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Abstract: A novel MicroMegas detector based on microbulk technology with an embedded XY strip structure was developed, obtained by segmenting both the mesh and the anode in perpendicular directions. This results in a very low-mass device with good energy and spatial resolution capabilities. Such a detector is practically "transparent" to neutrons, being ideal for in-beam neutron measurements and can be used as a quasi-online neutron beam profiler at neutron time-of-flight facilities. A dedicated front end electronics and acquisition system has been developed and used. The first studies of this new detection system are presented and discussed.

Development of a novel segmented mesh MicroMegas detector for neutron beam profiling

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Abstract

A novel MicroMegas detector based on microbulk technology with an embedded XY strip structure was developed, obtained by segmenting both the mesh and the anode in perpendicular directions. This results in a very low-mass device with good energy and spatial resolution capabilities. Such a detector is practically “transparent” to neutrons, being ideal for in-beam neutron measurements and can be used as a quasi-online neutron beam profiler at neutron time-of-flight facilities. A dedicated front end electronics and acquisition system has been developed and used. The first studies of this new detection system are presented and discussed.

Keywords: microbulk MicroMegas, Position-sensitive detector, neutron beam profile

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1. Introduction

The MicroMegas detector is a two stage gaseous detector [1], widely used in nuclear and high energy physics thanks to the high versatility in the detection of different kinds of radiation, from X-rays to fission fragments. The gas-filled region of the detector is separated into two volumes, by the so-called “*micromesh*” (or simply “*mesh*”): the *drift region* between cathode and mesh and the *amplification region* between mesh and anode. Electrons, produced in the drift region by ionisation of gas molecules from the incoming radiation, are drifted by the low electric field applied in this region (typically 0.1 kV/cm) towards the micromesh and pass through the holes to the amplification region. Due to the high field applied in this region, they are amplified in electron avalanches. The “*microbulk*” MicroMegas is nowadays a well established production technology for the structure of the amplification region of the detector [2], based on the etching of a double sided copper-clad polyimide (Kapton) foil. Typically, the copper and Kapton layers are 5 μm and 50 μm thick, respectively. The micromesh is etched from the top copper layer and thus forms a thin electrode with holes of 40 to 50 μm , distributed in different topologies. Thanks to the uniformity of the amplification region of the microbulk Micromegas, leading to a high homogeneity of the electric field between the micromesh and the anode, microbulk detectors offer nowadays one of the best energy resolutions achievable for gaseous detectors operating in proportional mode [3]. Additional advantages are the very low material budget, the high radiopurity of the material [4] and the long term stability [5]. These features make these detectors suitable for a variety of applications, such as rare event searches [6] or neutron detection [7].

In order to form a position sensitive microbulk, the bottom copper layer (anode) is usually segmented into strips or pixels, connected to the readout electronics through conductive vias and strip lines in extra layers, added below the anode. Thus, if two-dimensional particle hit information is required, two extra conductive planes (copper) and two Kapton layers need to be added. This manufacturing process is complicated and time-consuming and involves a

31 considerable risk of damaging the detector. Furthermore, the addition of extra
32 material for the readout strips makes the detector less attractive for applications
33 where a minimal material budget is mandatory, such as in-beam neutron mea-
34 surements. Finally, the charge produced in the amplification volume is shared
35 among the anode pads. In standard XY detectors, the pads are interconnected
36 to form strip readouts, so an unequal charge sharing between the two strip layers
37 can occur.

38 Recently, a novel microbulk detector prototype has been presented, with
39 the micromesh segmented for the first time [8]. The anode is also segmented
40 into perpendicular strips. The goal of this new design was to simplify the
41 construction process of a microbulk detector with a real two-dimensional readout
42 structure (better determination of the two coordinates of the position from the
43 charge in the amplification area) and to minimise the material budget of the
44 detector. The design was optimised by testing a series of small size prototypes in
45 order to maintain the good microbulk properties (presented in [8]). Based on the
46 topology of the prototype with the best performances the first real size detector
47 has been produced at the CERN EP-DT-EF workshop ¹. The characteristics
48 and performance of this new detection system are presented here.

49 **2. Detector setup**

50 The main challenges to overcome with this kind of detector are the microbulk
51 design, the need of auto-trigger electronics in the absence of an undivided mesh
52 electrode as well as the high voltage distribution to the mesh strips in order to
53 ensure the proper field in the amplification volume. All these challenges had to
54 be overcome as described in this section.

¹The Engineering Facilities (EF) section of the Detector Technologies (DT) group of the
Experimental Physics (EP) Department of CERN.

55 *2.1. Segmented mesh microbulk*

56 A schematic view of the amplification structure of the segmented mesh mi-
57 crobulk is shown in Fig. 1.

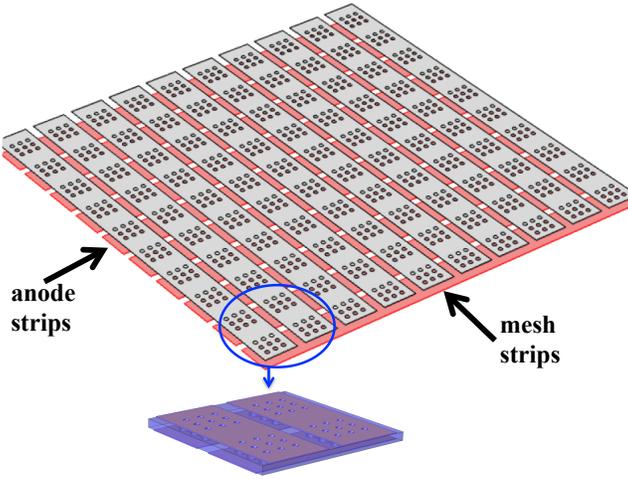


Figure 1: (Color online) Schematic view of the segmented mesh microbulk detector. The holes of the micromesh are arranged in matrices with a fixed number of holes/column in the overlapping region of mesh and anode strips.

58 The manufacturing process, described in detail in ref. [8], starts with a dou-
59 ble sided copper-clad 50 μm thick Kapton foil as raw material. In the first step,
60 the mesh holes are photolithographically created, respecting the special topol-
61 ogy shown in Fig. 1. In a second step, the strips in perpendicular directions are
62 formed on both sides of the copper-clad Kapton foil. The study of the proto-
63 types revealed that the main challenge in the manufacturing process, although
64 it is much simpler than for the previous microbulks with two-dimensional strip
65 readout, lies upon the proper etching of the Kapton below the mesh holes, with-
66 out completely removing the material between the mesh strips, and the good

67 alignment of the anode strip edges with the regions without holes of the mesh
68 strips. Furthermore, it has been shown (by simulations of the electric field lines
69 and by measurements with the prototypes) that the hole topology on the mesh
70 strips as well as the interstrip gaps considerably influence the performance of
71 the detector. Ideally, the mesh holes need to be homogeneously distributed on
72 the strip surface and the interstrip gaps reduced as much as possible in order
73 to minimise the loss of electrons and the consequent deterioration of the good
74 energy resolution of the microbulk.

75 The first two detectors were made, based on the $2 \times 2 \text{ cm}^2$ prototype which
76 showed the best performance, with an active area of $6 \times 6 \text{ cm}^2$ divided into 60+60
77 strips with 1 mm width. The characteristics of the microbulks can be found in
78 Table 1.

	Interstrip gap (μm)	Hole topology
Prototype	35	10 columns - 8 holes/column
Detector No. 1	35	5 columns - 8 holes/column 5 columns - 7 holes/column
Detector No. 2	60	9 columns - 8 holes/column

Table 1: Segmented mesh microbulk characteristics. The holes had a diameter of $60 \mu\text{m}$ and a pitch of $100 \mu\text{m}$ for all three detectors. In detectors No. 1 and 2 the interstrip spacing and hole topology have been modified.

79 The microbulk structures of Detector No. 1 and 2 were manufactured on
80 a 4 mm thick PCB ring in order to ensure the detector rigidity and allow the
81 connection to the front-end electronics. A photo of the sensitive area of the final
82 detector is shown in Fig. 2. The drift gap typically used for the measurements
83 reported here was 1 cm.

84 *2.2. Electronics system*

85 Unlike in non-segmented Micromegas detectors, where the micromesh signal
86 can be used to trigger the readout electronics connected to the anode strips,

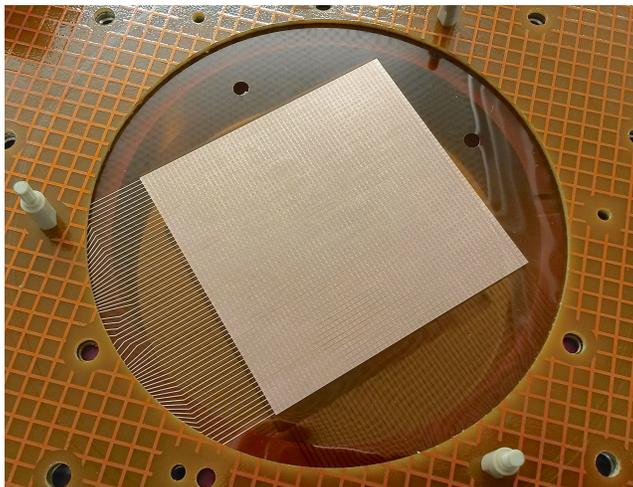


Figure 2: (Color online) Photo of the first 6×6 cm² segmented mesh microbulk detector produced, mounted on the thick PCB.

87 the readout electronics used for a segmented mesh microbulk needs to be self-
88 triggering. For this purpose the GET electronics was chosen (R-CoBo configu-
89 ration, see below) based on the AGET ASIC chip [9, 10]. This chip is adapted
90 to Time Projection Chamber readouts, allowing to reconstruct the event track
91 in the detector gas. It features 64 analog channels, each equipped with a Charge
92 Sensitive Preamplifier (CSA) with adjustable input sensitivity (maximum dy-
93 namic range 120 fC - 10 pC) and peaking time (70 ns - 1 μ s) values, and the
94 possibility to work with both positive and negative input signal polarities. The
95 CSA output signal is stored in an analogue memory based on a Switched Ca-
96 pacitor Array (SCA) of 512 samples with adjustable sampling frequency (1 -
97 100 MHz). An external 12-bit ADC is used for the readout at 25 MHz fre-
98 quency. Three readout modes (all channels / only channels that passed the
99 chosen threshold value / selected channels) and adjustable number of memory
100 cells (1 - 512) are available. The GET electronics provides a threshold and
101 multiplicity trigger when running in the auto-trigger mode, as well as the possi-
102 bility to accept an external trigger. In the version of the GET electronics used
103 for this work, 4 AGET chips and a four channel ADC were soldered on the

104 AsAd (ASIC Support & Analog-Digital conversion) card, and a concentration
105 board (“reduced” CoBo or R-CoBo) was used as a communication intermediary
106 between the AsAd and the computer.

107 Special front-end (FE) cards were designed and built, to properly connect
108 the mesh and anode strips to the AsAd board for the strip readout, provide
109 the high voltage to the mesh strips and protect the AGET chips from potential
110 discharges in the detector. These functionalities were divided in two cards, one
111 directly plugged on the detector PCB (different design for the mesh and anode
112 strips) and one directly plugged on the AsAd card with the protection diodes
113 against the discharges. Series of tests were performed with X-rays and with a
114 neutron beam at the 10 m flight path neutron beam line of the GELINA facility
115 of JRC-Geel [11], which helped to finalise the design.

116 **3. Detector characterisation**

117 *3.1. Characterisation with low energy X-rays*

118 The detector performance was tested with X-rays, using a ^{55}Fe source ($E_{K_\alpha}=5.9$
119 keV, $E_{K_\beta}=6.5$ keV). The detector chamber was filled with a gas mixture of 95%
120 argon - 5% isobutane (iC_4H_{10}) at atmospheric pressure, circulated at a constant
121 flow of ~ 6 Nl/h. The detector voltages were typically $V_{\text{mesh}} = 340$ V and V_{drift}
122 $= 430$ V. The whole AGET + front-end electronics chain was used to record the
123 X-ray signals. For each X-ray energy deposition in the detector gas, mesh and
124 anode strips were read out. Typical signals recorded from the electronics for
125 one X-ray energy deposition, with 100 MHz sampling frequency, are shown in
126 Fig. 3. A good signal-to-noise ratio was achieved and typically 1-3 consecutive
127 strips for the mesh and the anode were triggering an event for this gas, voltage
128 and threshold settings.

129 The electron transparency as a function of the ratio of the electric fields in
130 the drift and amplification region is shown in Fig. 4. The detector presents a
131 wide plateau in the transparency for $E_d/E_m \geq 0.001$, where E_d and E_m are the
132 electric field in the drift and the amplification region respectively.

133 Reading each strip of the mesh and the anode electrodes independently al-
 134 lows for an efficient rejection of background events. Criteria can be applied for
 135 the selection of good events, either independent of or dependent on the type
 136 of radiation to be measured. First, signals induced on mesh and anode strips
 137 are simultaneous and have equal but inverted amplitude by construction. Slight
 138 differences in the recorded signal amplitudes can occur due to different elec-
 139 tronics channel gains. Indeed, for all the tests with this detector with different
 140 particles and types of gas the mean ratio of the charge induced on the anode
 141 to the one induced on the mesh was close to 1 with a moderate variation of
 142 ± 0.1 (similar to the one of Fig. 10). Furthermore, criteria such as the consecu-
 143 tivity of the strips hit and the maximum multiplicity expected can be applied
 144 to various types of radiation. More specifically, for X-ray energy deposition, the
 145 simultaneity of the strip signals can also be considered as a criterion for the
 146 good events. The above mentioned criteria were applied and only less than 1%
 147 of the total events were rejected in the case of the optimised setup, thanks to
 148 the very low noise. The total amplitude distributions, obtained by adding the
 149 signal amplitudes from anode and mesh strips separately for each event, were
 150 clean and the argon escape peak at 2.9 keV was clearly separated. Optimum
 151 energy resolution was observed with the source irradiating only the central 20 to
 152 30 strips of the detector. An exemplary total amplitude distribution for anode
 153 signals is shown in Fig. 5.

154 The energy resolution was estimated by fitting the dominant ^{55}Fe peak with
 155 two gaussians corresponding to the expected K_α and K_β peaks and was $(13.0$
 156 $\pm 0.5)\%$ (FWHM). This energy resolution is comparable to, or even better
 157 than microbulk detectors with non-segmented micromeshes [2, 12]. The energy
 158 resolution observed for the mesh strips was slightly worse, $(13.5 \pm 0.5)\%$, possibly
 159 due to additional noise related to the circuit for the application of high voltage
 160 at these strips. The theoretical energy resolution for proportional counters at a
 161 given energy E is given by $\text{FWHM}_E/E = 2.35 \times \sqrt{W(F+b)/E}$, where W is the
 162 energy required to form an ion pair, F the Fano factor and b the gain fluctuations
 163 factor due to the avalanches [13]. Thus, the corresponding theoretical limit of the

164 energy resolution for a non-segmented 50 μm microbulk at this energy is $\sim 11\%$
165 [14]. The experimental resolution obtained with the new segmented microbulk
166 detector was slightly worse. This can be attributed to various factors related to
167 the microbulk structure as well as the electronics and the electrical connections.

168 Firstly, the loss of ionisation electrons in the interstrip gaps and areas on
169 the mesh strips without holes (see Fig. 1) deteriorates the resolution. The value
170 stated above was observed for the detector No. 1 (Table 1), while the energy
171 resolution of detector No. 2 was of the order of 16-17%, attributed to the larger
172 interstrip gap and the reduced number of micromesh holes, resulting in increased
173 electron losses. Furthermore, the best resolution reported in ref. [8] for the small
174 segmented microbulk prototypes was 11.5% FWHM at 5.9 keV with the same
175 gas mixture and different electronics, and it was shown that misalignments in
176 the mesh and anode strips can significantly deteriorate the resolution.

177 Secondly, the amplitude variations among the strips (due to electronics gain
178 variations, different charge collection etc.) affect the resolution. In order to
179 check the amplitude variations among the strip signals, the whole detector sur-
180 face was irradiated with X-rays from an uncollimated ^{55}Fe source and the posi-
181 tion of the dominant peak in the amplitude spectrum was determined for each
182 strip. This most probable amplitude is shown in Fig. 6 as a function of the strip
183 number. The amplitude varies very little among the central 40 strips, within
184 2% (1σ), while it drops rapidly for the 10 strips at the borders, due to drift
185 field inhomogeneities. Because of these field inhomogeneities at the border, the
186 energy resolution was degraded and reached values of 16-17%. This is a known
187 issue for such detectors and can be solved with the addition of an extra thin
188 electrode surrounding the active area (“rim” electrode) [15].

189 Another factor deteriorating the resolution in the case of the segmented
190 microbulk is the incomplete charge collection from strip signals not passing the
191 acquisition threshold chosen. Indeed, the best resolution values were achieved
192 when this threshold was kept as low as possible.

193 Finally, some grounding issues on the detector PCB were discovered (the
194 bottom and top grounding layers were not properly interconnected), creating

195 extra noise to the system, which were bypassed with external connections.

196 The above mentioned results indicate that with the optimisation of the hole
197 topology and interstrip gap and with good alignment of the strips, as well as
198 special attention to the grounding design during the microbulk and PCB fab-
199 rication processes respectively, this already good energy resolution value could
200 be further improved.

201 A radiography of a copper mask using 5.9 keV X-rays is shown in Fig. 7.
202 A very clean image of the copper mask was obtained, indicating good event
203 reconstruction capabilities of the new system.

204 *3.2. Characterisation of operation as neutron beam profiler*

205 The new detection system was tested with respect to the detection of neu-
206 trons at the Orphée reactor of the laboratory LLB (Laboratoire Léon Brillouin)
207 of CEA-Saclay [16, 17]. It is a 14 MW reactor with a small core highly enriched
208 in ^{235}U , which provides a high neutron density, surrounded by a heavy water
209 reflector tank to obtain a high thermal flux (3×10^{14} n/cm²s). The detector
210 was placed at the G3-2 neutron beam line in order to study the performance in
211 the detection of the neutrons and the reconstruction of neutron beam profiles.
212 At this station, the neutron flux has a nearly Maxwellian distribution peaking
213 at a wavelength of 1.7 Å (corresponding to a neutron kinetic energy of 3 meV).
214 B_4C and Cd masks with different shapes were used for localised neutron irradi-
215 ation of the detector. In most cases, extra PMMA plates were used in order to
216 reduce the very high counting rate that was causing dead time in the readout
217 electronics.

218 The detection of neutrons is performed by the interaction of neutrons with a
219 target (neutron converter) that undergoes a nuclear reaction with a well known
220 cross section. Thus, the detection of neutrons turns into the detection of the
221 reaction products from the neutron interaction. The neutron converter used
222 was ^6Li , producing a triton and a ^4He particle via the well known $^6\text{Li}(n,t)^4\text{He}$
223 reaction [18]. Provided that the incoming neutron energy is negligible compared
224 to the reaction Q-value the two reaction products are emitted back to back with

225 energies $E_t=2.73$ MeV and $E_{4\text{He}}=2.05$ MeV. A 9 cm diameter ${}^6\text{LiF}$ layer of 91.8
 226 $\mu\text{g}/\text{cm}^2$ was deposited on a thin aluminised mylar backing (used as the drift
 227 electrode). The detection gas used in this case was 90% argon - 10 % CO_2 at
 228 atmospheric pressure and the drift region was 1 cm thick. When the charged
 229 particles from the neutron interactions exit the target and travel through the
 230 detection gas, electrons are produced along their track in the drift region and are
 231 detected by consecutive anode and mesh strips of the MicroMegas detector. The
 232 first strip that gives a signal corresponds to the point of the particle track that
 233 is closest to the mesh while the last one corresponds to the point of interaction
 234 of the neutron with the neutron converter and is used for the reconstruction of
 235 the beam profile (the principle is shown in Fig. 8). The sampling frequency for
 236 the recording of the signals was 100 MHz.

237 The characteristics of the different masks used are listed in Table 2. The
 238 detector was mounted on an X-Y table in order to irradiate different points of
 239 the ${}^6\text{LiF}$ layer and estimate the homogeneity and the reconstruction of the same
 240 image at different positions of the detector. In order to estimate the homogeneity
 241 of the converter at the surface covered by the detector, the rectangular hole was
 242 used to sample a surface of approximately 6×6 cm^2 , and the counting rate of the
 243 alpha particle peak at the various points was compared. In total 71 points were
 244 sampled, with a step of 5-8 mm. The converter was found to be homogeneous
 245 within less than 5% (1σ). At the edges of the detector the alpha counting rate
 246 was generally smaller, up to 10-12%.

Mask shape	Dimensions (mm)
Circular hole	$\varnothing 5$
Circular hole	$\varnothing 2$
Square hole	5×5
Rectangular hole	1×5

Table 2: Characteristics of the masks used. In most cases, PMMA plates were used in order to reduce the neutron fluence (by a factor of 16).

247 *3.2.1. Charged particle tracks selection*

248 As shown in Fig. 9, the multiplicities typically varied from 1-9 strips. The
249 small multiplicities mainly correspond to forward tracks (i.e. perpendicular
250 to the sample surface) or tracks nearly parallel to one strip (1-2 strips), and
251 the higher multiplicities correspond to tracks emitted at bigger angles with
252 respect to the normal to the sample, crossing many strips. The distinct shape
253 of the distribution is probably due to tracks that are not crossing the strips
254 perpendicularly, promoting specific regions of the low multiplicities in the case
255 of alpha particles and of the high multiplicities in the case of tritons.

256 The first event selection criterion was, also in this case, the balance of the
257 induced charge at the mesh and anode strips. In Fig. 10, a typical distribution of
258 the ratio between the total amplitudes of anode and mesh signals for all events
259 in a run is shown. The ratio is centered at 0.98 (and not 1, due to different
260 electronics channel gains between the mesh and anode strips), with tails that
261 are attributed to events with incomplete charge collection either on the mesh
262 or anode strips (due to single strip threshold effects, i.e. a signal not recorded
263 from a strip because the amplitude is smaller than the threshold applied). The
264 events with ratio smaller than 0.8 and bigger than 1.2 were rejected.

265 The next two criteria are based on the nearly continuous ionisation of the
266 charged particle in the gas, taking advantage of the independent recording of
267 the strip signals. Firstly, the strips recorded in an event had to be consecutive,
268 both for the mesh and the anode. Secondly, the time difference Δt between
269 the first and the last strip that gave a signal (Fig. 8) should be less than or
270 equal to the expected drift time of the electrons from the converter to the mesh
271 electrode, i.e. $\Delta t \leq d/v$, where d is the drift distance and v is the velocity
272 of the electrons in the drift region which depends on the gas and the electric
273 field applied. Taking into account that the time 0 corresponds to the time of
274 the first strip that gave a signal (auto-triggering mode), the maximum Δt value
275 corresponds to tracks that reach the mesh electrode, as the one schematically
276 shown in Fig. 8. The value of Δt is smaller for tracks with bigger angles with

277 respect to the normal of the target surface and goes down to 0 for tracks nearly
278 parallel to the target surface. A typical histogram of the experimental Δt values
279 obtained for tracks recorded by the mesh and the anode strips can be found in
280 Fig. 10. Indeed, assuming $d = 1$ cm and $v = 3.4$ cm/s for this type of gas and
281 electric field strength applied in the drift region [19], it occurs that $\Delta t \leq$ (294
282 ± 30) ns, which agrees with the observation (Fig. 10).

283 Typical total amplitude distributions for mesh and anode strips can be found
284 in Fig. 11. Single strip threshold effects were observed, mainly for the very
285 low amplitude signals. This is more evident for the anode strips because of
286 extra noise that was observed during the measurement, necessitating a higher
287 single strip acquisition threshold. Nevertheless, with the criteria applied, the
288 background or not well recorded charged particle events were sufficiently rejected
289 and the final total amplitude distribution histograms were clean.

290 3.2.2. Monte Carlo simulations

291 In order to estimate the expected energy deposition of the alphas and the
292 tritons in the gas and understand the experimental total amplitude histograms,
293 Monte Carlo simulations were performed with the codes FLUKA [20, 21] and
294 GEANT4 [22, 23]. The geometry of the detector setup was implemented in de-
295 tail, and thermal neutron beams of different cross section shapes corresponding
296 to the masks used were impinging on different points of the ${}^6\text{LiF}$ target. The
297 energy deposition of the alphas and the tritons was scored independently in
298 the active gas volume of the detector. Results obtained for the 5 mm diameter
299 circular mask can be found in Fig. 12.

300 As expected, alpha particles have a shorter range than the tritons due to
301 their larger energy loss per unit path length. Thus, alpha particles emitted
302 in forward directions have on average lost less energy in the ${}^6\text{LiF}$ layer and
303 have longer tracks than those emitted under larger angles (Fig. 12a). As a
304 result, the energy deposition of the alpha tracks is recorded by a few strips
305 around the point of interaction of the neutron beam with the ${}^6\text{LiF}$ layer (\pm
306 1 cm) and corresponds to the right peak of the total amplitude distribution

307 (Fig. 12b). On the contrary, the tritons deposit little energy along their track
308 and thus have longer tracks that extend to the edges of the detector (Fig. 12a).
309 Consequently, they deposit only part of their total energy in the gas and form the
310 lower peaks/bumps of the experimental total amplitude histograms (Fig. 12b).
311 Furthermore, they are recorded with small signals by each strip, and thus the
312 experimental total amplitude distribution from these tracks is more sensitive
313 to single strip threshold effects and gain variations (mainly at the edges of
314 the detector). This difference of the alpha/triton tracks observed from the
315 simulations is reflected in the experimental amplitudes of signals for the different
316 strips, as shown in Fig. 13.

317 Taking the above into account, it can be concluded that the qualitative
318 agreement between the simulated energy deposition histogram (Fig. 12b) and
319 the experimental total amplitude histograms (Fig. 11), even in the absence of
320 the proper resolution function, is quite satisfactory, especially in the case of the
321 mesh strips. Moreover, the criteria applied are also excluding some of the triton
322 tracks, for the reasons explained above.

323 Based on the simulated energy deposition of the alpha/triton peaks, the
324 calibration of the experimental spectra was made, and the single strip threshold
325 applied at the acquisition was estimated to be 65 ± 6 keV (for the mesh strips).

326 Finally, the neutron detection efficiency of the new system with this ${}^6\text{LiF}$
327 layer was estimated to be as low as 0.21%, according to the simulations. The
328 results obtained with GEANT4 were in perfect agreement with the FLUKA
329 results.

330 *3.2.3. Image reconstruction with neutron beam*

331 An example of the neutron beam profile obtained when using the latest
332 strip as measure for the neutron interaction point in the converter can be seen
333 in Fig. 14, for the 5mm diameter circular mask. A clear improvement in the
334 neutron beam profile reconstruction was observed when the good events selected
335 with the above mentioned criteria were used (Fig 14 (right)).

336 The spatial resolution of the detector, assuming that the interaction can take

337 place anywhere on the 1.1 mm wide strip, is expected to be $(1.1 \text{ mm})/\sqrt{12} \approx$
 338 0.32 mm (the width of the strip was 1.065 mm according to the technical draw-
 339 ings). In order to experimentally confirm the spatial resolution, the circular
 340 beam profiles obtained were fitted with a function corresponding to a gaussian
 341 convoluted with a step function. The 2D formula of this function is given in
 342 Eq. 1, also used in ref. [24].

$$B(x, y) = \frac{A}{2\alpha} (\text{Erf}(\alpha + \sqrt{f(x, y)}) - \text{Erf}(\sqrt{f(x, y)} - \alpha)) \quad (1)$$

343 where

$$344 \text{Erf}(u) = \frac{2}{\sqrt{\pi}} \int_0^u e^{-t^2} dt \text{ and}$$

$$345 f(x, y) = \frac{1}{2(1-\rho)^2} \left(\frac{(x-\mu_x)^2}{\sigma_x^2} + \frac{(y-\mu_y)^2}{\sigma_y^2} - 2\rho \frac{(x-\mu_x)(y-\mu_y)}{\sigma_x \sigma_y} \right)$$

346 containing 7 free parameters: A is a normalisation factor, α is the parameter
 347 of the step function which determines the “plateau” at the center of the beam
 348 profile, ρ is the correlation coefficient between the two axes and $\sigma_x(1-\rho)$ and
 349 $\sigma_y(1-\rho)$ the standard deviations in the frame of the principal axes of the gaus-
 350 sian. The σ values reflect the spatial resolution of the beam profile convoluted
 351 with the neutron beam broadening due to the scattering at the edges of the
 352 masks. However, the latter value is difficult to estimate due to the inhomog-
 353 eneities of the mask edges.

354 An exemplary fit using Eq. 1 can be found in Fig. 15, for the profile of the
 355 circular mask of 5 mm diameter. The 1D projections of the slices correspond-
 356 ing to the middle Y (anode)- and X (mesh)- strips onto the X- and Y- axis
 357 respectively are also shown in Fig. 15. The ρ parameter was found to be close
 358 to zero, while $\sigma_x \approx \sigma_y$ for the circular profiles and were in the range 0.45-0.55
 359 mm (depending on the profile, with fitting parameter uncertainties of the order
 360 of 1-2%), including the non negligible neutron beam broadening (mainly due to
 361 the neutron scattering at the edges of the masks and the PMMA plates).

362 The reconstructed images shown in Fig. 14 and Fig. 15 are obtained by as-
 363 suming that the neutron interaction position is defined by the latest strip, with-
 364 out any deeper localisation on the 1.1 mm wide strip. In an effort to further

365 improve the image reconstruction, a correction factor was implemented for the
 366 position of the point of interaction, with the simplified assumption that the en-
 367 ergy loss is constant for the two last strips that had a signal, i.e. the first two
 368 strips at the track of the emitted particle from the point of interaction. With
 369 this assumption, if $dE1$ and $dE2$ are the charges deposited at the last strip and
 370 the previous one respectively, and $dX1$ and $dX2$ the track length projections
 371 onto the respective strips, then $dX1 = dX2 \times \frac{dE1}{dE2}$, with $dX2 = 1$ strip, since
 372 the previous strip is fully crossed. From this relation the position of the neutron
 373 interaction $dX1$ on the last strip was determined. The value of the correction
 374 factor $\frac{dE1}{dE2}$ is expected to follow a uniform distribution between 0 and 1. Due to
 375 the amplitude threshold effects, it deviated from the expected uniform distribu-
 376 tion at borders. To take this effect into account, in a first approximation, when
 377 this value was close to 0 or 1, it was re-sampled with a random distribution, in
 378 order to achieve an approximately uniform distribution.

379 With the above described procedure, a finer binning could be used for the
 380 reconstruction of the beam profiles, since the probability of interaction was no
 381 longer equally probable on the 1.1 mm wide strip, and the quality of the images
 382 was further improved. The beam profiles obtained can be found in Fig. 16.

383 The quality of the images is improved with the more refined analysis. By
 384 fitting such profiles with Eq. 1 or the projection of the middle X- and Y- slices
 385 of the 2D profile onto the Y- and the X-axis respectively with the 1D expression
 386 of this formula, the σ_x and σ_y values were reduced to 0.32 ± 0.05 mm. (the
 387 uncertainty corresponds to the standard deviation of the σ values from all the
 388 profiles fitted).

389 A final remark on the detector spatial resolution capabilities is worth to be
 390 added. The collimator with the rectangular hole (see Table 2) was used in order
 391 to irradiate different points on the ${}^6\text{LiF}$ foil within ± 1 mm (i.e. the strip size).
 392 By taking into account the mean values of the reconstructed images, it was
 393 possible to resolve shifts of the point of irradiation with good accuracy. More
 394 precisely, the agreement between the expected shifts (X-Y table) and the recon-
 395 structed ones was better than 1% for shifts bigger than 0.2 mm. These results,

396 although they cannot be directly used as spatial resolution results, indicate the
397 high resolving power of the system developed.

398 In order to further improve the spatial resolution capabilities of this new
399 detector and fully exploit it as a Time Projection Chamber, a more detailed
400 methodology is needed, with simulations taking into account the energy loss
401 per strip, the gain variations among the strips and the response function of the
402 electronics, and it will be part of the future development of the system.

403 **4. Conclusions**

404 A new microbulk MicroMegas detector has been developed, having for the
405 first time both the mesh and the anode segmented into strips at perpendicular
406 directions, offering a real 2D readout scheme, with the minimum material bud-
407 get possible with such detectors. The $6 \times 6 \text{ cm}^2$ detector has been successfully
408 tested with X-rays and neutron beams, showing very good energy and spatial
409 resolution and offering the possibility to reconstruct charged particle trajectories
410 in the active gas region. Possible improvements have been pointed out from this
411 work and considered for the next detector and electronics designs, such as the
412 improvement of the microbulk fabrication precision (using Laser Direct Imaging
413 for example) leading to the reduction of the micromesh regions without holes
414 and the reproducibility of the fabrication process, a better grounding scheme,
415 the addition of the “rim” electrode etc. Two other important characteristics
416 of this detection system, thanks to the microbulk technology materials, are the
417 low intrinsic radioactivity and the very low interaction probability with neutron
418 beams. The new detector is now operational, used as a neutron beam profiler
419 at the n_TOF facility (CERN) [25, 26], but is also considered for demanding
420 experiments including angular distribution of products from neutron induced
421 reactions, dark matter searches and the search of the neutrinoless double-beta
422 decay.

423

424 5. Acknowledgements

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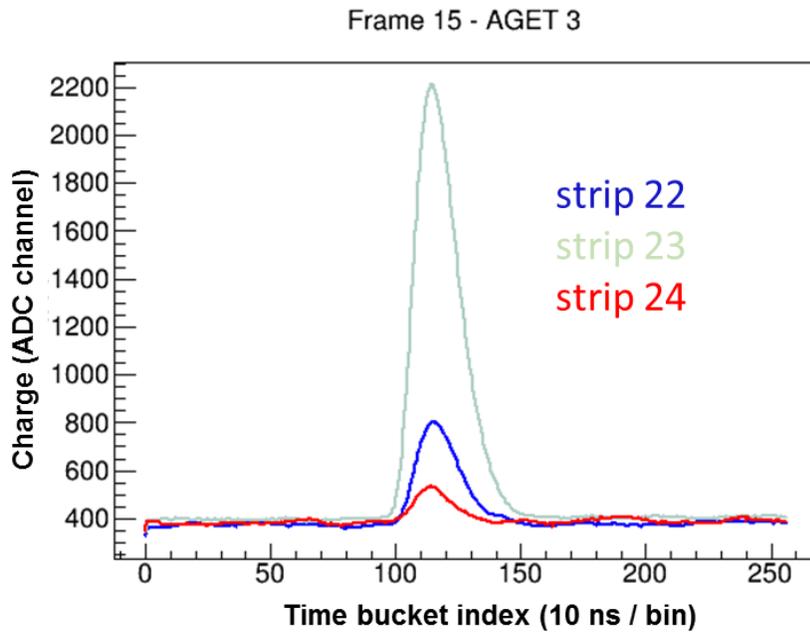
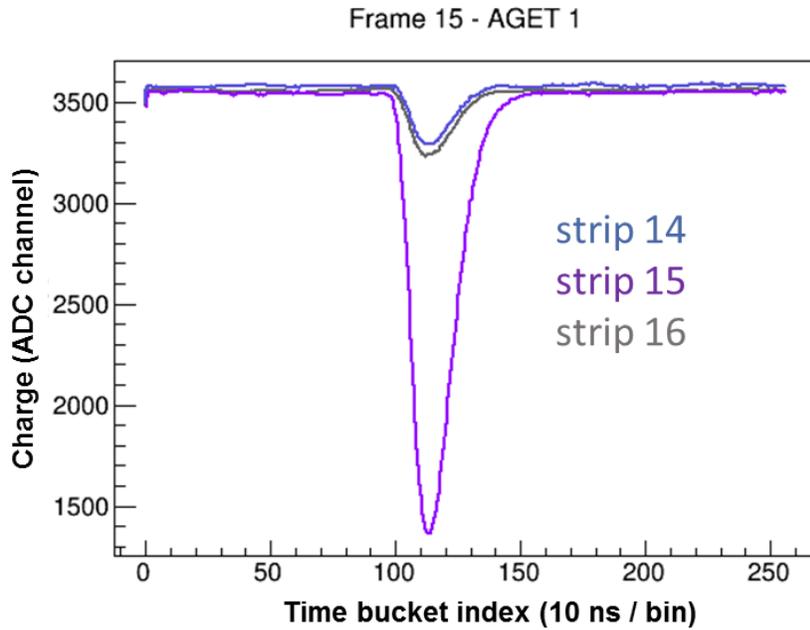


Figure 3: (Color online) Typical X-ray signal recorded from the mesh (up) and anode (down) strips, with a gas mixture of 95% Argon - 5% Isobutane (iC_4H_{10}) at atmospheric pressure. Different strip signals correspond to different colours. The full range corresponds to 240 fC charge and the sampling frequency chosen was 100 MHz.

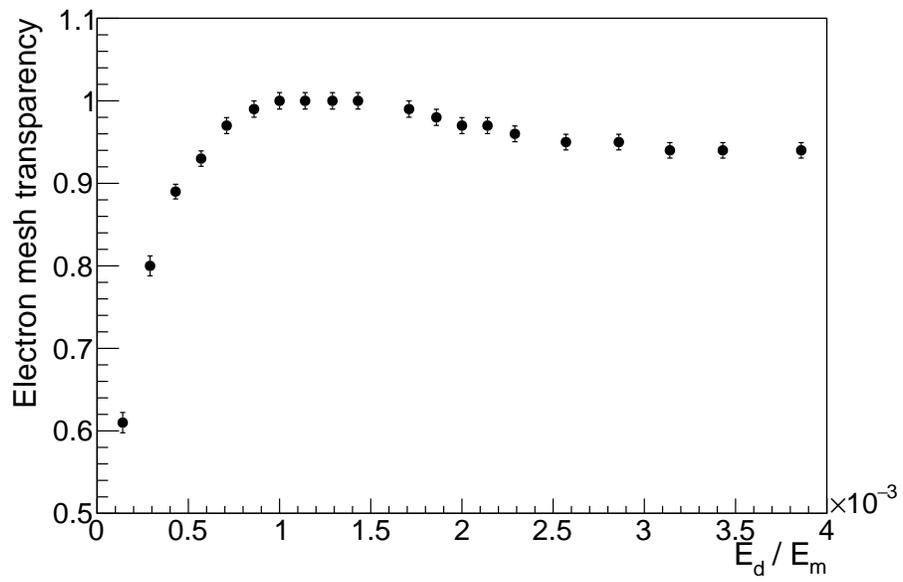


Figure 4: (Color online) Transparency curve, obtained from the position of the ^{55}Fe dominant peak in the amplitude distribution, normalised to the maximum peak position, with respect to the E_d/E_m ratio, where E_d and E_m are the electric field in the drift and the amplification region respectively.

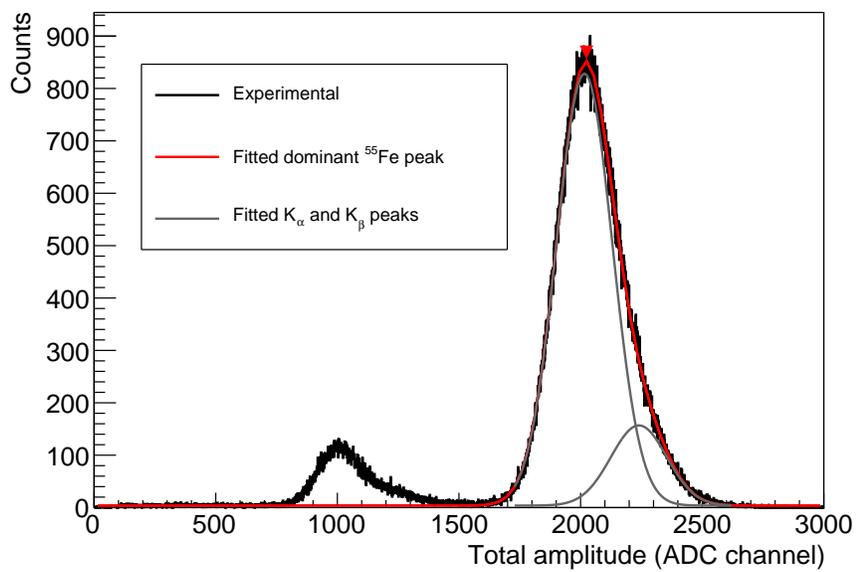


Figure 5: (Color online) Reconstructed total amplitude histogram from the anode strips from a collimated ^{55}Fe source irradiating mainly the central part of the detector (Detector No. 1). The dominant peak of the experimental spectrum (black line) was fitted with two gaussians corresponding to the K_{α} and K_{β} peaks (grey lines), the sum of which is plotted with a red line. The argon escape peak on the left is clearly separated.

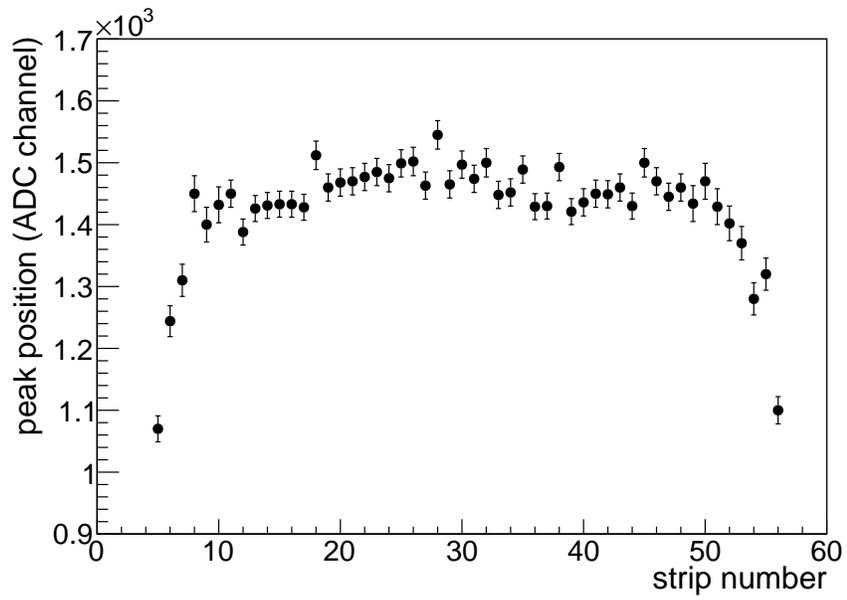


Figure 6: The dominant peak position from the energy deposition of the ^{55}Fe X-ray for the various strips (anode).

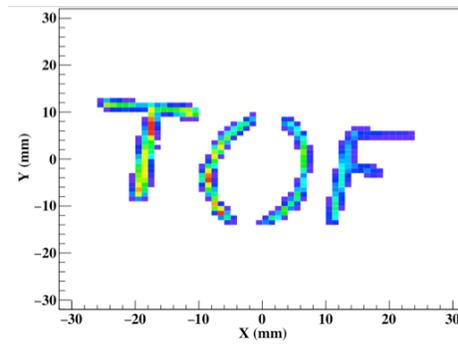


Figure 7: (Color online) Reconstruction of a copper mask using X-rays of 5.9 keV. The width of the grooves was $\approx 1-2$ mm.

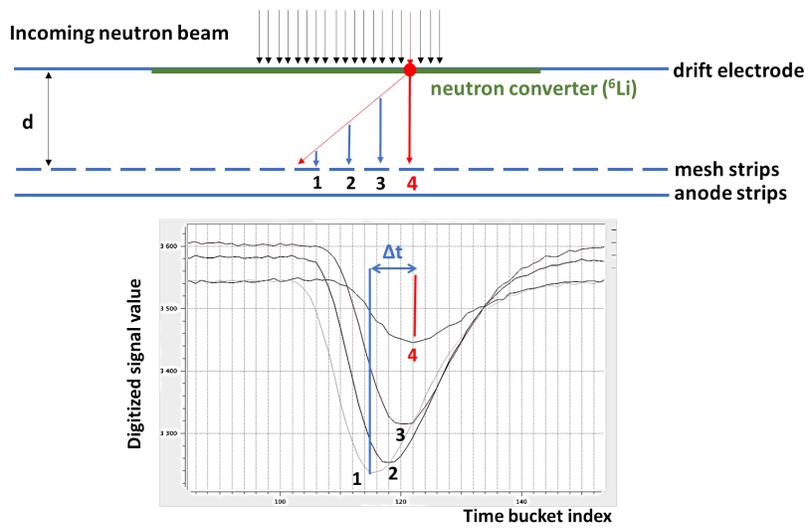


Figure 8: (Color online) Schematics of the reconstruction of the neutron beam profile. The proper neutron converter is used depending on the desired neutron energies.

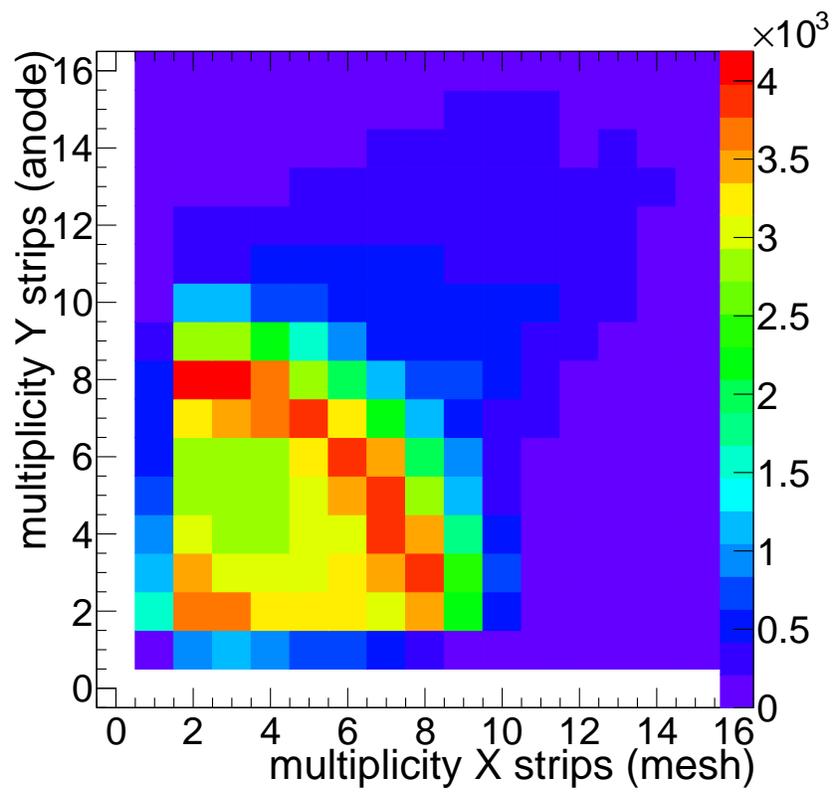


Figure 9: (Color online) Multiplicity distribution of alpha/triton tracks for the mesh and the anode strips.

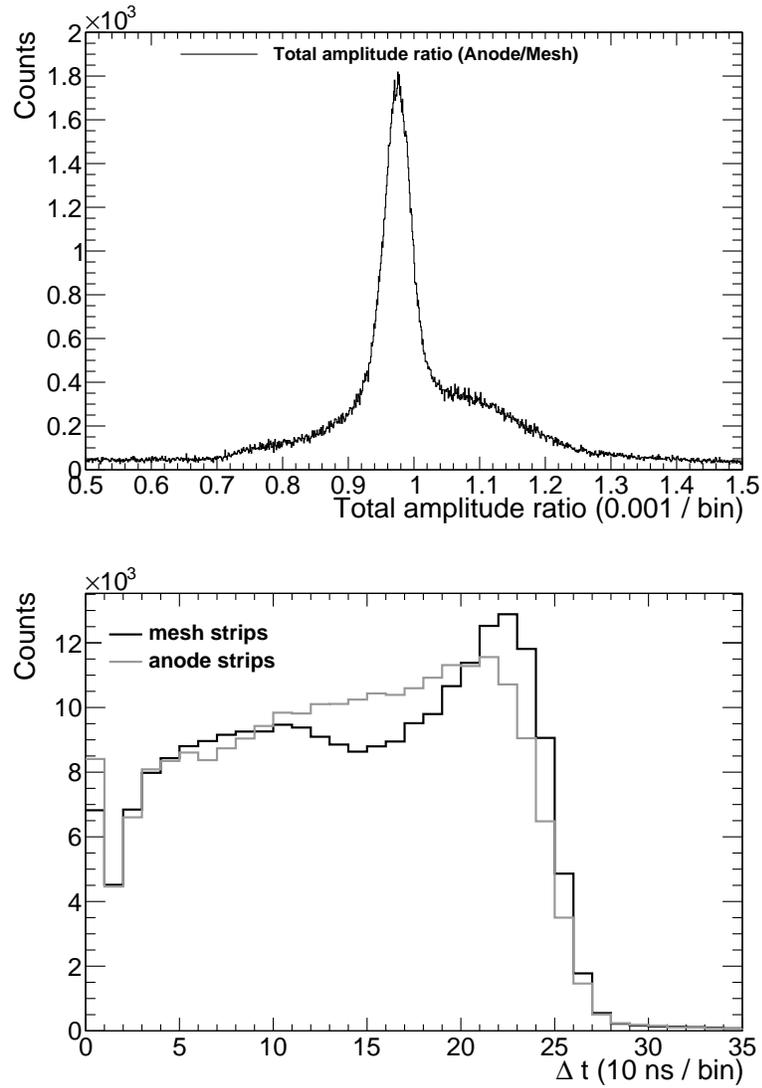


Figure 10: Up: Typical total amplitude ratio (anode strips / mesh strips) from all the alpha/triton tracks, strongly peaked at ≈ 1 (see text). Down: Δt distribution for the alpha/triton tracks recorded with the mesh (black) and the anode (grey) strips.

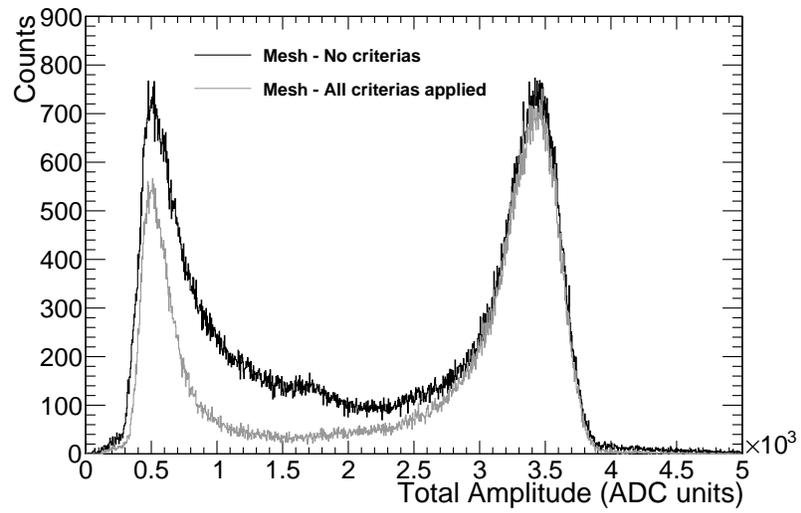
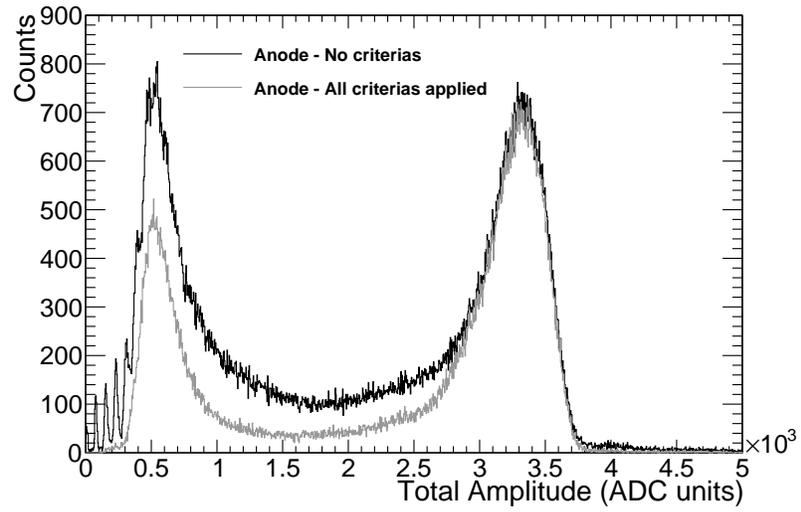
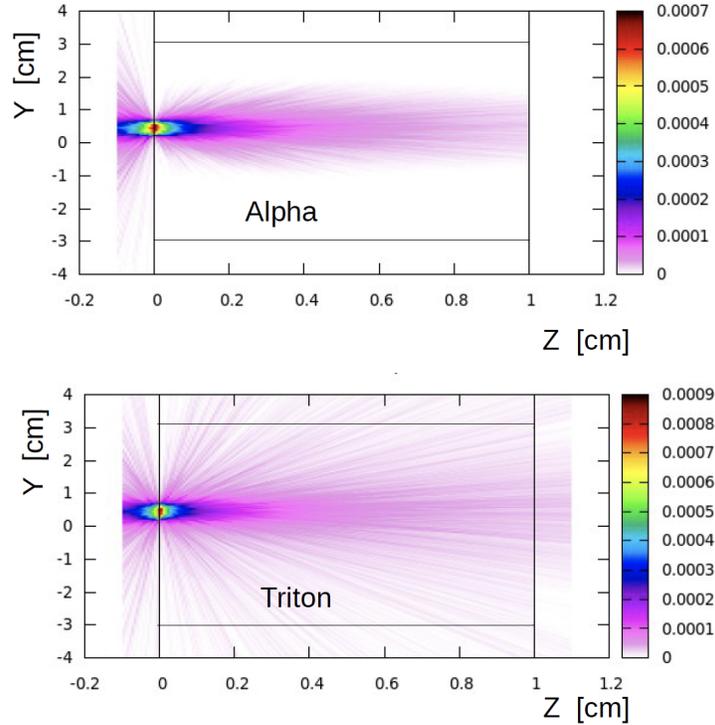
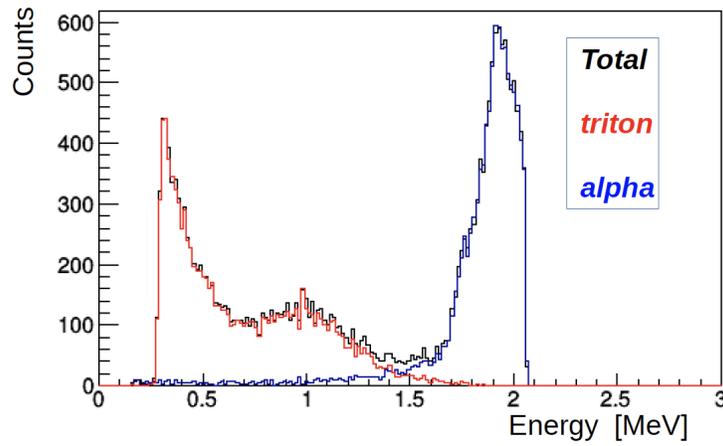


Figure 11: Reconstructed total amplitude distribution histogram, by adding the amplitudes of all the strip signals in each event, for the anode (up) and the mesh (down), from all the events (black) and only from the selected ones with the criteria applied (grey).



(a) (Color online) The simulated fluence (track-length density - particles/cm²/primary) for alpha (up) and tritons (down) emitted from the ⁶LiF layer at Z=0. The solid black lines determine the borders of the active gas volume.



(b) (Color online) The simulated energy deposition histogram of the alphas (blue curve) and the tritons (red curve) and the sum of the two (black line) in the active gas.

Figure 12: Monte Carlo simulation results of a perpendicular thermal neutron beam of \varnothing 5 mm hitting the ⁶LiF layer, using the code FLUKA.

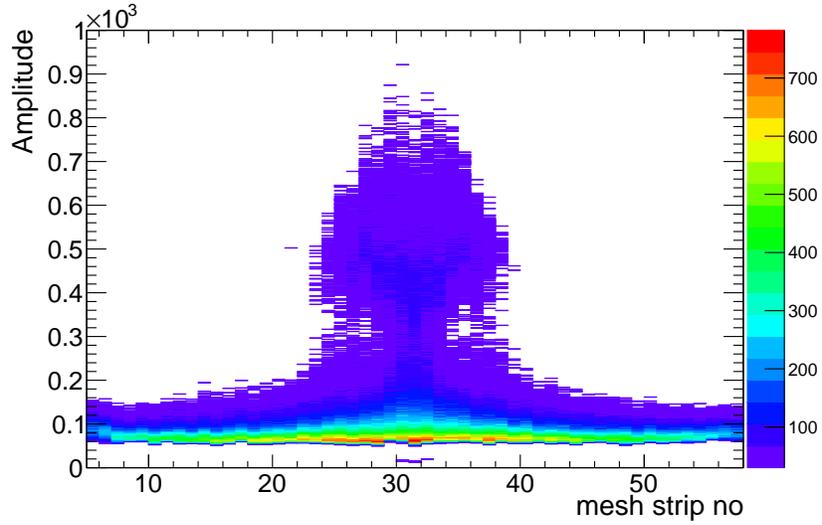


Figure 13: (Color online) Signal amplitudes as a function of the strip number (mesh strips). The neutron beam interaction point corresponds to the mesh strips 29-34. The high amplitudes at central strips correspond mainly to alpha particle tracks, while the low amplitudes recorded from all the mesh strips correspond mainly to the triton tracks, as explained in the text.

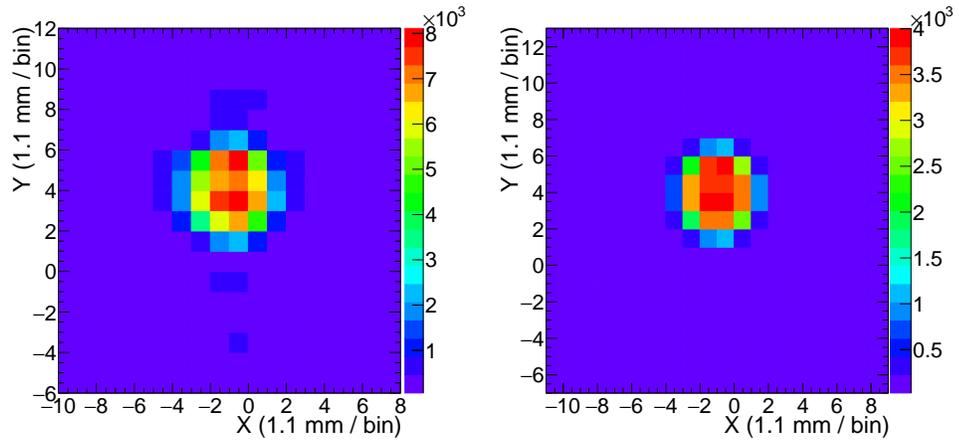
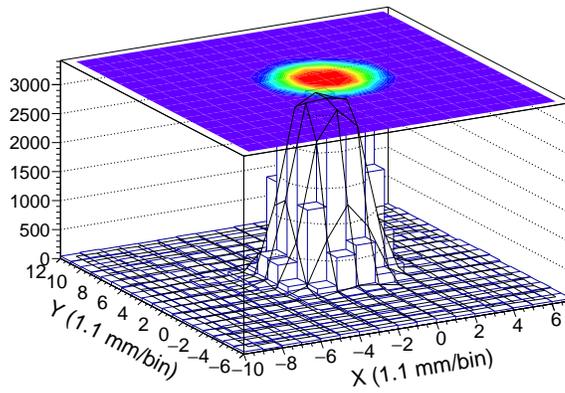
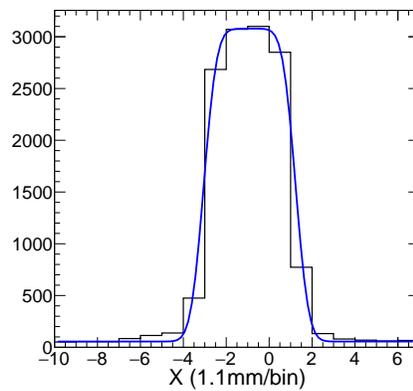


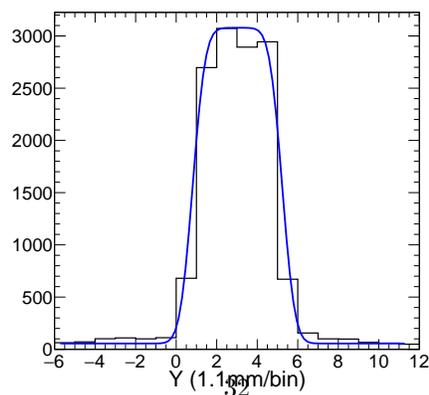
Figure 14: (Color online) Reconstructed beam profiles of the thermal neutron beam passing through the \varnothing 5 mm circular mask considering (a) all the events recorded during the acquisition (left), (b) the events chosen by applying the criteria described in the text (right).



(a)



(b) 1D projection of the experimental profile (middle strip) and of the 2D function used after the fitting, for the X axis.



(c) 1D projection for the Y axis.

Figure 15: (Color online) An example of the 2D fitting of the experimental beam profile in order to estimate the spatial resolution of the system. The FWHM of the projections for the $\varnothing 5$ mm hole from the various profiles analysed was 5.0 ± 0.5 mm.

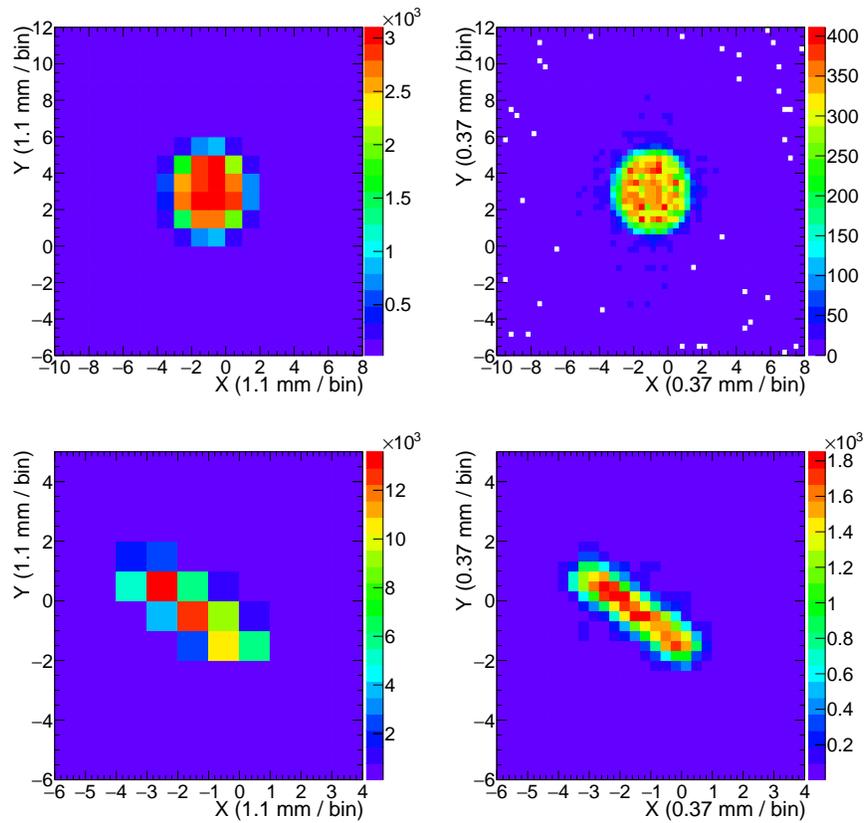
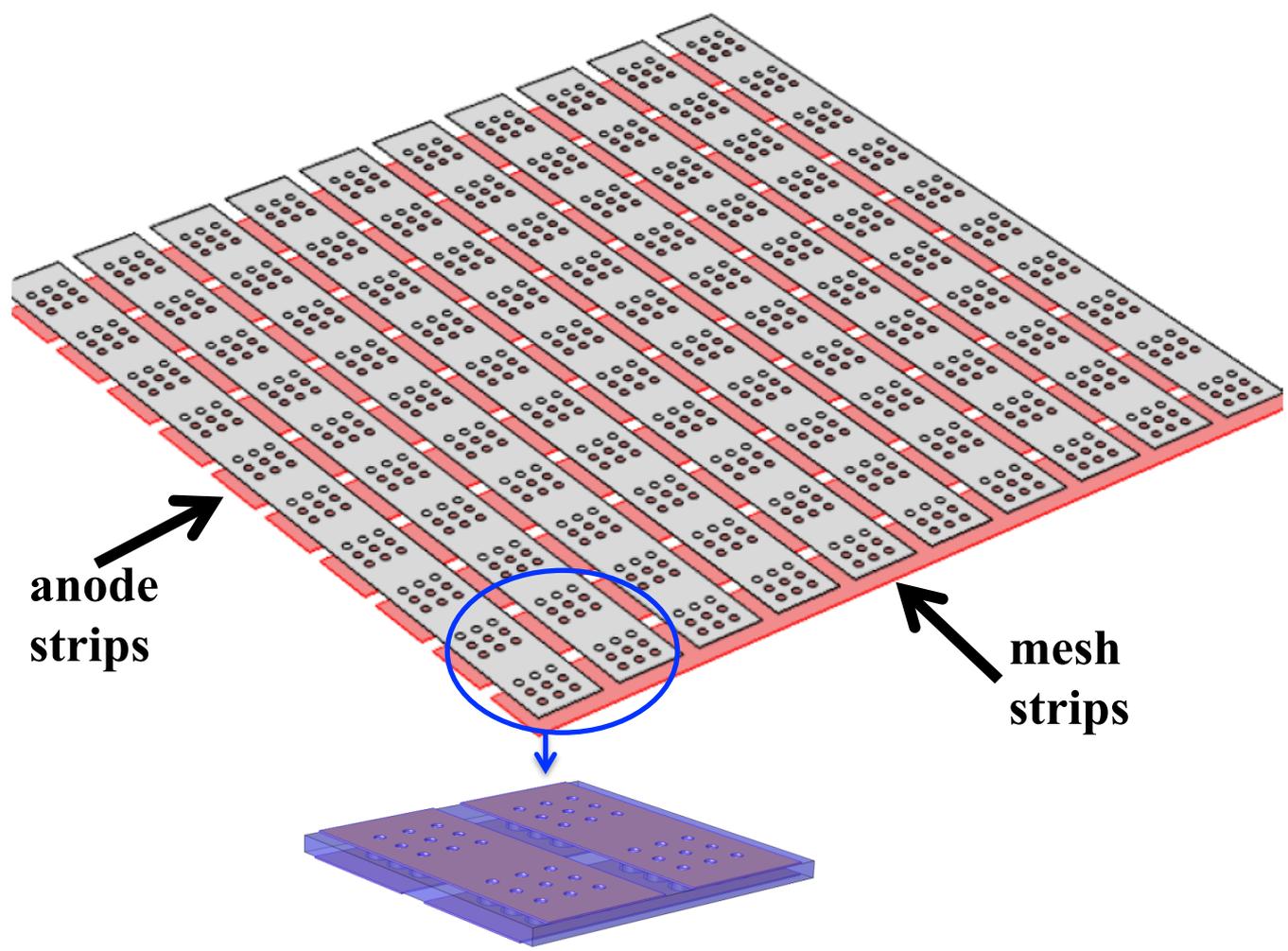
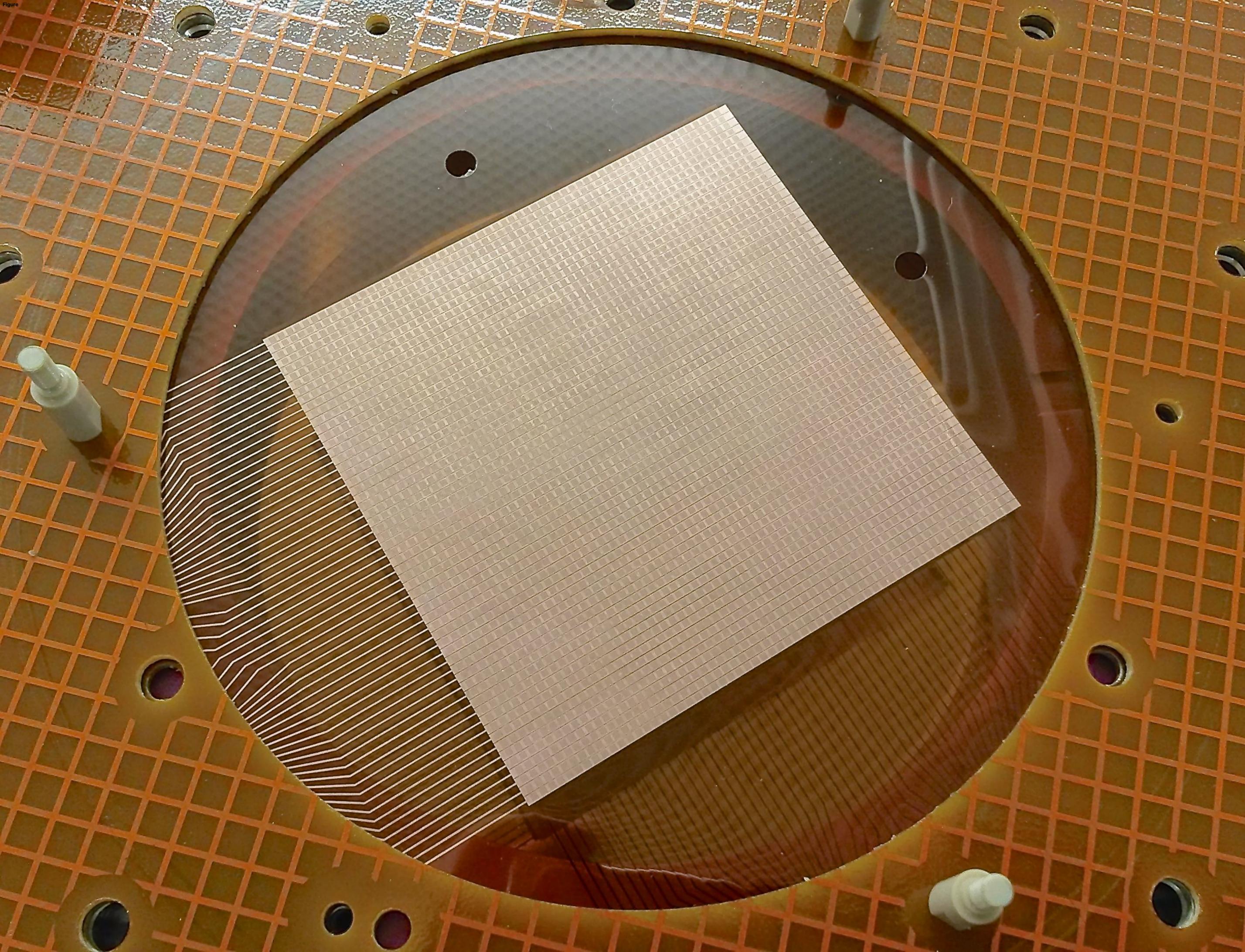


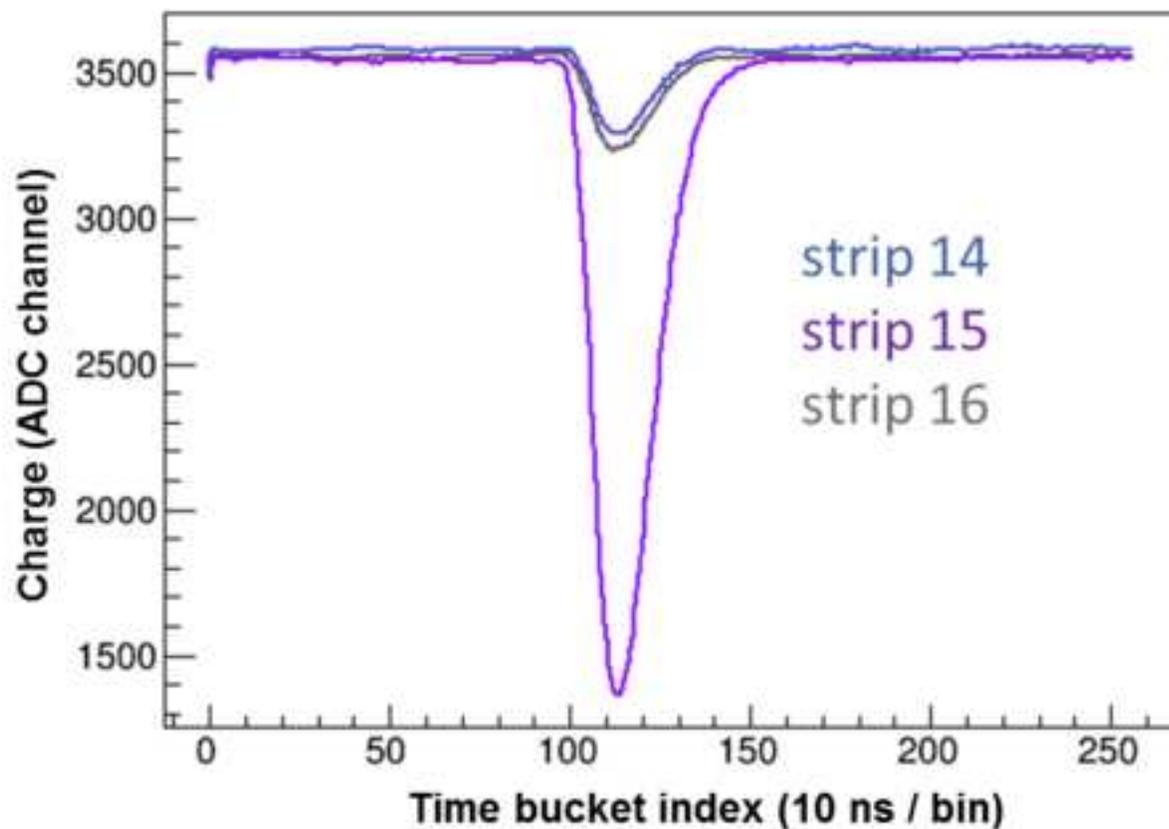
Figure 16: (Color online) Examples of reconstructed neutron beam profiles from two of the masks used. The left figures correspond to the images obtained taking the last strip into account and the right figures correspond to the refined analysis explained in the text.

Figure

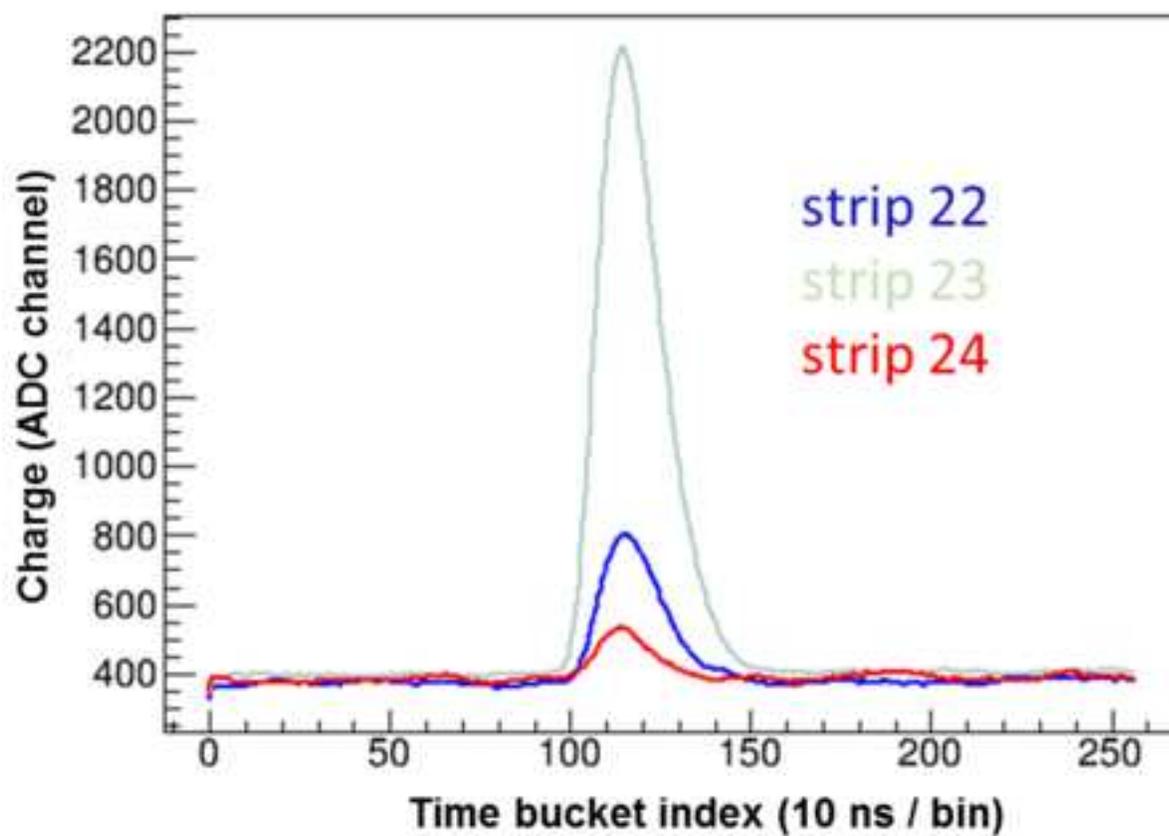


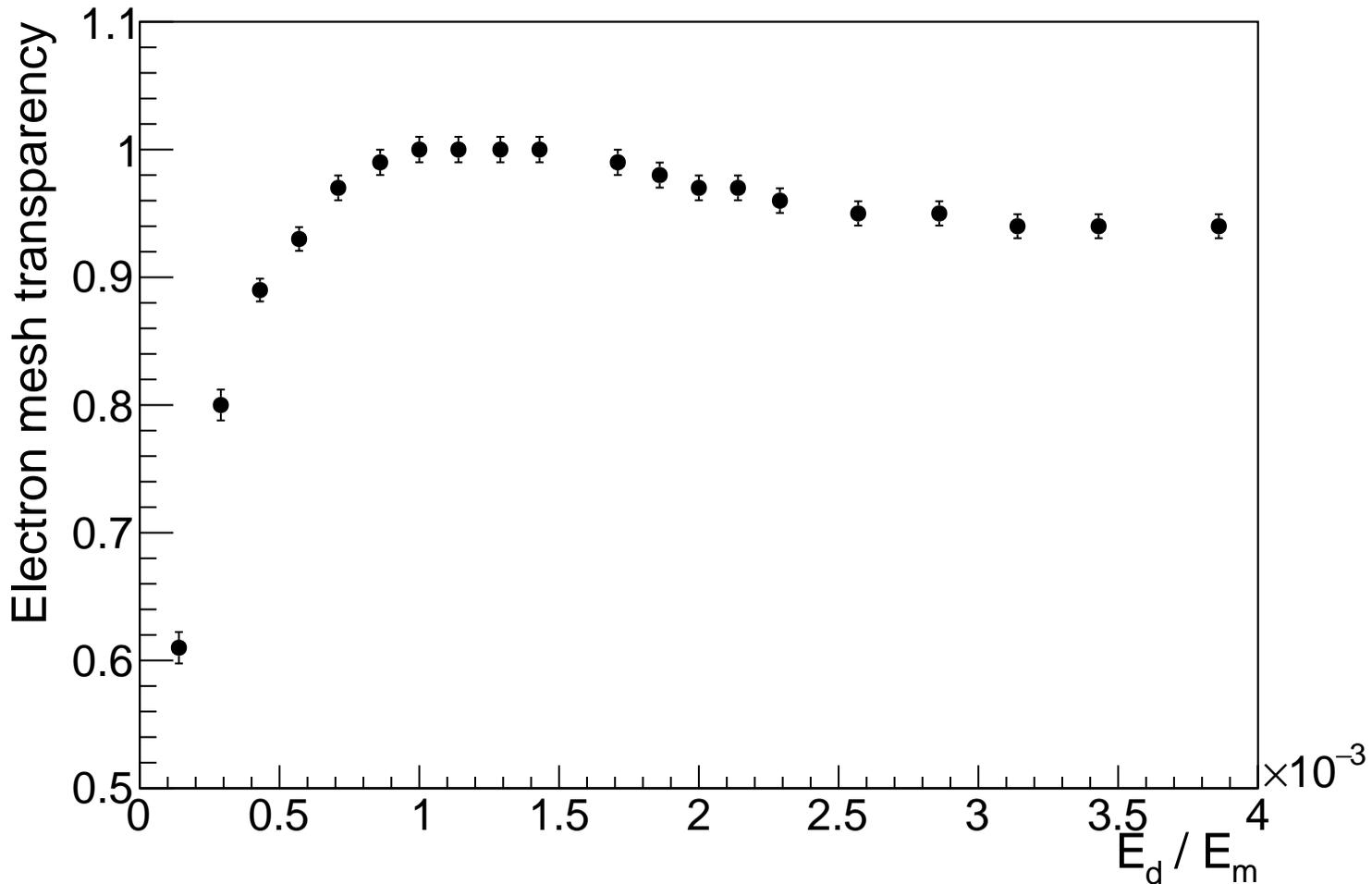


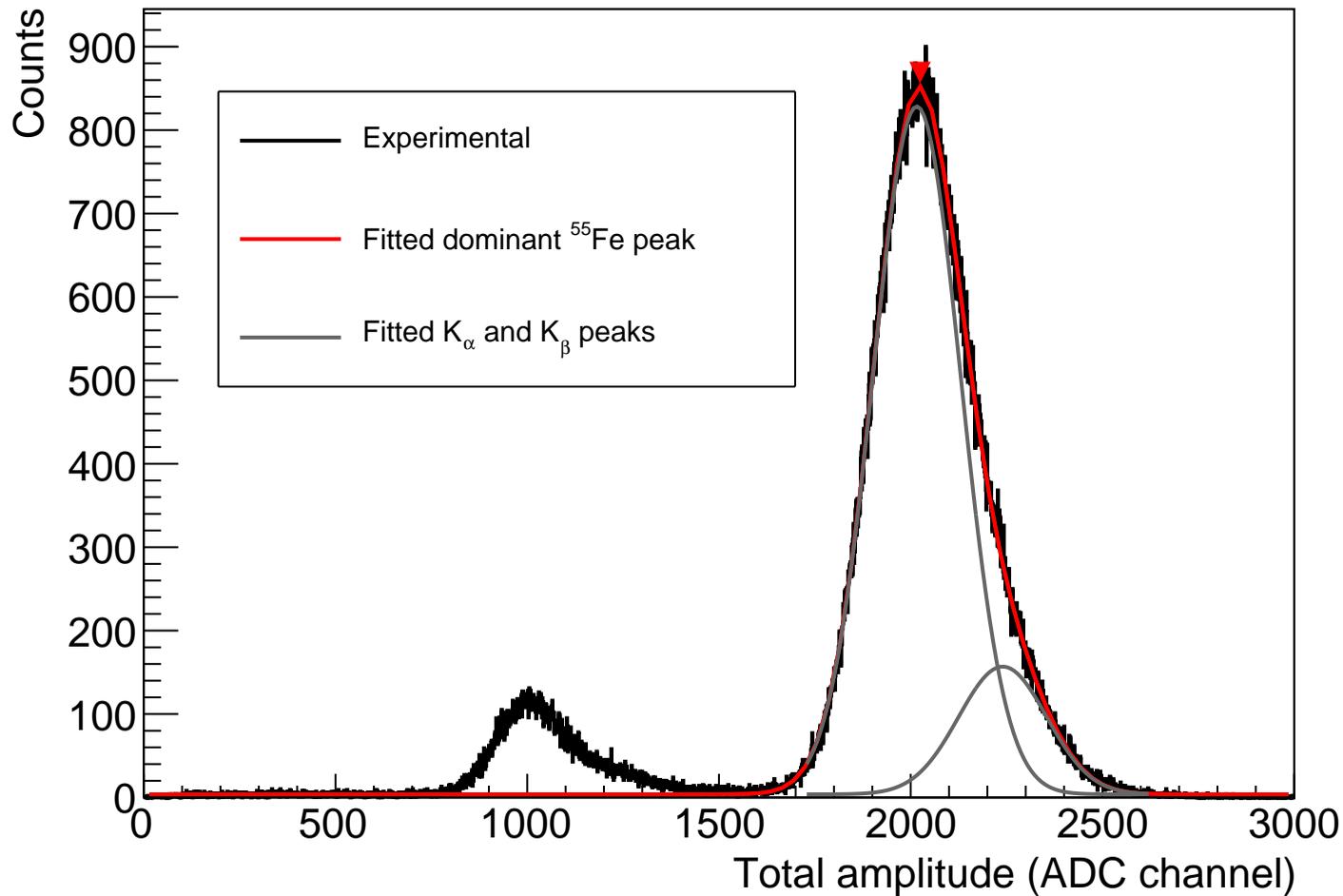
Frame 15 - AGET 1

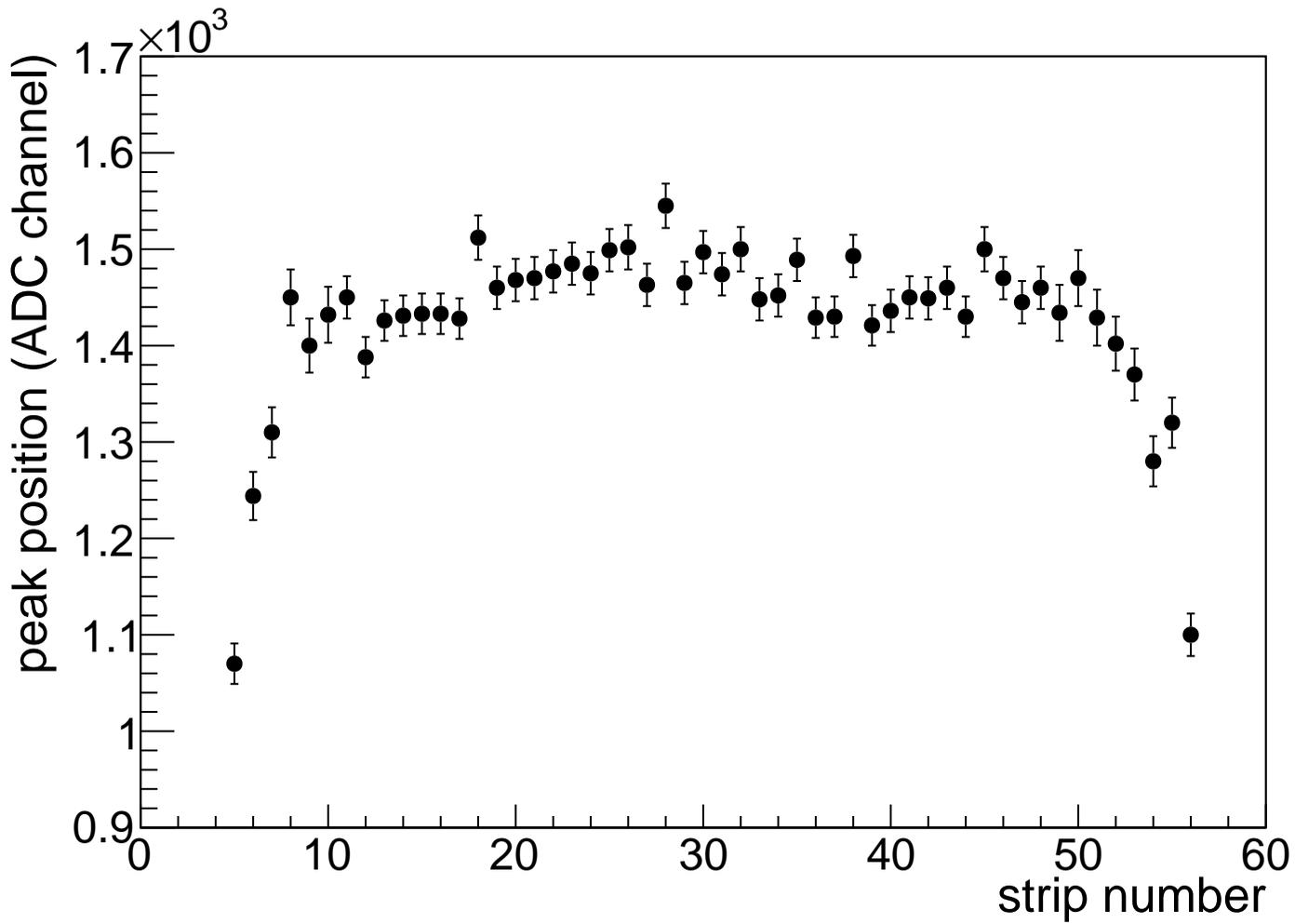


Frame 15 - AGET 3

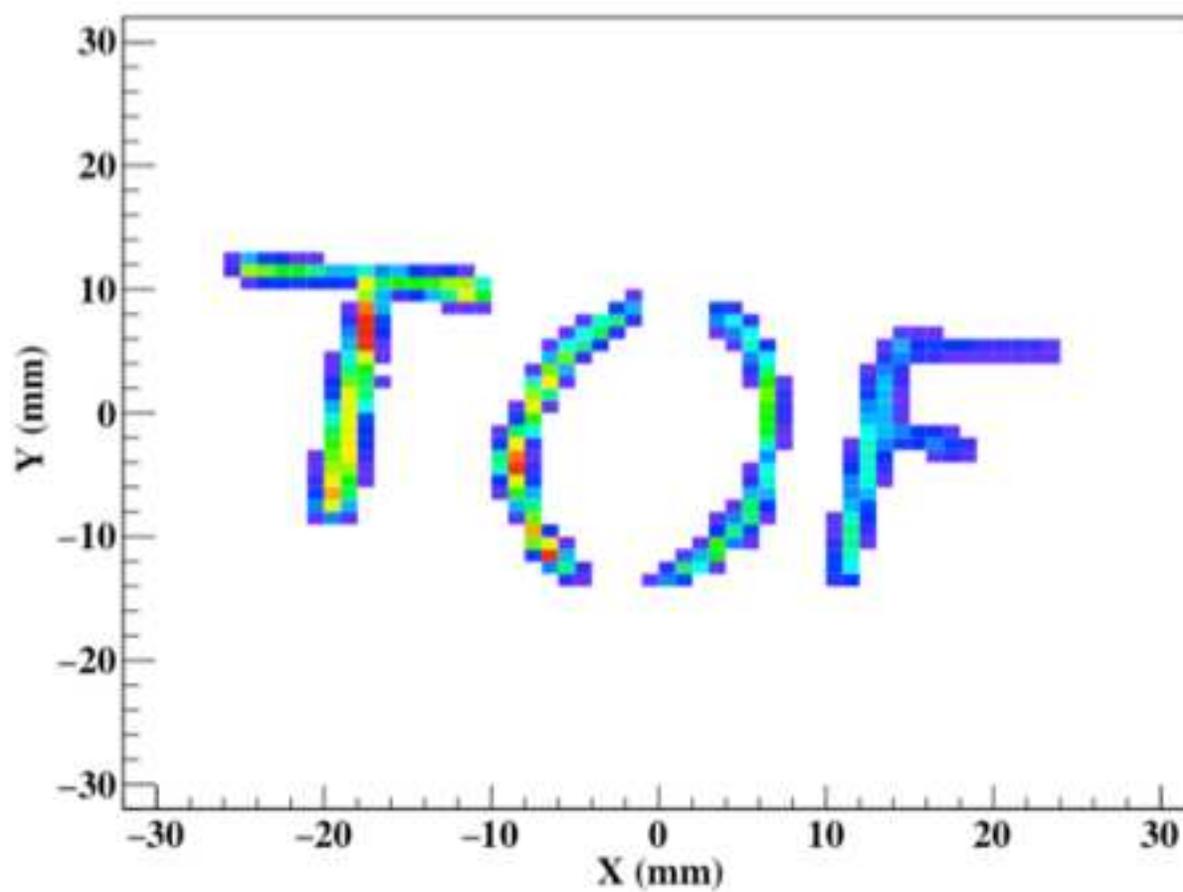




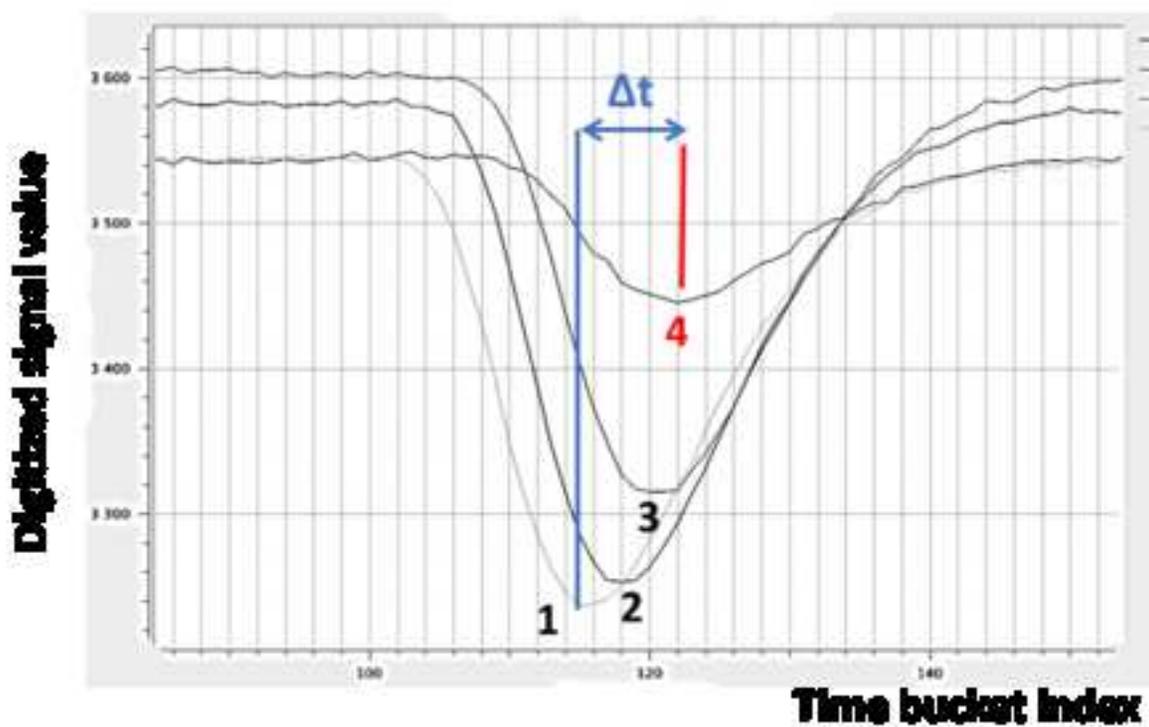
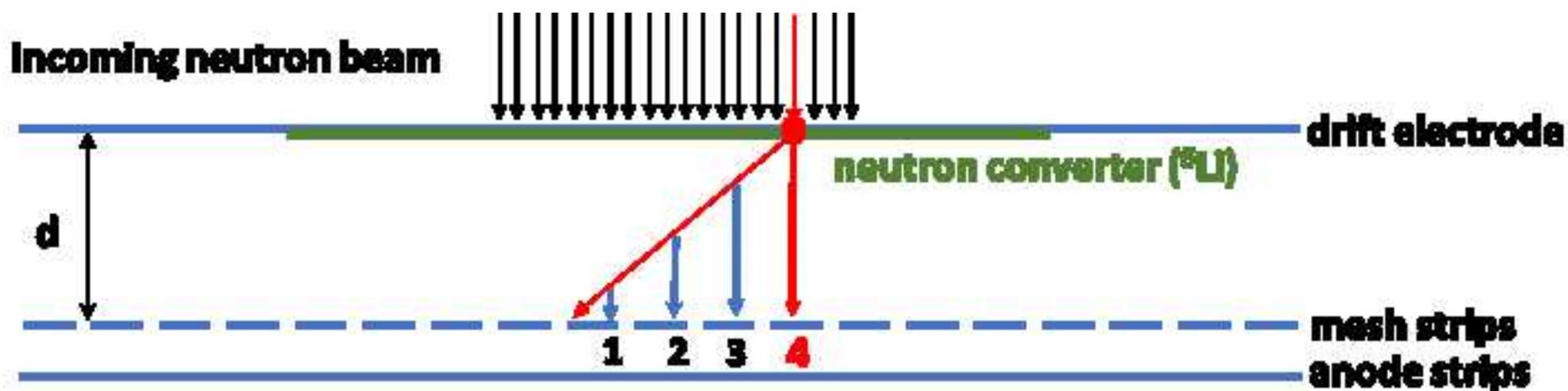


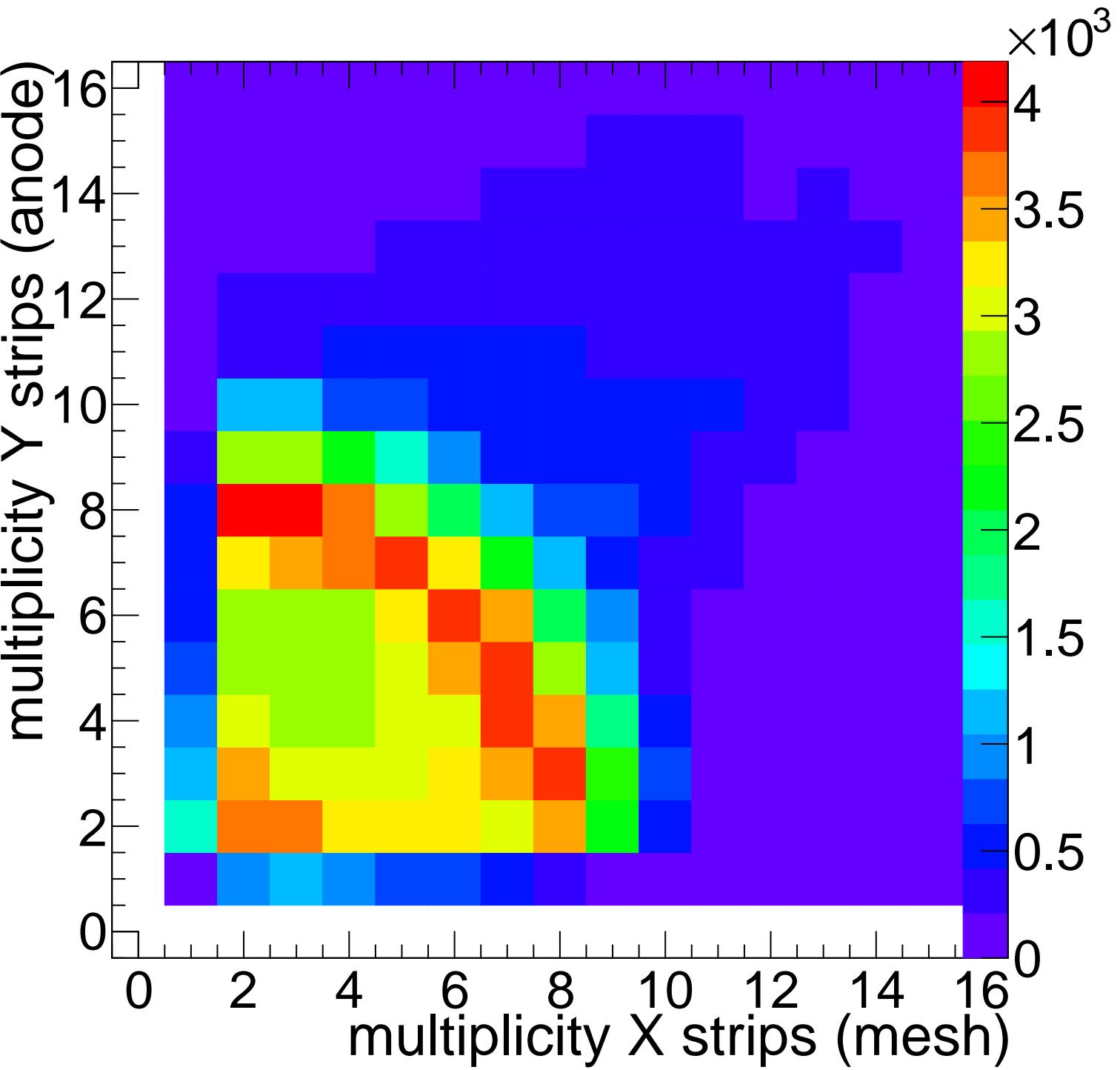


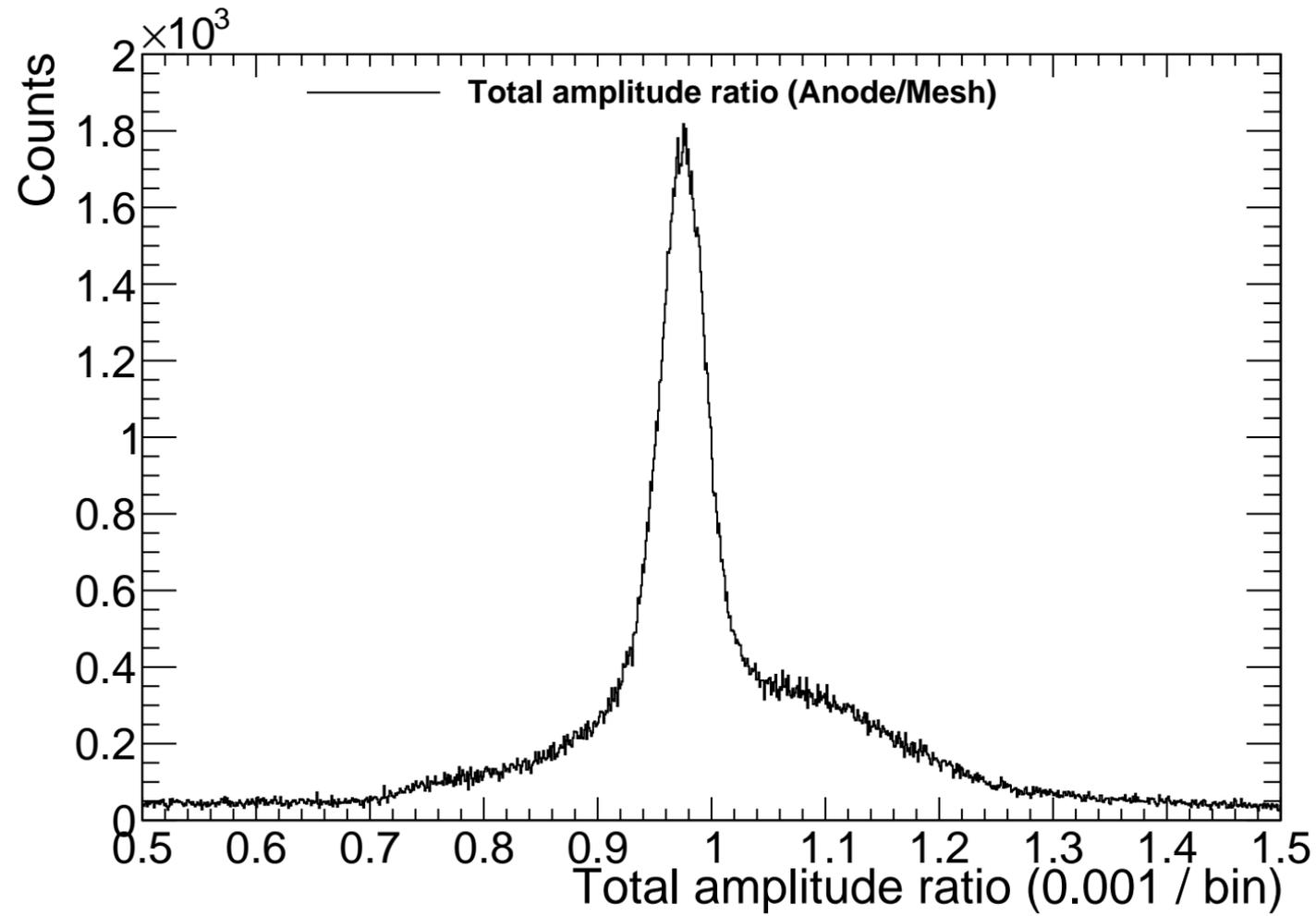
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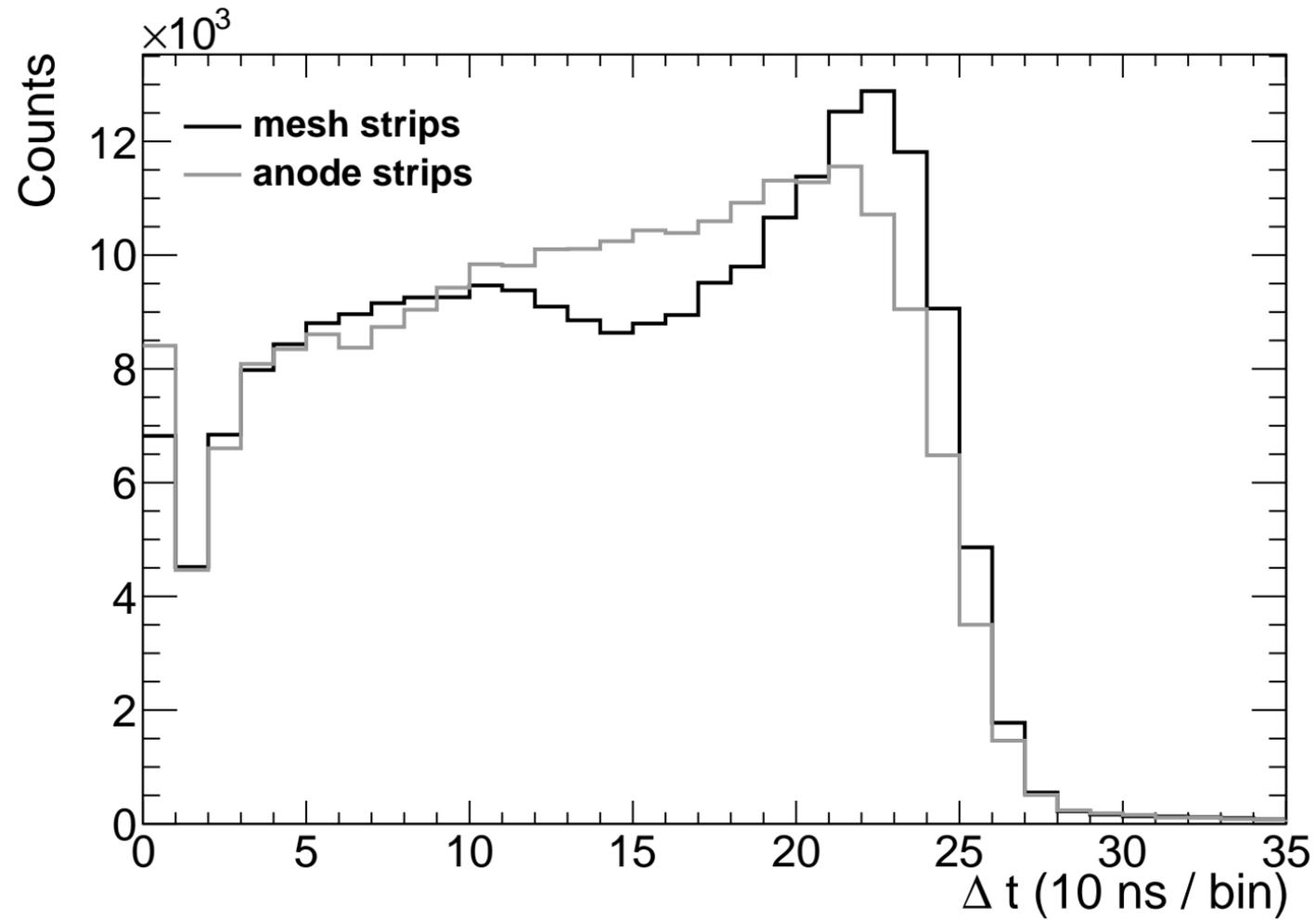


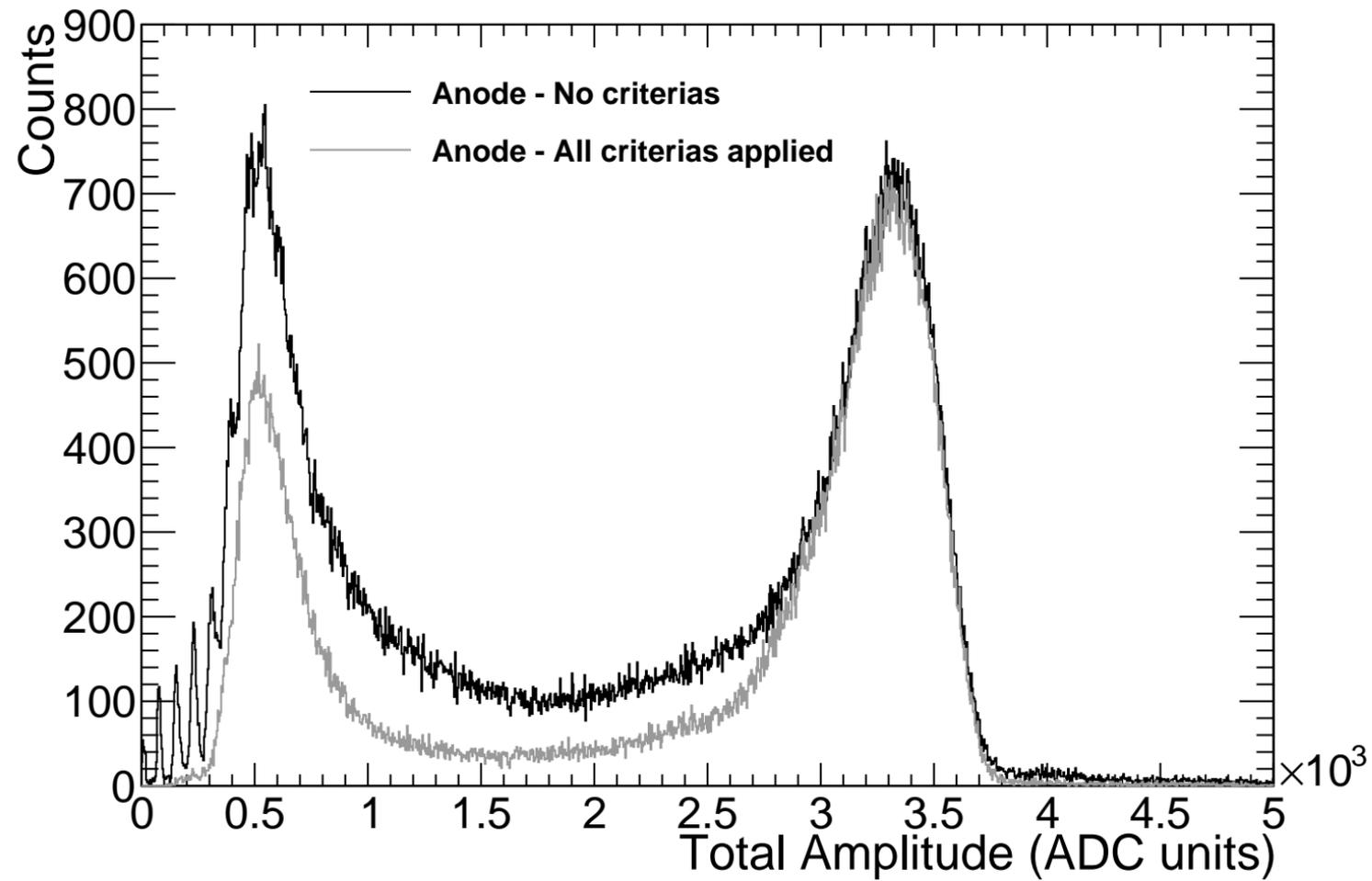
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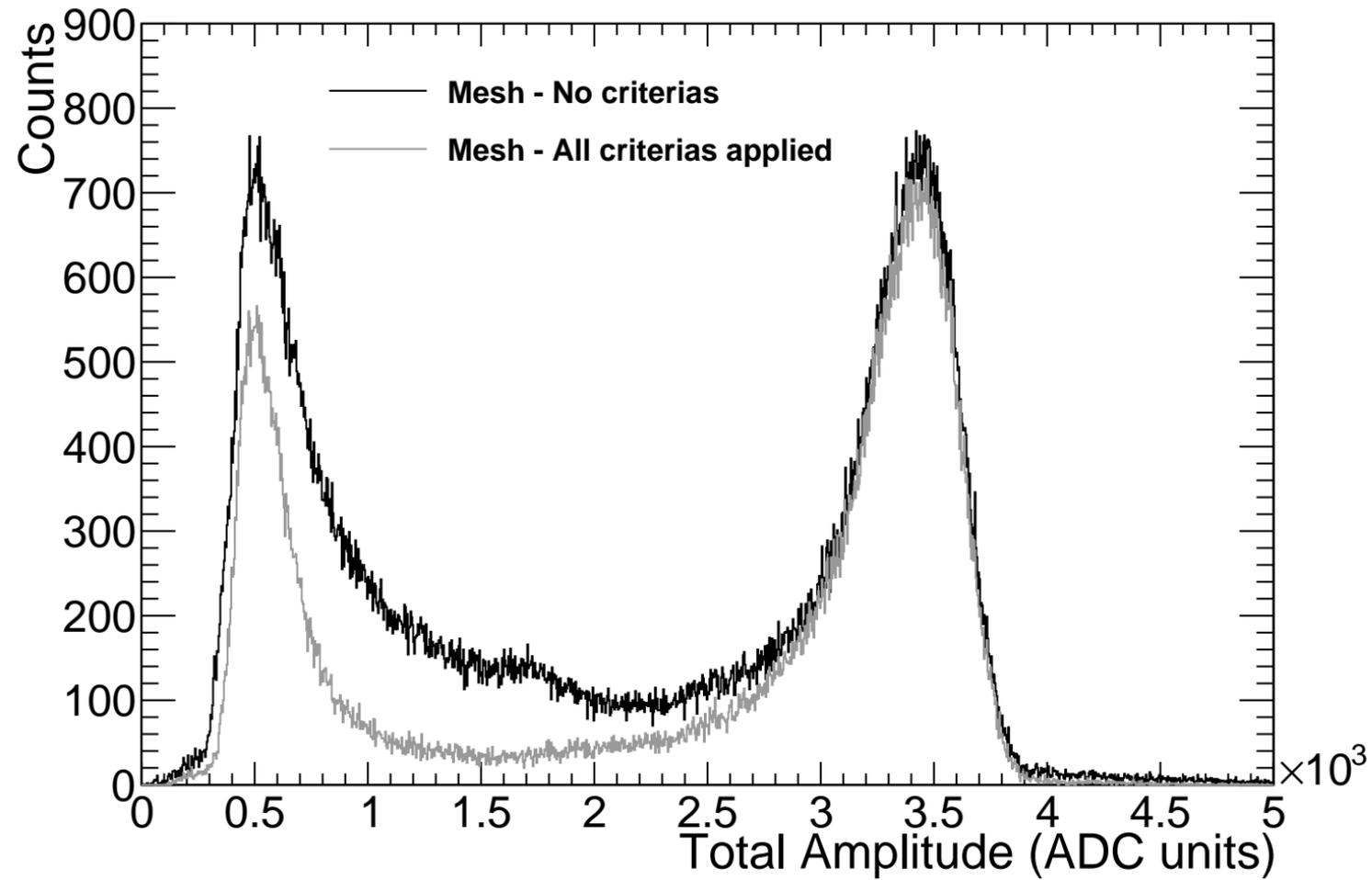




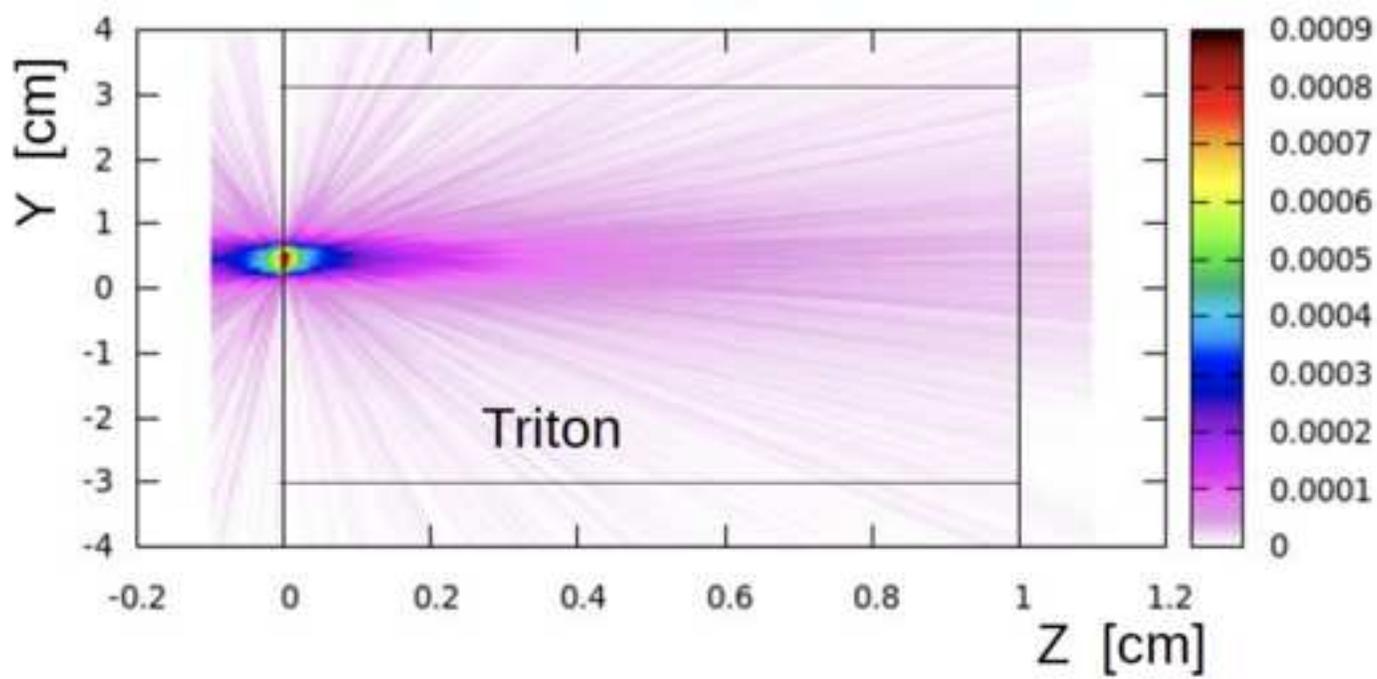
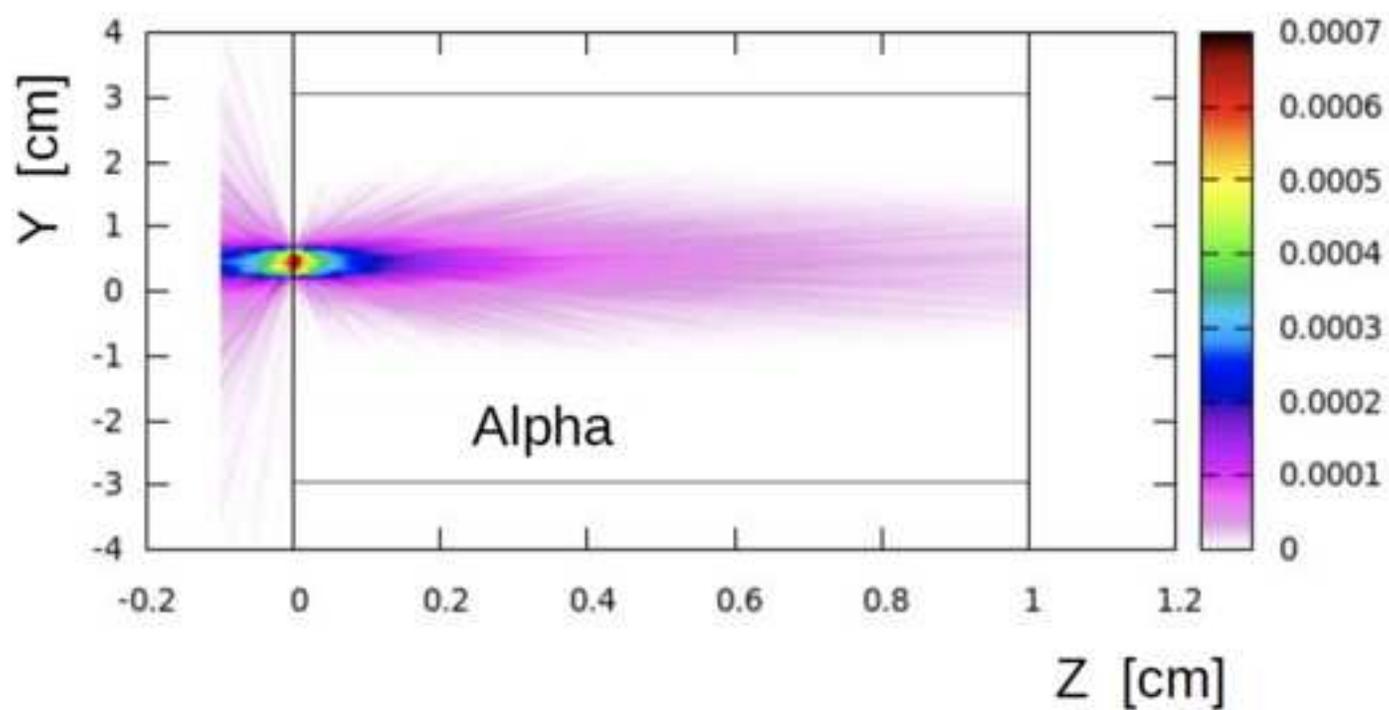




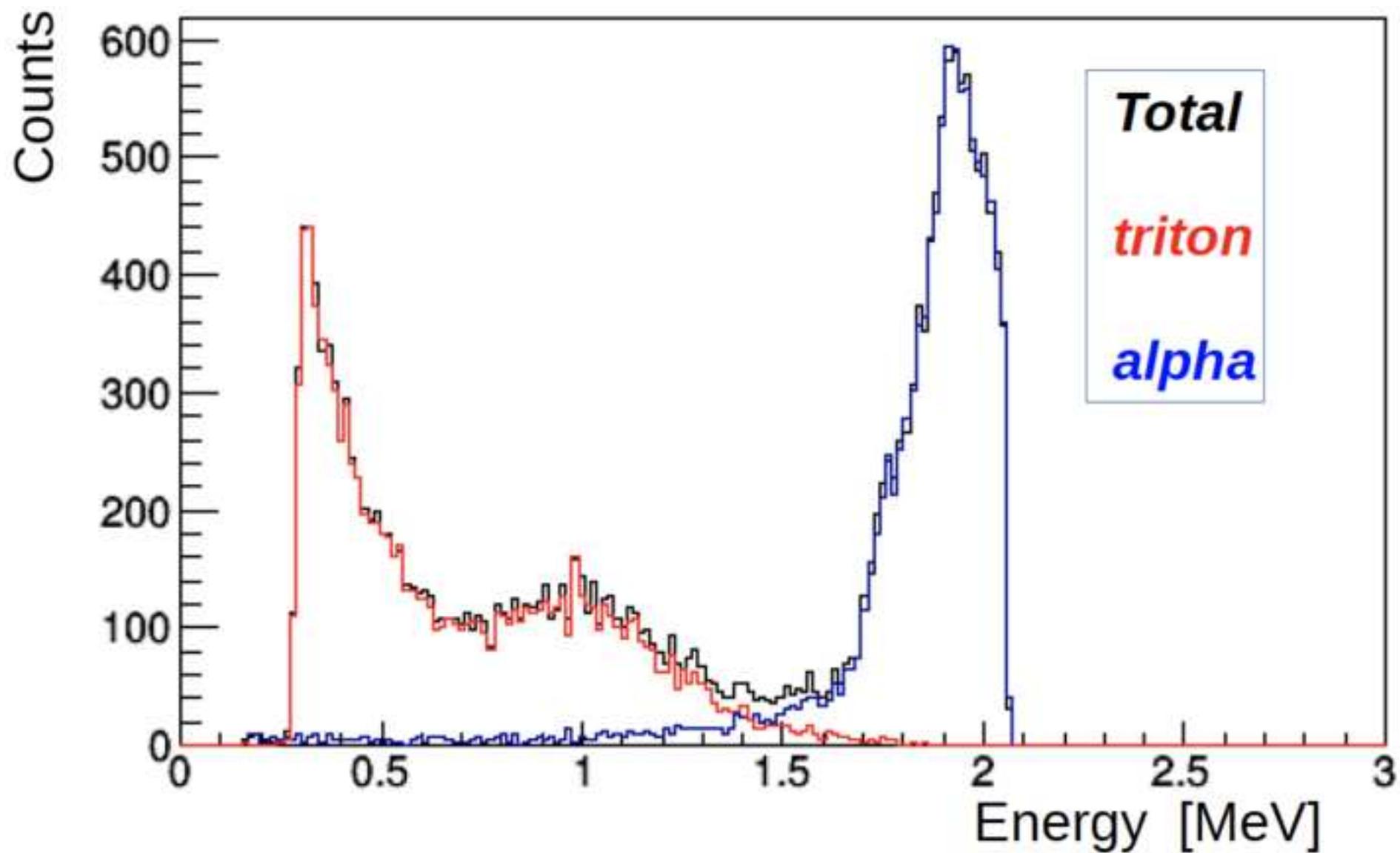


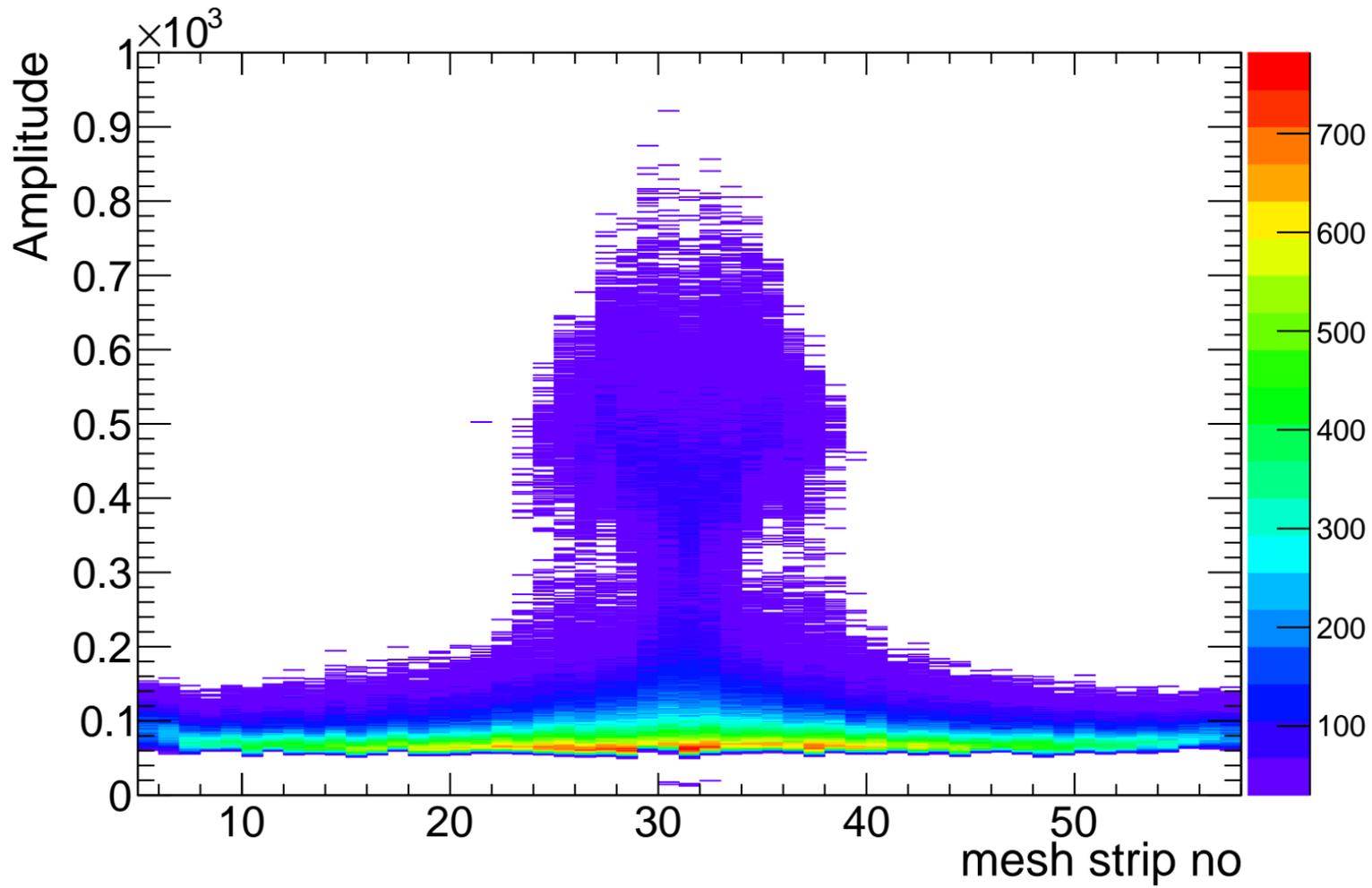


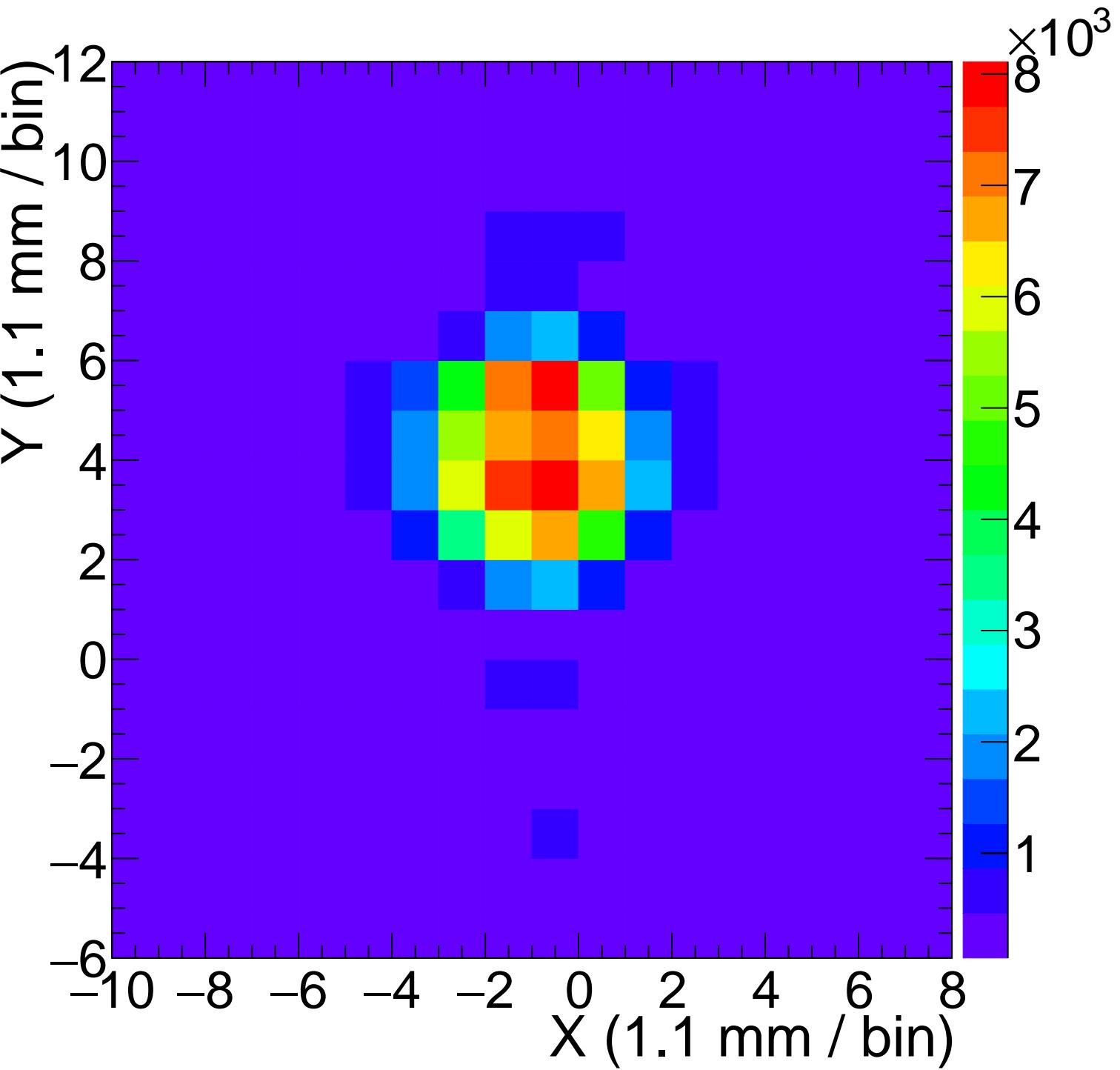
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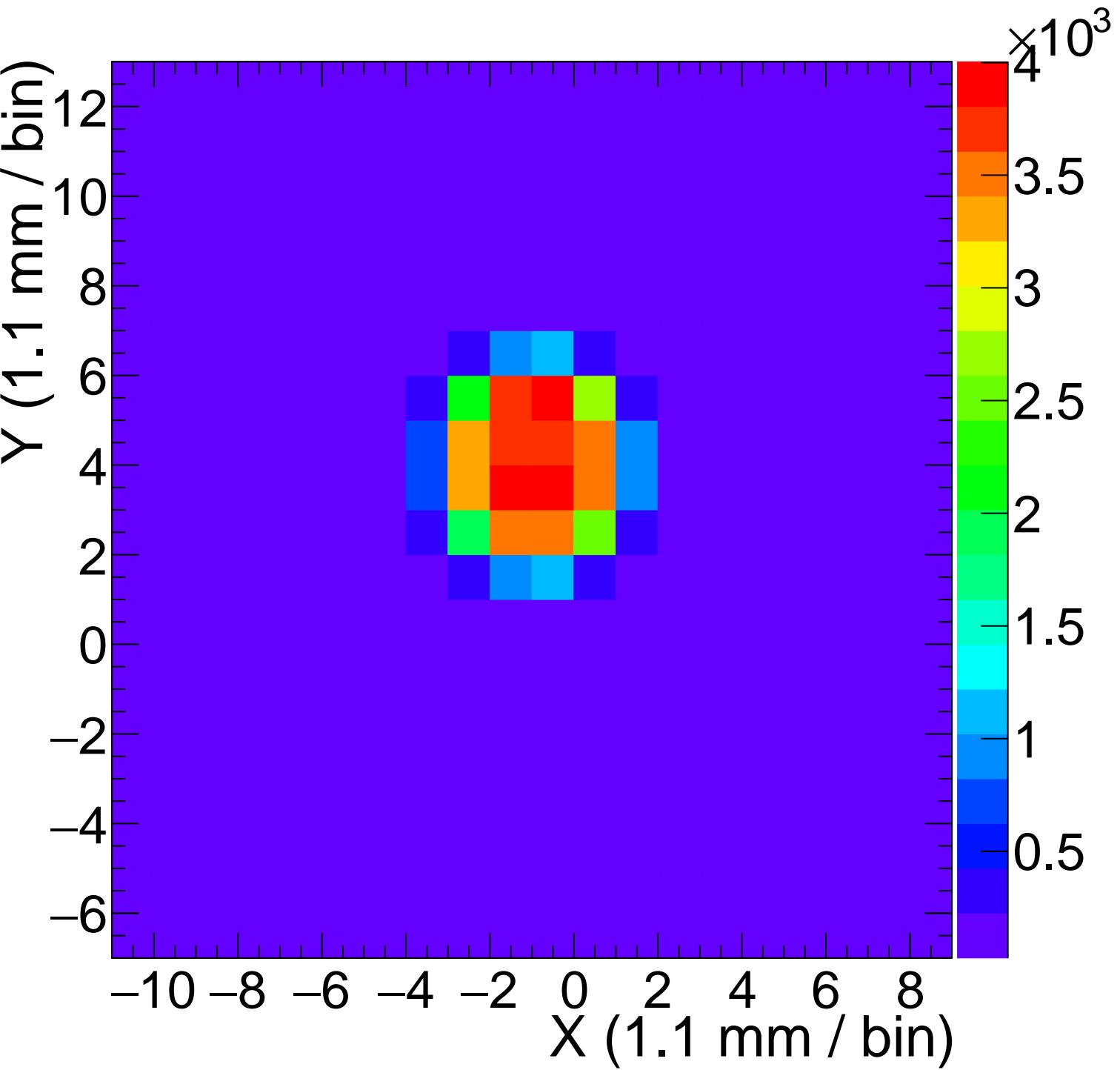


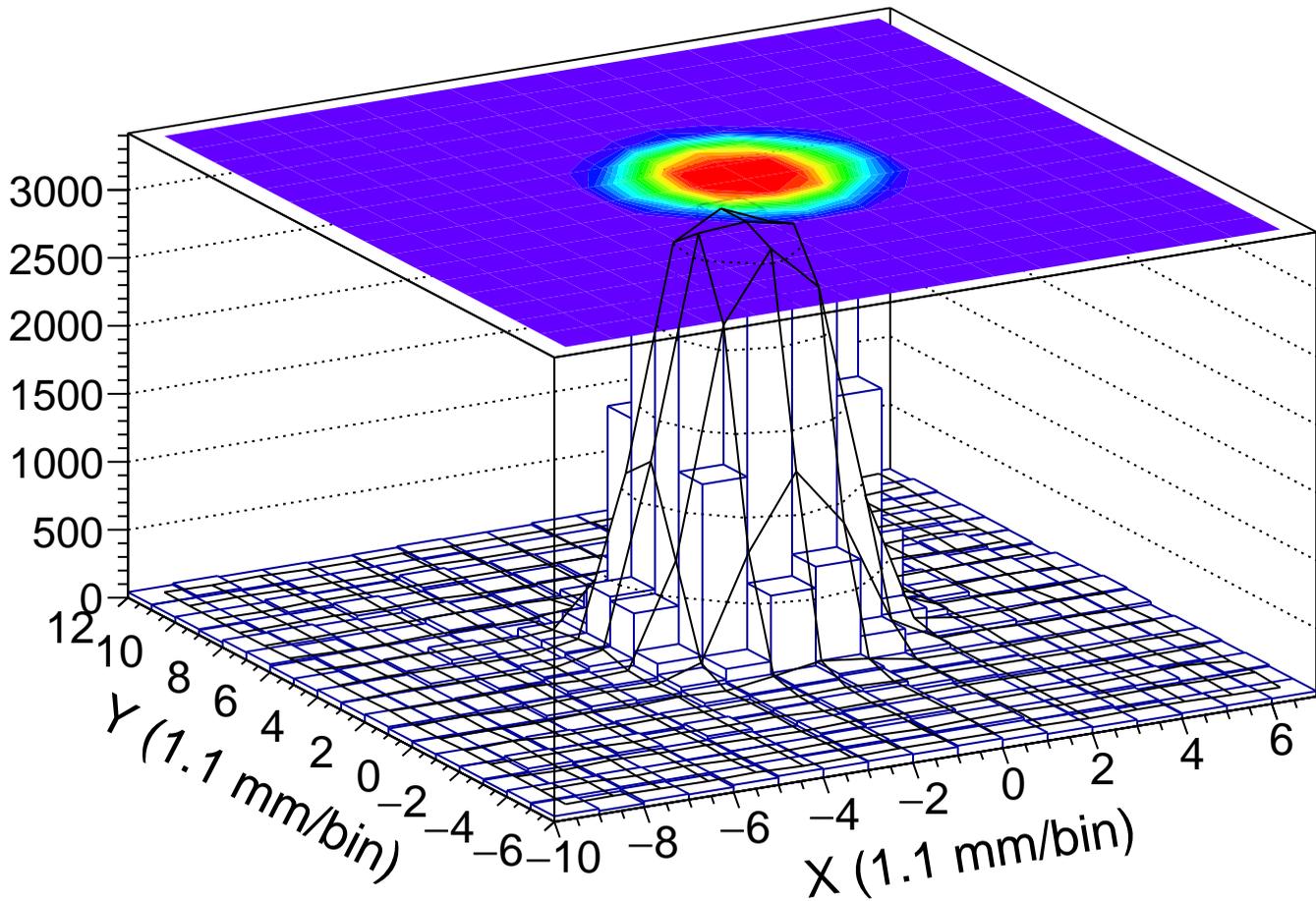
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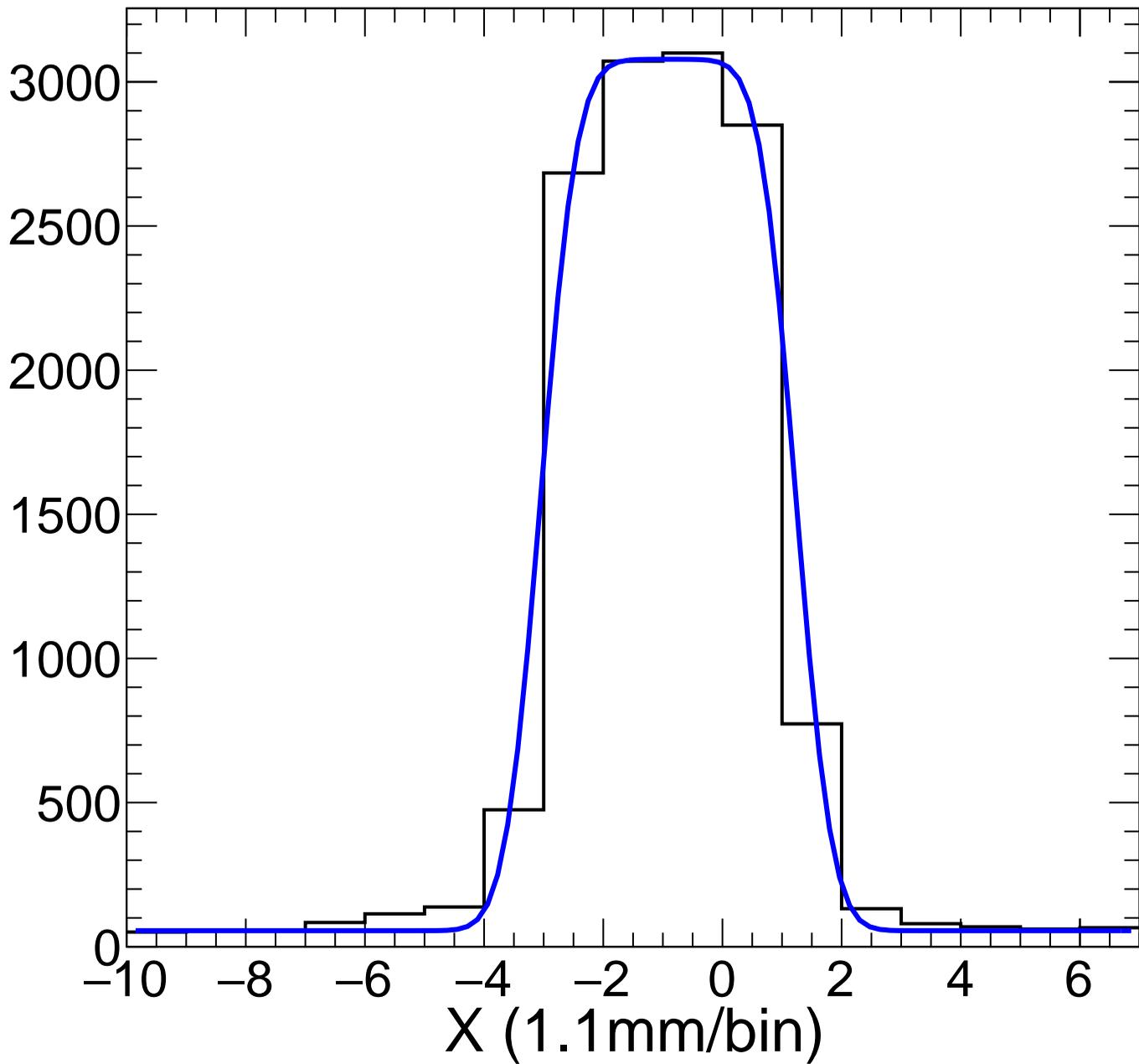


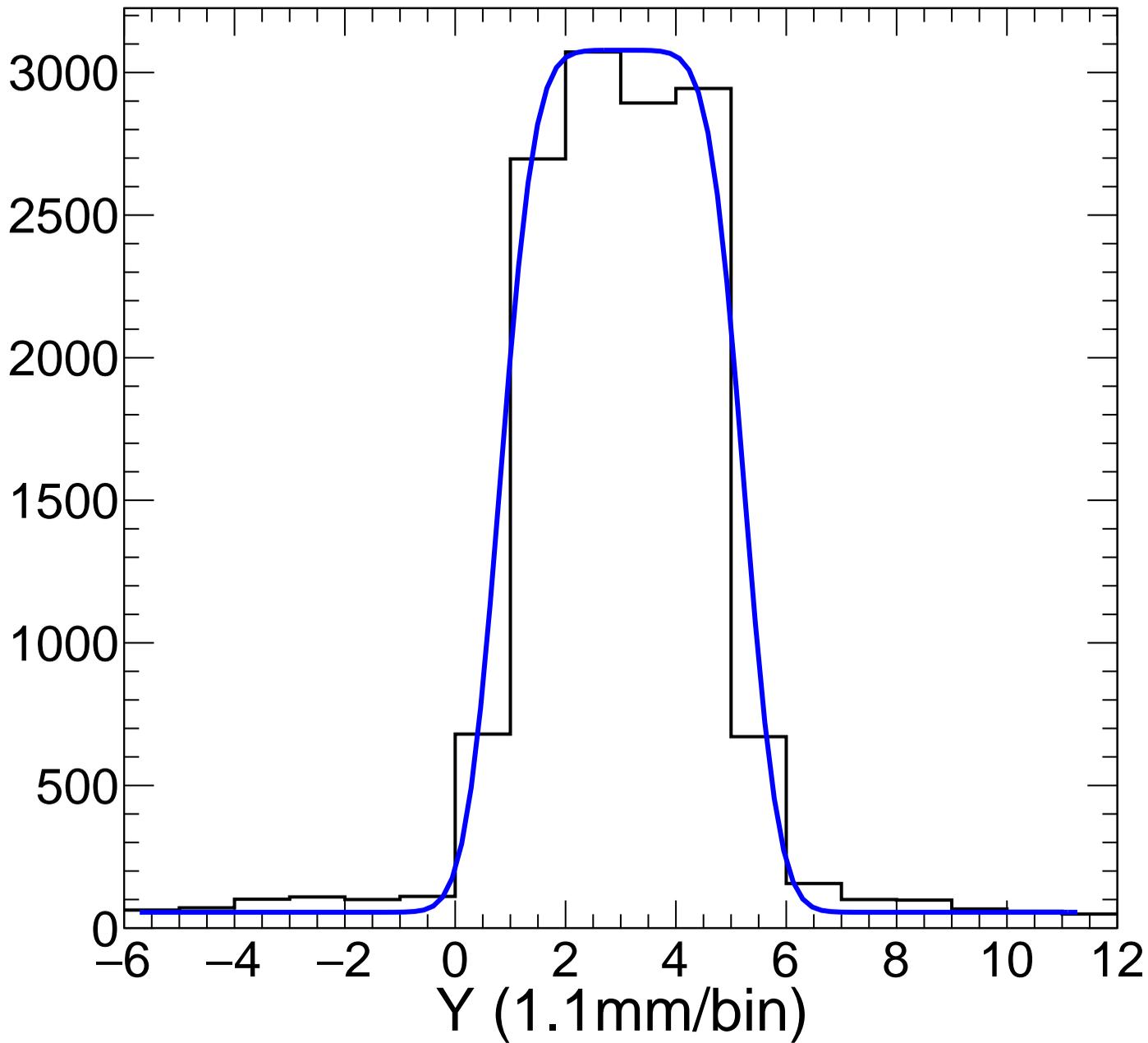


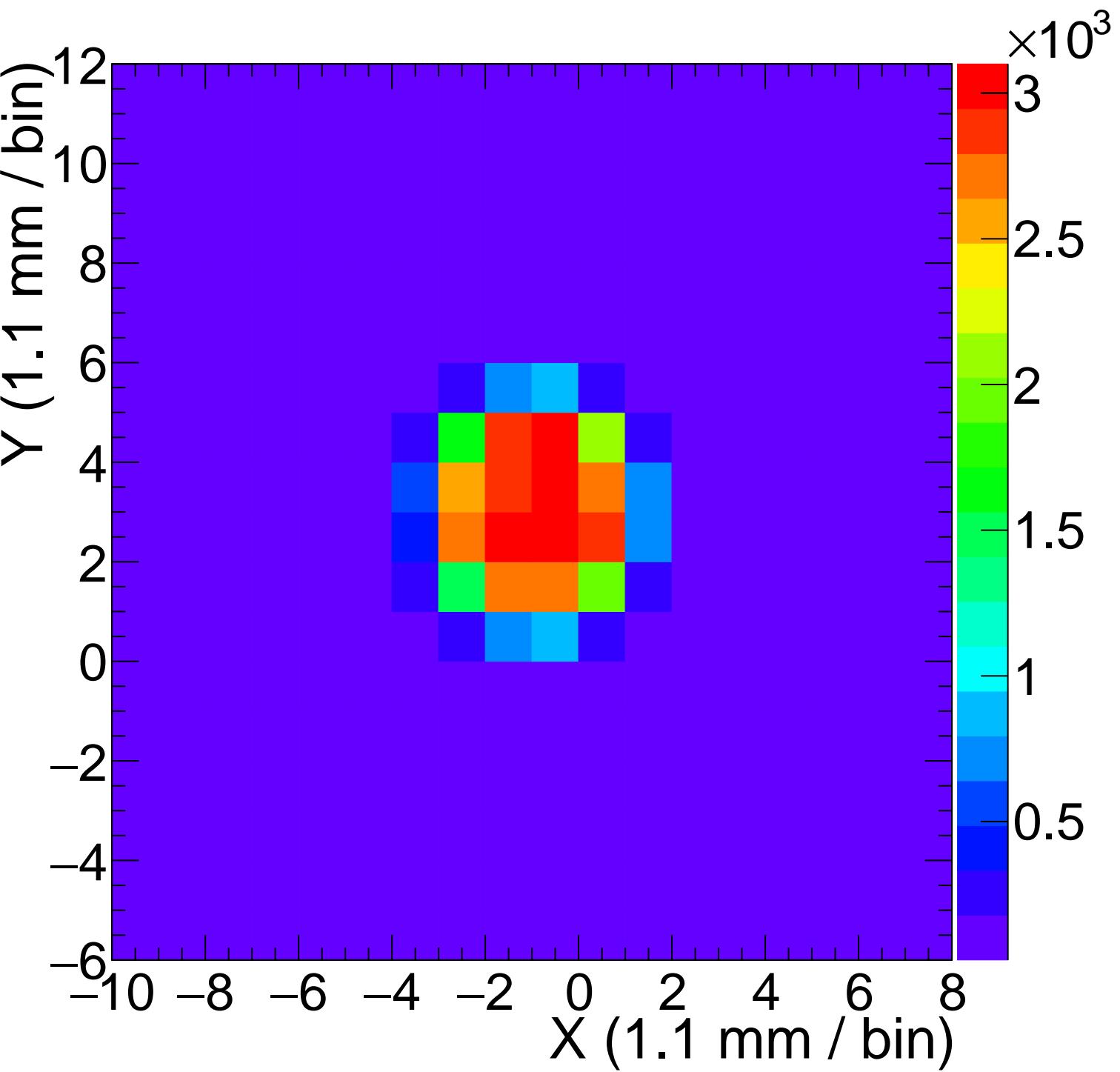


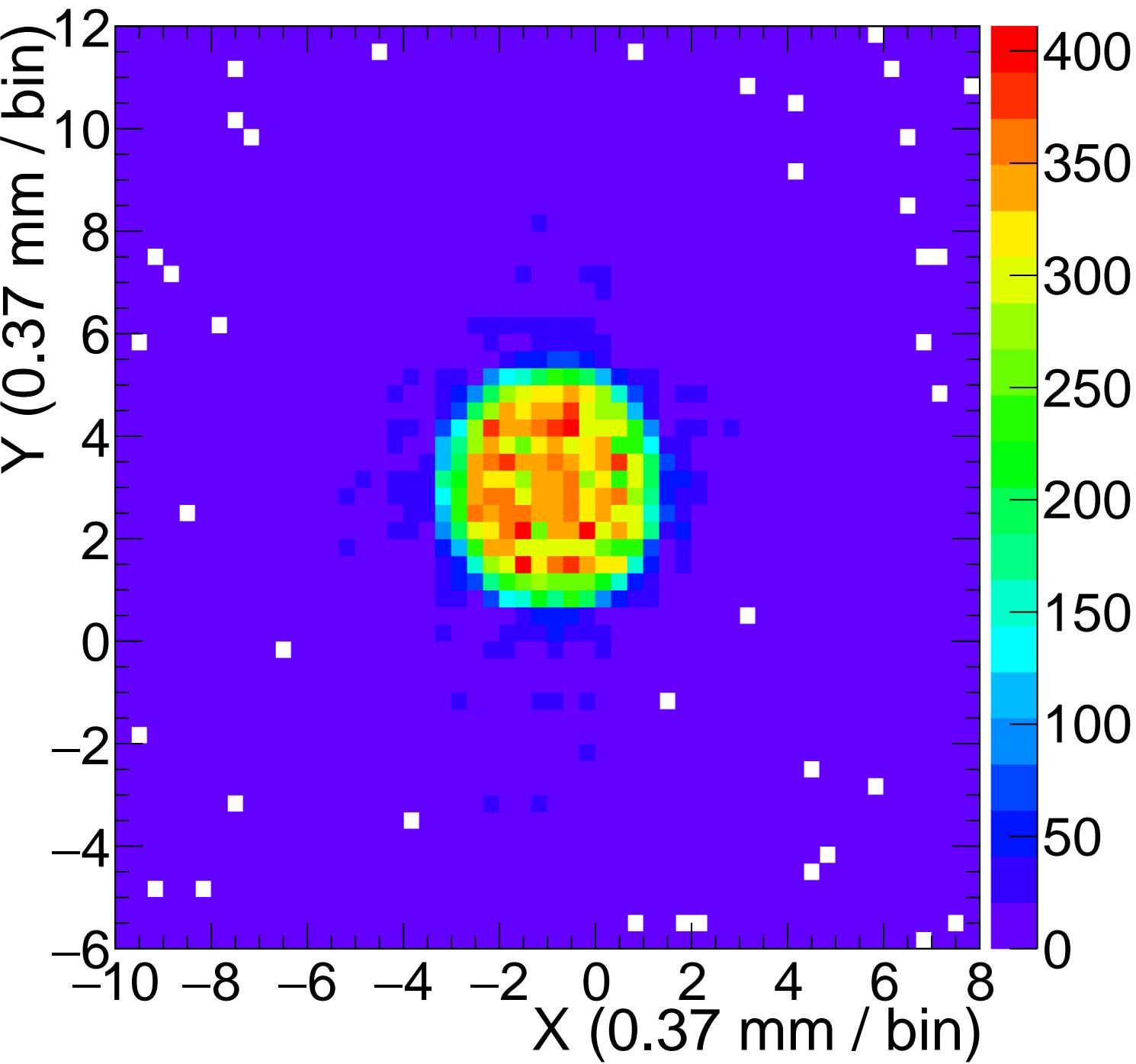


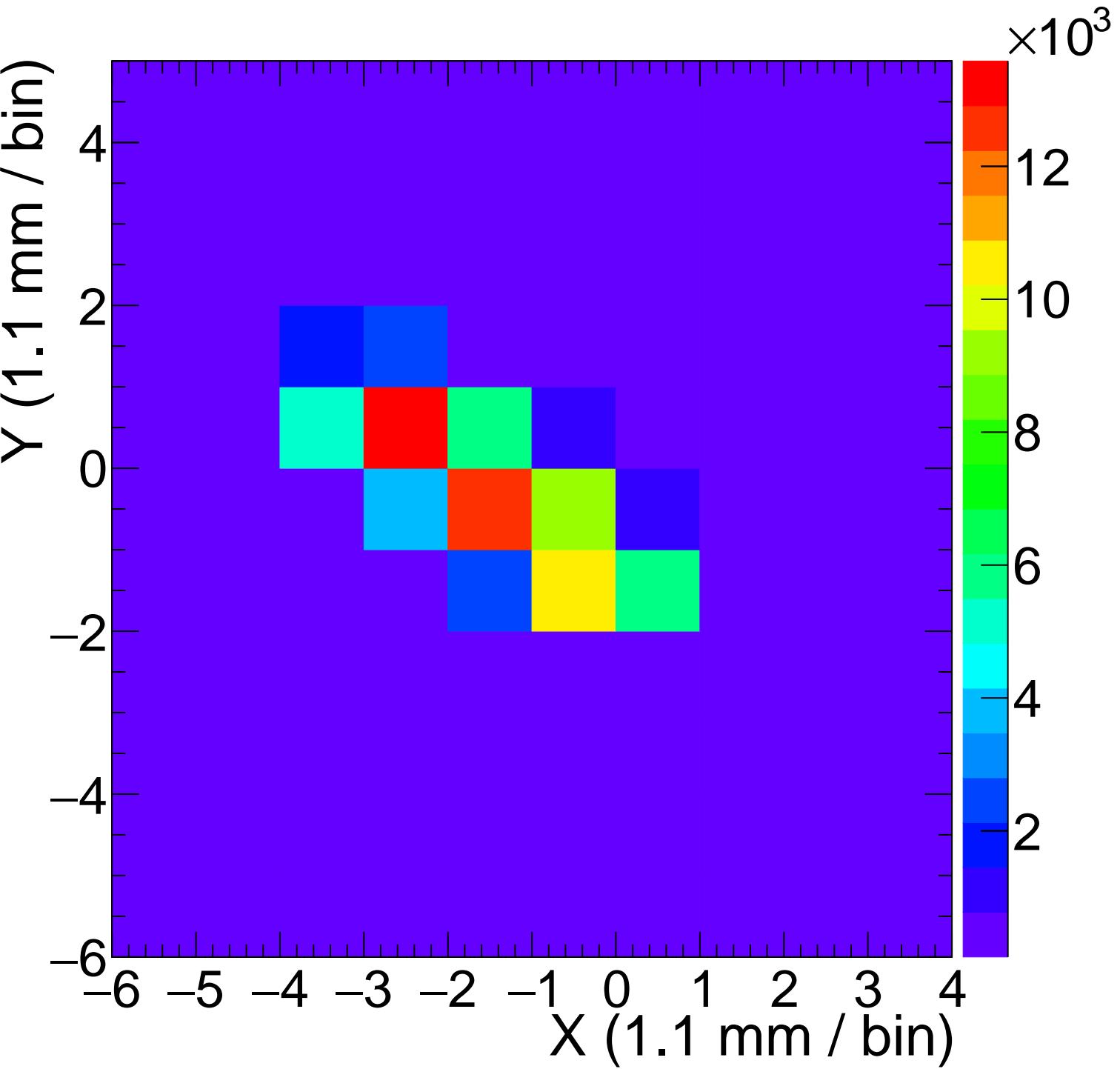


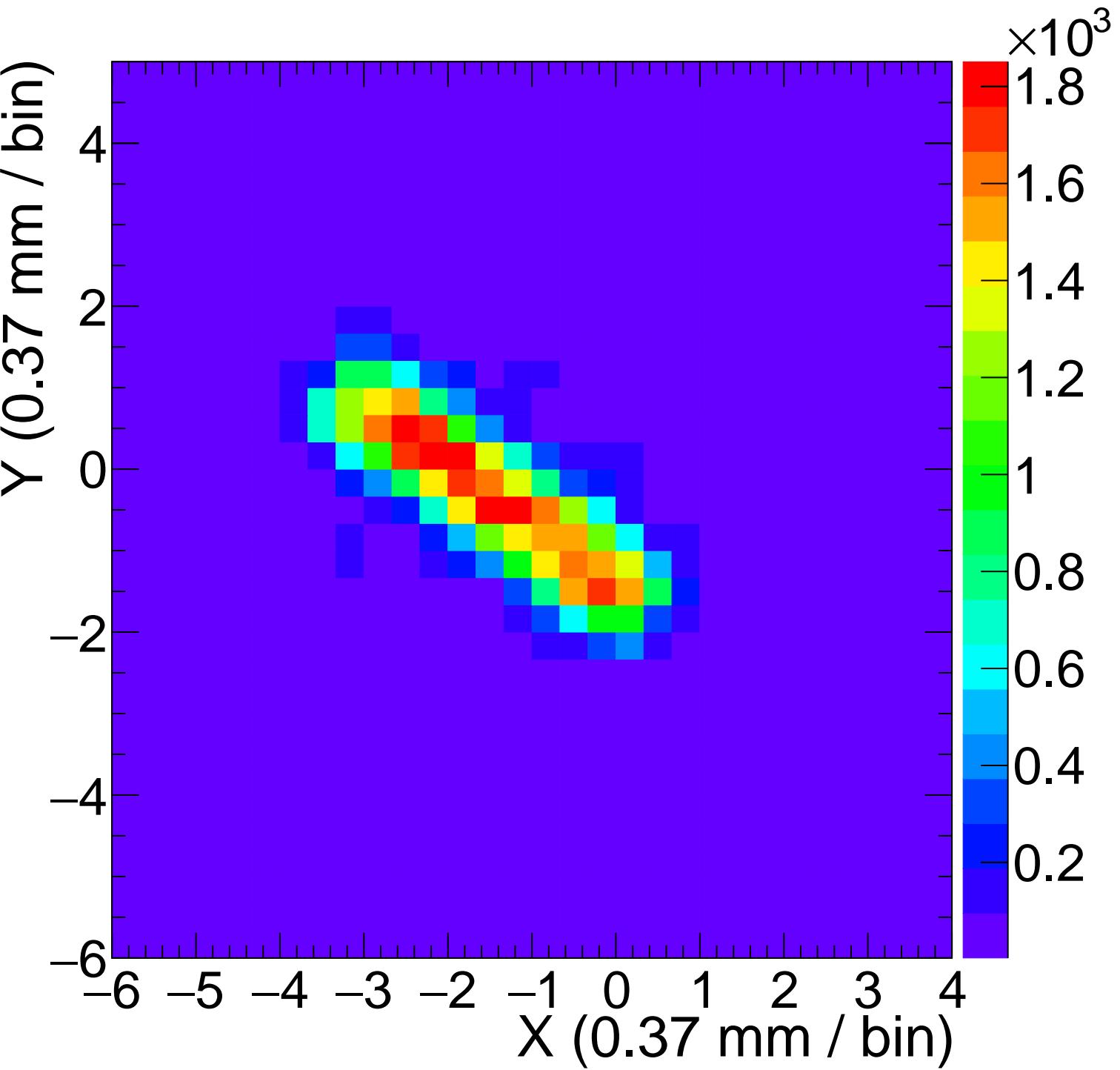












Dear Dr. Barletta,

On behalf of all the authors I would like to thank you for your consideration of our manuscript and both referees for their kind comments. You can find below the detailed list of changes performed in the new version of the manuscript based on the suggestions of the second Reviewer.

The initial Reviewers' comments are in italic and the corresponding changes at the text are explained in bold.

Reviewer #1:

I have no additional comment, everything was answered clearly!

Reviewer #2:

I would like to thank the authors for their careful consideration, implementation and their detailed answers to comments. The revised publication is very well readable and presents the work done and the results in a concise way. Warmest congratulations to the authors.

I recommend the manuscript for publication in NIM A.

Below few minor comments, that the authors may chose to implement or ignore. Answers to the comments are not necessary. Line numbers refer to the revised version.

- 13: *Maybe "amplification region structure" -> "amplification structure"*

It has been replaced by "structure of the amplification region..." which is more explicit (since I refer to the "amplification region" in line 7. (line 13 of the new version).

- 34: *the term "charge cloud" is slightly misleading as part of the signal is due to the drift of ions in the amplification region. Consider removing the word "cloud".*

The proposed change has been made (line 34 of the new version). The same term has been corrected in line 43.

- 51ff: *Consider replacing "fabrication design" -> "definition of fabrication process" or "design process". Also "distribution at..." -> "distribution to ...".*

Concerning the first proposition, I changed to "the microbulk design" (because I really want to refer to the design and not to the fabrication process) (line 50-51 of the new version).

The second correction has been made (line 52 of the new version).

- 197ff: *Consider rearranging to "...by optimising the hole topology and interstrip gap, special attention to the grounding design and with good alignment of the strips during microbulk and PCB fabrication processes respectively,..."*

I corrected the phrase as follows: «The above mentioned results indicate that with the optimisation of the hole topology and interstrip gap and with good alignment of the strips, as well as special attention to the grounding design during the microbulk and PCB fabrication processes respectively,...», because «special attention to the grounding design» refers to the PCB fabrication process, this is why it should go third. (lines 196-199 of the new version).

- 410: *twice "the possibility"*

It has been corrected (line 409 of the new version).

- 416: *missing space between "rim" and "electrode"*

It has been corrected (line 415 of the new version).

- caption Figure 11: *red -> grey*

It has been corrected.

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