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Section A

Microstrip gas chambers: Recent developments, radiation damage and long-term behavior

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Abstract

In the past years the technology of Microstrip Gas Chambers (MSGC) has made considerable progress offering a variety of possible new applications in various fields of research. MSGC are used to detect neutrons, X-rays, synchrotron radiation and VUV light as well as the full range of ionizing particles in nuclear and high energy physics. A variety of systematic studies led to a considerable increase in understanding of the functional principle and limiting parameters of the MSGC technology and enabled improved performances. In view of the large (HERA-B) and very large (CMS) detector systems planning to use MSGC in intense hadronic particle fluxes, the question of radiation hardness and long-term stability is of special importance. The problem of micro discharges, induced by heavy ionizing particles and destroying the electrode structure, turned out to be a major limitation to the applicability of MSGC in hadronic beams and demanded for new and revised solutions. The present status and future perspectives of the various technologies are discussed.

1. Introduction

Ten years after the fundamental paper by Anton Oed [1] the field of Microstrip Gas Chambers (MSGC) is still expanding and of increasing importance and interest. There are new and innovative techniques in various fields of applications and the MSGC technology is at the threshold for large-scale detector systems in high-energy physics. In the last years considerable progress has been made in the understanding of the fundamental properties and problems of MSGCs and from that a variety of considerable improvements have emerged. In the following a few examples from neutron imaging and X-ray detection will be presented to demonstrate the innovative power of MSGC technology whereas the bulk part of the paper deals with MSGC application in high-energy physics, especially with the challenging problem of using MSGC in the high radiation density environment of future experiments with hadron machines.

2. Neutron imaging

The meanwhile classical technique for neutron imaging by MSGC, as it has been pioneered by Anton Oed, uses high pressure He-3 as a neutron converter medium. At reasonable pressures of a few atmospheres the space resolution of such a device is

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limited to about 1 mm by the range of the nuclear reaction products in the gas [2]. Using this technique quite large detector systems with up to 50 MSGC have been built [3] and operated. A recent approach at HMI (Berlin) combines a variety of innovative techniques to improve the performance considerably [4]. The new generation neutron camera under development there uses a very sophisticated two-stage converter foil in the center of the detector to convert the neutrons via nuclear reaction and subsequent emission of secondary electrons into a detectable cluster of low-energy electrons. This electron cluster will be pre-amplified in parallel plate amplification mode in a low-pressure gap between the converter foil and the MSGC plate. The MSGC plate has a multilayer structure of gold electrodes, a diamond like surface coating, a 2 μm SiO_2 insulating layer and induction strips for the second coordinate. Despite the fact that this very ambitious design still requires further technological development, it demonstrates the innovative power and complexity of future MSGC devices. The expected performance of this neutron camera, with a position resolution below 0.5 mm, a detection efficiency above 50% and count rate capabilities up to 10^7 neutrons per second, surpasses conventional technologies considerably.

3. X-ray imaging

Another field of application where MSGC technology allows for new and improved experiments is X-ray imaging, especially the time and space resolved detection of diffraction patterns in synchrotron radiation scattering experiments (SAXS and WAXS) [5]. The high count rate capabilities of MSGC offer the opportunity to record diffraction patterns with good signal-to-noise ratio in milliseconds and thus to allow for time resolved observations in material science and biology. The approach of a group at Tokyo University can be taken as an interesting example [6]. Their X-ray camera consists of a two-dimensional MSGC made in Multichip Module Technology, a prototype of $10 \times 10\,\text{cm}^2$ has been produced and tested successfully. In this case the insulating layer separating the front strips from the induction strips on the back side consist of a thin Polyimid layer whereas the necessary surface conductivity is achieved by a layer of organic titanium. It could be shown that the chamber is able to tolerate rates of up to 10^7 photons/mm^2 s with a position resolution below 0.3 mm in both coordinates. For a real application in X-ray scattering the detector was equipped with a newly developed fast position encoding system and allowed to measure the position and energy of more than 10^6 photons per second. With this performance, time resolved diffraction patterns from rotating samples of organic complexes could be measured (Fig. 1). There is a good chance, that industrially produced MSGC based on that technology will become very powerful standard tools for synchrotron radiation experiments in the future.

4. High-energy physics

4.1. Early findings and solutions

By far the most challenging application for MSGC is the field of high-energy physics where large systems of up to 20 000 MSGC are under study and development. The application of the MSGC technology as tracking device in accelerator experiments is burdened by several severe boundary conditions. First of all the primary ionization from a passing highly relativistic particle is minimal, orders of magnitude less than the charge deposited from X-rays or even neutron reaction products. Thus a high intrinsic gain of the device is required to achieve a reasonable efficiency with present days VLSI electronics. The problem is enhanced by the fact that the detectors have to cope with short inter-event times, 25 ns in the case of LHC, 96 ns for HERA-B. Since the internal time scale of the MSGC is limited by the movement of electrons (drift time dispersion) and ions (signal formation) the scarce primary ionisation is further reduced to an even smaller usable ionization by a considerable factor. For an experiment like HERA-B, where fast signals for the First Level Trigger have to be produced with good efficiency and a tolerable fake rate in wrong bunch crossings, an intrinsic gain of the MSGC well above 2000 seems to be mandatory.

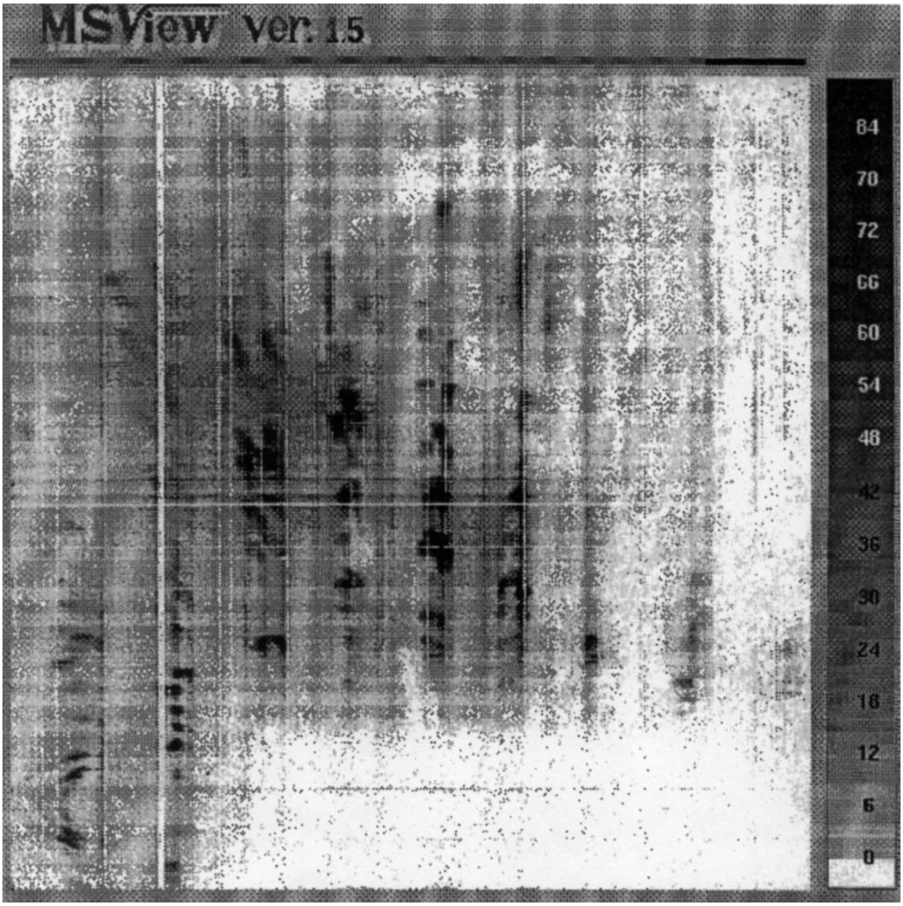

Fig. 1. Rotational image of phenothiazine-benzilic acid complex with a two-dimensional $10 \times 10\,\mathrm{cm}^2$ MSGC [7].

Whereas such amplification factors are an easy task at low rates, things become more critical if the chamber has to operate at high radiation levels for longer times. The problem of anode aging, well known to all types of gaseous detectors, has entered a new dimension of sensitivity with MSGC, mainly due to the filigree nature of the electrode structure and catalytic effects on the MSGC surface. The problem has been studied in great detail during the past years, especially by Fabio Sauli's group at CERN [8] with positive results: if no 'bad' hydrocarbons (methane, ethane, iso-butane) are used and the use of high purity gas systems and detector components avoids pollution of the gas with dangerous species (large organic molecules, halogen, silicon, etc.) a lifetime of the detector corresponding to several years of LHC or HERA-B operation could be achieved. For this, gas mixture based on DME (dimethylether) or CO_2, diluted with argon or neon are the favorite candidates, combining very slow aging with reasonable drift velocity and density of primary ionization.

Another problem concerning the MSGC community for considerable time is the stability of the mandatory finite surface resistivity of these devices. Whereas at low rates the 'natural' ionic conductivity of normal glass (DESAG 263 as an example) allows for stable operation of the detector, this turned out not to be sufficient at rates of 10^3–10^4 particles/mm^2 s as they are typical for the LHC or

HERA-B environment. Under these particle flux, in combination with the electric fields of the MSGC structure, the distribution and concentration of ions in the glass surface is destroyed very rapidly leading to instabilities and severe gain reduction. The way out by using iron loaded, electronically conductive Pestov glass is impracticable for most of the high-energy physics experiments since this type of glass is not available in large thin plates and represents a very unpleasant source of photon conversion due to its short radiation length. From a multitude of unsuccessful attempts to coat the glass surface with a thin electronically conductive layer, the so called 'diamond like coating' (DLC) with hydrogen and nitrogen loaded amorphous carbon [9,10] turned out to be a reliable and stable solution which is available on sizes of up to $40\times40\,\mathrm{mm}^2$ in good quality. As an example from our own research for HERA-B Fig. 2 shows the typical good long-term stability of a DLC coated MSGC operated with Ar-DME 50/50 gas [11]. After a charge accumulation corresponding to more than 4 years of HERA-B operation the detector exhibits no significant loss in gain and quality of the pulse height spectra.

4.2. The problem of induced discharges

About two years ago, a new pest entered the scene of MSGC development: the phenomenon of induced discharges. It turned out that under conditions, where chambers survived very strong particle flux of electrons or X-rays without complaining, the very chambers were destroyed almost immediately in beams of pions or protons [12]. The electrode structure of a chamber operated under HERA-B or LHC equivalent hadron flux for few hours was strewn with marks in the anodes and cathodes (Fig. 3) and a considerable number of anodes was broken. The obvious reason for the electrode damage are discharges between anodes and cathodes, induced by heavy ionizing particles passing very close to the MSGC surface and depositing a large amount of charge in the anode–cathode gap. Reproduction of the phenomenon without hadronic beam by introducing a gaseous source of α particles in the detector fixed the heavily ionizing particles as discharge trigger and offered the possibility to study the effect in the laboratory [12]. In a strong hadronic beam the heavy ionizing particles are produced by nuclear reactions with the material of the MSGC, especially with the MSGC plate itself.

From very detailed studies about the phenomenology of these induced discharges [13] rather depressing conclusion emerged. For a given electrode pattern and gas composition there are only two parameters to play with: the anode–cathode potential U_K and the drift field E_D. It turned out that for a fixed gas gain the discharge rate rises almost exponentially with U_K but is completely

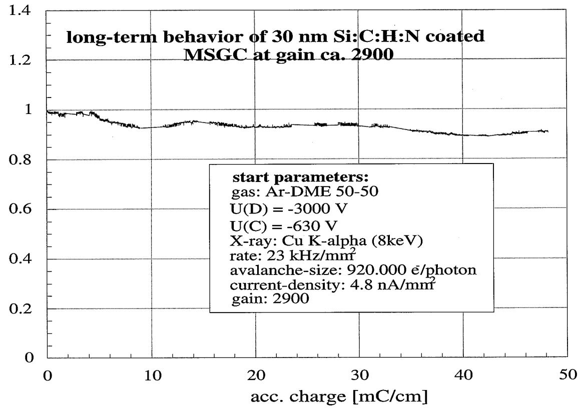

Fig. 2. Long-term behavior of the gas gain in a Diamond Like Coated MSGC. The gas gain was 2900 and the current density $5\,\mathrm{nA/mm}^2$.

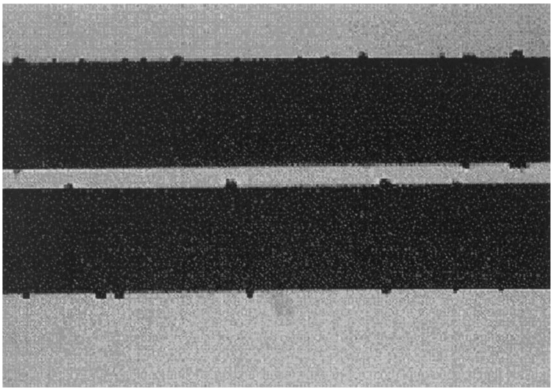

Fig. 3. Microscopic view of the electrode structure after running in an intense hadronic beam at gain 3000 for several hours.

independent of E_D, even if the field is reversed. Since the gas gain of the MSGC depends on both, U_K and E_D, there is a possibility to reduce the discharge rate by running the detector at the highest possible drift field. But even at the upper limit of technological feasibility (10 kV/cm) the discharge rate under nominal HERA-B conditions (gain 3000, 10^4 particles/mm^2 s) destroys the electrode structure within a few hours. Attempts to cure the problem by finding a more clever counting gas, suppressing the induced discharges to a tolerable level, failed completely. Within very narrow bounds the discharge rate for a given gas gain turned out to be independent of the gas composition and unaffected by all kinds of magic additives like alcohol, methylal or ammonia. As a general summary we had to conclude, that induced discharges in hadronic beams are an intrinsic problem of the MSGC structure and geometry and a consequence of the high electric fields between anode and cathode strips close to the MSGC surface, especially if a linear potential drop is forced by the conductive surface layer. If the MSGC is operated with a gas gain of 2000 or higher in a hadronic flux which is typical for HERA-B or LHC experiments, the electrode structure is severely damaged (leading to an increasing discharge probability!) within a few hours. Thus either the detectors have to be operated at very restricted gains or completely new solutions for these applications have to be found.

4.3. The influence of the strip material

The influence of the strip material on the damage caused by the induced discharges has been studied by the HERA-B group, details can be found in a contribution to this conference [14]. The basic idea was to see, if it would be possible to find a discharge resistant material and thus to be able to tolerate a certain discharge rate without destroying the chamber. From studies with MSGC structures made from gold, aluminum, chromium, rhodium and tungsten the basic conclusion was, that all materials with low electric resistivity are rapidly destroyed whereas chromium, a fairly bad conductor, turned out to be extremely spark tolerant. Unfortunately the signal propagation in a MSGC structure is dominated by the anode resistivity. With chromium strips longer than a few centimeters the charge extraction speed becomes too long for applications with high particle rates and short inter-event times. Fast signals and spark tolerance seem to be incompatible requirements.

In fact this is true only for the standard MSGC geometry. Looking a bit more in the details of the signal propagation it turns out, that basically two fundamental modes of signal propagation exist in a MSGC-like structure. One of these modes normally is much faster than the other one. (For a MSGC with N anode cathode pairs there are $N/2$ fast and $N/2$ slow propagation modes grouped in two well distinct bands, the fast and the slow band). In a conventional MSGC, where the cathode resistivity is much less than the anode resistivity, signal propagation occurs almost entirely in the slow propagation mode. If constructional changes allow to make the cathode resistivity higher than the anode resistivity while keeping the cathode backplane capacity high, the propagation switches to the fast mode and becomes independent of the cathode resistivity. Additionally the high cathode resistivity acts as a current limiting resistor in the case of discharges, protecting the electrode structure from being damaged. The validity of these ideas has been recently demonstrated using a special MSGC structure with 10 μm anodes made of gold and 170 μm cathodes made of titanium[1] with a resistivity ratio cathode/anode of 5. As shown in Fig. 4 this chamber exhibits no signal damping along the strips, in contrast to a pure chromium chamber where the signal amplitude decays within a few centimeters. Probing the chamber with an α source showed the remarkable spark tolerance of the device [15]. Despite of the interesting properties of such a Mixed Material MSGC which could be advantageous in special fields of applications, it seems not to be a favorable solution for the large tracking systems in HERA-B and CMS. The technology is quite fragile and expensive and excessive discharge rates deteriorate the performance of the detector even if the electrode structure stays intact.

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[1] The author would like to thank Dr. A. Sonderer from IMT (Greifensee, Switzerland) for his efforts to produce this device.

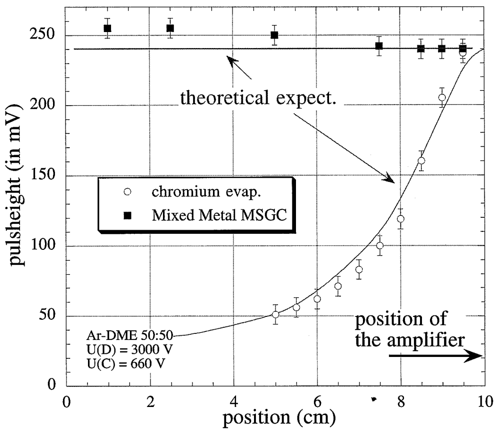

Fig. 4. Signal amplitude as function of the avalanche position along the strips for a conventional MSGC with chromium strips and a MSGC with high resistive cathodes. The shaping time of the amplifier was 50 ns.

4.4. *The CMS approach*

By far the largest application of MSGC planned in high-energy physics is the MSGC tracker of CMS where about 20 000 MSGC are foreseen to cover a total area of about 600 m^2[16]. Since the details of the CMS approach for a MSGC tracker and the present status is presented in various contributions to this conference [17,18] only a brief summary will be given here. The CMS base line solution are conventional MSGC with 'advanced passivation' of the cathode edges [19] and an elaborated definition of working points and operational parameters [20]. The basic idea of the 'advanced passivation' is to cover the edges of the cathodes by insulating strips of polyimid and thus to avoid field emission and cathode feedback from this critical high field regime. Unfortunately the distribution of the electric field is not unaffected by the presence of the insulating strips if the detector is exposed to strong radiation fields and the effectiveness of the method is not out of concern. The main issue of the definition of the working point for CMS is a gas gain of only 1700 which seems to be sufficient if used in conjunction with a very powerful front end electronics and if no fast trigger signals have to be derived from the chambers. Last year the CMS group has demonstrated in various beam test that under these conditions the chambers can be operated safely with LHC like particle intensities [21,22]. The proper definition and the elaboration of this working point has to be taken as remarkable success, but in view of the very small safety margins the application of the solution for a very large system under severe conditions seems to be of considerable risk.

4.5. *The HERA-B approach*

Despite the fact that the total area of the HERA-B Inner Tracker is only about 1/10 of the CMS tracker the following parameters [23] should illustrate, that the demands for the MSGC exceed the CMS demands in various respects, making a CMS-like approach to solve the problem of induced discharges almost impossible. The particle flux in the inner most part is about a factor of 5 higher, the signal-to-noise is intrinsically worse by a factor of 2 due to the longer strips. The necessity to extract fast signals for the first level trigger requires a fairly short pulse shaping in the pre-amp stage leading to an additional reduction of the usable signal amplitude. From simulations it became apparent that gas gains well above 2000 are required to achieve a reasonable efficiency of the system. Since we have to allow for a further deterioration of the signal-to-noise ratio during operation due to radiation damage of the front end electronics, the conventional MSGC solution with or without advanced passivation is completely ruled out.

After a variety of severe and exhaustive tests, HERA-B decided to use MSGC with a Gas Electron Multiplier (GEM) [24] as pre-amplification structure for their Inner Tracking system. A more detailed description of the HERA-B ITR system can be found in Refs. [25,26]. The design of the GEM geometry and the verification of the suitability for the HERA-B environment was done in close collaboration with the group of F. Sauli at CERN, a detailed description of the GEM optimization and the performance of various GEM geometries is presented in a contribution to this conference [27]. The basic benefit of the GEM pre-amplification is the factorization of the total gain of the detector in two factors, the GEM gain (usually set to 10–20) and the MSGC gain of the order 150–500. In both amplification regimes the electric field strength is *undercritical* for the formation of induced discharges and both regimes are well separated by a low field region preventing streamers to grow from one amplification zone to the other. Very quickly it could be proven that a GEM-MSGC does not suffer from induced discharges neither with an internal α source nor in the HERA-B environment under full interaction load [13]. As a final test in November 97 a full size HERA-B-ITR chamber was exposed to a mixed pion/proton flux of 25 kHz/mm^2 at PSI (Switzerland) and operated at a total gain of 6000 for 150 h. No single induced discharge or strip damage was observed. The GEM-MSGC offers ample gain reserve even under the harsh conditions of the HERA-B Inner Tracker.

One of the main concerns was the influence of the GEM on the resolution, the strip multiplicity and the performance in magnetic fields. All of them could be completely cleared up. A beam test at CERN demonstrated that the resolution of the chamber is in fact unaffected by the GEM, resolutions of 40 μm with a 200 μm pitch could be achieved (Fig. 5). A beam test at DESY with electrons [29] showed that the strip multiplicity (most critical for HERA-B since it determines the occupancy) is less increased by the GEM than the expected factor of $\sqrt{2}$ from the twice as high drift gap. In the same test the chambers were exposed to a magnetic field of up to 1 T parallel to the strips without any visible deterioration of the efficiency of the device (Fig. 6). At the high drift field of 10 kV/cm used, the broadening of the charge distribution can be tolerated without tilting the chambers.

Aging studies with Ar/DME and Ar/CO$_2$ mixtures have demonstrated that no fast aging is introduced neither by the GEM itself nor by the complicated construction and assembly procedure if appropriate glue and insulating materials are used. The present status of the HERA-B-ITR is that a pre-series of 12 chambers has been build and assembled to a 8 layer package of the tracking and triggering system (Fig. 7). The full lot of 200 chambers will be produced during 1998 and installed in HERA-B in 1999.

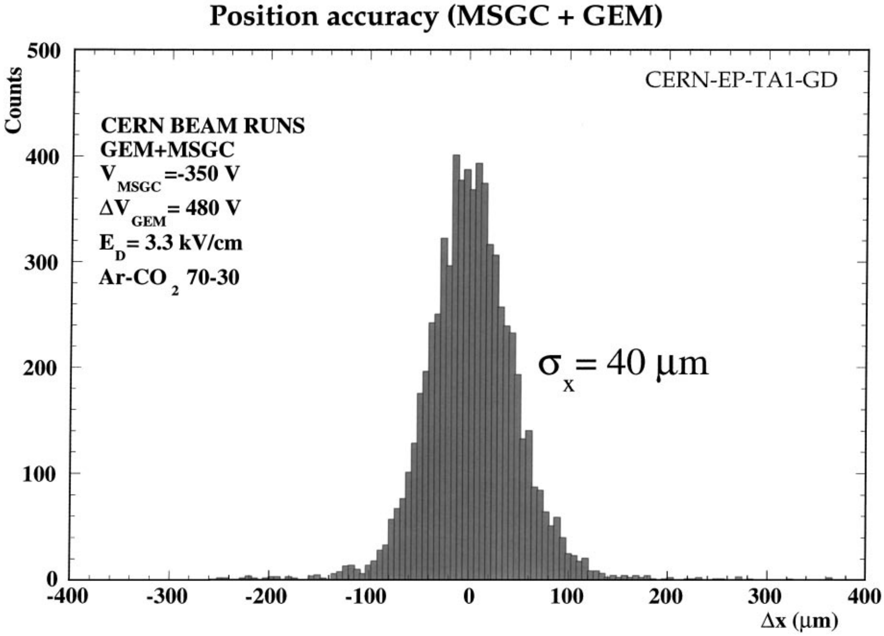

Fig. 5. Space resolution of a GEM-MSGC with 200 μm pitch operated with Ar/CO$_2$[28].

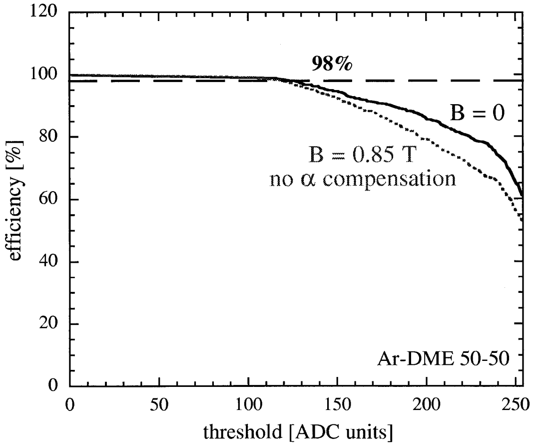

Fig. 6. Efficiency of a GEM-MSGC as function of threshold with and without magnetic field parallel to the strips. In both cases the chamber was oriented perpendicular to the electron beam.

It was interesting to see that the installation and optimization of dedicated production tools strongly enhanced the quality of the large size ($25\times25\,\mathrm{cm}^2$) MSGC plates. Using a semi-automatic test apparatus [30] it was shown that the mean value of broken anodes could be reduced to less than 1% with very good production yield.

Despite the fact that this now available GEM-MSGC technology seems to be adequate for high-flux – long-time experiments, opening an important new field of applications for gas filled detectors, it still lets room and partially asks for further improvements. First of all the GEM is a monolithic device and a single short in one of the millions of holes ruins the entire chamber. Good ideas of how to segment the GEM or how to build- in clever self-curing properties would be highly welcome. Another imperfection comes from the fact that the amplification in GEM holes is influenced by

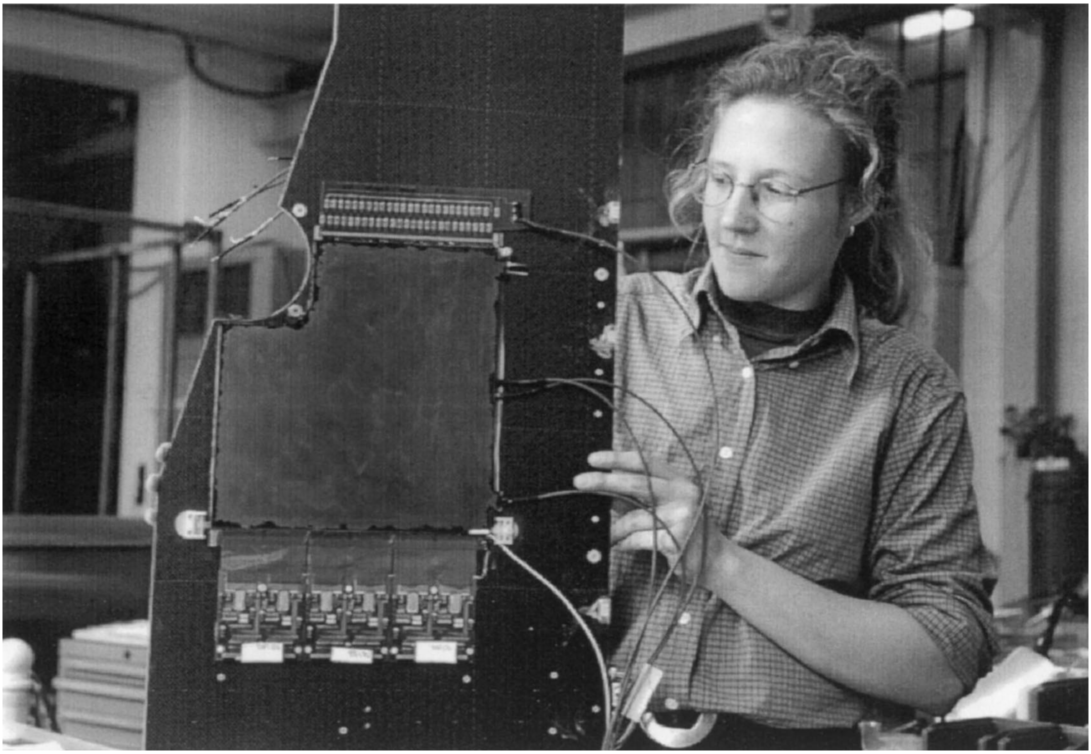

Fig. 7. A GEM-MSGC for the HERA-B Inner Tracker with front end electronics, mounted on its carbon fiber support structure. The round cutout in the chamber allows for the proton beam pipe. Four such chambers represent one detector plane.

polarization effects in the insulator leading to time and space dependent gain fluctuations. This effect can be completely cured by coating the entire GEM with a DLC layer by plasma CVD, similar but not identical to the procedure used for the coating of the MSGC plate [31]. First results look very promising, very recently the successful coating of a large size GEM has been reported.

5. Summary and outlook

In the past years the MSGC technology could be considerably improved and the field of applications has been continually expanding. Elaborated double sided designs have led to powerful two-dimensional detectors allowing for new and innovative applications in X-ray and neutron imaging. One of the most challenging applications, the detection of minimum ionizing particles in high intensity hadronic flux, made a quantum step by the introduction of the GEM as pre-amplifier. With the HERA-B Inner Tracker the GEM-MSGC reached the level of application in a large and complex detector system. In parallel to this impressive development of detectors with 'classical' MSGC structure, a variety of descendants and modifications have been developed and studied, partially promising impressive new features and capabilities. A completely new class of 'micro structure gas filled detectors' entered the scene as can be seen from various contributions to this conference [32–35]. A centenary after the invention of the basic principle of gas amplification, gas filled detectors are still good for further improvements and promising a rich and exciting future.

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