaneously. The tracking requirements are rather moderate, 100 $\mu$m resolution in the bending plane and 1 mm resolution parallel to the B-field are sufficient. Part of the detectors have to operate in a magnetic field of 0.85 T.
The tracking information is obtained in the conventional way using analog signals from individual strips. The second coordinate is measured from stereo layers under small angles (5°) with respect to the magnetic field. The small stereo angles are necessary to keep the combinatorial background reasonably small.

For the trigger signals 4 neighbouring strips are electrically ored to reduce the number of trigger channels while keeping the occupancy at the 10-15 % level. To enhance the trigger efficiency, all trigger layers are double layers of identical orientation. The chambers have to cope with particle fluxes up to $10^4$ particles per mm$^2$ and second, accumulating to a total radiation dose of up to 1 Mrad per year. The fundamental question of MSGC development and design was to find a solution which guarantees a stable operation with high gain and high efficiency over several years of HERA-B operation.

The demand for fast trigger signals puts specific boundary conditions to the operating parameters of the chambers. The pulse shaping has to be done in a way that pile up and resulting fake triggers in successive bunch crossings are kept at tolerable low level. A possible shaping as it could be realized with the foreseen Helix pre-amplifier is shown as inset in figure 1.

Taking the charge collection time, the ion movement and the amplifier shaping into account it becomes apparent that the effective number of electrons contributing to the signal at optimal sampling time (95 nsec after bunch crossing) has a broad distribution with a mean number of only 15.6 electrons (Figure 1). Taking 7000 electrons as a realistic threshold for a strip capacity of 40 pF (25 cm long strips) it turns out that a minimal gas gain above 2000 is required to exceed the 95 % efficiency level.

Simultaneously the number of fake triggers due to pulse fluctuations into the subsequent bunch crossing does not exceed 25 %. (Figure 2). It should be mentioned that the rather delicate balance between efficiency and fake trigger rate requires a sufficiently high uniformity of gas gain, electronic amplification and trigger threshold.

To summarize the scope of the project, a few numbers should be given: The Inner Tracker of HERA-B will consist of 46 detector planes grouped into 10 superlayers consisting of 184 MSGC and covering a total area of about 16 m$^2$. 147456 channels are equiped with analog read-out and 9984 fast trigger signals provided for the first level trigger.

The entire project comprising the development of the chambers, the infrastructure and the read-out electronics is realized by groups at the universities of Heidelberg, Siegen and Zürich.
3 Early findings and solutions

At the time of the technical design report (1994) the development of MSGC for high rate operation seemed to be settled.

Unfortunately it turned out rather quickly, that the misgivings of various people were justified and the available MSGC technology did not allow a stable operation at high rates on a time scale required for HERA-B. Even observing the strongest precautions for gas quality and chamber material, the detectors died suddenly after collecting only moderate amounts of total charge. Typical examples are given in figure 3. Especially operation at the required high gains turned out to be very short lived.

The reason for that delicacy comes from the fact, that in a MSGC, produced on bare glass plates with ionic conductivity, the electric field close to the surface strongly depends on the distribution of the ions in the glass. Under the combined action of radiation and electric fields this distribution is disturbed in a way, that the gas gain finally breaks together and stable operation is not longer possible. To get rid of accumulating surface charges only electronic conductivity of the substrate promise a steady and uniform operation. Electronically conductive glass is not available in the required large plates and ruled out due to its very short radiation length.

From a variety of efforts to find an adequate stable surface coating of the glass the diamond like coating (DLC) with amorphous carbon using a plasma CVD process turned out to be the most promising solution. The DLC coatings could be well adjusted to the required surface conductivity of $10^{14} - 10^{16}$ Ω per square and offer reasonable surface quality for the MSGC production process.

The successful reproduction of the pioneering results of reference 6 showing stable operation even under strong conditions and high gas gains, mark the first milestone of MSGC development for HERA-B (Figure 4).

4 The phenomenon of induced discharges

After a variety of successful tests in the lab we went on a first hadronic beam test with fullsize HERA-B chambers at PSI in April 1996. There we made the painful discovery that testing with x-rays in the lab is not sufficient to simulate the conditions of high intensity hadronic beams. As a new phenomenon we observed frequent anode-cathode discharges visible as short current spikes under conditions where the chambers operated with x-rays of similar intensity completely quietly and un conspicuous. After a few hours operation, an alarming number of anodes was broken.
Visual inspection of the chambers showed an enormous number of correlated marks in anodes and cathodes in the area where the chamber had been exposed to the beam (Figure 5). Part of them had led to anode breaks. The fact that comparable phenomena had never been observed with x-rays or with $\beta$-sources but only in the hadronic beam made it fair to assume that the discharges are induced by heavy ionizing particles. In a hadronic beam these heavy ionizing particles can be easily produced by nuclear reactions in the MSGC substrate.

To simulate these conditions and to verify the assumption we introduced a gaseous $\alpha$-source in the chamber by flushing the counting gas through a cylinder containing thorium oxide. The Rn-220 emanating from the thorium powder is transported to the chamber with the gas stream and decays with the half life of 55 s emitting 6.3 MeV $\alpha$-particles. In fact the phenomenon of induced discharges could be reproduced with all aspects: current spikes, anode-cathode marks and finally broken anodes.

A concluding test of the chambers at the HERA-B beam line made clear that under nominal conditions of a gas gain around 3000 the chambers are destroyed within a few hours. In the following we concentrated all efforts to study this phenomenon of induced discharges in more detail in view of how to avoid it and to extend the lifetime of the chambers.

From the bulk of results, the most important will be summarized here.

Figure 6 shows a strong dependence of the discharge rate on the cathode potential at constant gas gain. The obvious recommendation from this is to operate the chamber at the highest possible drift field. For a constant cathode potential no dependence of the discharge rate on the drift field could be observed, even if the drift field was reversed (Figure 7). This could be taken as a strong evidence that the triggering high primary ionization has to be produced very close to the MSGC surface.

With special emphasis we checked the possibility to reduce the proneness to induce discharges by changing the composition and the nature of the counting gas. For various reasons (aging, drift velocity, diffusion, density of primary ionization) Ar/DME 50:50 was chosen at the optimal composition till then. Within the scope of these investigations we studied different Ar/DME mixtures as well as mixtures of Ne/DME, Ar/CO2, Ar/DEE with water, alcohol, methylal and ammonia as additives.

Unfortunately, none of these mixtures turned out to be significantly less prone to induce discharges than the standard Ar/DME mixture. For identical gas gain all mixtures exhibited comparable discharge rates under the influence of the gaseous $\alpha$-source.

As a typical example figure 8 shows the discharge rate in two different
Ar/DME mixtures:

For identical gain and drift field the discharge rate is completely independent of the gas composition.

Another interesting observation is the fact that MSGC on uncoated and resistively coated substrates show quite different discharge rates under otherwise identical conditions. If we take the pulse height to define the operation point of the chamber, the discharge rate on uncoated plates is reduced by a gain dependent factor between 10 and 20 compared to diamond coated MSGC’s (Figure 9).

The reason for that becomes obvious from figure 10, where for both cases the strength of the electric field between anode and cathode is shown for various heights above the MSGC plane. For the coated plate, a constant surface resistivity was assumed whereas the field for the uncoated plate was calculated using infinite surface resistivity.

Since the actual ion distribution is not known, the latter has to be taken as an approximation to the real conditions. Whereas for uncoated plates the anode-cathode field is strongly peaked close to the electrodes with a broad regime of strongly reduced field in between, coated plates have an almost uniform field between anode and cathode. The low field regime on uncoated plates efficiently stops the evolution of streamers and suppresses the tendency for induced discharges.

Summarizing we have to conclude, that induced discharges are an intrinsic problem of the MSGC geometry and principal; gain and discharge rate are strongly entangled parameters.

Under any reasonable condition chambers operated at gas gains around 3000, even using a very high drift field of 10 kV/cm, are severely damaged within hours running under HERA-B conditions. This sad conclusion we verified experimentally in December 1996. To survive 5 years the discharge rate has to be reduced by 4 orders of magnitude, resulting in a gas gain below 1000 and a marginal efficiency of the device.

In view of this universal nature of the induced discharge phenomenon we tried to find out if the tolerance of the chamber to discharges can be positively effected by using a clever strip material. In fact we learned very soon, that gold strips are extremely delicate whereas chromium strips tolerate an enormous number of sparks before showing visible marks or even anode breaks.

For gold strips on the other hand the charge stored in the capacity of a

\[ \text{The calculations have been done using the programme ACE by courtesy of ABB Cooperation} \]
single anode-cathode system with 10 cm long strips is sufficient to damage the anode in a single discharge severely. Unfortunately, the resistivity of chromium is so high that the signal risetime for strips longer than a few centimeters becomes unacceptably long for a fast detector. After troublesome experiments with electrodes made from gold, chromium, aluminum, rhodium, and tungsten, we had to conclude that it is the mere resistivity and resulting current limitation what protects the electrodes from being damaged. Spark tolerance and fast signals are therefore incompatible requirements.

5 The GEM-MSGC

The recovery of the HERA-B MSGC tracker came with the introduction of the Gas Electron Multiplier (GEM) by F. Sauli. The basic idea is to separate the total gas gain in two independent factors both sufficiently small to strongly suppress induced discharges. The initial major concerns against the technology of the GEM-MSGC were as follows:

- Does it really solve the induced discharge problem or is the total achievable gain now limited by induced GEM- or combined GEM-MSGC discharges?
- How is the efficiency, the strip multiplicity and the resolution of such a device especially if operated in a magnetic field?
- What is the long term stability of the GEM in view of aging and the negative experience with uncoated glass plates?

Since March 1997 we tried to answer these questions in fruitful collaboration with F. Sauli and his team at CERN. The most fundamental answer we got rather quickly:

The GEM-MSGC showed now induced discharges under the combined action of the gaseous a source and an x-ray charge load of 20 times HERA-B conditions, even when operated at total gas gains above 4000. After troublefree operation of a prototype chamber at the HERA-B beamline with full interaction rate and a total gas gain of 3000 for more than 58 hours we came to the conclusion that the problem of induced discharges is solved by using a GEM-MSGC combination.

The second concern could be settled using the electron test beam at DESY in July 1997. As shown in figure 11, the efficiency of the GEM-MSGC is excellent and completely unaffected by a magnetic field of 0.85 T parallel to the strips.
Operated with Ar/DME 50:50 the strip multiplicity at 95% efficiency is 1.65 for 300 µm wide strips, only slightly higher than without the GEM (1.4).

The long term behaviour and aging properties of the GEM-MSGC was one of the main concerns which finally could be dispelled by painstaking tests at Heidelberg and CERN. The problem was aggravated by the fact that not only the GEM introduced new materials in the chamber but also the more robust frame replacing our initial glass tube design. All GEM’s produced on polyimide foil exhibit time dependent and local gain variations whose amplitude depends on the details of the GEM geometry. Part of these variations are due to surface charge and can be avoided by adding a small amount of water to the counting gas. Another part has to do with polarization of the polyimide foil and is unaffected by the gas humidity.

Unfortunately adding water to the gas negatively affects the aging properties at the MSGC surface. With 3000 ppm of water we observed a very rapid degradation of the MSGC gain which turned out to be due to deposits on the anode strips. Both, Ar/DME and Ar/CO$_2$ mixtures behaved very similarly and thus excluded the use of water admixture to reduce surface charge.

In figure 12 the behaviour of otherwise identical chambers with and without water admixture are confronted.

The entire gain history of a GEM-MSGC running with Ar/DME up to an accumulated rate corresponding to 3.5 years of HERA-B operation at gain 3000 is shown in figure 13. The initial gain excursion by a factor of 1.5 is clearly seen as well as the stabilisation after a few days of operation. After the initial period the gain is constant even if the chamber is switched off and repowered after several hours.

The GEM-MSGC obviously is a device that can be expected to run reliably under HERA-B conditions with high rates for several years. Even if the initial gain variations as well as the local fluctuations of the GEM amplification factor are no fundamental problem for the envisaged HERA-B tracker, they are a drawback making the operation of the chamber and the definition of the trigger threshold more delicate.

Recently it has been shown by the HERA-B group at Siegen that both effects can be completely avoided by overcoating the GEM with a high resistive layer of amorphous carbon using the same plasma technology as for the MSGC plate. If this technology can be successfully applied to the sizes as needed for the HERA-B chambers, it would further enhance the performance of the detectors.
6 Passivation of strip ends

Passivation of the strip ends is usually done by coating this dangerous area by insulating glue either inside or outside the counting gas volume. In our initial design the passivation was combined with the gluing of the frame on the MSGC plate. With this technology it is unavoidable that small amounts of glue protrude on the MSGC surface leading to the situation shown in figure 14 with an insulating layer on top of the electrodes inside the counting gas. For whatever reasons such topping insulators are introduced, they are a source of potential severe trouble.

In figure 15 we show the time dependent calculation of the electric field under these conditions. The insulator surface is charged until no more field lines ending there. By this very dangerous hot spots right after the edge of the insulator are created. At these points the chamber is prone to discharges in radiation fields even at very moderate gains below 1000.

Fortunately the problem can be cured in a very elegant way, by just leaving the strip ends unpassivated without any coating in the counting gas volume. We verified experimentally that free, properly designed, strip ends will not cause any trouble even under the combined action of the gaseous $\alpha$-source and a very heavy x-ray load of several times HERA-B conditions. This positive result could be confirmed in the high-intensity pion beam at PSI in Switzerland. Avoiding the notorious strip end passivation strongly simplifies the chamber construction and reduces the demands on the glue and the gluing procedure.

7 Status and prospects of chamber production

The MSGC plates for the HERA-B inner tracker are designed by the HERA-B group at the University of Zürich and produced at IMT in Greifensee, Switzerland. Meanwhile a first batch of 40 plates for the 1998 preseries has been produced. The diamond coating was done at Fraunhofer-Institut für Schicht- und Oberflächentechnik, Braunschweig. These coatings are of very good homogenity and surface quality. All GEM’s have been designed by Fabio Sauli and produced at the CERN workshop. Now in January 1998, we have started the production of a preseries of chambers which will be installed for the 1998 running of HERA-B. During this year the mass production of the full set of about 200 chambers is foreseen. Installation and commissioning of the chambers will take place in the winter shut-down of HERA 1998/99.

8 References
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9 Figures
Figure 1: Distribution of the number of electrons contributing effectively to the signal for fixed sampling time of 96 nsec. The shaping of the amplifier for different input currents is shown in the inset.

Figure 2: Fake trigger rate as function of efficiency for the amplifier shaping given in fig 1. This curve is independent of the specific choice of threshold and gain and entirely determined by the amplifier shaping.
Figure 3: Typical long term behaviour of uncoated D263 plates with gold strips operated in Ar/DME 50:50. The accumulated charge of 4 mC/cm corresponds to about 2/3 of one year HERA-B operation.

Figure 4: Long term behaviour of a diamond like coated MSGC with gold strips in Ne/DME 50:50. The gain was 2900 and the acceleration factor compared to HERA-B was about 20.
Figure 5: Damaged electrode structure after operation of the chamber in a pion beam of 3 kHz/mm² at a gas gain of 3000. The correlated marks due to induced discharges are clearly visible on the thin anode and the two adjacent cathodes.

Figure 6: Normalized rate of induced discharges as function of cathode potential for a fixed gain of 3000. The drift field varied between 1 kV/cm and 10 kV/cm.
Figure 7: Normalized rate of induced discharges and rate of detected α-particles as function of the drift potential for a fixed cathode potential. The vertical line indicates the average potential of the MSGC plate.

Figure 8: Normalized rate of induced discharges as function of the cathode potential for two different mixtures of Ar-DME at fixed gain of 3000.
Figure 9: Normalized rate of induced discharges as function of gain for identical 
MSGC with and without diamond like coating. In both cases the gas was Ar/DME 
50:50.

Figure 10: Strength of the electric field close to the MSGC surface: a) coated plate, b) 
uncoated plate. The curves refer to lines parallel to the MSGC surface in heights of 
1,2,5,10,20 and 50 µm.
Figure 11: Efficiency of a GEM-MSGC as a function of the threshold with and without magnetic field. In both cases the gas was Ar/DME 50:50.

Figure 12: Long term behaviour of a GEM-MSGC operated with Ar-DME 50:50 with and without addition of water vapour. The gain loss in the case of water admixture is caused by the formation of deposits along the anode strips.
Figure 13: Long term behaviour of the relative gain of a GEM-MSGC starting with a virginal GEM. The gas was Ar/DME 50:50 and the total gain was 3000. The gain variations are entirely due to variations of the GEM amplification factor. The irradiated area was 500 mm$^2$.

Figure 14: Temporal development of the static electric field close to an insulating layer on top of the electrodes. The time scale strongly depends on the radiation density.
Figure 15: Typical damage of the electrodes close to the border of insulating layers (seen from the back side) in strong radiation fields.