4 Particle Physics at LHC/CMS

C. Amsler , M. Glättli, R. Kaufmann, F. Ould-Saada, P. Robmann, C. Regenfus,
S. Spanier, S. Steiner, P. Truöl and T. Walter
in collaboration with ETH-Zürich, Paul Scherrer Institut (PSI), Universität Basel
and the CMS collaboration.

In 1995 the Physik-Institut of the University of Zürich joined the CMS collaboration at the Large Hadron Collider. We participate (i) in the development and construction of the barrel silicon pixel detector (design of the pixels and readout chips and construction of the support structure and cooling system) and (ii) in the design and development of microstrip gas chambers (MSGC).

4.1 Pixel developments

The CMS pixel detector consists of two forward detectors and a barrel detector. The forward detectors are under the responsibility of the U.S. groups. According to the current layout [1] the barrel detector is made of three cylindrical layers, 53 cm long with radii of 4, 7 and 11 cm. The support structures are made of tubes with trapezoidal cross sections (providing water cooling) connected with carbon fibre blades and supported at both ends by carbon fibre end rings. Each layer is made of two half-cylinders to allow insertion into the CMS detector. Due to radiation damages close to the interaction point which limit the lifetime of the detectors, the two innermost layers will be used in the beginning during low luminosity run. The two outermost layers will be used during full luminosity runs and we anticipate that the 7 cm radius detector will have to be replaced after 5 years of LHC running.

A pixel cell contains 53 $\times$ 52 pixels of dimensions 150 $\times$ 150 μm^2. Two rows of 8 cells build a module and a row of 8 modules builds a facet of length 53 cm and width 1.75 cm. The total number of pixels to be read out are 6.3×10^6, 1.1×10^7 and 1.6×10^7, respectively.

Due to the deflection in the magnetic field which is parallel to the beam axis (z), the deposited charge in the wafer does not move to the closest pixel but drifts at an angle Θ_L, the Lorentz angle, towards the adjacent row. The charge deposit is therefore shared among several (mostly two) adjacent pixels. The averaged amplitude thus leads to an improved resolution in the $r\phi$ direction. In the z direction the charge is shared between up to 5 pixels, depending on the track polar angle. We anticipate a resolution of typically σ = 15 μm in both $r\phi$ and z directions.

With prototype detectors a depletion thickness of 150 - 200 μm has been achieved with 300 V bias voltage even after having irradiated the pixels with $6{\times}10^{14}$ pions, a flux corresponding to the lifetime of the CMS experiment. The depletion thickness is larger than was expected in the experimental proposal and therefore the pixel size has now been increased from 125 $\times$ 125 μm^2 to 150 $\times$ 150 μm^2. This will still provide charge sharing among two adjacent pixels and the larger pixel size will also increase the space available on the readout chip under the pixel for the readout electronics. The total pixel thickness will be 250 μm.

Silicon has been chosen as substrate material. Gallium-arsenide and diamond were finally discarded, the former due to its poor radiation hardness and the latter due its insufficient charge collection length. We will use n-doped silicon because of the larger drift velocity of the electron charge carriers (and hence the larger Lorentz angle). Also, radiation damages will induce type inversion and the resulting p-layer will grow on the opposite side of the pixels.

Every pixel is connected to its own readout electronics on the readout chip through a pellet of indium (bump bonding). The readout contains a preamplifier, a shaper and a comparator driven by a DAC which sets the threshold. When a hit occurs in a column (2 pixel row), the column and the time stamp is copied and stored into a column area. The readout occurs when the trigger verifies the time stamp. The pixel hit rate is typically 14 kHz in the 7 cm radius detector and the column multiplicity typically 2.

The Zürich group has prepared and performed tests of pixel detectors designed at PSI during two running periods at CERN. We used 300 μm thick detectors made of 256 pixels (125×125 μm^2) manufactured by CSEM (Neuchâtel). The first beam test was performed in 1995 at the CERN-SPS with 50 GeV pions to measure the position resolution [2]. Since no magnet was available for this test, data were taken at different detector inclination angles with respect to the beam axis to simulate the Lorentz angle in the magnetic field of CMS. An average signal to noise ratio of ~ 25 was achieved. We obtained a resolution $\sigma = 13$ μm for a tilt angle of 35° - which corresponds to the Lorentz angle in the CMS magnetic field of 4 T - in accord with forecasts from the experimental proposal [3].

The second beam test was performed in 1996 in a strong magnetic field with 225 GeV/c pions [4]. The Lorentz angle was determined by measuring the cluster size as a function of tilt angle. We obtained $\Theta_L = (15.5 \pm 2.4)°$ at 2 T, in good agreement with expectations (18.6°) from the known electron mobility in silicon. Details and results can be found in ref. [2, 4] and in last year's annual report.

For these first attempts the data collection efficiency was rather poor due to the large beam spot compared to the detector size. A good definition of the incident π tracks (e.g. with silicon microstrip detectors) was also not possible due to heavy multiple scattering from other detectors tested simultaneously in the same beam. An algorithm was used instead to measure indirectly the average spatial resolution without tracking, employing charge sharing between pixels [2, 4].

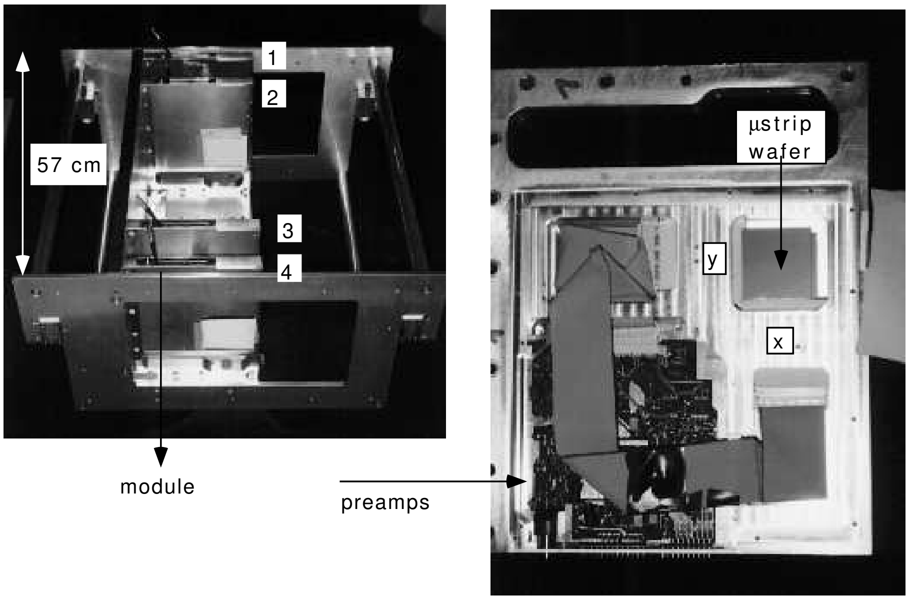

Figure 4.1: Left: telescope assembly showing the 4 $x - y$ microstrip modules; right: module with associated preamplifiers.

To alleviate the difficulties with multiple scattering from other detectors in the test beam and to perform a direct measurement of the position resolution of pixel (and later MSGC) devices we have built in the mechanical workshop of our institute a precision beam defining telescope (under the supervision of K. Bösiger). The telescope (Fig. 4.1) is made of four modules, each containing two 32×32 mm^2 single-sided microstrip silicon wafers, one providing the x-coordinates and the other the y-coordinates. The space between the two upstream and the two downstream modules is used for the pixel test device which will be sandwiched between two triggering diodes and mounted on a remotely controlled rotating support. The microstrip wafers were bonded at CERN.

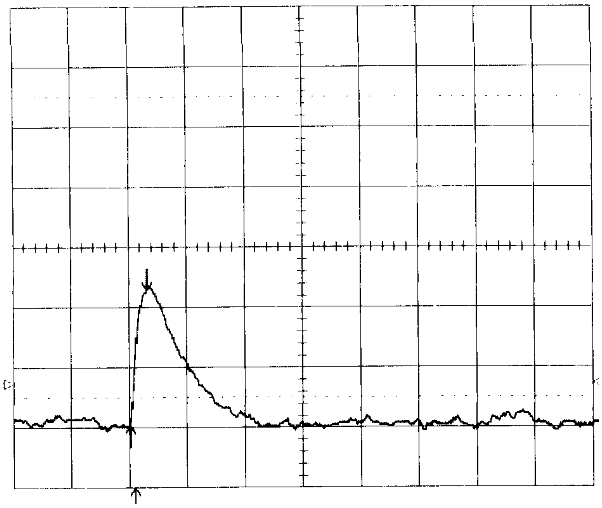

Figure 4.2: Preamplified signal from a 20 keV γ-source; horizontal scale: 5 μs/div.; vertical scale: 50 mV/div.

A microstrip wafer is 300 μm thick and contains 1280 strips with a pitch of 25 μm. However, only every second strip is connected to the readout electronics and the charge collected by the floating strips induces a charge on the readout strips by capacitive coupling. The signals from the 640 active strips are amplified, shaped and the total charge is stored (5 VA2 Viking chips each with 128 channels). Figure 4.2 shows the analog output signal from one of the preamplifiers, using a 20 keV γ-ray source.

A 2 MHz multiplexer reads sequentially the charge deposits which are then digitized by a Flash ADC (CAEN VME V550, 2 inputs for 2040 channels). The readout and data acquisition system are controlled by a VME FIC 8234 processor running on OS9. Data are written to disk or to DLT. We have developed this system for the data acquisition of our neutrino experiment at the Bugey reactor.

The telescope was tested in 1997 in a 100 GeV muon beam. The trigger signal was provided by the coincidence between two photodiodes. Seven out of the eight wafers worked satisfactorily with similar performances, while one of them had to be exchanged. Figure 4.3a shows the typical Landau distribution for the energy deposit of about 16'000 muons traversing one of the wafers. The detectors were fully depleted with a bias voltage of 45 V. A signal to noise ratio of 250 for minimum ionizing particles was achieved.

The typical cluster size was two strips per incident muon. The hit coordinates were determined accurately by using the energy deposit shared among the strips. The mechanical alignment accuracy of the detectors was typically 50 μm. A more accurate alignment was achieved by software with a large number of passing muons. We then determined the position resolution of each detector by fitting straight tracks and comparing the hit coordinates y with the predicted coordinate y(fit) from the fit. The distribution of residuals is shown in Fig. 4.3b for one of the detectors. A resolution of $\sigma \simeq 2.5$ μm was obtained for all eight detectors.

This kind of resolution represents the current state of the art in microstrip technology. It is more than sufficient for measuring the position resolution of pixel detectors. However, in the high rate environment of LHC, radiation damage will slowly reduce the depletion thickness of our pixel detectors. In spring 1998 we will therefore determine how the depletion thickness varies with radiation damage. Irradiated pixels at PSI will be submitted to a high

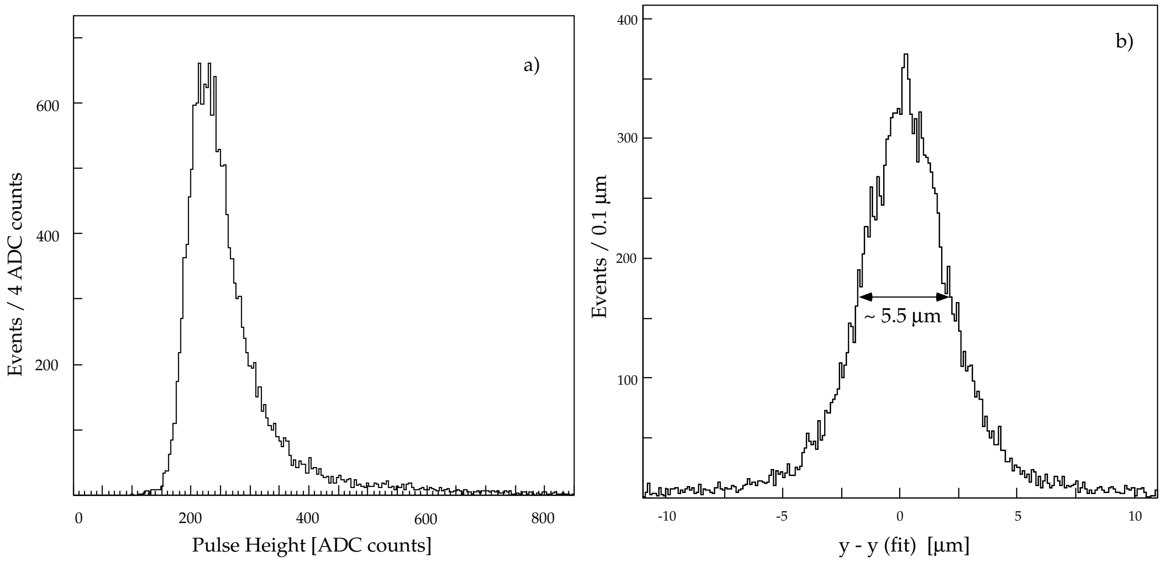

Figure 4.3: a): Distribution of the energy deposit for minimum ionizing particles in one of the microstrip detectors; b): Distribution of the residuals (differences between measured hit coordinates and expected coordinates).

energy beam at CERN. The beam will traverse the pixel detectors at grazing angles (i.e. nearly parallel to the depletion layer). The pixel cluster size, which depends on the incident angle and on the depletion thickness, will be measured. This obviously requires an accurate determination of the incident tracks which will be achieved with our telescope. At the same time we will repeat our measurement of the Lorentz angle in a strong magnetic field.

4.2 Microstrip gas chambers

The research and development effort in the area of microstrip gas chambers (MSGC), which are able to sustain high rates, still continues in many institutes within and outside of the CMS collaboration [5]. Though impressive progress has been made the final solution for the type of chamber which is going to be used has not been found, and hence the final plan for our contributions to CMS MSGC construction has not been agreed upon. Presently we are still concentrating on the chambers, which are going to be used for the inner tracking system of the HERA-B detector. Here also large fluxes of up to 10^4 cm^{-2}s^{-1} at small radii near the beam pipe demand a very high granularity, lead to a design not too different from what is planned for CMS and hence these MSCG's may serve as a realistic large scale prototype. Our partners within the HERA-B collaboration since 1995 are groups from the Universities of Heidelberg (Profs. F. Eisele, U. Straumann) and Siegen (Prof. G. Zech).

At the University of Zürich we are responsible for the design of the masks, the supervision of the production and the quality control of the substrates for all modules, the support of the complete modules within the magnet, and for the pion beam tests at PSI. It is these areas, where our work concentrated last year.

Several new masks have been laid out in Zürich in two standard sizes, 12.7×12.7 cm^2 and 30×30 cm^2, with 10 μm anode width, 170 μm cathode width and pitch 300 μm, with 305 and 767 anodes, respectively. From these masks chamber planes have been produced at IMT (Greifensee) on diamond coated AF45 glass substrates (ion conducting, surface resistivity $> 10^{16}$ Ω/square; after coating by chemical vapour deposition, 8×10^{14} Ω/square). The full

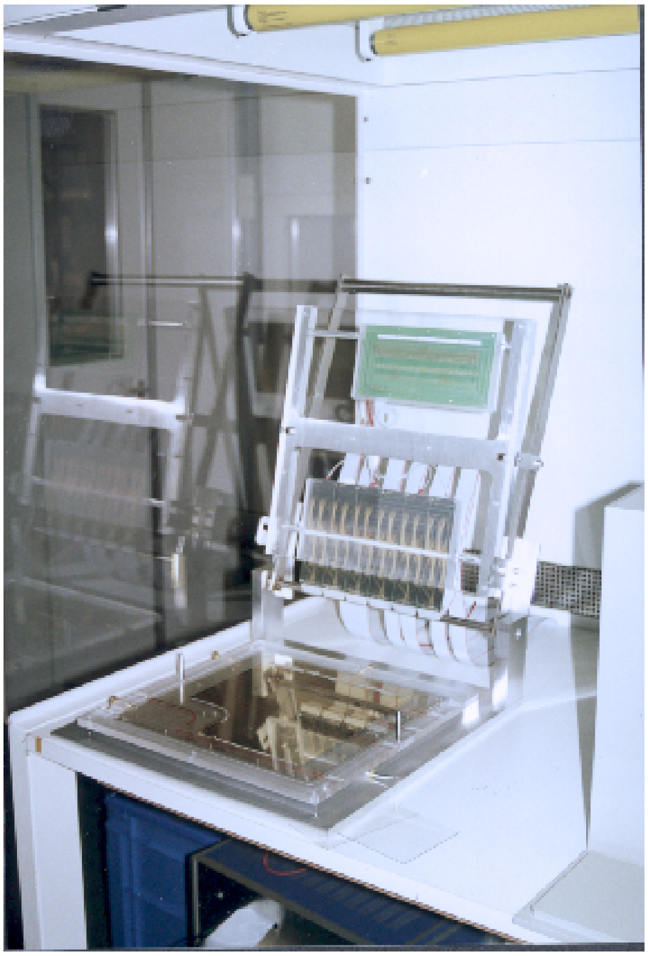

Figure 4.4: Photograph of the electrical MSGC anode break tester, designed by and built at the University of Zürich, during testing of the first larger series of HERA-B substrates at IMT (Greifensee). The cover, which contains the electronics board and anode contacts, is open. When it is closed and locked, contact is being made. The whole installation is within a clean box.

size prototypes (masks UZHHERA3 to UZHHERA5) belong to the largest MSGC's ever built. The different versions of the same size essentially differ in the distribution of high voltage feeds and reference points, but not in pitch and electrode width. Because of their large size new special tools were required and produced in our workshops. These tools were needed to handle the large substrates in the production process at IMT, and also for the transport of the finally more than 200 substrates to and from the Frauenhofer-Institut (Braunschweig), where the coating is done, IMT (Greifensee), and the University laboratories.

The quality control of large numbers of chambers is quite time consuming, if it is done solely under our microscope, even though the latter is equipped with computer controlled positioning, as shown in last years annual report. Substrates with too many anode breaks can be eliminated quicker using an electrical method which we have developed. The principle of the method was described in a diploma thesis [6], but it has been modified since then. Instead of capacitively coupling radio frequency signals to all anodes and using the height of the pickup signal as an indication for a fault, we are now contacting all the cathodes at one end and the anodes at the other end of the plate. A DC voltage (400 V) is then applied across the gap and the current of each anode measured separately. The new setup is shown in Figure 4.4, the measuring scheme in Figure 4.5, and the result of a measurement for a chamber plate in Figure 4.6. Compared to the prototype the system has also been mechanically improved to faciliate the positioning of the substrates and to guarantee reproducible contacts without damage to the electrodes, and now allows measurement of the surface resistance.

While the chamber tests in Heidelberg and Siegen with sources and X-ray tubes indicated

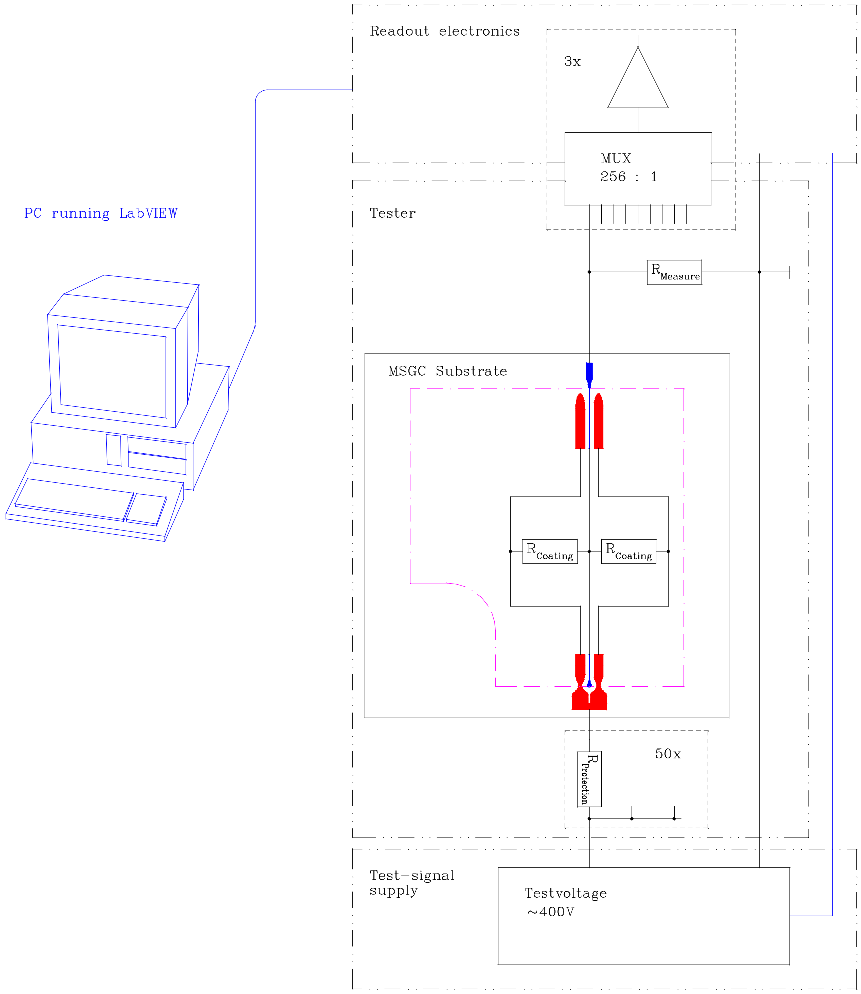

Figure 4.5: Measuring principle of the electrical MSGC anode break tester. The current over the anode to cathode gap is measured by recording the voltage drop across a control resistor with a computer controlled ADC.

satisfactory operation at gain factors around 3000 despite the sometimes microscopically poor quality of the anode borders [7], it was discovered during a PSI test in 1996, that chamber breakdowns occured at an intolerably high rate. As reported last year visual inspection of the chamber after the test indicated a close correlation of the number of anode defects and holes in cathodes with the number of sparks, most noteably for the gold plated anode, where often large pieces were found missing. This phenomenon was further investigated and confirmed in the laboratory (see the summary given by B. Schmidt [8]). Different remedies for this problem were proposed and studied by us and other groups. Only the gas electron multiplier (GEM) technique [9] showed promising features. In the GEM technique a thin mesh made from a double sided metal clad polymer is added in front of the microstrip plate (see Figure 4.7). The mesh has conical holes of 50 (or 80) μm diameter with a 140 (or 200) μm pitch (see Figure 4.8). A moderate voltage difference ($\approx$ 500 V) across the mesh produces an electrical field, that renders the mesh fully transparent and multiplies the number of electrons typically by a factor of 20, which in turn allows to operate the subsequent MSGC at lower gain and in a safer mode. Figure 4.8 shows measurements of the gas gain with and without the GEM foil.

A MSGC modified with a GEM foil was tested in Heidelberg at the tenfold HERA-B rate with X-rays and alpha particles without observation of sparks, because the cathode voltage can be reduced by 150 V. This behavior was confirmed with intense exposure to X-rays and tests in the HERA-B beam. Electron beam tests showed, that the chambers can be operated

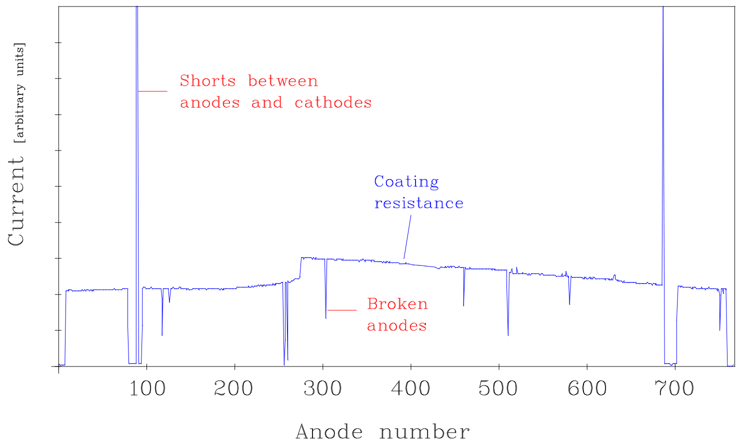

Figure 4.6: Result of a chamber plane test indicating shorts (2) and broken anodes (8). From the current measured for intact electrodes the surface resistance may be deduced.

in magnetic fields up to 0.85 T, and that the Lorentz angle of 7° (Ar/DME 50/50) only leads to a moderate increase in strip multiplicity [8]. A chamber with Au-electrodes was operated equivalent to a dose of one HERA-B year with Ar/CO_2 (70/30 %) with constant GEM and gas gain. Electrodes and GEM foil showed no damages after this exposure. No discharges induced by heavily ionizing particles were observed.

The production of large area GEM-foils has been started at CERN. To support stretched foils of up to 25 $\times$ 25 cm^2 the glas tube frame used so far for the MSGC prototypes has been replaced by a glasfibre reinforced plastic (GFK) frame of 10 mm width, closed by a Kapton cover. Twenty diamond coated glas substrates with Al electrodes, which are more robust against occasional breakdowns, are available for a preseries to be equipped with the CERN GEM foils. The number of anode breaks and shorts was found to be below the allowed tolerance, as revealed by our measurements (see e. g. Figure 4.6). For the frontend electronics the HELIX128 chip, which underwent several revisions, will be used, for the one complete station (eight detectors) to be installed in HERA-B this year.

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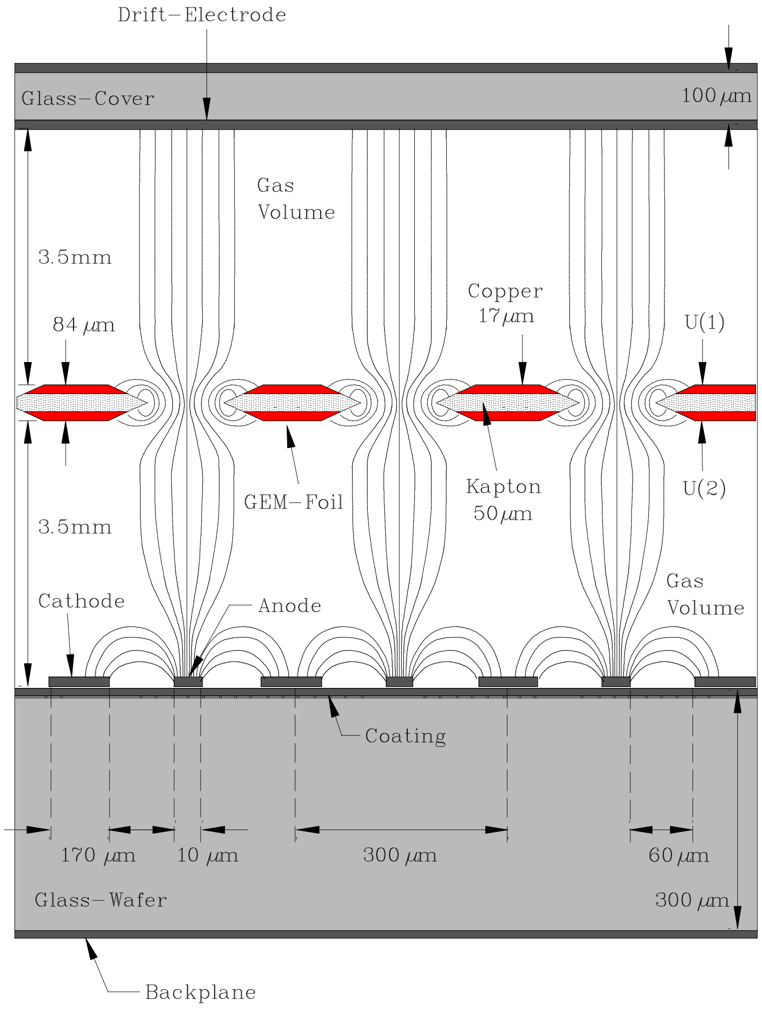

Figure 4.7: MSGC with an additional gas electron multiplier (GEM) foil.

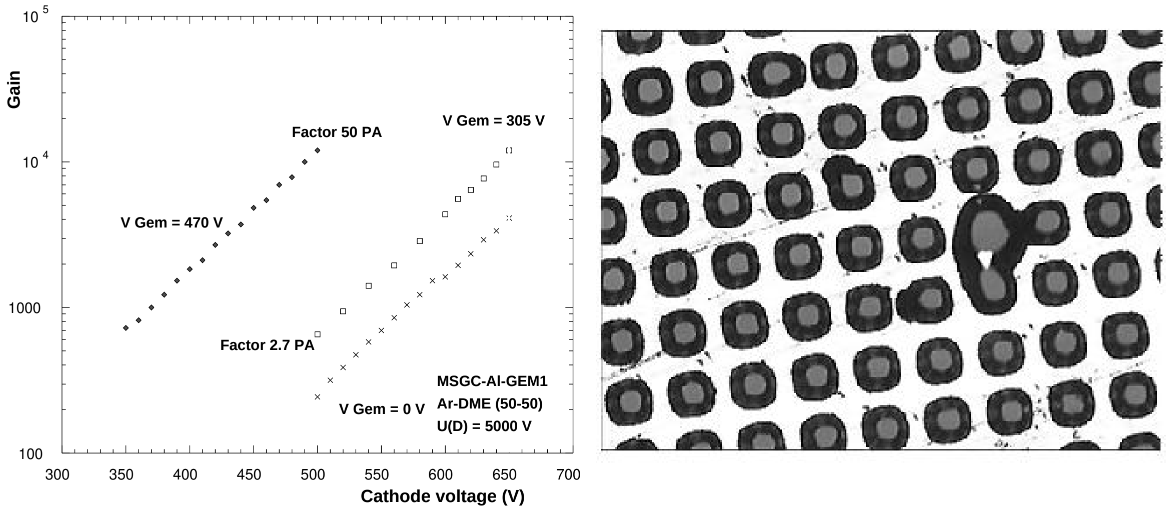

Figure 4.8: Left: gas gain in a GEM prototype compared to a standard MSGC. Right: a GEM foil with holes every 140 μm viewed under a microscope. The light area is the Cu surface, the dark shaded area is the insulating Kapton layer, the holes appear grey. This section of the foil shows a defect from the production process.