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Title: Secondary electron flight times and tracks in the carbon foil time pick-up detector

Year: 2014

Version:

Please cite the original version:

Laitinen, M., Rossi, M., Julin, J., & Sajavaara, T. (2014). Secondary electron flight times and tracks in the carbon foil time pick-up detector. Nuclear Instruments and Methods in Physics Research, Section B: Beam Interactions with Materials and Atoms, 336(October), 55-62. <https://doi.org/10.1016/j.nimb.2014.06.014>

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1 **Secondary electron flight times and tracks**
2 **in the carbon foil time pick-up detector**

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19 **Abstract:**

20 Carbon foil time pick-up detectors used in the time-of-flight measurements of MeV
21 energy ions have been studied in connection to time-of-flight-energy spectrometer used
22 for heavy ion elastic recoil detection analysis. In experimental coincident TOF-E data
23 characteristic halos are observed around light element isobars, and the origin of these
24 halos were studied. The experimental data indicated that these halos originate from single
25 electron events occurring before the electron multiplication in the microchannel plate. By
26 means of electron trajectory simulations, this halo effect is explained to originate from
27 single electron, emitted from the carbon foil, hitting the non-active area of the
28 microchannel plate. This electron creates a secondary electron from the surface and
29 which ends up to the microchannel plate pore, is multiplied and create now a detectable
30 signal. Other general timing gate parameters such as wire-to-wire spacing of the grids,
31 acceleration potential of the 1st grid and the mirror grid potential gradient were also
32 studied in order to improve the detector performance.

36 **Keywords:**

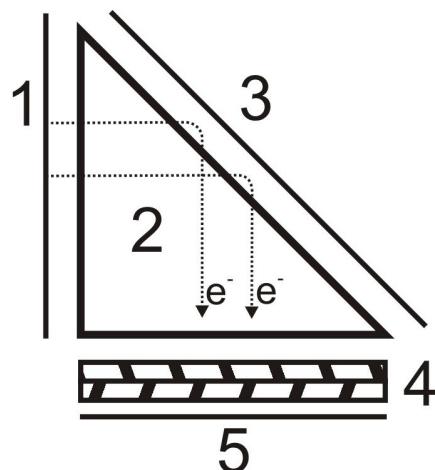
37 timing gate, carbon foil time pick-up detector, Time-of-Flight, ToF-ERDA, spectrometer.

38 **1 Introduction**

39

40 Modern time-of-flight elastic recoil detection (ToF-ERD) spectrometers often use two
41 carbon foil time pick-up detectors [1–3], similar to the design by Busch et al. [4]. This
42 type of timing detector has typically five basic components (see Fig. 1): 1) The carbon
43 foil that emits the electrons due to ion passage, 2) the toblerone-part which accelerates
44 the electrons from the carbon foil and is accompanied by transparent grid, or mesh
45 structures providing field free central region, 3) electrostatic mirror to bend the path of
46 the electrons by 90 degrees back to the field free toblerone-part, 4) microchannel plate
47 (MCP) for electron multiplication and 5) the anode to collect the electrons. In addition to
48 these, the decision of using the timing gate in forward or backward direction related to
49 the incident ion needs to be made.

50



51

52 *Figure 1. Basic components of the carbon foil time pick-up detector. This type of timing*
53 *gate has five components: 1) carbon foil, 2) field free toblerone-part, 3) mirror grid, 4)*
54 *MCP for electron multiplication and 5) anode to collect the electrons.*

55 All of these individual detector components affect the timing performance through their
56 material properties, structural geometry or by applied voltages. Energetic ion impact into
57 the carbon foil will induce emission of zero to multiple secondary electrons, that can have
58 wide energy and angular distributions [5,6]. The number of emitted electrons can be
59 increased by other materials deposited on top of the carbon foil. These materials, such as
60 LiF [2] or Al₂O₃ grown by atomic layer deposition (ALD) [7] can enhance the electron
61 emission and therefore increase the detection efficiency for light ions. The emitted
62 electrons having both the high energy and large emission angle perpendicular to the foil,
63 can distort the timing signal already before the first accelerating grid causing non-
64 isochronous electron transportation to the MCP. The grid spacing grid
65 uniformity/smoothness and voltages applied to the mirror grid and toblerone-part also
66 affect the electron trajectories before the MCP. The voltage, pore size and pore length of
67 the MCP, and the distance between the individual MCP plates and their potential
68 difference in chevron composition affect the rise time and width of the electron pulse [8].
69 Finally the anode design can have a big effect to the timing properties of the carbon foil
70 time pick-up detectors in the time-of-flight measurements. In addition to these individual

71 timing gate components, the decision of using the timing gate in forward direction related
72 to the incident beam i.e. the foil faces the beam first or in the backward geometry where
73 mirror faces towards the incident beam, needs to be made as well.

74

75 In this paper we focus on the timing pulse properties of the single carbon foil time pick-
76 up detector. Main emphasis is given to the individual parts before the MCP and how the
77 different grid designs can affect the electron flight time properties from the carbon foil to
78 the MCP. An explanation to the halo effect typically seen also in other studies [9,10]
79 around the hydrogen events in the ToF-E histograms is proposed. The MCP and anode
80 part are left for less attention as ready MCP solutions with fast rise times (down to 300 ps
81 in standard products [8,11]) and matched anodes can be acquired commercially by
82 several suppliers. For the case of timing gate orientation, one can for example win few
83 centimeters in the ToF length if the first timing detector is facing forward and the second
84 in backward electron emission direction. The forward direction can also produce more
85 electrons due to the ion impact but their energy and especially their angular distribution is
86 not that favorable than in the backward direction, according to the data in [6]. The angle
87 and energy distributions of electrons and their effect to the timing properties are
88 discussed in more detail in the following.

89

90 **2 Experimental and simulation parameters**

91

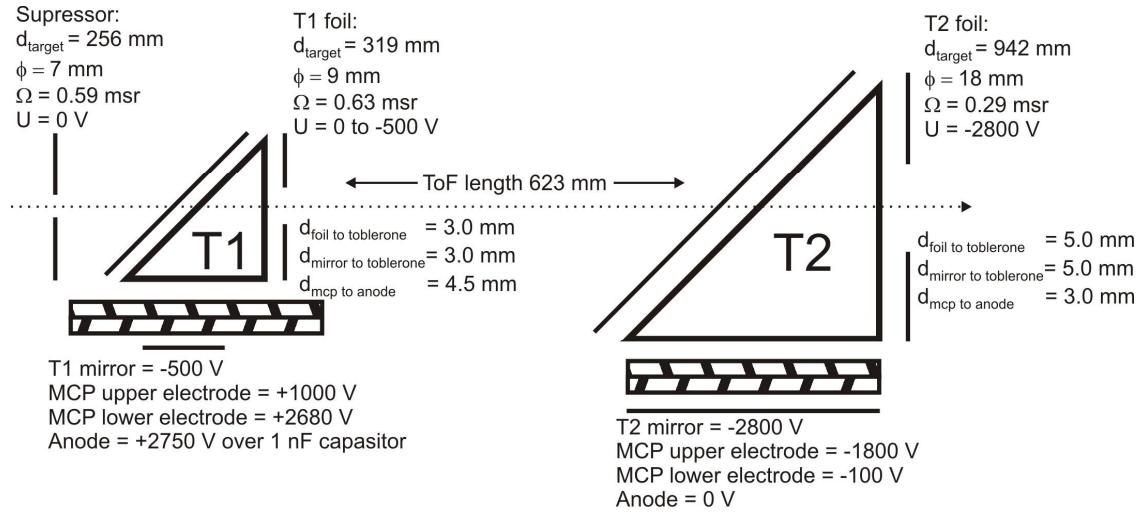
92 ToF-ERDA spectrometer with two carbon foil time pick-up detectors is located at the
93 +15 degree beam line of the 1.7 MV Pelletron accelerator of the Accelerator Laboratory,
94 University of Jyväskylä. ToF-ERDA method is best suited for light elements on heavy
95 substrates, but the hydrogen recoils are often the most difficult ones to detect. One reason
96 for this is the small stopping force of the detector carbon foils for hydrogen. Due to this,
97 only a very small number of electrons is emitted from the carbon foil by the passing
98 hydrogen ion. The single electron events are studied as a cause for the halos observed in
99 the hydrogen isobars. The halos were experimentally studied with 2 MeV $^1\text{H}^+$ beam
100 scattered from a thick target. The model system in the simulations was the second timing
101 gate.

102

103 **2.1. Timing gates of the ToF-ERDA spectrometer**

104

105 The first (T1) and second (T2) timing gates are not identical in our system. The main
106 differences are the physical sizes and the voltages of the different individual components.
107



108

109 *Figure 2. Distances, carbon foil sizes, solid angles and voltages of the Jyväskylä ToF-*
110 *ERDA timing gates.*

111 The measures and voltages of the TOF telescope are shown in Fig. 2. The T2 has a solid
112 angle of 0.29 msr, roughly half of the T1, although it is physically considerably larger.
113 The total solid angle of the ToF-E telescope is governed by the T2 carbon foil holder (see
114 also Fig. 3 b) as the silicon energy detector, placed right after the T2, has larger surface
115 area of 450 mm². The same MCP's (>40 mm active area, 12 µm pore size, d/L=1:40) are
116 used in both of the timing gates. The anodes in both timing gates are modified from the
117 original MCP stack-structure and are currently made from a printed circuit board. Anode
118 to MCP electrode distance is 4.5 mm and 3.0 mm for the T1 and T2, respectively.
119 Supplier for the MCP's was Tectra [11].

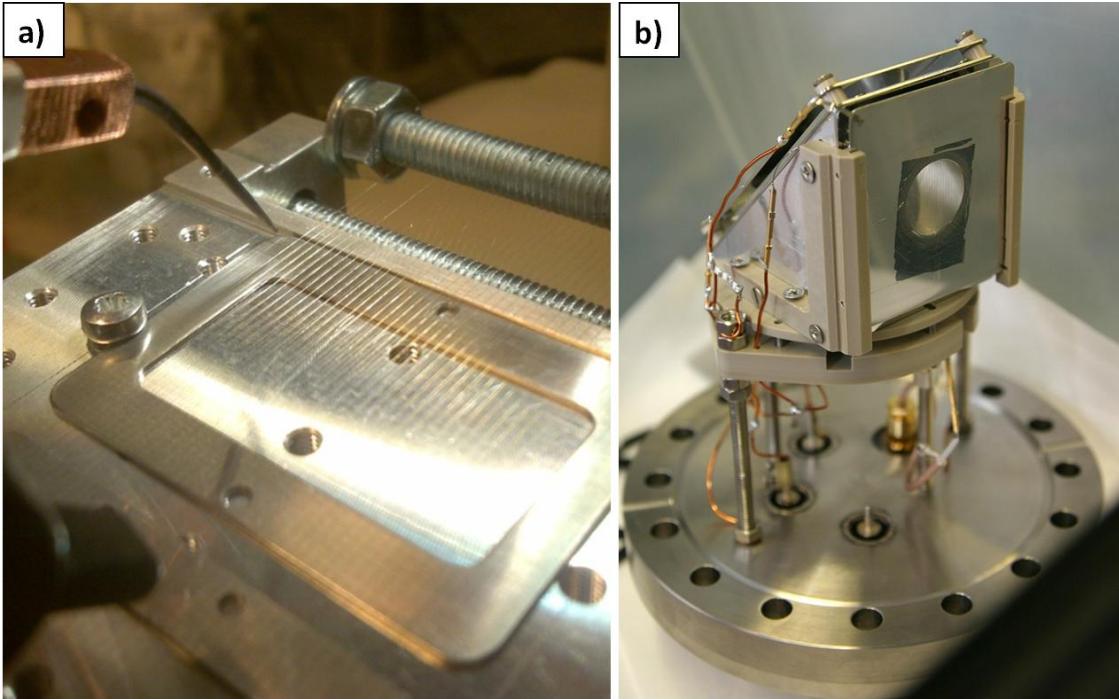
120

121 The used voltages are different for T1 and T2. In the T1 the anode is at +2750 V, MCP
122 lower (closer to anode) and upper electrodes are at +2660 V and +1000 V respectively,
123 and the carbon foil can be grounded or slightly negatively biased. The T1 mirror grid
124 needs to be negatively biased as it otherwise would accelerate free electrons towards the
125 grid and the MCP; typically -500 V is used in our measurements. The signal is taken
126 from the T1 anode over a 1 nF capacitor. For T2 -2800 V is applied on both mirror and
127 foil, -1800 V on MCP upper electrode and on toblerone-part and anode is at ground
128 potential.

129

130 High transparency grids in our timing gates compose of thin (diameters 25 and 20 µm)
131 Au plated tungsten wires [12] that are point welded to their support frames (see Fig.3 a).
132 The wire-to-wire spacing is 1.0 mm which was adopted from the timing gates developed
133 earlier in our lab for nuclear physics experiments [13,14]. Distances from the foil to the
134 first accelerating grid are 3.0 mm and 5.0 mm for T1 and T2, respectively. The distances
135 of the mirror grids from the toblerone grids are the same than those of the foils. By using
136 this type of point welded grid structure we have achieved better than 86 % optical
137 transmission through two timing gates (6 wire grids in total) together with the highly
138 parallel and well aligned grid structure.

139



140

141 *Figure 3. a) Point welding jig used in the fabrication of a grid. Wire (here 20 μm) is first*
 142 *wound around the jig where the pitch is determined by the pitch of the threads in both*
 143 *ends. Then, each wire is point welded from both ends to the frame holding the final grid*
 144 *structure. b) T2 timing detector fully assembled with 10 $\mu\text{g}/\text{cm}^2$ carbon foil.*

145 **2.2. Electron flight time and -path simulation at the timing gate**

146

147 A 2D model of the T2 timing gate was brought to the Simion program [15]. Simion is a
 148 software package primarily used for calculating electric fields and the charged particle
 149 trajectories in those fields [15].

150

151 Physically larger T2 was selected for the simulations as electron flight times, and possible
 152 time spreads were expected to be larger in it. Possible results were expected to scale
 153 down for the smaller T1. The model of the T2 timing gate had $20\,000 \times 20\,000$ pixels so
 154 that one pixel corresponded to about $3.5\,\mu\text{m}$. Thus $25\,\mu\text{m}$ wires in the real system had
 155 diameter of 7 pixels in the simulations.

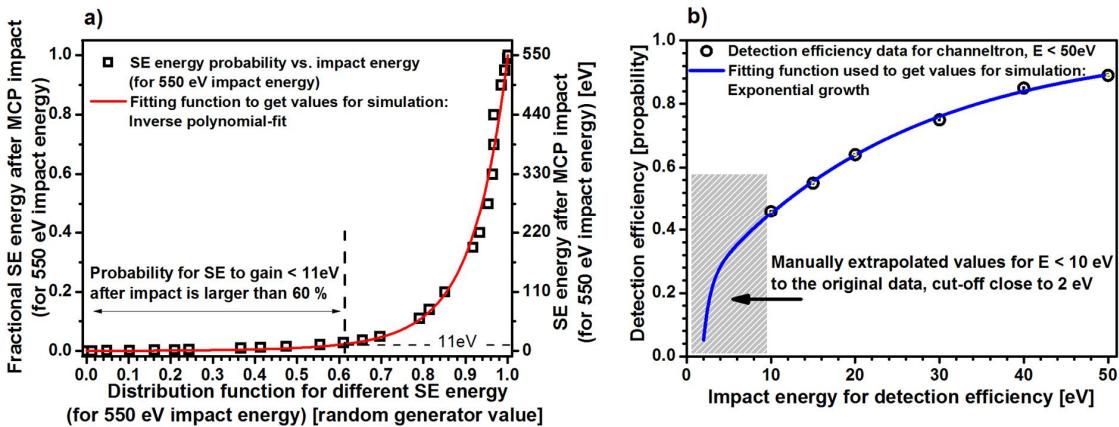
156

157 The focus in the simulations was to find the optimal wire-to-wire spacing and potentials
 158 for the best achievable isochronous electron transport from the foil to the MCP electrode.
 159 The wire-to-wire spacing was varied from the ideal case (transparent, flat electric
 160 potential field) to 0.5 mm, 1.0 mm, 1.5 mm and 3.0 mm. During the selection of the
 161 initial standard parameters for electron emission values, which was a sort of a
 162 compromise of the literature data available, mainly values from the Ref. [6] was finally
 163 used. The standard electron emission parameters were kept as: $E_{\text{kin}} = 4 \pm 4\,\text{eV}$ (Gaussian
 164 distribution) and incident angle of electron emission was uniformly distributed $\pm 30^\circ$
 165 from the normal of the foil surface. The potentials were nominally the same as in the

166 experimental configuration. Also other electron emission parameters from the carbon foil
167 were studied to cover wider electron energy and angular distributions and to verify their
168 effect to the electron flight times compared to the standard electron emission parameters.
169

170 In other simulations the electron scattering from the wire grids and from the MCP upper
171 electrode was studied in order to find the explanation to the longer than average electron
172 flight times seen in the experimental spectrum. The electron coming from the carbon foil
173 has energy about 1000 eV when hitting the wires or the MCP electrode. A single
174 secondary electron was created from the single impact and the emission direction was set
175 as a specular reflection (incident angle = reflection angle). Estimation of the created
176 secondary electron kinetic energy and the detection probability at the MCP pore was
177 problematic. Experimental data for the secondary and backscattering electron energies
178 and probabilities used in these simulations were taken from [16,17]. A function fitted to
179 the data shown in Fig. 4 a) was used by a random generator to determine the SE emission
180 energy after the initial impact. However, the data points in Fig. 4 a) were taken directly
181 from the Ref. [16] and are for the 550 eV incident impact energy. Although the energy
182 data for incident electron reach only 550 eV at [16] and not 1000 eV it can be concluded
183 from [16] and [17] that most of the secondary electrons are always emitted with low
184 energies <20 eV, having an intensity maximum at around 2 eV. This is regardless of the
185 impact energy. When going to higher energies the secondary electron emission intensity
186 drops close to zero for energies above 50 eV. However, there is always a small amount of
187 true backscattered/reflected electrons which have nearly the same energy as the incident
188 particle but their probability at 550 (and 1000) eV is very small. For this reason we have
189 neglected the material differences between [16] and our system (Cu at [16] vs. Au plated
190 W at wire grids and Ni at the MCP electrode material).

191



192

193 *Figure 4. a) The secondary electron emission energy distribution as a distribution*
 194 *195 probability function in a) was used to calculate the energy for the emitted electron after*
 196 *the primary electron had hit to the wire or the MCP surface. About 60 % of these*
 197 *198 secondary electrons had less than 11 eV (= 0.02 × 550 eV) energy although small*
 199 *amount of the emissions occurred almost at impact energies (true backscattering events).*
 200 *In b) estimated values for the detection efficiency of the MCP were taken from Ref. [49]*
 201 *down to 10 eV and the points below the 10 eV impact energy are approximated with a*
 202 *cut-off value of < 2 eV. Higher than 50 eV impact energies were assumed to have*
constant detection efficiency (~90 %) in the simulations.

203 The energy distribution of the secondary electrons (from the MCP electrode) influences
 204 not only the electron flight time distribution before the MCP but also the detection
 205 efficiency of the MCP. The detected hydrogen yield can be greatly affected by the MCP
 206 detection efficiency for low energy electrons. The MCP detection efficiency for our
 207 configuration was not available for very low electron energies. An approximation for the
 208 MCP detection efficiency at smallest energies was obtained partly (down to 10 eV) from
 209 [18] and is shown in Fig. 4 b).

210

211 3. Results

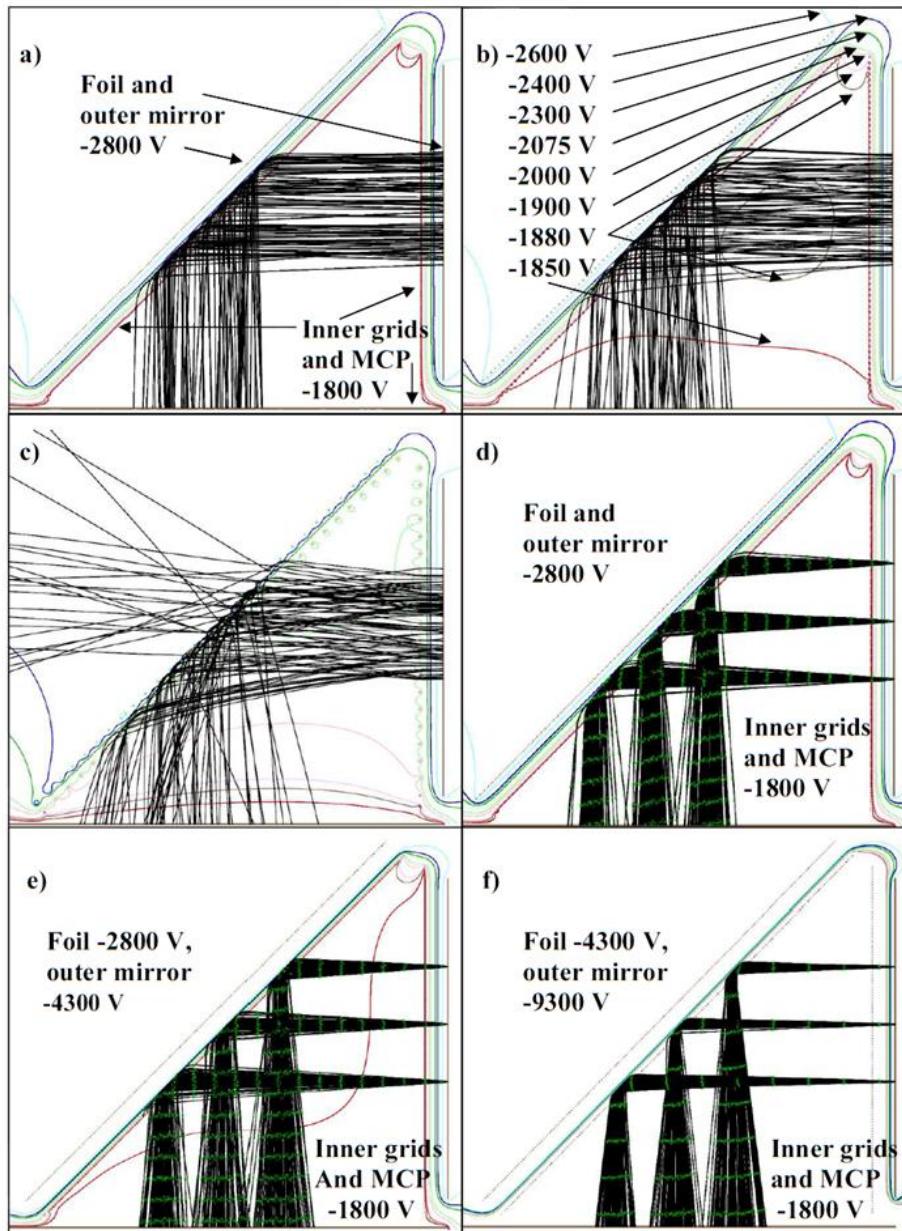
212

213 3.1. Electron paths and flight times: the effect of the grids and voltages

214

215 Both wire-to-wire spacing and the applied foil, toberone part and mirror grid voltage
 216 affect the electron transport from the foil to the MCP surface. Visual examples are
 217 presented in the Fig. 5. Here a) to c) represent different wire spacings (and also mirror
 218 grid distance change in c) which illustrate the need for obtaining both smooth
 219 acceleration from the foil to the 1st grid and a field free region inside the toberone-part.
 220 The voltage configuration can affect the isochronous transportation of electrons and also
 221 the position information of the electron impact location on the MCP. This is
 222 demonstrated in Fig. 5 d) to f) where the time scale (200 ps ticks) is visualized by green
 223 markers.

224



225

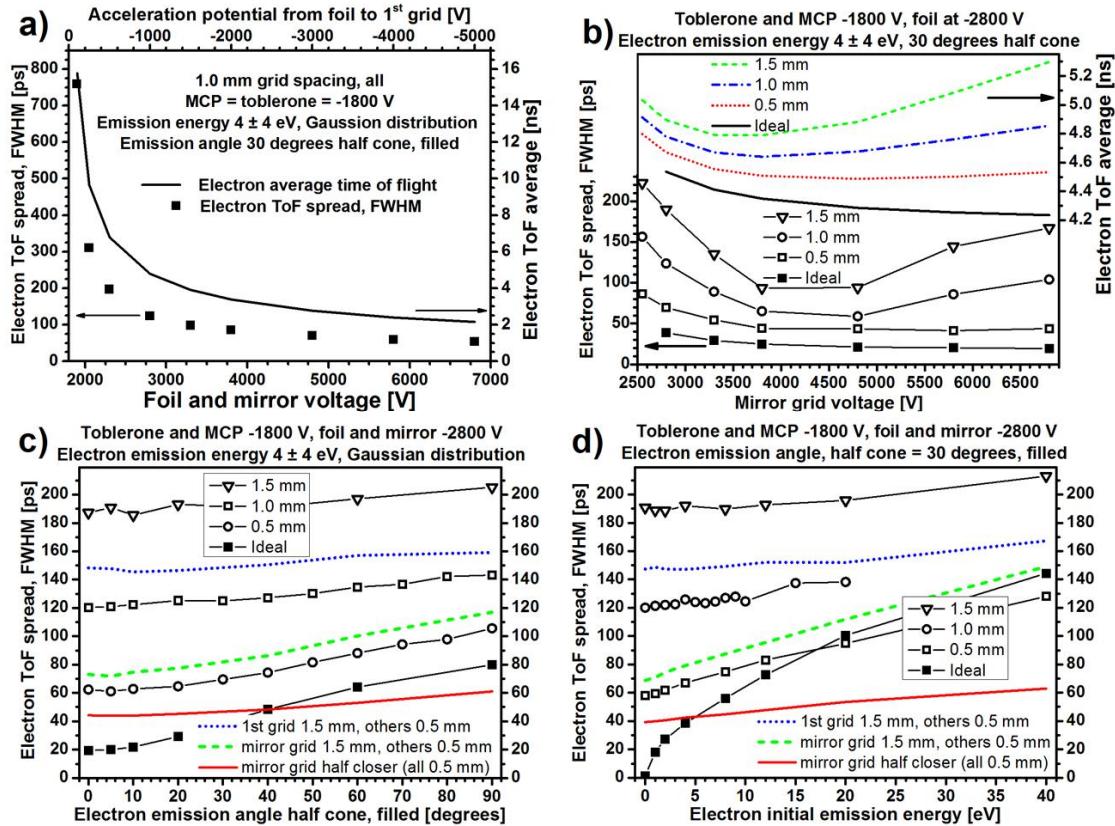
226 *Figure 5. Electron trajectory simulations made with SIMION program for the T2 timing*
 227 *gate with different wire-to-wire spacings and applied voltages. In a), b) and c) the wire-*
 228 *to-wire spacings are 0.5 mm, 1 mm and 3 mm, respectively, where b) represents the*
 229 *experimental configuration in Jyväskylä. In c) the outer mirror grid is brought 1/3 closer*
 230 *to the inner mirror grid from the original perpendicular distance of 5.0 mm. In d), e) and*
 231 *f) the accelerating foil potential and the outer mirror potential has been changed for the*
 232 *0.5 mm wire-to-wire spacing –case. The (green) markers on the black electron paths*
 233 *indicate 200 ps time intervals. In these simulations, all electrons emitted from the foil*
 234 *have initial energy of (4 ± 6) eV with uniform distribution of ± 40 degree perpendicular*
 235 *to the foil surface (note: these emission values are slightly different than the standard*
 236 *electron emission parameters used elsewhere in this paper).*

237 In general, the larger the individual wire-to-wire spacing is, the greater is the spreading of
238 the electron tracks. To reduce the electron track and electron flight time spread, one
239 should use small wire-to-wire spacing particularly in the 1st accelerating grid. To further
240 reduce the electron flight time spread, the potential difference between mirror grids
241 should be about 2 to 2.5 times higher than the potential difference from the foil to the 1st
242 accelerating grid (see Fig. 6 b). The high mirror grid potential reduces the time the
243 electrons spend in the mirror volume and thus reduces the deviation in the lengths of the
244 electron flight paths. This path length deviation is originally caused by the non-uniform
245 entering angle to the mirror volume. However, as seen from the Fig. 6 b), one cannot
246 increase the mirror voltage infinitely to reduce the flight time spread as when the
247 electrons are pushed too close to the toblerone wire grid their flight times start to deviate
248 from the shortest achievable value. This does not happen for the ideal grid because this
249 spread originates from the influence of the individual wire potentials of the non-ideal grid
250 to the electron flight paths.

251

252 One can reduce the electron flight time by increasing the acceleration potential and this
253 also reduces the electron flight time spread (Fig. 6 a). The spread almost saturates for
254 acceleration potentials above 1000 V. Very high potential differences between the foil
255 and the toblerone can quickly lead to practical problems like bulging of the carbon foil
256 due to electric field or sparking, and it will clearly make the tandem effect [19] larger in
257 the case of T1, especially if the foil is in high potential and not grounded.

258



259

260 *Figure 6. The effect of different timing gate and electron emission parameters to the*
 261 *electron flight time spread. a) The electron ToF spread and the electron flight times as a*
 262 *function of foil and mirror voltage. b) The TOF spread as a function of mirror grid*
 263 *potential for a fixed foil voltage. The TOF spread as a function of electron emission half*
 264 *cone c) and electron emission energy d).*

265 Simulation results shown in the Fig. 6 c) and d) confirm that those electrons having the
 266 highest energy and widest emission angle when exiting the carbon foil will result the
 267 greatest time spread in electron flight times. While these events cannot be avoided, it is
 268 possible to minimize the timing spread caused by these electrons by design. Having as
 269 small wire-to-wire spacing as possible in the first acceleration grid, electric field strength
 270 in the mirror about two times as high as in the accelerating grid, one can still save some
 271 effort during the grid construction if having only 1.5 mm wire-to-wire spacing in the
 272 outer mirror grid. As our simulations indicate that, our current wire-to-wire spacing and
 273 used voltages in the timing gates are not optimal when electron flight time spread is
 274 concerned. By reducing the current 1.0 mm wire-to-wire spacing to 0.5 mm and by
 275 increasing the current mirror voltage from -2800 V closer to -4000V for T2 one can
 276 reduce the estimated electron flight time spread from 125 ps to less than 50 ps (taken
 277 from Fig. 6 b)) without touching the foil or MCP/toblerone voltages.

278

279 The impact of the electron flight time spread in the single timing gate to the actually
 280 measured ion ToF spread in the two timing gates is not linear. It can be estimated that for

281 the heavier ions, which emit more electrons when passing through the carbon foils, the
282 spread of electrons flight times have smaller effect to the ion time-of-flight spread. This
283 is due to more uniform electron emission cone at the carbon foil and because the fastest
284 electrons will always cause the initial signal rise at the anode after the MCP. However,
285 the lighter ions such as hydrogen to carbon which emit only one (even zero) to few
286 electrons from the carbon foil, the single electron flight time is more important. This is
287 because if the only emitted electron(s) flew the shortest and the longest flight times
288 before the MCP in the T1 and T2, respectively, a larger spread for the ion ToF will be
289 measured. If compared to the other effects [3,20] causing the measured ion ToF spread,
290 including the straggling in the first carbon foil, the overall contribution of the electron
291 flight time spread in a single time gate is small. If for example timing resolution cannot
292 be pushed down to 150 ps regime (corresponding about 30 keV for 4 MeV ions for
293 Jyväskylä ToF-ERDA [21]) and the kinematic effect due to large solid angle cannot be
294 compensated, the electron flight time spread is very small compared to other sources of
295 ion ToF spreads.

296

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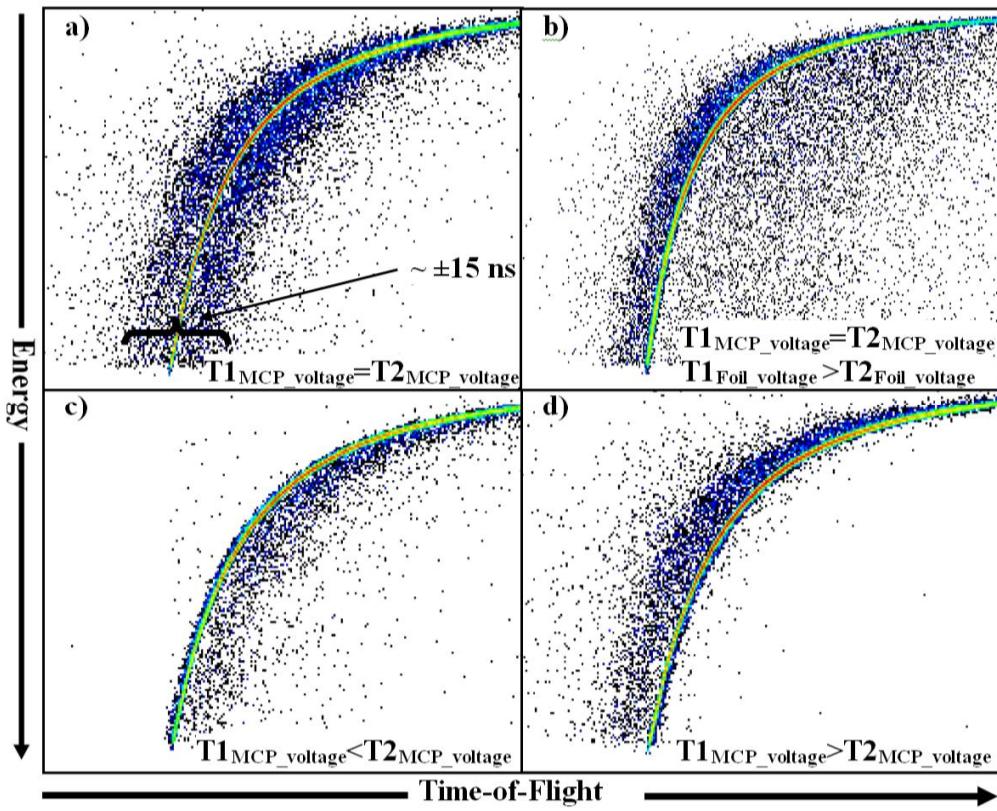
298

299 **3.2. Halo around the hydrogen time-of-flight events**

300

301 Measured ToF-E isobars for the hydrogen have a clearly structured halo on both longer
302 and shorter time-of-flights (see Fig. 7). For hydrogen these halo events can contribute at
303 high energies up to 25 % of all hydrogen events compared to the tight selection (see Fig.
304 7). Although this type of halo is most pronounced for the hydrogen, similar halos but
305 with reduced intensity can also be seen up to mass of carbon. The halo is typically about
306 ± 15 ns wide from the center of the as-expected ToF-value. By varying both the MCP and
307 the foil (and mirror) voltages as shown in Fig. 7 it can be deduced that the events that
308 give birth to the halo are generated after the foil and before the MCP. As seen in Fig. 7 b)
309 the T2 foil voltage reduction (nominally -1000 V compared to the MCP upper surface
310 electrode) also spreads out the halo to the right side, longer ToF, but not completely
311 smooths it out. The Fig. 7 c) and d) on the other hand indicate that the halo is generated
312 from those events that have longer than normal ToF and especially from those events that
313 have smaller than average pulse height as they vanish earlier with smaller MCP voltages
314 (gain) compared to the main peak intensity. This pulse height difference in the halo and
315 the main peak was also confirmed with the fast CAEN N6751 digitizer unit with full
316 signal shape recording. From the Fig. 7 b) it is also more evident that there is a small gap
317 between the halo-events and the main peak in which less events are detected. This
318 shallow event free gap is more clearly visible in Fig. 9.

319

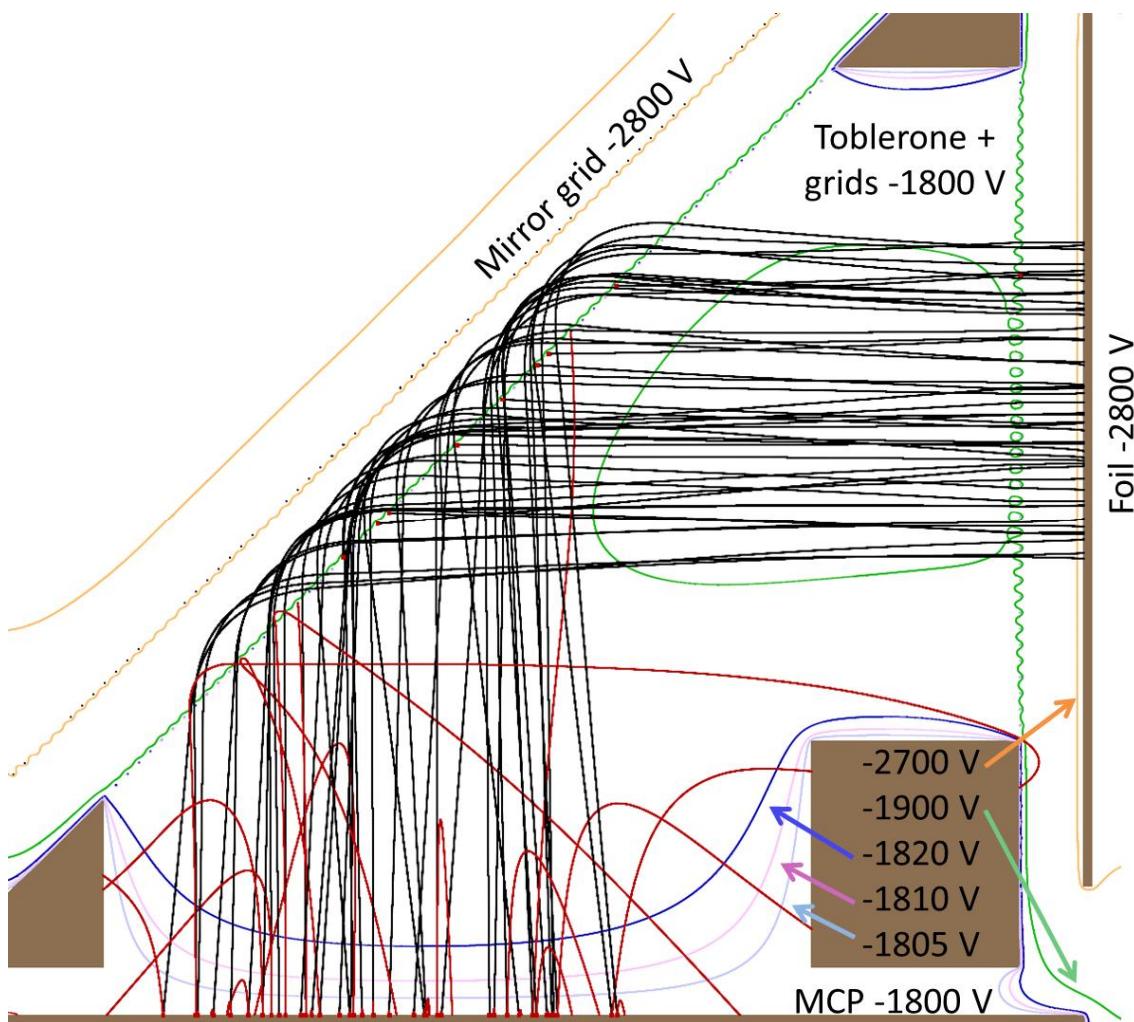


320

321 *Figure 7. Time-of-flight–energy histogram showing the influence of the MCP voltage*
 322 *and foil voltage to the scattered hydrogen ion TOFs. When operating at nominal voltages*
 323 *for our system, hydrogen has a clear background distributing over ± 15 ns from the main*
 324 *isobar as well as lighter background spreading further away as shown in a). In b) only*
 325 *the T2 foil has reduced voltage and therefore only smaller electron energies are*
 326 *available within the T2. In c) only T1 MCP gain has been lowered so that only multiple*
 327 *electron events generate detectable signals at T1 (similarly for T2 in d).*

328
329

330

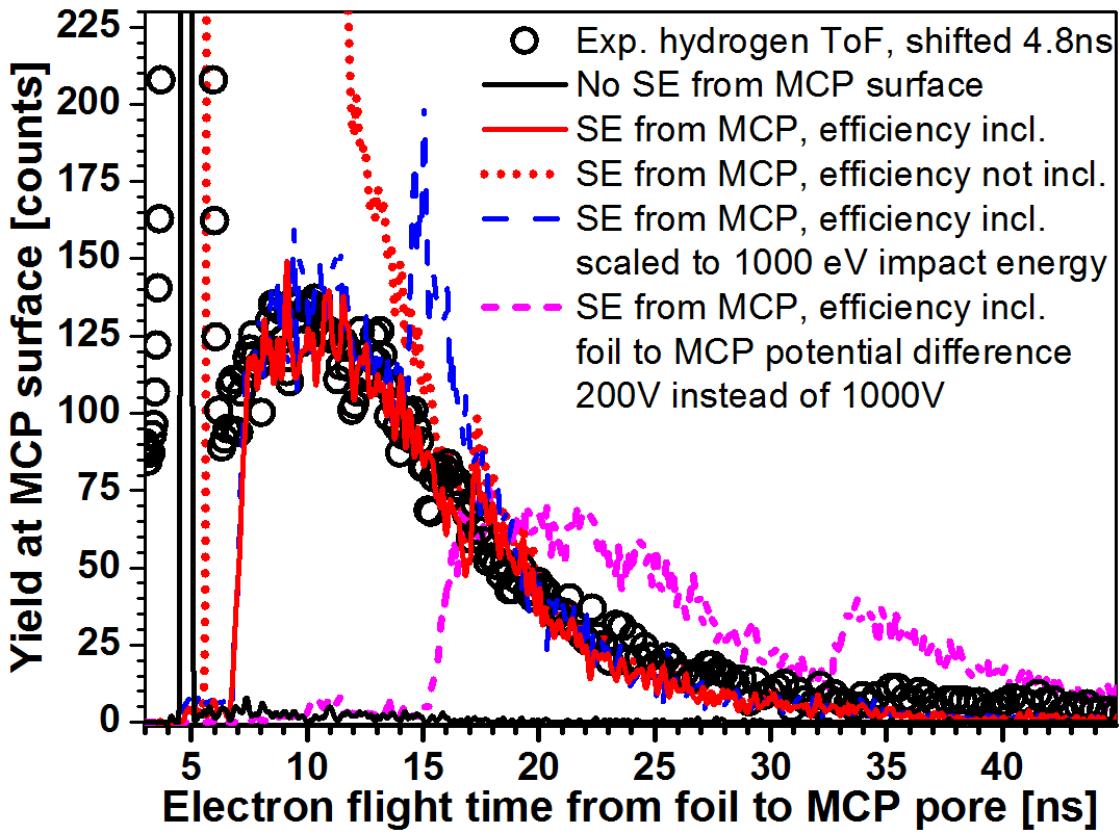


331

332 *Figure 8. Electron paths (43) in our current T2 timing gate simulated with nominal*
 333 *parameters. Single secondary electron emission was set to occur due to the primary*
 334 *electron impact. About half of the secondary electrons (48 in total) from the MCP have*
 335 *too little energy to be visible in this scale. In total, 10 secondary events end up to the*
 336 *toblerone side mirror grid and 5 to the walls of the toblerone block, while majority of the*
 337 *secondary electrons from the MCP surface end up back to the MCP surface and can*
generate a signal.

338

339 Figure 8 shows simulated electron trajectories in a timing gate. In Fig. 8 most of the
 340 secondary electron paths are not even visible and do not reach the -1805 V equipotential
 341 line above from the MCP as SE energy distribution intensity maximum is smaller than 5
 342 eV. For the same reason most of the SEs created by the primary electron hitting the wire
 343 grids cannot escape the potential field of the individual wire.



344

345 Figure 9. Experimental time-of-flight data from the hydrogen ions and corresponding
 346 electron flight time simulations from the carbon foil to the MCP surface in our current T2
 347 detector. The use of 1000 eV impact energy instead of 550 eV changes very little the
 348 overall shape of the extended flight times with the exception of the shifted peak which is
 349 present at the simulations (see text). The solid black line represents the case in which
 350 scattering/secondary events only from the wire grids are considered. The dashed pink
 351 line shows the extended electron flight times for reduced foil and mirror potentials. In the
 352 experimental data the main peak (at 4.8 ns) has about 75 % of all events detected.

353 In the Fig. 9 are shown both the experimental data and simulated electron flight times in
 354 different cases. The experimental data in Fig. 9 is shifted +4.8 ns which corresponds the
 355 simulated, as-expected, electron flight time from the foil to the MCP. As seen from the
 356 Fig. 9 only a very small contribution comes from the events that have scattered only from
 357 the wires and scattering from the MCP surface dominates. The case in which MCP
 358 detection efficiency for different energies is not included (pointed line) the electron flight
 359 times between 6 and 15 ns are considerably pronounced compared to the experimental
 360 data. However, if the MCP efficiency estimation for low electron energies is included, the
 361 yield for the shortest secondary electron flight times between 6 and 15 ns drops
 362 considerably, and simulations agree with the experimental data. There is, however, a
 363 small peak in the simulation data at about 17 ns (and a larger peak at ~15 ns for impact
 364 energies scaled to 1000 eV). The origin of this extra peak, which changes very little the
 365 overall shape of the extended flight times, is due to the highest energy electrons which

366 have emitted from the MCP surface. The high energy electrons, most likely backscattered
367 ones, have enough energy to wiggle back to the mirror and foil grids in the toblerone-part
368 before ending back to the pore of the MCP. As this type of peak is not seen in the
369 experimental data it can be concluded that the high energy backscattering yield is
370 overestimated in the simulation parameters. If voltage of 200 V is used for both foil and
371 mirror instead of 1000 V, the simulated distribution of secondary electrons (Fig. 9)
372 becomes much broader. The same effect is visible in Fig. 7 b) where roughly the same
373 parameters were in use in an experiment.

374

375 **4 Conclusions**

376

377 Electron transport properties in the carbon foil time pick-up detectors, being in use in the
378 Jyväskylä ToF-ERD setup, have been investigated. Experimentally detected halo around
379 the hydrogen isobar in the ToF-E histogram could be reproduced by simulations and its
380 origin is understood. Experimentally it was confirmed that the halo events had smaller
381 MCP pulses indicating that they originate from single electron events. In the simulations
382 the halo was confirmed to form from those secondary electrons from the MCP surface
383 that ended up to the active MCP pore after a short time period.

384

385 More simulations were made to study the different wire-to-wire spacings and voltages in
386 the grids for electrons with different incident energy and angle. By decreasing the wire-
387 to-wire spacing and increasing the acceleration potential together with the mirror voltage,
388 smaller flight time spreads were observed. By using less tightly spaced mirror grids (1.5
389 mm spacing), 0.5 mm spaced toblerone grids and 2–2.5 higher mirror potential difference
390 than for the acceleration the timing spread reduces considerably.

391

392 **Acknowledgements**

393

394

395 This work was supported under the auspices of Finnish Centre of Excellence Programme
396 2006-2014 (Project No. 213503, 251353 Nuclear and Accelerator Based Physics),
397 Finnish Funding Agency for Technology and Innovation (Tekes) project ALEBOND
398 (decision no. 40079/08), MECHALD (decision no. 40207/11) and HIUDAKE (decision
399 no. 70027/11) and Tekes EU-regional funds project (decision no. 70039/08).

400

401

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