Performances of a resistive MicroMegas module for the Time Projection Chambers of the T2K Near Detector upgrade

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Abstract

An upgrade of the Near Detector of the T2K long baseline neutrino oscillation experiment, ND280, has been proposed. This upgrade will include two new Time Projection Chambers, each equipped with 16 resistive MicroMegas modules for gas amplification. A first prototype of resistive MicroMegas has been designed, built, installed in the HARP field cage, and exposed to a beam of charged particles at CERN. The data have been used to characterize the performances of the resistive MicroMegas module. A spatial resolution of 300 µm and a deposited energy resolution of 9% were observed for horizontal electrons crossing the TPCs at 30 cm from the anode. Such performances fully satisfy the requirements for the upgrade of the ND280 TPC.

Keywords:

1. Introduction

T2K (Tokai To Kamioka) is a long baseline neutrino oscillation experiment [1] taking data since 2010 in Japan. An intense beam of muon neutrinos or antineutrinos is produced at the J-PARC accelerator complex (Tokai) and measured twice, at a distance of 280 m from the production target with the near detector complex (ND280) and at a distance of 295 km with the water Cherenkov detector, Super Kamiokande (SK).

The combined measurement of the neutrino spectra before and after oscillations allowed to observe for the first time the appearance of electron neutrinos in the muon neutrino beam [2, 3] and recently provided first hints, at 2 σ Confidence Level, of charge-parity (CP) violation in the lepton sector by comparing $\nu_\mu \rightarrow \nu_e$ and $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ oscillation probabilities [4].

The ND280 detector used for these analyses consists of a $\pi^0$ detector (P0D) [5] which is based on water and scintillator materials with the main purpose to measure neutral current events and a tracker complex with two fine grained detectors (FGD) [6] and three time projection chambers (TPC) [7] designed to measure charge, momenta and particle identification for leptons and hadrons produced in neutrino interactions. The P0D and the tracker are surrounded by an electromagnetic calorimeter (ECAL) [8] which is enclosed in the former UA1/NOMAD dipole magnet. In addition, Side Muon Range Detectors (SMRD) [9] are embedded in the iron yokes of the magnet.

To improve the measurements of oscillation parameters, and in particular observe CP violation with more than 3σ CL, a continuation of the physics
run beyond 2021, named T2K-II, has been proposed by the collaboration.

The T2K-II proposal consists of an upgrade of the beam power from 485 kW to 1.3 MW \textsuperscript{[10]} and an upgrade of the current Near Detector complex \textsuperscript{[11]}.

For the ND280 upgrade it is foreseen to remove the P0D and to replace it with a new tracker system consisting of a Super Fine Grained Detector (SuperFGD), two horizontal TPCs and a Time-of-Flight (TOF). The upgraded detector will have twice the target mass of the current FGDs, will improve the detection efficiency for leptons emitted at large angles with respect to the neutrino beam direction and will allow for a better reconstruction of the hadronic part of the interaction, thanks to the superior granularity of the SuperFGD.

For the horizontal TPC a new readout system, based on the Resistive Micromegas technology is foreseen. This novel technology will be used for the first time in a full size experiment and is expected to provide better performances in respect of spark resistance and either point resolution or reduction of electronics channels. However, for the usage in ND280, the ionization energy loss (dE/dx) capabilities of the resistive Micromegas for different particles with momenta below 1 GeV/c has to be verified.

In order to test these capabilities, a resistive MM prototype was designed, constructed and exposed to various charged particles in a testbeam at CERN and the performances are described in this paper. In Sect. \textsuperscript{2} we describe the resistive Micromegas module that was used for the test beam reported in Sect. \textsuperscript{3}. The track reconstruction algorithms are shown in Sect. \textsuperscript{4} and in Sect. \textsuperscript{5} we discuss the gas quality during the test beam.

In Sect. \textsuperscript{6} and \textsuperscript{7} we show the uniformity of the gain of the Micromegas and we characterize the charge spreading induced by the resistive plane. Finally Sect. \textsuperscript{8} and Sect. \textsuperscript{9} are devoted to the observed performances in terms of deposited energy and spatial resolution.

2. Resistive MicroMegas

The well known 'bulk' technology for building Micromegas detectors \textsuperscript{[12]} is used for the existing TPCs taking data as part of the ND280 detector since 2009. It provides an easy and robust manufacturing, with very limited dead area, the mesh being fixed on the whole detector surface between two arrays of cylindrical pillars. The result is a permanent dust-tight assembly, for dust particles down to 10 $\mu$m size.
An improvement with respect to this technology, the Resistive Anode, has been developed for a Linear Collider (LC) TPC, where the position resolution requires charge sharing between pads [13]. In the case of T2K, the resolution in reconstructing neutrino energy is limited by the Fermi motion of nuclei inside the nucleus, thus reducing the benefits of an improved spatial resolution. Nevertheless, resistive Micromegas for T2K will allow to keep the original spatial resolution capabilities by using fewer and larger pads, thus reducing the number of electronics channels.

The resistive anode provides mainly two advantages: by spreading the charge between neighbouring pads it improves greatly the resolution with respect to the pitch/$\sqrt{12}$ provided by a mere hodoscope, and it suppresses the formation of sparks and limits their intensity. A further and novel improvement of this technique is a new High Voltage powering scheme, where the mesh is set to ground while the anode is set to a positive amplification voltage. The insulation of the resistive anode from the pads, hence from the electronics, allows a safe operation by a capacitive coupling readout, thus allowing to get rid of the cumbersome anti-spark protection circuitry necessary in the case of the standard bulk readout. Another advantage of the anode encapsulation is that the detection plane is fully equipotential, as the grounded mesh is at the potential of the detector frame and supporting mechanics. This allows a better uniformity of the electric field, especially near the module edges, and minimizes track distortions. Moreover, it provides more flexibility in the operation, allowing the High Voltage on a module to be different from the neighbours without degrading the drift field uniformity. Even if a module has to be disconnected this does not affect the drift field. The goal of this test beam was to demonstrate that the encapsulated scheme with grounded mesh was functional. In parallel, a multi-module test of this technique with the LC TPC design demonstrated the suppression of the distortions [14] [15].

The Micromegas used for the test beam was developed on the basis of the already existing Micromegas PCB used in the present ND280 TPC. This module has a sensitive area of $36 \times 34 \ cm^2$ and is covered by pads of $0.98 \times 0.70 \ cm^2$. The thickness of the PCB is 2.2 mm and comprises three layers of FR4 with blind vias in the inner layer. The top conductive layer forming the anode pad plane is made of 25 $\mu m$ thick copper deposited on FR4. The other conductive layers are used for the routing network, grounding and pad-readout connectors. The pad surface was covered by a 200 $\mu m$ insulating layer acting as the capacitance, and then a 50 $\mu m$ kapton (Apical) with a
thin Diamond-Like-Carbon (DLC) layer. The resistivity was 2.5 MΩ/□. On top of this surface, a bulk Micromegas was built, with a 128 µm amplification gap. The electronics used was the same that had been developed for the T2K TPCs and is based on the AFTER chip [10].

3. Experimental setup

3.1. The setup

During the test beam, the resistive Micromegas module was installed in the HARP field cage. A detailed description of the HARP field cage can be found in [17]. A cylindrical volume of 2 m long and 0.8 m diameter host the drift volume. The drift distance is 1.5 m. The field cage is made by Stesalit with a double interleaved strip pattern to avoid electric field inhomogeneities and high field gradients. A foil of individual aluminized Mylar strips has been glued inside the cylinder, and an aluminium foil has been glued onto the outside surface.

The cathode is at one extremity of the field cage and at about 50 cm from the edge of the external cylinder. On its rear holes it hosts calibration sources. During the TPC operation a voltage of 25 kV have been applied to the cathode generating an electric field in the drift volume of 167 V/cm. On the extremity opposite to the cathode a circular flange close the cylinder where the Micromegas MM0 is installed.

The TPC has been operated using a premixed gas with Ar : CF4 : iC4H10 (95:3:2) which is the same mixture used for the existing ND280 TPCs. A simple gas system with only one line has been set up to operate the detector. Before starting the data taking the TPC has been extensively flushed with Nitrogen gas. Later it has been flushed with the gas mixture for several hours (3 or 4 times the volume of the TPC) to remove impurities. During normal operation the gas flux was kept of about 25 litres/hours. Temperature measurement on the exhaust line were taken to monitor environmental condition which might induce a difference in the electron drift velocity and thus on the performances of the detector.

3.2. The trigger

Test beam data were taken using the T9 beamline with copper target to have an “hadron enriched beam configuration”. The breakdown of the beam composition as a function of the momentum is shown in Figure [1]. Positively charged tracks were used for the analyses presented in this paper.
The beam composition at low energies is largely dominated by electrons and positrons. The use of copper target allows to reduce the contamination by about a factor of 8.

Figure 1: Breakdown of the beam composition as a function of the momentum for hadron enriched beams at the T9 area at CERN.

Charged particles have been tagged using three plastic scintillator detectors called respectively S1, S2, S3 and two Cherenkov detectors called C1 and C2. Figure 2 shows a cartoon of the locations for those detectors along the beamline. The selection for the different particle types have been done by the combination of the NIM signals coming from those detectors. A summary of the different options is presented in Table 1.

Figure 2: Sketch of the detectors used to tag the particles from the beam and set up trigger selections. The beam is coming from the left.

To trigger on cosmic rays going through the TPC two scintillator plastic panels have been positioned on the top and the bottom of the TPC. The surface is coated with reflective paint and two grooves are made to host fibres. The readout is done at one side with Hamamatsu MPPC while the
other end-side of the fibres is made reflecting. Plastic bars are installed inside aluminum boxes to get good light-tightness conditions.

<table>
<thead>
<tr>
<th>Particle</th>
<th>Selection</th>
</tr>
</thead>
<tbody>
<tr>
<td>Positrons</td>
<td>Scintillators + Cherenkov</td>
</tr>
<tr>
<td>Protons (+Kaons)</td>
<td>S1(delayed) * S2 (delay proton TOF between S1 and S2)</td>
</tr>
<tr>
<td>Pions (+ muons)</td>
<td>Scintillators protons * positrons</td>
</tr>
<tr>
<td>Cosmic ray</td>
<td>From the scintillators panels (only out of spill)</td>
</tr>
</tbody>
</table>

Table 1: Summary of the different signal combinations to tag the different particle types coming from the beam.

3.3. Collected data

In the standard condition, the Micromegas was operated with a voltage of 340 V. The settings chosen for the AFTER chip were a sampling time of 80 ns, a shaping time of 600 ns and a gain of 120 fC.

The results described in this paper were obtained with proton, pion and electron triggers with momenta of 0.8 GeV/c and at three different drift distances (10, 30 and 80 cm).

In addition we performed a scan of the MM voltage that was varied from 330 to 380 V and we took data with a 1 GeV/c pion trigger with different voltages applied to the detector (360 and 380 V). Finally also the shaping time was varied to 100 ns and 200 ns.

During all the beam data taking period we were continuously collecting data with the cosmic trigger. In addition a radioactive source of $^{55}$Fe has been positioned at the cathode to have a reference point for energy calibration.

4. Track reconstruction

As described in the previous section, different types of data were collected at the same time, including cosmics, beam, and an $^{55}$Fe source. A simple 3D track reconstruction algorithm was developed in order to remove noise and distinguish between cosmics and beam tracks. The reconstruction takes the pads at the beginning and at the end of the module and associates all the hits along a straight line. Such algorithm showed enough purity for beam and cosmic track separation and also for removal of noise and hits due to the $^{55}$Fe source. An example of reconstructed tracks is shown in figure 3.
We also considered the selection based on the 3D matching algorithm DBSCAN [18] (fig. 4). Both selections provide similar results in terms of number of reconstructed tracks and performances for point and energy resolution.

Figure 3: The example of the track selection algorithm performance, that is based on the track start and end position matching.

Figure 4: Example of the DBSCAN 3D matching algorithm performance. The time is expressed in units of 80 ns.
5. Gas quality

The gas quality has been analyzed after the data taking by measuring the drift velocity and the electron attenuation length.

5.1. Drift velocity

The drift velocity can be computed by using the arrival time on the Micromegas of cosmic tracks crossing the cathode or the anode, as shown in Fig. 5a. The different amount of tracks at each end was caused by the significantly lower acceptance of the cosmic trigger for tracks close to the anode.

The evolution of the drift velocity as a function of time is shown in Fig. 5b. We observed a smooth reduction of the drift velocity during the data taking, until we reached a point where the end of the chamber could no longer be seen in the acquisition window. This limit velocity depends on the electronics sampling rate and on the available time bins and it has been computed to be 4.45 cm/µs.

The observed reduction of the drift velocity is probably due to the presence of contaminants, such as O$_2$ and H$_2$O, absorbed by the TPC field cage while it was stored in air.

These contaminants were efficiently removed at the beginning of the data taking, while the gas flow inside the TPC was 60 litres per hour (L/h). The removal was less efficient at the end of the data taking, since the gas flow was reduced to 30 L/h (25 L/h) after 30 hours (35 hours) of run.

5.2. Attenuation length

The presence of contaminants on the gas is also expected to attenuate the signal. The gas quality can be studied by measuring the signal attenuation as a function of the drift distance.

Vertical cosmic tracks at different drift distances have been selected. At each distance, the average measured charge has been computed and the resulting distribution fitted with an exponential function as presented in Fig. 6a. The so-obtained attenuation length, as a function of the run time is shown in Fig. 6b.

The precision on the measurement of the attenuation length is limited by the low acceptance for cosmic tracks close to the anode, nonetheless, a reduction of the attenuation length is observed, indicating the progressive growth of the contaminants, as observed also from the measurement of the drift velocity shown in Sect. 5.1.
Figure 5: a) Time distribution of tracks crossing the end caps of the chamber for a set of 25k triggers. b) Drift velocity time evolution, the dashed blue line is set at the minimum measurable value.

Figure 6: A) Average charge versus drift time for 2 sets of data taken at the beginning and at the end of the test beam period. B) Evolution of the signal attenuation length during the data taking.
6. MicroMegas gain

The Micromegas gain and its uniformity are key elements for successful particle identification in the TPC. The gain of the resistive Micromegas module was measured with a $^{55}$Fe source, emitting 5.9 keV gammas, installed at the center of the cathode. The uniformity of the gain was measured with cosmic tracks.

6.1. Time evolution of the gain

To measure the gain a $^{55}$Fe source was placed on a transparent mylar foil window on the cathode. This radioactive source has a characteristic photon emission at 5.9 keV, as shown in Fig. 7a. A resolution of about 8.9% was obtained, allowing to observe also the 2.9 keV escape line in argon.

This value is obtained with a source at a distance of $\sim 1.5 \text{ m}$ from the Micromegas module and cannot be directly compared with the results for bulk Micromegas shown in [7], obtained with -350 V on the Micromegas and with the source placed close to the read-out plane and hence not affected by distortions or by electron attachment.

The dependence of the gain and of the resolution on the Micromegas voltage, ranging from -330 V to -380 V is shown in Fig. 7b and Fig. 7c. The gain grows exponentially with the voltage with values for the absolute gain ranging from 500 to 2500 and the resolution improves. The voltage scan, however, was performed at the end of the test beam, when the gas quality was lower, affecting both the gain and the energy resolution. To have a reference, the data from Fig. 7a taken at -340 V and at the beginning of the data taking is also shown.

The evolution of the absolute gain, for data taken with a Micromegas voltage of -340 V is presented in Fig. 7d. A decrease of the gain of $\sim 10\%$ during the data taking was observed, likely due to the growth of oxygen contaminants that absorb part of the electrons in the avalanche process.

6.2. Gain uniformity

The iron source cannot be used to study the uniformity of the gain, since it illuminates only the central pads of the module.

The uniformity of the gain, however, can be assessed by selecting vertical cosmic tracks, crossing the whole module, and looking at the average charge on each pad. As it will be also described in Sect. 8, a better estimator of the gain is the truncated average of the charge per pad, obtained by retaining
Figure 7: a) X-ray energy spectrum. The energy resolution at 5.9 KeV is 8.9%. b) Micromegas gain for different micromesh voltages. c) 5.9 KeV resolution for different micromesh voltages. d) Time evolution of the gain during the data taking.
only a certain fraction of measurements with lower charge. For the study presented in this section, a truncation fraction of 0.7 was used to compute the truncated mean.

The distribution of the mean and of the truncated mean for all the pads is shown in Fig. 8. Except for the pads at the edge of the Micromegas, that have roughly half of the gain, due to their smaller size, the gain uniformity is better than 3%. By taking the truncated mean (Fig. 8b), it is also possible to recognize different regions on the module with slightly different gains, as shown in Fig. 9. This could be due to non-uniformities of the resistive plane or to electronics routing and it shows that the intrinsic Micromegas gain uniformity is at the 1% level.

7. Characterization of charge spreading

As described in Sec. 2, the resistive Micromegas technology produces a spreading of the collected charge into neighboring pads. This is a novelty with respect to the ND280 TPCs. The charge spreading can be clearly observed in the signal waveforms of adjacent pads, as shown in Fig. 10. The charge spreading phenomenon which drives the waveform shape is described in [19].

The pads adjacent to the one collecting most of the charge contain a signal smaller in amplitude and longer in time. In order to characterize the size and the timing of the signal spread, we considered nearly horizontal tracks selected with pion trigger, as described in Sec. 3. A cluster is defined
as the ensemble of the pads on the same column (row in case of vertical tracks). In Fig. 11 the pad multiplicity per cluster and the fraction of charge in the pad with largest signal ($q_{\text{max}}/q_{\text{cluster}}$) are shown. Most of the clusters are formed by 2 or 3 pads and the pad with largest signal contains typically 80% of the total collected charge.

Fig. 12 shows the difference in peak time between the leading pad and the other pads. The delay of the charge spreading can be up to few µs for columns with signal above the threshold in 3 pads.

In Fig. 12 the time difference between the leading and the second (third) pad is also shown as a function of the fraction of signal in the leading pad. Such fraction is a proxy for the position of the track and can be exploited to extract an estimation of the velocity of the charge spreading. A large fraction corresponds to a charge deposition in the middle of the leading pad. Decreasing the fraction corresponds to move closer to (away from) the second (third) pad. In the limit of large charge fraction in the leading pad the difference in time peak between the second and the third pad should converge to the same value, which corresponds to the time needed by the charge to spread along half a pad. From these consideration, an effective charge spreading velocity of about 0.6 cm/µs can be extracted.
Figure 10: Signal waveforms in the three leading pads 600 ns shaping time. The total area of each waveform is normalized to one. The value of each time bin is 80 ns.

Figure 11: Multiplicity of the clusters (left) and fraction of the cluster charge which is collected in the pad with largest signal (right). The histogram for pion, electron and proton clusters are normalized to the same area.
Figure 12: Distribution of peak-time differences between pads, for different cuts on the fraction of charge in the leading pad. Top left (right): difference between the leading and the second (third) pad in 3-pads clusters. Bottom left: difference between the leading and the second pad for 2-pads clusters. Bottom right: peak of the time difference distributions as a function of the cut value. The time is measured with a granularity of 80 ns. The error bars corresponds to two time-bins.
8. Deposited energy resolution

The TPCs are pivotal to perform particle identification in ND280. The PID method is based on the measurement of the energy loss by a charged particle in the gas. In the existing ND280 TPCs, the deposited energy resolution for a minimum ionizing particle crossing two Micromegas modules is $\sim 8\%$. In this section the performances of the resistive Micromegas module are evaluated for different particle types.

The method used to estimate the energy loss in the TPC is the truncated mean method: the clusters of each track are ordered as a function of the charge, and only a fraction of them with the lowest charge is used to compute the mean deposited energy. As shown in Sect. 6, clusters on the edge of the Micromegas have a smaller gain and are removed from the computation of the truncated mean.

The impact of the truncated mean method on the deposited energy resolution is shown in Fig. 13a. The best resolution is obtained for values of truncation fraction between 50\% and 70\%. For the results presented in this section, a truncation factor of 62.5\% was used, corresponding to retaining 21 measurements for tracks with 34 clusters.

The deposited energy distribution for different triggers is presented in Fig. 14a. The double peaked spectrum of the distribution with pion trigger
indicates a low purity on the selected tracks since a large fraction of them were positrons. Fig. 14b shows the deposited energy for pion triggers taken with different drift distances. After applying corrections to account for the different gain and attenuation lengths (see Sect. 6 and 5) the deposited energy spectrum is not affected by the drift distance, as it is also shown in Fig. 15.

Deposited energy resolutions ranging from 9.0% to 11.2% were obtained. These measurements cover drift distances up to 85 cm, close to the maximal drift distance of the TPCs in the upgraded ND280 (90 cm). In the horizontal TPCs for the ND280 upgrade, tracks moving perpendicular to the beam direction are expected to cross two Micromegas modules. A larger number of measurements will then be available for each track and this will improve the deposited energy resolution.

To extrapolate the expected deposited energy resolution to the whole TPC, we measured the deposited energy resolution as a function of the number of clusters used to compute the truncated mean. The distribution for positrons is shown in Fig. 16. The curve is fitted with

$$\frac{\sigma(dE/dx)}{(dE/dx)} = A n^B$$  \hspace{1cm} (1)

Where $n$ is the number of clusters. The fitted values of $A$ and $B$ are shown in tab. 2 for different drift distances and confirm that, with two Micromegas modules a resolution of $\sim 7\%$ is expected.

### 9. Spatial resolution

As mentioned above, the main advantage of the TPC with the resistive anode is improved transverse spatial resolution while keeping the same pad size [13]. We performed the analysis using collected data and estimated the accuracy of the transverse position for different particle types at various drift distances.

<table>
<thead>
<tr>
<th>trigger</th>
<th>momentum [GeV/c]</th>
<th>drift distance [cm]</th>
<th>$A$</th>
<th>$B$</th>
</tr>
</thead>
<tbody>
<tr>
<td>positron</td>
<td>0.8</td>
<td>80</td>
<td>51.9 ± 2.9</td>
<td>−0.46 ± 0.02</td>
</tr>
<tr>
<td></td>
<td>0.8</td>
<td>30</td>
<td>47.5 ± 2.6</td>
<td>−0.45 ± 0.02</td>
</tr>
<tr>
<td></td>
<td>0.8</td>
<td>10</td>
<td>46.2 ± 2.5</td>
<td>−0.44 ± 0.02</td>
</tr>
</tbody>
</table>

Table 2: Values of $a$ and $b$ for different triggers.
Figure 14: a) Energy deposited for three different triggers. The particles crossed the chamber at 30 cm from the Micromegas module. b) Energy deposited using pion trigger at 10, 30, and 80 cm drift distance.

Figure 15: Deposited energy resolution for 0.8 GeV/c positrons, pions, and protons at different drift distances. The total drift distance of the new ND280 horizontal TPCs will be 90 cm.

9.1. Pad Response Function method

Due to charge spreading in time discussed in Sect. 7, the simple weighted mean of the pad position (Center Of Charge, CoC) will not give an accurate
position. A better estimator of the position is obtained by using the Pad Response Function (PRF), defined as

$$\frac{Q_{pad}}{Q_{cluster}} = PRF(x_{track} - x_{pad})$$  \hspace{1cm} (2)

where $x_{pad}$ is the pad center, $Q_{pad}$ is the charge on the pad and $Q_{cluster}$ is the total charge on the cluster containing the pad.

To parametrize the PRF we used the ratio of two symmetric 4th order polynomials proposed in [20]:

$$PRF(x, \Gamma, \Delta, a, b) = \frac{1 + a_2x^2 + a_4x^4}{1 + b_2x^2 + b_4x^4}$$  \hspace{1cm} (3)

The coefficients $a_2$ and $a_4$, and $b_2$ and $b_4$ can be expressed in terms of the full width half maximum $\Gamma$, the base width $\Delta$ of the PRF, and two scale parameters $a$ and $b$.

To infer the position of the track, we minimize the $\chi^2$ between $Q_{pad}/Q_{cluster}$ and $PRF(x_{track} - x_{pad})$:

$$\chi^2 = \sum_{pads} \frac{Q_{pad}/Q_{cluster} - PRF(x_{track} - x_{pad})}{\sqrt{Q_{pad}/Q_{cluster}}}$$  \hspace{1cm} (4)

The analysis was performed in several iterations. In the first iteration the CoC method is used to extract the track position. Then, based on the

![Figure 16: Deposited energy resolution versus number of clusters for positrons at 30 cm of drift distance.](image)
CoC, the track is fitted with a straight line. The PRF scatter plot is filled and the distribution of $Q_{pad}/Q_{cluster}$ is obtained for each bin in $x_{track} - x_{pad}$. The peak and the full width half maximum are then taken as estimator of $Q_{pad}/Q_{cluster}$ and its uncertainty. This procedure is shown in Fig. 17.

![PRF scatter plot and distribution](image)

Figure 17: PRF from the pion 1 GeV/c sample with 30 cm drift distance with 360 V at MM: a) 2D histogram, b) example of the 1D histogram for $x_{track} - x_{pad} = -0.5$, c) final PRF plot with errors and fit with analytical function.

With this method the PRF function is estimated with the CoC method as a prior. Since this prior could be far from the $x$ position, we repeated the procedure for several iterations. At each iteration, the analytical formula from the previous step is used to estimate the track position and then a new fit is performed. We observed the improvement of the fit in the first few iterations, while the fit quality does not improve further after about 5
iterations.

The spatial resolution is defined with the residuals $x_{\text{track}} - x_{\text{fit}}$ for each cluster. The obtained distribution is fit with a Gaussian and the $\sigma$ is considered as the final accuracy. The improvements obtained with the PRF method with respect to the CoC method are shown in Fig. 18: a spatial resolution at the level of 300 $\mu$m is observed for horizontal tracks over the whole Micromegas.

![Figure 18: Comparison between PRF method (red line) and CoC method (blue line). a) sigma of the residual as a function of the column number, b) mean of the residual as a function of the column number.](image)

Figure 18: Comparison between PRF method (red line) and CoC method (blue line). a) sigma of the residual as a function of the column number, b) mean of the residual as a function of the column number.

![Figure 19: Spatial resolution as function of the tangent of the angle in the detector plane for cosmics. The CoC method is used to compute the spatial resolution](image)

Figure 19: Spatial resolution as function of the tangent of the angle in the detector plane for cosmics. The CoC method is used to compute the spatial resolution.
The spatial resolution performances are expected to depend on the angle of the track with respect to the Micromegas pads. This is due to the fact that ionization fluctuations increase the variance of charge sharing for tracks at an angle to pad boundaries. Such behavior cannot be tested with test beam data, since mostly horizontal tracks were produced, and we investigated it using cosmics. The dependence of the spatial resolution on the angle in the detector plane, using the CoC method, is shown in Fig. 19. Due to the limited geometrical acceptance of the cosmic trigger described in Sect. 3, only tracks with drift distances comprised between 50 and 100 cm and with angles between 0 and 20 degrees could be used for this study. The difference with respect to beam tracks, for which the resolution with the CoC method is 590 $\mu$m at 80 cm, is due to the smaller pad length in the vertical direction (0.7 cm) with respect to the horizontal direction (1.0 cm).

9.2. Dependence of spatial resolution on the drift distance

The spatial resolution is expected to be affected by the drift distance, since tracks with larger drift distances will be more affected by transverse and longitudinal diffusion. The average spatial resolution for pions, positrons and protons at different drift distances is shown in Fig. 20 and, as expected, the spatial resolution is worst for long drift distances. The dependence of the resolution on the particle type can be explained with the different energy loss through the ionisation. Higher energy deposition causes larger charge spreading resulting in higher cluster multiplicity. As a result with a higher number of pads per cluster the track position could be reconstructed more precisely.
9.3. Dependence of spatial resolution on the Micromegas voltage

Finally we studied the spatial resolution for different Micromegas voltages. These data were taken only with 1 GeV/c pion trigger at drift distance of 30 cm.

The higher voltage provides larger amplification of the signal. That is helpful for detection of the small charges at the edge of charge spreading. This is shown in Fig. 21 where the number of pads in each cluster is shown for different voltages. The spatial resolution for different voltages is shown in Fig. 22. The spatial resolution improvements was reached with the PRF method, while the CoC method shows the result degradation.
Figure 21: Pad multiplicity for different Micromegas voltages for 1 GeV/c pion sample with 30 cm drift distance.
Figure 22: Spatial resolution versus the voltage at the Micromegas for 1 GeV/c pion sample with 30 cm drift distance. Blue line corresponds to the CoC method, red line corresponds to the PRF method. The summary is shown with PRF method.

10. Conclusions

In this paper we showed the performances of a resistive Micromegas module installed in the HARP field cage and exposed to a beam of charged particles at CERN, with momenta ranging from 500 MeV/c to 2 GeV/c. The Micromegas had an excellent uniformity of the gain and the data were used to characterize the properties of the charge spreading process of the collected charge.

The performances of the Micromegas in terms of spatial resolution and deposited energy resolution have been evaluated and found to be satisfactory for the TPCs that will be built for the upgrade of the T2K Near Detector.
Thanks to the resistive anode a spatial resolution of 300 $\mu m$ for horizontal electrons at 30 cm drift distance was measured while for the dE/dx we observed a resolution of 9% for positrons of 800 MeV/c by using 34 measurements of the charge.

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References


