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1 Demonstrator Detection System for the Active Target
2 and Time Projection Chamber (ACTAR TPC) Project

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21 **Abstract**

The design, realization and operation of a prototype or “demonstrator” version of an active target and time projection chamber (ACTAR TPC) for experiments in nuclear physics is presented in detail. The heart of the detection system features a MICROME GAS gas amplifier coupled to a high-density pixelated pad plane with square pad sizes of 2×2 mm². The detector has been thoroughly tested with several different gas mixtures over a wide range of pressures and using a variety of sources of ionizing radiation including laser light, an α -particle source and heavy-ion beams of ²⁴Mg and ⁵⁸Ni accelerated to energies of 4.0 MeV/u. Results from these tests and characterization of the detector response over a wide range of operating conditions will be described. These developments have served as the basis for the design of a larger detection system that is presently under construction.

22 *Keywords:* Active Target, Time Projection Chamber, MICROMEAS,
23 Nuclear Physics

24 1. Introduction

25 The use of active targets and time projection chambers (TPCs) for ex-
26 periments in nuclear physics can be traced back nearly 30 years. Histor-
27 ically, their intrinsic luminosity, three-dimensional tracking and particle-
28 identification capabilities and relatively low-energy detection thresholds were
29 some of the main characteristics where these types of detection systems of-
30 fered a more attractive option when compared to conventional experimental
31 techniques. Examples include IKAR at GSI [1], the MSTPC at RIKEN [2], the
32 Maya active target at GANIL [3], the University of Warsaw optical TPC [4]
33 and the CENBG TPC [5]. A detailed review of existing active targets can
34 be found in Ref.[6]. While extremely successful, many of these previous-
35 generation detectors were each faced with a number of experimental chal-
36 lenges and limitations that were a result of the technology available at the
37 time of their construction.

38 With recent technological developments in micro-pattern gaseous detec-
39 tors (MPGDs) [7–10], connectors and cables to achieve higher-density point-
40 to-point contacts and electronics and data-acquisition systems that feature
41 front-end data processing with high data throughput, present-day active tar-
42 gets and time projection chambers can achieve significantly higher channel
43 densities than could previously be contemplated. Combined with ongoing
44 developments in the production and acceleration of short-lived beams of rare
45 isotopes at radioactive ion-beam facilities worldwide, the demand for active
46 targets and time projection chambers in the nuclear physics community has
47 increased dramatically [11].

48 The active target and time projection chamber (ACTAR TPC) is an
49 ambitious detector development project whose goal is to develop a state-of-
50 the-art detection system that consists of one (or possibly several) MPGDs
51 coupled to a pixelated pad plane consisting of square pads with a pitch of
52 $2 \times 2 \text{ mm}^2$. Both the overall channel density of 25 pads/cm^2 and the total

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53 number of channels (16384) are, to the best of our knowledge, the highest that
54 have been achieved by any detector in nuclear physics to date. In the present
55 article, the design construction and operation of a 2048-channel prototype
56 or “demonstrator” version of the ACTAR TPC design is described in detail.
57 Calibration methods used to characterize the detector as well as the results
58 of radioactive source, laser and in-beam tests will be presented.

59 **2. ACTAR TPC Demonstrator Design**

60 *2.1. General layout*

61 The main goal of the ACTAR TPC demonstrator was to develop a fully
62 functional prototype detector that would be used to assess the feasibility and
63 robustness for all aspects related to its mechanical design. Some of the most
64 crucial components that required verification before moving towards the final
65 design included the mechanics of the pad plane, the design of the electrostatic
66 field cage, the choice of connectors and cables, and the electronics integration.
67 The ACTAR TPC demonstrator has a total of 2048 channels, which is 8 times
68 smaller than the full-size detector that is presently under construction.

69 The ACTAR TPC demonstrator was designed at the Institute de Physique
70 Nucléaire d’Orsay (IPNO). The base geometry of the detector consists of an
71 aluminum inner skeleton whose central volume is $300 \times 250 \times 210 \text{ mm}^3$. The
72 detector is encased with 6 removable side flanges (top, bottom and 4 sides)
73 as shown in Figure 1. One of the side flanges was designed with a 12 mm
74 diameter circular entrance window to allow the detector to be coupled to a
75 beam line. A $6 \mu\text{m}$ thick Mylar foil serves as the sole interface between the
76 beam line (vacuum, 10^{-6} mbar) and the gas volume of the detector itself that
77 is typically operated with pressures ranging from 100 to 1000 mbar. The re-
78 maining 3 side-flanges are dedicated to support optional ancillary detectors.
79 Gas flow into and out of the chamber uses two connectors located on oppo-
80 site side flanges. The top flange (cathode) was designed to support vertically
81 adjustable radioactive sources that can be located in one of two possible po-
82 sitions. The cathode voltage is supplied through a safe high-voltage (SHV)
83 connector located on this flange. The bottom flange (the pad plane) houses
84 the core of the TPC detection system. The chamber was designed to sustain
85 1 atm differential pressure, so that the active target can run from ~ 0 bar to
86 ~ 2 bar, if equipped with proper O-rings.

87 The rectangular pad plane consists of an active area of $64 \times 128 \text{ mm}^2$.
88 Individual square copper pads with a pitch of 2 mm and separated by $80 \mu\text{m}$

89 tile the surface of the pad plane for a total 32×64 pads or 2048 total pixels. A
90 MICROMEGAS amplification system [7] was deposited on top of the pad plane
91 using the bulk technique [8]. A wire field cage surrounds the pad plane at a
92 distance of 5 mm from the edge of the micromesh and extends to a vertical
93 height of 170 mm. The role of the field cage is to maintain a homogeneous
94 vertical electric field across the entire drift region above the pad plane. The
95 precise geometry of the field cage will be described below in section 3.2. Both
96 the pad plane and the field cage are fixed onto the bottom flange, as shown
97 in Fig. 1. An additional 3 SHV connectors situated on this flange are used to
98 supply the voltage for the MICROMEGAS and the field cage. A more detailed
99 view of the mechanical design of the pad plane is presented in Fig. 2.

100 *2.2. Micromegas and pad plane*

101 Ionization electrons produced in the gas volume will be guided to the bot-
102 tom of the detector under a uniform electric field. Amplification of the elec-
103 tron signals is performed using a MICROMEGAS system situated at the bottom
104 of the field cage. The MICROMEGAS consists of a 45/18 stainless-steel woven
105 micromesh laminated on 256 μm high insulating pillars. The amplification
106 gap between the pad plane and the micromesh is approximately 220 μm af-
107 ter the lamination process. The MICROMEGAS bulk was manufactured by
108 the CERN PCB workshop. This particular gap thickness is relatively large
109 when compared to standard MICROMEGAS detectors. This choice was mo-
110 tivated by results obtained in our previous study that demonstrated that
111 the larger gap was better suited to a wider range of operating gas pressures
112 including low pressures of ~ 100 mbar [12]. Typical operating voltages of the
113 MICROMEGAS range from -200 V to -1000 V depending on the type of gas,
114 pressure and desired gain. In order to minimize the capacitance of the pixel
115 routing and the total number of layers in the PCB pad plane, the connectors
116 on the exterior side of the pad plane were chosen so that they occupy the
117 same surface area as the active surface on the interior side. The pad plane
118 serves as the primary interface between the gas volume of the detector and
119 the outside (atmospheric pressure). To clean the chamber before filling it
120 with gas, it must be pumped down to primary vacuum. The pad plane must
121 therefore be able to sustain ~ 1 atm differential pressure with minimal me-
122 chanical deformation. To further reinforce the mechanical rigidity, the PCB
123 pad plane was then glued and screwed onto a 15 mm thick aluminum plate.
124 Small openings of 30×7 mm² were machined into the plate to allow the con-
125 nectors on the PCB to pass through it, as shown in Fig. 2. The 2×48 -channel

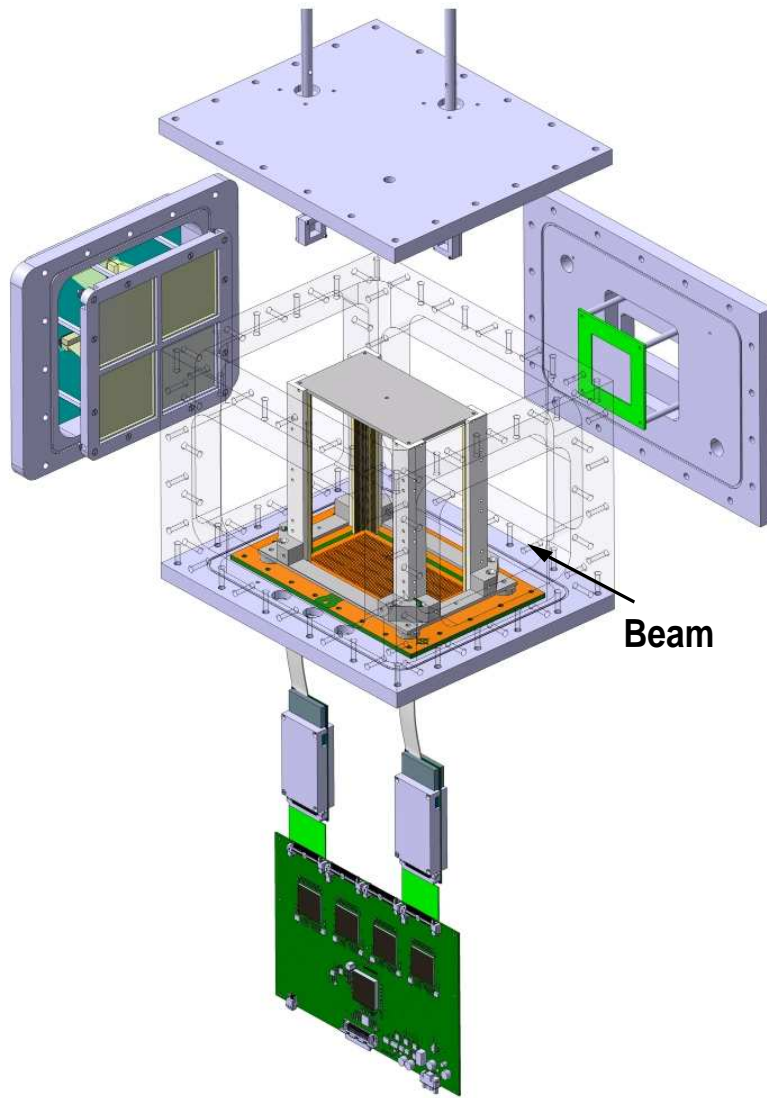


Figure 1: (Color online) 3D drawing of the ACTAR TPC demonstrator. The downstream (left) and the right side flanges are shown equipped with four and one double sided stripped silicon strip detectors, respectively. The top flange holds two retractable and vertically adjustable radioactive source arms. The four field cage pillars and the cathode above them are mounted on the pad plane (bottom flange). Outside the chamber and situated below the pad plane, the connection of a single front end electronics card via two spark-protection circuits is shown. A total of 8 cards are required to process the 2048 channels of the demonstrator.

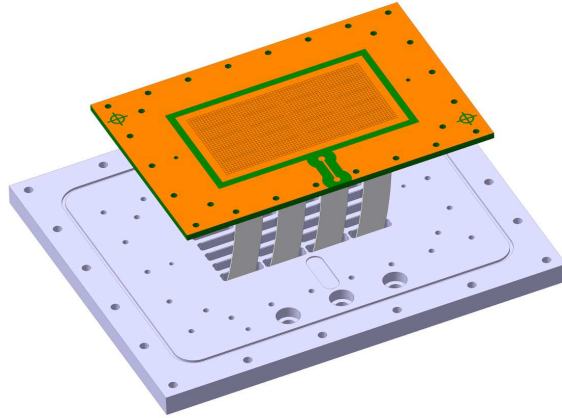


Figure 2: (Color online) Drawing of the pad plane and aluminum frame assembly.

126 SAMTEC connectors have a pitch of 0.8 mm and were wave soldered onto
 127 the pad plane before the MICROMEAS were assembled above. The final pad
 128 plane is a 4-layer PCB with a thickness of 4 mm. Mechanical simulations
 129 were performed to confirm that the deformation of the entire assembly (pad
 130 plane PCB and the aluminum frame) was less than 100 μm at a differential
 131 pressure of 1 atm.

132 *2.3. Electronics and data-acquisition system*

133 Data from the 2048 channels of the ACTAR TPC demonstrator are pro-
 134 cessed and stored using the General Electronics for TPCs (GET) system [13].
 135 Between the pads and the electronics a set of 32 protection circuits with 64
 136 channels each were designed to protect the front end from highly saturat-
 137 ing signals that could arise from sparks. The spark-protection circuits were
 138 connected to the pad plane using 12 cm Teflon NEXAN coaxial cables with
 139 85 pF/m linear capacitance.

140 The GET system is a comprehensive and generic digital electronics and
 141 data-acquisition system that was designed for nuclear physics instrumenta-
 142 tion with up to 30000 channels. A full description of the GET system is
 143 provided in Ref. [13]. A brief summary is provided here for some of the fea-
 144 tures that are of relevance to the ACTAR TPC demonstrator. The front-end
 145 electronics consists of a custom designed and versatile 64-channel Application
 146 Specific Integrated Circuit (ASIC) chip called “ASIC for GET” or AGET.
 147 The AGET provides, for each channel, a charge sensitive pre-amplifier with

148 adjustable gain (dynamic ranges of 120 fC, 240 fC, 1 pC and 10 pC), an ana-
149 logue filter (shaper) with a peaking time ranging from 70 to 1014 ns, a leading
150 edge discriminator and a 512-cell switch capacitor array to continuously sam-
151 ple the signal with a maximum frequency of 100 MHz. Four AGET chips
152 (4×64 or 256 channels) each followed by a 12-bit Analogue to Digital Con-
153 verter (ADC) are integrated onto a front-end board called AsAd (ASIC and
154 ADC). A schematic of one AsAd card with 4 AGET chips is shown in Fig.1.
155 Digitized data from up to 4 AsAd cards (4×256 or 1024 channels) are col-
156 lected and processed by a concentration board (CoBo). The CoBo cards
157 are compatible with the Micro Telecommunications Computing Architecture
158 (μ TCA) and are operated in a Vadatech VT893 μ TCA chassis. A total of
159 2 CoBo cards are required to read the 2048-channels of the demonstrator
160 pad plane. Synchronization and distribution of the 100 MHz global master
161 clock through the μ TCA backplane is performed using the Multiplicity Trig-
162 ger and Time (MuTanT) module. The MuTanT also provides multi-level
163 triggering capabilities. System master trigger decisions can be derived from
164 external sources (L0), overall pad multiplicity (L1) or through a user-specific
165 hit-pattern algorithm (L2).

166 Communication between the μ TCA chassis and the data-acquisition com-
167 puter is achieved through an optical fibre from the 10 GbE network switch on
168 the μ TCA Carrier Hub (MCH). The MCH is a commercially available module
169 that operates in a dedicated slot of the μ TCA chassis. Detailed technical de-
170 scriptions of the μ TCA architecture and the MuTanT module are provided in
171 Ref. [14]. The data-acquisition computer is a DELL PowerEdge R420 server
172 with dual 6-core/12-thread Xeon E5-2430 2.2 GHz, 32 GB of random-access
173 memory (RAM) and 8 TB of total disk space. The data acquisition soft-
174 ware running on LINUX CentOS was developed for the GET system and
175 consists of 3 main subsystems. The electronics control core (ECC) is used
176 to load the particular hardware configurations and monitor the electronics
177 boards. The data flow subsystem is based on the existing NARVAL modu-
178 lar data-acquisition framework [15] that contains specific processes that are
179 used for data collection, event building and merging, online data processing
180 and filtering, and data storage. The run control subsystem is a user-friendly
181 graphical user interface that incorporates the ECC and data flow subsystems
182 to provide global control and monitor the status of the entire system.

183 The configuration of the GET electronics is performed using a java-based
184 Graphical User Interface developed at GANIL. This software provides an
185 easy way of configuring the electronics parameters such as the gain, threshold

186 and peaking time of the individual channels as well as setting the triggering
187 conditions.

188 **3. Operation of the ACTAR TPC Demonstrator**

189 *3.1. Electronics and MICROMEAS calibration*

190 Amplified signals from the charge pre-amplifiers of the GET system ex-
191 hibit channel-by-channel gain fluctuations that are typically on the order of
192 $\sim 10\%$. A relative gain alignment of the individual channels must therefore
193 be applied before performing any detailed analysis. Aligning the individual
194 channels requires a two-step process. The first is to send an external pulser to
195 the mesh of the MICROMEAS so that a charge can be injected in all channels.
196 While this step is relatively straightforward, the amount of charge deduced
197 at the channel level will depend upon both the gain of the pre-amplifier for
198 that specific channel and the size of the gap between the mesh and the pad
199 at that particular location. To disentangle the relative contributions from
200 both of these, a second step is then required to deduce the height of the
201 mesh-pad gap on a pad-by-pad basis. A measurement of the gap homogene-
202 ity for the MICROMEAS detector used in the ACTAR TPC demonstrator
203 was performed using the method described in Ref. [16]. A collimated ^{55}Fe X-
204 ray source mounted on an automated 2-dimensional scanning table was used
205 to correlate the measured response of the mesh with the precise position of
206 the source. The relative gap of the micromesh was then reconstructed using
207 Magboltz [17] and converted into an effective gain for any combination of gas
208 species or amplification voltage used.

209 A scan of the pad plane was performed using an $\text{Ar}(97\%)+\text{iC}_4\text{H}_{10}(3\%)$ gas
210 mixture at a pressure of 1021 mbar. The resulting gain map and deduced
211 micromesh-pad gap values are presented in Fig. 3. The gain fluctuation
212 measured was of the order of 10%. The deduced gap height across the entire
213 surface was found to be homogeneous to within $\pm 1\%$. Such small variations
214 are negligible when compared to the channel-by-channel gain fluctuations
215 associated with the electronics. Injecting an external pulser on the mesh as a
216 means to calibrate the gain fluctuations of the electronic channels is therefore
217 fully justified for a relatively homogeneous MICROMEAS gap.

218 *3.2. Field cage and drift field homogeneity*

219 The homogeneity of the electric field is essential for accurately recon-
220 structing particle trajectories through the drift volume. The ideal field cage

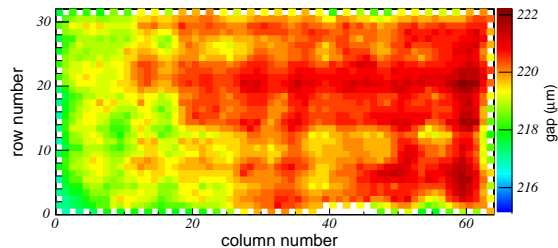


Figure 3: (Color Online) MICROMEAS gap homogeneity map deduced with an Ar(97%)+iC₄H₁₀(3%) gas mixture at 1021 mbar. A reference gap of 220 μm was chosen for the Magboltz calculations.

221 is one that would maintain a static and homogeneous electric field that is
 222 completely perpendicular to the surface of the micromesh (vertical in the
 223 case of ACTAR TPC) with absolutely no components acting in the parallel
 224 (horizontal) direction. In practice, small parallel fields can be tolerated pro-
 225 vided that their magnitude, relative to the perpendicular electric field, are
 226 less than the ratio of half the pad size (1 mm) to the drift height (17 cm).
 227 This upper limit of 0.6% for the field-cage tolerance is to ensure that the
 228 difference between the creation points of the ionization electrons and their
 229 corresponding mesh arrival points are smaller than 1 pad.

230 In many experiments, the reaction products will have sufficient energy to
 231 escape the drift volume. The field cage must therefore be transparent to allow
 232 these particles to pass through the cage so that they can be detected in a set of
 233 auxiliary detectors such as scintillators or silicon detectors. Special care must
 234 also be taken to ensure that the presence of these auxiliary detectors do not
 235 disturb the drift field. Following several tests and a detailed simulation study
 236 (described below), a double wire-plane field-cage design was chosen. This
 237 design, while more complex, outperformed a single wire-plane cage design in
 238 terms of overall electric field homogeneity. The field cage is connected to two
 239 separate power supplies, to fix the potentials on the top of the cathode and
 240 at the bottom, via a set of resistors to the ground. The value of the resistor
 241 depends on the voltage applied on both power supplies. It is of the order of
 242 10 M Ω . The mesh is polarized separately to be able to tune its voltage to
 243 a different value than for the field cage bottom, in order to compensate for
 244 side effects of the electric field on the border of the pad plane, and to avoid
 245 the field cage current to be sent in the mesh.

246 The double wire-plane field cage designed for the ACTAR TPC demon-

247 strator consists of an internal cage with 4 wire planes situated at a distance
248 of 5 mm from the edge of the pad plane. The distances between the field
249 cage and the interior walls of the chamber are 40 mm in the vertical direction
250 (above the cathode) and about 70 mm on all four sides. The voltage between
251 the cathode and the mesh of the MICROMEGAS is homogeneously degraded
252 using $4.7 \text{ M}\Omega$ (1%) surface-mounted resistors soldered between each wire.
253 Each wire plane consists of 169 wires each with a diameter of $20 \text{ }\mu\text{m}$ and a
254 1 mm spacing. The second field cage surrounds the first and consists of 4
255 wire planes with 34 wires each. The wire diameter is also $20 \text{ }\mu\text{m}$ and the wire
256 spacing is 5 mm. The distance between the inner and outer wire planes is
257 10 mm on all sides and their total height (the height of the drift volume) is
258 170 mm. With this design, the optical transparency is deduced to be nearly
259 98%.

260 The majority of unwanted stray electric fields in the drift region arise,
261 in our particular case, from electric fields that are generated between the
262 field cage and an array of silicon detectors that were placed at a distance
263 of $\sim 5.0 \text{ cm}$ from the sides of the cage. Assuming that the cathode bias is
264 3500 V , which corresponds to a drift electric field of approximately 200 V/cm
265 in the vertical direction, and that the Si detectors are at ground, then the
266 maximum horizontal electric field will be at the cathode and will be on the
267 order of 700 V/cm . The magnitude of this field decreases linearly with the
268 drift height. As described above, the goal of the field cage is to suppress these
269 fields from reaching the interior of the drift volume. Ideally this suppression
270 factor should therefore be on the order of 600 in order to achieve the 0.6%
271 design goal. A simple calculation of this suppression factor was performed
272 using the formalism described in Ref. [18] for a single wire cage (with 1 mm
273 wire pitch and $20 \text{ }\mu\text{m}$ diameter wires) and the resulting suppression factor
274 of ~ 90 was found. This is in good agreement with estimates from electric
275 field calculations using Garfield [19]. The Garfield calculations were then
276 extended to estimate the overall suppression factor for the double wire-plane
277 field-cage configuration using the geometry described above. The resulting
278 suppression factor was determined to be ~ 270 . The additional factor of 3
279 gained with the double wire field cage is therefore essential for reducing the
280 transverse electric fields while maintaining a suitable optical transparency.

281 The homogeneity of the drift electric field was characterized using a colli-
282 mated alpha source. Identical tests were performed using both a single field
283 cage with a wire spacing of 1 mm and the double field cage (inner cage with
284 1 mm wire pitch surrounded by a second cage with 5 mm wire pitch). With

285 the single cage, alpha-particle trajectories showed clear evidence for horizon-
286 tal deformation. The amplitude of this deformation increased even further
287 for particles emitted in the direction of the cathode where the transverse elec-
288 tric fields are largest. An example of a deformed trajectory is presented in
289 Fig. 4a) for the single wire-plane field cage. In this event, the alpha particle
290 was emitted from the left side of the figure and traverses the active volume of
291 the TPC before being detected in one pixel of a double sided Si strip detector
292 (DSSSD) placed outside and approximately 5 cm from the field cage. This
293 particular pixel of the DSSSD was chosen because it was situated close to the
294 cathode in the vertical direction and near the corner of the field cage in the
295 horizontal. This event thus corresponds to one of the largest deformations
296 observed.

297 A similar alpha-particle trajectory recorded using the same pixel of the
298 DSSSD but with the double wire-plane field cage is shown in Fig. 4b). The
299 overall horizontal deformation in the double cage is significantly reduced
300 compared to the single wire-plane field cage. Again, this particular trajectory
301 represents one of the most extreme cases. Considering all possible horizontal
302 and vertical alpha-particle emission angles, the majority of events would be
303 significantly less deformed.

304 *3.3. Laser tests*

305 The horizontal and vertical angular resolution with 2×2 mm² square pads
306 was investigated in Ref.[12] where it was shown that the resolution was largely
307 dominated by the straggling of the alpha particles in the gas. A new method,
308 that relies on the use of an ultra-violet laser light, was designed and tested
309 as a means to determine the intrinsic angular resolution of the detector in
310 the absence of straggling. The titanium sapphire (Ti:Sa) laser employed
311 was pumped by a 75 W 532 nm neodymium-doped yttrium aluminum gar-
312 net (Nd:YAG) laser (photonics industries CM57-532) frequency doubled at
313 10 kHz repetition rate. After triple harmonic generation, the Ti:Sa laser pro-
314 duced 162 mW pulses of 140 ns duration at a wavelength of 259 nm. These
315 pulses were of sufficient energy to ionize aromatic hydrocarbons, present in
316 the detector as impurities, via two-photon absorption. The laser light en-
317 tered the detector through a quartz window that was mounted on one of the
318 side flanges of the detector. At 259 nm, the transmission of this window
319 was measured using a photo sensor to be $\sim 98\%$. The horizontal angle of the
320 laser light was adjusted using a set of mirrors placed just before the entrance
321 window to the detector. The active volume of the TPC was filled with 1 bar

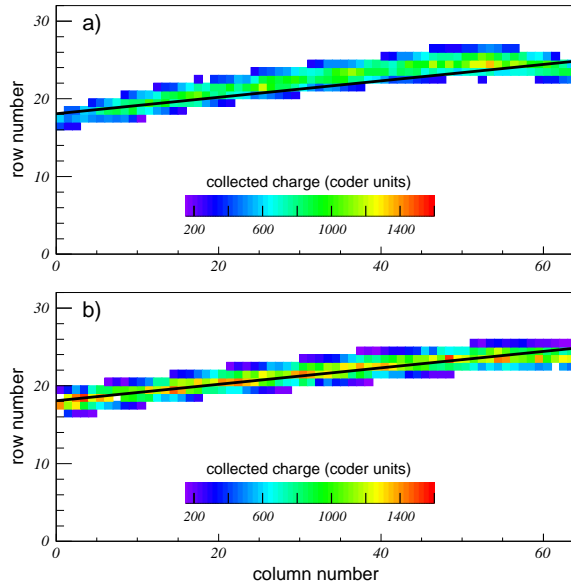


Figure 4: (Color online) Charge projection of an alpha-particle track in 40 mbar of isobutane, with a single wire-plane field cage (a) and with a double wire-plane field cage (b). In both figures, the cathode voltage was set to -2500 V and the mesh voltage was -400 V. The trigger for the data acquisition was provided by one pixel (near the cathode or top of the drift field) of a double sided Si strip detector (DSSSD) located approximately 5 cm behind the field cage. In both figures, the black solid line represents the physical trajectory of the alpha particle from the collimated alpha source to the center of the pixel of the DSSSD.

322 of Ar(97%)+iC₄H₁₀(3%) gas mixture. The cathode voltage was -2500 V
 323 and the mesh voltage was set to -380 V. The recorded charge projection
 324 for a typical laser pulse aimed at the corner of the field cage is presented
 325 in Fig.5a). The curvature exhibited near the end of the trajectory is again
 326 due to deformation induced by the single wire-plane field cage that was de-
 327 scribed above in Sec. 3.2. The three-dimensional angle of the tracks was
 328 reconstructed using an algorithm derived from those presented in Ref.[20].
 329 As the curvature arises from a systematic effect, a fit to the entire trajectory
 330 using a straight line will result in a systematic shift to the reconstructed
 331 angle. However the width of the angular distribution presented in Fig.5b) is
 332 not affected by this curvature. From Fig.5b), and neglecting the divergence
 333 of the laser beam, an angular resolution of 0.06° FWHM was achieved. This
 334 result indicates that, for the case of long trajectories, the angular resolution

335 for tracking particles through the active target will be entirely limited by the
 336 straggling of the ions in the gas rather than geometrical effects associated
 337 with the size of the individual pixels.

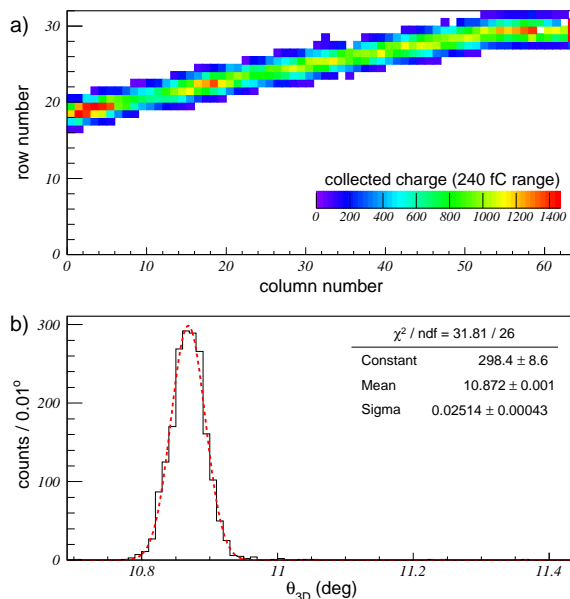


Figure 5: (Color Online) a) Recorded charge projection of a single 259 nm laser pulse in a gas mixture of Ar(97%)+iC₄H₁₀(3%) at 1 bar pressure. b) Three-dimensional angular resolution deduced from fitting many trajectories

338 3.4. Alpha-particle source tests

339 The energy resolution of the detection plane was further investigated us-
 340 ing a ²³⁹Pu, ²⁴¹Am and ²⁴⁴Cm mixed alpha source placed 35 mm downstream
 341 the pad plane. The detector was filled with 148 mbar of pure isobutane, which
 342 is sufficient to fully stop the alpha particles inside the active volume. The
 343 voltages applied on the cathode and the micromesh were set to -4000 V and
 344 -400 V, respectively. The total charge deposited by the alpha particles was
 345 obtained on an event-by-event basis by summing all of the individual charges
 346 collected on each pad. The individual charges were reconstructed using the
 347 procedures described in Ref.[21]. A typical total charge spectrum for the al-
 348 pha source is presented in Fig. 6. This spectrum was obtained by restricting
 349 the analysis to horizontal angles between $\pm 1^\circ$ in order to minimize the effect
 350 of the dead zone between the source and the beginning of the pad plane. A

351 fit to this spectrum using three Gaussian distributions yielded energy resolu-
 352 tions of 5.4%, 4.9% and 5.5% (FWHM) for alpha-particle energy deposit of
 353 3.74 MeV, 4.14 MeV and 4.53 MeV, respectively. These results are encourag-
 354 ing when compared to the previous values of 5%, 4.5% and 6% (FWHM) that
 355 were obtained in Ref. [12] and that used a mixture of Ar(98%) + CF₄(2%) at
 356 1100 mbar gas pressure and a MICROMEGAS detector with a gap of 256 μ m
 357 coupled to a 2 \times 2 mm² pad plane.

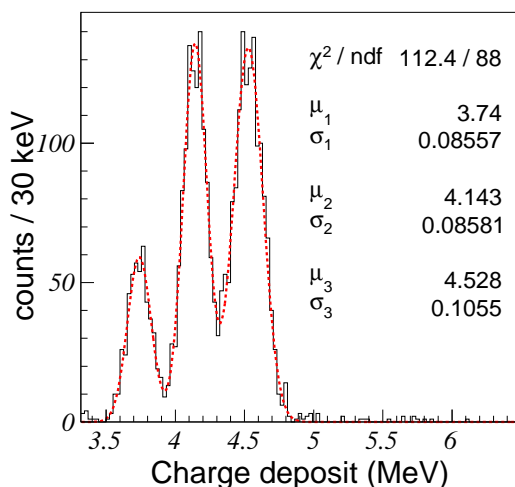


Figure 6: (Color Online) Total charge spectrum from a ²³⁹Pu + ²⁴¹Am + ²⁴⁴Cm mixed alpha source. The red dashed line corresponds to a fit to the histogram using 3 Gaussian distributions. The fit parameters are indicated in the inset. The fit parameters A , σ , and μ correspond to the maximum peak height, the standard deviation, and the position of the centroid, respectively.

358 3.5. Gain characterization measurements

359 The highest energy alpha particle at 5.8 MeV from ²⁴⁴Cm decay was also
 360 used to characterize the gain of the MICROMEGAS amplification system for
 361 various gas mixtures at several different pressures. For each gas mixture and
 362 pressure, measurements were performed using several different mesh volt-
 363 ages. For each measurement, approximately 30 horizontal alpha trajectories
 364 were selected, and the average charge deposited was calculated on a pad-by-
 365 pad basis. This averaged alpha-particle trajectory was then projected along
 366 its axis in order to obtain the average energy-loss profile. This profile is a

367 convolution of the true energy loss of the alpha particles with a Gaussian dis-
 368 tribution to describe the lateral straggling of the ionization electrons in the
 369 gas. Examples of several average energy-loss profiles that were measured in
 370 a He(90%)+iC₄H₁₀(10%) gas mixture at 700 mbar are presented in Fig.7a).
 371 At high mesh voltage, the gains of the charge pre-amplifiers were reduced to
 372 avoid saturating the electronic signals. The gain of the MICROME GAS was
 373 then deduced through a comparison of the registered charge profile with a
 374 SRIM simulation [22] of the energy loss of the alpha particles in the gas con-
 375 voluted with the lateral straggling of the electrons. The gain of the amplifier
 376 as a function of the applied mesh voltage is presented in Fig. 7b) for sev-
 377 eral different gas mixtures and pressures including He(90%)+iC₄H₁₀(10%)
 378 at 96 mbar and 700 mbar, He(95%)+iC₄H₁₀(5%) at 139 mbar and for pure
 379 iC₄H₁₀ at 98 mbar and 148 mbar. The gain curves of the low pressure He +
 380 iC₄H₁₀ mix exhibit a smaller slope than those of the other gases tested due
 381 to a saturation of the Townsend coefficient for the low partial pressure of
 382 isobutane. The maximum gain achieved for each of the gas mixtures tested
 383 corresponds to a detection threshold that is smaller than 2 keV/pad.

384 3.6. *In-beam tests*

385 The ACTAR TPC demonstrator was further characterized using low-
 386 energy beams of stable ions. Beams of ⁵⁸Ni and ²⁴Mg were produced at
 387 GANIL and were accelerated in the first separated sector cyclotron (CSS1)
 388 to energies of 4.0 MeV/u and 4.6 MeV/u, respectively. The beams were then
 389 sent to the G3 experimental area where they passed through a thin (100 or
 390 200 μg/cm²) carbon stripper foil and a set of two position-sensitive tracking
 391 detectors before traversing the Mylar foil entrance window of the detector.

392 The first test used the ⁵⁸Ni beam that had an average energy of ~3.0 MeV/u
 393 after the Mylar entrance window. The detector was filled with 90 mbar of
 394 pure iC₄H₁₀ and the cathode and mesh voltages were set to -1500 V and
 395 -300 V, respectively. With this beam energy, gas and gas pressure, the ⁵⁸Ni
 396 ions had a range of approximately 15 cm and thus were stopped in the ac-
 397 tive volume of the detector. The electron drift velocity was estimated using
 398 Magboltz [17] to be 2.5 cm/μs. The gain of the MICROME GAS was deduced
 399 to be 70, which is in good agreement with the results obtained in Fig. 7b) for
 400 pure iC₄H₁₀. Based on the SRIM/TRIM calculations [22] shown in Fig. 8a),
 401 the energy losses of the ⁵⁸Ni beam, the ¹²C ions and the scattered protons
 402 span nearly two orders of magnitude. To avoid saturating the signals on
 403 the 6 rows of pads directly under the beam axis, a lower gain of 1 pC was

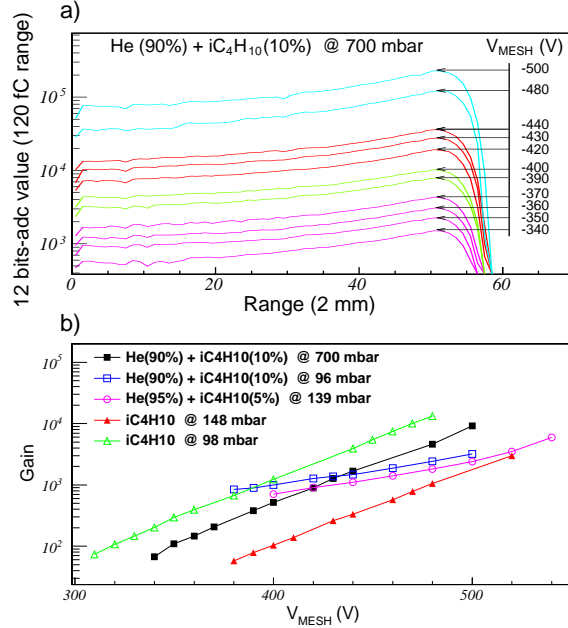


Figure 7: (Color Online) a) Average charge profiles of 5.8 MeV ^{244}Cm alpha particles obtained in a gas mixture of He(90%)+ iC_4H_{10} (10%) at 700 mbar using several different voltages applied to the micromesh. The gain setting of the pad electronics is indicated by the color of the profiles: pink for 120 fC, green for 240 fC, red for 1 pC and blue for 10 pC. b) Gain curves obtained for: He(90%)+ iC_4H_{10} (10%) at 700 mbar (black solid squares), He(90%)+ iC_4H_{10} (10%) at 96 mbar (blue open squares), He(95%)+ iC_4H_{10} (5%) at 139 mbar (pink open circles), iC_4H_{10} at 148 mbar (red solid triangles) and iC_4H_{10} at 98 mbar (green open triangles).

404 applied to these channels. A higher gain of 120 fC was used for the pads that
 405 were off beam axis. The geometry-dependent gain settings that were applied
 406 are shown in Fig. 8c). In Fig. 8e), the charge projection of a single event
 407 corresponding to the scattering of a proton in the gas by an incident ^{58}Ni
 408 beam ion is presented. In this figure, the ^{58}Ni ion is stopped in the chamber.
 409 The tail of the Bragg peak begins near column 42 and steadily decreases. At
 410 column 50, the tail extends past the 1 pC low-gain region and reaches the
 411 120 fC high-gain region where the remaining signal is amplified.

412 Identification of the scattered particles was performed using the correlation
 413 between the reconstructed range of the particles in the chamber and the
 414 total charge collected on the pad plane. In Fig. 9a), this method is clearly
 415 able to distinguish between the scattered protons and the ^{12}C ions. After

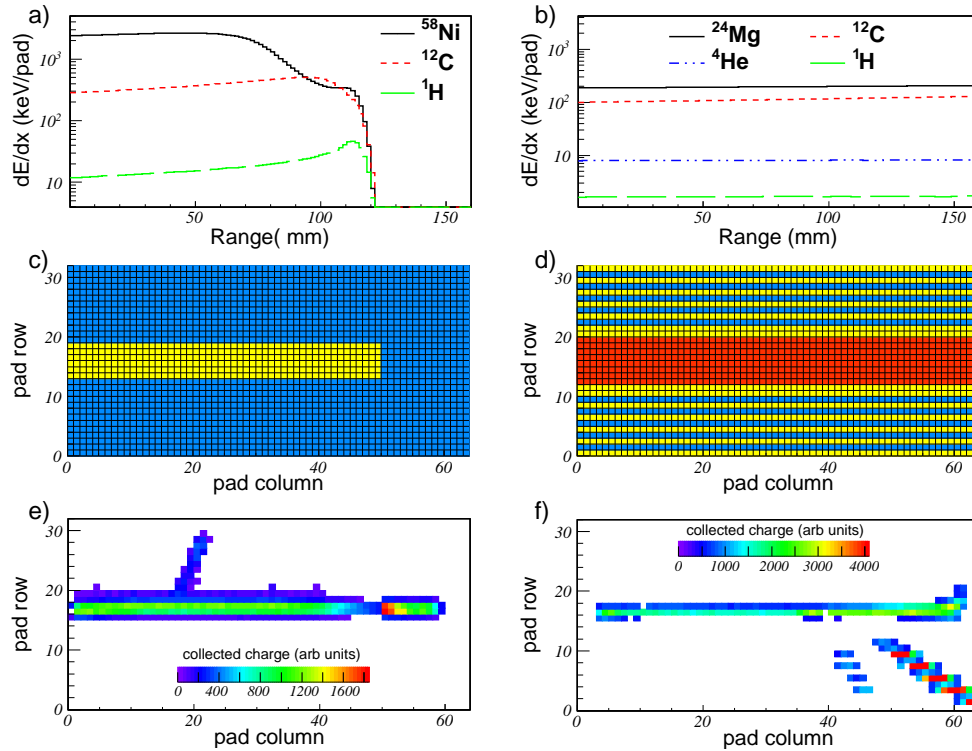


Figure 8: (Color Online) Top: SRIM energy-loss profiles of the particles involved in the ^{58}Ni test (a) and the ^{24}Mg test (b). Middle: Gain settings applied to the pad plane for the ^{58}Ni test (c) and the ^{24}Mg test (d). Blue indicates pads with 120 fC range, yellow for 1 pC range and red for 10 pC range. Bottom: Charge projection of the scattering of a proton by a ^{58}Ni ion (e) and the scattering of a proton and ^4He by a ^{24}Mg ion (f).

416 selecting proton scattering events, the excitation energy spectrum of ^{58}Ni at
 417 center of mass angles between 30 and 100 degree was reconstructed using the
 418 correlation between the angle of the proton, its energy (determined from its
 419 range in the gas) and the reaction energy (from 1.7A to about 0.2A MeV)
 420 estimated from the position of the reaction vertex that is the intersection of
 421 the beam and proton trajectories. The resulting excitation energy spectrum
 422 is presented in Fig.9b), with in the inset, the center of mass angular domain
 423 and the reaction energy domain covered. The energy resolution obtained was
 424 ~ 175 keV (FWHM), which is excellent for these types of detectors. For com-

425 parison, a recent result obtained with a similar prototype detector achieved
 426 a resolution of 800 keV (FWHM) for the reconstructed excitation energy
 427 spectrum of ${}^6\text{He}$ [23].

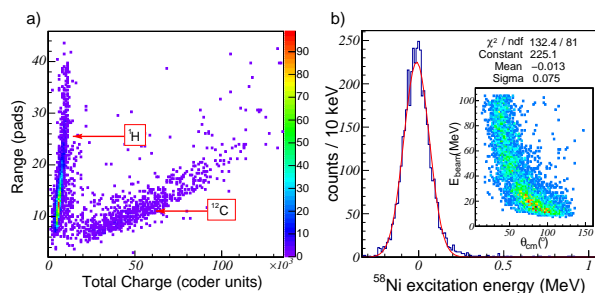


Figure 9: (Color Online) a) Particle identification plot obtained by correlating the range of the particles stopping in the active volume with the total charge deposit. Scattered protons and carbon ions are well separated. b) Excitation energy spectrum reconstructed for the ${}^{58}\text{Ni}+p$ reaction. A Gaussian fit to this distribution (red line) results in an energy resolution of ~ 175 keV (FWHM). Inset) center of mass angular and reaction energy domain covered by the present analysis.

428 A second test was performed using a ${}^{24}\text{Mg}$ beam at 4.6 MeV/u. After
 429 passing through the carbon stripper foil, the beam tracking detectors and the
 430 Mylar entrance window of the TPC, the ${}^{24}\text{Mg}$ beam energy was ~ 4.0 MeV/u.
 431 The demonstrator was filled with a mixture of He(90%) + $i\text{C}_4\text{H}_{10}$ (10%) at
 432 200 mbar. The cathode voltage was set to -1900 V and the mesh voltage
 433 to -380 V. With these settings, the electron drift velocity was estimated to
 434 be 1.7 cm/ μs and the gain of the MICROME GAS was approximately 500 (see
 435 Fig. 7). As shown in Fig.8b), the energy loss of the scattered ${}^{12}\text{C}$, ${}^4\text{He}$ and ${}^1\text{H}$
 436 ions span nearly two orders of magnitude. To be able to detect all 3 particles
 437 simultaneously with a transverse multiplicity of three pads to ensure a good
 438 track reconstruction, the electronics gain across the pad rows were alternated
 439 between high gain (120 fC) and low gain (1 pC). The central region directly
 440 under the beam axis was set to an even lower gain of 10 pC. The geometrical
 441 gain map employed is shown in Fig. 8d). A sample pile-up event is presented
 442 in Fig. 8f) and shows the charge projection that contains scattering events of
 443 both a proton and a ${}^4\text{He}$ ion. The proton track is only visible on the pads at
 444 120 fC gain and thus cannot be observed on the alternating 1 pC rows. The
 445 track of the ${}^4\text{He}$ ion is clearly visible on the 1 pC rows but its signals saturate
 446 the rows set to 120 fC gain. The ${}^{24}\text{Mg}$ beam above the 10 pC gain region is

447 also observed without saturating the channels. By carefully optimizing the
 448 gain settings for the individual rows, this technique can be used to extend
 449 the effective dynamic range of the system. A second method to identify the
 450 scattered particles employed a set of silicon detectors that were placed on
 451 the sides of the chamber. A plot of the energy loss (total charge) of the
 452 particles in the active part of the TPC (obtained by summing the charges
 453 on alternating rows as appropriate) versus the energy recorded in the silicon
 454 detectors is presented in Fig. 10. The two distinct groups of events in this
 455 figure correspond to ^1H and ^4He ions.

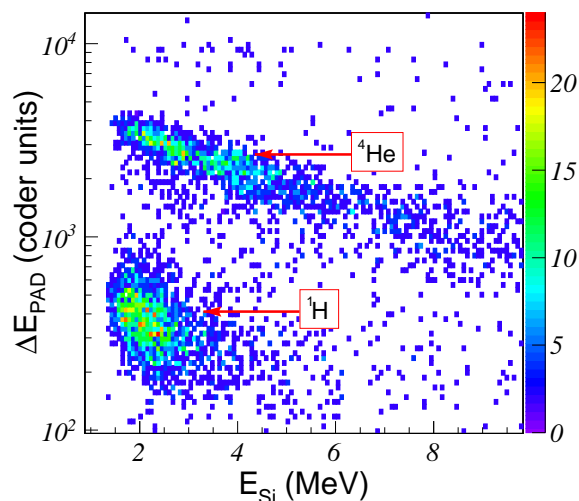


Figure 10: (Color Online) Particle identification for scattered ^1H and ^4He particles from a beam of ^{24}Mg ions at 4.0 MeV/u. The energy deposited (charge) on the pad plane is plotted versus the energy recorded in a set of Si detectors located on the sides of the chamber (perpendicular to the beam axis).

456 Finally, the multi-particle tracking capabilities of the ACTAR TPC demon-
 457 strator coupled to the GET electronics were investigated during the beam
 458 tests. Some typical events recorded using both the ^{58}Ni and the ^{24}Mg beams
 459 are presented in Fig. 11. The voxel reconstruction of the system permits to
 460 resolve the pileup of events, as illustrated on the two 3D plots on the left,
 461 and to track multi-particle final states (more than two particles) as depicted
 462 on the plots at the right of the figure.

463 *3.7. Summary and discussion*

464 Some of the key results that were obtained from the tests and calibrations
465 described above are summarized and where applicable compared to results
466 previously obtained from similar detectors.

467 Using the laser light calibration technique described above in Sec. 3.3,
468 a horizontal angular resolution of $\pm 0.06^\circ$ (FWHM) was obtained. For a
469 detector length of 128 mm, this corresponds to position resolution of only
470 ± 0.13 mm (FWHM). As straggling effects in the gas are absent with the
471 laser light, this result can be considered to be the intrinsic angular resolution
472 of the detector and depends primarily on the use of 2×2 mm² pixels. For
473 particles with long trajectories, straggling effects will completely limit the
474 angular resolution with typical results being on the order of $\pm 1^\circ$ in both the
475 horizontal and vertical directions [12]. In terms of angular resolution, the
476 use of larger pixels would therefore be expected to yield similar results. In
477 the Maya active target that uses 8 mm long hexagonal pads, for example,
478 angular resolutions of $\pm 1^\circ$ have also been obtained [20].

479 Energy resolutions obtained from summing the total charge on the pad
480 plane were obtained using a mixed 3α source. The results obtained were
481 typically 5% (FWHM) for α particles that deposited about 4 MeV in the
482 active volume of the detector. These results are in good agreement with our
483 previous study that achieved 4 to 5% (FWHM) using a similar micromegas
484 detector coupled to a 2×2 mm² pixelated pad plane [12]. These results are
485 about a factor of 2 to 3 better than the value of 11% (FWHM) obtained in
486 Ref. [24] from a MICROMEGAS segmented into one dimensional strips with a
487 pitch of 5 mm and 13% (FWHM) deduced in Ref. [23] from a similar pitch
488 MICROMEGAS detector with a circular geometry. As described in Ref. [12],
489 these results may not be fully comparable as they depend significantly on
490 the details of the analysis procedures.

491 When tested in beam, an energy resolution of 175 keV (FWHM) was
492 obtained in Fig. 8 for the reconstructed excitation energy spectrum of elas-
493 tically scattered ⁵⁸Ni ions by protons. This is about a factor 10 better than
494 the 2 MeV (FWHM) obtained for ⁶⁸Ni with the active target MAYA [25].
495 The improved energy resolution obtained in the present work compared to
496 Refs. [23, 25] is presumably dominated by the overall range resolution ob-
497 tained from alpha-particle source measurements.

498 In terms of overall gain and energy thresholds, several measurements
499 obtained in a variety of different gases, mixtures and pressures were presented
500 in Fig. 7b). These gain curves show that the detector can be operated up to a

501 maximum gain of about 10^4 (at 1 kHz beam intensity), which corresponds to a
502 low-energy threshold of approximately 0.15 keV/pad, considering that a track
503 can be properly treated if the transverse multiplicity is three pads. Through
504 careful adjustments of the electronic gains on a channel-by-channel basis
505 using the GET system, the effective dynamic range can be increased by an
506 additional order of magnitude to approximately 10^3 . In the ^{24}Mg in-beam test
507 described above, this feature was necessary to be able to observe scattered
508 protons (2 keV/pad), alpha particles (10 keV/pad) and the ^{24}Mg ion beam
509 (200 keV/pad) simultaneously and without saturating the electronics. The
510 future version of ACTAR TPC will allow the polarization of the central
511 pads located below the beam path in order to locally reduce the micromegas
512 electric field and hence the gain, further increasing the dynamic range of the
513 active target while limiting the risk of reaching the Raether limit, as shown
514 in Ref. [23].

515 Particle identification and tracking capabilities of the detector were also
516 explored in detail. Depending on the energies of the particles, a number of
517 complementary measurements such as the energy loss (charge collected) in
518 the target, the range of the particles in the gas and the energy deposited in
519 auxiliary detectors can be combined to discriminate between particles with
520 sufficient resolution. The use of a two dimensional segmented pad plane
521 coupled with state-of-the-art electronics to digitize the electron arrival times
522 on the pad plane are essential for studying reactions that lead to multi-
523 particle final states (more than two particles) or to discriminate and remove
524 pile up from the analysis as shown in Fig.11. Both of these will improve
525 the overall efficiency and allow new studies to be performed that were not
526 possible with previous active targets and TPCs in nuclear physics.

527 4. Conclusion

528 A novel 2048-channel prototype active target and time projection cham-
529 ber for nuclear physics experiments was presented. The heart of the demon-
530 strator features a $128\text{ mm} \times 64\text{ mm}$ pad plane that consists of a bulk MI-
531 CROMEGAS, with a $220\ \mu\text{m}$ gap, mounted on a highly pixelated pad plane
532 that features square pads with a pitch of $2 \times 2\text{ mm}^2$. An electric field cage
533 based on planar wire grids surrounds the pads and encompasses the 17 cm
534 height of the drift volume. In order to maintain a homogeneous drift elec-
535 tric field at the required level of $\leq 0.6\%$, the use of a double wire cage was
536 found to be essential. The use of wires rather than a solid structure is crucial

537 for our applications as the field cage must be transparent to particles that
538 escape the active volume of the detector. The double field cage design pre-
539 sented here, has achieved the homogeneity requirement while maintaining an
540 optical transparency of 98%.

541 Characterization and tests of the demonstrator were presented under a
542 wide variety of conditions and with several different sources of ionizing radi-
543 ation. These tests have provided many opportunities to test the electronics,
544 to validate or improve upon the mechanical aspects of the design, to develop
545 unique methods of calibration and to characterize the detector response with
546 several different gases over a wide range of pressures. In terms of resolution,
547 the horizontal angular resolution deduced using laser light was found to be
548 $\sim 0.06^\circ$ (FWHM) while the energy resolution obtained from the total charge
549 collected on the pad plane was deduced to be $\sim 5\%$ (FWHM) for a ~ 4 MeV
550 alpha particle. Tests performed with heavy ion beams of ^{24}Mg and ^{58}Ni have
551 also clearly shown the particle identification and multi-particle tracking capa-
552 bilities of such a detector. With more than 1 month of in-beam tests and now
553 more than 4 years of intensive operation, the mechanical design has proven to
554 be robust and reliable. All of these characteristics are extremely encouraging
555 for the long-term use of such a detector for applications in nuclear physics
556 with heavy-ion beams.

557 This prototype detector was designed and operated as a “demonstrator”
558 for the much larger ACTAR TPC detection system that is presently being
559 constructed. The new system will continue to use square pads of $2 \times 2 \text{ mm}^2$
560 but the size of the pad plane will be increased to 16384 pads/channels. The
561 design and experience gained with the demonstrator have thus played a cru-
562 cial role in the development of ACTAR TPC. First experiments with this
563 novel detection system are foreseen in 2018.

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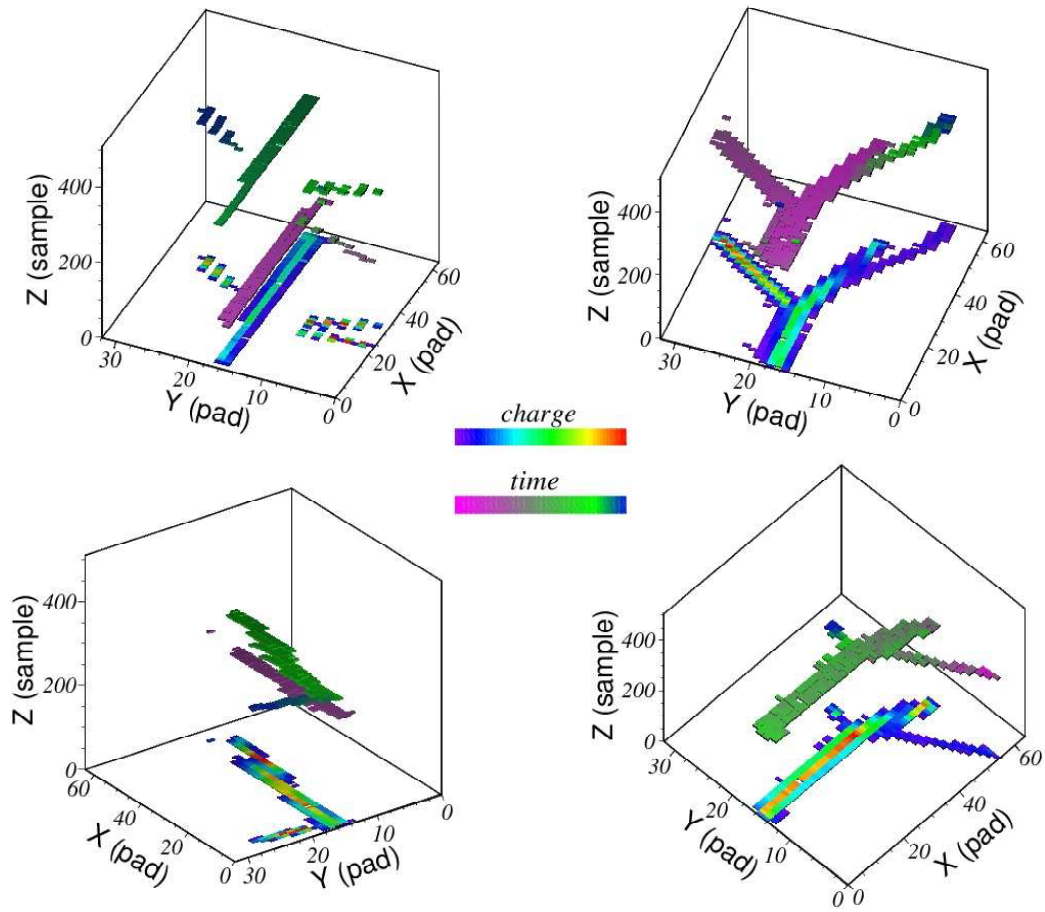


Figure 11: (Color Online) 3D events recorded by the ACTAR TPC demonstrator during the ^{58}Ni and the ^{24}Mg beam tests. The charge projection is plotted using a violet-to-red color palette, while the third dimension (time) is indicated on the voxels using a pink-to-blue color palette. The left two plots show pileup events while the right two plots show multi-particle final state tracking capabilities.