

Analysis of test beam data taken with a prototype of TPC with resistive Micromegas for the T2K Near Detector upgrade

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Abstract

In this paper we describe the performance of a prototype of the High Angle Time Projection Chambers (HA-TPCs) that are being produced for the Near Detector (ND280) upgrade of the T2K experiment. The two HA-TPCs of ND280 will be instrumented with eight Encapsulated Resistive Anode Micromegas (ERAM) on each endplate, thus constituting in total 32 ERAMs. This innovative technique allows the detection of the charge emitted by ionization electrons over several pads, improving the determination of the track position.

The TPC prototype has been equipped with the first ERAM module produced for T2K and with the HA-TPC readout electronics chain and it has been exposed to the DESY Test Beam in order to measure spatial and dE/dx resolution. In this paper we characterize the performances of the ERAM and, for the first time, we compare them with a newly developed simulation of the detector response.

Spatial resolution better than $800\ \mu\text{m}$ and dE/dx resolution better than 10% are observed for all the incident angles and for all the drift distances of interest. All the main features of the data are correctly reproduced by the simulation and these performances fully fulfill the requirements for the HA-TPCs of T2K.

Keywords: Resistive Micromegas, T2K Near Detector Time Projection Chambers

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1. Introduction and physics motivations

T2K is a long-baseline neutrino oscillation experiment that is taking data in Japan since 2010 [1]. By using an intense muon neutrino beam produced at the J-PARC accelerator complex and searching for the appearance of electron neutrinos at the far detector, Super-Kamiokande, T2K provided the first indications of θ_{13} mixing angle being different from zero [1] followed by the first measurement of neutrino oscillations in appearance mode [2]. Recently first hints of Charge-Parity (CP) violation in the leptonic sector were also published by T2K [3].

In order to confirm these hints, T2K is now preparing the second phase of the experiment, that includes an upgrade of the neutrino beamline [4] and of the off-axis Near Detector complex, ND280 [5].

ND280 is a magnetized multi-purpose detector with several sub-detectors installed inside the UA1/NOMAD magnet that provides a magnetic field of 0.2 T. The core of ND280 is a tracker system, composed by two Fine Grained Detectors (FGDs) [6] and three Time Projection Chambers (TPCs) [7] instrumented with Bulk Micromegas modules [8]. The TPCs are used to track charged particles emitted in neutrino interactions and to measure their charge and momentum as well as to perform particle identification based on the ionization energy losses in the gas. The ND280 has been extensively used in all T2K oscillation analyses and it allows a reduction of systematic uncertainties to the level of 4–5% [9]. These uncertainties mostly come from our limited knowledge of neutrinos interactions with nuclei, and of the neutrino beam properties (energy spectrum and composition).

An upgrade of ND280 is being constructed [10], with the goal of further reducing these systematic uncertainties [11]. It consists in replacing one of the ND280 sub-detectors, the P0D, with a new tracker system composed by a 3-dimensional scintillator target (Super-FGD) [12], made of ~ 2 millions of 1 cm^3 scintillator cubes each readout by three wavelength shifting fibers, two High Angle TPCs (HA-TPCs) and six Time-Of-Flight (TOF) planes [13]. Among other improvements, this upgrade, that will be installed at J-PARC in 2023, is expected to have a better efficiency to reconstruct high angle and backward going tracks (with respect to the incoming neutrino direction) emitted in neutrino or antineutrino interactions thanks to the presence of the HA-TPCs. As for the already existing ND280 TPCs [7], the main goals of the two new HA-TPCs are the charged track reconstruction (to measure particle momentum) and the particle identification. This requires a good

spatial resolution on the reconstructed tracks and a precise ionization energy loss measurement.

Each endplate of the HA-TPC will be instrumented with 8 Encapsulated Resistive Anode Micromegas (ERAM). The first ERAM detector produced for ND280-Upgrade was initially tested using an X-ray test bench at CERN and then mounted on a prototype of the field cages that are being constructed for the HA-TPCs. This field cage prototype has the same construction materials, the same drift length and the same strip foils configuration to produce a uniform electric field as the cages that are being constructed for the ND280 Upgrade. Also the final front-end electronics chain that will be used for the HA-TPCs, including two Front-End-Cards (FEC) each hosting eight AFTER chips [14], and one Front-End-Mezzanine (FEM) both equipped with their cooling plates, was mounted on the field cage. The FEM was connected to a Trigger and Data Concentrator Module (TDCM) [15] used for the data transfer to a DAQ computer via a MIDAS [16] front-end.

The TPC prototype was placed at the DESY T24/1 facility [17] inside a large-bore superconducting solenoid, called PCMAG, that provides a magnetic field of up to 1.25 T and it was exposed to an electron beam with momenta between 1 and 4 GeV/c. As we will show in this paper, this test beam campaign allowed to validate the performances of the TPCs for tracks with different incident angles with respect to the ERAM detector and for all the drift distances of interest for the T2K TPCs. With respect to the results presented in [18], the ERAM performances are also compared with a simulation that has been developed by using the ND280 software, adding the HA-TPCs ERAM geometry and the features of the resistive layers and of the AFTER chip electronics response.

This paper uses similar methods as those described in Refs. [18, 19] to analyse the test beam data, and the new results are consistent with the previously published ones. Some main changes should also be stressed:

- The field cage of the TPC prototype uses the same materials as the future HA-TPC and moreover, the maximal drift distance (~ 1 m) is much larger than the short drift distance of previous prototypes.
- The readout electronics is the same as the one of the final HA-TPC, and the response of the electronics has been studied and understood accurately.
- A Monte-Carlo simulation of ERAM response is now available and

74 agrees well with the data. This is new compared to previous analy-
 75 ses based only on data. This simulation is crucial as a tool to validate
 76 our understanding of the detector. It will be also crucial for future
 77 physics analysis with the upgraded ND280.

78 As it will be shown in the rest of this paper, the ERAM detector allows
 79 to reach an excellent spatial resolution, below 800 μm for all the incident
 80 angles and drift distances, and an excellent dE/dx resolution, below 10% for
 81 tracks crossing the entire ERAM module. These performances are in good
 82 agreement with the ones predicted by the simulation that is able to reproduce
 83 both, low level variables, such as the charge sharing between neighboring pads
 84 or their time difference, as well as the spatial and the dE/dx resolution.

85 The paper is organized as follows. Section 2 introduces the ERAM tech-
 86 nology and its use for the HA-TPC prototype. Section 3 presents the exper-
 87 imental setup. The simulation of the ERAM response is described in Sec-
 88 tion 4. Section 5 is devoted to the characterization of the ERAM detector.
 89 The data collected during the DESY test beam are presented in Section 6,
 90 while Section 7 provides a description of reconstruction algorithms. Section 8
 91 is devoted to a comparison of ERAM response between data and simulation.
 92 Spatial and dE/dx resolutions are presented in Sections 9 and 10, respec-
 93 tively, while Section 11 discusses a comparison between the data and the
 94 simulation. A study of the $E \times B$ effect is presented in Section 12. A short
 95 discussion on further potential improvements is given in Section 13. The
 96 conclusions in Section 14 close the paper.

97 **2. The ERAM technology and its use for the HA-TPC prototype**

98 The ERAM technology, initially developed for the ILC prototypes [20],
 99 allows the detection of the charge induced by ionization electron on one
 100 pad (“leading pad”) over several adjacent or “neighbour” pads; this induced
 101 charge signal as a function of time or “waveform” that can be predicted.
 102 Combining the information from these signals on different pads forming a
 103 “cluster”, allows us to improve the spatial resolution, and hence the deter-
 104 mination of the momentum of charge particles. Different ERAM prototypes
 105 have been tested at CERN [19] and at DESY [18] to characterize the ERAM
 106 response at short drift distances for tracks parallel to the ERAM detector
 107 plane, but with different angles compared to the pads borders. Tracks parallel
 108 (resp. inclined) to the horizontal borders of the pads are called “horizontal

109 tracks” (resp. “inclined tracks”) throughout this paper. Fig. 1 illustrates
 110 some typical waveform signals on pads of a cluster transverse to a horizontal
 111 track.

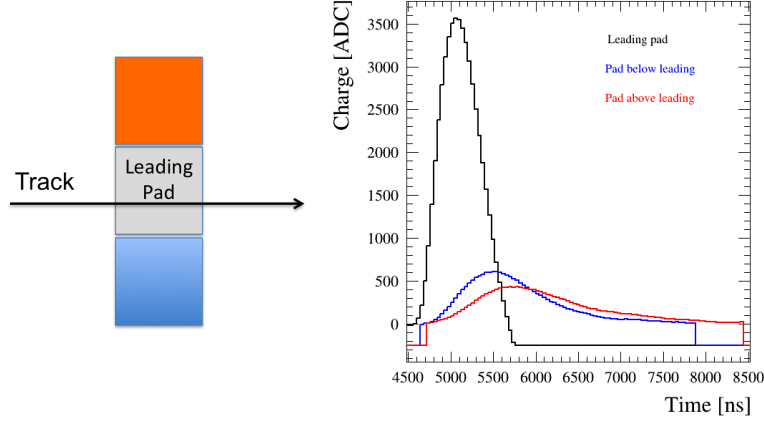


Figure 1: A schematic view of a column cluster (left) and the waveforms of each pad composing this cluster (right) for 412 ns shaping time of the electronics.

112 In the analyses of previous test beams at CERN [19] and at DESY [18],
 113 as well as in this paper, similar methods are used to reconstruct tracks. They
 114 are based on the maximal amplitudes of the waveforms in the pads of the
 115 clusters. Clusters of pads are defined as aligned transverse to horizontal
 116 tracks as in Fig. 1, or according to different and more precise topologies for
 117 inclined tracks. Each cluster allows to reconstruct a point or a “hit” of a
 118 track. A spatial resolution refers to the average accuracy of the position of
 119 one hit along a track. Studies are underway aiming at using simultaneously
 120 the full information of the waveforms of all the pads around the tracks in a
 121 global fit, to improve the track reconstruction accuracy. But a more simple
 122 approach is a robust reference for further studies, and can already show that
 123 the detector performances meet the physics requirements of the experiment.
 124 The results of these test beams allowed to validate the ERAM design and
 125 start the production of the 32 ERAMs that will be used to instrument the
 126 HA-TPCs.

127 The large drift distance available in the TPC prototype under tests, which
 128 is similar to the one of the final HA-TPC, is crucial to test our understanding
 129 of two important effects impacting the measured signals from the ERAM:

- The diffusion in the gas in the direction transverse to the track leads to what we call "charge sharing". Also the initial ionisation in the gas can lead to several avalanches reaching the same pad. This is a relatively simple statistical effect resulting in an effective "width" of the track, and increasing with the drift distance. The "sharing" of the charge with adjacent pads depends on this width and on the distance of the projected track in the ERAM plane, to the borders of the pads.
- The charge induced on pads adjacent to the "leading pad" due to the resistive effect is called "charge spreading" throughout this paper, though it is more complex phenomenon than the charge sharing between pads resulting from the diffusion in the gas during the drift. They are correlations between the signals from pads of a cluster, and the signals in neighbour pads are delayed compared to the one of the leading pad, as shown in Fig. 1. This is different from the charge sharing effect from the diffusion in the gas, which is fixed at the time the charge reaches the ERAM detector.

The impact of these effects will be discussed after a detailed presentation of the obtained results.

3. Experimental setup

3.1. HA-TPC field cage prototype

One of the main innovations of the HA-TPCs with respect to the vertical TPCs [7] currently used in ND280 is that the new field cage will use a single layer of solid insulator laminated on a composite material, while for the current ND280 TPCs, two gas-tight boxes, one inside the other, are used. This new design minimizes the dead space and maximizes the tracking volume by reducing the distance between the outer TPC wall and the active gas volume from 12 cm to 4 cm. The radiation length of the material composing the field cage is 2%.

In order to test the construction process of the HA-TPCs field cages, several prototypes have been produced. One of them, that shares all the characteristics of the final field cages, was used for the test beam described in this paper.

The field cage prototype is built with lightweight and low-Z mechanical structures with an hollow shell shape constituting the box. The box is

164 laminated on an Aluminum mold in several layers, namely Kapton[®] sheets,
 165 aramide fiber-fabrics peels and honeycomb spacer panels glued together. The
 166 field cage is then enclosed on the two sides with a cathode plane and the an-
 167 ode where the ERAM detector is located.

168 The innermost cage wall surface embeds a double layer of thin copper
 169 strips: the field strips for degrading the potential from the cathode to the
 170 anode and the mirror strips on the opposite side, for regularizing the field
 171 nearby the walls and for mitigating the effects of free charge deposition on
 172 dielectric surfaces. The strip foils are produced by the CERN Micro-Pattern
 173 Technologies service. In order to protect the field cage from the possible pres-
 174 ence of tiny carbon fibers embedded into the aramide fiber fabric (Twaron)
 175 the mirror strip side is protected with an additional Kapton[®] coverlay glued
 176 on it.

177 The prototype has the same drift length (97.25 cm) as the HA-TPCs
 178 and a reduced transverse area (0.42×0.42 m) suitable to host one ERAM
 179 module. It was produced by the NEXUS company (Barcelona, Spain) and
 180 the different phases of the production of the prototype are shown in Fig. 2.

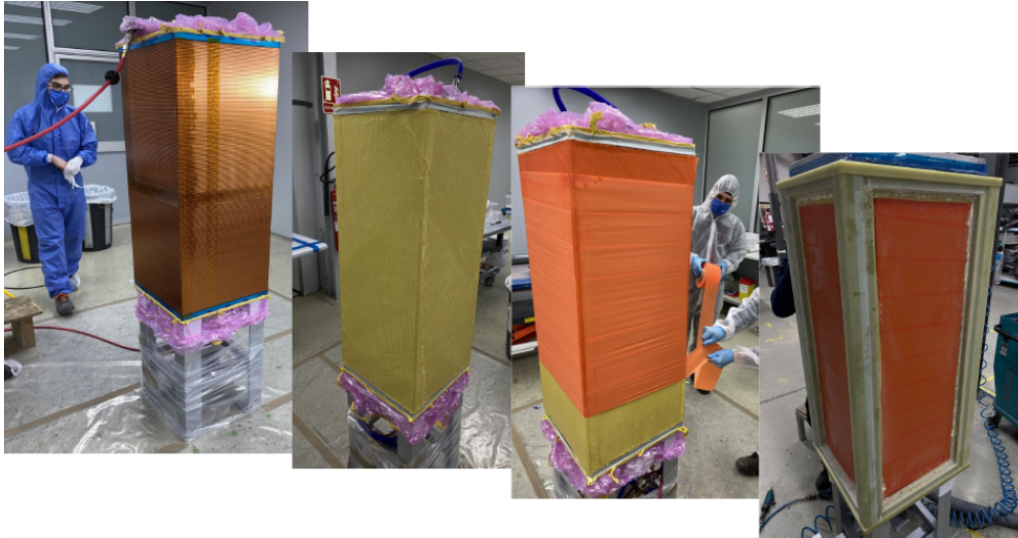


Figure 2: Phases of a field cage prototype production. From left to right: strip foil wrapped onto the mold, aramid fiber fabric (Twaron) glued onto the strip foil layer, Kapton[®] tape wrapped on the Twaron layer before glue curing phase, top and bottom flanges and angular bars applied. The vertical direction in these photos represent the drift direction and the ERAM will be installed on the top surface with the cathode on the bottom.

181 Prior to exposing the prototype to the electron beam at DESY, an ex-
 182 tensive characterization of the field cage has been done at CERN. The prop-
 183 erties were extremely good concerning fiberglass flanges smoothness quality,
 184 gas tightness (measured leakage below 0.1 l/h), inner surface quality and de-
 185 formations smaller than 0.2 mm, compatible with prototype mold tolerances.
 186 We also performed several measurements of resistance and capacitance on the
 187 field and mirror strips showing that the electric field is behaving as expected.

188 3.2. *ERAM detector*

189 A description of the ERAM technology and of the detector used for the
 190 HA-TPCs of T2K is given in [18]. The ERAM modules built for T2K have
 191 a size of $340 \times 420 \text{ mm}^2$ and are segmented in 32×36 rectangular pads of
 192 size $11.18 \times 10.09 \text{ mm}^2$.

193 The ERAMs are used to readout the ionization electrons produced by
 194 charged particles crossing the TPC gas volume. These electrons are drifted
 195 to the anode readout plane of the TPC under a uniform electric field. On the
 196 readout plane, an avalanche is generated by a high electric field in the ERAM
 197 amplification region. The resulting pattern of illuminated pads corresponds
 198 to the trajectory of the track.

199 The main difference between the bulk-Micromegas technology used for the
 200 existing ND280 TPCs and an ERAM is that, in the case of bulk-Micromegas
 201 and for short drift distances the position reconstruction is limited by the
 202 pad size that is large compared to the size of the avalanche which falls on
 203 a metallic anode. In the ERAM, instead, the anode is covered by a foil
 204 of insulating material with a thin resistive layer on top, inducing signals
 205 over several pads. This allows a better reconstruction of the position of the
 206 charged particles crossing the TPC.

207 The ERAM detector uses a Diamond-Like Carbon (DLC) thin layer sput-
 208 tered on a $50 \text{ }\mu\text{m}$ thick APICAL[®] (Kapton[®]) insulator sheet. The detector
 209 installed on the field cage, named ERAM-01, has a resistivity of 300–400
 210 kOhm/ \square using DLC foils stack on a $150 \text{ }\mu\text{m}$ glue layer.

211 3.3. *HA-TPC electronics*

212 The full electronics chain that will be used for the HA-TPCs has been
 213 installed on the ERAM-01 and tested during the test beam described in this
 214 paper. One of the goals of the test beam campaign was to validate the HA-
 215 TPC front-end electronics performance when placed inside a 0.2 T magnetic
 216 field. It has been then proved that their behavior is not altered.

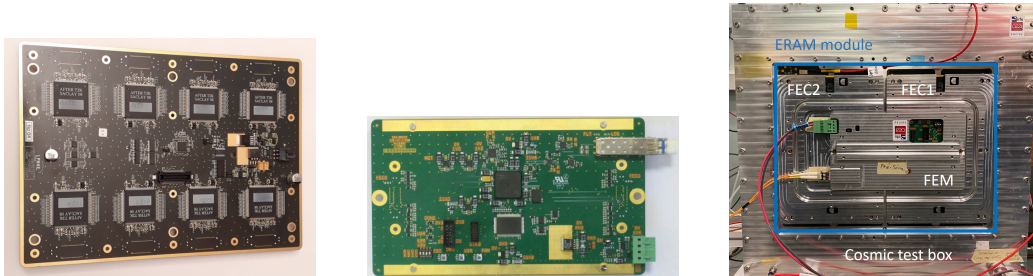


Figure 3: Photo of one FEC with the 8 AFTER chips (left), and of one FEM (center). The right picture illustrates the final assembly of the ERAM with two FEC boards connected to one FEM; all electronic boards are equipped with their cooling plates.

217 The HA-TPC electronics, the main components are shown in Fig. 3, is
 218 based on the use of the AFTER chips [14], that had been designed for the
 219 existing ND280 TPCs. The AFTER chip is a 72-channel ASIC that includes
 220 preamplifiers and shapers with programmable gain and peaking time coupled
 221 to a 511-time bucket switched capacitor array (SCA). During the test beam
 222 the electronics peaking time was set to 200 or 412 ns.

223 The Front-End Cards (FEC) have been newly designed and host 8 AF-
 224 TER chips. They are installed parallel to the ERAM modules and two FECs
 225 are used to readout one ERAM (1152 channels). The response linearity of the
 226 FEC has been measured with a dedicated campaign and showed a uniform
 227 response of all the channels with typical differences in linearity among neigh-
 228 boring pads smaller than 2%. The two FECs on each ERAM are connected
 229 to a Front-End Mezzanine (FEM) card that performs their control, synchro-
 230 nization and data aggregation. All connections, firstly between ERAM and
 231 FEC boards, secondly between FEC and FEM boards, are performed by
 232 using "floating" type connectors (HIROSE - FX23/FX23L series) in order
 233 to eliminate wired connections and all their drawbacks. The final produc-
 234 tion of electronic boards - both FECs and FEMs - was performed by the
 235 OUESTRONIC company in Rennes, France [21].

236 As back-end electronics we used the TDCM, a generic clock, trigger dis-
 237 tributor and data aggregator module [15] designed for several projects, in-
 238 cluding the HA-TPCs. The collected data are transferred to a DAQ computer
 239 via a MIDAS [16] front-end and stored on disk for further analysis.

240 4. Simulation of the ERAM response

241 In this paper we are presenting first comparisons between the data and a
 242 Monte Carlo simulation of the ERAM detector. To develop the simulation we
 243 benefited from the already extensively verified simulation of the T2K TPCs
 244 in the ND280 software [1]. The new feature that was implemented in the
 245 model for this work is the resistive layer of the ERAM detectors.

246 4.1. Simulation framework

247 The simulation starts from GEANT4 [22] that takes care of simulating
 248 the propagation of the charged particles in the TPC gas. To evaluate the
 249 energy loss and the produced ionization the PAI model [23] is used with at
 250 most a 1 mm computation step. The gas composition is the standard T2K
 251 gas [24], a mixture of Ar:CF₄:iC₄H₁₀ (95:3:2).

252 The primary energy deposition by a charged particle is converted into
 253 ionization electrons (typically 100 electrons per cm). The ionisation potential
 254 for T2K gas is set to 26.8 eV. These electrons are moved to the ERAM plane
 255 with the arrival time estimated based on the drift velocity. The electrons are
 256 distributed on the sensitive plane following a Gaussian distribution assuming
 257 a transverse diffusion of $\sigma_{\text{trans}} = 286 \mu\text{m}/\sqrt{\text{cm}}$ and a longitudinal diffusion
 258 of $\sigma_{\text{long}} = 210 \mu\text{m}/\sqrt{\text{cm}}$.

259 For each electron arriving to the ERAM the amplification is simulated
 260 based on the ERAM gain G . Fluctuations in the avalanche processes are
 261 taken into account by extracting the gain g_e for each electron as $g_e =$
 262 $-\log(1 - \text{uniform}(0, 1)) \times G$.

263 The amplified signal is then given as input to the simulation of the resis-
 264 tive layer that will be introduced in the next section. The resulting signal
 265 in each pad is then convoluted with the AFTER chip electronics response
 266 function and digitized with a sampling time of 40 ns.

267 4.2. Resistive layer simulation.

268 The behavior of the resistive layer can be approximated to a RC continu-
 269 ous network [25]. In this model, the charge density caused by the point-like
 270 electron deposited in $\vec{r}_0 = (x_0, y_0)$ ($\rho(\vec{r}, t = 0) = \delta_{\vec{r}_0}(\vec{r})$) is described with the
 271 solution of the 2D diffusion equation:

$$\rho(\vec{r}, t) = \frac{RC}{4\pi t} \times \exp\left(-\frac{r^2 RC}{4t}\right) \quad (1)$$

272 where $r = \sqrt{(x - x_0)^2 + (y - y_0)^2}$ is a distance from the initial charge depo-
 273 sition, t is time and RC is a network characteristic of the ERAM. For our
 274 case, ERAM is expected to have an RC within 50-120 ns/mm². To compute
 275 the observed charge in a given pad the equation above should be integrated
 276 over the pad surface

$$\begin{aligned}
 Q_{\text{unit}}(t) &= \int_{x_{\min}}^{x_{\max}} \int_{y_{\min}}^{y_{\max}} \rho(\vec{r}, t) dx dy \\
 &= \frac{1}{2} \pi \left(\text{Erf} \left[\frac{\sqrt{RC}(x_{\max} - x_0)}{2\sqrt{t}} \right] - \text{Erf} \left[\frac{\sqrt{RC}(x_{\min} - x_0)}{2\sqrt{t}} \right] \right) \\
 &\quad \times \left(\text{Erf} \left[\frac{\sqrt{RC}(y_{\max} - y_0)}{2\sqrt{t}} \right] - \text{Erf} \left[\frac{\sqrt{RC}(y_{\min} - y_0)}{2\sqrt{t}} \right] \right) \quad (2)
 \end{aligned}$$

277 where Erf is the error function and x_{\min} , x_{\max} , y_{\min} , y_{\max} are pad borders
 278 coordinates.

279 The evolution of the charge in the pad is convoluted with the derivative
 280 of the AFTER electronics response:

$$E(t) = \left(\frac{t}{t_p} \right)^3 \exp \left(-\frac{3t}{t_p} \right) \sin \left(\frac{t}{t_p} \right) \quad (3)$$

281 where t_p is the electronics peaking time. The unit waveform (WF_{unit}) is
 282 then:

$$WF_{\text{unit}}(t) = Q_{\text{pad}}(t) \circledast \frac{dE}{dt}(t) = \int_{-\infty}^{\infty} Q_{\text{pad}}(t - \tau) \frac{dE}{dt}(\tau) d\tau. \quad (4)$$

283 Finally, when considering an avalanche of electrons, the waveforms in-
 284 duced in each pad by each electron of the avalanche should be computed
 285 taking into account the arrival of each of them and summed in order to
 286 obtain the complete waveform (WF) of the avalanche.

287 Therefore, the numerical evaluation of the diffusion equation solution and
 288 of the convolution are extremely heavy in terms of computation time. To keep
 289 the simulation to a reasonable time some approximations were included as
 290 described below.

291 The first method is related to reducing the total number of avalanches to
 292 be simulated. The pad is divided into several smaller sub-pad regions e.g.
 293 3×3 or 5×5 . All the avalanches that are detected in the same pad sub-region

294 are merged into one and the charge Q is computed for the sum of all the
 295 contributions in this sub-pad.

296 The next and the most significant optimisation is related to the pre-
 297 computation of the diffusion equation solution and convolution. Before start-
 298 ing the simulation the detector response is pre-computed for a unit charge,
 299 a given RC that is input to the model, and for all the positions across a 2D
 300 grid in the pad, $Q_{\text{unit}}(\text{RC}, x_i, y_i, t)$, where x_i and y_i are the coordinates of
 301 a sub-pad center. The step of the grid can be tuned and for this work we
 302 divided the pad in a grid of 10×10 sub-pad regions. The obtained distri-
 303 butions are convoluted with the derivative of the electronics response to get
 304 the waveform (WF_{unit}) for a unit charge. The final waveform $\text{WF}(t)$ can be
 305 easily obtained by scaling the pre-computed solution WF_{unit} with the total
 306 charge Q_i in each sub-pad i obtained from GEANT4, so that:

$$\text{WF}(t) = \sum_i Q_i \times \text{WF}_{\text{unit}}(x_i, y_i)(t). \quad (5)$$

307 The main approximation in this computation is the assumption that all
 308 the electrons in a sub-pad arrive at the center of this sub-pad. This implies
 309 that no numerical computations are needed during the simulation.

310 Two examples of the resulting WF , one for the data and one for the
 311 simulation, are shown in Fig. 4 for the leading and for two neighboring pads.
 312 Here and in the following of this paper, the leading pad is defined as the pad
 313 with the largest maximum of the waveform while neighboring pads are the
 314 ones adjacent to the leading pad in the direction perpendicular to the track
 315 (see discussion on clustering algorithms in Sect. 7).

316 The optimization methods described above reduce the computing time by
 317 more than two orders of magnitude without impacting the simulation output
 318 as it can be seen in Fig. 5 where no differences are observed in the charge
 319 ratio and time differences between the leading and the neighbour pad.

320 5. Characterization of ERAM detector

321 Each ERAM detector is scanned after the production on an X-ray test
 322 bench at CERN. The test bench consists of a 3 cm width gas chamber and a
 323 robotic X-Y-Z arm system on an optical breadboard of $120 \times 60 \text{ cm}^2$ holding
 324 a 250 MBq ^{55}Fe source emitting 5.9 keV photons that deposit all their energy
 325 in the gas.

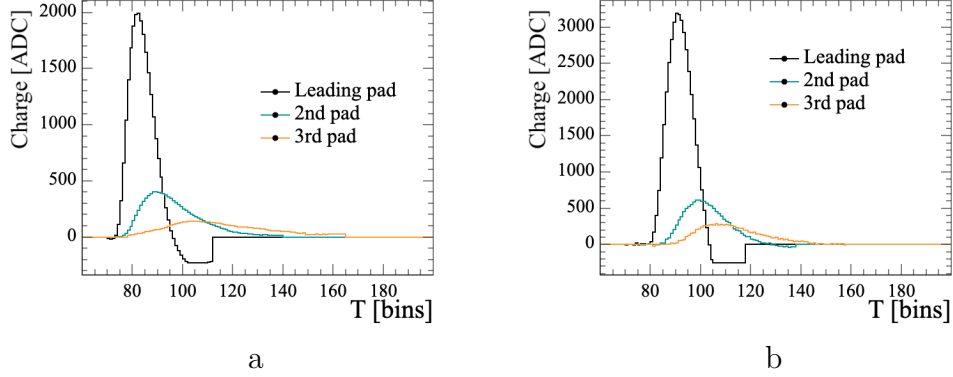


Figure 4: The example waveforms for the leading and adjacent pads in (a) data and (b) MC. The truncation of the underflow is due to the fact that in both, data and simulations, pedestals for each channel are equalized to 250 and, when the waveform goes below 0 they are set to 0. The 250 baseline is then subtracted offline and is not shown in the plot.

326 A 1.5 mm diameter collimation hole in front of the source assures that the
 327 majority of photo-electrons arrives on the targeted pad. Prior to the scan,
 328 the ERAM is aligned to ensure the position of the source with respect to the
 329 center of each pad.

330 Each channel of the ERAM is scanned for ~ 3 minutes at a rate of 100 Hz,
 331 to reconstruct the spectrum of the ^{55}Fe source and compute the gain for each
 332 pad. The gain is computed as the mean of the sum of the waveforms in a
 333 3×3 matrix around each channel. The map of the gain on the ERAM-01 and
 334 the gain uniformity are shown in Fig. 6.

335 The data from the test bench can also be used to measure the RC unifor-
 336 mity of the ERAM. This measurement campaign will be subject of a future
 337 publication. For the comparisons between data and simulations that will be
 338 presented in this paper, we assumed uniform gain and RC in the simulation.

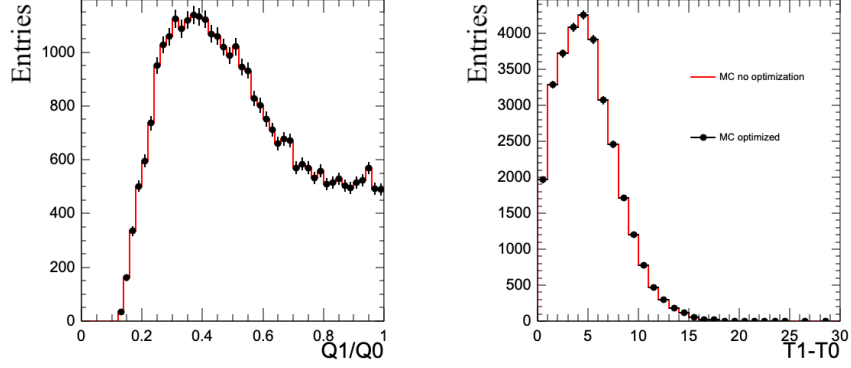


Figure 5: Charge ratio (left) and time difference (right) between leading and neighbour pad with and without the optimization needed to reduce computation time.

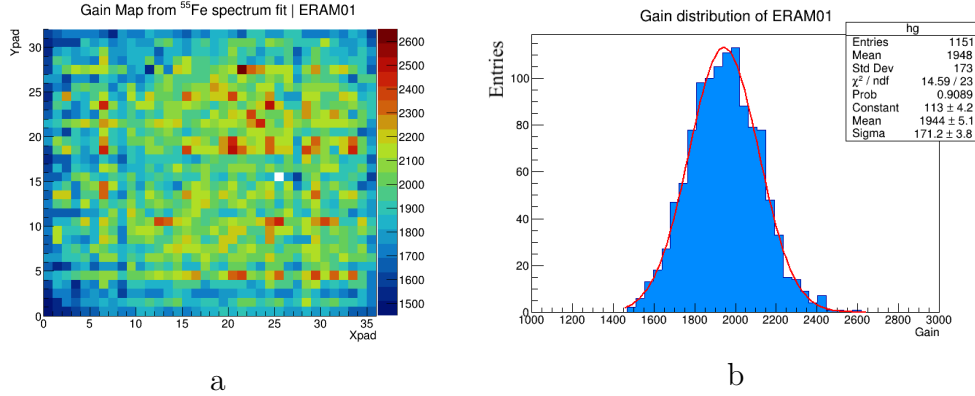


Figure 6: XY-map of the gain (a) and gain distribution (b) obtained with a ^{55}Fe source for the ERAM used in the test beam. The channel (25,16) is a dead channel on ERAM-01.

339 6. Data collected at DESY

340 The tests at DESY were aimed to ensure that the HA-TPC prototype
 341 design fully satisfies the requirement of the ND280 upgrade for drift distances
 342 up to 97.25 cm that corresponds to the maximum drift length of the HA-
 343 TPC. Therefore, this test beam covered all the possible tracking conditions
 344 of the final HA-TPC.

345 The High-Angle TPC prototype equipped with ERAM-01 was flushed
 346 with T2K gas mixture and tested at DESY T24/1 facility. The chamber was

placed inside the PCMAG solenoid providing a magnetic field up to 1.25 T and exposed to the electron beam with tunable momenta between 1 and 4 GeV/c. The solenoid is equipped with a movable stage that allows moving the detector along the horizontal and vertical directions, and rotating by ± 45 degrees around a vertical axis. The TPC holder can be manually rotated inside the magnet.

Most of the data were taken with the cathode High Voltage set at 26.7 kV corresponding to an electric field in the TPC of 275 V/cm and at $B = 0.2$ T as used in T2K. This field configuration corresponds to a drift velocity of 7.9 cm/ μ s. In order to study the dependence on different parameters and configurations, various scans were performed.

Thanks to the PCMAG movable stage we could rotate the TPC, performing scans of the ERAM-01 in X and Y (by rotating the prototype) directions as well as scans in Z (drift distance). This is particularly interesting because it allows a study of the impact on the performances of possible non-uniformities in the gain or in RC.

The drift distance scan was done for two values of the electronics peaking time of 412 ns and 200 ns.

The data were also collected for different rotation angles around the horizontal axis (ϕ angle), within varying magnetic fields and for three drift distances, one close to the ERAM, one in the middle of the chamber, and one close to the cathode.

7. Reconstruction and selection of tracks

Both, simulated and test beam tracks were reconstructed with the same analysis framework that uses DBSCAN [26] algorithm and the PRF method (discussed in Sect. 9)

The track is composed by "clusters" that are groups of pads in the direction perpendicular to the track. In order to be selected, a track needs to cross the whole detector.

Due to the large number of pads per cluster (multiplicity) induced by the ERAM, two close parallel tracks may not be separated by a gap and thus mis-reconstructed as one single track.

To reject such a topology and also to remove superimposed tracks, a cut on the mean multiplicity of a track is applied. This cut depends on the track clustering algorithm that is used to reconstruct the tracks. As it was introduced in [18], we use horizontal and vertical clustering for tracks with

incident angles below 30 degrees and above 60 degrees respectively, while for inclined tracks we use a diagonal clustering algorithm in which pads are combined into clusters according to their diagonal.

The mean multiplicity depends on the reconstruction algorithm and on the peaking time for the electronics. It is shown in Fig. 7 for horizontal and inclined tracks at various drift distance and peaking time. For inclined tracks the multiplicity tends to increase with the drift distance due to the transverse diffusion of the electrons while crossing the gas volume. For horizontal tracks, instead, this effect is hidden by the larger effect induced by RC.

For the analyses presented in this paper we select tracks with mean multiplicity comprised between 2.4 and 3.2 (1.5 and 2.2) for horizontal (inclined) tracks with 200 ns peaking time. For 412 ns peaking time only horizontal tracks were taken and, for this sample, we required a mean multiplicity comprised between 2.7 and 3.6.

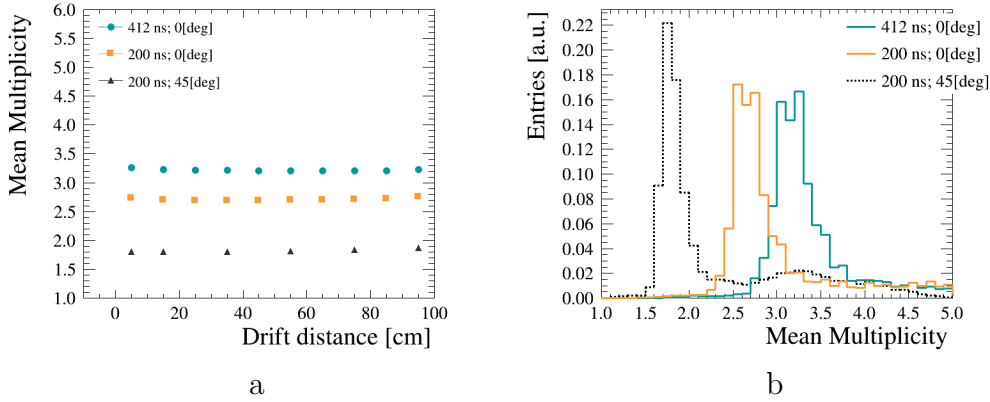


Figure 7: Mean multiplicity as a function of drift distance (a) and mean multiplicity profile (b) at different peaking time for horizontal and inclined tracks.

Finally, to avoid edge effects, the pads at the border are excluded from the reconstruction and hence horizontal tracks have 34 clusters while vertical tracks have 30.

8. ERAM response in data and simulation

To validate the simulation described in Sect. 4, we produced electrons propagating in the Y direction and compared some low-level variables describing the ERAM response, including charge sharing and time differences

between neighboring pads in data and simulation. These comparisons are done also with respect to the data taken at DESY in 2019 with a different ERAM module that is described in [18]. The comparison between data and simulation for spatial resolution and dE/dx resolution will be shown in Sect. 11.

The most important variables for the resistive feature characterisation are the charge ratio and the time difference between the WFs observed in the adjacent pads and the one in the leading pad.

For these comparisons, the charge in the pad is defined as the maximum of the waveform and the time is defined as the time bin at which the waveform reaches its maximum. The pads in a cluster are then ordered according to their charge (Q_1 and T_1 refer to the pad with the largest charge, Q_2 and T_2 the second, Q_3 and T_3 the third).

Since these variables depend on the relative position of a track with respect to the pad center, we sampled the distributions based on the reconstructed track position. These distributions are shown in Fig. 8 for 5 cm drift distances.

In order to make a more quantitative comparison between data and Monte Carlo, the distributions of Fig. 8 were fit with the Landau function and the most probable value (MPV) is plotted in Fig. 9 for these data (DESY 2021), the one from the previous test beam (DESY 2019) and MC samples generated with $RC=55$ ns/mm² and $RC=100$ ns/mm².

This comparison clearly shows the different behaviour of the two ERAM modules, especially for what concerns the time differences that are most affected by RC.

The difference in the data can be explained by a different value of RC between the two modules. The data from 2021 are better reproduced by using $RC=100$ ns/mm², however, even for this RC value, some visible differences between the data and simulation are observed. As we will show in Sect. 11, these differences do not affect the detector performances in terms of spatial or energy resolution.

The charge ratio and time differences for larger drift distances, where effects induced by the diffusion in the gas play an important role, show in general a better agreement between data and simulation, as illustrated in Fig. 10.

For the future, we expect to improve the agreement between data and MC by using in the simulation the value of RC that will be measured with the Test Bench described in Sect. 5 and taking into account possible non-

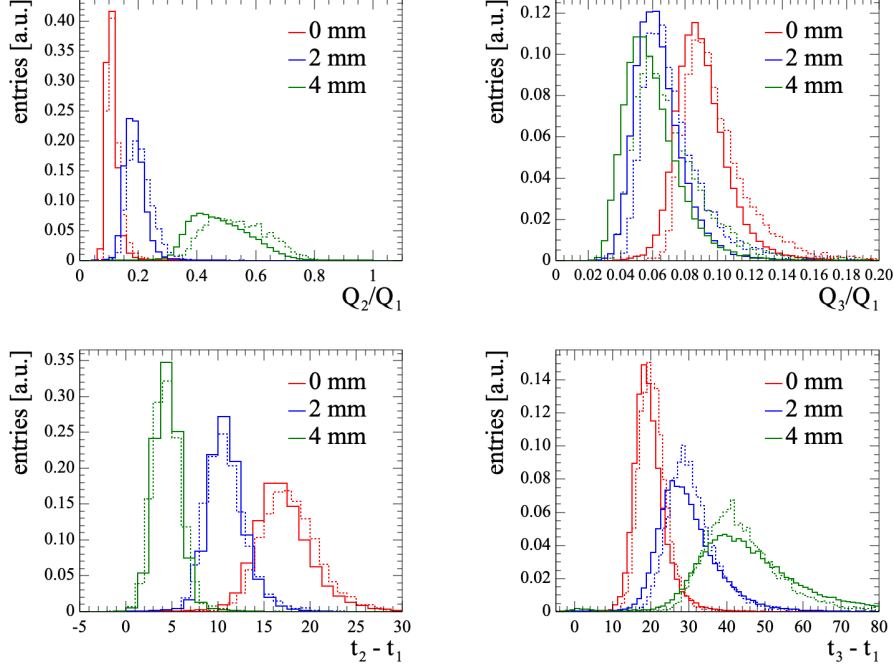


Figure 8: Ratio of the charge in the second pad (top left) and third pad (top right) with respect to the leading pad and time difference between leading and second (bottom left) and third pad (bottom right) as a function of the reconstructed distance from the pad center. The solid lines represent data (DESY 2021) and the dashed ones are the simulation.

442 uniformities within the detector.

443 9. Spatial resolution

444 The ND280 TPCs measure the momenta of the outgoing particles from
 445 neutrino interactions in order to reconstruct the energy of the incoming neu-
 446 trino, one of the critical elements for precise measurement of neutrino oscil-
 447 lations parameters.

448 The TPC momentum resolution depends on the spatial resolution (SR) [27]
 449 that can be characterized with test beam data. For this analysis, the spatial
 450 resolution is measured by employing a “pad response function” (PRF) in the
 451 same manner as in [19, 18].

452 In this method we define, for each cluster, the residual as the difference
 453 between the position of the track reconstructed locally (e.g. in one column)

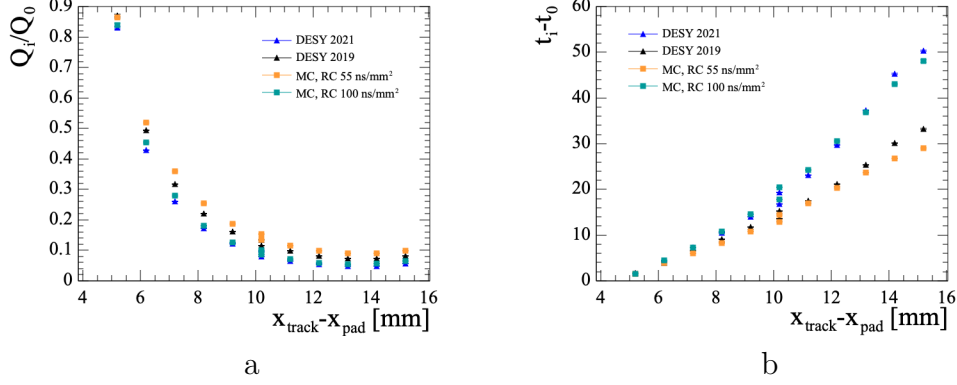


Figure 9: The comparison of the MC simulations and two test beams (DESY 2021 and DESY 2019) for the charge ratio (a) and time difference (b) between leading and adjacent pads as a function of the difference between pad centre (x_{pad}) and reconstructed track position (x_{track}). Two points are shown for $x_{\text{track}} - x_{\text{pad}} = 10$ mm because, for tracks in the center of the pad, the two adjacent pads have the same distance from the track.

and the fitted track position. The distribution of the residuals in each cluster is fitted with a Gaussian and its width represents the spatial resolution.

The measurement of the track position is performed with an iterative procedure. For the first step, all the tracks are reconstructed using the charge barycentric method. Such a method estimates the position of the track in a certain cluster by weighting the centre of the pad position by the charge in this pad. The estimated primary track positions in each cluster are then fit with a parabola over the whole detector (global fit). Based on the results of the fit, a pad response function scatter plot is filled for each pad. The PRF function is defined as:

$$\text{PRF}(x_{\text{track}} - x_{\text{pad}}) = Q_{\text{pad}}/Q_{\text{cluster}} \quad (6)$$

where x_{track} and x_{pad} are positions of the track from the global fit and the center of the pad, respectively, and Q_{pad} and Q_{cluster} are charges collected by the pad and by the whole cluster.

The PRF scatter plot is fitted with a ratio of two polynomes (the same as in [18, 28]). The scatter plot and the parametrization of the PRF are done independently for samples at different drift distances and inclination. The estimated parameters of the PRF analytical function are used further in the χ^2 minimization procedure to estimate the track position in each cluster.

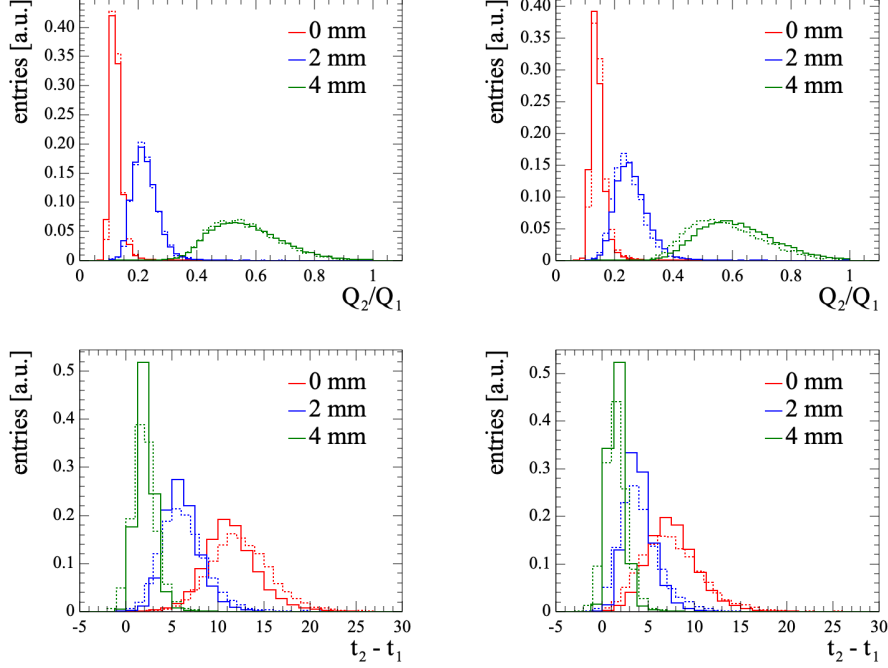


Figure 10: Charge ratio between second and leading pad for drift distances of 50 cm (top left) and 90 cm (top right) and time difference between first and second pad for drift distances of 50 cm (bottom left) and 90 cm (bottom right) as a function of the reconstructed distance from the pad center. The solid lines represent data (DESY 2021) and the dashed ones are the simulation.

$$\chi^2 = \sum_{\text{pads}} \left(\frac{Q_{\text{pad}}/Q_{\text{cluster}} - \text{PRF}(x_{\text{track}} - x_{\text{pad}})}{\sigma_{Q_{\text{pad}}/Q_{\text{cluster}}}} \right)^2 \quad (7)$$

472 where $\sigma_{Q_{\text{pad}}/Q_{\text{cluster}}} = \sqrt{Q_{\text{pad}}/Q_{\text{cluster}}}$.

473 In the following iterations the track position was evaluated from the fit.
 474 The iteration procedure is repeated while the spatial resolution keeps im-
 475 proving and it typically converges after three iterations. Examples of PRF
 476 for horizontal and inclined tracks are shown in Fig. 11. A small dip around
 477 zero can be observed in PRF for inclined tracks. This is due to the width of
 478 the distribution around zero and to the freedom of the polynomial fit.

479 The spatial resolution was defined as a mean of the residual distribution
 480 for each cluster. Examples for horizontal and inclined tracks are shown in

481 Fig. 12. The distribution is expected to be centered at zero and differences
 482 with respect to zero are the biases that will be discussed in Sect. 9.3.

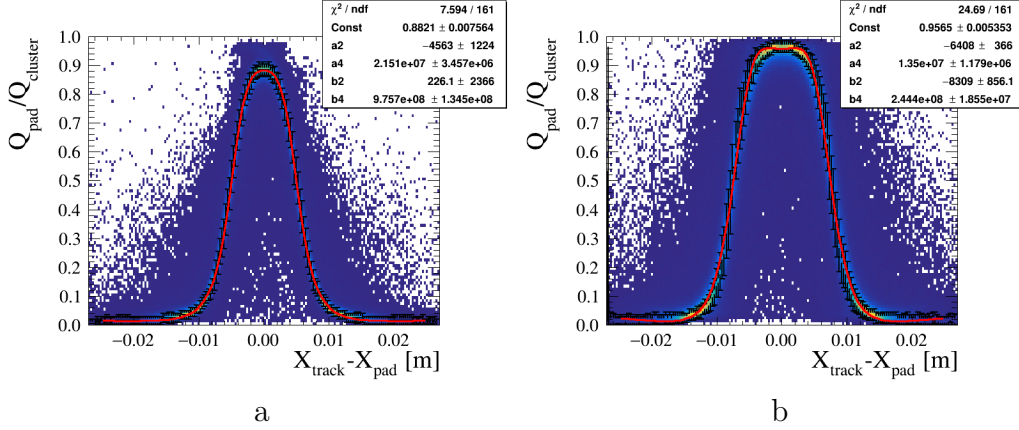


Figure 11: PRF function for (a) horizontal and (b) inclined tracks.

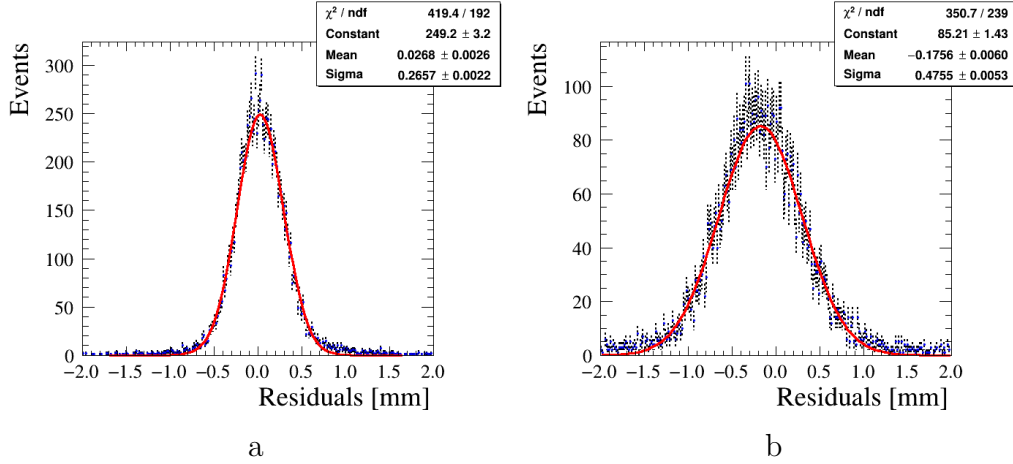


Figure 12: Residuals distribution for single cluster for (a) horizontal and (b) inclined tracks.

483 As an external cross-check of the performance of tracking algorithm, typ-
 484 ical distributions of reconstructed track position for incoming electron beam
 485 are shown in Fig. 13.

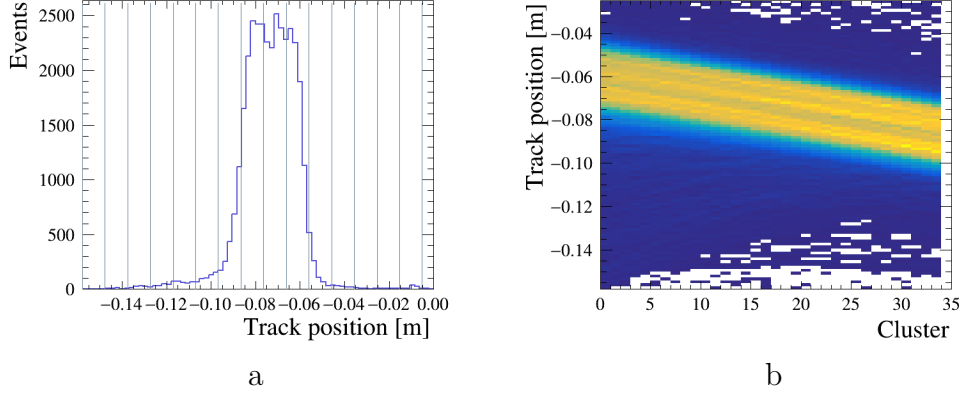


Figure 13: A typical distribution of the reconstructed track position for incoming electron beam; vertical lines correspond to the center of each pad (a) and reconstructed track position with respect to the cluster number (b).

9.1. Spatial resolution for horizontal tracks

With this method we can evaluate the spatial resolution for different track topologies. The results for the horizontal tracks as a function of the drift distance for different electronics peaking time are presented in Fig. 14.

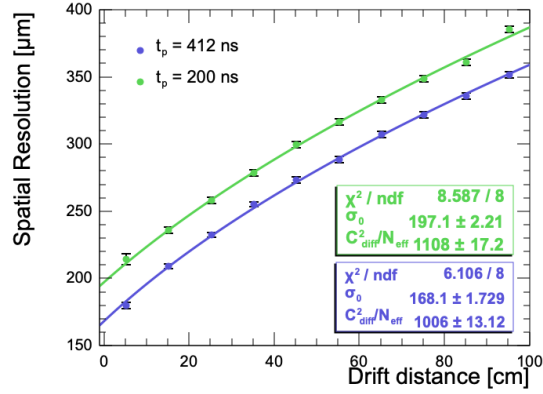


Figure 14: Spatial resolution with respect to the drift distance for the beam parallel to the pad side with a magnetic field of 0.2 T, and peaking times of 200 ns and 412 ns.

The resolution over the drift distance is expected to follow this dependence.

$$\sigma(Z) = \sqrt{\sigma_0^2 + C_{\text{diff}}^2/N_{\text{eff}} \times Z} \quad (8)$$

where σ_0 is the resolution at null drift distance, C_{diff} is the transversal diffusion constant and N_{eff} is the number of effective electrons [29]. The observed dependence is in agreement with this prediction. The peaking time mildly affects the $C_{\text{diff}}^2/N_{\text{eff}}$ term, but changes the σ_0 . A larger peaking time results in a higher amplitude in the neighbour pads and higher pad multiplicity. Thus we have more robust information for the PRF fit and the track position reconstruction is more precise.

The spatial resolution can also depend on the ERAM module characteristics, such as its gain and the local RC value. To investigate these possible dependencies we used a scan done at fixed drift distance but with horizontal tracks crossing the ERAM at different X positions and vertical tracks crossing the ERAM at different Y positions. The spatial resolution obtained for these different X and Y positions is shown in Fig. 15. No large differences are observed indicating that possible local non-uniformities on the ERAM module do not affect the spatial resolution.

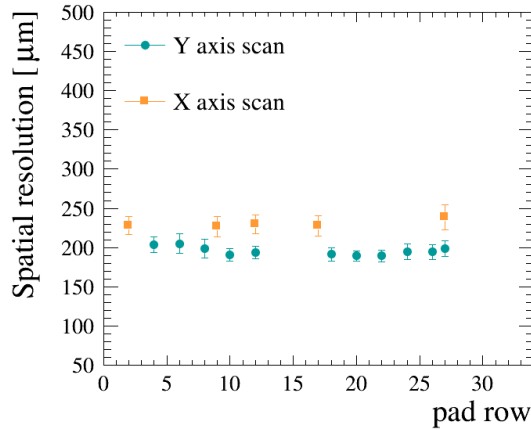


Figure 15: Spatial resolution for different Y and X positions at 412 ns peaking time.

9.2. Spatial resolution for inclined tracks

The collected test beam data allow studying spatial resolution as a function of the angle of inclination of the tracks within the ERAM module plane. The novelty with respect to the studies performed in [18] is that we could

511 evaluate the spatial resolution performances for inclined tracks at long drift
 512 distances. The results are presented in Fig. 16 (a), where angles from 0 to
 513 30 degrees and from 70 to 90 clusters are defined perpendicular to the track
 514 direction (horizontal/vertical fit), and for the highly inclined tracks, with the
 515 angle between 40 and 60 degrees, the clusters defined along the diagonals as
 516 described in Section 7. In [18] it has been shown that the use of a diagonal
 517 fit for highly inclined tracks significantly improves the spatial resolution with
 518 respect to the use of horizontal or vertical fits.

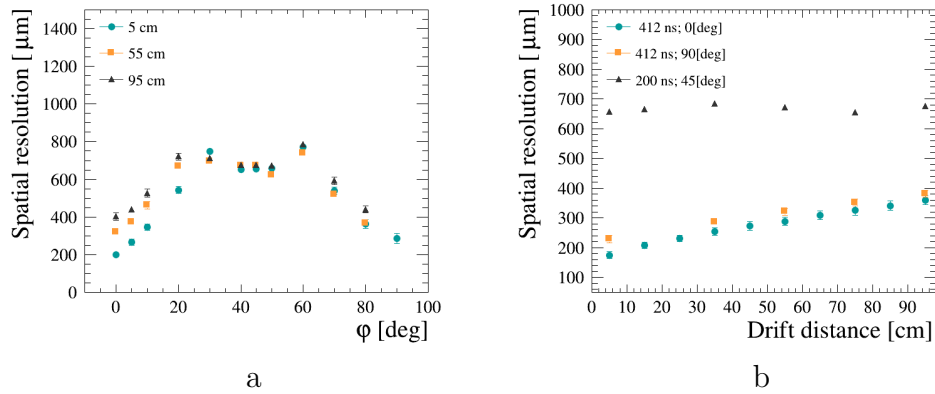


Figure 16: Spatial resolution for different angles of the electron tracks inclination in the pad plane with 200 ns peaking time, 0.2 T magnetic field and for various drift distances: 5 cm, 55 cm, 95 cm (a) and spatial resolution versus drift distance for horizontal (0 deg.), inclined (45 deg.) and vertical (90 deg.) tracks.

519 Fig. 16 (a) demonstrates that, while the spatial resolution depends on
 520 the angle, it stays between 200 and 800 μm for all the analyzed samples. In
 521 particular, it is interesting to notice in Fig. 16 (b) that, while the spatial
 522 resolution degrades with the drift distance for horizontal and vertical tracks,
 523 it is constant for inclined tracks.

524 The behavior for diagonal tracks can be understood considering that the
 525 spatial resolution depends on the charge spread over a certain amount of
 526 pads (multiplicity). A diagonal clustering algorithm leads to a smaller mean
 527 multiplicity than in the case of horizontal/vertical fit as it was shown in Fig. 7.
 528 With the diagonal fit pad size becomes effectively $\sqrt{2}$ times larger, thus
 529 degrading the spatial resolution but also making the effect of the transverse
 530 diffusion less significant.

531 Moreover, diagonal fit implies a dependence of the resolution on the length

of the track in the cluster. This causes an oscillatory behavior in the spatial resolution versus the cluster that is shown in Fig. 17 (a). Fig. 17 (b) shows the dependence of the spatial resolution on the track length per cluster for inclined tracks. It is clearly seen that, as expected, the resolution improves for longer track segment lengths within the cluster.

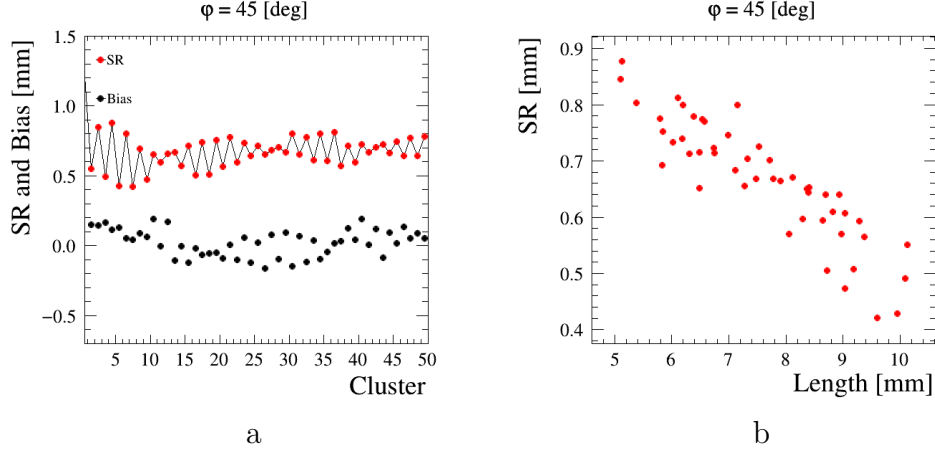


Figure 17: Tracks of 45 degrees inclination: spatial resolution per cluster (a) and spatial resolution with respect to mean track segment length in a cluster (b).

9.3. Biases in spatial resolution

The bias of the track position in each cluster of the ERAM pad plane is defined as the mean of the Gaussian fit of the distribution of residuals per cluster, and can be referred to as the systematic uncertainty of the track position estimation. In [18, 30] it is shown that the biases depend on the track position. The data collected during this campaign allow a deeper study of biases, in particular their dependence on drift distance for both horizontal and inclined tracks, as well as their behavior for various magnetic field strengths (see Sec. 12).

Fig. 18 (a) shows the bias as a function of the drift distance for horizontal tracks. In this figure, the bias is defined as the mean of the absolute values of the biases per cluster. It is observed that biases are larger at short and long drift distances than at distances corresponding to the middle of the drift volume.

For inclined tracks, instead, as shown in Fig. 18 (b), the biases do not depend on the drift distance or on the ϕ angle of the tracks reconstructed using diagonal clustering.

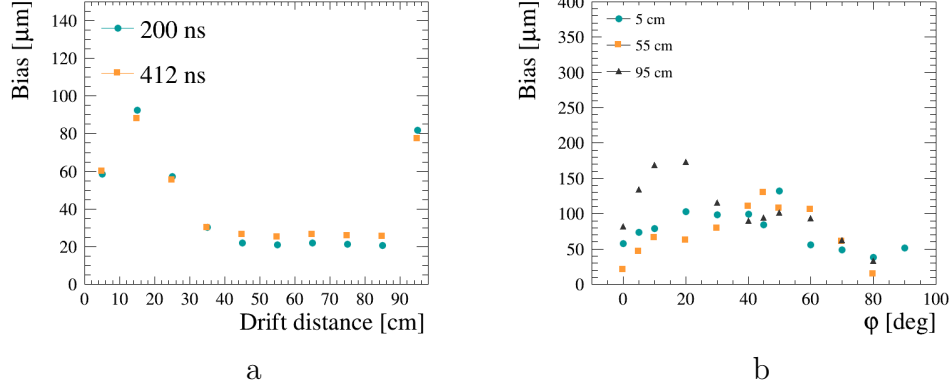


Figure 18: Track position bias with respect to the drift distance for the beam parallel (a) and inclined (b) to the pad side with a magnetic field of 0.2 T, and peaking time of 200 ns.

554 In order to further investigate the behavior observed in Fig. 18, the de-
 555 pendence of the spatial resolution and bias per column on the drift distance
 556 is shown in Fig. 19. For the smallest and largest drift distances, biases have
 557 visible patterns with large and opposite biases at the beginning and at the end
 558 of the track. This pattern is not observed for tracks in the center of the
 559 ERAM.

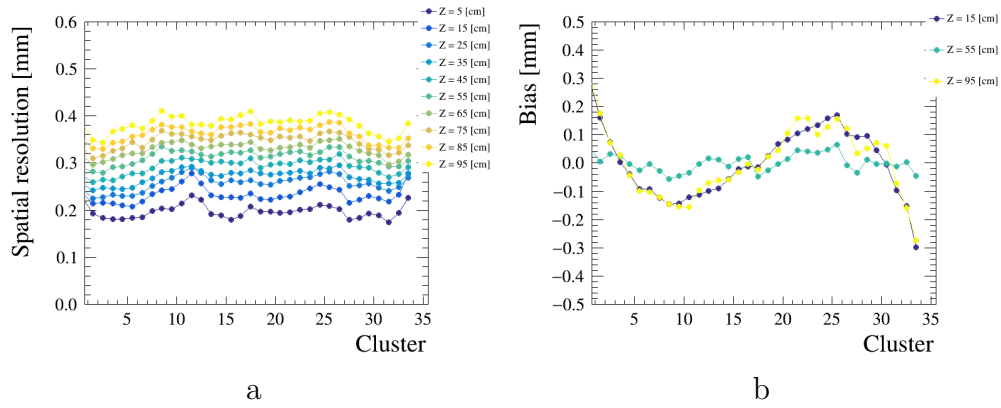


Figure 19: Spatial resolution (a) and track position bias (b) distributions per cluster for the beam parallel to the pad side with a magnetic field of 0.2 T, and peaking times of 200 ns at various drift positions (z axis).

560 The observed dependencies of the biases are not reproduced by the sim-

561 ulation and can point to effects related to non-uniformities in the magnetic
 562 field, not accounted for in the simulation, and the $E \times B$ effect. In Sect. 12 we
 563 will discuss the impact of these effects on the observed tracks, together with
 564 a study of the observed biases as a function of the applied magnetic field.

565 For all the configurations the biases are bellow $200 \mu\text{m}$ and their size is
 566 small with respect to the spatial resolution for highly inclined tracks.

567 10. dE/dx resolution

568 The other main goal of the HA-TPC is to perform particle identification
 569 by measuring the deposited energy by charged particles crossing the gas. The
 570 TPC particle identification capability will depend on the dE/dx resolution
 571 that can be evaluated with the data from this test beam.

572 In the context of T2K it is particularly important to be able to distinguish
 573 electrons and muons. Such an effort is crucial to estimate electron neutrino
 574 contamination in the muon neutrino beam and to predict the expected
 575 number of un-oscillated electron neutrinos in the far detector. To distinguish
 576 electrons and muons the deposited energy resolution requires to be better
 577 than 10% in order to achieve a more than 3σ separation between electrons
 578 and muons.

579 The deposited energy is calculated per track using the truncated mean
 580 method already introduced in [18].

581 The method consists in calculating the track mean deposited energy by
 582 summing the deposited energy in the reduced number of clusters fired by the
 583 electron and ignoring the fraction of those that have a large energy contribu-
 584 tion. Such contribution is caused by fluctuations in the ionization processes
 585 and leads to the smearing of the energy spectrum.

586 The truncation factor is optimized with the data and we found it to be
 587 0.7 which is the same as for the DESY 2019 test beam data [18]. This means
 588 that 70% of the clusters are kept for deposited energy calculations.

589 The deposited energy per cluster was calculated by taking the maximum
 590 of the sum of the waveforms of the pads constituting the cluster. Various
 591 cluster charge definitions were studied in [18] and it was shown that the
 592 charge defined using the sum of the waveforms results in a better deposited
 593 energy resolution.

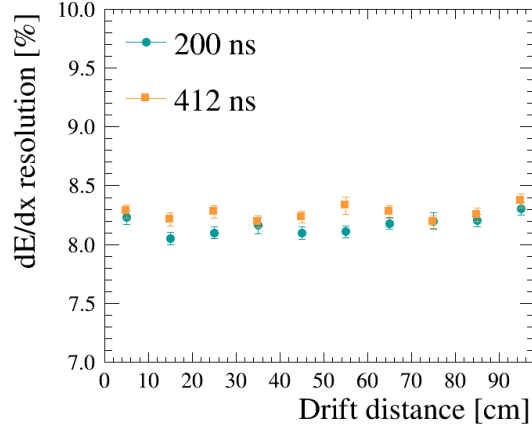


Figure 20: dE/dx resolution with respect to the drift distance for the beam parallel to the pad side with a magnetic field of 0.2 T, and peaking times of 200 ns and 412 ns.

594 The deposited energy resolution was measured for both parallel and in-
 595 clined tracks with respect to the pad side. Fig. 20 shows the deposited energy
 596 resolution measured for the parallel tracks for various drift distances.

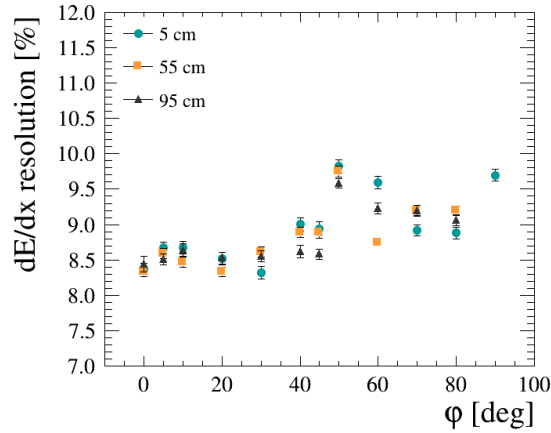


Figure 21: dE/dx resolution versus different angles of the electron tracks inclination in the pad plane with 200 ns peaking time, 0.2 T magnetic field and for various drift distances: 5 cm, 55 cm, 95 cm. A 10% discrepancy observed around $\phi = 60^\circ$ is under study.

597 Fig. 21 shows the dE/dx resolution at various drift distances as a function
 598 of the angle within the pad plane.

599 Additionally, the deposited energy for tracks reconstructed with the di-
600 agonal fit was corrected for the track length in each cluster. Such correction
601 accounts for the non-linear dependence of the charge with respect to the track
602 length caused by the charge contribution from the neighbouring clusters for
603 short track cluster length.

604 The study shows that the dE/dx resolution is $\sim 8.5\%$ for horizontal tracks
605 and stays between 7.5% and 9.6% for inclined and vertical tracks. Further-
606 more, it is independent of drift distance and of the electronics peaking time.
607 It has been observed that dE/dx resolution is controlled by balancing two
608 factors: the mean charge per cluster and the number of clusters. Fig. 21
609 shows that dE/dx resolution worsens for the angles > 45 degrees since for
610 such angles a smaller number of clusters is reconstructed per track due to
611 the rectangular shape of the ERAM.

612 Finally, as in the case of the spatial resolution, we looked for effects due
613 to non-uniformities of the ERAM by using the X and Y scans. The results
614 are show in Fig. 22. We observe some differences, possibly due to non-
615 uniformities in the gain of the ERAM, but in general the resolution is below
616 10% for all the Y and X scans.

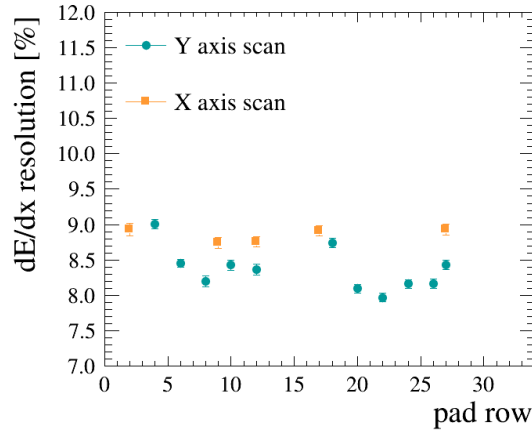


Figure 22: dE/dx resolution for tracks entering the ERAM at different X and Y positions.

617 The observed results prove that the ERAM energy resolution fulfills the
618 requirements for the ND280 upgrade.

11. Comparison between data and simulation

In this section we compare the performances of the ERAM for spatial and dE/dx resolution between data and simulation.

Fig. 23 shows the spatial resolution for the data and MC samples as a function of the drift distance. The dependence over the drift distance was found to be slightly different using the default value used in the ND280 simulations of the vertical TPC that has a transverse diffusion $\sigma_{\text{trans}} = 286 \mu\text{m}/\sqrt{\text{cm}}$. The diffusion can be affected by the magnetic field configuration as well as environmental conditions such as temperature and pressure, or by the amount of oxygen and water contamination in the chamber.

We made simulations with different values of σ_{trans} . As expected, in general, increasing σ_{trans} results in a worst spatial resolution for large drift distances. A satisfactory agreement was found by increasing the transverse diffusion by 8%, changing it to $\sigma_{\text{trans}} = 310 \mu\text{m}/\sqrt{\text{cm}}$. Furthermore, while in the data we observe a dependence on the drift distance in good agreement with the one expected from Eq. 8, in the simulation we find that this dependence is linear. The origin of this difference between data and simulation is under investigation.

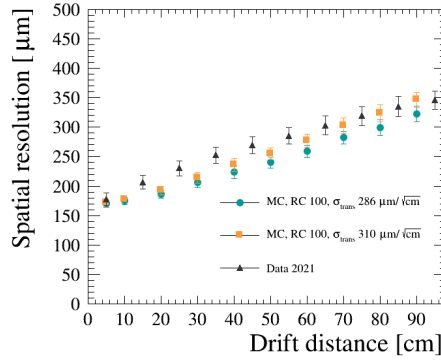


Figure 23: Spatial resolution over the drift distance for DESY 2021 data at 412 ns peaking time and MC samples generated with different values of transverse diffusion at 400 ns peaking time.

In Fig. 24 (a) we show the comparison in the spatial resolution between data and simulation for tracks at different angles. It should be noticed that the ϕ scan was done using different electronics peaking times and we did the

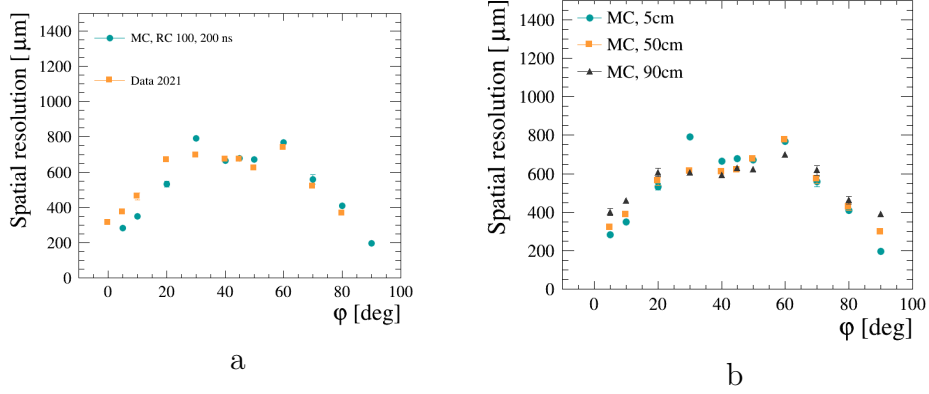


Figure 24: Spatial resolution over angle with respect to pad borders for (a) data and MC samples at 200 ns peaking time and 55 cm drift distance and (b) simulation for the different drift distances.

simulation for the two cases. The simulation rather correctly reproduces the behaviour observed in the data.

In Fig. 16 (b) it was found that the spatial resolution weakly depends on the drift distance for the highly inclined tracks. This effect was cross-checked and confirmed with the simulation. Fig. 24 (b) shows large effect of the drift distance on the tracks close to 0° and 90° , but much smaller effect at 45° .

Concerning the deposited energy resolution, the simulation reproduces reasonably well the data for both, horizontal and inclined tracks, as shown in Fig. 25.

12. $\mathbf{E} \times \mathbf{B}$ effect

Inhomogeneities in the magnetic field can create distortions of the image of the track projected on the ERAM. These distortions are not expected to impact the spatial resolution that is computed based on the track image on the ERAM, but can affect the determination of the reconstructed momentum. This effect is expected to be small in ND280, where the magnetic field inside the magnet has been measured with a dedicated campaign [1], and can be larger in the PCMAG used in DESY, where inclined tracks were observed even for horizontal beam, as shown in Fig. 26.

It is worth saying that this effect cannot be explained by the curvature induced by the magnetic field that is negligible for the operational magnetic field and electron momenta used in the test beam.

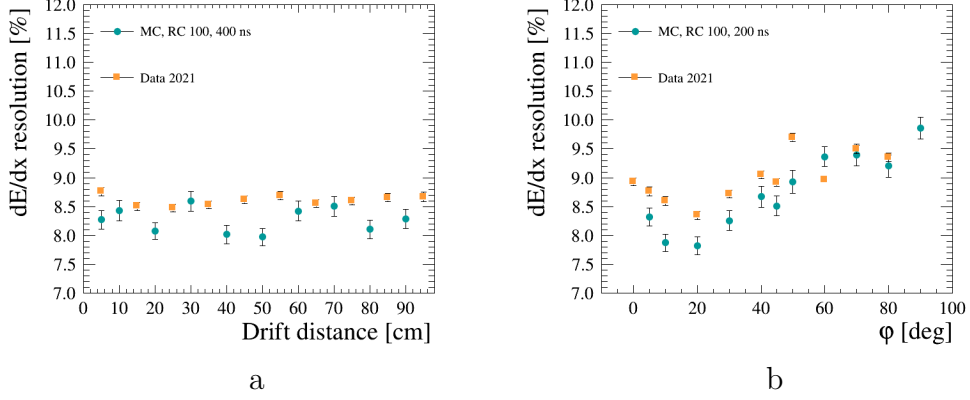


Figure 25: dE/dx resolution in data 2021 and MC for (a) horizontal tracks (at 412 ns peaking time) as a function of the drift distance and for (b) inclined tracks (at 200 ns peaking time) as a function of the track inclination angle. The dE/dx is calculated using the sum of the cluster charge.

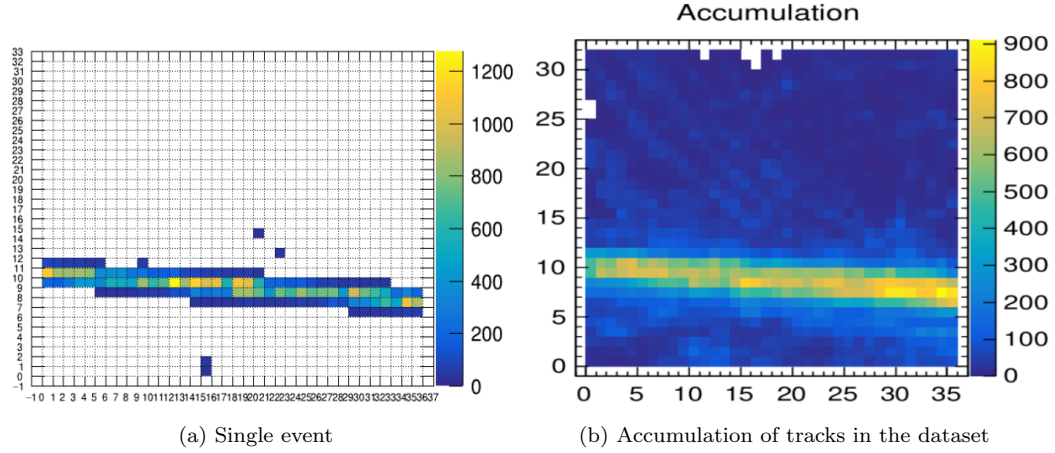


Figure 26: Event display of nominally horizontal beam. (a) single track; (b) accumulation plot of the tracks from the same dataset ($B = 0.2$ T).

661 Compelling arguments support the hypothesis of “ $E \times B$ effect” account-
 662 ing for the inclination of tracks projected on the ERAM. Below we present
 663 the explanation of the effect. The drift velocity is given by the Langevin
 664 equation:

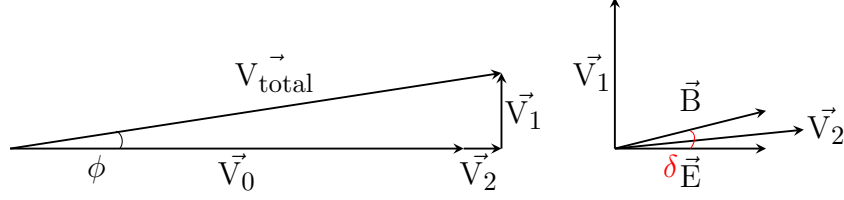


Figure 27: Schematic view of the drift velocity components according to the Langevin equation.

$$\vec{V}_d = \frac{\mu}{1 + (\omega\tau)^2} \left(\vec{E} + (\omega\tau) \frac{\vec{E} \times \vec{B}}{|\vec{B}|} + (\omega\tau)^2 \frac{\vec{B} \cdot (\vec{E}\vec{B})}{|\vec{B}|^2} \right), \quad (9)$$

where $\mu = \frac{e}{m}\tau$ is the electron mobility in the gas, $\omega = \frac{eB}{m}$, and τ is the time between two collisions.

The scheme visualizing the drift velocity components is shown in Fig. 27, in which we have defined the components of \vec{V}_d as $\vec{V}_0 = \frac{\mu}{1 + (\omega\tau)^2} \vec{E}$, $\vec{V}_1 = \frac{\mu}{1 + (\omega\tau)^2} \cdot (\omega\tau) \frac{\vec{E} \times \vec{B}}{|\vec{B}|}$ and $\vec{V}_2 = \frac{\mu}{1 + (\omega\tau)^2} \cdot (\omega\tau)^2 \frac{\vec{B} \cdot (\vec{E}\vec{B})}{|\vec{B}|^2}$. The angle between the electric and magnetic field is defined as δ so that $|\vec{E} \times \vec{B}| = EB \sin(\delta)$.

Assuming small δ , the \vec{V}_2 component aligns with \vec{V}_0 component. Then the drifting electrons will move transversely in the \vec{V}_1 direction and will be projected on the ERAM with a shift Δ :

$$\Delta = Z_{\text{drift}} \times \left\langle \frac{v_y}{v_z} \right\rangle = Z_{\text{drift}} \times \left(\frac{\langle \delta \rangle \omega\tau}{1 + (\omega\tau)^2} \right) \quad (10)$$

where Z_{drift} is the drift distance and $\langle \delta \rangle$ is the average value of δ along the drifting electrons trajectory.

Since $\langle \delta \rangle$ varies along the track, an apparent inclination of the track is observed which can be evaluated with ϕ_{app} :

$$\phi_{\text{app}} = \text{atan} \left(\frac{y_L - y_R}{X_{\text{ERAM}}} \right) \quad (11)$$

where X_{ERAM} is the width of the ERAM (40.6 cm) and y_L and y_R are the track vertical positions on the Left and Right edges.

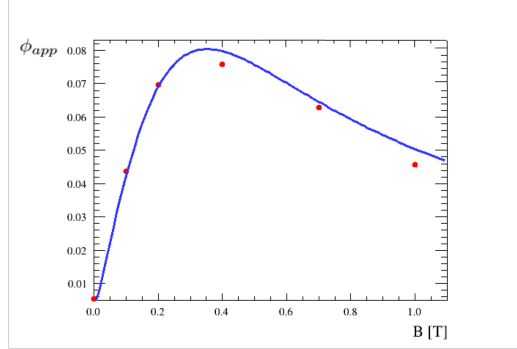


Figure 28: The red points show the dependence of observed track inclination on the magnetic field strength. Assuming that the δ values at each end of the track are opposite, these inclinations correspond to twice the displacement given by Eq. 11. The theoretical prediction is shown in blue; the model depends only on $|\delta|$ and the fit finds $|\delta| = 0.018$ as the best estimate. Notice the slight deviation for high magnetic field, where the bending effect of the longitudinal magnetic field starts to be relevant.

677 It follows from Eq. (10) that the apparent inclination due to $E \times B$ effect
678 is maximum for $\omega\tau = \mu B = 1$. In our case, where the electron mobility is
679 expected around $\mu = 2.8 \text{ T}^{-1}$, this means $B \simeq 0.36 \text{ T}$, which is consistent with
680 what Fig. 28 shows.

681 As it can be seen in Fig. 26, the electrons drifting to the leftmost region of
682 the ERAM are shifted upwards, while the ones drifting to the rightmost re-
683 gion are shifted downwards. The displacements perpendicularly to the track
684 depend on the component of the magnetic field on the track direction. It
685 turns out that this component flips sign when the track crosses the inner vol-
686 ume of the PCMAG solenoid due to the symmetry of the radial components
687 of its field.

688 To study this effect, we simulated the motion of drifting electron with
689 Garfield++ [31], under the proper electric and magnetic field conditions and
690 the gas mixture used in the detector. For the magnetic field, we use the map
691 based on previous measurements at DESY [32] and shown in Fig. 29. For
692 the electron mobility the value $\mu = 2.84 \text{ T}^{-1}$ was used in the simulation.

693 From both data and simulation, we compute the inclination of tracks
694 projected on the ERAM, and compare the results. Fig. 30 shows that the
695 simulation is able to reproduce the vertical displacement of drifting electrons

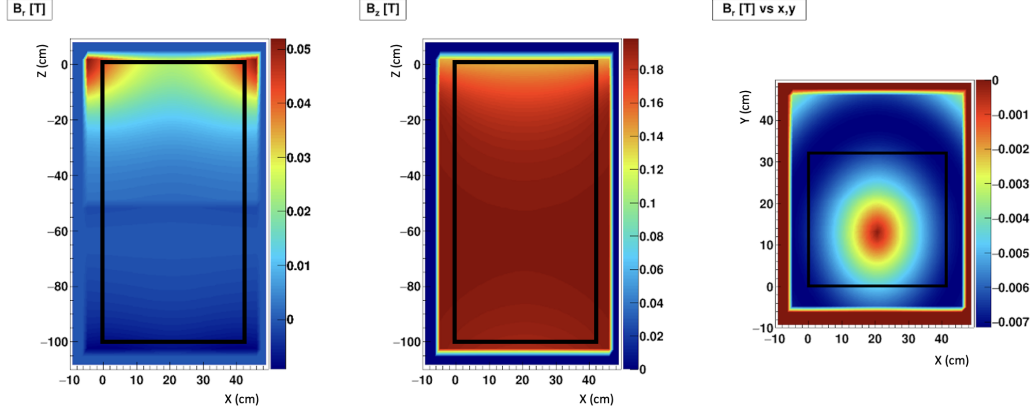


Figure 29: Map of the magnetic field. Left: radial component, top view. Central: longitudinal component, top view. Right: radial component, front view. The black boxes represent the contours of the TPC's drift volume. Notice the non-negligible radial component of the field especially in the rear of the TPC.

as observed in the data.

The $E \times B$ effect dependence on magnetic field is shown in Fig. 31 for different values of magnetic field and different drift distances. As expected, without magnetic field, there is no displacement in Y . When the magnetic field is on, as expected, the larger displacement is observed for small values of magnetic field.

The $E \times B$ effect generates displacements of the charge landing position on the anode surface which result in the observed inclination of the tracks. However these displacements do not scale linearly along the track and deviations from the inclined direction are expected which could explain the biases observed in the spatial resolution described in Sect. 9. Further investigations are ongoing on this point but it is already clear that these biases share the same behavior with respect to the magnetic field as the $E \times B$ effect reported above.

In Fig. 32 we show the biases in the spatial resolution for different values of the magnetic field and as a function of the drift distance. The biases are small for all the drift distances when the magnetic field is off. When the magnetic field is on we observe larger biases for short and long drift distances, similarly to the ones shown in Fig. 19. The larger biases are observed for values of magnetic field of 0.2 and 0.4 T where the $E \times B$ effects are largest.

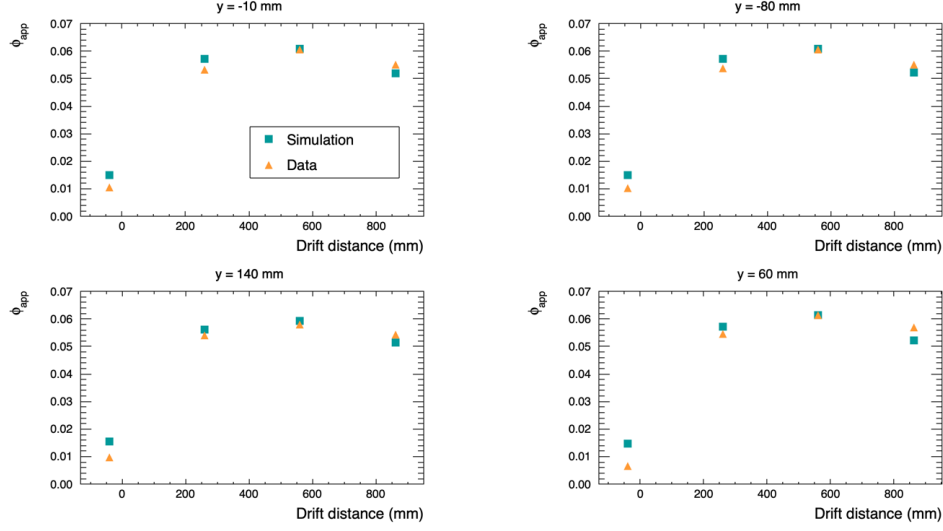


Figure 30: Track inclinations in data and simulations for $B = 0.2$ T. Each plot represents a different vertical position of the initial ionization track. The simulation uses Garfield++ [31] as described in the text.

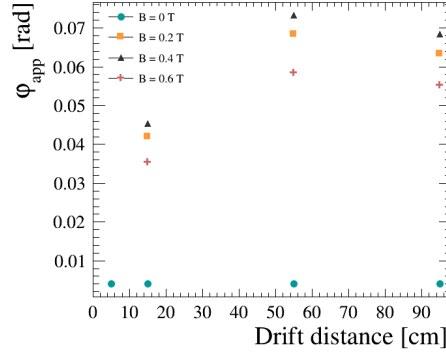


Figure 31: Track inclinations with respect to the drift distance for the beam parallel to the pad side for different values of magnetic field at the drift velocity of 78.7 mm/ μ s and peaking time of 200 ns.

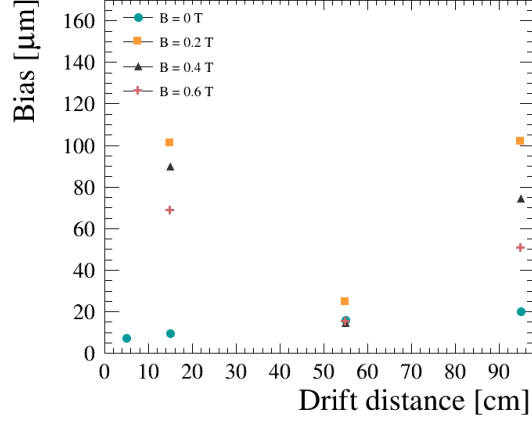


Figure 32: Track position bias with respect to the drift distance for the beam parallel to the pad side for different magnetic fields with drift velocity of $78.7 \text{ mm}/\mu\text{s}$ and peaking times of 200 ns.

13. Discussion and further improvements

A brief discussion of the obtained results is presented below.

The ERAM "charge spreading" effect has a small impact on the resolution of the measurement of the dE/dx . In this approach, when adding up the charges "shared" between pads due to the diffusion, the "charge spreading" time-dependent effect has to be taken into account not to bias the dE/dx measurement.

In contrast, the ERAM "charge spreading" effect allows for a dramatical improvements of the spatial resolution. As shown in Sect. 11, if the maximal amplitude of the waveform is used, the spatial resolution does not depend significantly on the ERAM RC value. In fact one can calculate that the ratio of the maximal amplitude of a neighbour pad to the one of the leading pad, before convoluting with the electronics response, is independent of RC. But the shape of the charge signal as a function of time depends on RC and the integration of the electronics response will induce some dependence of this ratio on RC.

The spatial resolution also depends on the relative gain between neighboring pads. This gain and its variation from pad to pad needs to be well measured and calibrated.

That is why measurements of RC and gain maps of the ERAM modules

736 are performed using a point-like iron X-ray source placed close to the ERAM.
737 These measurements are complementary to the test beams data analyses and
738 will be a subject of a future publication.

739 The simulation allows to understand deeper the data from the test beam,
740 and to disentangle different effects, when associated to the simpler data from
741 the X-ray surveys.

742 14. Conclusions

743 In this paper we present the performances of the prototype of the HA-
744 TPCs for the T2K Near Detector upgrade obtained during a test beam at
745 DESY performed in 2021. The TPC was instrumented with one of the ERAM
746 detectors that will be installed in the HA-TPCs and the final HA-TPC read-
747 out electronics chain.

748 The test beam data allowed spatial and dE/dx resolutions to be deter-
749 mined as a function of the angle of the track with respect to the ERAM plane
750 for all the drift distances of interest for T2K. Spatial resolution better than
751 $800\text{ }\mu\text{m}$ is obtained for all the angles and all the drift distances using a ded-
752 icated clustering algorithm which is adapted to the track angle. Deposited
753 energy resolution better than 10% is obtained for all the angles.

754 The data are compared with a simulation of the ERAM response, includ-
755 ing the features of the resistive layer. As shown in this paper, the simula-
756 tion is able to satisfactory reproduce the observed charge sharing between
757 neighboring pads. Spatial resolution and dE/dx resolution are also in good
758 agreement between data and simulation.

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