MICROMEGAS: results and prospects

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Introduction

A lot of effort has been invested in the development of the Microstrip Gas Chamber (MSGC) [2] in order to be used as tracker for the LHC project. This technique allows good localization accuracy and double track resolution. However, it is necessary to operate it with a relatively low gas gain because of the presence of the insulator near the amplification region and because of the fragility of the structure.

Recently a new preamplification structure, called GEM [3], has been introduced which can give an additional gas gain, and compensates the lack of gain of the original MSGC. Other concepts of novel proportional counters have been proposed recently: CAT [4], MICRO-DOT [5]. A review of recently developed gaseous detectors can be found in reference [6].

MICROMEGAS [1] is a high gain gaseous detector, which can stand up alone without a need of an additional preamplification. It combines high accuracy, high rate capability, excellent timing properties and robustness. These results were confirmed by a similar structure having wider amplification gap and thicker metallic grid [7].

1. Detector description

A detailed description of Micromegas is given in [1,8,9]. It is a two-stage parallel plate avalanche chamber that has a narrow amplification gap defined by the anode plane and a cathode plane made by a Ni electroformed micromesh. Several 15x15 cm^2 chambers with a conversion gap of 3 mm, an amplification gap of 100 or 50 µm with a strip pitch of 317.5 µm have been designed and fabricated. The parallelism between the micromesh grid and the anode is maintained by spacers of 150 µm in diameter, and placed every 2 mm. They are printed on a thin epoxy substrate by conventional lithography of a photoresistive polyamide film. The thickness of the film defines the amplification gap. This is a cheap and simple process that allows the construction of large detectors with excellent uniformity (10%) and energy resolution over the whole surface.

1. Electric field configuration

The knowledge of the shape of the electric field lines close to the micromesh is a key issue for an optimal operation of the detector and especially for an efficient transfer of electrons to the amplification gap. The electric field is homogeneous in both the conversion and the amplification gap. It exhibits a funnel like shape around the openings of the microgrid: field lines are highly compressed towards the middle of the openings, into a small pathway equal to a few microns in diameter. The compression factor is directly proportional to the ratio of the electric fields between the two gaps.

Figure 1 displays details of the field lines near the grid used in the present test (50 µm opening pitch).

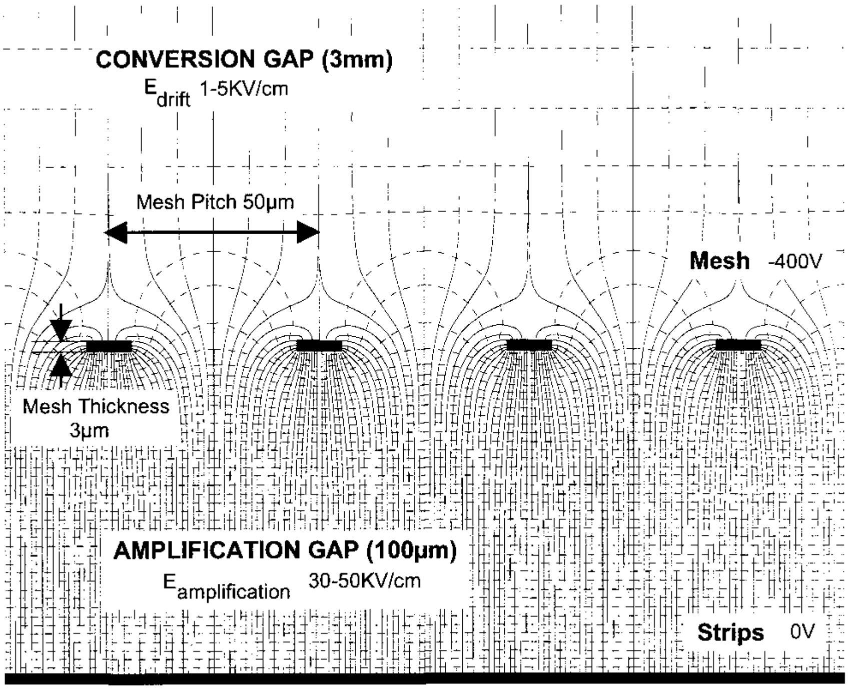

Figure 1. Map of the electric field lines around the micromesh (50 µm step, 37 µm diameter of the openings).

The electrons liberated in the conversion gap by the ionizing radiation follow these lines and are focused into the multiplication gap where amplification process takes place. The ratio between the electric field in the amplification gap and that in the conversion gap must be set at large values (>5) to permit a full electron transmission, and to reduce a part of ion cloud, produced in the avalanche, to escape into the conversion gap.

2. Advantage of the small gap

An interesting property of MICROMEGAS is that, thanks to its narrow gap, locally small variations of the amplification gap, due to, for instance, mechanical defects, do not induce gain fluctuation; they are compensated by an inverse variation of the amplification coefficient. This behavior can be explained by a simple theory :

The electron multiplication (M) in the uniform electric field between two parallel plates in a gas at a pressure p, is described by:

$$M = e^{a\,d} \qquad (1)$$

Where d is the gap of the two parallel electrodes and a is the 1-st Townsend coefficient, which represents the mean free path of the electron between two ionizations. A good approximation of this coefficient is given by Rose and Korff formula:

$$a = p\,A\,e^{-Bp/E} \quad , \qquad (2)$$

where E is the electric field and A, B are parameters depending on the gas mixture.

At high electric field values of the 1-st Townsend coefficient saturates because its value approaches the mean free path given by the inelastic collision cross-section. The electric field is E = V/d where V is the applied voltage. By substituting equation (2) in (1) we get:

$$\mathrm{Log}(M) = A\,p\,d\,e^{-Bpd/V} \quad . \qquad (3)$$

The multiplication factor M is a function of the quantity pd. Figure 2 shows M as a function of the gap (d) for a typical mixture of Ar + 5% DME, and for V=300, 350 and 400 Volts at 1 bar.

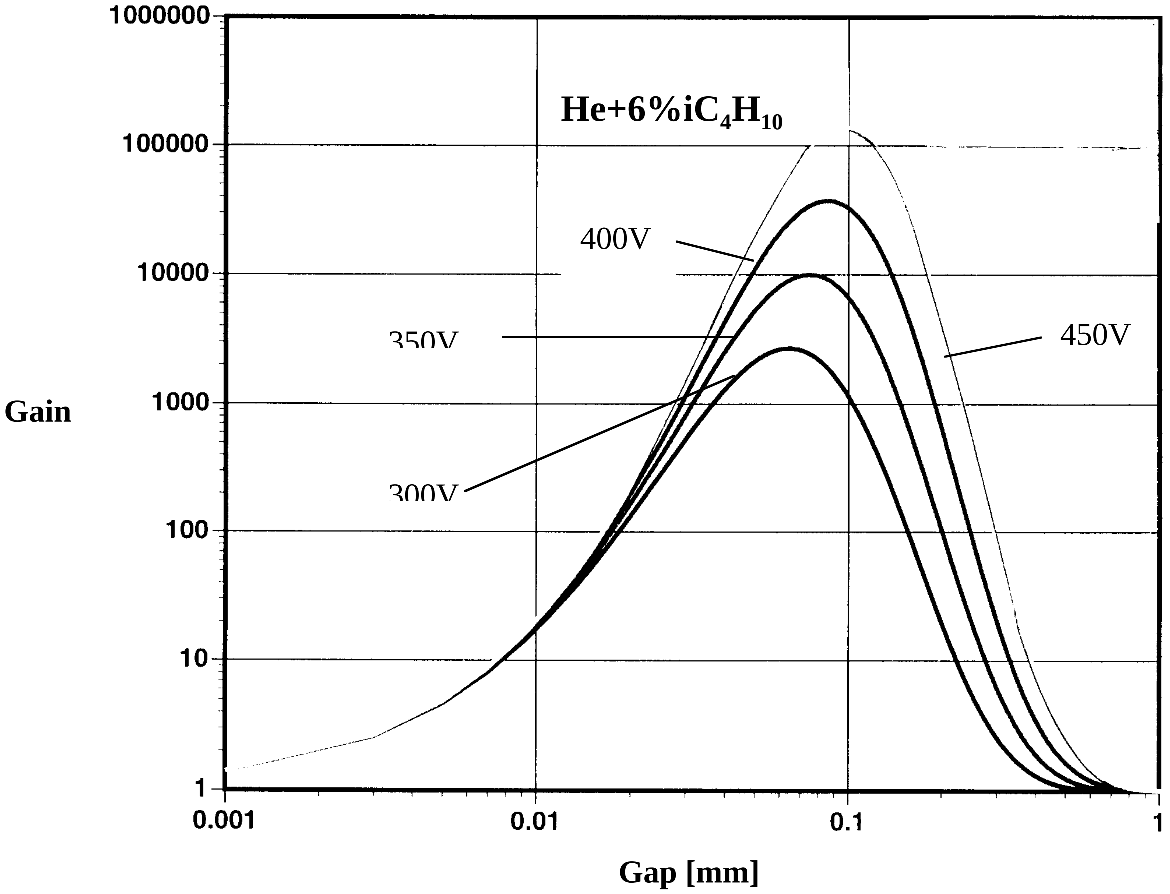

Figure 2. Calculated gas gain in He + 6% Isobutane as a function of the amplification gap for various potentials applied on the microgrid.

One can see that M rises as d increases, it reaches a maximum and then falls at large values of d. The maximum is obtained by a differentiation of the equation (3), resulting in $\Delta M/M = ad(1- Bd/V)$. The maximum value is for $d = V/B$ at $p = 1$ bar. The amplification gap chosen in this way depends slightly on the gas mixture; for a given applied potential, the multiplication factor is at maximum in the range of gaps between 30-100 microns. This is the range currently used by the MICROMEGAS detectors. In this range the multiplication factor is maximized and fluctuations due to defects of flatness of the two parallel electrodes are canceled. In few words such narrow gaps are ideal for an optimal operation of the parallel plate gaseous detectors, since all fluctuations due to mechanical defects, atmospheric pressure or temperature variations are suppressed.

It is quite difficult to verify experimentally the previous calculation, as a large variety of very narrow gaps are needed. It needs to be pointed out that this has been verified for two gaps (d=100 and 50 μm), but further work is needed to complete the study. It is much easier to verify the variation of M with pressure, which is expected to be equivalent to the gap variation.

Figure 3 shows the multiplication factor obtained from our measurements as a function of the pressure for He + 6% Isobutane for the gap of 50 microns.

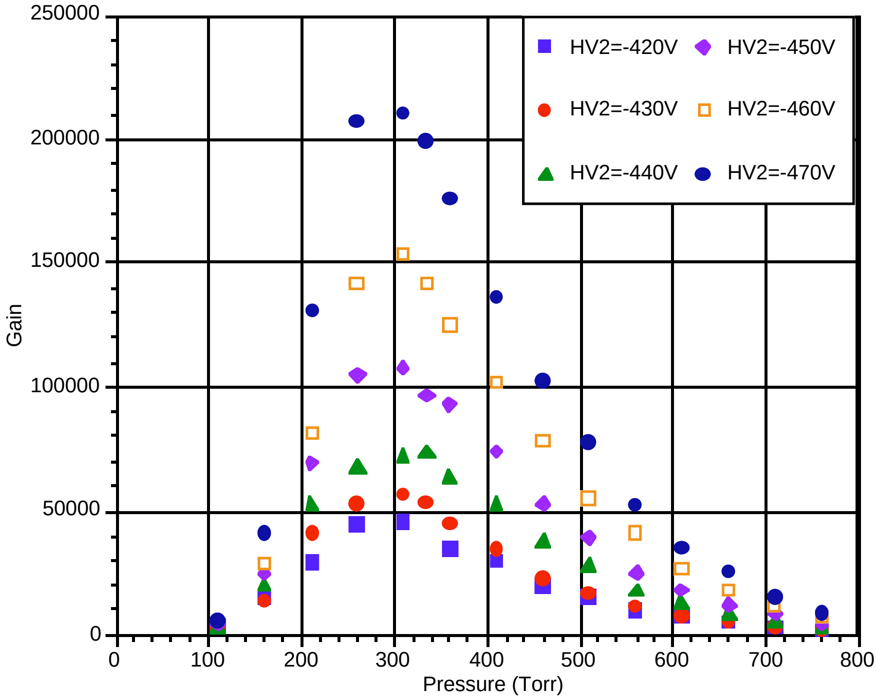

Figure 3. Measured gain in He + 6% Isobutane as function of the gas pressure for various potentials applied on the micro-grid.

The curve clearly shows that there is a maximum of multiplication at p = 500mbar. Notice that the optimal operation of a conventional parallel plate avalanche chamber (d=4 mm) is at pressures of the order of 10 mbar.

3. Gain properties

The highest gas gain obtained by a gaseous detector is a key issue for the large number of applications. In particular, a detection of minimum ionizing particles requires a large dynamic range because of the Landau fluctuation of the deposited energy and the emission of heavy ionizing particles. The goal of a "good" detector is to achieve a stable operation before the breakdown, which corresponds to a total charge per avalanche approaching 10^7-10^8 (so called Rather limit).

MICROMEGAS has been tested with a large variety of gas mixtures. Results have been published for Argon mixtures with various hydrocarbons [8,9]; the maximum safe gain is close to 10^5 with 5-10% addition of Isobutane, and three times higher with a small amount of Cyclohexane. Adding CF_4 to the previous mixtures is important, because it improves the time resolution and the total deposited energy [10]. Neon or He mixtures with hydrocarbons allow an increase of the total charge per single avalanche that approaches the highest Rather values (about 10^8).

As an example, Figure 4 shows the gas gain measured in He + 6% Isobutane mixture using single photoelectrons produced under UV illumination; the maximum gas gain reached was ~$1.8*10^7$.

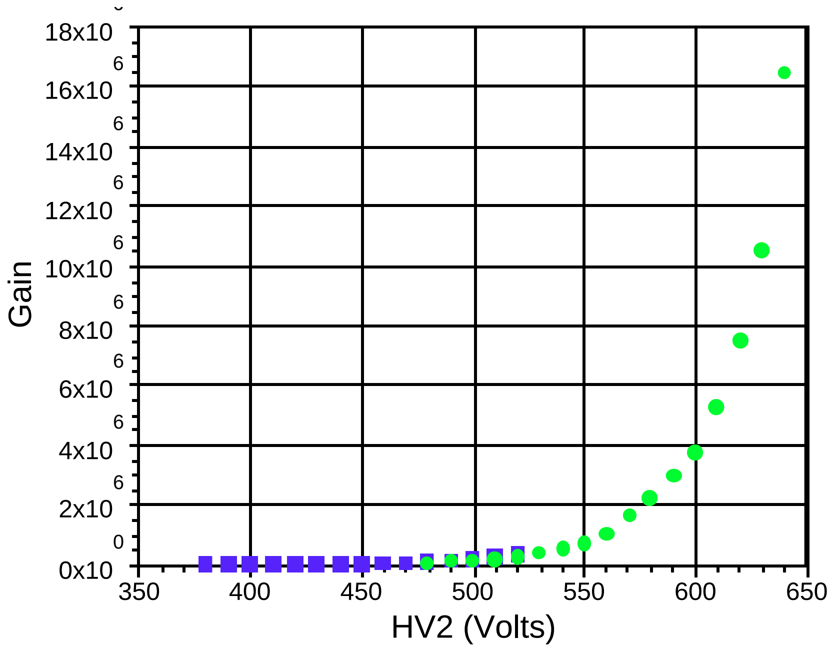

Figure 4. Gas gain measured in He + 6% Isobutane as a function of the applied potential.

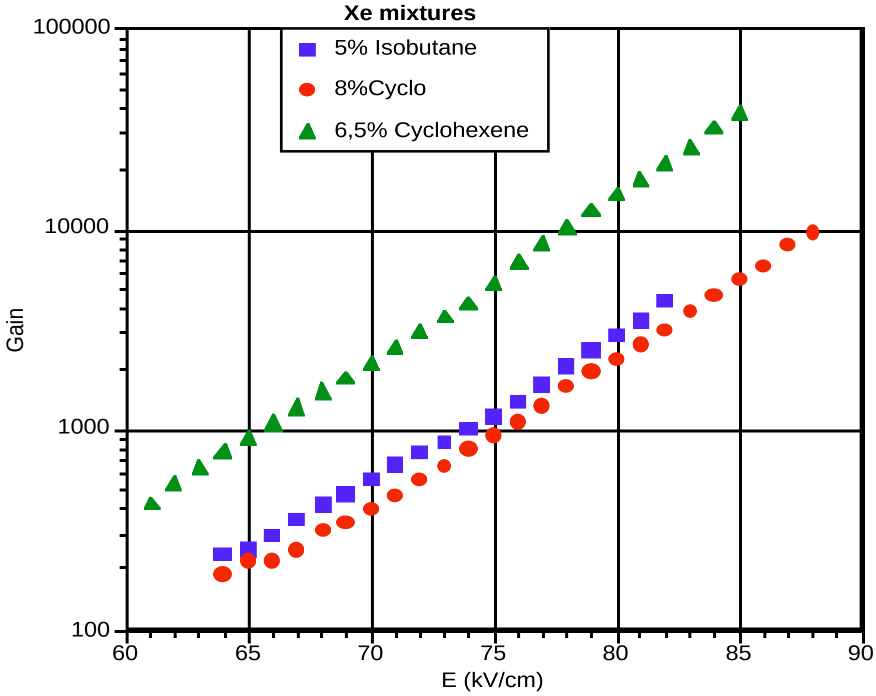

Figure 5. Gas gain measured in various Xe mixtures as a function of the applied potential.

Mixtures of high-Z gases, such as Krypton or Xenon, are relevant for many applications in X-ray digital radiography, crystallography and synchrotron radiation studies. A lot of tests have been performed in our laboratory to optimize the operation of our detector, using such gas mixtures. The general conclusion is that the maximum achievable gas gain increases with heavier hydrocarbon quenchers with lower ionization potentials. As an example, Figure 5 shows the gas gain measured as a function of the applied voltage and for various quenchers added to the Xenon carrier gas. The maximum achievable gas gain is increasing as one goes from the Isobutane (4500) to Cyclohexane (10^4), and finally to Cyclohexene (3.10^4). Such high gas gain gives the required margin factor when a detector has to cope with very-high X-ray environments, or at high-pressure operations.

6. Signal development and time resolution

A signal induced on the anode strips is a sum of the electron and ion signal. The charge signal is mainly due to the positive ion drifting to the micromesh electrode, which takes place typically within 100ns, depending on the amplification gap and the gas mixture. Figure 6 shows the preamplifier response for an Argon + 10% Isobutane gas mixture and for various gaps. A reduction of the amplification gap from 100 to 50 microns reduces the signal rise time by a factor 3. Using a gap of 30 μm the rise time is only 17ns, another reduction of a factor of two. So, in the latter case, shaping of the signal around 17ns allows to catch-up the fully induced charge and therefore permits a comfortable operation of the detector at moderate gains. One must also take into consideration that the ion collection time decreases by using higher ion mobility carrier gas (Ne or He).

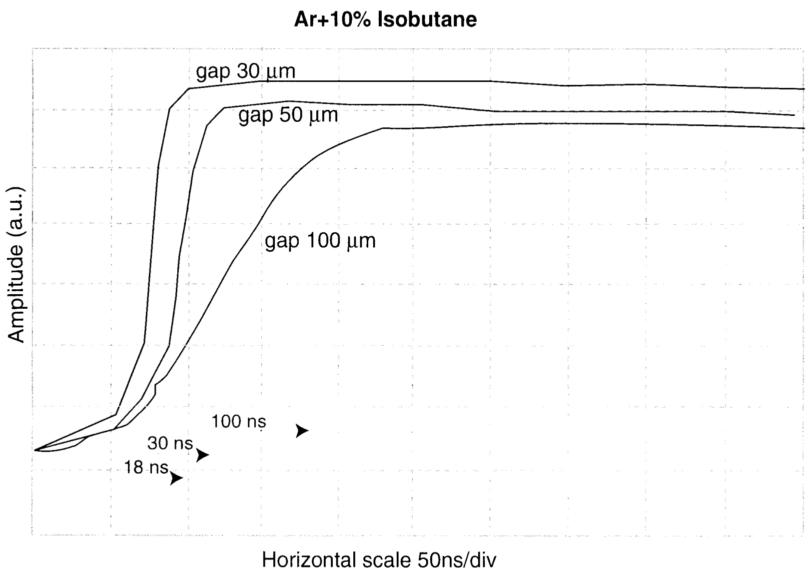

Figure 6. Signal provided by a charge preamplifier for various amplification gaps: 100, 50 and 25 μm.

The conclusion is that MICROMEGAS can be used with low-noise charge preamplifiers without loss due to ballistic deficit, which occur in other micro-strip devices; choosing the right amplification and the right gas mixture, the rise of the detector can be compatible with the shaping of the charge amplifier. Due to the faster drift velocity, the electron current is larger and faster (about 1ns instead of 100ns for the ion signal). Therefore a very fast rise of the signal, followed by a tail due to the ion drift, is expected. Such fast electron signal is quite difficult to catch, but is within reach with present electronics. For example, using the current-sensitive preamplifier with a fast rise time (t<1 ns), the result is spectacular (see Figure 7).

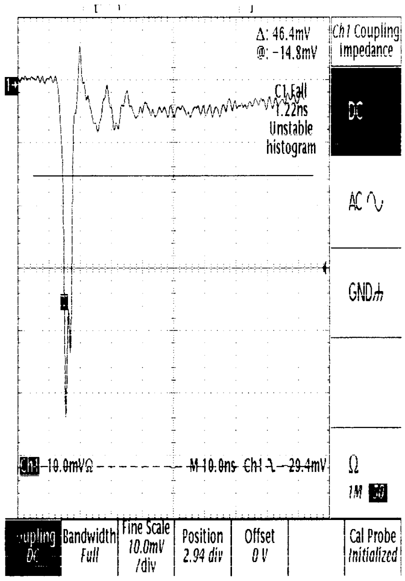

Figure 7. Fast electron signal from the current preamplifier in Ar + 10% Isobutane gas mixture. Notice that the electron signal and the ion tail are developed within 5 ns and 80 ns respectively.

The fast signal has a rise of 1ns and amplitude ten times higher than the ion tail. Such fast signals will allow the development of novel drift chambers or small TCP’s with a time resolution below 1ns.

The time resolution of MICROMEGAS was first investigated using the Lecroy-MQS104 preamplifier. The measurement showed that the time accuracy is dominated by the time-jitter of the ionization clusters produced by the minimum ionizing particles traversing the conversion gap. The best result (4.5ns) was obtained with a high drift velocity gas: a mixture of Argon, CF_4 and Isobutane. It is therefore quite logical to speculate that using CF_4 as carrier gas, a conversion depth of 1 mm and faster electronics, one can reach a time accuracy of 1ns.

7. Space resolution

Several groups, using various detector configurations, in terms of pitch, amplification gap and operating gas have investigated the space resolution. The results obtained are already published and are summarized in Table I.

The Saclay group has initially tested detectors having 317 micron pitch [8]. Accuracy of 60 µm has been measured using an Argon + DME mixture [9]. Recent results with small pitch detectors (50 and 100 µm) gave a spatial resolution of 25 µm with a mixture of He + 20 % DME, and 12 µm with a mixture of CF_4 and 20% Isobutane. The Subathec-Nantes group, using a 200 µm pitch, has measured an accuracy of 45 µm [6]. A comparable result has been obtained by the Mulhouse group using a Ne+ 10% DME gas.

The conclusion is that the accuracy of MICROMEGAS can satisfy the needs of most of the high-energy experiments for tracking purposes. Moreover, using narrow strips and low-diffusion gas fillings, the spatial resolution is closed to that of the silicon micro-strip detector. One can speculate that MICROMEGAS can be used as a micro-vertex detector close to the interaction region of particle colliders with several advantages over the silicon detector: higher radiation resistance, lower cost and lower material budget.

Table I

Resolution MICROMEGAS			
σ (μm)	PITCH (μm)	Gas mixture	Institute
80	317	Ar+10% iC_4H_{10}	Saclay
60	317	Ar+10% DME	Saclay
45	200	Ar+25% CO_2	Subatech
		Ne+10% DME	UNI-Mulhouse
24	50	He+10% DME	Saclay
12	100	CF_4+20% iC_4H_{10}	

8.Rate capability and comparison with other detectors

Many tests have shown that the rate capability of the gaseous detector strongly depends on the type of the incident particle beam. Two particular cases will be distinguished.

8.1. Rate capability with X-ray particles

This environment is relevant for applications in the medical field. Detailed results with various mixtures and various fluxes are presented in reference [11]. We have observed that gas gain does not saturate with rate, up to fluxes of 10^9/mm/s. Systematic studies in the laboratory show that the maximum achievable gas gain decreases with the flux. At a flux of $10^7/mm^2/s$ and X-rays of 8 keV energy, the gas gain is higher than 10^3, which allows a full detection efficiency.

8.2. Rate capability with charged particles.

Investigations, using high flux of incident beta particles, low energy protons or high-energy muons, have shown that the detector has a similar behavior to the X-rays, i.e., MICROMEGAS can cope with very high rates of these particles. However, undesirable effect has been observed when the incident beam is composed by high-energy hadrons: a high discharge rates proportional to the incident hadron flux.

It is believed that large ionization deposits trigger discharges. These deposits are probably released by recoil nuclei produced by charged particles, especially hadrons, traversing the detector. As ionization losses are proportional to z^2, the recoil nuclei resulted from elastic or quasi-elastic interactions, with energy in the MeV region, are quite efficient to produce heavy ionization in the gas. A typical example is a nuclear interaction on the Argon nuclei producing fully ionized Argon nuclei having a 1 MeV kinetic energy. The whole energy will be lost within 100 microns producing about 10^5 electron-ion pairs in the conversion gap. This enormous quantity of charges is again multiplied by the detector gain in the amplification gap, exceeding the Rather limit (a few 10^7), thus triggering a breakdown. Taking into account the nuclear collision length for hadrons, which is about 10^4 cm in Argon, the probability to produce such process in the conversion gap is of the order of 10^{-6}. This spark probability produces a serious limitation when the detector has to deal with very high hadron flux.

In the case of muons the corresponding cross section is several order of magnitudes lower, therefore the probability to induce sparks is negligible. MICROMEGAS has been tested with ~$5*10^7$ muons in a small area (a few cm^2) without serious loss of its performance.

It is quite important to note that in MICROMEGAS the induced sparks are not propagating in the whole area of the detector, instead they are limited in area to maximum of a few mm^2, and the duration of this phenomena doesn't exceed 100ns. The possible consequences the discharges vary from a dead time to a destruction of the electronics or even the detector itself.

Dead time

As it has been already mentioned that the discharges are local and have very low duration in MICROMEGAS. Large RC charging circuits, which can produce significant dead times, have to be avoided.

Destruction of the electronics

Several protections have been tested: protecting diodes, a small resistor or an appropriate capacitor, between the anode strip and the front-end chip, can prevent damage of the electronics.

Destruction of the detector

This is a serious problem in delicate micro-strip detectors. For example, MSGC detectors are easily damaged by the sparks, because of a presence of the insulator and thin delicate anode strips surrounded by a region of a strong electric field. Adding a preamplification stage, using, for example, a GEM structure, provides additional safety to the MSGC. However, GEM itself suffers of high capacitance, large stored charge that is dangerous when it is released: the released charge is again multiplied in the second amplification structure that can be damaged. Moreover the GEM structure consisting of million of individual multipliers is quite delicate; any short-circuit due to defects or discharges is not tolerable. In both cases, the sparking rate must be reduced to a very low level, i.e., to at most a few sparks per hour or so.

In comparison, MICROMEGAS is extremely robust; the detector has been tested with a sparking rate of 1000 sparks/s in small 1 mm^2 area. After a total accumulated number of sparks of $10^7/mm^2$ the detector was still alive without any loss of its performances.

9. Radiation resistance

Parallel plate detectors exhibit high radiation resistance. The electric field is homogeneous over the whole amplification gap and accumulation of undesirable effects, like polymerization during the avalanche process, has a little effect. The radiation resistance of the detector has been tested in the laboratory using an intense X-ray generator. With a gas mixture of Argon + 6% Isobutane, the gas gain of the detector remained stable up to a total accumulated charge of 18.3 mC/mm^2, which corresponds to about 10 years of LHC operation at the full luminosity, and at 40 cm from the interaction point [11].

10. New developments

2. **Two dimension read-out**

In High-Energy experiments, the two-dimension read-out is usually not a crucial demand, because the tracking of charged particles can be performed using several X-Y planes. In some medical applications, employing, for example, the scanner technique, one-dimensional read-out is usually sufficient. For example, anode strips pointing to the X-ray source can be used.

In some applications, however, the two dimensional read-out is mandatory. A straightforward way is to use the anode pads. Any pad size is compatible with MICROMEGAS, but a careful study of the implementation of the electronic chain is required. A drawback is the increase of the number of the read-out channels, especially when a high accuracy is required. In order to decrease the number of electronic channels, a second plane consisting of strips perpendicular to the anode strips is required. Several solutions are presently under investigation. For example, the Nantes group has investigated a solution based on strips printed on a thin 50 micron FR4 insulator on the backside [12]. These strips are perpendicular to the anode strips that are printed on the upper side of the insulator. The first attempt has shown a quite important suppression of the pick-up signal on the second strip plane. A second study used the resistive anode strips and the charge division method. Recent results obtained in a particle beam are promising. Our group is pursuing a novel way to resolve this problem: micromesh made of strips. The first results are encouraging.

2. Photo-detector

The first idea is to benefit, as it has been already discussed, from the very high gas gain obtained with He-based gas mixtures. Such mixtures have a low sensitivity to the ionizing particles and are ideal for the photon counting.

The second idea is the design of a special configuration of the photo-cathode, deposited on top of the metallic grid of MICROMEGAS, that will allow achieving high gas gains, and at the same time fully suppressing the dangerous effect of photon feedback. The first results are encouraging; the detection efficiency of single electrons is close to 100% and the time resolution in the sub-nanosecond range [13], is below 1ns.

3. Micro-TPC

The idea has been recently mentioned in the last Vienna Conference [14]. It is a new concept of a TPC-like structure, surrounding the beam pipe, mounted very close (about 1 cm) from the interaction point of a particle collider. The MICROMEGAS detector covers the two end plates of the TPC and has fine anode pads (about 200 micron) as read-out elements.

A sketch of the micro-TPC is shown in Figure 8. It illustrates a cylindrical TPC with a 10 mm internal radius, 30 mm external radius and a length of 80 mm.

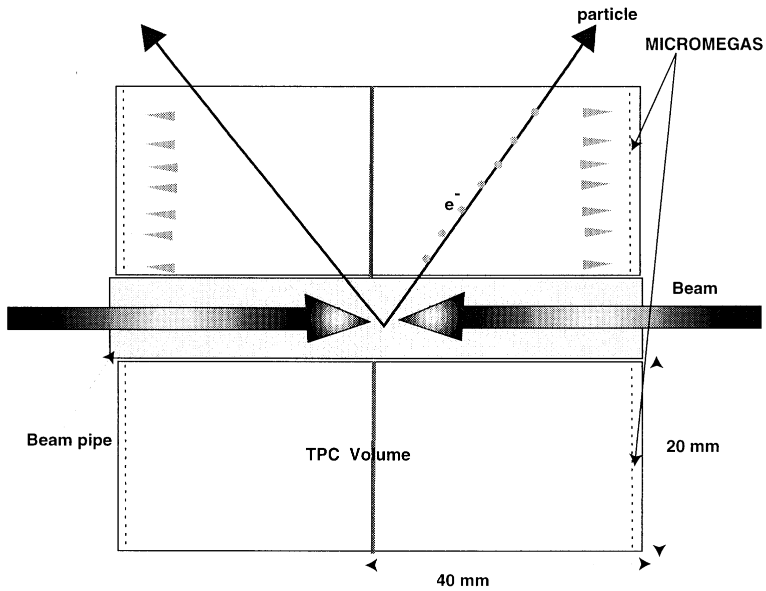

Figure 8. Schematic of micro-TPC structure read-out by a MICROMEGAS micro-pad detector.

The total drift length is 40 mm that corresponds to a maximum drift time of 32ns for CF_4 gas mixture or about 100ns for slower gas fillings (i.e. He mixtures). With a low diffusion gas mixture, crude calculations show that the spatial resolution per each detected point should be about 20 micron in the end plate and 100 micron in the middle of the TPC. Taking into account the large number of detected clusters (about 100) a mean accuracy of a few microns is expected.

Such performance exceeds by far that of the Silicon detector, where the spatial resolution is limited by the multiple scattering effect occurring in the material of the semiconductor. Moreover the high radiation resistance of MICROMEGAS offers the possibility to install the structure close to the beam pipe (in a more challenging configuration is placed inside the beam pipe), in order to improve the impact parameter resolution.

This is a good challenge for the B-meson tagging and the particle identification. Examples of possible applications are the electron colliders; especially those dedicated to B-physics. The idea can be extended to other accelerators, including the very-high luminosity hadron machines.

11. Applications

The high counting rate, the excellent time resolution and the high accuracy of MICROMEGAS combined with its low cost, radiation resistance and robustness, offer a lot of potential applications in high energy physics as well as in the domain of the X-ray imaging. We now present several examples.

11.1. COMPASS

It is a new fixed target experiment [15], recently approved by the CERN-SPS committee, with a main objective to measure the gluon polarization inside the nucleus. It uses a large 40x40 cm^2 MICROMEGAS detector for the up-stream tracking (SAT) system.

For that purpose a special electronics has been developed by the Saclay COMPASS-group, based on the low-noise charge preamplifier – discriminator followed by a multi-hit TDC. The detector equipped with the new electronics is actually under test: The first results are promising.

11.2. HELLAZ

The aim of this experiment is to measure the energy spectrum of the solar neutrinos in the low energy range, and in particular the p-p neutrino emission, by employing a high-pressure He TPC volume. Such measurement is important to clarify the puzzle that arises from present results made at higher neutrino energy: only 50% of the neutrino flux predicted by the standard solar model reaches earth.

The idea is to fully reconstruct the recoil electron produced by the elastic scattering of the incident neutrino with He gas. Using the kinematics and assuming the neutrino direction (from the sun) one can then evaluate the neutrino energy.

A major experimental deal is to detect the ionization cloud produced by the electron from the primary interaction. For that a challenging time resolution is required in order to detect single electrons close in time (σ_t<10ns). Using a small MICROMEGAS prototype and He mixture, the College de France group, has achieved the required performance [16].

11.3. TOF

It is a European collaboration for high-resolution measurements of neutron cross section [17], both fission and capture reaction, between 1 eV to 250 MeV. MICROMEGAS is proposed for two purposes :

1) Neutron detection based on the ionization produced by 3He(n,p)T reaction using a standard MICROMEGAS with a gas mixture of 3He and CF_4. The idea is to measure the beam profile and monitor the neutron fluence.
2) MICROMEGAS is used as photo-detector with CsI coating to read-out the fast component of BaF_2 scintillation light emitted around 190nm. At that wavelength the quantum efficiency of the CsI is ~15%.

The objective is to measure the multiplicity of the gammas produced by a neutron in the range of 1–8MeV. The excellent time resolution of MICROMEGAS (1ns) is of great importance in order to reject accidentals and other backgrounds.

11.4. TESLA

The use of MICROMEGAS for the future linear collider (TESLA) experiment [18] is under study by a Saclay group of physicists. The idea is to design a pad detector, placed at the end plate of the drift volume of a central TPC in order to improve its performance and reduce the ion build-up which is a basic limitation in large drift volumes.

11.5. Medical and biological applications

Biological imaging studies, such as protein crystallography, using synchrotron radiation beams, are very demanding in terms of particle flux, accuracy, robustness and fast read-out. These studies are often performed with soft X-rays [19,20], in the range of about 10keV. At higher X-ray energy, however, one requires either heavier gas mixtures or a high-pressure operation of the detector. The optimal use of the Xenon gas mixtures could be valuable.

Table II

	Measured	Ultimate
SPATIAL RESOLUTION μm (rms)	12 μm in CF_4	< 10
TIME RESOLUTION ns (rms)	4.5	< 1
ENERGY RESOLUTION at 5.9 keV (FWHM)	13%	13%
SIGNAL to NOISE for M.I.Ps	> 100	> 100
RADIATION HARD (mC/mm^2)	10 - 30 years of LHC	> 30
RISE TIME OF THE FAST SIGNAL (ns)	< 1	< 1

Another application of our detector is in medical radiology where the trend is the digital read-out technology in order to replace the photographic film, with improved sensitivity and a spatial resolution comparable to the film. Beta radiography is employed in medical and biological investigations to image human or animal tissues labeled with beta-emitting radionucleides. One approach has found industrial applications consisting of using a multi-step parallel-plate avalanche chamber coupled to an image intensifier and a CCD to read-out the UV light emitted during the avalanche development in the detector [21].

These are some examples of a large field of possible applications where the use of MICROMEGAS can simplify the construction and improve the performance in terms of accuracy and read-out speed. Table II summarizes the results obtained and the ultimate performance expected.

12. Conclusions

The main characteristics of a novel gaseous detector MICROMEGAS have been described. The measured performances of MICROMEGAS detector can be summarized by :

- High efficiency for minimum ionizing particles with large plateau has been measured.
- Spatial resolution of 12 μm has been achieved in CF_4 gas.
- A time resolution of 4.5 ns has been measured in a particle beam. Using fast current preamplifiers and CF_4 mixture, a time resolution of 1 ns is expected for minimum ionizing particle detection.
- The detector is able to cope with X-ray fluxes, as high as 10^7/mm^2/s. Similar results are obtained when ionization particles are electrons or muons. With high energy hadron beam, however, a limitation has been observed due to the production of highly ionizing particles inducing local breakdown. The detector is, however, radiation hard and can cope with a very-large amount of such discharges, without significant dead time and damage of the electronics.
- A new photo-detector using the MICROMEGAS structure was presented, giving excellent single electron efficiency (close to 100%) and time resolution below 500ps.
- A new micro-vertex suitable to measure the impact parameter with an accuracy of a few microns was proposed. It is called micro-TPC and can surround the beam pipe close to the interaction point.
- The detector is suitable for many application in physics or for high rate imaging device.

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