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Spatial Resolution in Micromegas detectors

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The performance of a telescope of Micromegas detectors has been studied in a pion beam at the CERN PS. With a gas filling of CF₄ and 20% isobutane and with a strip pitch of 100 μm an accuracy of $14 \pm 3 \mu\text{m}$ on the spatial resolution has been measured at normal incidence. A simulation demonstrates that the resolution is limited by the size of the holes of the mesh of the detector and could be reduced to 11 μm in the same conditions with smaller holes. Even further improvement down to 8.5 μm is feasible for the same gas with an optimized 75 μm strip pitch.

1 Introduction

In response to an increasing demand for a high resolution tracking detector with high rate capability, a new gas chamber, Micromegas, was introduced in 1995 [1]. Since then extensive studies were carried out both in the laboratory and in test beams. Besides the high rate capability and the excellent spatial and time resolutions, these studies have demonstrated many interesting features which are well adapted to the use of these chambers in future particle physics experiments. Large area detectors with excellent radiation resistance are easy to build with low material budget. They can easily be produced in industry. Experience has also been gained in handling discharges initiated by heavy ionizing particles following a nuclear interaction in the gas of the chamber.

In this paper we concentrate on the ultimate space resolution which can be obtained with Micromegas detectors at atmospheric pressure. The paper is or-

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ganized in the following way: section 2 describes the detectors and the experimental setup; section 3 is devoted to the electronics and the data acquisition system; section 4 presents the data analysis and the experimental result which are discussed and compared with simulation in section 5.

2 Detectors and experimental setup description

Micromegas is a parallel plate avalanche gas chamber with a single amplification stage. A detailed description, the electric field configuration and the principle of operation are given in [2,3]. It consists of a conversion and drift space which is followed by a narrow amplification gap defined by a cathode plane and an anode plane. The cathode is a Ni electroformed micromesh with square holes of $39 \times 39 \mu m^2$ at a $50.8 \mu m$ pitch (500 LPI: Lines Per Inch). The anode is a simple PCB with copper strips on an epoxy substrate. The distance between the strips and the micromesh is precisely maintained by small spacers printed on the anode strips using conventional lithography of a photoresistive polyamide film. The detectors we used for this study all have a conversion gap of 3 mm, an amplification gap of $100 \mu m$ and a 1.6 mm thick epoxy substrate.

To measure the spatial resolution a set of Micromegas detectors were installed along a 10 GeV/c pions beam on the T9 line of the CERN PS accelerator. The particles were crossing the detection planes perpendicularly and the divergence of the beam was of the order of 1 mrad. All detector planes had strips parallel to each other, so only one coordinate (y) of the track was measured. No information was available in the x direction. To reduce systematic errors due to possible misalignment of the strips (i.e. any defect in the y parallelism), the range along the unknown coordinate x was limited by a trigger scintillator of 2 cm width in the x direction. For each detector plane the amount of matter represent about 1% of a radiation length and is essentially given by the PCB epoxy thickness. At 10 GeV/c momentum, the mean deviation angle of the track due to multiple scattering through one detector is about 0.2 mrad. With a 1 mrad beam divergence and this amount of multiple scattering, an attempt to measure the spatial resolution of the studied chamber placed in between the others would fail. Large errors on the spatial resolution measurement could not be avoided: with a long lever arm the multiple scattering would dominate and with a short lever arm the error on the track angle would become too big. It is worth to mention here that in experiments where a high accuracy tracking is required, the amount of material could be reduced if a thin epoxy sheet (down to $100 \mu m$) or a kapton foil is glued on top of a honeycomb light structure.

To overcome this difficulty we have adopted a doublet configuration. Two Micromegas detectors were mounted back-to-back at a distance of 10 mm. To

provide an unambiguous reconstruction of the track and a precise measurement of its angle, at least two other detectors have been used with a total arm length of about half a meter. The spatial resolution is determined from the difference of the positions (centroid of the cluster of adjacent hit strips) measured in each plane of the doublet which is corrected by the track angle. The error on this difference due to multiple scattering is of the order of $2\text{ }\mu\text{m}$. Furthermore, as we will demonstrate later on, the measurement error in Micromegas never exceeds $50\text{ }\mu\text{m}$. So the error due to the track angle correction is less than $1\text{ }\mu\text{m}$. These two sources of error will be neglected in the determination of the accuracy of the spatial resolution.

The chambers we used to track the incident particles have an active area of $14 \times 12\text{ cm}^2$ with a strip pitch of $317.5\text{ }\mu\text{m}$ ($70\text{ }\mu\text{m}$ inter-strip space), leading to a reasonable number of 384 read-out strips. The spacers are small cylinders of $200\text{ }\mu\text{m}$ diameter, $100\text{ }\mu\text{m}$ high and set every 2 mm .

The doublet of chambers used to investigate the spatial resolution have a strip pitch of $100\text{ }\mu\text{m}$ ($50\text{ }\mu\text{m}$ inter-strip space). However the active surface was reduced to $5 \times 4\text{ cm}^2$ in order to keep the same number of read-out channels. The spacers have an oval shape, $100\text{ }\mu\text{m}$ long and $50\text{ }\mu\text{m}$ large, to fit the strip width. They are disposed every $600\text{ }\mu\text{m}$ along every sixth strips. The spacers cover about 17 % of the corresponding strip or about 3 % of the total active area. This is a safe configuration, although not optimized with respect to dead space.

One early measurement was also performed with a special doublet with strips deposited on glass at a pitch of $50\text{ }\mu\text{m}$ with a smaller active area and the same number of read-out channels.

3 Electronics and data acquisition system

The read-out chip we used is the CMOS Gassiplex chip developed at CERN [4]. It consists of a charge sensitive preamplifier with a gain of 7 V/pC , followed by a CR-RC shaper, together with a track-and-hold circuit, which stores the analog information coming from each of the 16 input channels of the chip. This information is then multiplexed to one single output in synchronization with an external clock. We used a special PCB card containing 6 of these chips (96 channels altogether), each channel of the board being chained on the same output. Each strip is AC coupled to the Gassiplex input through a protection circuit. This protection against occasional sparks consists of a $1\text{ M}\Omega$ resistor to the ground, a decoupling capacitor of 100 or 47 pF to limit the size of the discharge, two diodes mounted back to back and a second capacitor of 1 nF . This protection is really useful. On some cards both diodes were

plugged by mistake with the same direction and the protection of these cards against the undershoot of very high signals was therefore no more ensured; as a consequence, a few chips died during the data taking, inducing dead spaces on the detector. The whole setup allows a maximum external clock frequency of 1 MHz. This frequency was however set to 30 kHz because of the speed limitation of our CAMAC data acquisition system.

The shaper reaches its maximum 400 ns after a particle has hit the detector. This delay fits the trigger signal delay (due to the cables length and the processing by electronic modules). The total electronic noise we expect for such a peaking time is 700 ENC plus 25 ENC per pF of the detector capacitance. The measurement of this noise on an operational detector gave us a value of 1000 electrons.

The output signal of each card was fed into FERA's (4300B Lecroy ADC's having 16×12 bits input channels and 2048 bins, with a sensitivity of 0.25 pC per bin). These modules were read out through a CAMAC interface by a 1 Mwords HYTEC processor, which was driven through a Sparrow crate controller SCM-301 by the data acquisition computer (a Power Macintosh 8500/180). The data were then stored on a permanent device (1 or 2 Gb disks) for later off-line analysis. The data acquisition, storage management and on-line analysis were achieved with the Kmax acquisition program.

4 Analysis and results

The first step of the analysis consists in determining for each channel the pedestal distribution. This is done after subtraction for each Gassiplex card of the correlated noise. For the 100 μ m doublet used for the spatial resolution measurement, the average rms width of the pedestal distributions is equal to 5 ADC units, equivalent to 1000 electrons (ENC) as expected. Then for each plane, clusters of adjacent channels with a signal above 3 pedestal standard deviations are formed. Dead channel are identified and listed.

To study the efficiency of one detector of the doublet, the incident track is reconstructed in the other chambers. When its intercept with the studied detector is close to a dead region, the track event is abandoned, otherwise the track is used to determine the efficiency. The efficiency is defined as the fraction of tracks for which the residual between the extrapolated intercept and the closest cluster position is less than 0.5 mm. The efficiency depends on the operating conditions, specially the voltage set on the micromesh. But even at high gain it also depends on the position of the track with respect to the spacers. Fig. 1a and 1b show typical efficiency responses of each doublet detector as a function of the position (y) of the track intercept. The local loss,

at a level of 20% seen every sixth strips, corresponds to the strips which hold the spacers and is compatible with the area of the spacers. Later on such an area around a spacer will be considered as a dead space. Note that this affects less than 3% of the total active area. This effect could have been reduced by at least a factor 2 by reducing the size of the spacers.

The detection efficiency increases with the voltage set on the micromesh until a saturation close to 100% is reached. This happens when the most probable value of the signal to noise ratio is larger than 15. The signal to noise ratio S/N is here defined as the total collected cluster charge S divided by the mean strip noise N .

To determine the spatial resolution, we select data for which the detectors are fully efficient.

4.1 *The CF_4 -isobutane gas mixture*

Among all gases investigated, the best spatial resolution was obtained with a CF_4 80% and iC_4H_{10} 20% as quencher, gas mixture. In such a mixture a 10 GeV/c pion produces an average of 50 primary charges in the 3 mm conversion gap. With a 1000 electrons noise a gain as low as 300 is in principle sufficient to reach full efficiency. Typical distributions of the total cluster charge collected on strips are shown on Fig. 2a and 2b for each of the two detectors of the doublet. They are well fitted by a Landau type distribution. The corresponding cluster size distributions are shown on Fig. 2c and Fig. 2d. They peak around a cluster size of 2 which is not the most suitable situation to get with the centroid of the cluster a good estimation of the position of the intercept of the track in the detectors as will be discuss in the next section.

Fig. 3a shows the distribution of the difference between the two cluster centroids for a track detected in both chambers of the doublet. This difference has been corrected for the track angle as measured by the other chambers. The distribution is well fitted by a gaussian with a standard deviation of $17\ \mu\text{m}$. If one assumes that both chambers of the doublet have the same resolution and that the centroids measurements are not correlated, one can estimate the spatial resolution of one chamber to be: $17\ \mu\text{m}$ divided by $\sqrt{2}$, which is $12\ \mu\text{m}$. A discussion on this point at the light of our simulation is given in the next section.

Although the resolution is insensitive to the gain of the chamber, it improves by 30 % when the electric field in the drift gap increases from 0.5 to 1.5 kV/cm. To get the best resolution, a field of at least 1.5 kV/cm has to be applied in the drift space. This observation is related to the behavior of the transverse diffusion in the gas. A similar effect has been observed [5] for the longitudinal

diffusion.

4.2 Other gas mixtures

The spatial resolution of Micromegas has also been studied for other gas mixtures. For comparison with the above results, the corrected position difference distribution in a doublet operated with our standard gas mixture Ar-isobutane (90%,10%) is shown in Fig. 3b. The measurement shows a clear degradation of the accuracy which is $42.5 \mu\text{m}$ (standard deviation divided by $\sqrt{2}$).

Table 1 summarizes all the results obtained with a doublet of detectors. For each gas mixture we give the measured resolution and the transverse diffusion coefficient. The transverse diffusion coefficient results from an adjustment in our simulation to reproduce the charge and cluster size distributions shown by the data.

The spatial resolution improves when the amount of quencher is increased in the gas mixture and the amount of CF_4 is large. The best result was obtained with CF_4 as carrier gas. With isobutane as quencher the mixture combines a low transverse coefficient (as long as the drift field is higher than 1.5 kV/cm) and a high primary ionisation.

Table 1
Micromegas spatial resolution

Gas Mixture	Measured Resolution (μm)	Transverse Diffusion Coefficient ($\mu\text{m}/\sqrt{\text{cm}}$)	Strip pitch (μm)	Drift Field (kV/cm)
Ar + 10% iC ₄ H ₁₀	42.5	370	100	1.0
He + 6% iC ₄ H ₁₀ + 5% CF ₄	35	180	100	1.8
He + 6% iC ₄ H ₁₀ + 10% CF ₄	30	160	100	1.8
He + 20% DME	25	130	50	1.0
CF ₄ + 20% iC ₄ H ₁₀	18	170	100	0.4
CF ₄ + 20% iC ₄ H ₁₀	11	100	100	2.7

5 Monte-Carlo simulation and discussion

5.1 The simulation

A detailed Monte-Carlo simulation of the detector has been developed. It includes a description of the electromagnetic interaction of the incident particle with the gas and the production of primary pairs of charges. However delta rays production and recoils following nuclear interactions have been neglected. The migration of electrons to the amplification gap, the development of the avalanche and the formation of the induced signal on the strips is fully simulated assuming that all field lines end on the top of strips. Electronic noise is added to the charges on the strips. The Monte-Carlo contains two free parameters: the amplification gain and the transverse diffusion coefficient. These are adjusted to reproduce respectively the charge and cluster size data distributions. The agreement with the data which is shown in Fig. 2 for our best measurement with CF₄-isobutane is quite good.

Three effects contribute to the spatial resolution: 1) the transverse diffusion in the gas for which the adjusted coefficient is $100 \mu\text{m}/\sqrt{\text{cm}}$; its effect on the resolution is equal to $8.0 \mu\text{m}$, which is given by the mean dispersion of the electrons in the 3 mm drift space ($56.4 \mu\text{m}$) divided by the square root of their mean number (50); 2) the pitch of the strips inducing a error in the calculation of the centroid of cluster which is estimated by our Monte-Carlo program to be equal to $7.5 \mu\text{m}$. The quadratic sum of these two effects is equal to $11.0 \mu\text{m}$; 3) the pitch of the mesh, an effect which was not foreseen before the measurements. It was demonstrated by the simulation and will be discussed below. Its consequence is that the resolution in one chamber depends on the position of the track as long as the relative position of the mesh with respect to the strips is not known.

5.2 Systematic effects due to the pitch of the mesh

The following discussion is an analytical interpretation of the simulation. First note that the pitch of the mesh holes, $50.8 \mu\text{m}$, is close to one half of the $100 \mu\text{m}$ strips pitch. Let's call p_s the pitch of the strips and p_g the pitch of the mesh holes. The simulation showed that the current which is induced on the strips by the moving charges behaves as if there was no space between each strips. We therefore assume in the following calculation that the strip width is equal to the strip pitch p_s , as if each strip could touch its neighbors.

We then define $\delta = y_{\text{mesh}} - y_{\text{strip}}$, the distance between the center of a hole and the beginning of the nearest strip (see Fig. 4). Because of the periodicity

of the basic cell, consisting of a strip and two mesh holes, we restrict our computation to $0 \leq \delta \leq p_g$. We should now stress the fact that because of the electric field configuration around the holes, drift electrons produced in front of a given hole will then be collected in the center of this hole. If the strips and the holes are aligned (i.e. $\delta = \frac{p_g}{2}$), this does not matter: a given strip will collect all the drift charges that are really produced in front of it. But if not, electrons that are produced between the end of the strip we consider and the end of the hole (between δ and $\frac{p_g}{2}$), will also be collected on this strip, although they were produced in a region lying in front of the next strip. As a consequence, the measured position of the track that produced such electrons will be shifted by a quantity equal to p_s .

If tracks within one cell are uniformly distributed along the y coordinate, the fraction of such shifted track measurements among all tracks is:

$$f = \frac{\epsilon(\frac{p_g}{2} - \delta)}{p_s} \quad (1)$$

where ϵ is the sign of $(\frac{p_g}{2} - \delta)$,

and the mean shift on the track coordinate is given by:

$$y_{\text{meas}} - y_{\text{track}} = (y_{\text{track}} + \epsilon p_s) f + y_{\text{track}} (1 - f) - y_{\text{track}} = \frac{p_g}{2} - \delta \quad (2)$$

Now, in addition, we have to take into account the smearing due to the extension σ of the avalanche. This extension is due to the transverse diffusion in the gas. Our simulation shows that the barycenter of the avalanche is close to 1/4 of the amplification gap above the strip plane and the extension is equivalent to a diffusion on a path of 25 μm . That gives a standard deviation σ equal to 5 μm .

As σ is small with respect to p_g , we can neglect the smearing at a distance from a hole greater than p_g , and the previous equation becomes:

$$y_{\text{meas}} - y_{\text{track}} = \frac{p_g}{2} - \delta - p_g \frac{CL(\delta)}{2} + p_g \frac{CL(p_g - \delta)}{2} \quad (3)$$

where

$$\frac{CL(x)}{2} = \frac{1}{\sqrt{2\pi}\sigma} \int_x^\infty e^{-\frac{u^2}{2\sigma^2}} du$$

The two last terms in the previous equation correspond to the smearing due to the avalanche extension issued from the two holes which are in front of a

strip. One term is for the hole close to the beginning of the strip, the second for the hole close to the end of the strip. They correspond respectively to the mean shift in the track position on the left side (first term) or the right side (second term) for the fraction $\frac{CL(\delta)}{2}$ or $\frac{CL(p_\ell - \delta)}{2}$ of the avalanche which hits on the left or the right neighbor strip.

The result is shown on Fig. 5. Note that the mean of the systematic error is null on the total range of δ . With the 500 LPI mesh we have a systematic error on the position of the track which can be as big as $14 \mu\text{m}$. The effect is greatly reduced if the pitch of the mesh is a factor of two smaller (1000 LPI). Since the pitch of the mesh is not exactly a sub-multiple of the pitch of the strips δ changes from cell to cell. The period of the recurrence is 6.35 mm. As we reconstruct tracks in a range of about 2 cm, we can consider δ as randomly distributed. In that condition, the systematic mean quadratic error is equal to $9.6 \mu\text{m}$.

To evaluate the resolution in one detector, we measure the difference of the reconstruction points in a doublet of chambers. In that case we can write:

$$y_{mesh2} - y_{strip2} = y_{mesh1} - y_{strip1} + (y_{mesh2} - y_{mesh1}) - (y_{strip2} - y_{strip1})$$

or, with the same notation as previously:

$$\delta_2 = \delta_1 + \delta_c$$

with

$$\delta_c = \Delta y_{mesh} - \Delta y_{strip}$$

As the two detectors are the same, δ_c is a constant, independent of the track position. A shift δ_1 in the first detector for a track at y_1 is associated with a shift δ_2 in the second detector at the translated position $y_1 + \delta_c$. So the shift in the first detector, $y_{meas1} - y_{track}$, for a track at y_1 corresponds to a shift in the second detector at a position which is translated by a constant. And the difference, $y_{meas2} - y_{meas1}$, is affected by a systematic error which is the difference between these two shifted track positions as shown on Fig.6a for different values of δ_c . By randomizing δ_1 (and the correlated δ_2), we get the expected resolution on the difference as shown on Fig.7.

5.3 About the experimental result

The simulation has demonstrated that the error on the difference $y_{meas2} - y_{meas1}$ is equal to the quadratic sum of $15.6 \mu\text{m}$ ($\sqrt{2} \times 11.0 \mu\text{m}$) with a sys-

tematic error which depends on the track intercept (which corresponds to any value of δ_c). The experimental result, $17\text{ }\mu\text{m}$, corresponds to a misalignment of the mesh and strips of the second detector with respect to the first one. This misalignment can be evaluated (Fig.7) to $5\text{ }\mu\text{m}$. As a conclusion and as long as we do not know the relative position of the mesh with respect to the strips, the spatial resolution in a detector is the quadratic sum of $11.0\text{ }\mu\text{m}$ with a systematic error running from 0 to $14\text{ }\mu\text{m}$, leaving a quadratic mean value of $9.6\text{ }\mu\text{m}$. We can summarize by saying that the measured spatial resolution is $14 \pm 3\text{ }\mu\text{m}$. Note that with a 1000 LPI mesh, Fig. 5, Fig. 6b and Fig. 7 show that the effect of the mesh is highly reduced and become negligible compared to the diffusion or strip pitch contributions.

5.4 *The simulated dependence of the spatial resolution accuracy with the track angle*

By simulation we estimate the accuracy of the spatial resolution with the incident track angle on the detector plane (0 degree at normal incidence). With CF_4 (80%) and isobutane(20%) as gas mixture, 3 mm of drift space, $100\text{ }\mu\text{m}$ of strip pitch, and a 1000 LPI mesh, the simulated accuracy on the spatial resolution grows from 11 to $70\text{ }\mu\text{m}$ when the track angle increases from 0 to 10 degree of incidence as shown on Fig.8a. An improvement can be obtained by reducing as much as possible the drift space without a significant loss of the efficiency. The Fig.8b indicates that a drift space as small as 0.75 mm could give an efficiency greater than 0.98, whereas with 0.5 mm the efficiency does not exceed 0.96. One can conclude that for a drift space of 0.75 mm we combine a high efficiency and a limited degradation of the resolution with the track angle, as shown on Fig.8a. Compared with the 3 mm case, the resolution is better at large angles but worse at small angles. So the choice of the depth of the drift space is crucial and experiment dependent.

6 Conclusion

With Micromegas, the best spatial resolution which has been obtained so far for tracks at normal incidence is $14 \pm 3\text{ }\mu\text{m}$. Such a spatial resolution is a world record for a gaseous detector at atmospheric pressure. This result was obtained with a CF_4 -isobutane (80%,20%) gas mixture and an electric drift field higher than 1.5 kV/cm . With such a gas, the accuracy was limited by the pitch of the micromesh. Under the same conditions, we expect that the use of a 1000 LPI mesh instead of the 500 LPI would have given a resolution of $11\text{ }\mu\text{m}$. Our simulation predicts that further improvements are still possible. With an optimized strip pitch of $75\text{ }\mu\text{m}$ and a gain of 2000, the mean cluster

size would be 3 and the resolution $8.5 \mu\text{m}$. Even better accuracy could be reached with the same gas mixture under pressure. At 2(4) bars, with a strip pitch of 50(35) μm , a drift gap of 3 mm and a 1500(2000) LPI micromesh, a resolution of 4.5(2.5) μm at normal incidence is expected.

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Figure captions

Fig.1 The detection efficiency of a) Det1 and b) Det2, the two detectors of a Micromegas doublet, as a function of the track intercept y .

Fig.2 The charge response, in ADC units, of a) Det1 and b) Det2. The line is the Landau distribution fit, the points are the result of our simulation. The corresponding cluster size of c) Det1 and d) Det2.

Fig.3 The difference between the intercept of tracks in the two detectors of a Micromegas doublet for a gas mixture of a) CF_4 and Isobutane b) Argon and Isobutane. The fitted lines are gaussian distributions.

Fig.4 The basic detector layout for the simulation.

Fig.5 The simulated average systematic error on the track intercept in a detector as a function of the position of the mesh (500 and 1000 LPI) with respect to the strip.

Fig.6 The simulated average systematic difference of the intercepts of tracks in the two detectors of a Micromegas doublet as a function of the relative position of the mesh and strip in one detector for different relative positions

of the mesh and strip in the other one, in case of a a) 500 LPI b) 1000 LPI mesh.

Fig.7 The simulated error on the difference of the intercepts of tracks in the two detectors of a Micromegas doublet as a function of the position of the mesh and strip in one detector with respect to the other one, in case of a 500 LPI and 1000 LPI mesh.

Fig.8 Simulation of a) the resolution as a function of the incident track angle b) the efficiency as a function of the amplification gain, for different drift gaps.

Fig. 1

80% CF₄ + 20% Isobutane, strip-pitch = 100 μ m

Fig. 2

Fig. 3

Fig. 4

Systematic error in a detector (100 μm strip pitch)

Fig. 5

Systematic error in a Doublet ($100\mu\text{m}$ strip pitch)

Fig. 6

Fig. 7

Fig. 8