# Simulation of RPC Performance for 511 keV Photon Detection

C. Lippmann *, H. Vincke, W. Riegler

*CERN, Geneva, Switzerland*

**Abstract**

Measurements of the time resolution of Timing Resistive Plate Chambers reveal some differences when comparing the results for 511 keV photons and for particle beams. The subject is of interest, since Timing RPCs are currently considered for Positron Emission Tomography (PET), where the sensitivity of the system depends largely on the time resolution of the detector. In this publication we discuss possible explanations, in particular the statistical fluctuations of the deposited charge and the Compton electron flight time distributions. Moreover, we rediscuss the reduction of the Townsend coefficient due to the space charge effect inside the avalanches as a function of the avalanche size. We shall see that the dependence assumed by different analytic models differs significantly from what is predicted by detailed Monte Carlo avalanche simulations.

*Key words:* Positron Emission Tomography, PET, Timing Resistive Plate Chamber, RPC, time resolution, Townsend coefficient, space charge effect
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## 1. Introduction

Timing Resistive Plate Chambers (RPCs) are currently explored as potential detectors for Positron Emission Tomography (PET) for the imaging of small animals, but also for high-sensitivity whole-body human PET [1,2]. In PET one takes advantage of the fact that two 511 keV photons from the electron-positron annihilation in the object of study are emitted simultaneously and almost anti-parallel. By accumulating many coincident photon events it is possible to reconstruct the activity distribution in the tissues. The advantages of Timing RPCs over the commonly used scintillator materials are the cost efficiency, excellent time resolution (300 ps FWHM for 511 keV photon pairs) and very good intrinsic position accuracy (50 $\mu$m in digital readout mode) [2].

For a single gap RPC like the one shown in Fig. 1 the measured time resolution is about 90 ps for single 511 keV photons [3,4], which has been confirmed in independent measurements [5]. However, this result is considerably worse than for particle beams, where one finds values below 60 ps. It would be surprising if the time resolution for photons was worse, since the charge is deposited by rather slow (and heavily ionising) Compton electrons in the case of the photon interactions and thus the amount of charge deposited in the gas gap is in general larger than for interactions of minimum ionising particles.

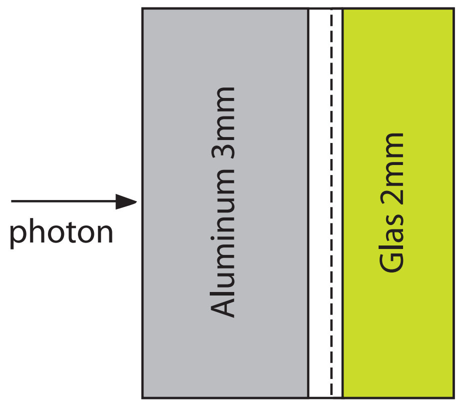


Fig. 1. RPC geometry investigated in this publication. It is similar to the one described in Ref. [3]. The photon enters either through the metal or glas electrode. For our analysis we divide the gas gap in two layers of 0.2 mm and 0.1 mm, respectively. The gas mixture is $C_2F_4H_2$ (96.7 %) / i-$C_4H_{10}$ (3 %) / $SF_6$ (0.3 %).

Moreover, measurements show that the time resolution is essentially independent of the applied high voltage (HV) for photons (see e.g. Fig. 8.24. in [6]). From the avalanche dynamics one would always expect that the time resolution improves, as the applied HV is increased. This immediately follows from the simple formula for the time resolution of an RPC [7]:

$$\sigma_t = \frac{1.28}{\alpha_{eff}(E)\, v_D(E)} \ . \tag{1}$$

Here $\alpha_{eff}$ is the effective Townsend coefficient and $v_D$ is the electron drift velocity in the gas. Both values increase as the

* Corresponding author; now at CERN, Geneva, Switzerland.
*Email address:* Christian.Lippmann@cern.ch (C. Lippmann).

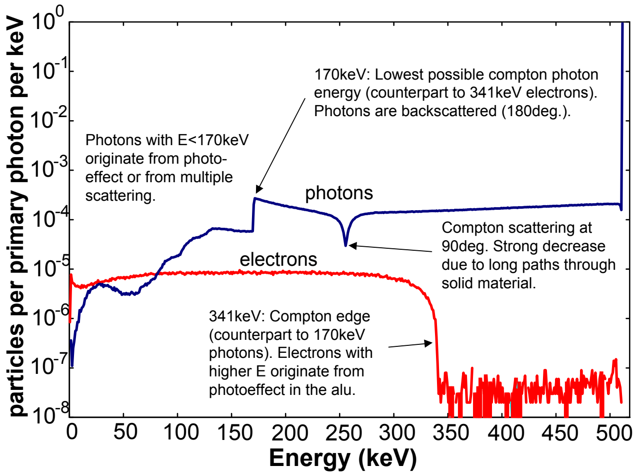


Fig. 2. Particle currents in the 0.2 mm layer of the gas gap.

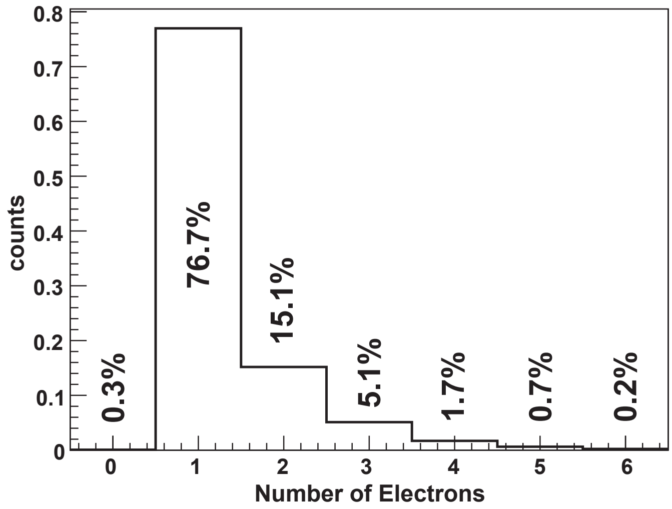


Fig. 3. Distribution of the number of electrons entering the 0.2 mm layer of the gas gap. In 76.7 % of the cases there is just a Compton electron. 23 % of the events are more complex.

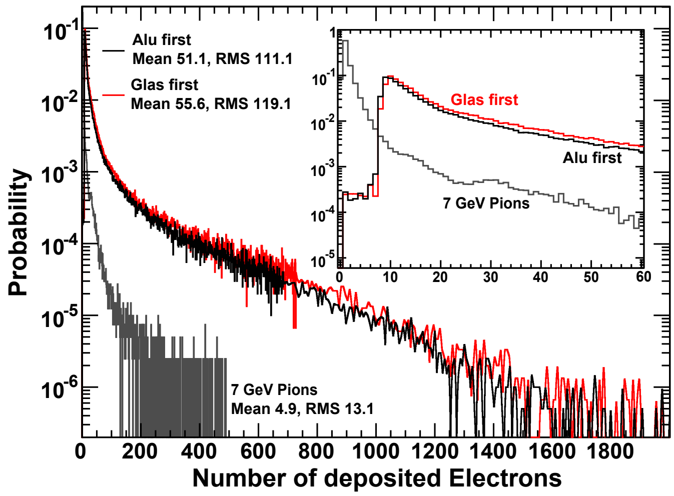


Fig. 4. Number of Electrons produced in the 0.2 mm layer of the gas gap for 511 keV photon interactions from both sides of the detector (aluminium first or glass first) and for 7 GeV pions. For the pions the mean free path between interactions is 0.1 mm and each interaction produces a fluctuating number of electrons. The insert shows in more detail the region with small electron numbers.

electric field $E$ is increased. However, on top of the avalanche dynamics other factors also influence the threshold crossing time and thus the time resolution. The most relevant are

– the statistical variance of the primary charge,
– the magnitude of the space charge effect as a function of the track angle,
– the (Compton) electron flight time into the gas gap and
– the time span where charge is deposited in the gas gap.

These factors are systematically studied in this publication in order to find an explanation for the observed results.

## 2. 511 keV Photon Interactions in an RPC

We use FLUKA [8,9] to simulate the interactions of 511 keV photons with the RPC material. The setup is shown in Fig. 1. The gas gap is divided in two layers of 0.2 mm and 0.1 mm. We are in the following focusing on the energy deposit in the 0.2 mm layer, since approximately only this part of the gas gap of a Timing RPC is efficient. Avalanches started in the inefficient layer do not reach the threshold and are thus not detected. Fig. 2 shows the particle currents in the 0.2 mm layer. Only one in 500 photons interacts with the setup. The main interaction process is Compton scattering in the electrode materials; the Compton edge is clearly visible in Fig. 2. At the given primary photon energy of 511 keV it corresponds to $\frac{2}{3}$ 511 keV for the Compton electrons and $\frac{1}{3}$ 511 keV for the photons which are backscattered at 180 degrees. At half the incident photon energy we find a strong decrease in the occurence of Compton photons. At this energy they are scattered at about 90 degrees and thus have rather long paths in the solid electrode materials before reaching the gas volume.

In 76.7 % of the events exactly one Compon electron enters the 0.2 mm layer of the gas gap (See Fig. 3). In 0.3 % of the events no electron enters the gas gap; here the photon interacts in the gas. In 23 % of the events more than one electron is created in a more complex interaction.

Free charges will be produced in the gas gap mainly by ionising collisions of the (Compton) electron(s) with the gas molecules. The Compton electrons are slow and thus highly ionising. Fig. 4 shows the number of electrons liberated for two cases:

– The photon enters through the aluminium electrode.
– The photon enters through the glass electrode.

The difference is very small. The value of 10 electrons is most probable, with a very pronounced tail towards thousands of electrons. This tail is mainly caused by a geometrical effect: The Compton electron enters the gas gap with different possible angles and the highest charge deposits are caused by electrons travelling almost parallel to the electrode planes for a long distance. It is very unlikely to find less than nine electrons for the photon interactions. For comparison we also show the electron number distribution for 7 GeV pions [7]. Here the most probable value is 1 electron with a less pronounced tail towards large electron numbers.

We conclude that an electron number smaller than nine is by far the most likely for particles, while for photons it is rather unlikely to find this number of electrons.

## 3. RPC Response to 511 keV Photons

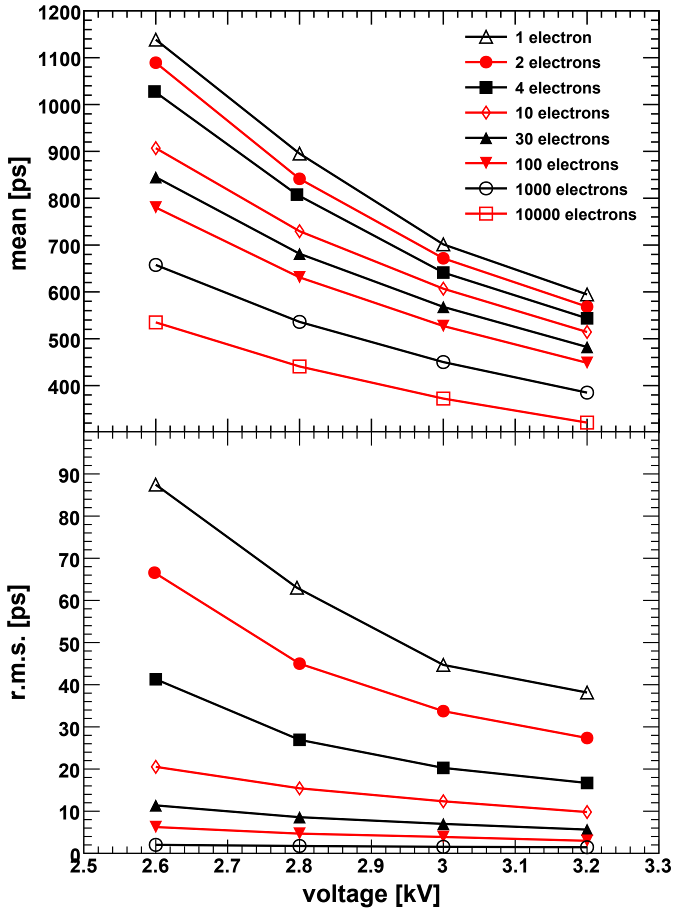


Fig. 5. Mean threshold crossing time (top) and r.m.s. (bottom) for avalanches started by a different number of electrons as a function of the applied HV. By increasing the HV for a fixed electron number the threshold crossing time is shifted to earlier times and the fluctuations around that value decrease. A larger charge for a fixed high voltage leads to earlier threshold crossing and smaller fluctuations as well.

We are now interested in the time response of a single gap Timing RPC for different values of the HV and for different amounts of primary charge (electron numbers in the gas gap). We use the '1.5 D'-Monte Carlo program [10] to simulate the time response. This model includes a space charge effect and can be used to simulate a large number of avalanches in an acceptable time. The model assumes that the space charge is situated in discs of certain radius connected to the transverse diffusion. This avoids the problem of divergence of electric fields calculated close to point or line charges. Moreover, the model uses the following simplifications:

– The avalanches are symmetric around the axis perpendicular to the electrode planes and
– the space charge does not influence the transversal growth of the avalanches.

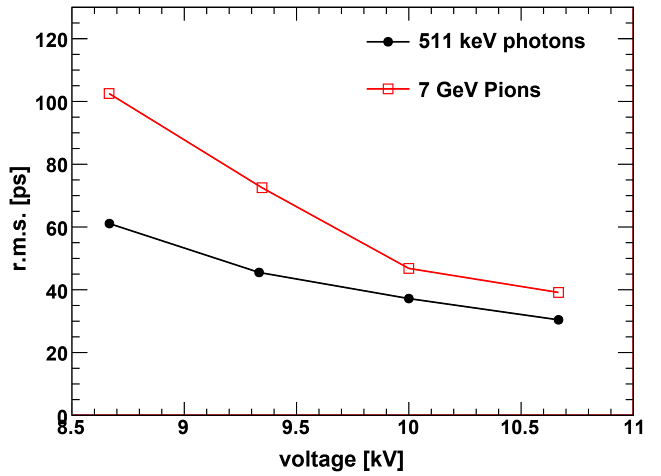


Fig. 6. Simulated time resolution as a function of the applied HV for photons and particles. For particles the simulations confirm the measurements while for photons the simulated results show a timing resolution that is much better than measured results. Moreover, the simulated time resolution improves when increasing the HV, while the measured results are essentially independent from the applied HV.

For the simulation of the RPC response to 511 keV photons we start the avalanches with all electrons situated on the same spot at the cathode, such that they always traverse the full gap length. We are interested in the threshold crossing time for a threshold of 20 fC. The results (mean and r.m.s.) are shown in Fig. 5. Clearly the effect of varying electron number is strongest for small electron numbers (less than ten). Thus, a better timing resolution must be expected for photons, since we have seen that here electron numbers smaller than nine are very unlikely. This is also found by our the detailed simulations using all the decribed data (see Fig. 6). We conclude that the larger statistical variance of the primary charge can not explain the measured values of the time resolution.

### 3.1. *Influence of Geometry and Space Charge Effect*

In Ref. [11] we showed that the space charge effect already influences the signal rise at the threshold level (we use a threshold of 20 fC). It is clear that the more charge is present, the earlier the space charge effect sets in and the stronger it delays the threshold crossing. So far we have assumed that all charge is deposited by the (Compton) electron in one spot. However, in reality the situation is different: The charge is deposited along the electron track, which has a certain angle with respect to the perpendicular to the electrode planes. In that case the space charge effect will be weaker than what we have assumed. It is safe to assume that the events with larger charge deposit (Fig. 4) correspond to events with long track length in the gas gap and thus a larger angle. At large angles one can not assume a single avalanche any more, on the contrary we have many parallel avalanches which influence each other only transversally.

This will have an influence on the threshold crossing time, which will differ from the values shown in Fig. 5. This effect can be estimated using the '1.5 D'-Monte Carlo by comparing the delay of the threshold crossing time due to the space charge effect for avalanches started by one electron and a large number of electrons. For 1000 electrons this difference is 22 ps, for 10 electrons it is 6 ps. Taking this into account in the simulation, a deterioration of about 10 % with respect to the values shown in Fig. 6 is calculated. However, this can not explain the measured values of the time resolution for photons.

### 3.2. *Influence of the Compton Electron Flight Time*

Another possible reason for a deterioration of the time resolution for 511 keV photons is the arrival time distributions of the (Compton) electrons. Fig. 7a shows the distribution of the times where electrons enter and exit the 0.2 mm layer of the gas gap. In some cases a delay of 300 ps or more is accumulated before the charge is deposited in the gas gap and the avalanches start. However, only in 2 % of the events the electron accumulates a delay of more than 10 ps. Thus this effect also can not explain the deterioration of the timing resolution.

Fig. 7b shows the distribution of the time span in which electrons are found in this layer. This is again not enough to explain the deterioration.

## 4. Multiplication in the Presence of a Strong Space Charge Effect

It is well known that in RPCs a strong space charge effect weakens the multiplication at large electron numbers. In different models it is commonly assumed that a saturation happens at about $10^7$ electrons. Many of these models propose a certain dependence of the effective Townsend coefficient on the avalanche size $N$:

$$\alpha_{eff} = \alpha_{eff}(N)\ . \tag{2}$$

An overview and comparison of these models has been given in Ref. [12]. $\alpha_{eff}(N)$ can also be calculated using a detailed simulation of the avalanche dynamics. We use the 2 D-Monte Carlo which has been introduced in Ref. [11]. In this model the only assumption is a rotational symmetry of the avalanche around the axis perpendicular to the electrode planes. This simplification can be used to save calculation time while still taking into account both the longitudinal and transverse effects of the space charge field on multiplication, drift and diffusion inside the avalanche. Using this program we calculate the weighted average effective Townsend coefficient. We average over all positions in the gas gap where electrons are situated and weigh with the number of electrons at those positions. The result is shown in Fig. 8. $\alpha_{eff}$ does not approach zero for large avalanche sizes as assumed in all of the mentioned analytic models. On the contrary it goes through rather complex changes:

- $\alpha_{eff}$ first decreases as the avalanche grows.
- $\alpha_{eff}$ then increases again as the avalanche reaches the anode.
- Finally $\alpha_{eff}$ becomes negative, as strong attachment sets in.

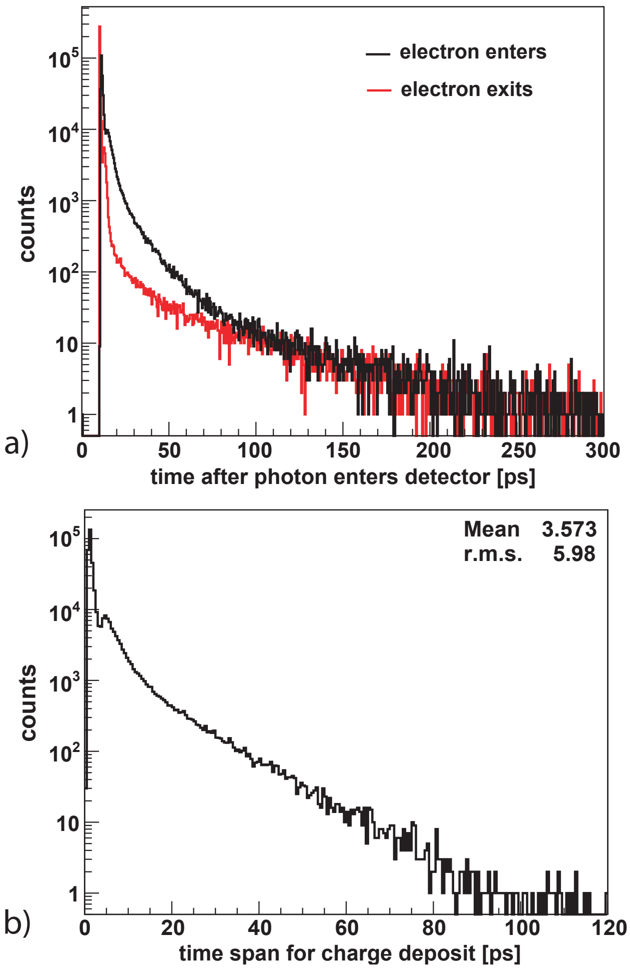


Fig. 7. a) Times of entry and exit for electrons for the 0.2 mm layer of the gas gap. In cases where there is more than one entry and/or exit, we use the earliest entry time and the latest exit time. The first 10 ps correspond to the minimum flight time (at speed of light) through the 3 mm aluminum electrode. b) Time span for the deposit of charges in the 0.2 mm layer of the gas gap. This is calculated by subtracting the earliest time an electron enters this layer from the latest time an electron leaves it. For the (dominant) case where there is only one electron entering and exiting this corresponds to the flight time of this electron through this layer.

The complex evolution of $\alpha_{eff}$ inside an avalanche is also documented in Fig. 23 of Ref. [11].

## 5. Summary and Conclusions

We have simulated the time reolution of a single gap Timing RPC for 511 keV photons and for 7 GeV pions. The simulated time resolution is better for photons than for particle beams, which is contradicting measurements. Moreover, the measurements show that the time resolution is independent from the applied high voltage. The simulations on the other hand show that the time resolution should improve when increasing the high voltage, as it is expected from the avalanche dynamics. The measured independence from the high voltage settings strongly indicates that the time resolution is in the case of photons dominated by effects independent from the avalanche dynamics. We ruled out the effects connected with the statistics of the charge

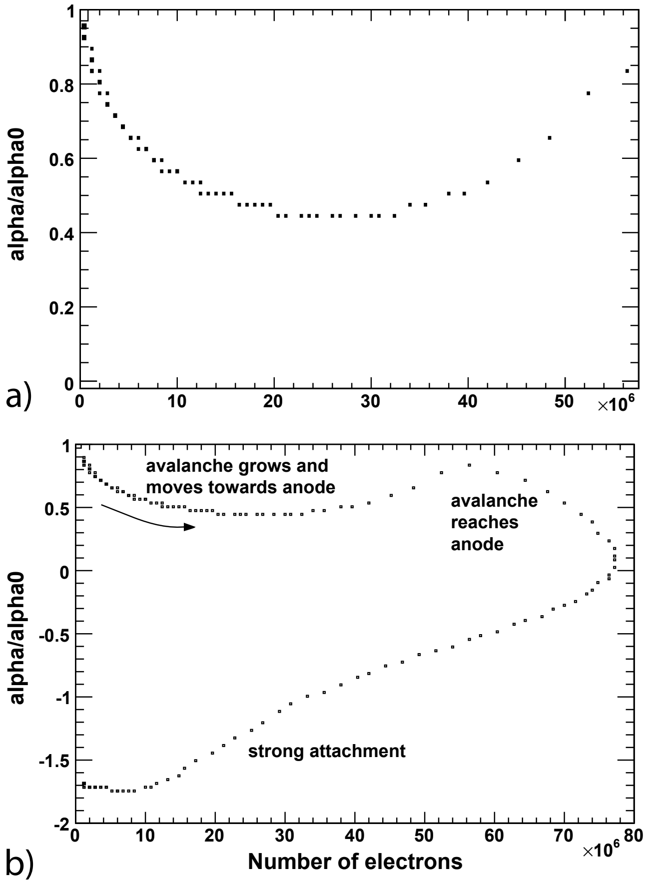


Fig. 8. Simulated evolution of the average effective Townsend coefficient $\alpha_{eff}$. We scale with the initial effective Townsend coefficient at the applied electric field ($\alpha_0$). It is worth pointing out that the pattern visible in the upper panel is the same as found in a previous measurement (Fig. 6 in Ref. [13]).

deposit, with geometry and with the flight times of the Compton electrons in the RPC. In order to finally understand the timing resolution for photons it now seems necessary to simulate the complete setup; while in this publication we focused only on the electrodes and the gas gap.

We have also discussed the evolution of the average effective Townsend coefficient in an avalanche in the RPC gas, as the avalanche size changes. We find a complex behaviour which is different from what is commonly assumed in analytic avalanche models.

## References


[1] A. Blanco et al., Nucl. Instr. Meth. A 508 (2003) 88-93.

[2] M. Couceiro et al., Nucl. Instr. Meth. A 580 (2007) 915-918.

[3] L. Lopez et al., Nucl.Instr. Meth. A 573 (2007) 4-7.

[4] A. Blanco et al., Nucl. Instr. Meth. A 508 (2003) 70-74.

[5] Discussions at this workshop.

[6] D. Gonzales-Diaz, *Research and Developments on Timing RPCs*, Doctoral Thesis, Santiago de Compostela, Spain, 2006.

[7] W. Riegler, C. Lippmann and R. Veenhof, Nucl. Instr. Meth. A 500 (2003) 144-162.

[8] A. Fasso et al, CERN-2005-10 (2005), INFN/TC_05/11, SLAC-R-773

[9] A. Fasso et al, Computing in High Energy and Nuclear Physics 2003 Conference (CHEP2003), La Jolla, USA, March 24-28, 2003, (paper MOMT005), eConf C0303241 (2003), arXiv:hep-ph/0306267

[10] C. Lippmann and W. Riegler, , Nucl. Instr. Meth. A 533 (2004) 11-15.

[11] C. Lippmann and W. Riegler, Nucl. Instr. Meth. A 517 (2004) 54-76.

[12] A. Mangiarotti et al., Nucl. Phys. B Proc. Suppl. 158 (2006) 118–122.

[13] W. Legler, Z. Naturforschg. 16a (1961) 253-261.